# Experimental Determination of the Conditions Associated with "Zebra Stripe" Pattern Generation in the Earth's Inner Radiation Belt

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#### Abstract

The "zebra stripes" are peaks and valleys commonly present in the spectrograms of energetic particles trapped in the Earth's inner belt. Several theories have been proposed over the years to explain their generation, structure and evolution. Yet, the plausibility of various theories has not been tested due to a historical lack of ground-truth, including in-situ electric field measurements. In this work, we leverage the new visibility offered by the database of NASA Van Allen Probes electric drift measurements to reveal the conditions associated with the generation of zebra stripe patterns. Energetic electron flux measurements by the Radiation Belt Storm Probes Ion Composition Experiment between January 1, 2013 and December 31, 2015 are systematically analyzed to determine 370 start times associated with the generation of zebra stripes. Statistical analyses of these events reveal that the zebra stripes are usually created during substorm onset, a time at which prompt penetration electric fields are present in the plasmasphere. All the pieces of experimental evidence collected are consistent with a scenario in which the prompt penetration electric field associated with substorm onset leads to a sudden perturbation of the trapped particle drift motion. Subsequent inner belt drift echoes constitute the zebra stripes. This study exemplifies how the analysis of trapped particle dynamics in the inner belt and slot region provides complimentary information on the dynamics of plasmaspheric electric fields. It is the first time that the signature of prompt penetration electric fields is detected in near-equatorial electric field measurements below L=3.

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2	Generation in the Earth's Inner Radiation Belt
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15	Key words
16	$Zebra\ Stripes-Superposed\ Epoch\ Analysis-Prompt\ Penetration\ Electric\ Fields-Inner\ Radiation$
17	Belt – Substorm
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20	Key Points
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22	1. An algorithm is designed to analyze the zebra stripes present in the spectrograms of energetic
23	electrons trapped in the inner belt.
24	
25	2. A superposed epoch analysis of 370 events is performed to determine the experimental
26	conditions associated with zebra stripe generation.
27	
28	3. Experimental evidence suggests that prompt penetration electric fields associated with substorm
29	onsets routinely generate zebra stripes.

#### 30 Abstract

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32 The "zebra stripes" are peaks and valleys commonly present in the spectrograms of energetic particles trapped in the Earth's inner belt. Several theories have been proposed over the years to 33 explain their generation, structure and evolution. Yet, the plausibility of various theories has not 34 been tested due to a historical lack of ground-truth, including in-situ electric field measurements. 35 In this work, we leverage the new visibility offered by the database of NASA Van Allen Probes 36 electric drift measurements to reveal the conditions associated with the generation of zebra stripe 37 patterns. Energetic electron flux measurements by the Radiation Belt Storm Probes Ion 38 Composition Experiment between January 1, 2013 and December 31, 2015 are systematically 39 analyzed to determine 370 start times associated with the generation of zebra stripes. Statistical 40 analyses of these events reveal that the zebra stripes are usually created during substorm onset, a 41 time at which prompt penetration electric fields are present in the plasmasphere. All the pieces of 42 experimental evidence collected are consistent with a scenario in which the prompt penetration 43 electric field associated with substorm onset leads to a sudden perturbation of the trapped particle 44 45 drift motion. Subsequent inner belt drift echoes constitute the zebra stripes. This study exemplifies how the analysis of trapped particle dynamics in the inner belt and slot region provides 46 complimentary information on the dynamics of plasmaspheric electric fields. It is the first time 47 that the signature of prompt penetration electric fields is detected in near-equatorial electric field 48 49 measurements below L=3.

#### 50 **1. Introduction**

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52 Spectrograms of energetic (tens to hundreds of keV) particles trapped in the Earth's inner radiation 53 belt commonly display time-varying structured peaks and valleys (Imhof and Smith, 1965; Imhof 54 et al., 1981a, 1981b; Datlowe et al., 1985; Sauvaud et al., 2013). These features have been recently 55 named the "zebra stripes" (Ukhorskiy et al., 2014). Newly found "Earth-like zebra stripes" have 56 also been reported in the electron radiation belt of Saturn (Sun et al., 2019).

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One characteristic of the terrestrial zebra stripes is that every peak, and similarly, every valley, 58 corresponds to a population of trapped particles with similar magnetic drift frequencies (Sauvaud 59 et al., 2013). As a result, the zebra stripes are usually straight lines when the measured fluxes are 60 represented in the (L, drift frequency) space. However, the zebra stripe pattern can appear 61 disturbed during times of enhanced magnetic activity (Ukhorskiy et al., 2014). Another feature of 62 the zebra stripes is that they seem to tighten and narrow when observed during consecutive passes: 63 The drift frequency separation between successive peaks (and valleys) decreases linearly with time 64 65 (Lejosne & Roederer, 2016; Liu et al., 2016). In that context, the structure of the zebra stripes is comparable a stopwatch in that the drift frequency separation between successive peaks and 66 valleys contains temporal information. This temporal information corresponds to the time spent 67 by the particles drifting since some initial "reset" time or "start time" (e.g., Lejosne & Roederer, 68 69 2016). What this start time represents has never been examined so far.

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71 Several theories have been proposed over the years in order to explain the generation, structure and evolution of the zebra stripe pattern in the Earth's inner belt (e.g., Cladis, 1966; Pinto et al., 72 73 1991; Sauvaud et al., 2013; Ukhorskiy et al., 2014; Lejosne & Roederer, 2016; Selesnick et al., 2016; Liu et al., 2016). While most theories involve an ad-hoc electric model, it has not been 74 75 possible to test their plausibility because of a historical lack of ground-truth (e.g. Su et al., 2016). Providing reliable electric field measurements near the magnetic equator in the plasmasphere is 76 77 indeed a technical challenge (e.g., Lejosne & Mozer, 2016a, 2016b; Mozer, 2016). As a result, it has been unclear how zebra stripes are generated in the Earth's inner belt. 78

The instruments onboard the Van Allen Probes were the first instruments to provide reliable 80 evaluation of the near-equatorial electric drift  $\mathbf{E} \times \mathbf{B}/B^2$  in the Earth's plasmasphere (e.g., Leiosne 81 & Mozer, 2016a, 2016b, Lejosne et al., 2017, Lejosne & Mozer, 2018, 2019). For this work, we 82 have leveraged the new visibility offered by Van Allen Probes electric drift measurements to 83 determine experimentally the processes associated with the generation of zebra stripe patterns. The 84 approach is as follows: First, we examine three years of electron flux measurements to detect zebra 85 stripe patterns in the Earth's inner belt. We use these observations to establish a list of 370 start 86 times associated with the generation of zebra stripes. The method developed for establishing the 87 list of zebra stripe generation events is detailed in the Section 2. Then, we conduct a superposed 88 epoch analysis to provide information on (Section 3.1) the zebra stripe lifetime, (Section 3.2) the 89 magnetic activity associated zebra stripe generation, (Section 3.3) the initial azimuthal locations 90 91 for the populations corresponding to the peaks and valleys in the zebra stripes, and (Section 3.4) the electric field dynamics during zebra stripe generation. 92

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94 Statistical analyses reveal that the zebra stripe generation is usually associated with substorm onset 95 and the emergence of prompt penetration electric fields. It also shows that the peaks in the zebra 96 stripes usually correspond to trapped particles present in the morning region at start time, while 97 the valleys in the stripes usually correspond to particles present in the dusk-premidnight region at 98 start time. All the gathered pieces of experimental information are consistent with a scenario in 99 which the zebra stripes usually result from the action of magnetospheric convection penetrating 100 the plasmasphere during substorm onset.

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### 103 2. Data and Methodology

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### 105 2.1. Data: Field and Particle Measurements by the NASA Van Allen Probes

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The study relies Van Allen Probes field and particle measurements between January 1, 2013 and December 31, 2015. This time interval corresponds to the prime phase of the mission, i.e., a time during which the best quality measurements were recorded in a sufficient number to perform a statistical analysis. The two Van Allen Probes RBSP A and RBSP B had an apogee at 5.8 Earth radii, a perigee around 1,000 km, a period of 9 hr and an inclination of 10°. The spacecraft orbits
drifted slowly so that it took little less than two years for spacecraft apogees to scan all local time
sectors.

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For the field measurements, we preprocessed the spin-averaged (12 s) electric (Wygant et al., 115 2013) and magnetic (Kletzing et al., 2013) field measurements to derive reliable evaluations of the 116 electric drift in a frame of reference fixed to the stars. The preprocessing consists of three steps: 117 (1) A slight misalignment in the magnetometer axes for both spacecraft is corrected (Lejosne & 118 Mozer, 2016a, 2016b). (2) The data from the less reliable short-axis electric field antenna is 119 replaced by the assumption that the parallel electric field is zero, because of the plasma's high 120 conductivity parallel to magnetic field lines. (3) The shorting factor is set to a value close to 1, 121 leading to margins of errors of a few m/s (Lejosne & Mozer, 2019). The electric drift measurements 122 are then projected to the magnetic equator, assuming equipotential field lines and a realistic 123 magnetic field model (Lejosne & Mozer, 2016b). 124

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For the particle measurements, we focus on the level 3 Pitch Angle and Pressure data by the Radiation Belt Storm Probes Ion Composition Experiment (RBSPICE) (Mitchell et al., 2013). The high energy resolution, low time resolution, electron species rates (ESRHELT) product provides unidirectional differential electron fluxes for 17 pitch angle channels and 64 energy channels. The pitch angle channels have a resolution of 10 degrees – expect in the first and last bins, where the resolution is15 degrees. The energy channels are logarithmically spaced and they cover the [20 keV-938 MeV] energy range.

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## 134 2.2. Methodology: "Zebra Stripe" Pattern Detection and Analysis

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Because the zebra stripes are approximate straight lines when the fluxes are represented in the (L, drift frequency) space, we first describe how information on particle energy, pitch angle and spacecraft location is converted into information on magnetic drift frequency (Section 2.2.1). Then, we present the algorithm designed to detect and analyze the zebra stripes observed by the RBSPICE instrument in the Section 2.2.2. In the Section 2.2.3., we explain how the results are compiled to establish the list of 370 start times associated with zebra stripe generation.

#### 143 2.2.1. Determining the drift frequency associated with each RBSPICE data point

144 Information on kinetic energy, *T*, pitch angle,  $\alpha$ , and spacecraft location, *L*, is converted into 145 information on trapped electron magnetic drift frequency,  $\Omega/2\pi$ , applying Schulz and Lanzerotti's 146 formulas (1974) in the case of a dipole magnetic field:

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$$\Omega = \frac{3L}{qB_E R_E^2} \frac{T(T+2E_0)}{T+E_0} \frac{D(y_0)}{T(y_0)}$$
(1)

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where  $E_0 = 0.511 \, MeV$  is the electron rest mass energy,  $y_0$  is the sine of the equatorial pitch angle,  $B_E = 30,000 \, nT$  is the equatorial magnetic field at the surface of the Earth,  $R_E = 6,371.2 \, km$  is one Earth radius, and *D* and *T* are the following pitch-angle functions:

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$$D(y_0) = \frac{5.520692 - 2.357194 \times y_0 + 1.279385 \times y_0^{3/4}}{12}$$
(2)

153 and

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$$T(y_0) = 1.380173 - 0.639693 \times y_0^{3/4}$$
(3)

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Because there can be up to 20 degrees between the spacecraft location and the magnetic equator the value of the equatorial pitch angle is obtained from the value of the local pitch angle,  $\alpha = \sin^{-1} y$ :

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$$y_0 = y \sqrt{\frac{B_0}{B}} \tag{4}$$

160

where *B* is the local magnetic field magnitude, and  $B_0$  is the magnetic field magnitude at the magnetic equator following the field line passing through spacecraft location at the time of measurement. The coefficients  $\sqrt{B_0/B}$  are computed using the Fortran Library International Radiation Belt Environment Modeling IRBEM-LIB (Boscher et al., 2012) assuming that the
magnetic field is well described by the International Geomagnetic Reference Field model (IGRF)
below L = 3.

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#### 168 2.2.2. Creating and analyzing the unidirectional spectra measured during each inner belt pass

We divide the three year interval of RBSPICE data into approximately 6,000 inbound or outbound 169 passes per spacecraft below L = 3. This results into the creation of approximately 12,000 three-170 dimensional matrices in which the electron flux is provided as a function of (1) kinetic energy, (2)171 pitch angle, and (3) time (or, equivalently, spacecraft location). Given the amount of data involved, 172 an algorithm has been developed to analyze all the spectrograms. The objective of the algorithm 173 is to detect and describe the structure of the zebra stripes when present. The different criteria set 174 for zebra stripe detection and analysis are documented in the following. The algorithm is made of 175 four steps. Three consecutive steps are applied to every pass, every pitch angle channel, and every 176 sampling time. The information resulting from these three steps is then compiled and analyzed in 177 a fourth step. 178

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### 180 <u>Step 1:</u> Detrending the fluxes

First, we define a smoothed flux following the approach presented by Liu et al. (2016). For each energy channel, the value of the logarithm of the smoothed flux is equal to the running average of the logarithms of the measured fluxes over nine consecutive energy bins (+/- four energy bins around the energy channel considered). The logarithm of the flux is then detrended by subtracting the logarithm of the smoothed flux to the measured logarithmic flux. An illustration for this step is provided **Figure 1**.



Figure 1. Detrending the unidirectional differential electron fluxes measured by Van Allen Probe
A (RBA) during an inner belt pass in January 6, 2015 (15:20 UT – 16:05 UT). The Panel A)

190 corresponds to the 90° pitch angle channel (y = 1), and it displays the flux as a function of kinetic 191 energy,  $E_c$ , and spacecraft location, L. B) The same spectrum as the one displayed Panel A), but 192 detrended. The logarithm of the detrended flux is represented as a function of spacecraft location, 193 L, and magnetic angular drift velocity,  $\Omega$ . C) The logarithm of the detrended flux for 150 keV 194 electrons, represented as a function of spacecraft location, L, and equatorial pitch angle  $x_o =$ 195  $\cos \alpha_o$ . The peaks and valleys are more apparent Panels B) and C) than Panel A). They correspond 196 to populations of particles with similar magnetic drift frequencies.

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198 The **Figure 1A** shows that the zebra stripe pattern was present in the inner belt on January 6, 2015, 199 between 15:20 UT and 16:05 UT. Detrending the fluxes emphasizes the zebra stripe patterns 200 (**Figure 1B-C**). The zebra stripes correspond to approximate straight lines when represented in the 201 ( $L, \Omega$ ) space at constant equatorial pitch angle,  $\alpha_o$ , as illustrated **Figure 1B**. They correspond to 202 curved lines when represented in the ( $L, \cos \alpha_o$ ) space, as illustrated **Figure 1C**. Both features are 203 consistent with the fact that every structured peak and valley corresponds to a population of 204 particles with similar magnetic drift frequencies,  $\Omega/2\pi$ , as described by the **equation (1)**.

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#### 206 <u>Step 2:</u> Extracting the spectrum peaks and valleys

207 For every pitch angle channel, we compute the derivative of the logarithm of the detrended spectrum with respect to the logarithm of the magnetic drift frequency. A local extremum in the 208 detrended flux (minimum or maximum) corresponds a magnetic drift frequency at which the 209 derivative is changing sign. We also compute the second derivative in order to determine whether 210 a local extremum corresponds to a local minimum or a local maximum in the detrended flux. In 211 addition, the value of the detrended flux at every extremum is stored in order to quantify the 212 213 magnitude of the stripes. Because the objective of the algorithm is to focus on clear zebra stripe patterns in the tens to hundreds of keV energy range, we filter the resulting data points according 214 215 to two selection criteria. We discard extrema corresponding to (1) high energy channels ( $\Omega \geq$ ~ 1mHz, thus  $\geq$  ~ 1MeV ) and (2) faint stripes (when the difference between the flux and the 216 smooth flux is smaller than 5% on average). 217

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219 <u>Step 3:</u> Converting the peak and valley information into time information

Following the theory proposed by Lejosne and Roederer (2016), we consider that the central energies of consecutive peaks and valleys correspond to those electrons that have swept the same angular portions  $\Delta \varphi$  modulo  $2\pi$  since some unspecified start time,  $t_0$ , from some unspecified initial angular location  $\varphi(t_0)$ . An illustration is provided **Figure 2**.

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Figure 2. The central energies of consecutive peaks and valleys correspond to those electrons 226 which have swept the same angular portions  $\Delta \varphi$  modulo  $2\pi$  since some undefined start time  $t_0$ , 227 and from undefined initial angular location  $\varphi(t_0)$ . The spacecraft is represented by a grey square, 228 229 and its azimuthal location at the time of measurement t is  $\varphi(t)$ . Two angular drift velocities indicative of two consecutive local minima (or two consecutive local maxima) in the detrended 230 flux are  $\Omega_i$  and  $\Omega_{i+1}$ . They both correspond to populations of particles located at  $\varphi(t_0)$  at the start 231 232 time  $t_0$ , and detected by the spacecraft instruments at time t. Thus, both populations are also located at  $\varphi(t)$  at time t. The population with angular drift velocity  $\Omega_{i+1}$  has traveled  $\Delta \varphi + 2\pi$ 233 during the time interval  $\Delta T = t - t_0$  while the population with angular drift velocity  $\Omega_i$  has 234 traveled  $\Delta \varphi$  during the same time interval  $\Delta T$ . 235

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237 With  $\Omega_i$  and  $\Omega_{i+1}$  two angular drift velocities indicative of consecutive local minima (or 238 consecutive local maxima) in the detrended flux:

$$\Omega_{i+1}(t - t_0) = \Omega_i(t - t_0) + 2\pi$$
(5)

241 Thus:

242

$$\Delta T_i = \frac{2\pi}{\Delta \Omega_i} \tag{6}$$

243

where  $\Delta T_i$  indicates the time spent since a potential start time,  $t_0$ , according to the separation 244 between two consecutive peaks or valleys present in a spectrum measured at time, t,  $\Delta \Omega_i =$ 245  $|\Omega_{i+1} - \Omega_i|$ . For both series of local minima and local maxima defined Step 2, the sets of time 246 intervals  $(\Delta T_i)$  and associated start times  $(t_{0,i} = t - \Delta T_i)$  are computed. If both theory and 247 observations were perfect, all the processed time intervals,  $\Delta T_i$ , would refer to the same initial start 248 time,  $t_0$ , in the presence of zebra stripes. In practice, each pass produces a set of potential start 249 times,  $(t_{0,i})$ , that is more or less scattered. Thus, we further analyze this set in order to differentiate 250 the information from the noise, and to determine the most likely start time, when defined. 251

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# 253 <u>Step 4:</u> Analyzing the set of potential start times $(t_{0,i})$

Once all the different pitch angle channels and sampling times are processed according to the Steps 254 1-3, the results are further analyzed to determine the most likely start time (when present). First, 255 for each pass, all the potential start times,  $(t_{0,i})$ , are compiled in a histogram with a bin size of one 256 hour,. The points corresponding to the less populated bins are discarded  $(n/N_{max} \le 0.5)$ , with 257  $N_{max}$ , the maximum number of points per bin, and n, the number of points in the bin considered). 258 Second, a Hough transform (e.g., Duda and Hart, 1972) is applied to each of the two sets of extrema 259 (minima and maxima) in the  $(L, \Omega)$  space in order to detect the presence of stripes. The Hough 260 transform is a technique used in image processing in order to extract imperfect features. Data points 261 that are not located along horizontal stripes (+/- 10 degrees) are discarded. This two-step sequence 262 263 (histogram, Hough transform) is repeated until no additional data point is discarded. An illustration of this filtering method is provided Figure 3. 264



Figure 3. the (A) valleys and (B) peaks extracted from the analysis of the detrended flux, during the same pass as Figure 1 (January 6, 2015 15:20 UT – 16:05 UT). The data points resulting from the analysis of the detrended flux (Step 2) are represented by black dots. The data points selected after Hough transform and histogram analysis (Step 4) are displayed in a square whose color is related to the pitch angle channel considered ( $x_o = \cos \alpha_o$ ). The set of potential start times, ( $t_{0,i}$ ), is represented as a function of the average magnitude of the associated stripes in the Panels C) and D). The data points selected after Hough transform and histogram analysis are shown Panel D).

During the pass illustrated **Figure 1**, multiple peaks and valleys are found in the unidirectional 275 differential electron fluxes. They correspond to the black dots displayed Figure 3A for the valleys 276 and Figure 3B for the peaks. Both cloud plots display some stripes in the  $(L, \Omega)$  space, together 277 with some noise, especially at low  $(\Omega \le 0.5 \, rad/hr)$  and high  $(\Omega \ge 5 \, rad/hr)$  energies. 278 Depending on the pass, the stripes are more or less regular, and more or less continuous. They can 279 280 even sometimes display a slight dependence on L (as illustrated for instance Figure 3B for  $\Omega \sim 4.5 \, rad/hr$ ). The Step 4 of the algorithm is designed in an attempt to differentiate signal and 281 282 noise. The data points selected after filtering are the color-coded squares Figure 3. The variety of 283 colors represents the variety of equatorial pitch angles present in the selection. This shows that the filtering process captures most of the stripes while successfully excluding most of the noise from 284 further analysis (Figure 3C-D). A limit to the procedure is that irregular stripes can also be 285 discarded (e.g.,  $\Omega \sim 1.8 rad/hr$  Figure 3B). 286

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#### 288 2.2.3. Determining a list of start time intervals associated with zebra stripe generation

The objective is to select a sufficient number of good (i.e., clear, strong) events to enable a statistical analysis of the conditions associated with zebra stripe generation. The approach chosen to determine a list of good events is detailed in the following.

All the potential start times,  $(t_{0,i})$ , resulting from the analysis described Section 2.2.2 are stored, 292 together with information on (1) the pass during which they are determined, (2) the couple of 293 angular drift velocities used to estimate this potential start time,  $(\Omega_i, \Omega_{i+1})$ , and (3) the average 294 magnitude of the associated flux fluctuation. We then use this information to create monthly 295 histograms called "zebra stripe generation indicators". The histograms are defined as follows. The 296 tables have a bin size of two hours, and each element corresponds to the number of points,  $(t_{0,i})$ , 297 that refer to the two-hour time interval considered. The tables are then normalized by the monthly 298 maximum per bin. The procedure is carried with and without weighting the number of points by 299 300 the average magnitudes of the corresponding flux fluctuations. The resulting histograms can be interpreted as local quantifications for the likelihood of zebra stripe generation. 301

Since the objective is to find as many good events as possible while limiting the number of false positives, we define a set of three criteria that a selected event must verify in order to be listed as a "good" event. First, the start time selected must be in a bin that corresponds to a local maximum in the "zebra stripe generation indicators". Second, the start time selected must be apparent in at least two different passes. Third, the average amplitude of the stripes associated with the process
occurring at the start time selected must relatively large (more precisely, the average amplitude
must be greater than 90% of the computed monthly max). For the three years of data considered,
370 events fulfilled this set of criteria.

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An illustration is provided **Figure 4** in the case of the month of August 2013. The nine start times 311 selected that month are also indicated. The histogram of "zebra stripe generation indicators" is 312 represented Figure 4D together with different time series of magnetic activity indices, namely, the 313 auroral electrojet index, AE (Figure 4A), the north-south component of the interplanetary 314 magnetic field, IMF,  $B_z$  (Figure 4B), the polar cap potential, *PCP*, computed according to the 315 formula by Boyle et al. (1997) (Figure 4C). Two different "zebra stripe generation indicators" are 316 317 computed (with and without taking into account the magnitude of the resulting stripes). The Figure 4 shows that both methods usually agree with each other, meaning that the most intense zebra 318 319 stripe events usually generate the highest numbers of consistent information (i.e., the strongest events are also usually the cleanest). 320

The Figure 4 suggests that favorable times to zebra stripe generation (i.e. large local maxima in 321 the zebra stripe indicators) are usually associated with an increase in the auroral electroject, a 322 decrease in the north-south component of the interplanetary magnetic field, and an increase in the 323 polar cap potential. Thus, Figure 4 suggests that there is a correlation between substorm onset and 324 the mechanism leading to the generation of zebra stripes. The Figure 4 also illustrates the 325 326 limitations of the proposed method. Indeed, the filter seems to have missed an event occurring during the day of the year (doy) 225 and one or two events occurring during the doy 243 for 327 instance. 328





Figure 4. Magnetic activity indices and "zebra stripe generation indicators" (A) the auroral 331 electrojet index, AE (B), the north-south component of the solar wind,  $B_z$  and (C) the polar cap 332 potential, PCP, according to the formula by Boyle et al. (1997). Different "zebra stripe generation 333 indicators" are computed with (in red) and without (in black) taking into account the magnitude of 334 the resulting stripes. Vertical red lines indicate the nine start times selected in August 2013. 335

#### 2.2.4. Determining the start time, $t_0$ , and the margin of error associated with each zebra stripe 337 generation event 338

339 For each of the 370 events, we compile all the corresponding information from the (>2) associated passes. The mean start time,  $t_0$ , is defined as the average of all possible start times, and the margin 340 of error is defined as the standard deviation of the set of possible start times  $(t_{0,i})$ : The average 341 standard deviation obtained is of the order of an hour. 342

A second method to determine the most likely start time has also been tested. This method relies 343 on the idea that all the particles with energies located at the center of peaks (or valleys) have swept 344 the same angular portions  $\Delta \varphi$  modulo  $2\pi$  since the start time,  $t_0$ . Thus, given a data point 345 corresponding to 1) a peak – or a valley  $(\Omega_i)$ , 2) a time and place of measurement  $(t, \varphi(t))$ , and 346 3) a potential start time  $t_0$ , the associated start time azimuthal location  $\varphi(t_0)$  is: 347

$$\varphi(t_0) = \varphi(t) - (\Omega_i + \Omega_E)(t - t_0) [2\pi]$$
(7)

where  $\Omega_i/2\pi$  is the magnetic drift frequency associated with the center of a peak (or a valley) and 349  $\Omega_E/2\pi$  is the corotation frequency. If both data and theory were perfect,  $\varphi(t_0)$  would not depend 350 on the data point  $\Omega_i$  considered (see also Figure 2). In practice,  $\varphi(t_0)$  varies with  $\Omega_i$ . Thus, the 351 most likely start time can also be defined as the time  $t_0$  which minimizes the scattering between 352 all possible initial azimuthal locations,  $\varphi(t_{0,i})$ , computed according to the equation (7). The most 353 likely start time found with this method is usually located 20 min after the most likely start time 354 found with the most straightforward method. Given that the standard deviation is of the order of 355 an hour, both methods provide equivalent answers. 356 357 The list of the 370 start times associated with the zebra stripe pattern generation between January 358 1, 2013 and December 31, 2015 is accessible online (https://doi.org/10.5281/zenodo.3637636). 359 360 361 **3.** Experimental Determination of the Conditions Associated With Zebra Stripe Generation: 362 a Statistical Analysis 363 364 3.1. Zebra Stripe Lifetime 365 366 Because zebra stripe patterns are often detected over consecutive passes (e.g. Fig.8 in Lejosne & 367 Roederer, 2016), we first use the list of 370 zebra stripe generation events to estimate the lifetime 368 of zebra stripe patterns. The typical start time for zebra stripe observations is defined as the average 369 370 of the minimum time intervals detected per event,  $min(\Delta T_i)$ . The typical stop time for zebra stripe observations is defined as the average of the maximum time intervals per event,  $\max(\Delta T_i)$ . The 371 resulting typical start time for zebra stripe observations is 6.5 hours after  $t_o$  while the typical stop 372 time for zebra stripe observations is 14.5 hours after  $t_o$ . Thus, zebra stripes are typically be 373 observed during 8 hours, from 6.5 to 14.5 hours after  $t_0$ . 374 375 376 That the zebra stripes are not detected directly after triggering can be explained by considering the equation (6). The smaller the time interval  $\Delta T_i$ , the bigger the difference between  $\Omega_i$  and  $\Omega_{i+1}$ . 377

Thus, in order to observe some zebra stripes just after their generation, i.e., in order to detect stripes 378 after a brief time interval,  $\Delta T$ , one needs to analyze a particle spectrum over a very wide energy 379 range. Yet, the amplitude of the stripes usually decreases with kinetic energy. (This is because the 380 effect of a disturbance in the electric drift is less and less significant as the kinetic energy increases. 381 This point will be further discussed Section 3.3). Thus, the zebra stripes are most apparent in the 382 tens to hundreds of keV energy range. As a result, the zebra stripes are usually undetected 383 immediately after generation. A time lag is required so that the distance between  $\Omega_i$  and  $\Omega_{i+1}$ 384 385 decreases and at least two stripes become apparent. Similarly, as the time interval  $\Delta T$  increases, the distance between  $\Omega_i$  and  $\Omega_{i+1}$  decreases until  $\Omega_i \cong \Omega_{i+1}$ . The stripes become too tight for the 386 finite energy resolution of the instrument. They are then indiscernible. In addition, as time goes 387 by, it becomes less and less likely that the zebra stripe pattern remains clear, as additional 388 disturbances to the electric drift may occur. As a result, zebra stripes have a finite lifetime that we 389 estimate to be of the order of half a day. 390

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#### 392 3.2. Magnetic Activity During Zebra Stripe Lifetime

393

The time series of different magnetic indices and solar wind parameters are stored for each of the 394 370 zebra stripe generation events. The time origin is set to the start time  $t_0$ . The time interval 395 examined starts 4 hours before  $t_o$  and ends 17 hours after  $t_o$ . At each instance between  $t_o - 4hr$ 396 and  $t_o + 17hr$ , the cumulative distributions are examined and the distribution deciles are stored. 397 The magnetic indices examined are the auroral electrojet (AE), the Kp index, the Dst index, and 398 399 the polar cap potential (PCP) according to the formula Boyle et al. (1997). The solar wind parameters considered are the orientation of the interplanetary magnetic field, IMF,  $(B_x, B_y, B_z)$ , 400 and the solar wind velocity,  $(V_x, V_y, V_z)$ . The results in the case of AE, PCP and  $B_z$  are displayed 401 Figure 5 and Figure 6. The superposed epoch analysis of  $B_x$ ,  $B_y$  and  $V_x$ ,  $V_y$ ,  $V_z$  shows no time 402 variation. 403



Figure 5. Superposed epoch analysis for the time evolution of the *AE* index. The time interval starts a few hours before zebra stripe generation. It ends a few hours after zebra stripe disappearance. The start time  $t_o = 0$  is indicated by a vertical red line, and the typical margin of error around  $t_o$  is depicted by a red rectangle. The typical time interval during which zebra stripes are observed is depicted by a purple rectangle. The average time evolution of the *AE* index is represented by a thick red line.



412

Figure 6. Similar to Figure 5, but for the time evolutions of A) the north-south component of the IMF,  $B_z$ , and B) the polar cap potential, PCP.

416

The time evolution of the magnetic indices around start time is indicative of substorm onset (Figures 5-6): The AE index increases (reaching average values greater than 400 nT), the interplanetary magnetic field becomes southward (reaching average values below -3nT), and the polar cap potential increases (reaching average values greater than 75kV). Because the disturbance lasts only a few hours on average, they have subsided by the time the zebra stripes become observable. That is why zebra stripes have been reported during both geomagnetically active and geomagnetically quiet times (e.g., Ukhorskiy et al., 2014).

We have also studied how the magnitude of the zebra stripe pattern varies with the peak magnitude 425 of magnetic activity around start time,  $t_0$ . To do so, we compute the extrema reached by the 426 different magnetic indices around start times (+/- 3 sigmas), and we attribute an average stripe 427 magnitude to every event. The average magnitude is equal to the average of the absolute values of 428 the ratios between the flux and the smoothed flux at all the identified extrema. The results, 429 displayed **Figure 7**, show a positive correlation between the magnitude of the zebra stripe pattern 430 431 and the magnitude of the substorm (as quantified by the maximum in the AE index, the minimum in  $B_z$ , or the maximum in *PCP* around start time). Given that 370 samples were used to compute 432 the correlation coefficients, we conclude that the correlation is statistically significant (p < 0.01). 433







Figure 7. Testing the correlation between the magnitude of different magnetic indices during the start time interval and the magnitude of the resulting stripes. The Pearson correlation coefficients between the average normalized amplitude of the stripes and A) the maximum of AE, B) the minimum of  $B_z$ , and C) the maximum of *PCP* are displayed in the top right corner of every panel. The time interval for the determination of the extrema is +/-3 hours around start time  $t_o$ . Linear interpolations of the different data sets are also displayed to guide the eye.

443

These results confirm and refine previous findings by Liu et al. (2016), who obtained a positive correlation between the amplitude of the stripes and the maximum in Kp index over the 12-hr interval preceding observation. The **Figure 7** suggests that the magnitude of the substorm 447 occurring a few hours to half day prior to observations somewhat controls the magnitude of the448 zebra stripe pattern.

449

#### 450 **3.3. Start Time Azimuthal Locations for the Zebra Stripe Peaks and Valleys**

451

Do the peaks (and valleys) originate from some preferred azimuthal locations or can they be 452 generated at any local time during substorm onset? To answer this question, we compute the start 453 454 time angular location  $\varphi(t_0)$  associated with every peak and valley  $(\Omega_i)$ , time and place of measurement  $(t, \varphi(t))$ , and event start time,  $t_0$ , applying the equation (7). We store the set of 455 456 resulting azimuthal locations (MLT) in a histogram with a 2-hr LT bin size, which we then normalize by the total number of data points in the sample. The resulting graph provides the 457 458 relative frequency distribution of the initial azimuthal locations. If the peaks and valleys were generated anywhere, without any preferred azimuthal location, the resulting relative frequency 459 distributions would be flat and equal to 1/12~8.3%. In practice, the frequency distribution 460 functions for the peaks and valleys present variations with local time (Figure 8). 461



Figure 8. Relative frequency distribution of the initial azimuthal location,  $\varphi(t_0)$ , (in red) for the data points corresponding to a peak in the zebra stripe pattern and (in blue) for the data points corresponding to a valley in the zebra stripe pattern. That the two functions vary with magnetic

local time, *MLT*, indicates that the peaks and valleys are created at preferred azimuthal locations:in the morning sector for the peaks, and in the premidnight sector for the valleys.

468

The peaks in the zebra stripe patterns are preferentially created in the morning sector, around 9 MLT. On the other hand, the valleys in the zebra stripe patterns are preferentially created in the premidnight sector, around 22 LT. Assuming conservation of the phase space density, a variation of the observed flux *j* can be reformulated in terms of radial motion  $\Delta L$ . For instance, in the equatorial case (e.g., Selesnick et al., 2016):

 $\frac{\Delta j}{j} = -\frac{3\Delta L}{L} \tag{8}$ 

475

476 where L corresponds to the normalized equatorial radial distance. Thus, Figure 8 suggests that a population of electrons located in the morning sector drifted inward at start time,  $t_0$  ( $\Delta L < 0$ , thus 477  $\Delta i > 0$ ), while a population of electrons located in the premidnight sector drifted outward at start 478 time,  $t_0$  ( $\Delta L > 0$ , thus  $\Delta j < 0$ ). In the inner belt, the magnetic field does not vary much and 479 disturbances in trapped particle drift motion originate mainly from disturbances in the electric drift 480 481 (e.g., Selesnick et al., 2016). As a result, the Figure 8 is suggestive of an average scenario in which the zebra stripes are generated by a large-scale electric field appearing during start times, oriented 482 such as to drive a large-scale morning-to-premidnight radial motion of the trapped inner belt 483 particles. Combined with previous findings (Fig.5-7), namely, that the start times usually 484 correspond to substorm onset times, and that the amplitude of the stripes is somewhat controlled 485 by the substorm magnitude, experimental evidence suggests that the zebra stripes are most likely 486 generated by the direct penetration of magnetospheric convection in the plasmasphere during 487 substorm onset. In the following Section 3.4, we present electric field observations that further 488 validate the proposed scenario. 489

490

#### 491 **3.4. Electric Field Perturbations During Zebra Stripe Generation**

492

493 Under quasi-steady conditions, the plasmasphere is expected to be shielded from the high-latitude494 electric fields generated by the interaction between the magnetosphere and the interplanetary

medium. Undershielding occurs when a rapid increase of magnetospheric convection generates 495 prompt penetration electric fields and currents that extend directly down to midlatitudes and the 496 equator. The disturbances are usually short-lived, with lifetimes from a few minutes to a few hours 497 (e.g. Fejer et al., 2017; Maruyama, 2020). Such a short lifetime makes the prompt penetration 498 electric fields more difficult to detect than the subcorotation related to the ionospheric disturbance 499 dynamo, the latter lasting from several hours to a couple of days (e.g., Blanc & Richmond, 1980; 500 Lejosne & Mozer, 2018). By analyzing as many events as possible, we increase the chances of a 501 spacecraft being at the right place and time to detect prompt penetration electric fields. 502

503

We compile all the electric field measurements sampled when a spacecraft was located between L 504 = 1.5 and L = 2.5 during one of the 370 start time intervals ( $t_0 + / -3$  hours). Because the 505 undershielding process is associated with times when the IMF becomes southward, we restrict the 506 database to the points measured when the IMF- $B_z$  is negative. The resulting dataset of electric field 507 508 measurements is then analyzed as a function of local time. There are 4000 data points on average per 2-hr local time bin (min: 2700 points per bin; max: 6500 points per bin), and the data covers 509 70 different events on average per 2-hr local time bin (min: 58 events per bin; max: 89 events per 510 bin). Thus, although the spacecraft were not always at the right place and the right time (i.e. in the 511 inner belt, between L = 1.5 and L = 2.5, during the 370 start time intervals), there is still enough 512 data points to statistically determine the electric field conditions associated with zebra stripe 513 generation. 514

515

A radial transport across L shells requires a perturbation in the electric field. Thus, the objective 516 is to analyze perturbations in the typical values of the electric field, rather than the total electric 517 field itself. To study the response of experimental electric field measurements to magnetic activity, 518 we follow the common practice that consists of detrending the electric fields (e.g. Fejer & 519 Scherliess, 1997; Huang, 2019). To detrend the electric fields, we first compute a typical value at 520 each sampling point by determining the median value of all electric field measurements at the same 521 location over the three days prior to measurement. The electric field perturbation is then defined 522 by subtracting the typical value to the instantaneous measurement. 523

For every 2-hr local time bin, the cumulative distributions are examined and the distribution deciles
are stored for both components of the electric field perturbations. The results are displayed Figure
9.



528

Figure 9. Superposed epoch analysis for the A) radial and B) azimuthal components of the electric field perturbation during the start time intervals associated with zebra stripe generation (when  $B_z < 0$  and the spacecraft location L is between 1.5 and 2.5). The average value of the electric field perturbation is represented by a red line. When mapped to the ionosphere, the radial component of the electric field is poleward, and the azimuthal component is zonal.

534

535 On average, the radial component of the electric field perturbation is positive. This indicates a 536 plasmaspheric subcorotation during the zebra stripe generation events. The azimuthal component 537 of the electric field perturbation is usually negative on the postmidnight-dawn sector, and positive 538 in the dayside sector. It is worth mentioning that the orientation of the penetration electric field is 539 different from what one would obtain by simply extrapolating a dawn-to-dusk convection electric 540 field, because of spatial variations in ionospheric conductivities (e.g. Senior & Blanc, 1984).

Since previous results (including **Figure 7**) suggest that the amplitude of the electric field perturbation depends on magnetic activity, we test this assumption by computing the Pearson correlation coefficients between the electric field perturbation at different LT bins, and magnetic activity. Both electric field perturbation components are considered, and different magnetic indices are tested (namely, AE,  $-B_z$ , and PCP). The results are displayed **Figure 10**.



Figure 10. Pearson correlation coefficients (cc) between (1) the azimuthal component of the 548 electric field perturbation measured during zebra stripe generation events, for LT = 6 + / - 1hr549 and  $L \in [1.5, 2.5]$ , and (2) A) the auroral electrojet AE, B) the south-north component of the 550 IMF:  $-B_z$  and C) the polar cap potential, *PCP*. The bottom panels present a compilation of the 551 different Pearson correlation coefficients as a function of local time, obtained D) for the radial 552 component of the electric field perturbation and different magnetic activity indices (AE in black, 553  $-B_z$  in green and PCP in red), and E) for the azimuthal component of the electric field perturbation 554 and the same magnetic activity indices. 555

556

The radial component of the electric field perturbation increases as magnetic activity increases. Thus, the plasmaspheric subcorotation increases as magnetic activity increases. The increase is uniform in LT, everywhere except in the morning sector (6-12LT). For the azimuthal component of the electric field, the field decreases as magnetic activity increases around 6-9LT. Thus, there is inward motion around 6-9LT as magnetic activity increases. Similarly, the azimuthal component of the electric field increases as the magnetic activity increases in the dusk sector, leading to

outward radial motion around 18-21LT. These findings are consistent with the results displayed 563

Figure 8. It is the first time that the signature of the prompt penetration electric fields is observed 564 in near-equatorial electric field measurements. 565

- 566
- 567

#### 4. Summary and Discussion 568

569

We designed an algorithm to detect and analyze the zebra stripes observed by the RBSPICE 570 instruments onboard the Van Allen Probes. Approximately 12,000 inner belt passes between 571 January 1, 2013 and December 31, 2015 were examined to determine 370 times associated with 572 zebra stripe pattern generation. The events selected are such that zebra stripes are strong and clean 573 enough to be detected during at least two Van Allen Probes passes in the inner belt. Statistical 574 analyses of these 370 events revealed that:

- 575
- (1) the zebra stripes have a lifetime of the order of half a day; 576
- (2) the zebra stripes are usually generated during substorm onset; 577

578 (3) the magnitude of substorm onset is somewhat correlated to the magnitude of the zebra stripe

pattern that is observed a few hours later; 579

580 (4) the peaks in the zebra stripe pattern are preferentially created in the morning sector, around 9

MLT, while the valleys in the zebra stripe pattern are preferentially created in the premidnight 581 582 sector, around 22 LT;

- (5) a perturbation in the electric field appears during zebra stripe generation events: it leads to 583 584 inward radial motion around 6-9LT and outward radial motion around 18-21LT.
- 585

586 Thus, experimental evidence is suggestive of a scenario in which the prompt penetration electric field associated with substorm onset leads to a large-scale perturbation of the trapped particle drift 587 588 motion. The inward motion of the population located in the dawn-morning sector at onset generates the peaks appearing in the trapped particle spectrograms. Similarly, the outward motion of the 589 590 population located in the dusk-premidnight sector at onset generates the valleys appearing in the 591 trapped particle spectrograms. In that context, the zebra stripes are nothing more than inner belt drift echoes due to asymmetric electric field variations that are sudden on the time scale of a drift 592 period (e.g. Brewer et al., 1969). Additional work is nonetheless necessary in order to test whether 593

the amplitude and duration of the prompt penetration electric fields are sufficient to account forthe observed amplitudes of zebra stripe patterns.

596

Large-scale electric fields in the plasmasphere evolve on a variety of timescales that are difficult 597 to disentangle. This study illustrates how the analysis of trapped particle dynamics in the inner belt 598 provides information on the timescales associated with the different electric field components. 599 Indeed, any asymmetric electric field variation that is sudden on the time scale of a drift period 600 drives irreversible radial transport. This leads to the apparition of drift echoes, whose amplitudes 601 relate to the strength of the electric field variation. On the other hand, slow electric field variations 602 lead to reversible effects. This drives electric drift shell splitting, whose magnitude relates to the 603 strength of the electric field asymmetry (e.g. Selesnick et al., 2016). In that context, the analysis 604 of variations in the spectrograms of energetic particles trapped in the Earth's inner belt constitutes 605 another tool to examine the dynamics of the middle and low latitude (i.e., plasmaspheric) electric 606 fields. 607

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- 609

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- 619 The Fortran Library International Radiation Belt Environment Modeling (IRBEM-LIB) can be
- 620 downloaded at http://sourceforge.net/projects/irbem/

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