Association of chorus waves and source/seed electrons with the enhancement of relativistic electrons in the outer Van Allen belt

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INTRODUCTION

- Local acceleration driven by whistler mode chorus waves is fundamentally important for the acceleration of seed electrons in the outer radiation belt to relativistic energies. Yet, this mechanism strongly depends on substorm activity and on the source and seed electron populations injected by the substorms into the inner magnetosphere.
- In this work we use Van Allen Probes (RBSP) data to investigate the features of source electrons, seed electrons and chorus waves for events of enhancement versus events of depletion of relativistic electrons in the outer Van Allen belt.
- To that end we calculate the electron phase space density (PSD) for three values of the first adiabatic invariant μ corresponding to source and seed electrons.
- Furthermore, we perform a superposed epoch analysis of 28 geospace disturbance events, out of which, 20 result in enhancement and 8 in depletion of relativistic electron PSD.

EVENT SELECTION and SUPERPOSED EPOCH ANALYSIS

- The events need to emerge after at least **12 hours** of quiet-time **average** solar wind conditions, meaning:
  V_{SW} < 400 [km/s] P_{SW} < 3 [nPa] SYM-H > -20 [nT] AL > -300 [nT] -5 [nT] < Bz < 5 [nT]
- They comprise of both storm and non-storm events, having either ICMEs or SIRs as a driver. This yields 71 events during the Van Allen Probes (RBSP) era (2012-2018), spanning the maximum/declining phase of Solar Cycle 24.
- The selected events are based on the work of *Katsavrias et al. [2019]*, and *Katsavrias [2019]*.
- In the SEA, the key time t_0 is defined as the start time of continuous substorm activity, as indicated by the decrease of AL index.

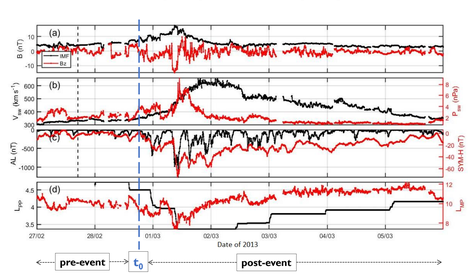


Figure 1. Example of solar wind properties, magnetospheric parameters and indices, and the selection of key time t_0, for a selected event (27 Feb – 5 Mar 2013). L_{MP} and L_{PP} calculation is based on *Shue et al. [1988]* and *O'Brien et al. [2003]*.

EVENT CATEGORIES

From the 71 events of the original database, we study only the 20 events resulting in enhancement and 8 events resulting in depletion of the **average PSD** for **relativistic** electrons of **μ=900 [MeV/G]** at **L*>4.5**, based on the results of *Katsavrias et al. [2019]*, and *Katsavrias [2019]*, where:

Enhancement: $PSD_{Post}/PSD_{Pre} \geq 6$
Depletion: $PSD_{Post}/PSD_{Pre} \leq 1/4$

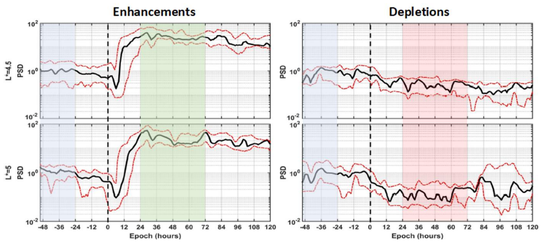


Figure 2. Evolution of PSD for electrons of μ=900 [MeV/G] at L*>4.5, according to which the event categories are defined by *Katsavrias et al. [2019]*.

SOLAR WIND PARAMETERS

IMF [nT], Bz [nT], V_{SW} [km/s], P_{SW} [nPa]

Figure 3. Enhancement events are caused by disturbances showing a two-step **increased IMF**, a **prolonged negative Bz**, a **highly increased and long lasting V_{SW}** with values reaching over 500 [km/s], together resulting in **enhanced magnetic reconnection** at the dayside magnetopause.

GEOMAGNETIC INDICES

SYM-H [nT], AL [nT]

MAGNETOSPHERIC PARAMETERS

L_{MP} [R_E], L_{PP} [R_E]

Figure 4. Enhancement events are characterised by **prolonged negative SYM-H and AL indices**, meaning statistically stronger and more prolonged **storm and substorm activity**, and a significantly **compressed plasmapause** reaching under L=4.

Figure 3. Solar Wind Parameters

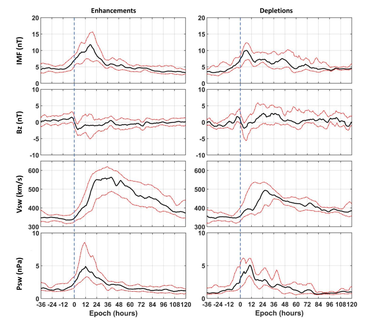
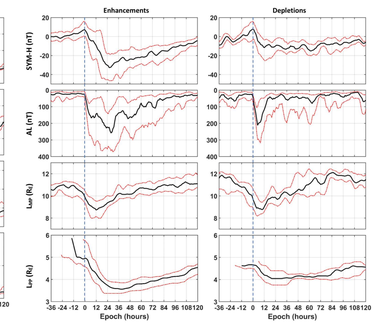


Figure 4. Geomagnetic Indices, Magnetopause, Plasmapause



CHORUS WAVE AMPLITUDE

Figure 5. Chorus wave amplitude inferred from POES electron (30–100 keV) precipitation *[Li et al., 2013]*. They correlate with substorm activity (AL index). In enhancement events the **chorus wave activity** is **more pronounced** and **long lasting**, over a **broad L-shell region**: at L=3-4 the waves appear negligible, probably due to the compressed plasmapause, at L=4-5 and L=5-6 their maximum value and duration are larger than that of depletion events.

Pc5 WAVE POWER

Figure 6. Pc5 wave power inferred by Morlet Wavelet Transform on magnetic field B data from Van Allen Probes. They correlate with P_{SW} and enhanced reconnection (Bz<0 and enhanced V_{SW}). In enhancement events the **Pc5 wave activity** is **more pronounced** and **longer-lasting**, especially at L*=4-5 and L*=5-6.

Figure 5. Normalised Chorus Wave Amplitude

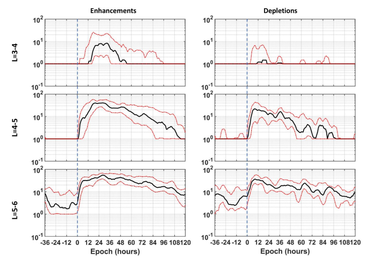
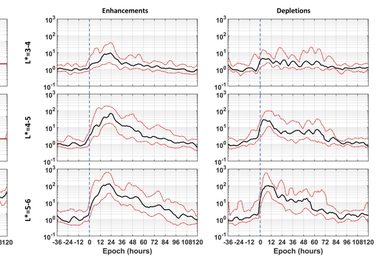


Figure 6. Normalised Pc5 Wave Power



ELECTRON PSD FOR:

▪ SOURCE ELECTRONS
μ = 1 [MeV/G] , E = 1 – 10 [keV]

Figure 7. Source electrons of μ=1 MeV/G show no significant difference between the two event groups, and generally **can be considered as negligible**, as they do not appear to be affected by geomagnetic disturbances or to have an effect in the variation of the rest of the electrons. Their behaviour suggests a **cut-off of E=10 keV** for the electron energies responsible for the excitation of chorus waves.

▪ SOURCE ELECTRONS
μ = 10 [MeV/G] , E = 10 – 100 [keV]

Figure 8. Source electrons of μ=10 MeV/G **appear in both** event categories, but in enhancement events they reach a more than 2 orders of magnitude **larger maximum** value at **L*=3-4**, 1 order of magnitude at L*=4-5, but a **comparable** or a bit lower maximum at L*=5-6, correlating with larger magnetospheric compression. We cannot use their appearance or their magnitude to predict the appearance of seed or relativistic electrons.

▪ SEED ELECTRONS
μ = 100 [MeV/G] , E = 100 – 600 [keV]

Figure 9. Seed electrons of μ=100 MeV/G, in enhancement events, also appear **more enhanced** at **L*=3-4 and L*=4-5**, and are **more pronounced** than in depletion events, during which they are rarely detected except at L*=4-5. They seem to emerge independently from source electrons.

Figure 7. Normalised PSD for μ=1 (Source e)

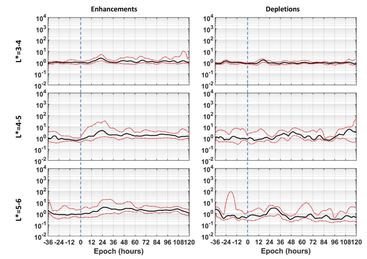


Figure 8. Normalised PSD for μ=10 (Source e)

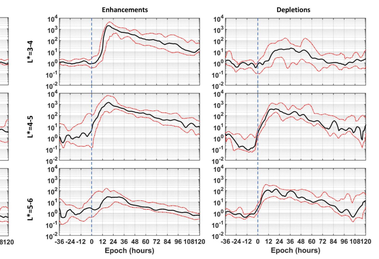
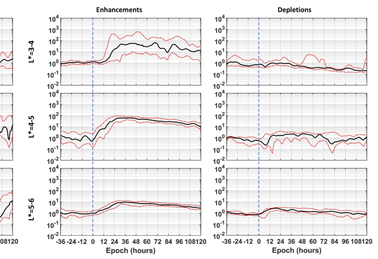


Figure 9. Normalised PSD for μ=100 (Seed e)



CONCLUSIONS

- The geospace disturbances that lead to **enhancement events** are preceded by a two-step increased IMF, a prolonged negative Bz, and a highly increased and long lasting V_{SW} reaching over 500 km/s, together resulting in enhanced magnetic reconnection rate at the dayside magnetopause.
- This leads to statistically stronger and more prolonged **storm and substorm activity**, and a significantly eroded plasmapause reaching under L=4. The **chorus and Pc5 wave activity** is more pronounced and prolonged during enhancement events, especially at the region of L=4-5.
- Regarding the source electrons of **μ=1 MeV/G**, we have shown that they can be considered negligible for the excitation of waves or the production of relativistic electrons.
- In contrast, the source electrons of **μ=10 MeV/G** seem to get injected to the inner magnetosphere, appearing pronounced and more prolonged during enhancement events. This combination indicates that only electrons with energy larger than their lower energy limit may be held accountable, defining a cut-off energy of E=10 keV.
- Regarding the seed electrons of **μ=100 MeV/G**, we showed that they can act as a proxy for the appearance of relativistic electrons. The appearance of these electrons does not depend on the appearance of source electrons alone, but additional mechanisms are important. So, they either get directly injected from the plasma sheet as an effect of substorm activity, or they are comprised by diffused electrons previously located at larger L*, source electrons or other.
- Overall, **the effect of VLF waves on the acceleration** of electrons to relativistic energies seems to be determined by **the abundance of seed electrons**, mostly at L*=4-5, the nominal heart of the outer radiation belt.

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