Association of relativistic electron enhancements with VLF/ULF wave activity and seed electrons

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November 21, 2022

Abstract

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. This mechanism depends strongly on substorm activity and on the source and seed electron populations injected by substorms into the inner magnetosphere. In this work, a selection of geospace disturbance events, emerging from single and isolated interplanetary drivers, is divided into two groups, one resulting in enhancement and one in depletion of the average relativistic electron Phase Space Density (PSD). Because substorm activity does not always coincide with or depend on magnetic storm occurrence, we have not limited our study to storms, but have included also non-storm events that are able to cause enhancements and depletions of the relativistic electrons in the outer radiation belt. We investigate solar wind and geomagnetic parameters, wave activity and the seed electron PSD in the outer Van Allen radiation belt, looking for the occurrence of characteristic patterns, by performing a Superposed Epoch Analysis (SEA). Our study indicates the importance of substorm-associated enhancements of seed electrons, along with prolonged, intense ULF and VLF wave activity and an earthward displaced plasmapause, as conditions leading to substantial enhancements of relativistic electrons in the outer Van Allen belt. This work has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 870437 for the SafeSpace project.

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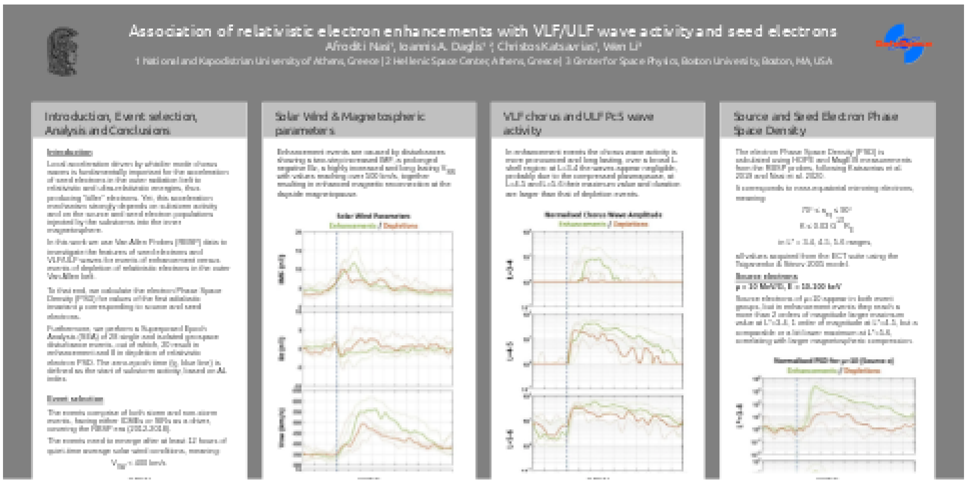

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PRESENTED AT:

INTRODUCTION, EVENT SELECTION, ANALYSIS AND CONCLUSIONS

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 and ultra-relativistic energies, thus producing "killer" electrons. Yet, this acceleration 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 seed electrons and VLF/ULF 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 values of the first adiabatic invariant μ corresponding to source and seed electrons.

Furthermore, we perform a Superposed Epoch Analysis (SEA) of 28 single and isolated geospace disturbance events, out of which, 20 result in enhancement and 8 in depletion of relativistic electron PSD. The zero-epoch time (t_0, blue line) is defined as the start of substorm activity, based on AL index.

Event selection

The events comprise of both storm and non-storm events, having either ICMEs or SIRs as a driver, covering the RBSP era (2012-2018).

The events need to emerge after at least 12 hours of quiet-time average solar wind conditions, meaning:

$$V_{SW} < 400 \text{ km/s}$$

$$P_{SW} < 3 \text{ nPa}$$

$$\text{SYM-H} > -20 \text{ nT}$$

$$\text{AL} > -300 \text{ nT}$$

$$-5 \text{ nT} < B_Z < 5 \text{ nT}$$

These criteria yield a total of 71 events, out of which, 20 result in Enhancement ($PSD_{post}/PSD_{pre} \geq 6$) and 8 result in Depletion ($PSD_{post}/PSD_{pre} \leq 1/4$) 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.

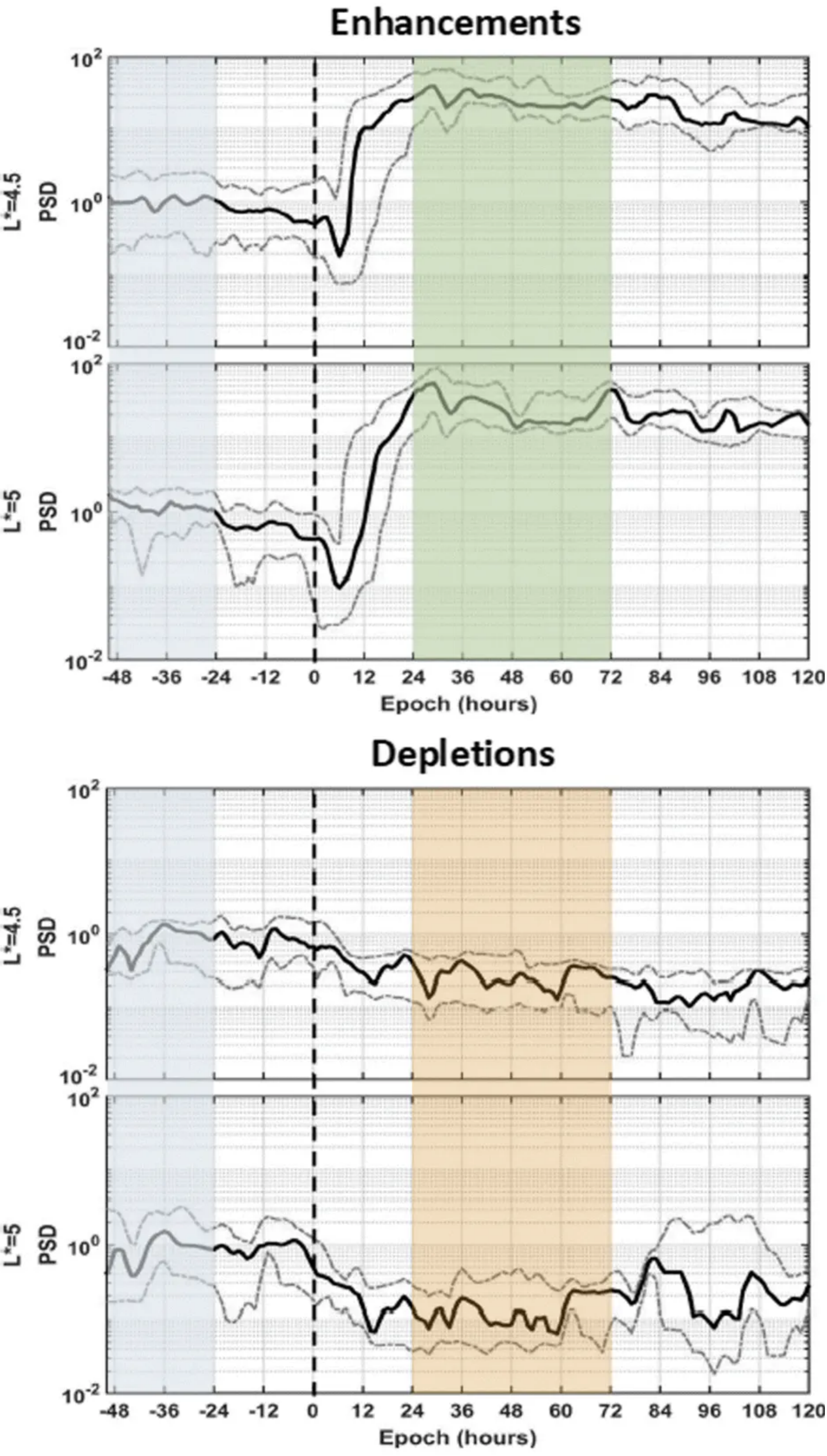

Figure 1. Evolution of PSD for electrons of μ=900 MeV/G at L*>4.5, according to which the event categories are defined, following

Katsavrias et al. 2019.

Results

Our results are presented in the following boxes, with green color corresponding to Enhancement events and orange to Depletion events. The solid plot lines correspond to the median values, and the dashed lines to the 25% and 75% quantiles. In the SEA, the zero-epoch time t_0 is defined as the start time of continuous substorm activity, as indicated by the decrease of AL index.

Conclusions

The geospace disturbances that lead to enhancement events are characterized by distinct solar wind and geomagnetic conditions: two-step increased IMF, prolonged negative Bz, long lasting V_{SW} reaching over 550 km/s, statistically stronger and more prolonged storm and substorm activity, a significantly eroded plasmapause reaching under L=4, and more pronounced and prolonged VLF/chorus and ULF/Pc5 wave activity, especially at the region of L or L*=4-5, the nominal heart of the outer Van Allen belt.

Our study highlights the importance of substorm-associated enhancements of seed electrons, along with prolonged, intense ULF and VLF wave activity and an earthward displaced plasmapause, as conditions leading to substantial enhancements of relativistic electrons in the outer Van Allen belt.

Media sources

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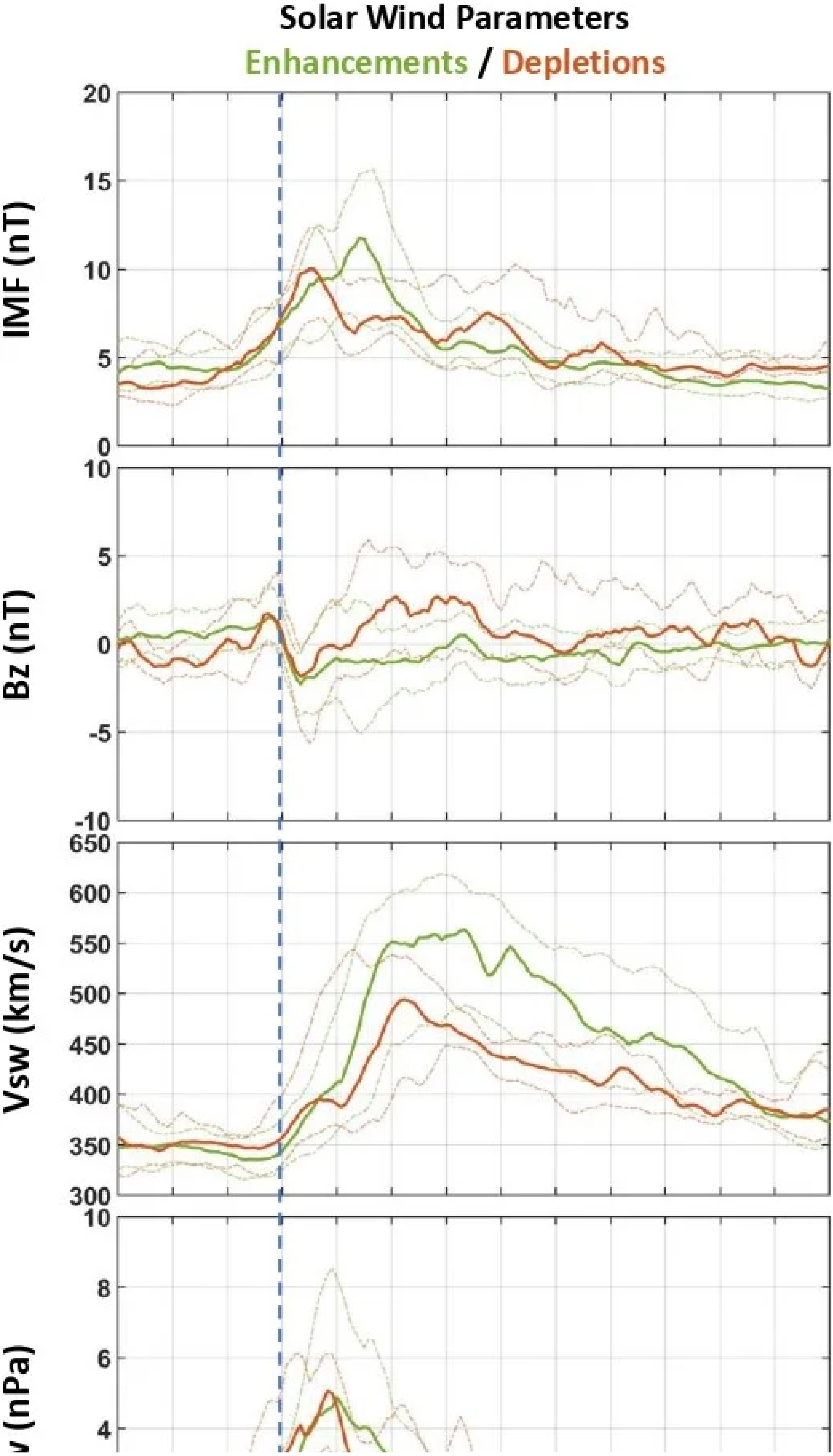
SOLAR WIND & MAGNETOSPHERIC PARAMETERS

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.



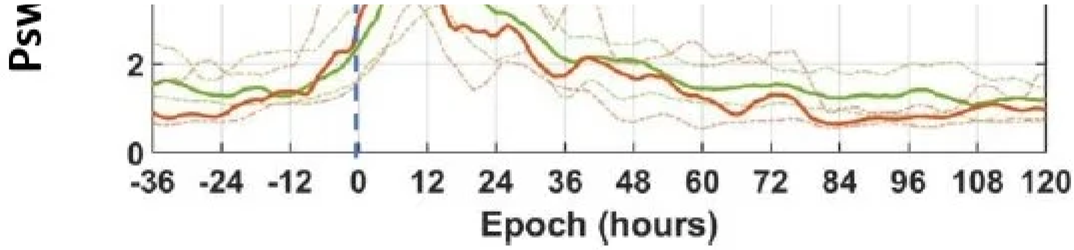


Figure 2. Interplanetary Magnetic Field IMF (nT), Bz component of IMF (nT), Solar Wind Velocity V_{SW} (km/s), Solar Wind dynamic Pressure P_{SW} (nPa). Data from NASA OMNIweb database.

Additionally, 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.

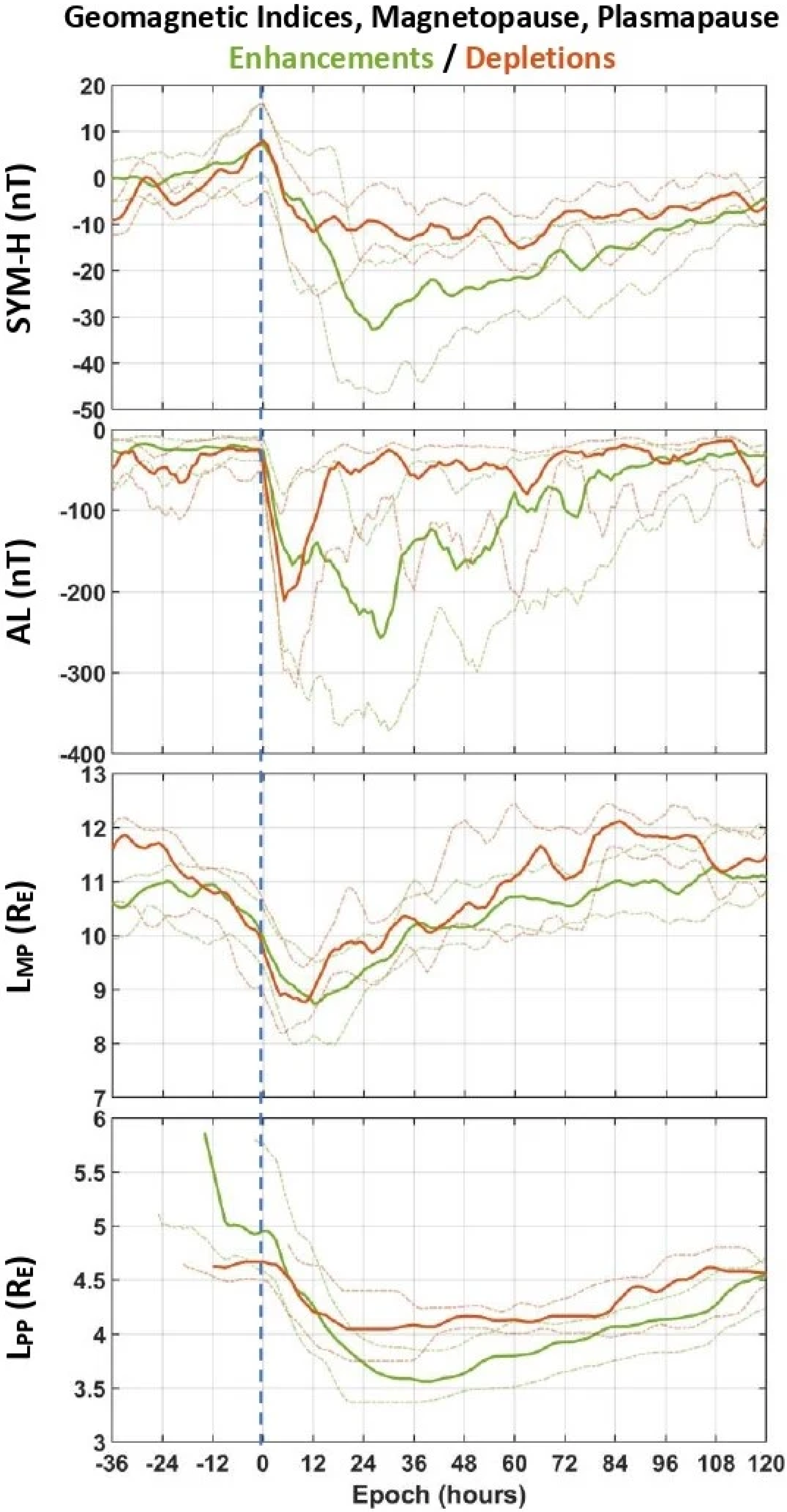

Geomagnetic Indices, Magnetopause, Plasmapause
Enhancements / Depletions
SYM-H (nT)
AL (nT)
LMP (RE)
LPP (RE)
20
10
0
-10
-20
-30
-40
-50
0
-100
-200
-300
-400
13
12
11
10
9
8
7
6
5.5
5
4.5
4
3.5
3
-36 -24 -12 0 12 24 36 48 60 72 84 96 108 120
Epoch (hours)

Figure 3. Geomagnetic indices SYM-H (nT) and AL (nT), from NASA OMNIweb database. Location of the Magnetopause L_{MP} (R_E) calculated using Shue et al. 1998. MLT-averaged location of the Plasmapause L_{PP} (R_E) calculated using O'Brien and Moldwin 2003.

VLF CHORUS AND ULF PC5 WAVE ACTIVITY

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.

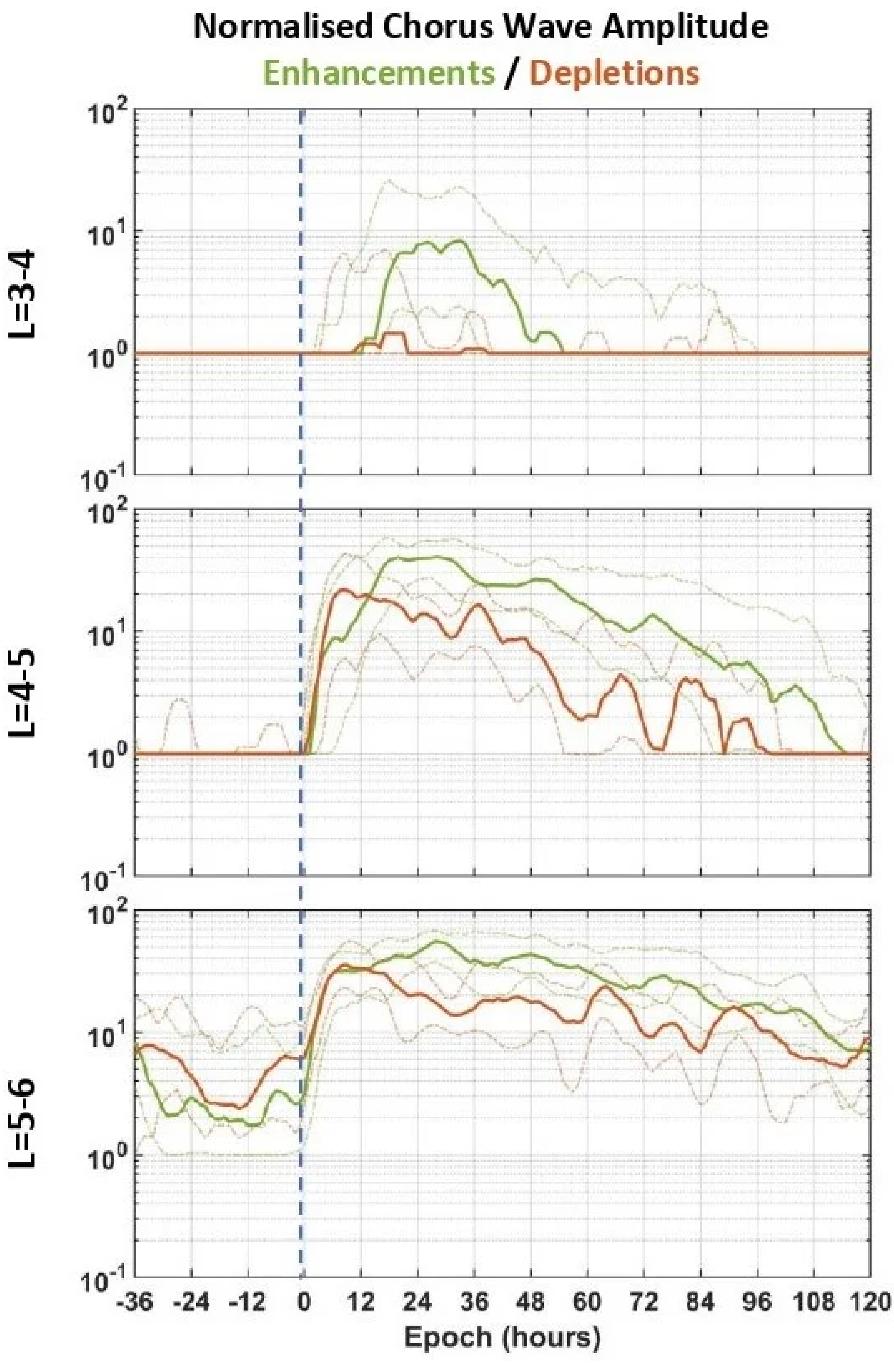


Figure 4. VLF Chorus wave amplitude inferred from POES & MetOp electron (30–100 keV) precipitation, following Li et al. 2013. They correlate with substorm activity (AL index) and the plasmapause location (L_{PP}). The use of L instead of L* for the chorus waves is done with caution. The broad binning that we use (dL=0.5 and dT=1h), as well as the qualitative nature of this study, leads as to believe that this will not significantly affect the nature of our results.

Additionally, in enhancement events the Pc5 wave activity is more pronounced and longer-lasting, especially at L*=4-5 and L*=5-6.

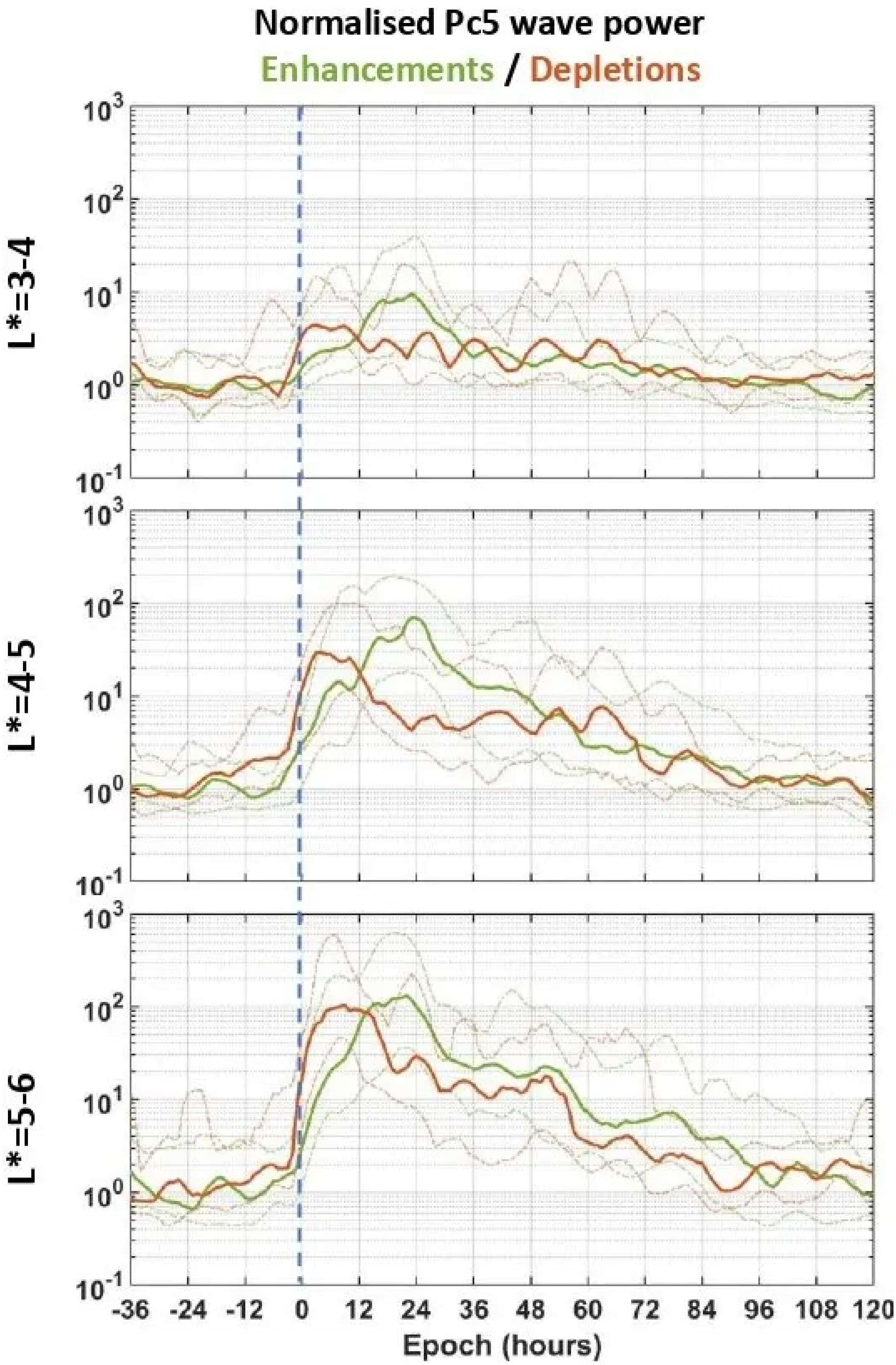


Figure 5. ULF Pc5 wave power inferred by Morlet Wavelet Transform on magnetic field B data from Van Allen Probes, using Balasis et al. 2013. They correlate with P_{SW} and enhanced reconnection (Bz<0 and enhanced V_{SW}).

SOURCE AND SEED ELECTRON PHASE SPACE DENSITY

The electron Phase Space Density (PSD) is calculated using HOPE and MagEIS measurements from the RBSP probes, following Katsavrias et al. 2019 and Nasi et al. 2020.

It corresponds to near-equatorial mirroring electrons, meaning:

$$70° \leq a_{eq} \leq 90°$$

$$K \leq 0.03\ G^{1/2}R_E$$

in L* = 3-4, 4-5, 5-6 ranges,

all values acquired from the ECT suite using the Tsiganenko & Sitnov 2005 model.

Source electrons
μ = 10 MeV/G, E = 10-100 keV

Source electrons of μ=10 appear in both event groups, 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.

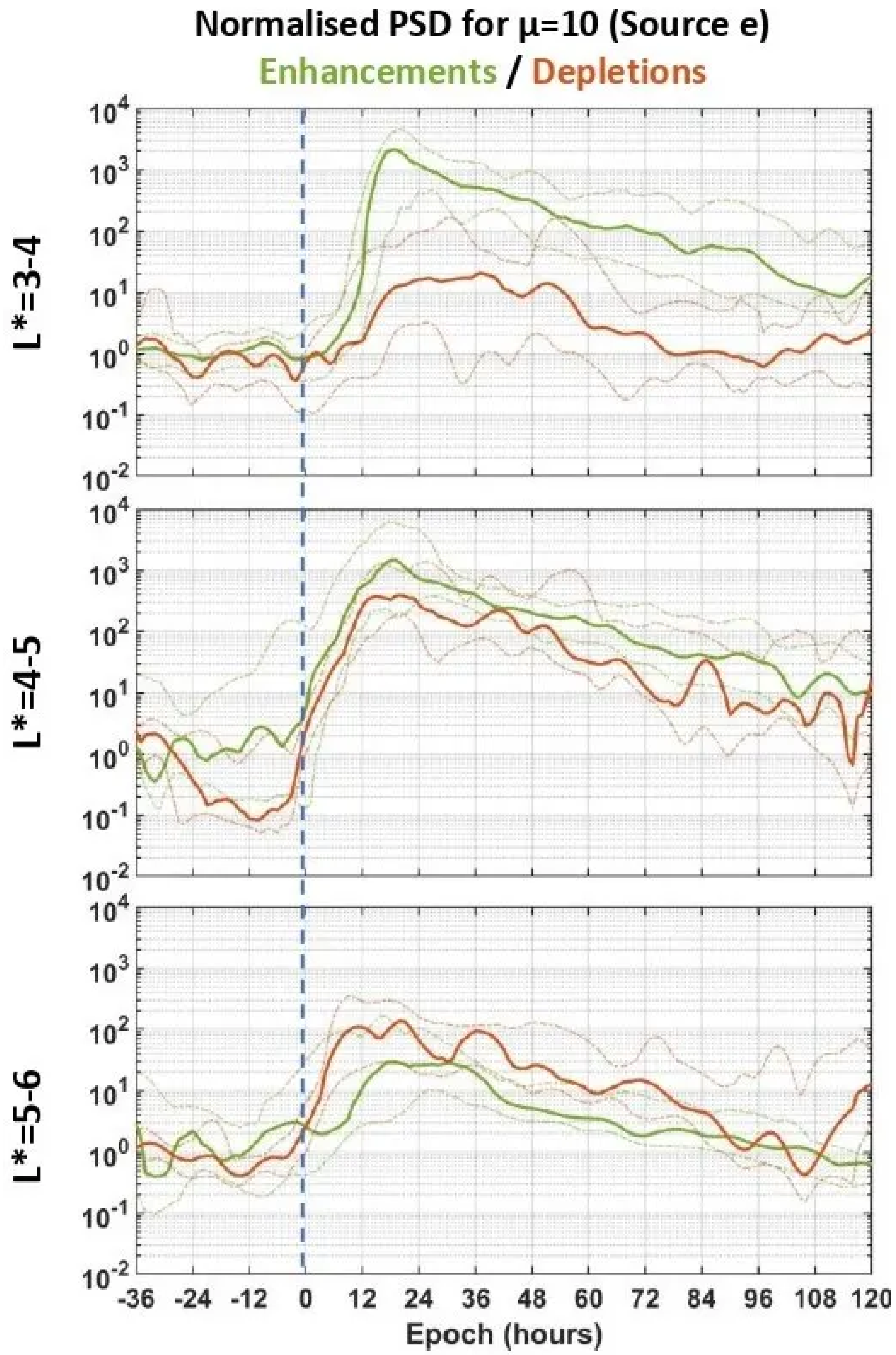


Figure 6. Normalised PSD of source electrons (μ = 10 MeV/G, E = 10-100 keV) following Katsavrias et al. 2019 and Nasi et al. 2020.

Seed electrons

μ = 100 MeV/G, E = 100-600 keV

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

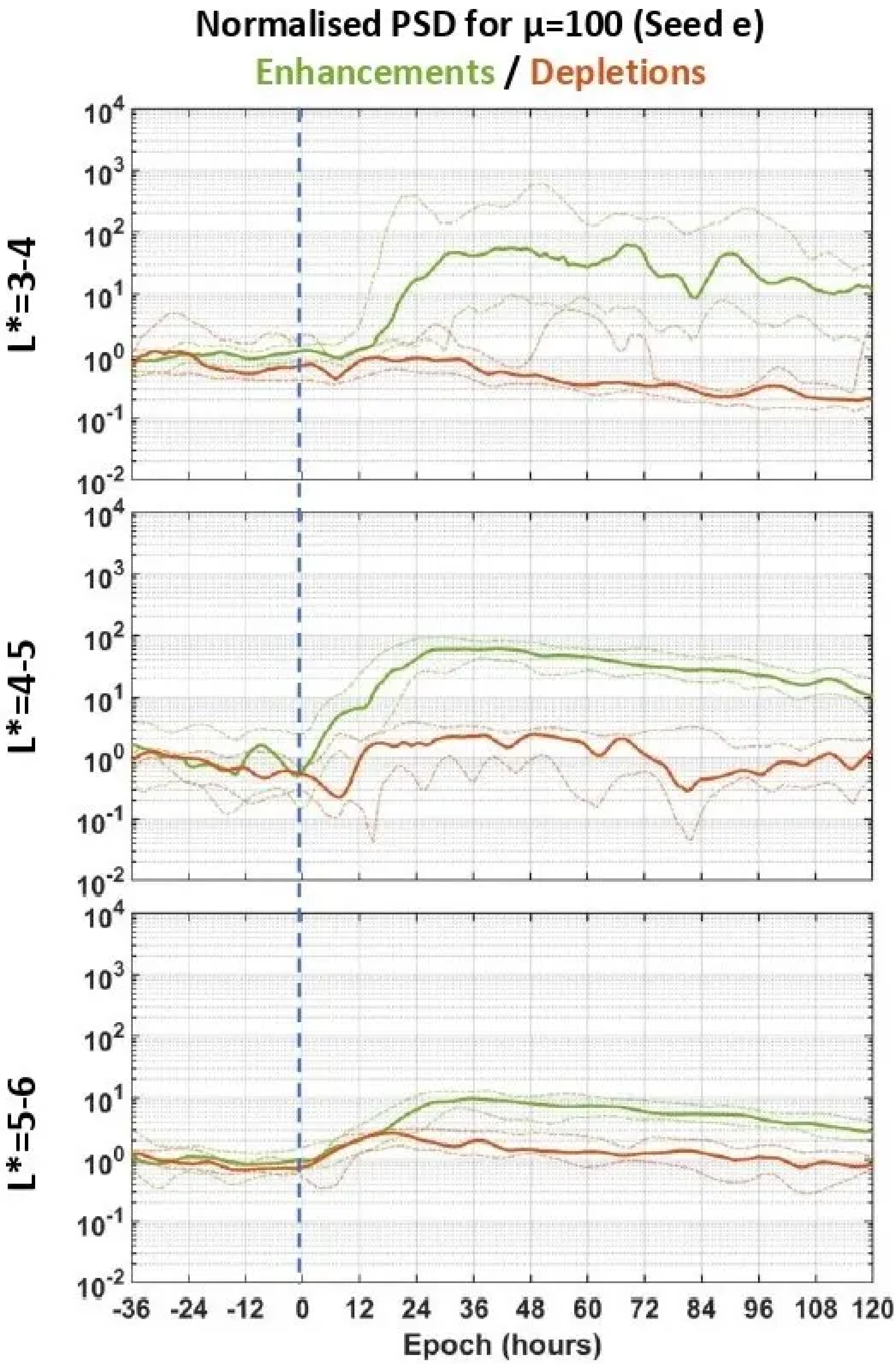


Figure 7. Normalised PSD of seed electrons (μ = 100 MeV/G, E = 100-600 keV) following Katsavrias et al. 2019 and Nasi et al. 2020.

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References

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