Differences in inner magnetospheric wave activity, outer Van Allen belt electron dynamics and atmospheric precipitation during CME sheaths and flux rope

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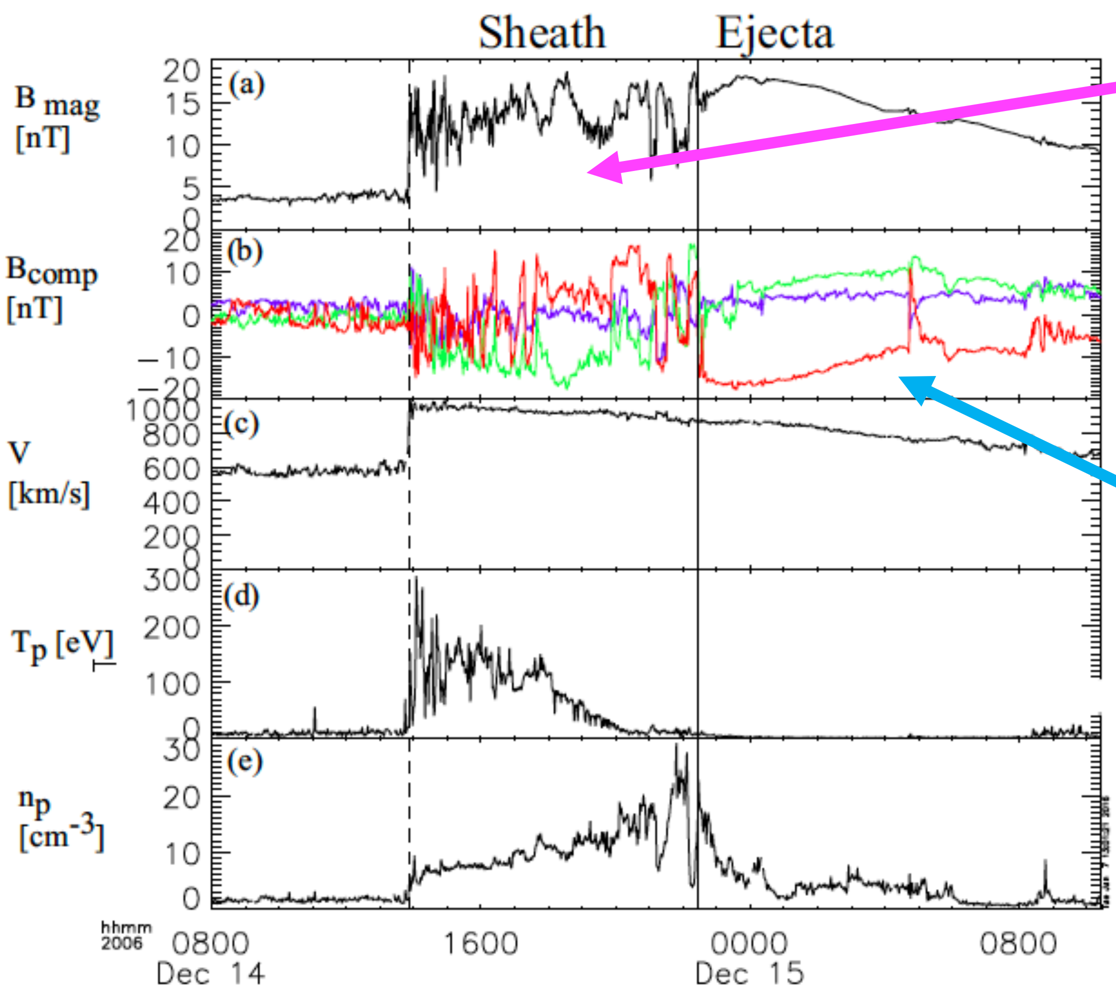
Motivation Interplanetary coronal mass ejections (ICMEs) are key drivers of magnetic storms. Different ICME substructures (shock, sheath, ejecta) have distinct solar wind conditions and magnetospheric responses (e.g., *Kilpua et al. Space Sci. Rev., 2017*) → different radiation belt response expected (see earlier studies by *Hietala et al.*, GRL 2014, *Kilpua et al*., 2019 & *Turner et al*., 2019)

Results shown We report here the results from studies investigating electron flux variations, inner magnetospheric wave activity (chorus, hiss, EMIC, Pc5) and precipitation* to the upper atmosphere obtained using Van Allen Probes, GOES and riometer data during sheaths and ejecta. In particular, statistical immediate response of radiation belt electron fluxes to sheaths is shown.

***See also the online EGU presentation**: George et al. Electron Flux and Precipitation During ICME Case Studies (POES data): EGU2020-5002

ICME sheath and ejecta

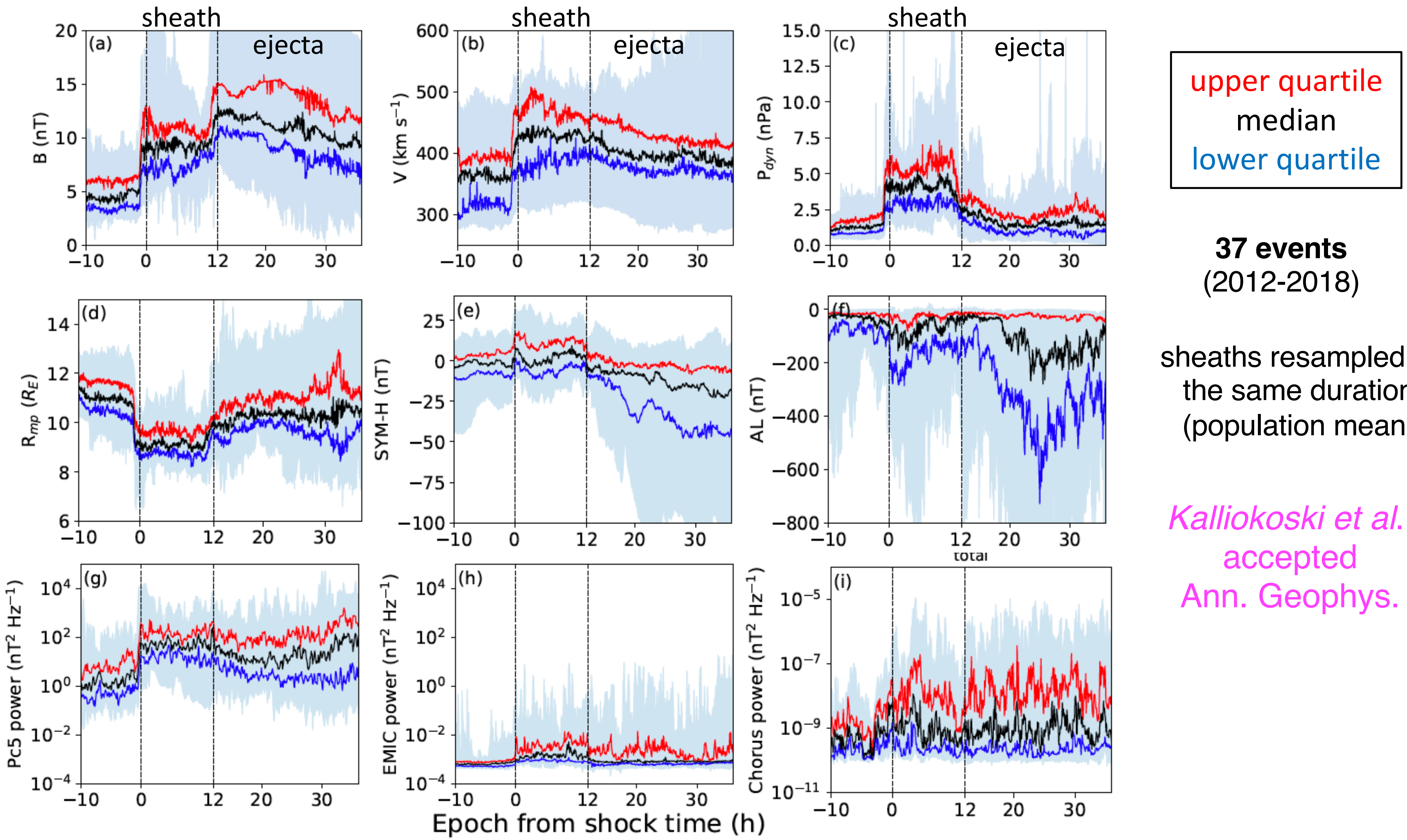


sheath: turbulent and compressed region with high solar wind dynamic pressure and variable magnetic field

ejecta: smooth changes of B-field direction (flux rope) and plasma parameters, low dynamic pressure

Kilpua, Koskinen & Pulkkinen, Living Reviews in Solar Physics, 10.1007/s41116-017-0009-6, 2017

Overview and wave response



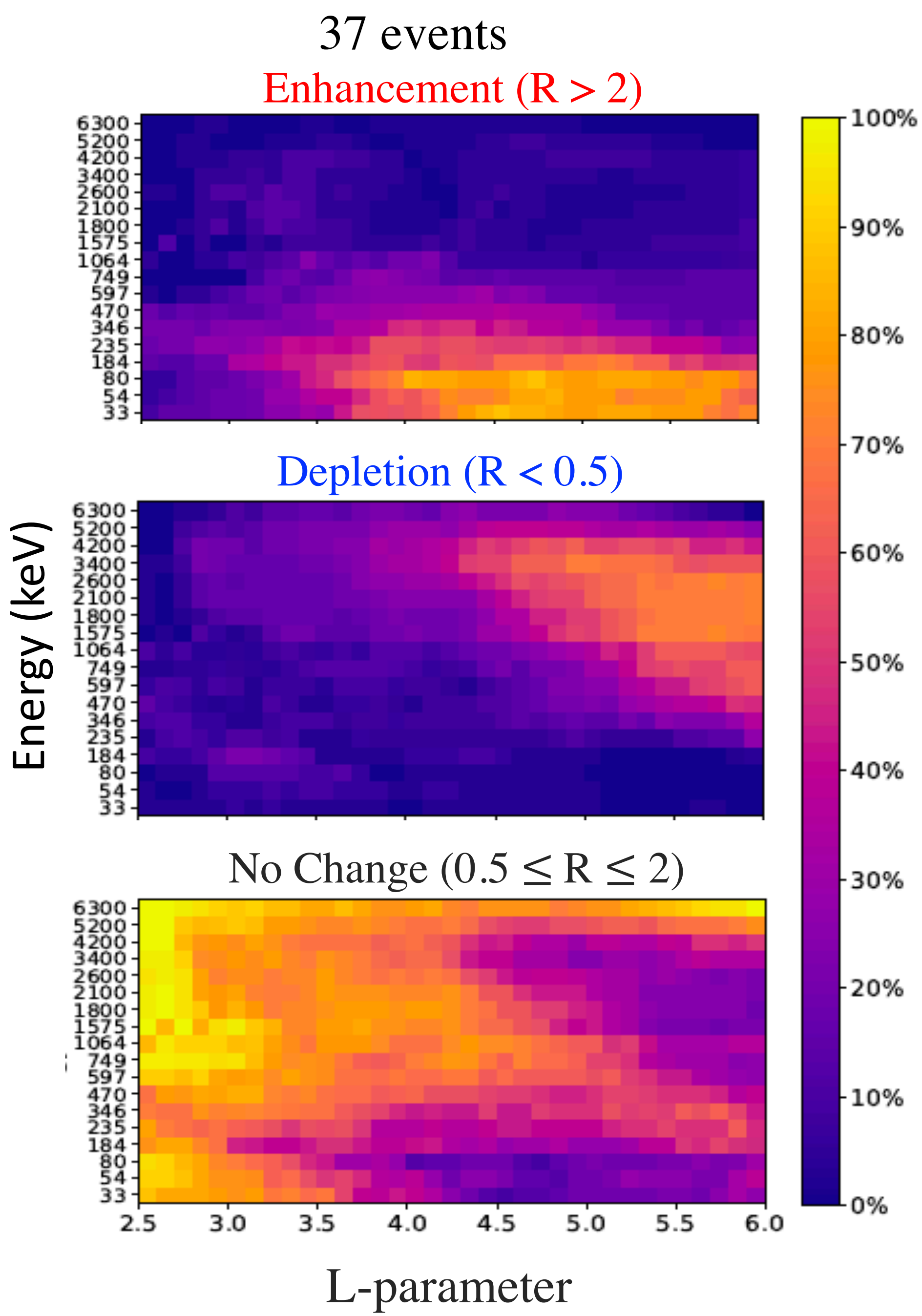
37 events
(2012-2018)

sheaths resampled to the same duration (population mean)

Kalliokoski et al., accepted Ann. Geophys.

- sheaths have higher P_{dyn}, and much more compressed subsolar magnetopause (R_{mp})
- ejecta more geoeffective (in terms of SYMH and AL), but sheaths cause similar level or even higher wave activity in the inner magnetosphere (panels g-i).

Immediate response to sheaths



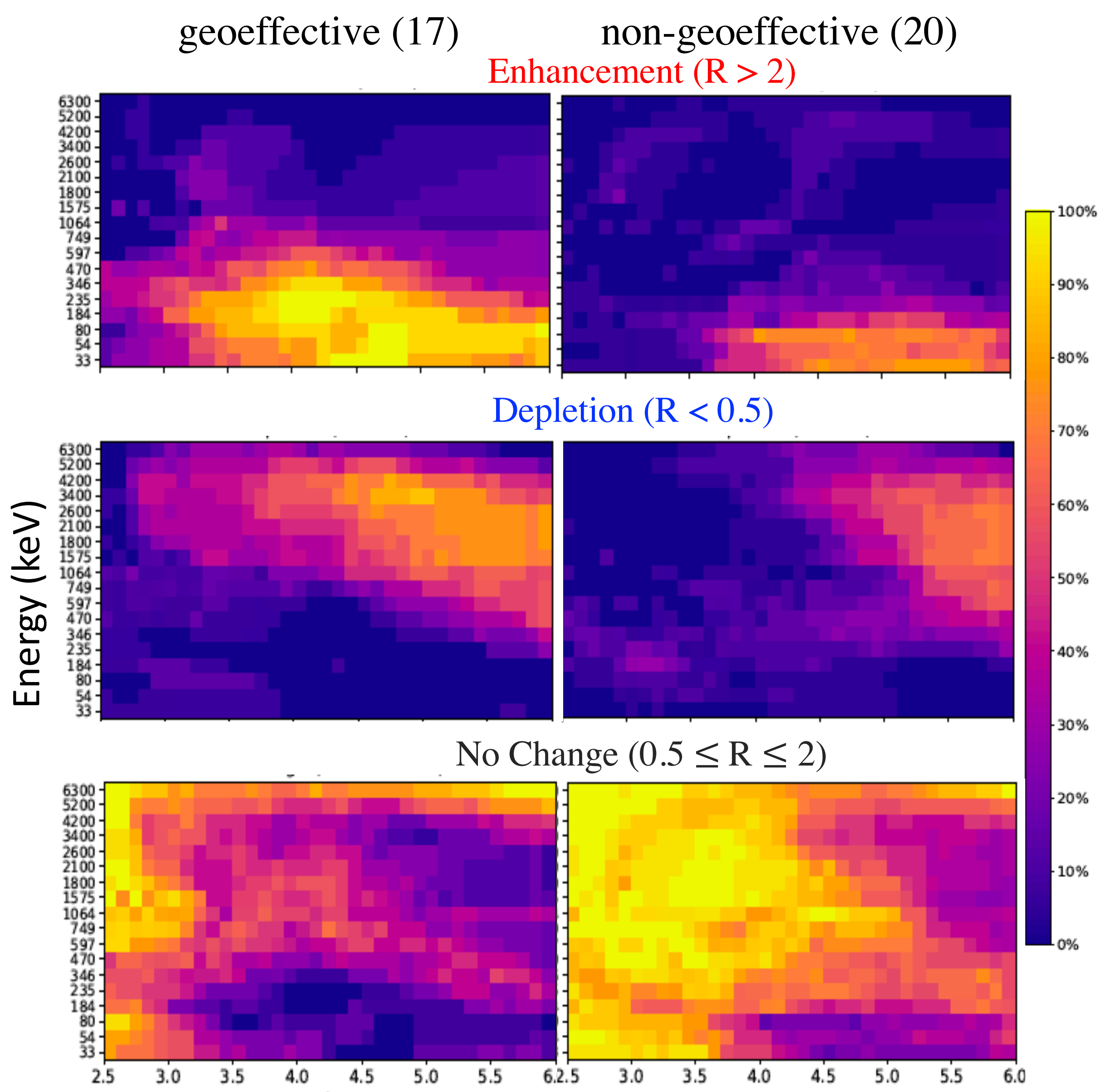
- **Source** (< 80 keV) population at $L > 3.5$ practically always enhance
- **Seed** population (~few hundreds keV) enhance about 50% of cases
- **Core** population (MeVs) deplete in the outer belt ($L > 4.5$) nearly always. At lower L shells ($L \sim 3$-4) enhance in about 20-30% of the cases.
- Depletions progress to lower energies when L increases → in the inner belt (energy-dependent) wave-particle interactions contribute significantly to losses, while at larger L magnetopause shadowing depletes all energies equally

$$R = \frac{\langle flux \rangle_{after}}{\langle flux \rangle_{before}}$$

$\langle flux \rangle_{after}$: 6 hrs after sheath ends
$\langle flux \rangle_{after}$: 6 hrs before shock

Kalliokoski et al., accepted, Ann. Geophys.

Geoeffective vs. non-geoeffective sheaths

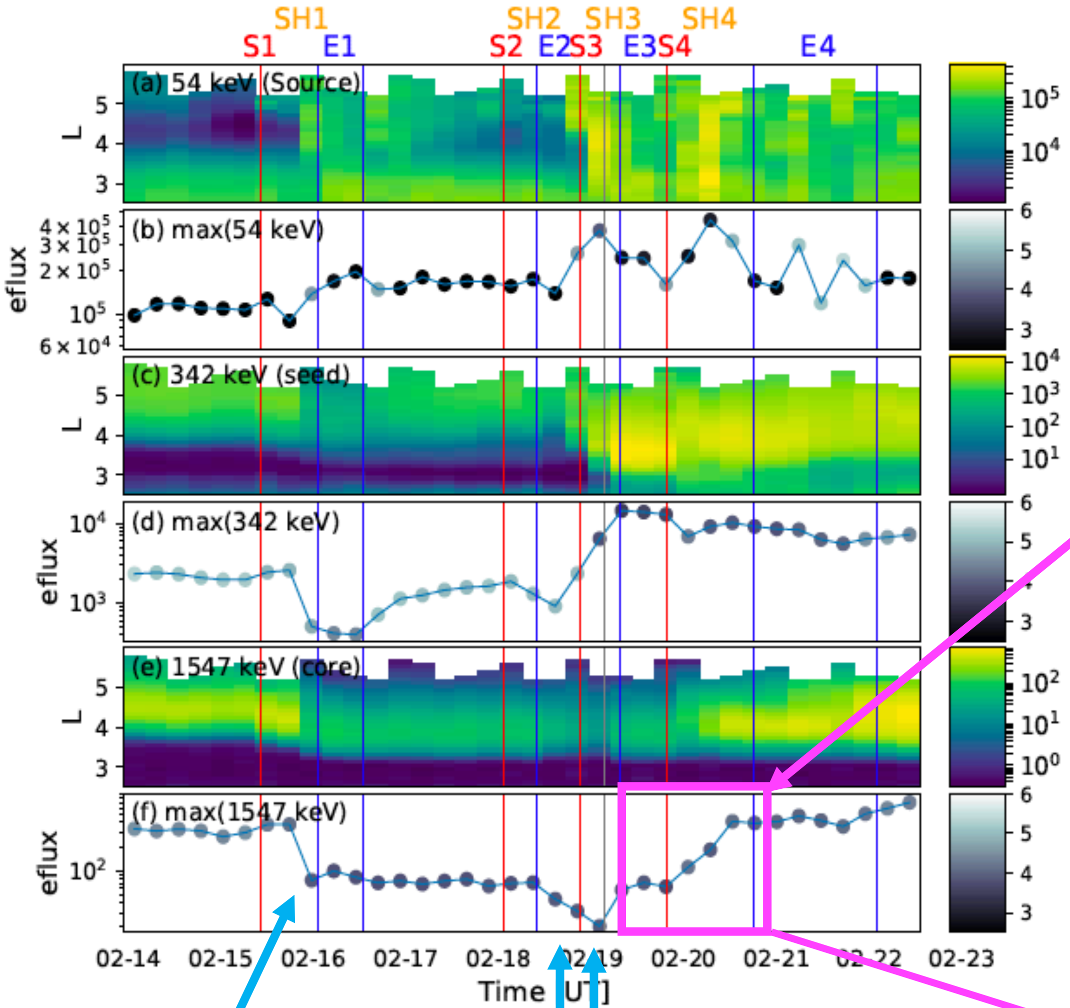


geoeffective sheath: SYMH < -30 nT

- **geoeffective** sheaths have enhancements more commonly at all energies and L-shells for seed and source energies, while MeV electrons deplete strongly throughout the belt
- **non-geoeffective** sheaths have very little response $L < 4.5 - 5$, but at higher L-shells core electrons deplete and source electrons enhance. Seed population shows little response. → non-geoeffective sheaths can cause some notable response to outer parts of the outer radiation belts
- Both geoeffective and non-geoeffective sheaths show progression in depletion to energies with increasing L

Kalliokoski et al., accepted, Ann. Geophys.

Case study of interacting ICMEs

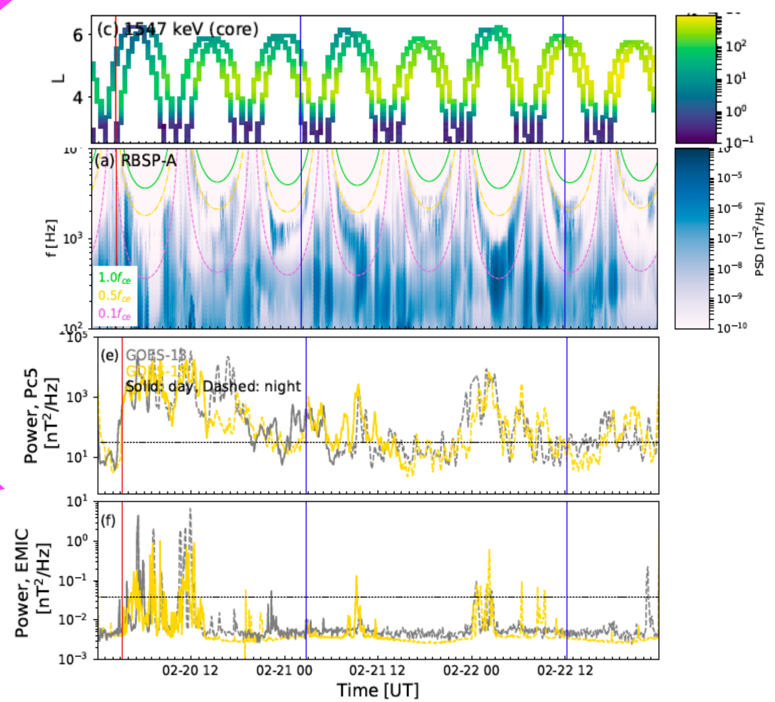


Sheath and ejecta mostly deplete core electrons

Multiple interacting ICMEs during February 14-23, 2014

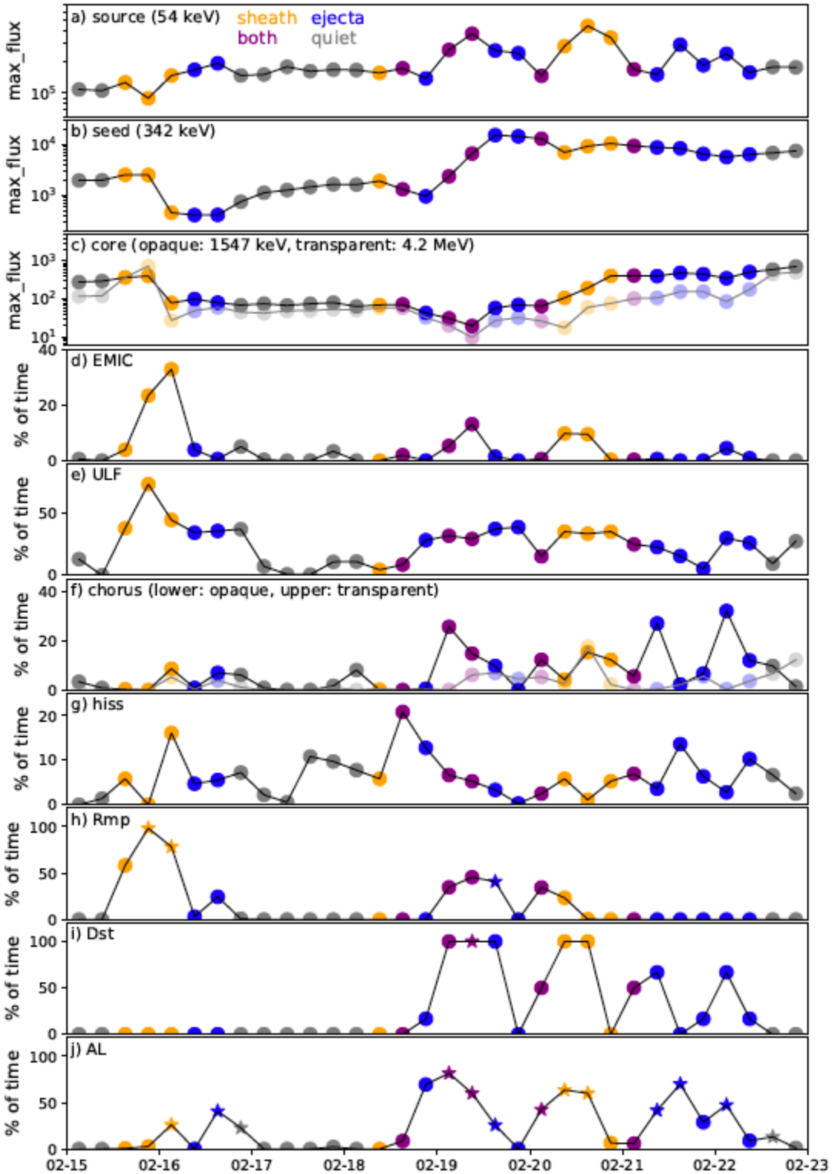
S: Shock SH: Sheath E: Ejecta

Core population enhance during edge encountered sheath + ejecta due to prolonged chorus acceleration + Pc5 inward radial transport



Kilpua et al., JGR, doi:10.1029/2018JA026238, 2019

Case study of interacting ICMEs



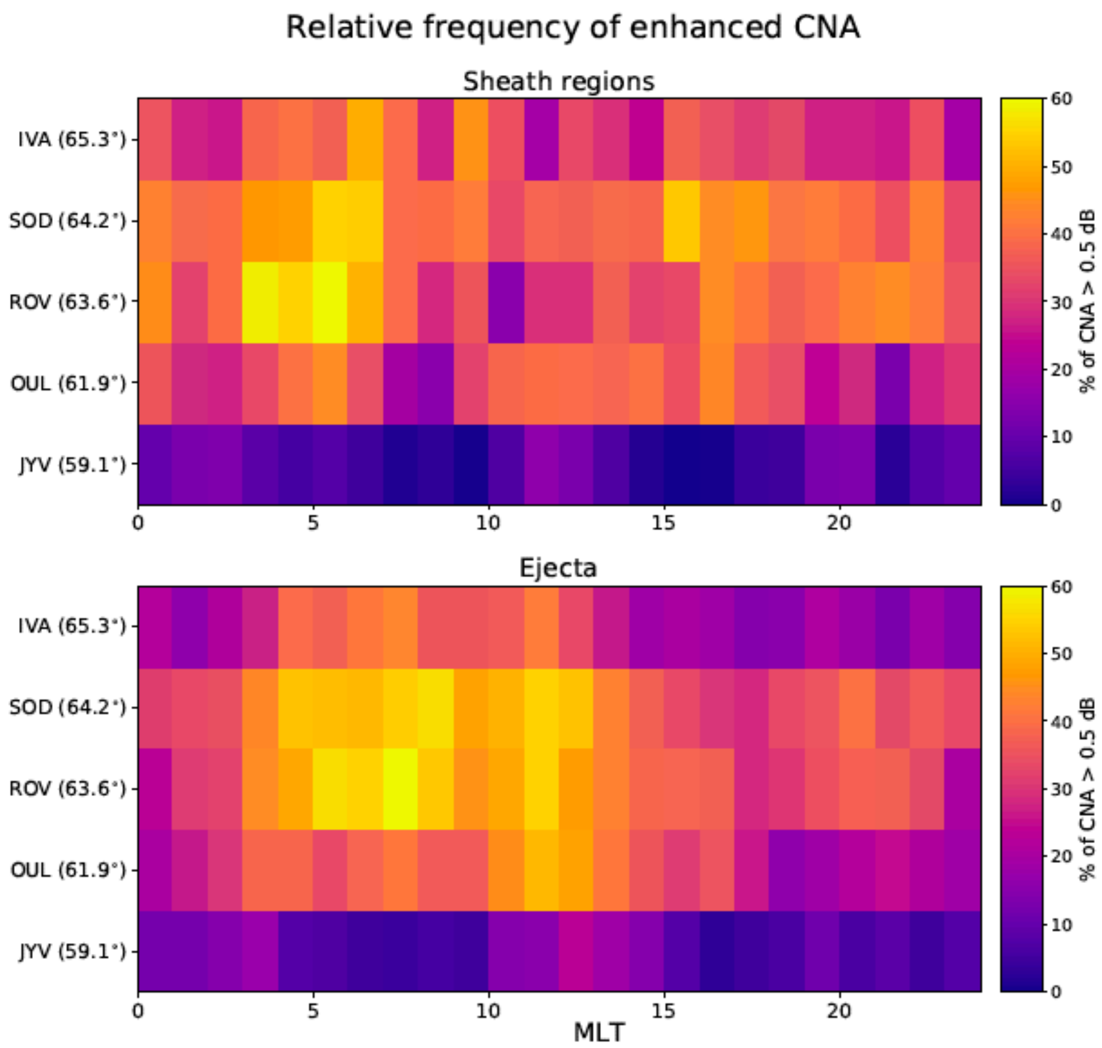
maximum electron flux

% of time exceeding the value

Parameter	Threshold
Lower band chorus	$> 1.3\times10^{-8}$ nT^{2}Hz^{-1}
Upper band chorus	$> 8.1\times10^{-10}$ nT^{2}Hz^{-1}
hiss	$> 3.5\times10^{-7}$ nT^{2}Hz^{-1}
ULF Pc5	> 31.2 nT^{2}Hz^{-1}
EMIC	< 0.039 nT^{2}Hz^{-1}
Rmp (star)	$< 8\ R_E$ ($< 7\ R_E$)
Dst (star)	$<$ -50 nT (-100 nT)
AL (star)	$<$ -300 nT (-600 nT)

Kilpua et al., JGR, doi:10.1029/2018JA026238, 2019

Precipitation response



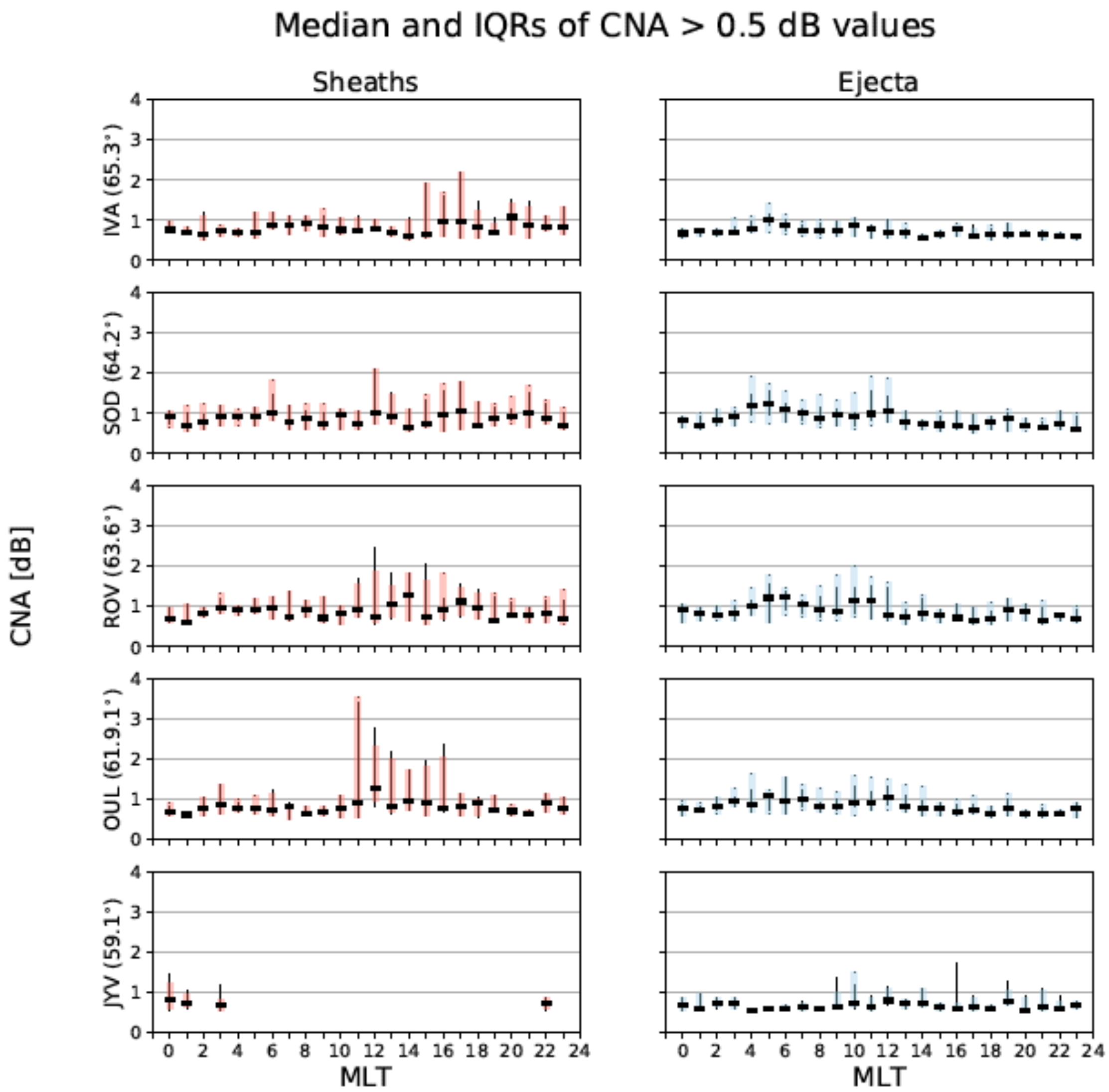
Enhanced CNA: CNA > 0.5 dB

- Cosmic Noise Absorption (CNA) response from the Finnish riometer chain as a function of magnetic local time (MLT)
- sheaths and ejecta were almost equally effective in inducing enhanced CNA
- Some clear MLT trends between the ejecta and sheaths: The occurrence frequency peaks for the sheaths in the morning and afternoon/evening sectors and for the ejecta in the morning and noon sectors.

Station	GGlat [deg]	GGlong [deg]	CGMlat [deg]	CGMlon [deg]	L-value	MLT	Freq [MHz]
Ivalo (IVA)	68.55N	27.28E	65.24N	108.29E	5.5	UT+2.97 h	30.0
Sodankylä (SOD)	67.42N	26.39E	64.13N	106.85E	5.1	UT+2.48 h	30.0
Rovaniemi (ROV)	66.78N	25.94E	63.49N,	106.11E	4.8	UT+2.46 h	32.4
Oulu (OUL)	65.08N	25.90E	61.75N	105.14E	4.3	UT+2.76 h	30.0
Jyväskylä (JYV)	62.42N	25.28E	59.01N	103.37E	3.7	UT+2.65 h	32.4

Kilpua et al., Ann. Geophys., https://doi.org/10.5194/angeo-38-557-2020, 2020

Precipitation response



- black dots show the medians and coloured bars Inter Quartile Range (IQR) of significant CNA values as a function of MLT. Vertical lines give the bootstrapping errors calculated for 10000 samples.
- Magnitude of CNA peaks for sheaths from morning to afternoon/early evening hours, while for the ejecta from morning to noon

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Summary

- ICME-driven sheath cause particularly intense wave activity in the inner magnetosphere and significant radiation belt response, even in cases when they are not geoeffective.

- Electron flux enhancements are common at low energies throughout the outer belt (L= 3-6), whereas depletion occurs predominantly at high energies for high radial distances

- Depletion extends to lower energies at larger distances → This L-shell and energy dependent depletion could result from magnetopause shadowing dominating the losses at large distances, while wave-particle interactions dominate closer to the Earth.

- Complex behaviour of the outer belt response during interacting ICMEs can be understood by the knowledge of electron dynamics during different substructures

- Differences in riometer CNA response between the sheath and ejecta (magnitude and relative occurrence) may reflect differences in typical MLT distributions of wave modes that precipitate substorm-injected and trapped radiation belt electrons during the sheaths and ejecta.