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

E. Kilpua (emilia.kilpua@helsinki.fi)\textsuperscript{1}, M. Kalliokoski\textsuperscript{1}, L. Juusola\textsuperscript{2}, M. Grandin\textsuperscript{1}, A. Kero\textsuperscript{3}, D. Turner\textsuperscript{4}, A. Jaynes\textsuperscript{5}, T. Asikainen\textsuperscript{6}, S. Dubyagin\textsuperscript{2}, H. George\textsuperscript{1}, H. Hietala\textsuperscript{7}, H. Koskinen\textsuperscript{1}, A. Osmane\textsuperscript{1}, M. Palmroth\textsuperscript{1,2}, N. Partamies\textsuperscript{8}, T. Pulkkinen\textsuperscript{9}, T. Raita\textsuperscript{3}, L. Turc\textsuperscript{1}, and R. Vainio\textsuperscript{10}

\textsuperscript{1}University of Helsinki, \textsuperscript{2}Finnish Meteorological Institute, \textsuperscript{3}Sodankylä Geophysical Observatory, Finland, \textsuperscript{4}The Aerospace Corporation, US, \textsuperscript{5}University of Iowa, US, \textsuperscript{6}University of Oulu, Finland \textsuperscript{7}Imperial College, UK, \textsuperscript{8}University Centre in Svalbard, Longyearbyen, Norway \textsuperscript{9}University of Michigan, US, \textsuperscript{10}University of Turku, Finland
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

- Sheaths have higher $P_{dyn}$, and much more compressed subsolar magnetopause ($R_{mp}$).
- Ejecta are 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).

37 events (2012-2018)

Sheaths resampled to the same duration (population mean)

Kalliokoski et al., accepted Ann. Geophys.
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.

\[
R = \frac{\langle \text{flux} \rangle_{\text{after}}}{\langle \text{flux} \rangle_{\text{before}}}
\]

(\( \langle \text{flux} \rangle_{\text{after}} \): 6 hrs after sheath ends)

(\( \langle \text{flux} \rangle_{\text{before}} \): 6 hrs before shock)

*Kalliokoski et al., accepted, Ann. Geophys.*
Geoeffective vs. non-geoeffective sheaths

- **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.

**Geoeffective sheath**: SYMH $<-30$ nT

---

*Kalliokoski et al., accepted, Ann. Geophys.*
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

Sheath and ejecta mostly deplete core electrons

Kilpua et al., JGR, doi:10.1029/2018JA026238, 2019
Case study of interacting ICMEs

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Threshold</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower band chorus</td>
<td>$&gt; 1.3 \times 10^{-8}$ nT$^2$Hz$^{-1}$</td>
</tr>
<tr>
<td>Upper band chorus</td>
<td>$&gt; 8.1 \times 10^{-10}$ nT$^2$Hz$^{-1}$</td>
</tr>
<tr>
<td>hiss</td>
<td>$&gt; 3.5 \times 10^{-7}$ nT$^2$Hz$^{-1}$</td>
</tr>
<tr>
<td>ULF Pc5</td>
<td>$&gt; 31.2$ nT$^2$Hz$^{-1}$</td>
</tr>
<tr>
<td>EMIC</td>
<td>$&lt; 0.039$ nT$^2$Hz$^{-1}$</td>
</tr>
<tr>
<td>Rmp (star)</td>
<td>$&lt; 8$ R$_E$ ($&lt; 7$ R$_E$)</td>
</tr>
<tr>
<td>Dst (star)</td>
<td>$&lt; -50$ nT (-100 nT)</td>
</tr>
<tr>
<td>AL (star)</td>
<td>$&lt; -300$ nT (-600 nT)</td>
</tr>
</tbody>
</table>

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

Precipitation response

**Median and IQRs of CNA > 0.5 dB values**

- 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.

**Table:**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Ivalo (IVA)</td>
<td>68.55N</td>
<td>27.28E</td>
<td>65.24N</td>
<td>108.29E</td>
<td>5.5</td>
<td>UT+2.97h</td>
<td>30.0</td>
</tr>
<tr>
<td>Sodankyla (SOD)</td>
<td>67.42N</td>
<td>26.39E</td>
<td>64.13N</td>
<td>106.82E</td>
<td>5.1</td>
<td>UT+2.44h</td>
<td>30.0</td>
</tr>
<tr>
<td>Rovaniemi (ROW)</td>
<td>66.78N</td>
<td>25.94E</td>
<td>63.49N</td>
<td>106.11E</td>
<td>4.8</td>
<td>UT+2.46h</td>
<td>32.4</td>
</tr>
<tr>
<td>Oulu (OUL)</td>
<td>65.03N</td>
<td>25.93E</td>
<td>61.73N</td>
<td>105.14E</td>
<td>4.3</td>
<td>UT+2.76h</td>
<td>30.0</td>
</tr>
<tr>
<td>Jyväskylä (JYV)</td>
<td>62.42N</td>
<td>25.28E</td>
<td>59.01N</td>
<td>103.37E</td>
<td>3.7</td>
<td>UT+2.65h</td>
<td>32.4</td>
</tr>
</tbody>
</table>

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.