Rapid radiation belt losses occurring during high speed solar wind stream driven storms: importance of energetic electron precipitation

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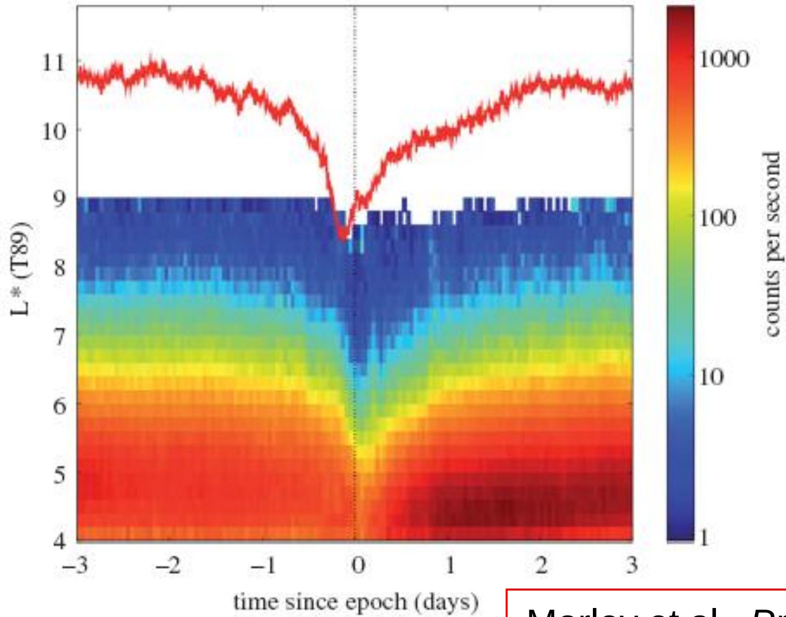
Radiation Belt dropouts in response to High Speed Solar Wind Stream Interfaces (HSSWSIs)

Morley et al. [2010a] examined flux data from the GPS spacecraft constellation for a list of 67 HSSWSI events in the period 2005-2008.

They observed a consistent “dropout” of high-energy electrons in response to the stream interfaces.



Morley et al., *Proc. R. Soc. A,* May 2010

They found:

- The dropouts occurred with a timescale of ~7 h
- The counts fell by 0.4-1.8 orders of magnitude
- The dropouts were observed across all L* and for energies from 230-2200 keV.

Radiation Belt dropouts in response to High Speed Solar Wind Stream Interfaces (HSSWSIs)

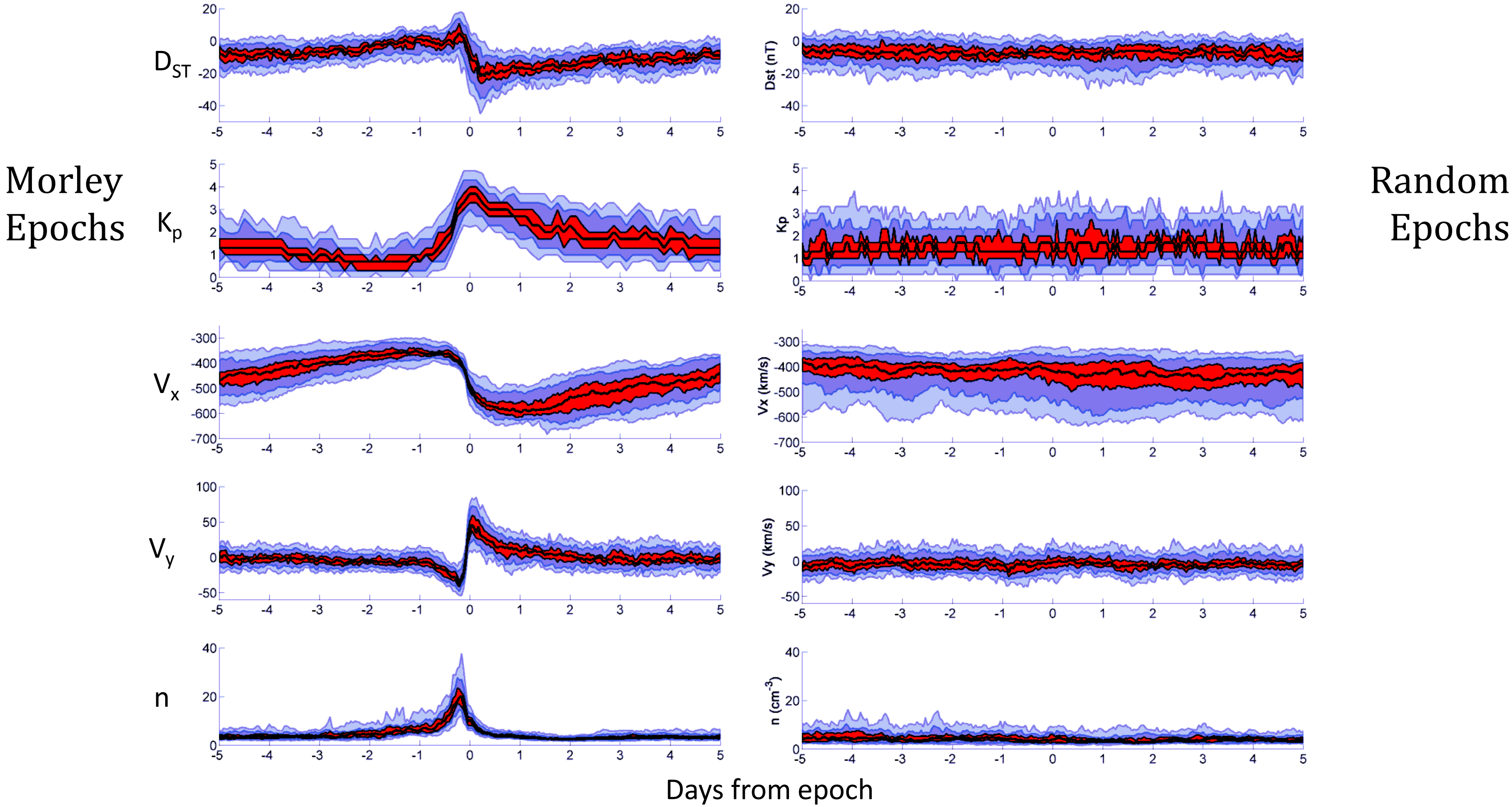
3 possible causes for the dropouts were suggested:

1. Losses through the magnetopause by outward diffusion (radial diffusion)
2. Losses through the magnetopause by magnetopause shadowing
3. Energetic electron precipitation (EEP) into the atmosphere due to wave-particle interactions

In an earlier paper, Morley [2010b] noted that:

1. an unrealistically high diffusion rate was needed to explain the losses, and
2. the observed timescales were ~10x too short to explain the losses via wave-particle interactions

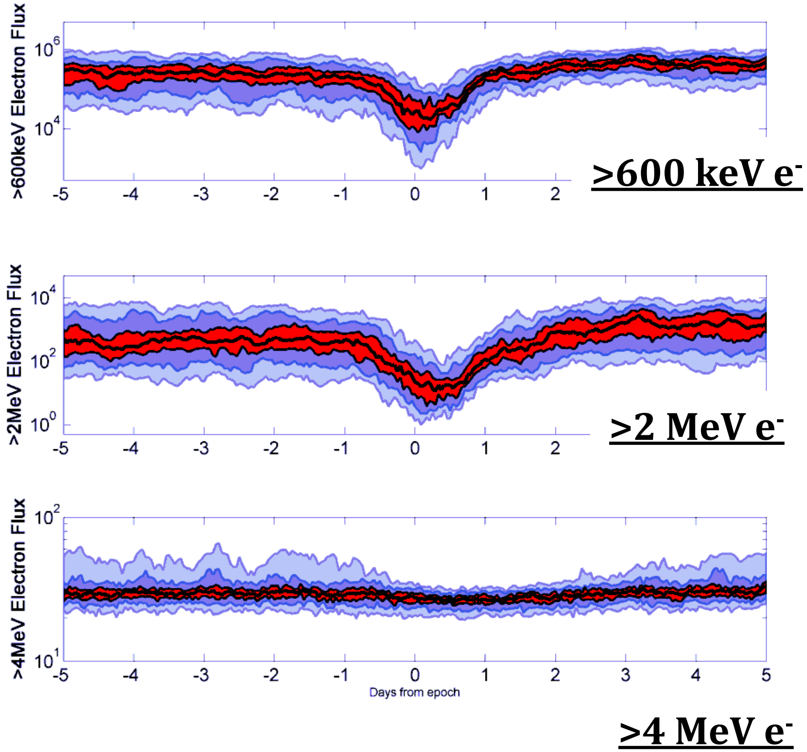
Morley epoch definition



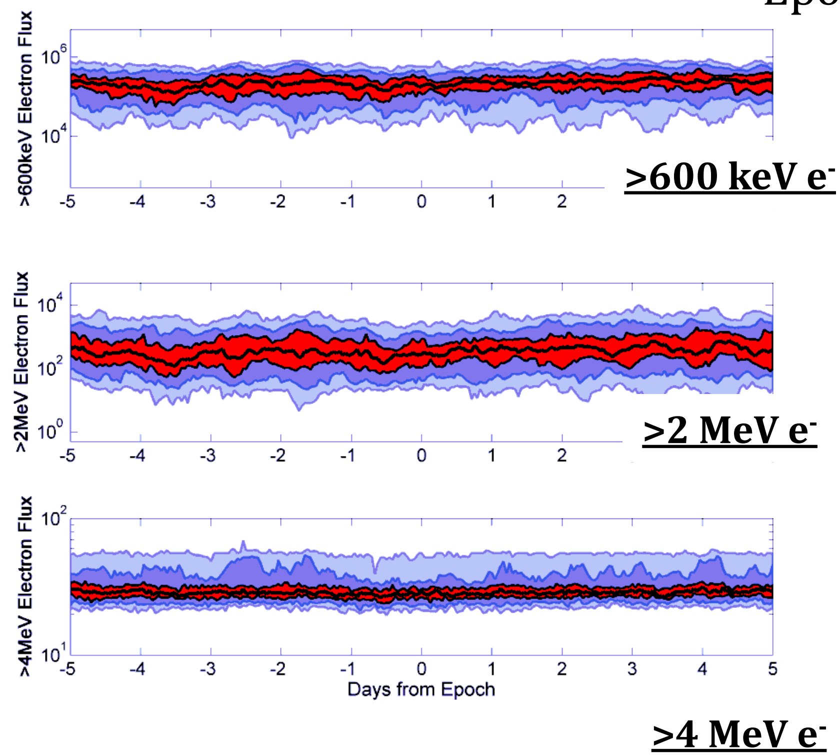
Each Morley epoch is the defined as the time at which the stream interface (SI) reached the Earth's bow shock. The SI itself was defined as being the point where the east-west flow deflection of the stream reversed.

Superposed Epoch analysis of GOES

Morley Epochs



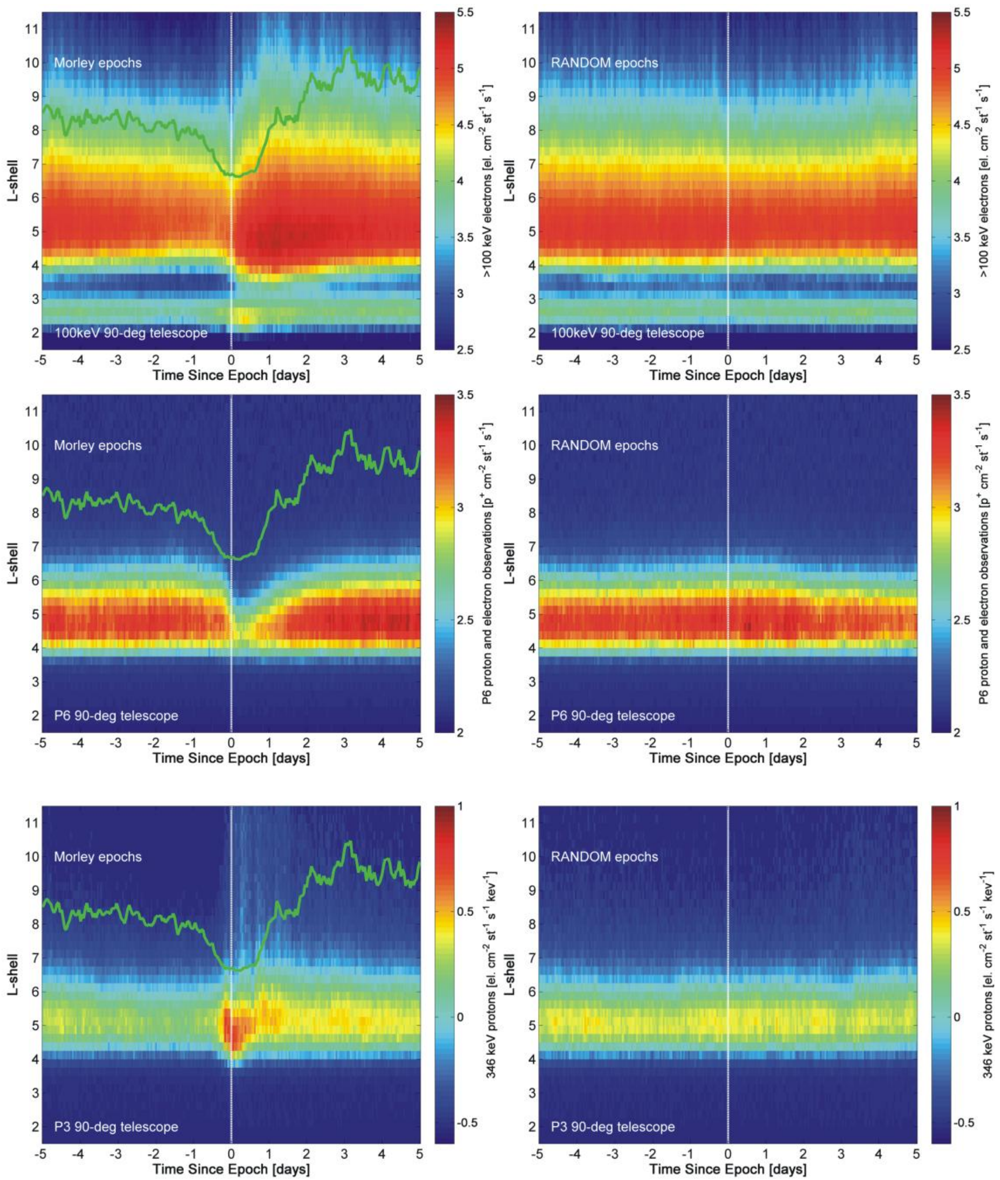
Random Epochs



We used the POES LEO satellites to investigate the radiation belt conditions inside geosynchronous orbit. The Superposed Epoch Analysis (SEA) of the GOES data served as a timing reference for our POES observations.

2 of the Morley epochs have been excluded from our final list due to the presence of solar protons in the data.

Superposed Epoch Analysis of POES Trapped Fluxes

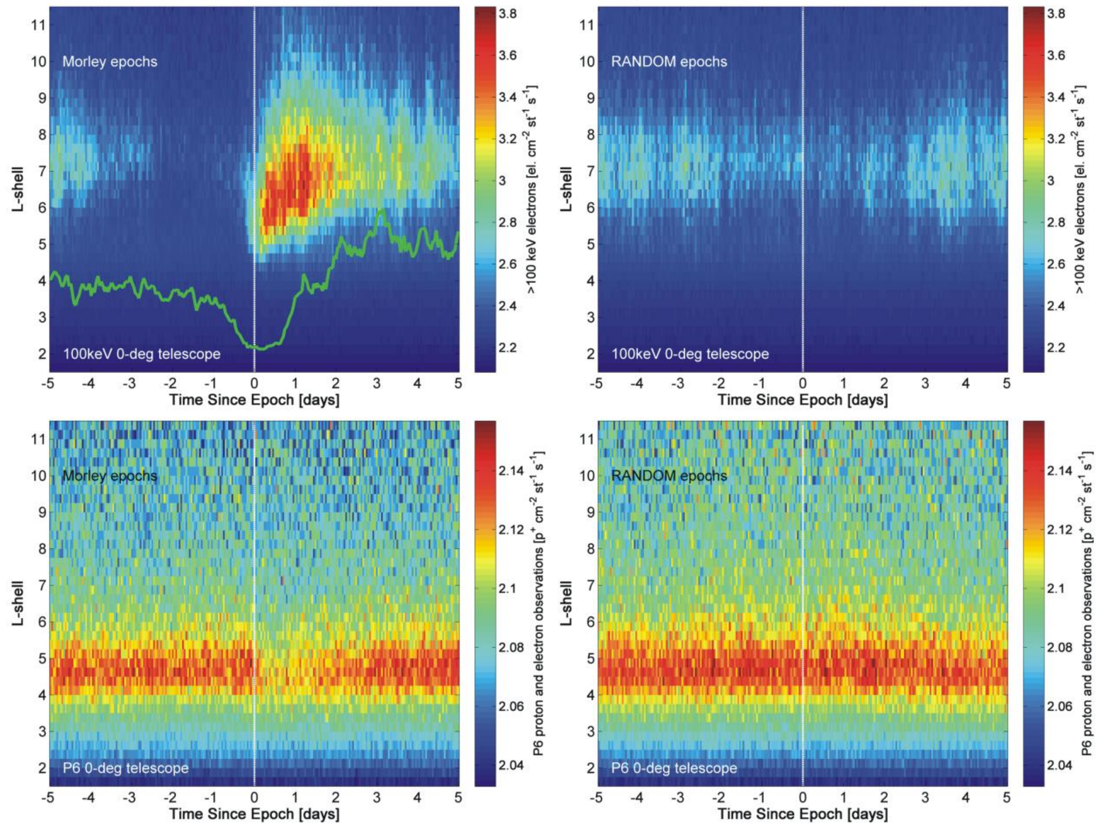


Particle losses due to magnetopause shadowing are independent of pitch angle, such that losses are expected for both LEO and GEO (i.e. GOES and POES).

Magnetopause shadowing also occurs independent of charge, mass and energy – both electrons and protons should be lost.

These requirements aren't met – **magnetopause shadowing cannot explain the electron flux dropout**

Superposed Epoch Analysis of POES Precipitating Fluxes



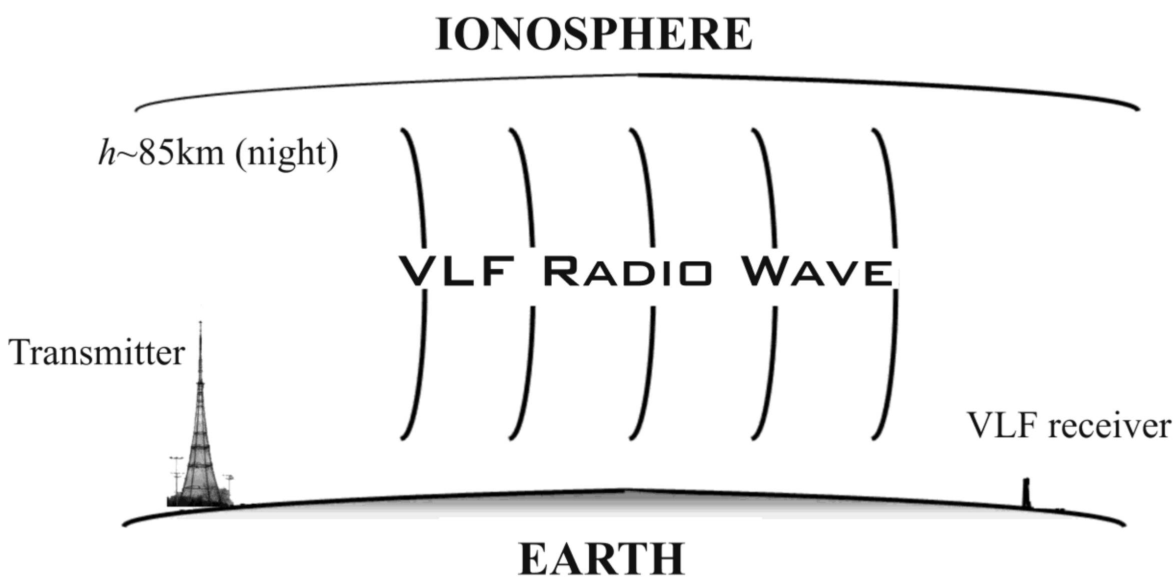
We see a clear increase in electron precipitation, but only for non-relativistic electrons.

The precipitation increase occurs *after* the peak in the GOES dropout, and remains constant throughout the GOES flux recovery.

How much precipitation is there?

We can’t measure precisely what is being lost from the radiation belts.

So how can we determine the magnitude of the electron precipitation?

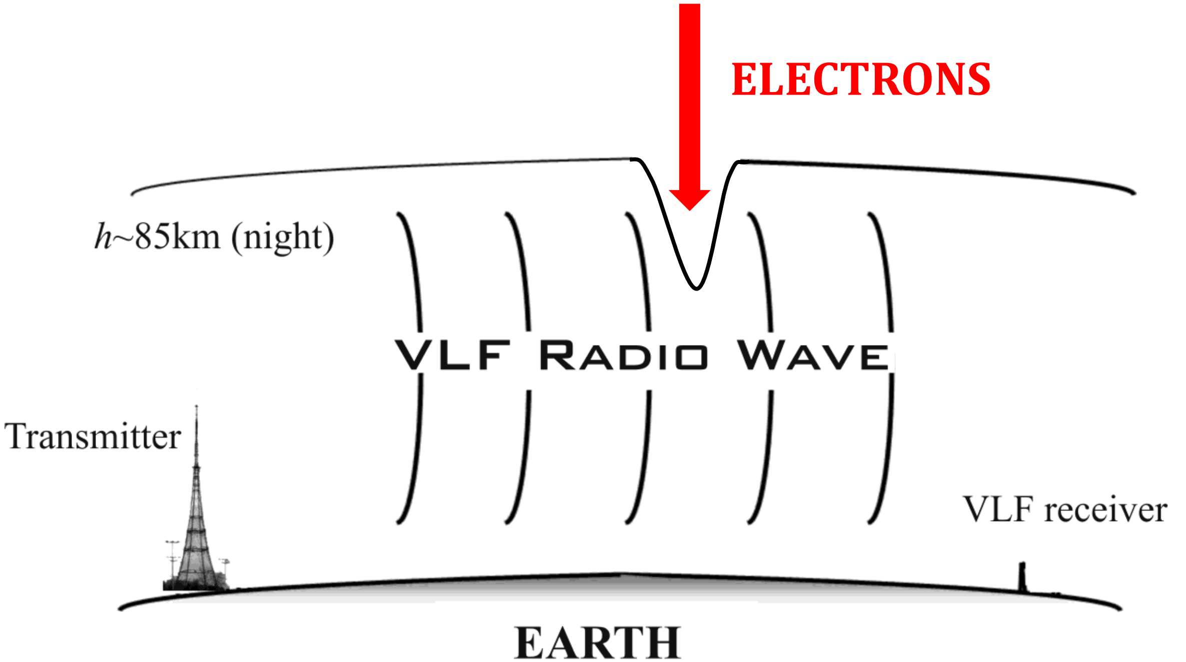


We use the ionosphere as a particle detector!

Subionospheric Radio Wave Propagation

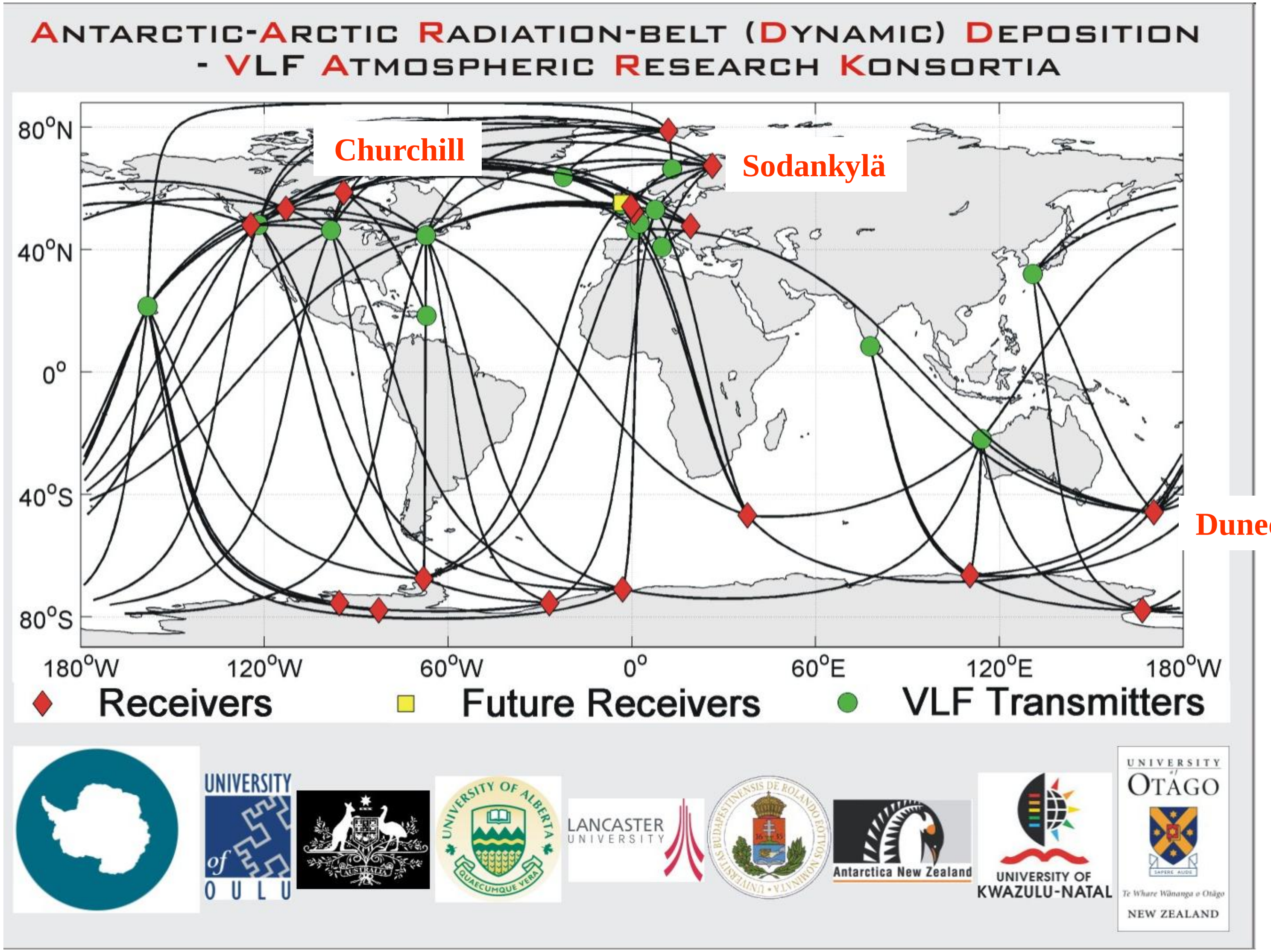
Very Low Frequency (VLF) radio transmissions are treat the Earth-Ionosphere waveguide cavity as a waveguide

EEP can cause perturbations in this waveguide, changing the propagation characteristics of the transmissions.



Comparing perturbed transmissions to quiet time transmissions allows us to remotely sense changes to the upper atmosphere.

The AARDDVARK Network



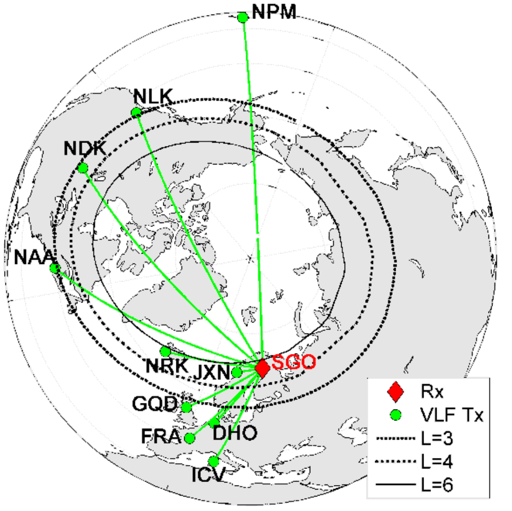
More Information: www.physics.otago.ac.nz/space/AARDDVARK_homepage.htm

AARDDVARK receivers

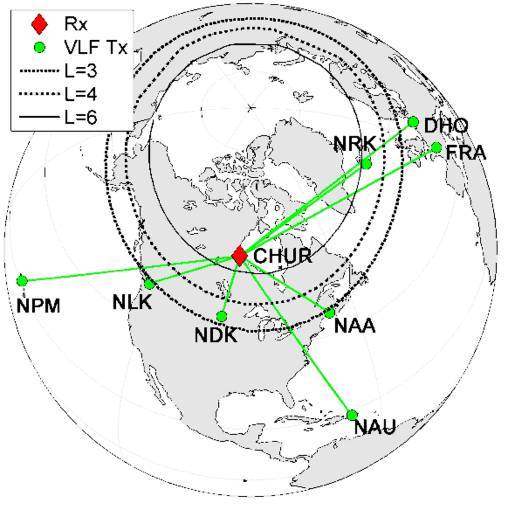
We used the VLF receivers located in Sodankylä, Finland (SGO) and Churchill, Canada (CHUR).

SGO (an OmniPAL receiver) can monitor 6 transmitters concurrently.

A total of 9 transmitters were monitored in the 2005-2008 period



Sodankylä



Churchill

CHUR (UltraMSK) is not limited in the number of transmitters it can monitor.

- It wasn’t installed until 2006 though.

Of the initial 67 Morley epochs, 2 were removed due to solar proton activity, while a further 4 were removed due to a lack of any data from either receiver.

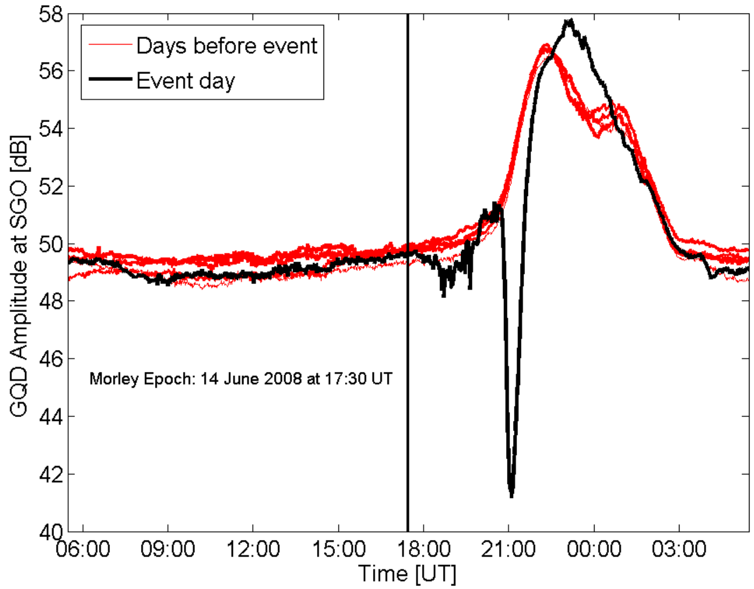
AARDDVARK Data

For each path of each epoch, we plotted several days prior to the event to attempt to create a quiet day curve (QDC).

We then compared the event day to the QDC, if possible.

A good QDC could not always be formed.

If there was a clear deviation across multiple transmitter->receiver paths, we classified the event as showing clear signs of EEP.



Of the 61 Morley epochs we examined, 15 did not have a good enough QDC for our purposes.

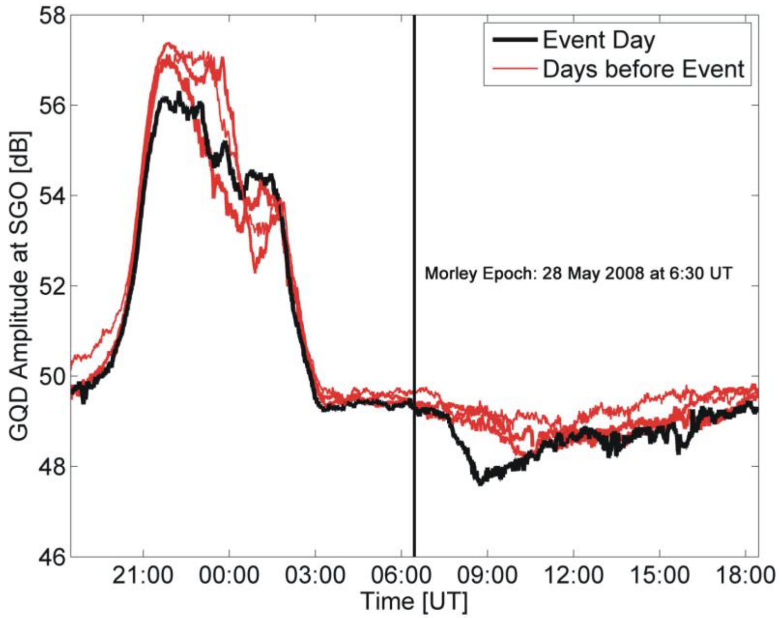
Of the remaining 46 epochs, 34 showed clear signs of EEP across multiple paths (~75%).

Evidence of EEP

Our next step was to measure the change in amplitude of each path.

We focussed on three paths:

GQD->SGO
NAA->SGO
NAA->CHUR



	ΔVLF obs.
NAA->CHUR	+2.0 dB
GQD->SGO	-1.5 dB
NAA->SGO	+2.5 dB
	ΔCNA obs.
	1.25 dB

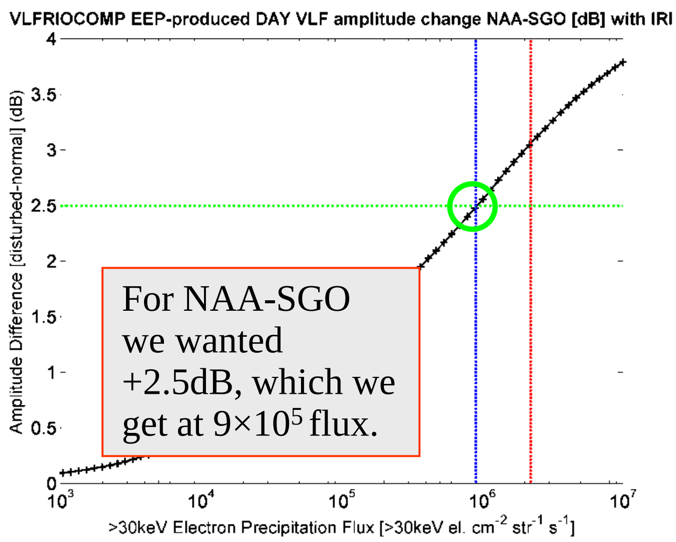
For each of these paths, we measured the peak of each deviation that occurred in the daytime sector, and then took the average over all events.

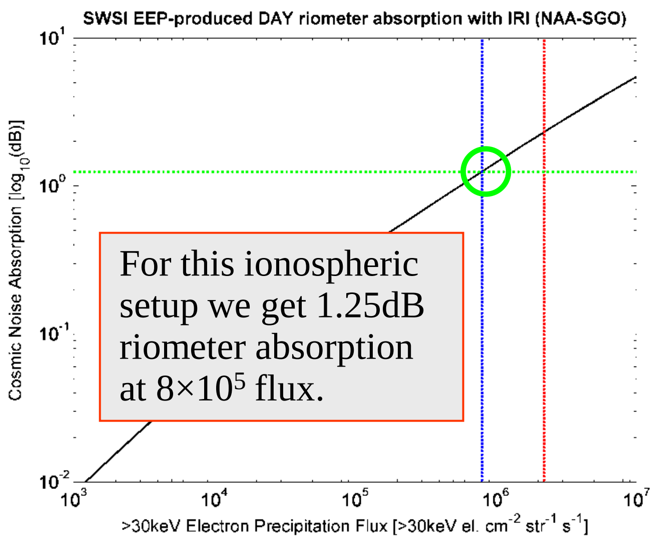
We also note that Morley reported daytime riometer peak of ~1.25 dB in both the European and Canadian sectors.

Modelling a HSSWSI impact

In order to determine the peak magnitude of the EEP occurring during the SWSI-events, we fit our calculated results to a modelled ionospheric response to precipitation.

- use a Wait ionosphere for the D-region + IRI
- assume the precipitation energy spectra is a power law with scaling given by the POES observations
- then use published modelling techniques [Rodger et al., Radio Sci., 2012] to describe the VLF and riometer changes with EEP magnitude





Modelling a HSSWSI impact

	ΔVLF obs.	ΔVLF calc.	ΔCNA calc.	>30keV EEP
NAA-CHUR	+2.0 dB	+2.0 dB	1.41 dB	1×10^{6}
GQD-SGO	-1.5 dB	-1.1 dB	1.05 dB	4×10^{5}
NAA-SGO	+2.5 dB	+2.5 dB	1.35 dB	9×10^{5}
	ΔCNA obs.	**ΔVLF calc.**	**ΔCNA calc.**	**>30keV EEP**
NAA-CHUR	1.25 dB	+1.7 dB	1.25 dB	8×10^{5}
GQD-SGO	1.25 dB	-0.9 dB	1.25 dB	8×10^{5}
NAA-SGO	1.25 dB	+2.4 dB	1.25 dB	8×10^{5}

The EEP values listed are >30 keV electron fluxes with units of electrons cm^{-2} st^{-1} s^{-1}.

Our modelling suggest a >30 keV electron precipitation flux of 9-10×10^{5} electrons cm^{-2} st^{-1} s^{-1} will reproduce our measured results (ΔVLF).

If we use these values to calculate the riometer response, we see a close correlation with the measured response.

Summary & Conclusions

- Our POES BLC observations suggest that atmospheric precipitation cannot be used to explain the electron flux dropouts but rather this is a signature of the acceleration process which leads to the recovery of the trapped fluxes.

- We found evidence of this precipitation in the AARDDVARK VLF data across multiple path, and measured the average response across a subset of these paths.

- Ground-based observations indicate that typical SWSI-triggered >30 keV electron precipitation fluxes are $8{\times}10^5$ electrons cm^{-2} st^{-1} s^{-1}. These are a large electron precipitation events lasting ~1.5 days, and might be explained by the acceleration process which is rebuilding the trapped electron fluxes.

THANK YOU!