Towards a better understanding of long term drivers of radiation belt electron acceleration and loss

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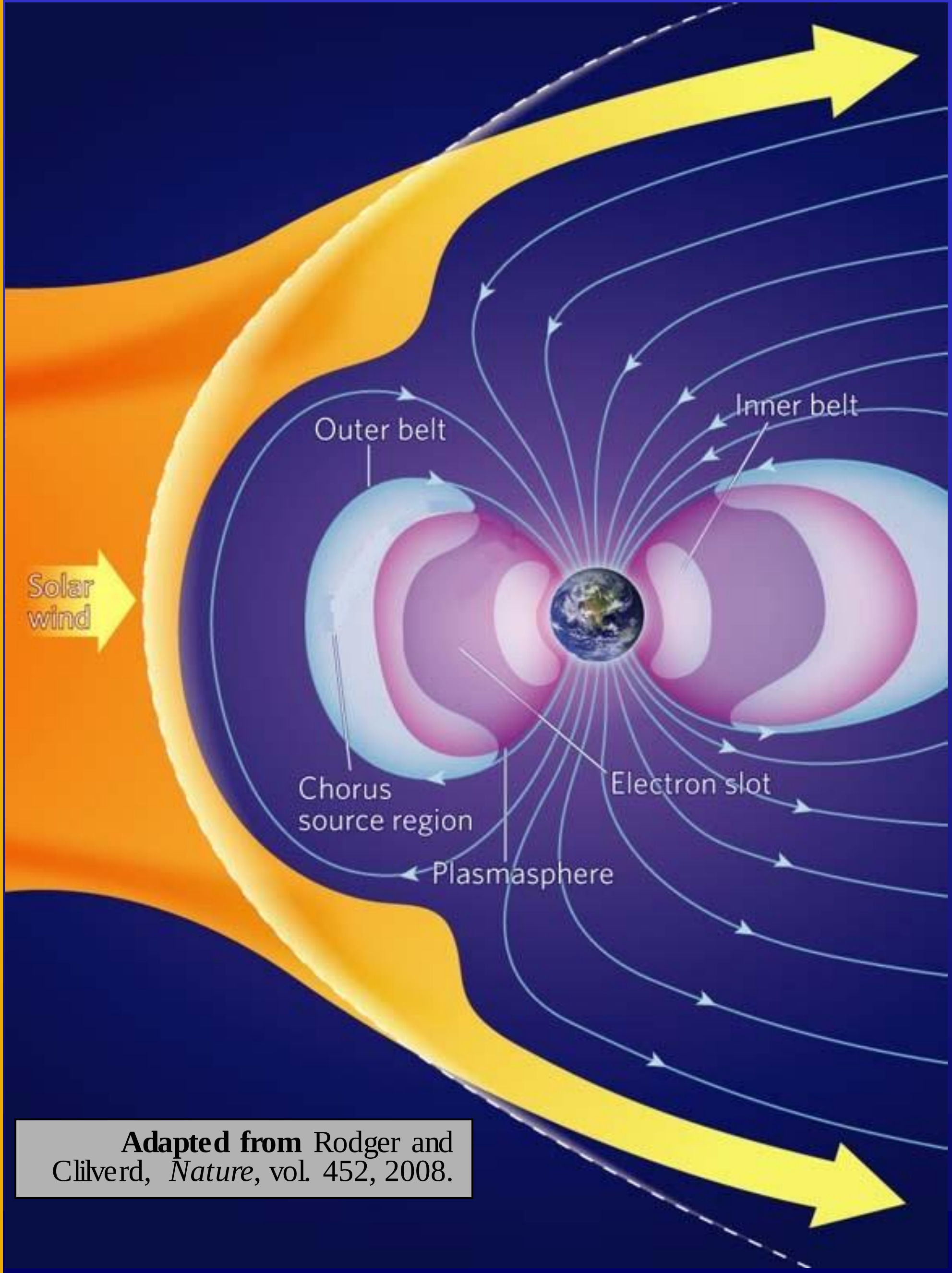
7th Space Climate Symposium
Canton Orford, Quebec, Canada
S7 Solar wind-magnetosphere-ionosphere interaction
1635-1715, Wednesday 10 July 2019

Basic structure of the Van Allen belts



Adapted from Rodger and Clilverd, *Nature*, vol. 452, 2008.

In 1958 the first US satellites were launched into orbit carrying Geiger counters. *Explorer I* and *Explorer III* discovered the Van Allen radiation belts.

On average the belts are structured with an inner and outer belt, separated by the "slot".

Explorer 1 – post launch press briefing.

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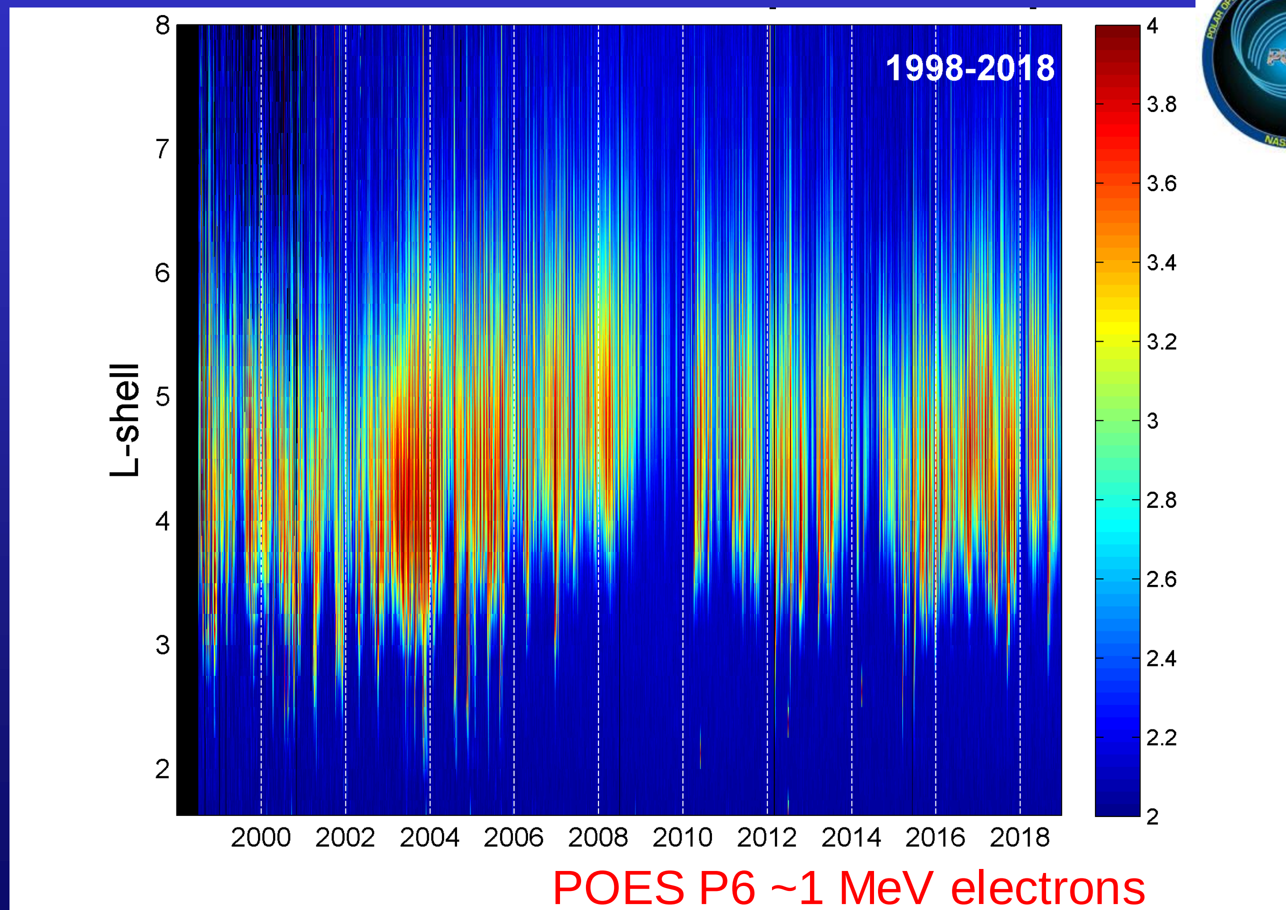
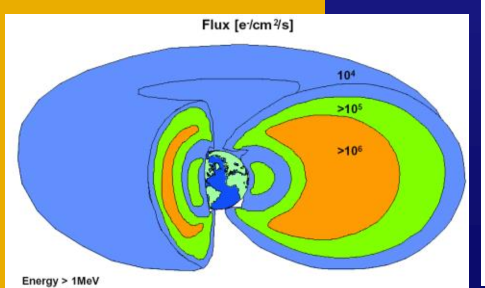
It's the Level of Dynamism which Matters

While the cartoons of the Radiation Belts tend to show them as fixed lozenges, there are actually highly dynamic. The flux of electrons in the belts change by many orders of magnitudes (thousands or tens of thousands of times) inside a few hours, maybe faster.

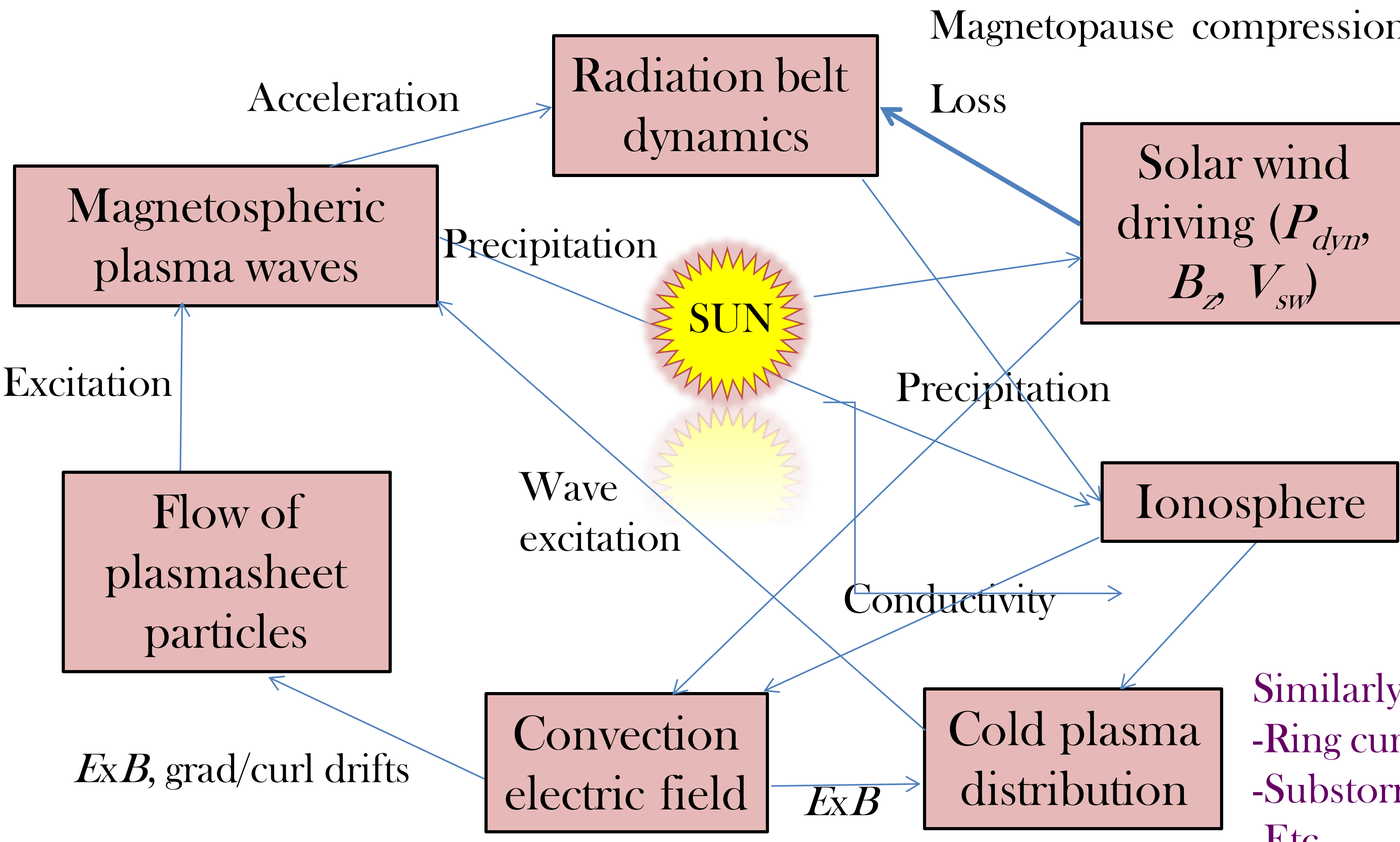




$$N(t) = N_0 + \text{Acceleration} - \text{Losses}$$

It’s a complex system!

There is a lot of coupling and lots of observations from space and ground are needed to characterise the processes (remember, we span ~6-orders of magnitude in Energy).



Similarly:
- -Ring current
- -Substorms
- -Etc.

Chorus acceleration of RB electrons

Growing evidence of the complex linkages between different parts of the inner magnetosphere. For some time there has been strong and increasing evidence that whistler mode chorus is a vital component to accelerate relativistic electrons.

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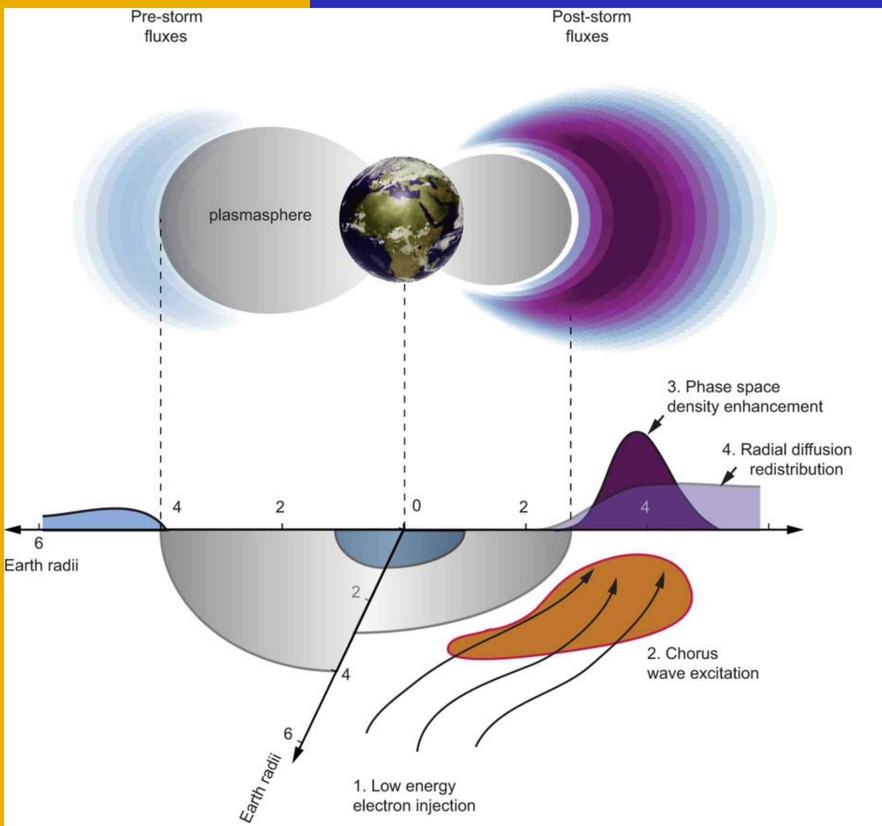
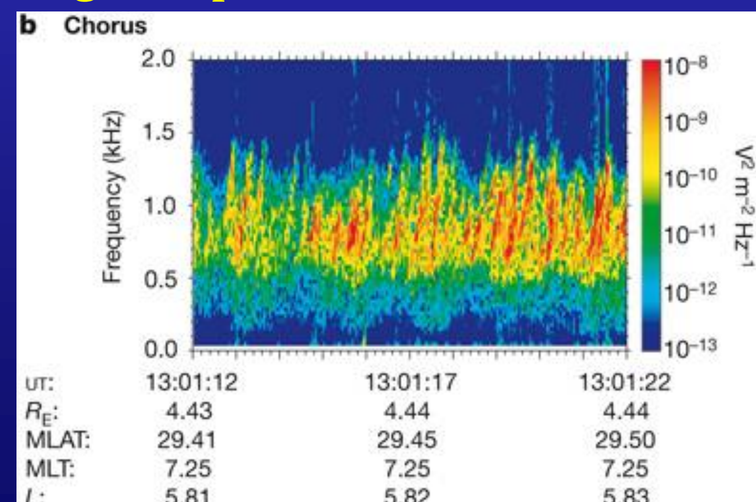


Thorne et al, R. M., et al. (2013), *Nature*, 504, 411–414, doi:10.1038/nature12889.

And an important factor here is that chorus itself is excited by a seed population provided low-energy plasma sheet electrons gaining access into the inner magnetosphere.



Adapted from Bortnik et al., *Nature*, vol. 452, 10.1038/nature06741, 2008.

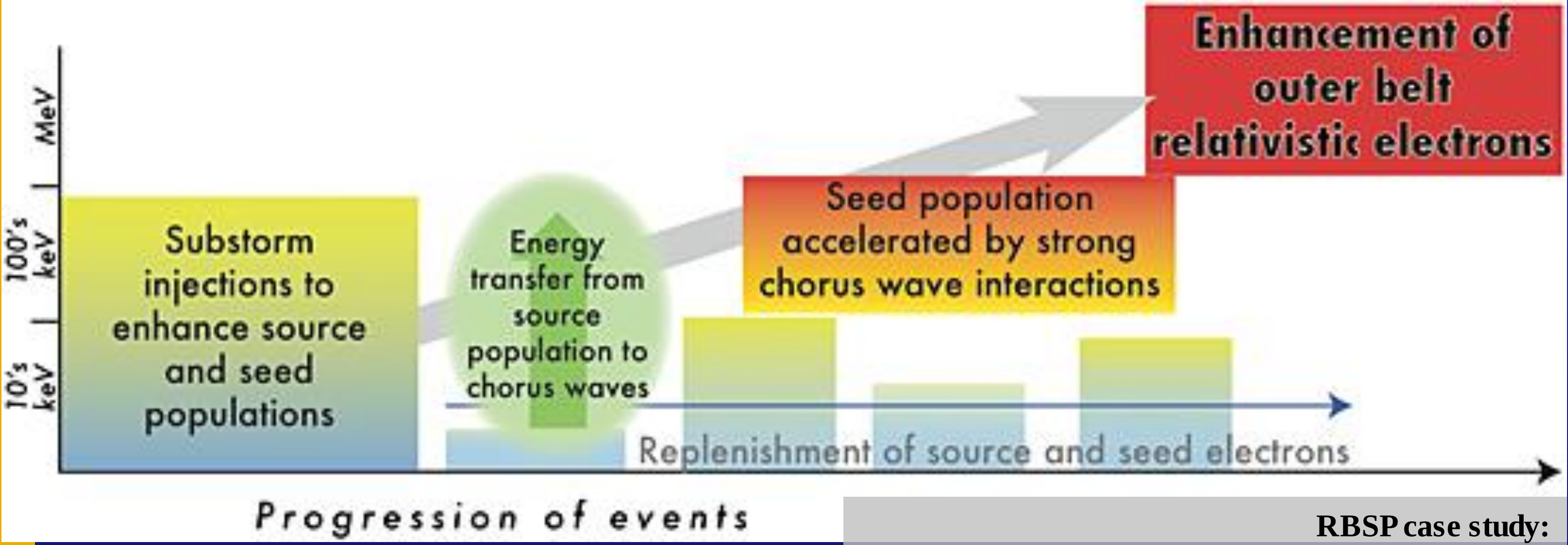
Chorus acceleration of RB electrons

One possible route by which this could happen was pointed out in Allison Jaynes' 2015 paper.

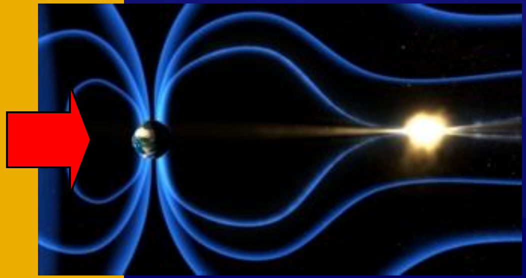
Substorm injection of seed electrons

→ **Whistler mode chorus**

→ **Accelerated relativistic electrons**



RBSP case study:
Jaynes, A. N., et al. (2015), *J. Geophys. Res.*, 120, 7240–7254, doi:10.1002/ 2015JA021234.



This paper suggested that magnetospheric substorm activity is a **"crucial element in the ultimate acceleration"**.

Chorus acceleration of RB electrons

A slightly different view of the process comes from an earlier paper by *Lyons et al*. [2005].

large-amplitude Alfvén waves within high-speed streams

→ **Enhanced magnetospheric convection**

→ **Enhanced seed electrons**

→ **Whistler-mode chorus**

→ **Accelerated relativistic electrons**

Lyons, L. R., et al. (2005), *J. Geophys. Res.*, 110, A11202, doi:10.1029/2005JA011254.

This paper notes that the Alfvén waves could lead to repetitive substorms, but suggests that "it is the periods of enhanced convection that **precede** substorm expansions **and not the expansions** themselves that lead to the chorus wave growth".

These authors argue that the seed electron population is important, but argue the dominant "seed source" is convective transport (due to large-scale convective electric field drift $E \times B$) rather than substorms.

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Chorus, trapped flux, convection, & substorms

Not so long ago we looked into the relationship between chorus, substorms/convection and trapped flux in an investigation into solar wind-magnetosphere-radiation belt coupling.

AGU PUBLICATIONS

JGR

Journal of Geophysical Research: Space Physics

RESEARCH ARTICLE

10.1002/2015JA021537

Special Section:
Variability of the Sun and Its Terrestrial Impact VarSITI

Nature's Grand Experiment: Linkage between magnetospheric convection and the radiation belts

Craig J. Rodger[1], Kathy Cresswell-Moorcock[1], and Mark A. Clilverd[2]

[1]Department of Physics, University of Otago, Dunedin, New Zealand, [2]British Antarctic Survey (NERC), Cambridge, UK

Key Points:
- Radiation belt substantially diminished during the prolonged solar minimum in 2009/2010
- This natural "Grand Experiment" allows us to test linkages between the belts and solar drivers
- Behavior is consistent with enhanced magnetospheric convection triggering whistler mode chorus

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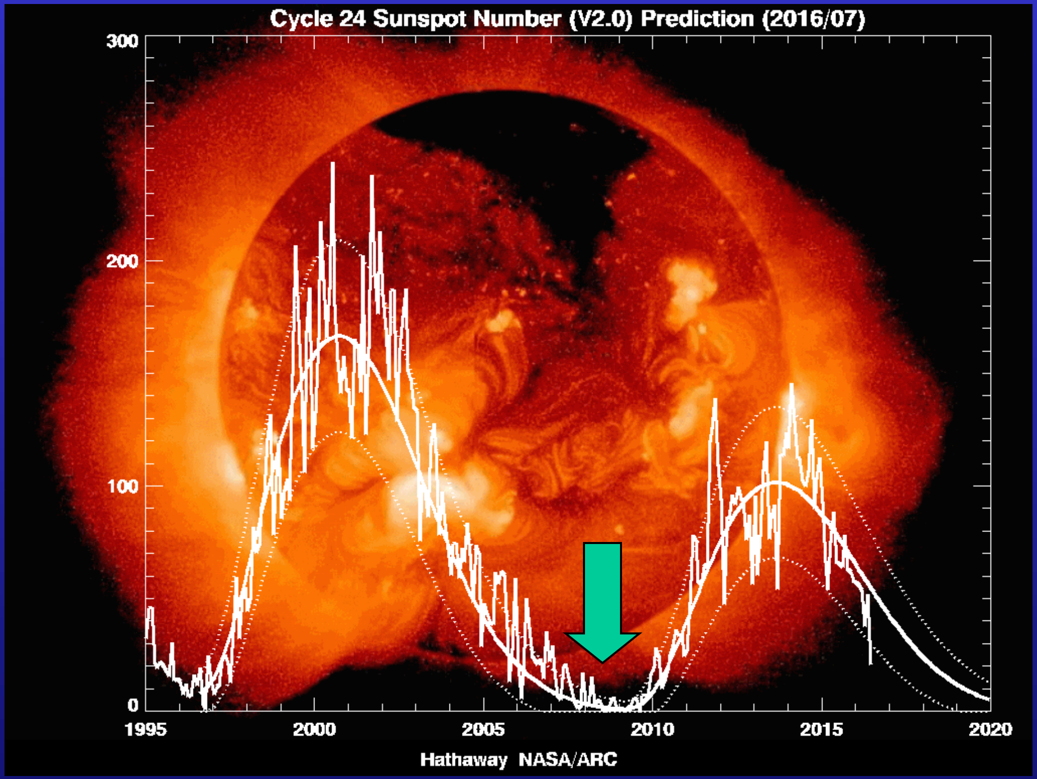
Citation:
Rodger, C. J., K. Cresswell-Moorcock, and M. A. Clilverd (2016), Nature's Grand Experiment: Linkage between magnetospheric convection and the radiation belts, *J. Geophys. Res. Space Physics*, *121*, 171–189, doi:10.1002/2015JA021537.

Abstract The solar minimum of 2007–2010 was unusually deep and long lived. In the later stages of this period the electron fluxes in the radiation belts dropped to extremely low levels. The flux of relativistic electrons (>1 MeV) was significantly diminished and at times was below instrument thresholds both for spacecraft located in geostationary orbits and also those in low-Earth orbit. This period has been described as a natural "Grand Experiment" allowing us to test our understanding of basic radiation belt physics and in particular the acceleration mechanisms which lead to enhancements in outer belt relativistic electron fluxes. Here we test the hypothesis that processes which initiate repetitive substorm onsets drive magnetospheric convection, which in turn triggers enhancement in whistler mode chorus that accelerates radiation belt electrons to relativistic energies. Conversely, individual substorms would not be associated with radiation belt acceleration. Contrasting observations from multiple satellites of energetic and relativistic electrons with substorm event lists, as well as chorus measurements, show that the data are consistent with the hypothesis. We show that repetitive substorms are associated with enhancements in the flux of energetic and relativistic electrons and enhanced whistler mode wave intensities. The enhancement in chorus wave power starts slightly before the repetitive substorm epoch onset. During the 2009/2010 period the only relativistic electron flux enhancements that occurred were preceded by repeated substorm onsets, consistent with enhanced magnetospheric convection as a trigger.

Rodger, C. J., et al. (2016), *J. Geophys. Res.*, 121, 171–189, doi:10.1002/2015JA021537.

Natures Grand Experiment

As this community well knows, the last solar minimum was unusually deep and long-lived. The Sun had a "wee nap" for a few years.



Dan Baker has described this period as a "grand experiment" – it should allow us to test our understanding of basic radiation belt physics and in particular the acceleration mechanisms which lead to enhancements in relativistic electrons in the radiation belts.

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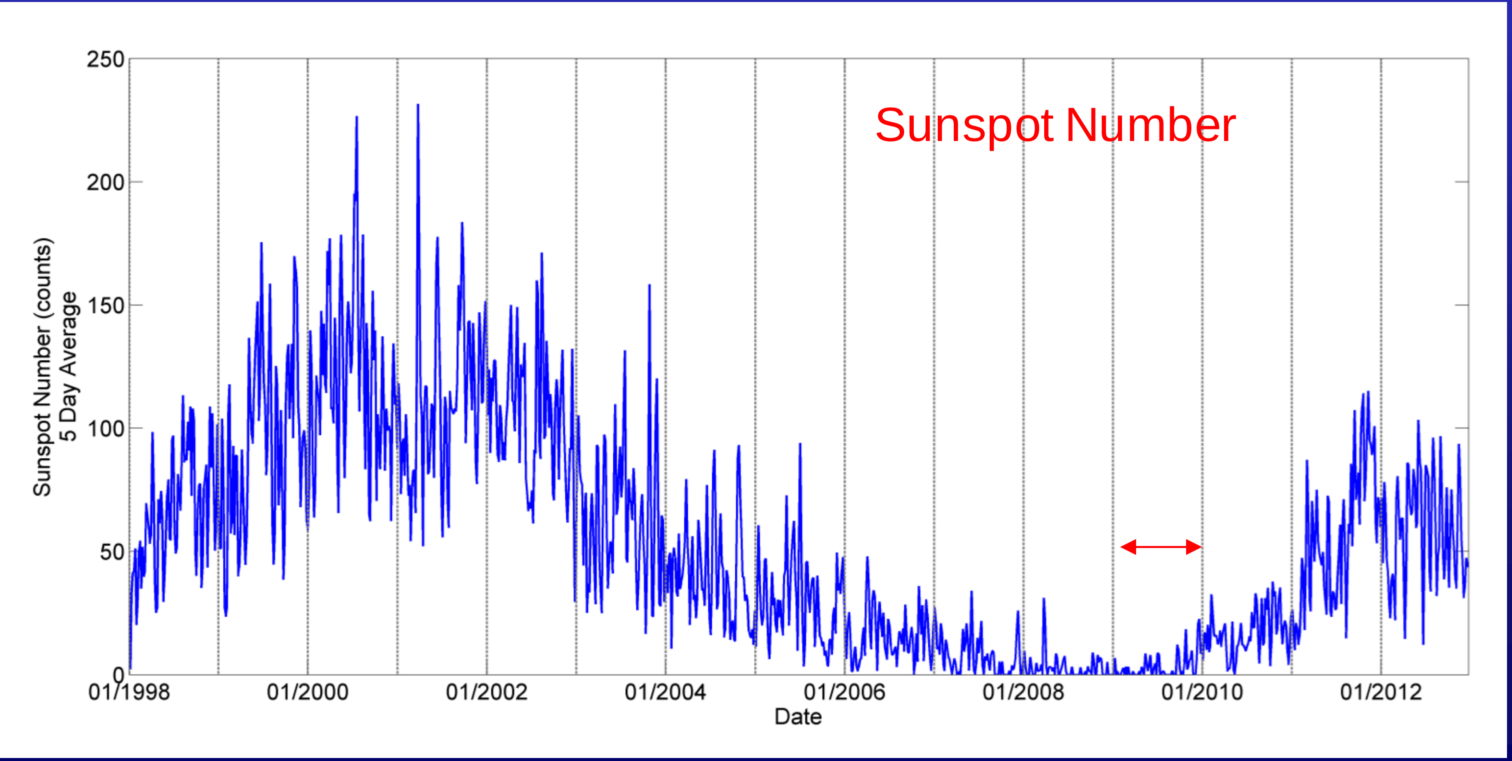
Natures Grand Experiment

The last solar minimum was unusually deep and long-lived. The Sun had a "wee nap" for a few years.

In this talk I will be mostly focusing on the period from 1998-2013, so let us look at the sunspot number variation in that time period.

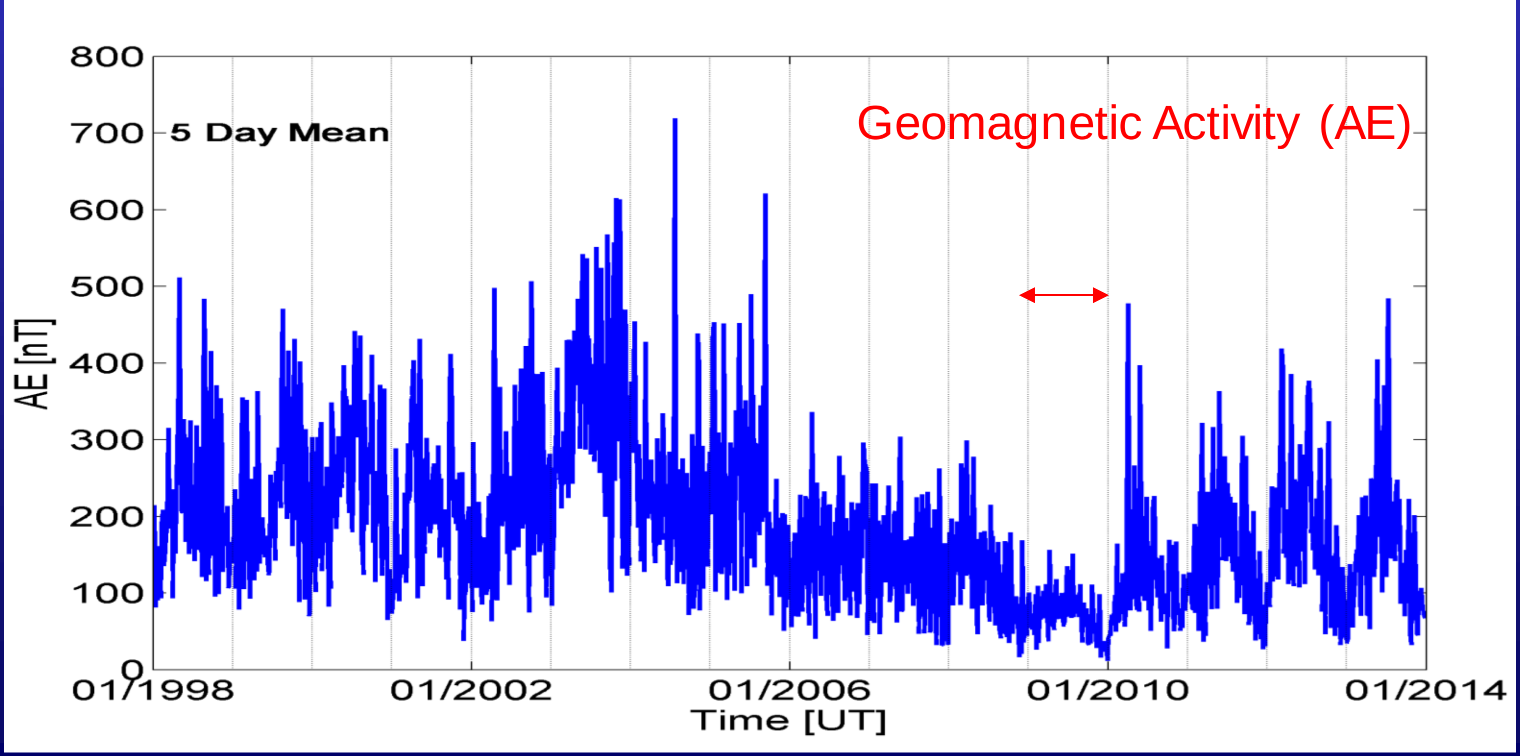
From a radiation belt perspective, the year 2009 is of most relevance.



Natures Grand Experiment - Context

When one plots out geophysical parameters, the year 2009 really leaps out as looking different from most of the surrounding period.

Try geomagnetic storms as measured by the geomagnetic index **AE** (this is an indication of substorm activity).



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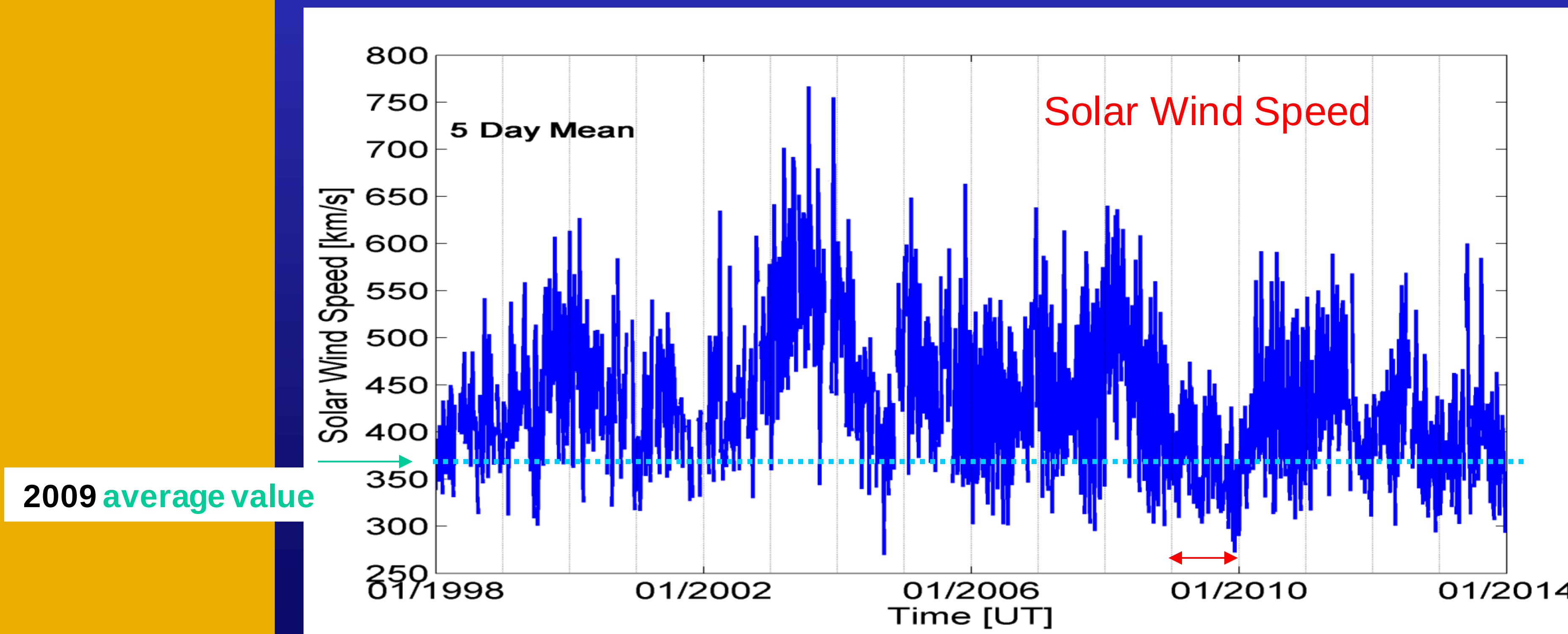
Natures Grand Experiment - Context

When one plots out geophysical parameters, the year 2009 really leaps out as looking different from most of the surrounding period.

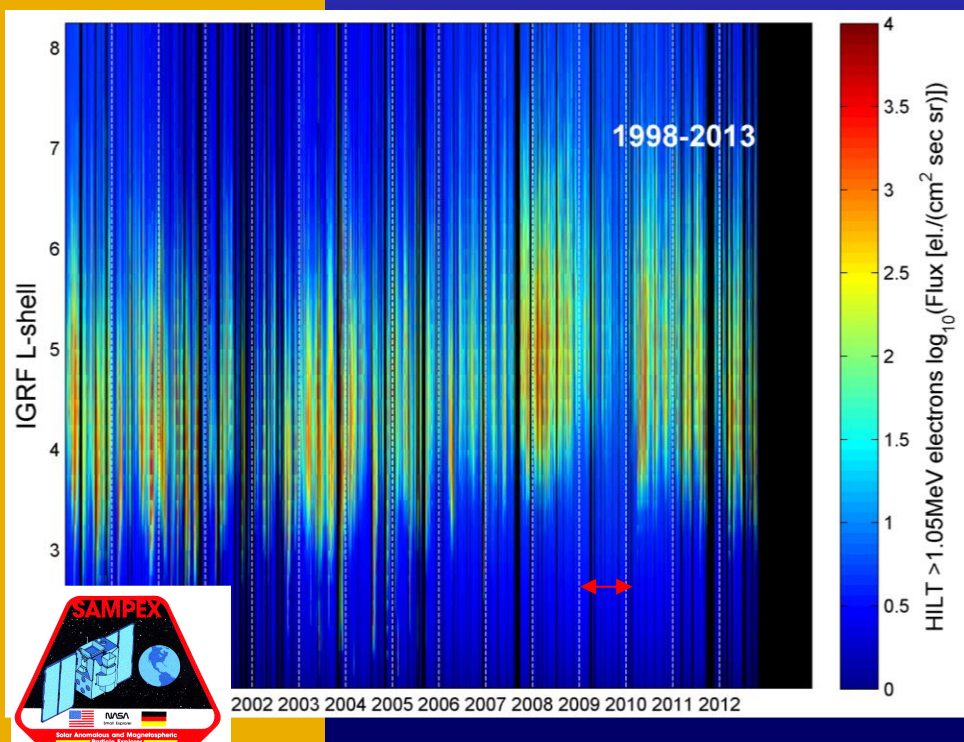
Try solar wind speed – not quite as clear in this parameter.

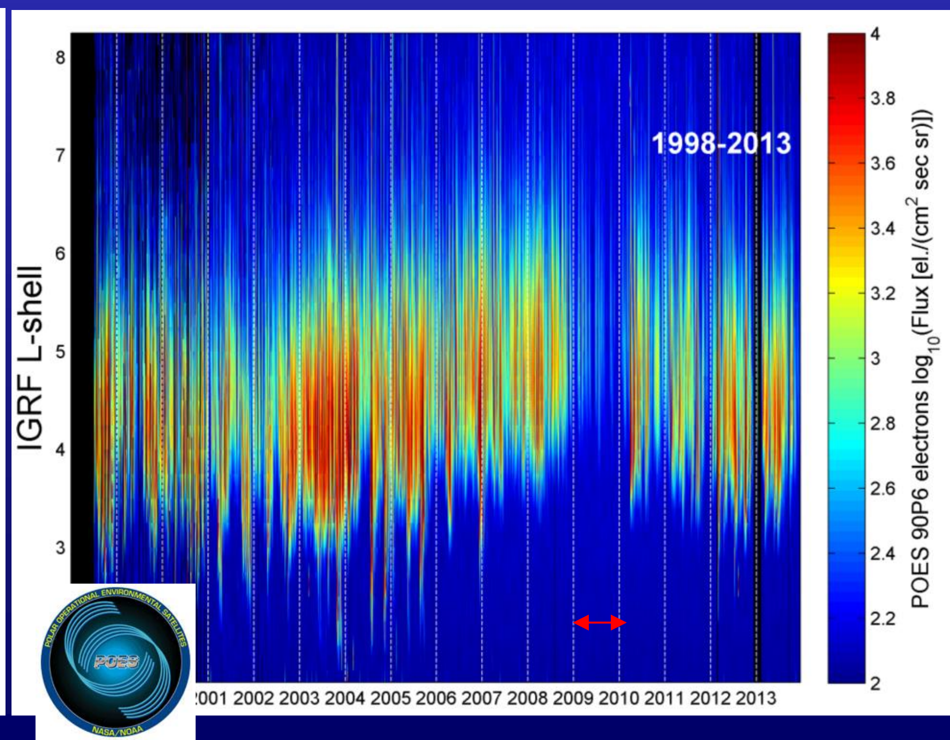


And the Radiation Belts? Not just POES

In the later stages of this period the electron fluxes in the radiation belts dropped to very low levels over most of the year 2009.

The flux of relativistic electrons largely dropped nearly below instrument thresholds measured by SAMPEX/HILT and POES/MEPED (P6) in low-Earth orbit.

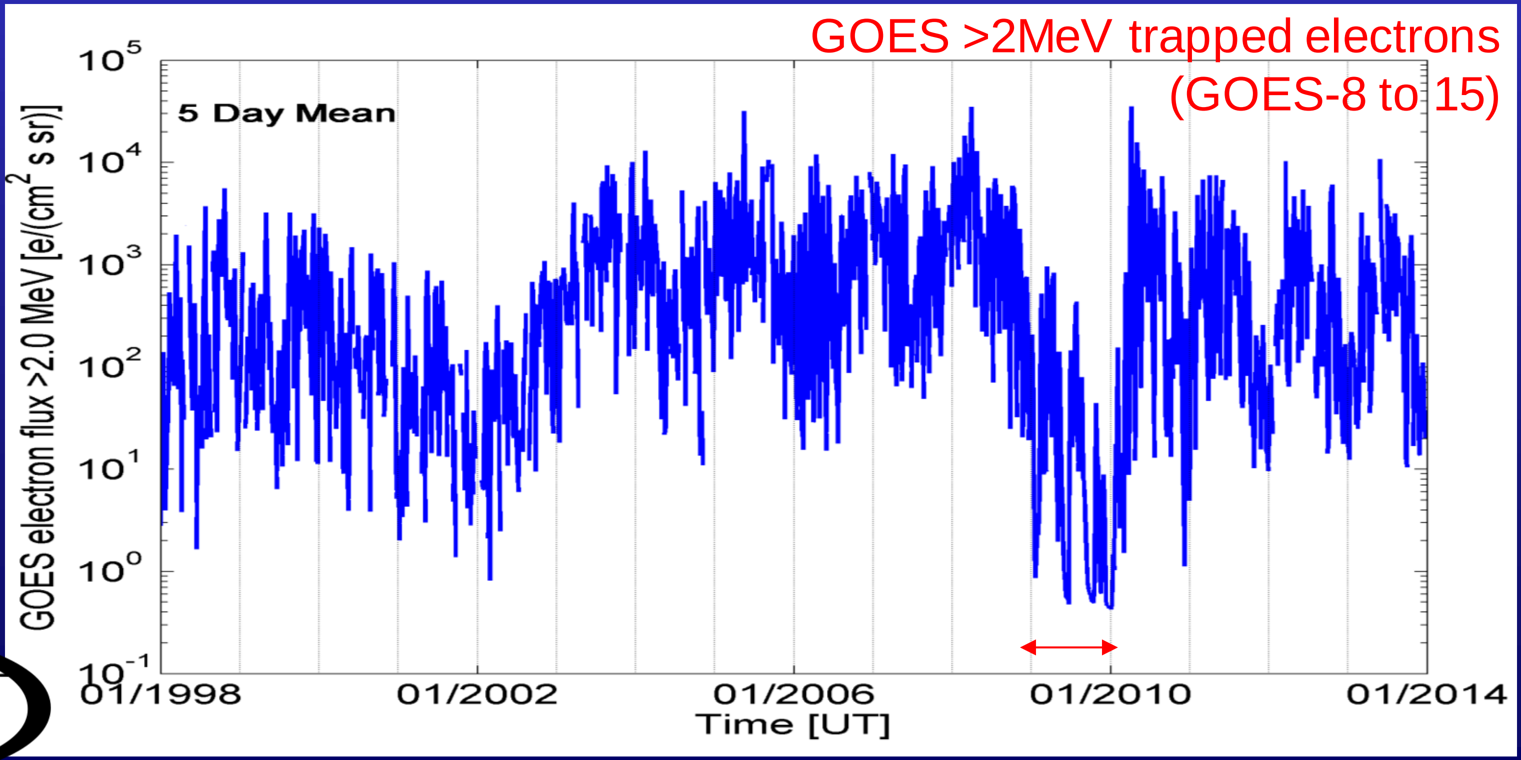




And the Radiation Belts? Not just LEO

In the later stages of this period the electron fluxes in the radiation belts dropped to very low levels over most of the year 2009.

The flux of relativistic electrons (>2 MeV) largely dropped to the instrument noise-floor thresholds at GOES in geostationary-Earth orbit for that year, before returning to more normal levels in 2010.



Natures Grand Experiment

If we look at a series of geophysical parameters, 2009 stands out as particularly "quiet" relative to the surrounding years (for example 2008, when the sunspot numbers were also almost near-zero).

Geophysical Parameters by year

Solar Wind Speed	**Years** All Years	2006	2007	2008	**2009**	2010
Mean values	419.75	424.53	440.79	455.99	**368.46**	407.09
Standard Deviations	104.34	100.34	112.66	118.03	**65.62**	92.12
Median values	392.45	399.65	416.90	435.60	**359.20**	383.03

Dst	**Years** All Years	2005	2006	2007	2008	**2009**	2010
Mean values	-7.69	-18.51	-7.32	-5.94	-6.57	**-2.13**	-7.32
Standard Deviations	13.15	17.41	13.52	10.84	9.89	**8.56**	12.21
Median values	-6	-16	-6	-5	-6	**-2**	-6

AE	**Years** All Years	2005	2006	2007	2008	**2009**	2010
Mean values	127.67	200.07	145.70	130.36	118.32	**69.48**	113.98
Standard Deviations	154.44	198.78	165.15	150.02	141.45	**90.10**	140.90
Median values	64	125	78	68	59	**39**	59

Kp	**Years** All Years	2005	2006	2007	2008	**2009**	2010
Mean values	1.42	1.98	1.54	1.51	1.45	**0.90**	1.24
Standard Deviations	1.21	1.37	1.25	1.22	1.17	**0.86**	1.08
Median values	1	1.7	1.3	1.3	1.3	**0.7**	1

Solar wind speed was particularly low, Kp (convection proxy) and the AE (substorm proxy) was too.

Natures Grand Experiment - Substorms

We can use the substorm list from the SuperMAG array of magnetometers to see if the variation in substorms is consistent with the physical processes we think are happening.

Substorm Type	All	2005	2006	2007	2008	2009	2010	2011
SuperMAG All	11396	2203	1506	1394	1336	464	923	1069
After solar proton events removed								
Isolated Epochs	2462	277	285	310	289	227	292	263
Recurrent Epochs	2052	374	300	316	307	73	157	173
Average #	2.9	3.0	2.8	2.8	2.7	2.3	3.1	2.6

Isolated substorm epoch: time difference between nearest event is > 3 hours
Recurrent substorm epochs: Start of a cluster of substorms

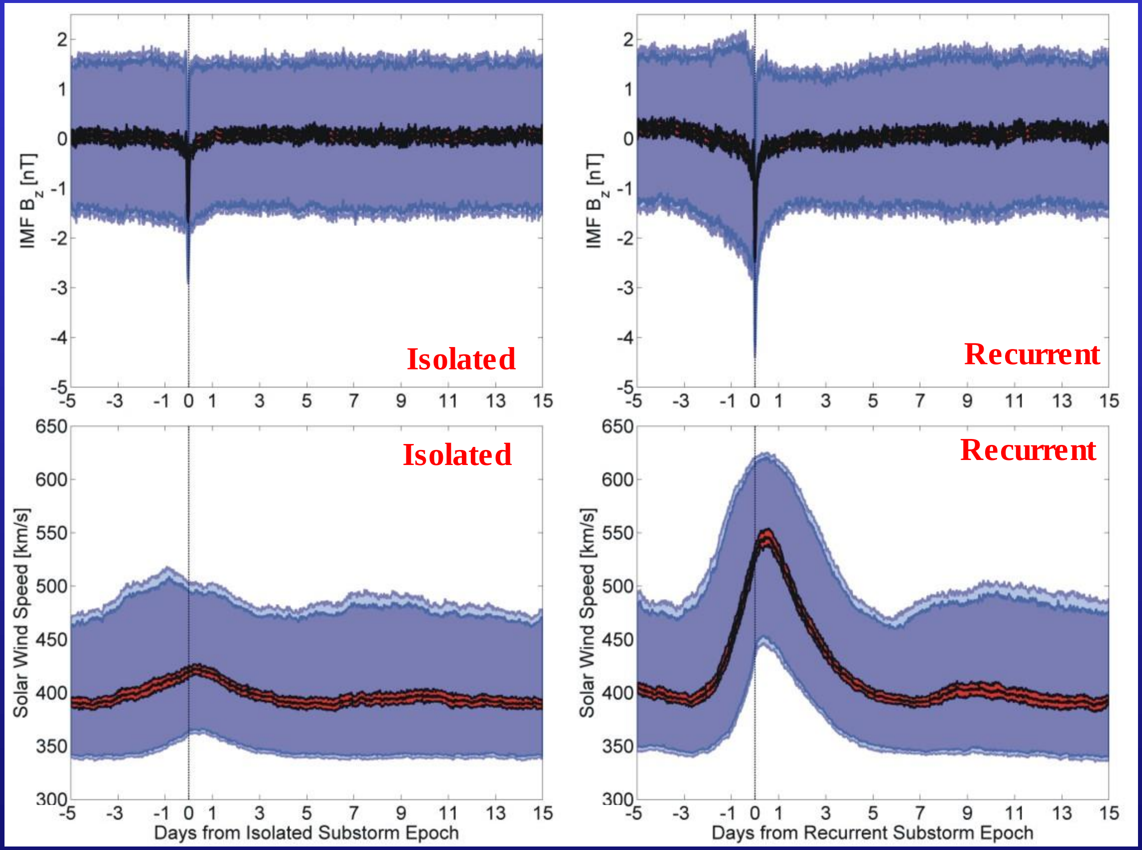
We find the number of "isolated substorms" in 2009 is slightly lower (8%) than the 10 year average.

SuperMAG substorm algorithm: Newell & Gjerloev (2011), *J. Geophys. Res.*, 116, A12211, doi:10.1029/2011JA016779).

In contrast, "recuurent substorms" had a very strong minimum in 2009 (64% lower) – which would be consistent with them having important role (either as injections themselves, or as an indication of convection).

SuperMAG substorms & solar wind drivers

Lets test if the occurrence of convection and recurrent substorms does actually seem to affect the energetic and relativistic electron fluxes in the radiation belt. Superposed Epoch Analysis for 1 Jan 2006- 31 Dec 2013.



As expected, recurrent substorm epochs occur during periods of high speed solar wind streams (and southward IMF), while isolated substorm epochs do not.

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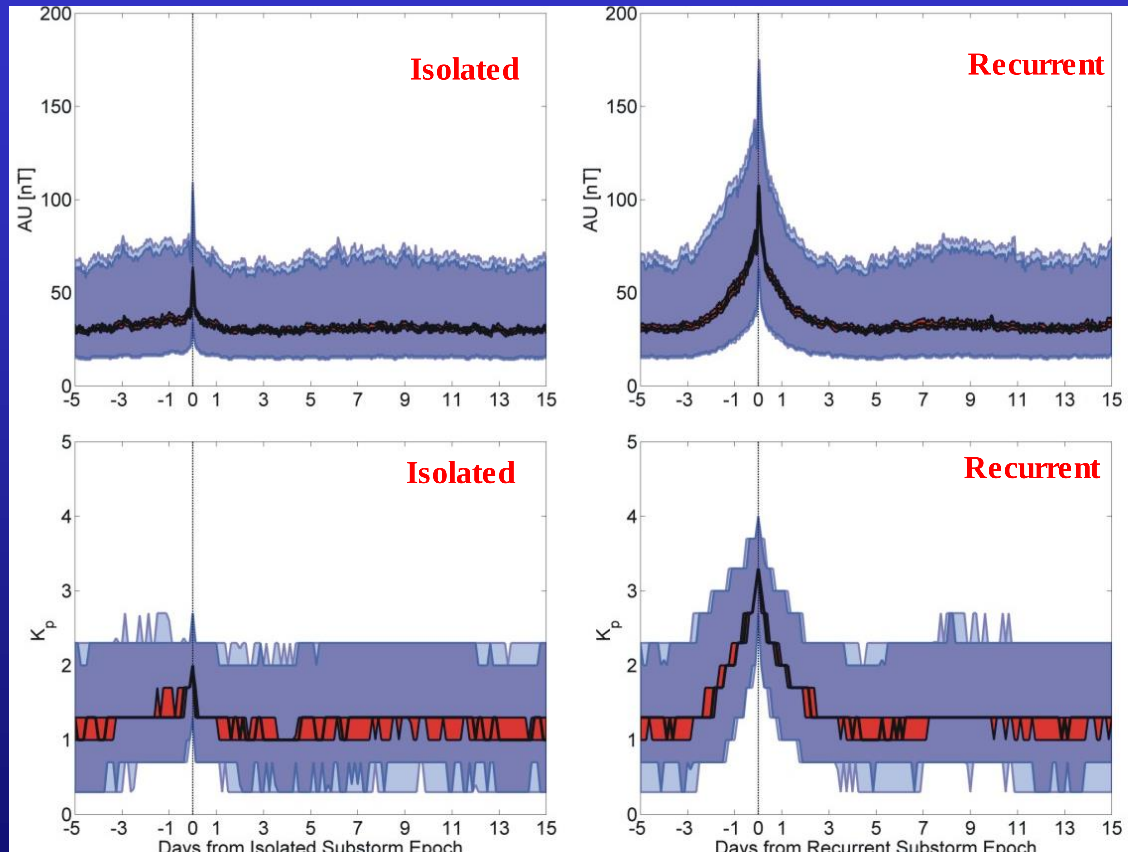
SuperMAG substorms & Convection Proxies

Lets test if the occurrence of convection and recurrent substorms does actually seem to affect the energetic and relativistic electron fluxes in the radiation belt. Superposed Epoch Analysis for 1 Jan 2006- 31 Dec 2013.



Both Kp and AU are a good measure of convection. For Isolated Substorms there is only convection at the epoch. For a cluster of Recurrent Substorms there is evidence of enhanced convection ~2 days before and after the epoch (consistent with *Lyons et al*. [2005], i.e. convection before the substorms).

SuperMAG substorms & POES trapped fluxes

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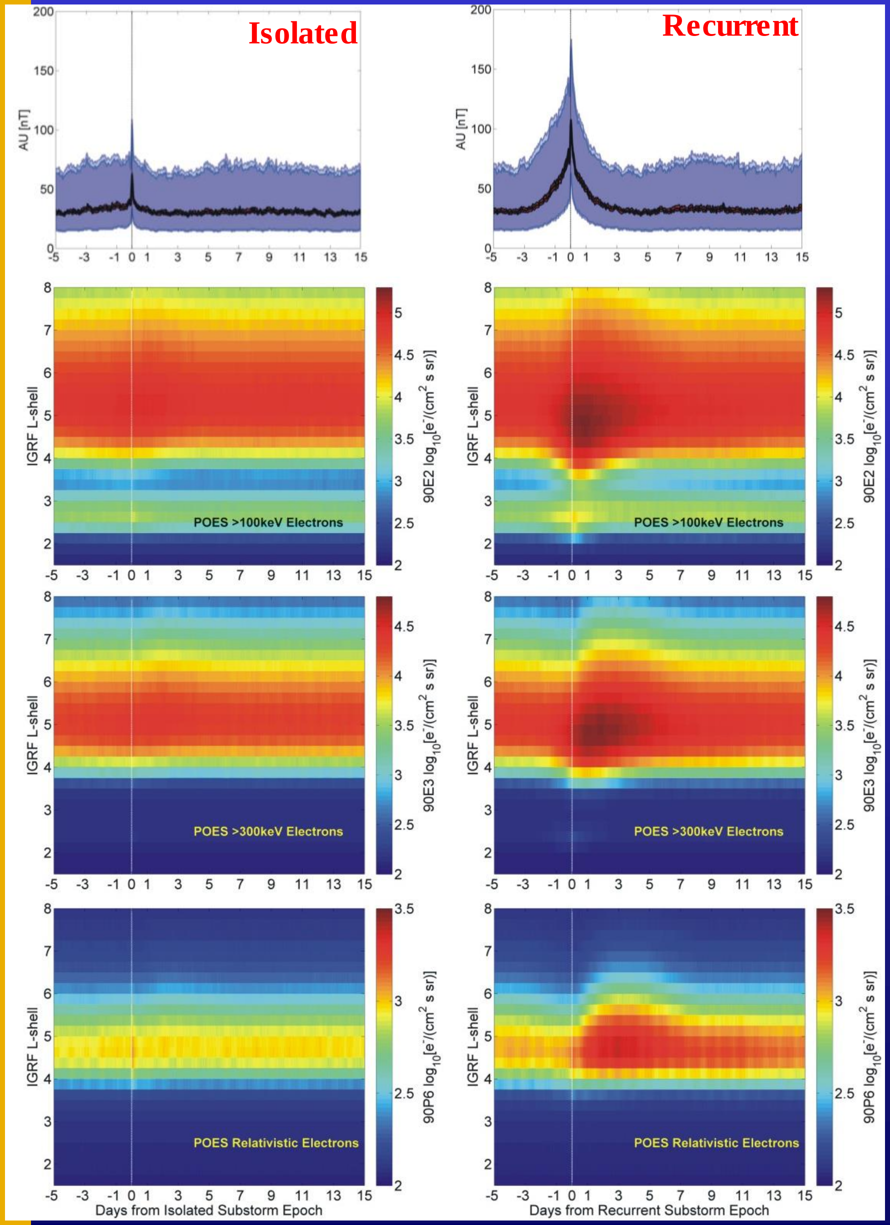


Lets test if the occurrence of convection and recurrent substorms does actually seem to affect the energetic and relativistic electron fluxes in the radiation belt. Superposed Epoch Analysis for 1 Jan 2006- 31 Dec 2013.

Isolated Substorm Epochs: weak convection and single injection = minimal effect on energetic & relativistic electrons.

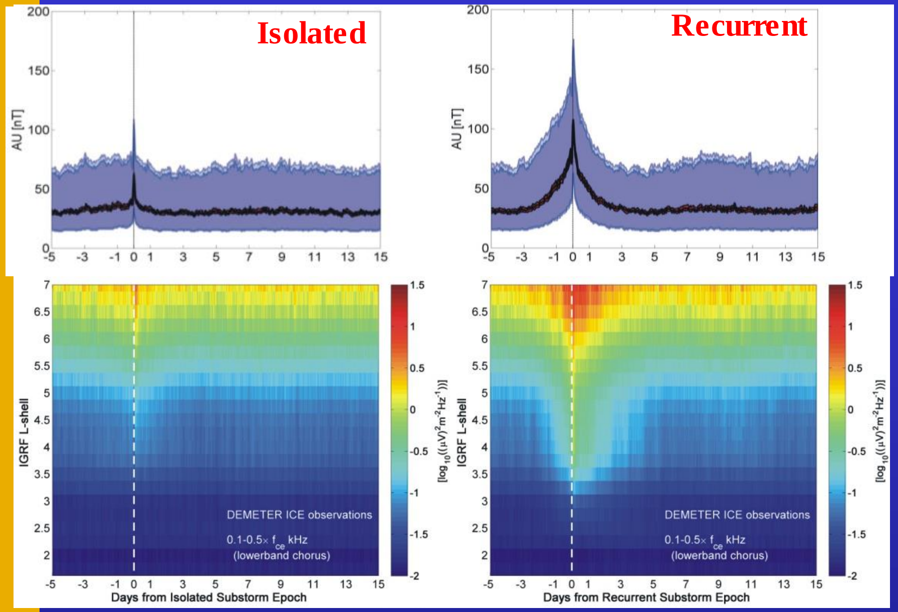
Recurrent Substorm Epochs: strong convection followed by cluster of substorms = clear effect on energetic & relativistic electrons.

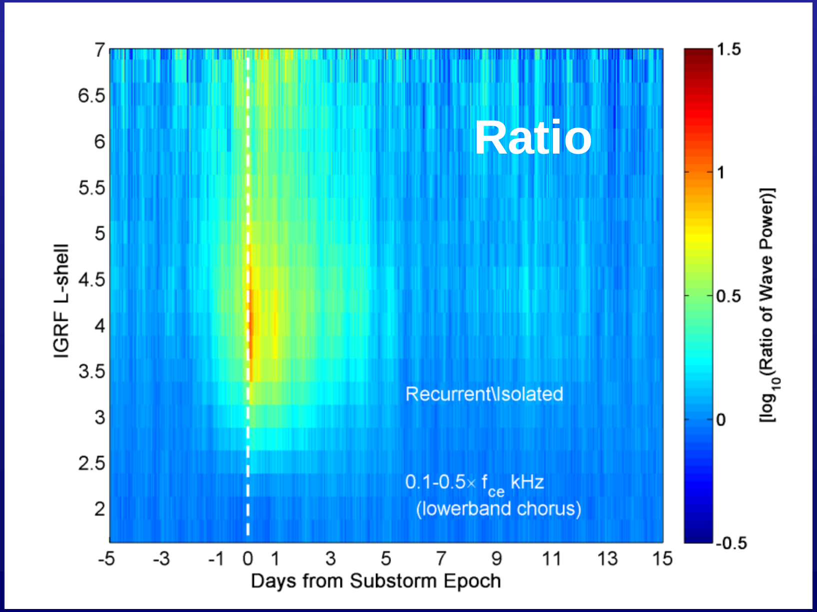
POLAR OPERATIONAL ENVIRONMENTAL SATELLITES

POES

NASA/NOAA

SuperMAG substorms & DEMETER chorus



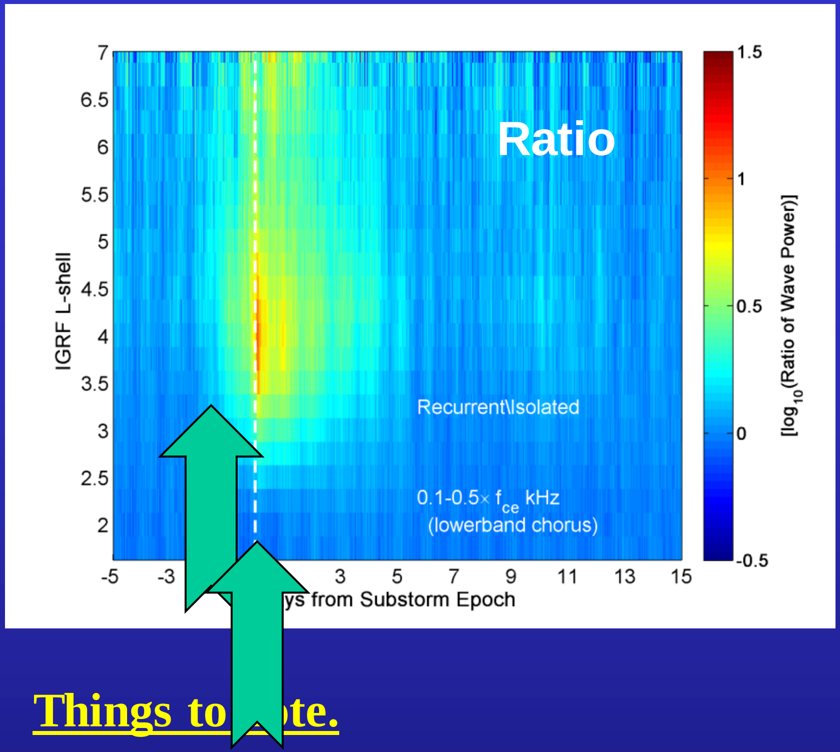


Lets test if the occurrence of convection and recurrent substorms does actually seem to affect the lower band chorus in the radiation belt which we expect to drive the acceleration. Superposed Epoch Analysis for 1 Jan 2006- 31 Dec 2013.

Isolated Substorm Epochs: weak convection and single injection = very small increase in outer RB chorus power.

Recurrent Substorm Epochs: strong convection followed by cluster of substorms = Significant effect on slot and outer RB chorus power.

SuperMAG substorms & DEMETER chorus



Lets test if the occurrence of convection and recurrent substorms does actually seem to affect the lower band whistler mode chorus in the radiation belt which we <u>expect</u> to drive the acceleration.

Superposed Epoch Analysis for 1 Jan 2006- 31 Dec 2013.

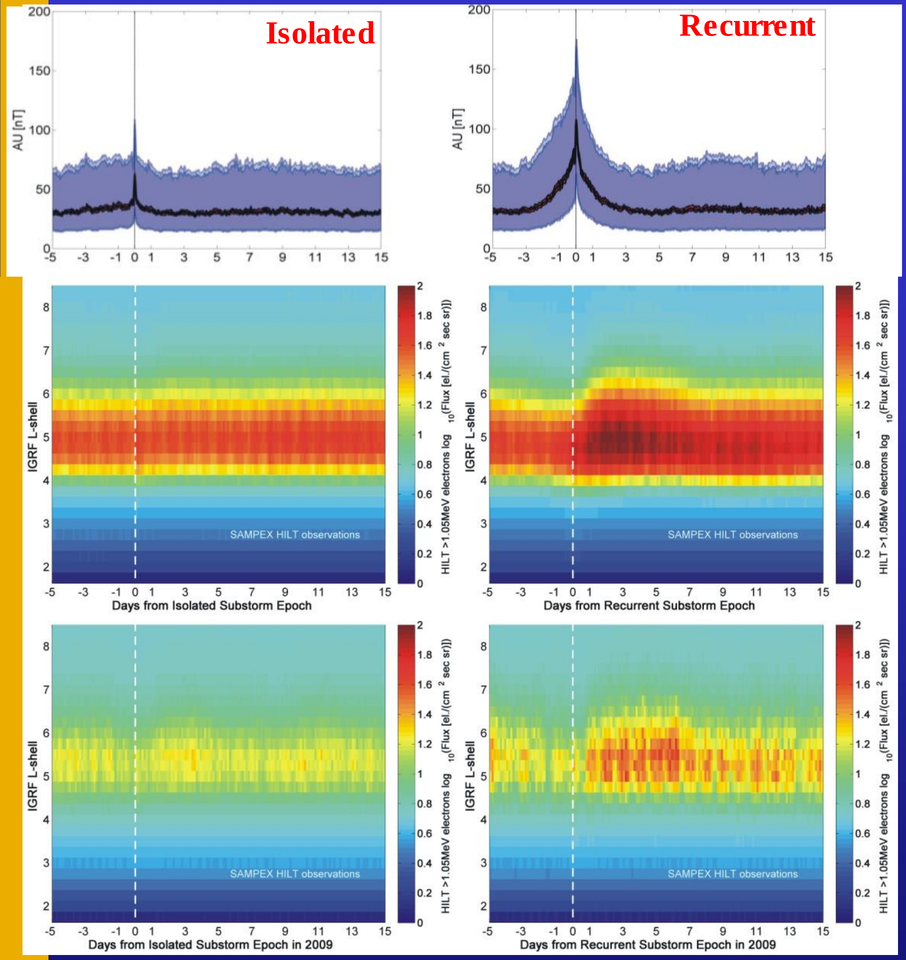
<u>**Things to note.**</u>

1. In the case of recurrent substorm epochs the lower-band chorus does begin to enhance <u>before</u> the start of the substorm cluster (i.e., the convection ~1 day before the substorms does indeed enhance chorus power).

2. However, there is a much larger increase in chorus power when the recurrent substorm cluster starts (at zero epoch), i.e., when the additional low-energy chorus "seeds" are injected during the series of substorms.

<u>Maybe</u> the substorm provided seed might be more important than the seed population from the earlier convection.

What about the "Grand Experiment" time?



We can also contrast the difference between the whole study period (1 Jan 2006- 31 Dec 2013) and that of the "Grand Experiment (2009).

←ALL TIMES

← JUST 2009

Similar patterns, but with a weaker background and smaller peaks for recurrent substorm epochs in 2009.

Same pattern suggestive of the same Physics occurring throughout these times.

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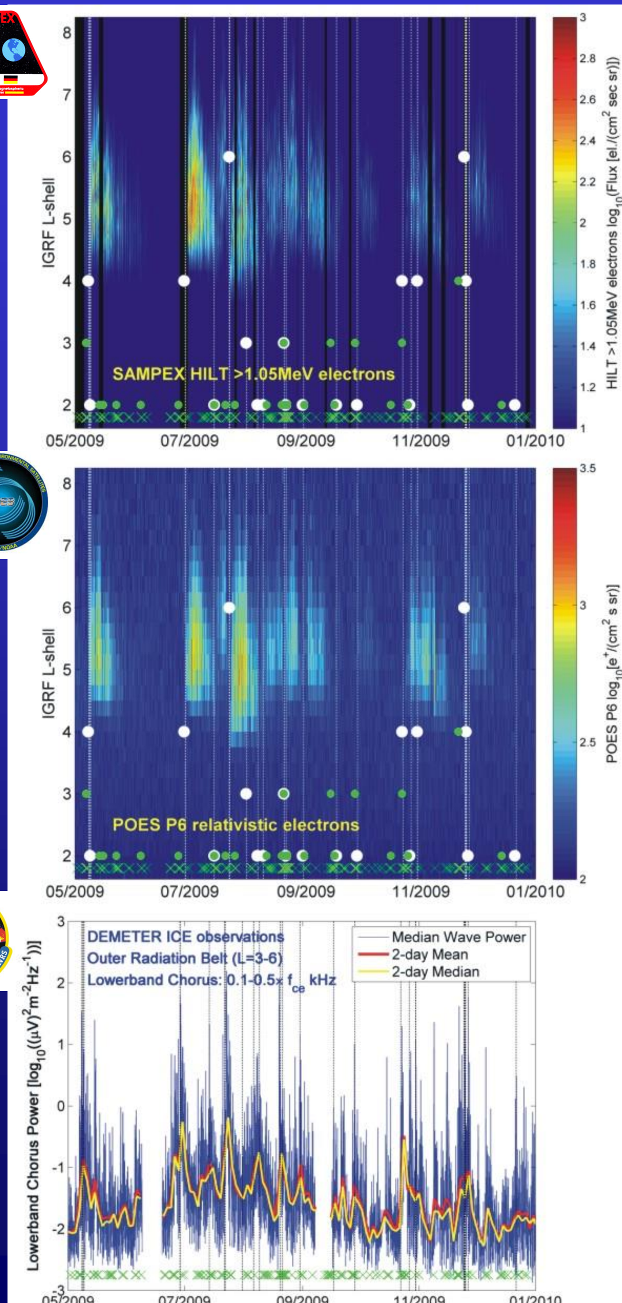
What about the "Grand Experiment" time?



We can also test the radiation belt response during part of the "Grand Experiment period (May 2009 – Jan 2010) as a set of case studies.

White dotted line is the start of a recurrent substorm cluster (● = daily number of substorms in cluster)

Green cross = isolated substorm events (● = daily number of isolated substorms)

The majority of recurrent substorm epochs are associated with increases in the outer RB relativistic flux. During periods with no recurrent substorm epochs, fluxes steadily decrease.

However, the number of substorms in a cluster does not seem to predict the acceleration "strength".

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What's the Physics here?

We suggest that what is happening is a combination of the models from the literature – noting that there is a lot of agreement that a source of "seed" electrons to make the whistler mode chorus is vital!

High Speed Solar Wind Stream

Enhanced convection of "low-energy" electrons from plasmasheet

Enhanced population of "seed" electrons

Whistler-mode chorus waves stimulated

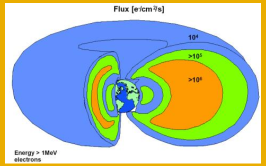
IMF B_z southwards

Clusters of recurrent substorms

Injections of "low-energy" electrons (i.e., yet **MORE** seed e^-)

MORE chorus stimulated

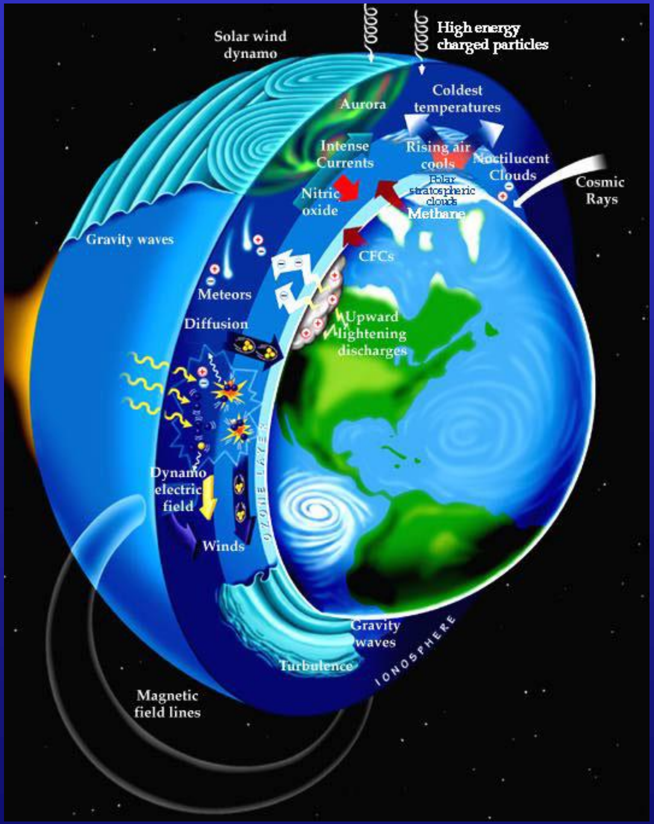
Acceleration of radiation belt electrons up to relativistic energies



Energetic Particle Precipitation

<u>Losses:</u> overall response of the RB to geomagnetic storms are a "**delicate and complicated balance between the effects of particle acceleration and loss**" [*Reeves et al.*, GRL, 2003].

Thus while there has been a lot of focus on the acceleration of radiation belt particles, it is also necessary to understand the losses to understand the radiation belts.

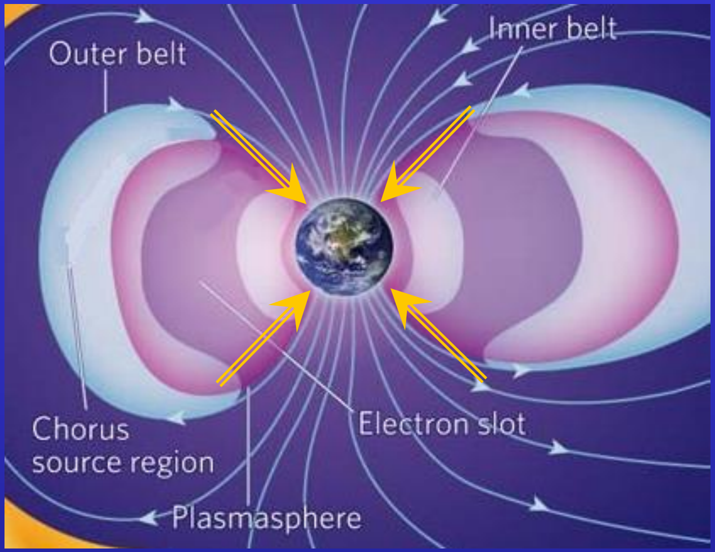


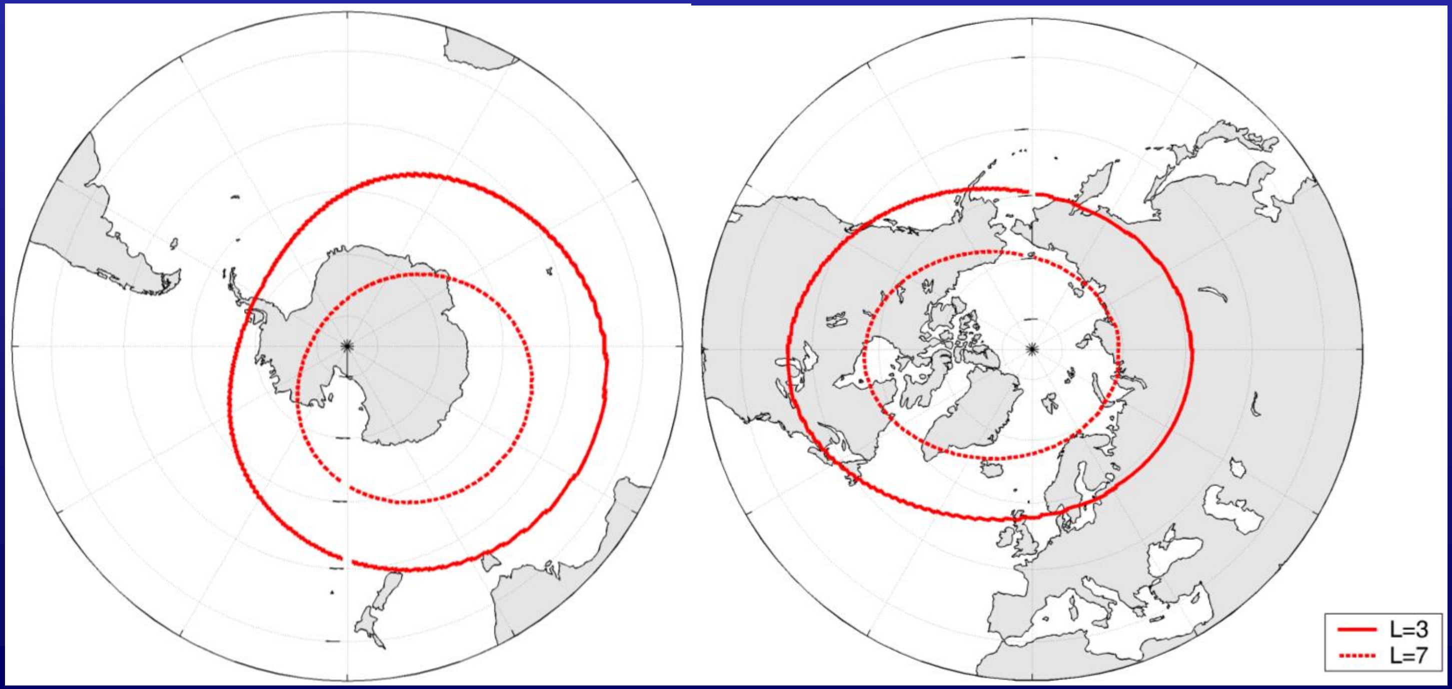
<u>Space Weather links to the atmosphere (and beyond?).</u> In addition, particle precipitation is one way that changes at the Sun, and around the Earth, can couple into the atmosphere - and possibly into the climate.

There are multiple "important" questions which need to be answered to understand Radiation Belt losses & the significance of Energetic Particle Precipitation.

These particles are lost to the polar upper atmosphere

<u>Losses:</u> The outer radiation belt deposits energy into the polar atmosphere in both the Antarctic and Arctic.





Radiation Belt Precipitation

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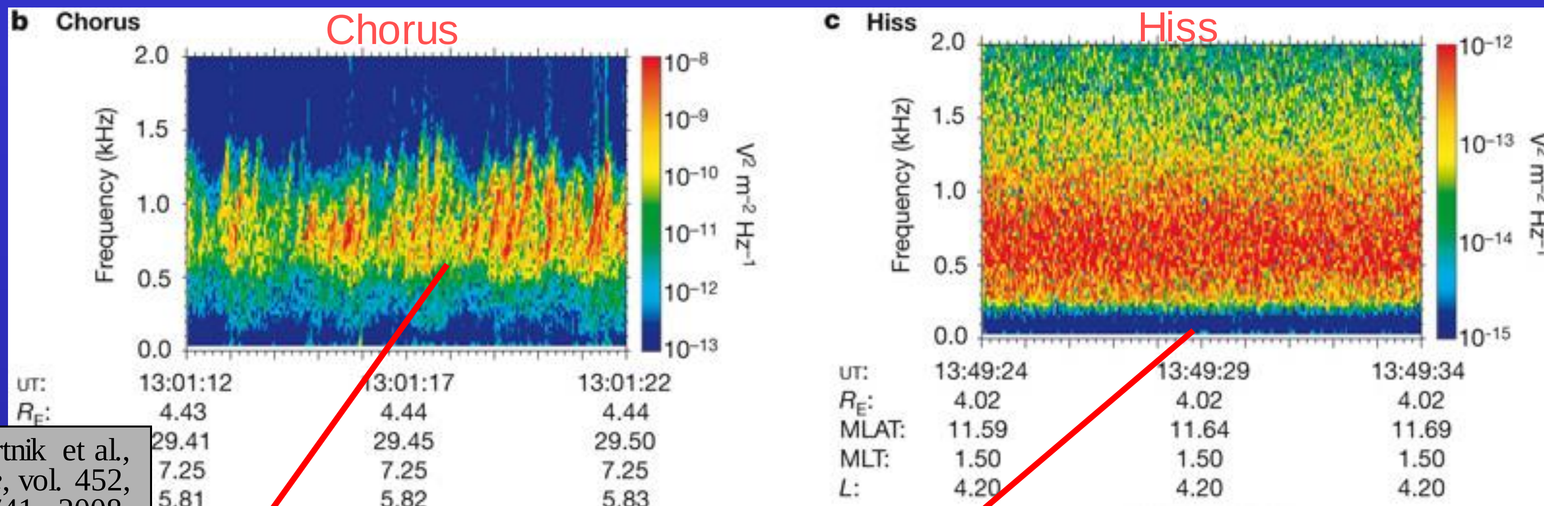
What causes precipitation? Plasma Waves! (of course)



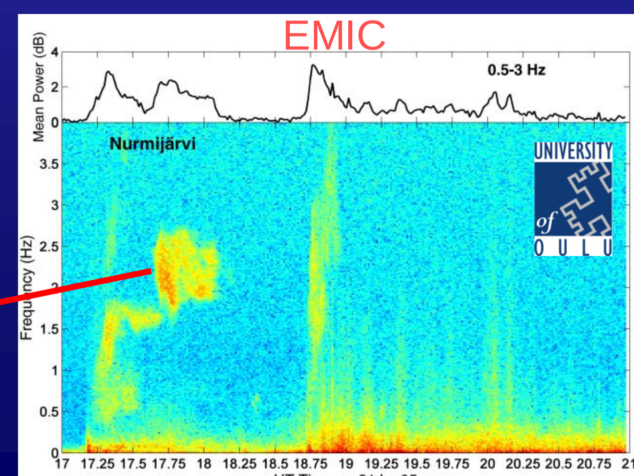
Adapted from Bortnik et al., *Nature*, vol. 452, 10.1038/nature06741, 2008.

W-M = "whistler mode"

W-M chorus: growing evidence that these waves have prime responsibility for the **acceleration** of electrons to form the relativistic population in the radiation belts and also drive losses.

W-M Plasmaspheric Hiss: Has long been suggested as the **reason the slot region exists**

Electromagnetic Ion Cyclotron waves: long understood as a likely important loss mechanism.



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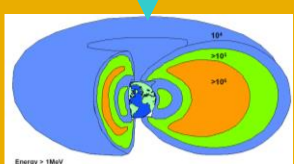
The potential importance of particle precipitation

Particle precipitation is one of the routes by which the Sun can link to the climate – energetic electrons and protons can change atmospheric chemistry. And in an environment where humanity is changing the climate, and polar ozone levels, we need to know about the "natural" variation too!

Plus of course the interest in precipitation from a strictly radiation belt physics viewpoint.

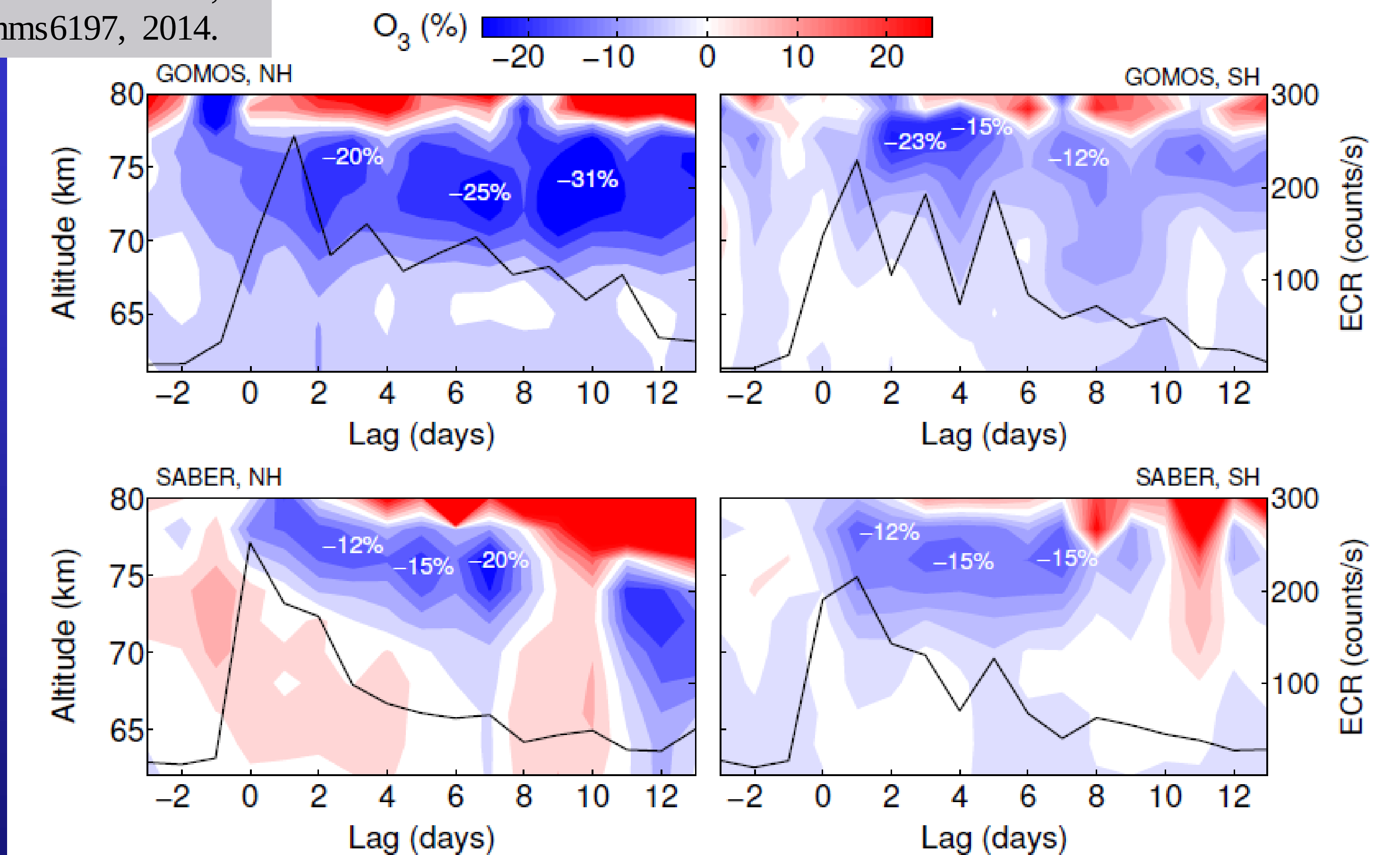


Particle precipitation
↓
Production of NO_x and HO_x
↓
Destruction of mesospheric and upper stratospheric O_3
↓
Change in dynamics mesosphere & stratosphere → "Climate"

(Probably, at some level)

Observations of O_3 loss caused by EEP

Andersson et al., *Nature Comm.*, doi:10.1038/ncomms6197, 2014.

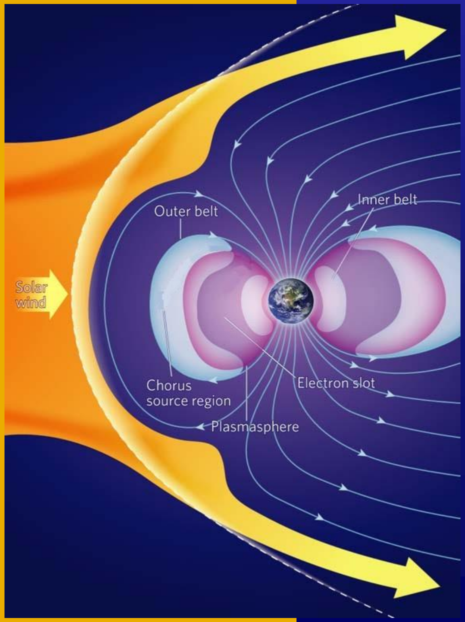


Superposed Epoch Analysis of mesospheric ozone observations from GOMOS and SABER after an EEP peak - ozone does indeed decrease significantly after strong precipitation events. The magnitude of the ozone decrease is similar to that from "large" Solar Proton Event, which are much less common occurrences!

It's the Level of Dynamism which Matters

In recent years there has been a much stronger focus on losses. Some of this has come from the new experimental opportunities which have appeared, some from the strong focus on radiation belt science as a whole.

In my opinion there has also been increased focus due to our increased understanding around coupling, and how parts of geospace influence one another - for losses that implies a focus on precipitation into the atmosphere.



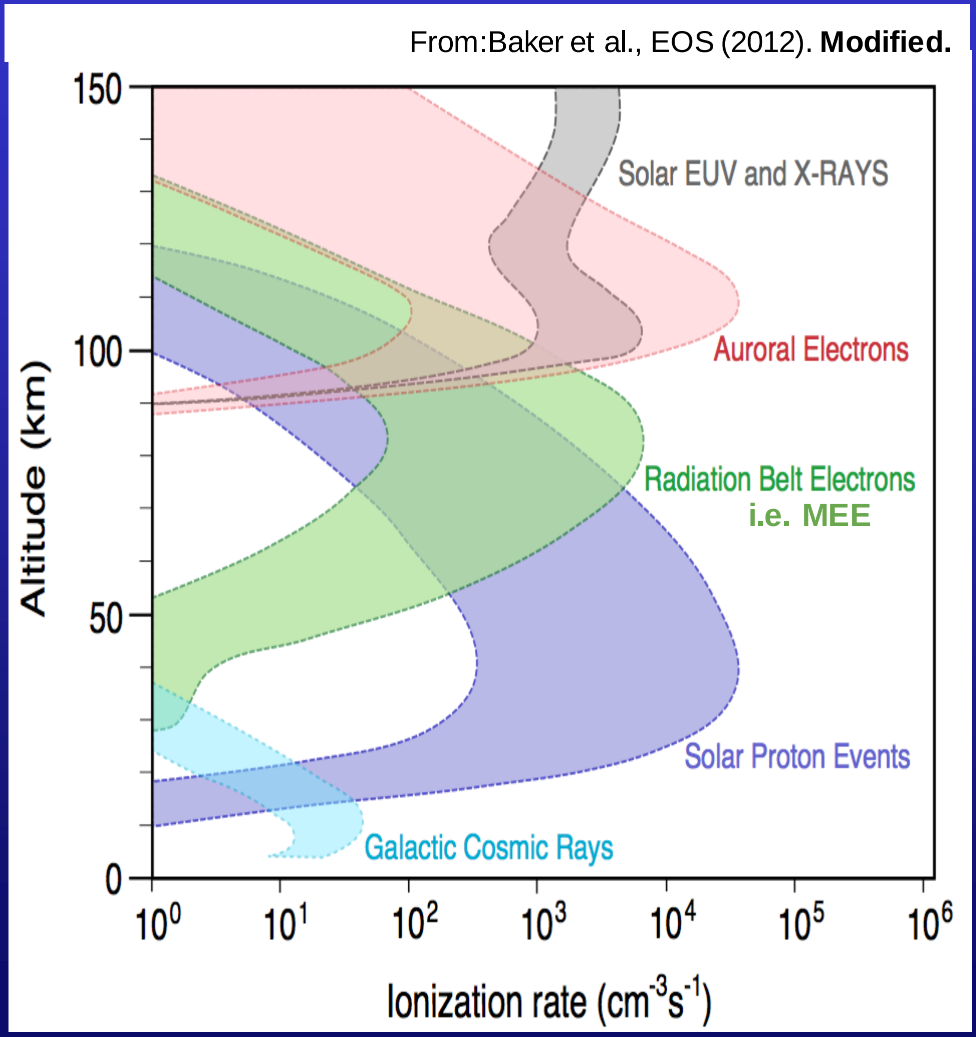
We have much improved understanding now, both in terms of case studies, and wider impacts.

In a sense this is the issue. We have an increasingly good grasp of how plasma waves cause precipitation and we are starting to do quantifiable testing. **But we lack the detailed understanding for long term physics-based prediction.**

!!

$N(t) = N_0$ + Acceleration - **Losses**

Particle precipitation and the atmosphere



Energy equates to how deep particles will penetrate the atmosphere.

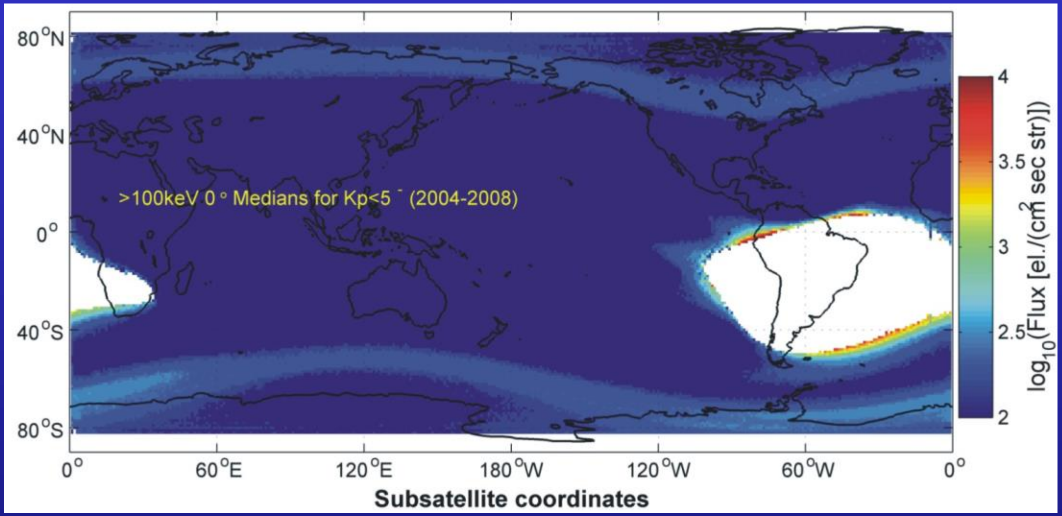
- Contribution of all should included for the assessment of decadal effects on climate
- Long-term modeling of the atmospheric impact of solar protons and auroral electrons has been undertaken and reported previously
- Medium Energy Electrons have been missing until recently,but they:

(a) cause direct ozone effect in the mesosphere below 80 km
(b) are more frequent than SPEs

Energetic Electron Precipitation at "Quiet Times"

Look at world maps of >100keV EEP from MEPED/POES, and separate by geomagnetic storm conditions. First take quiet time conditions.

Rodger et al. (2013), *J. Geophys. Res.*, 10.1002/2013JA019439.



Map of the median >100keV precipitating fluxes over the time period 1 January 2004-31 December 2008 for quiet and mildly disturbed timed (Kp≤4.7). Note that the dominant precipitation is in the Weddell Sea, south of the South Atlantic Magnetic Anomaly. This is understood to be a **weak diffusion** scattering process.

Similar results were reported earlier by ***Horne et al.*** [*Geophys. Res. Lett.*, doi:10.1029/2009GL040236, 2009].

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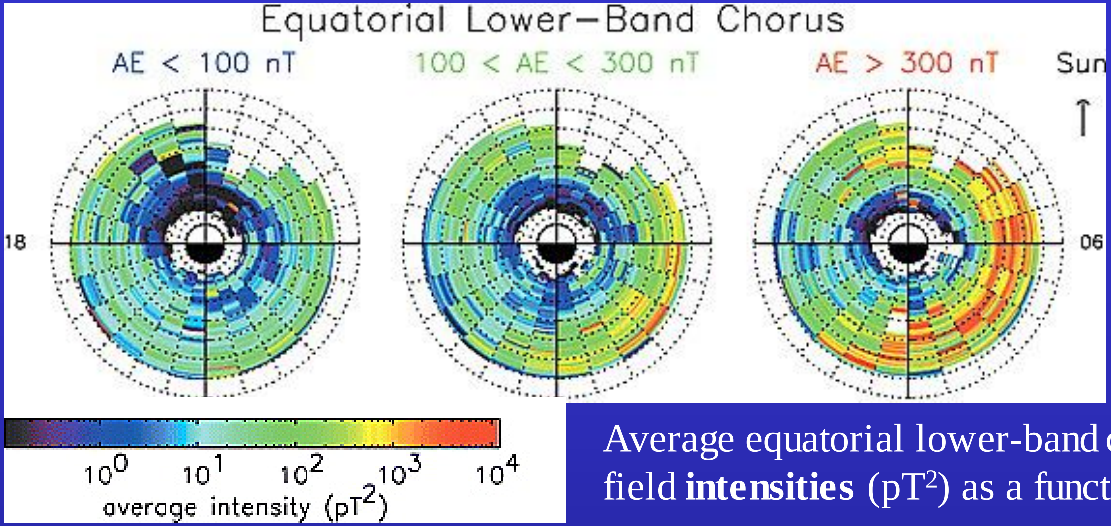
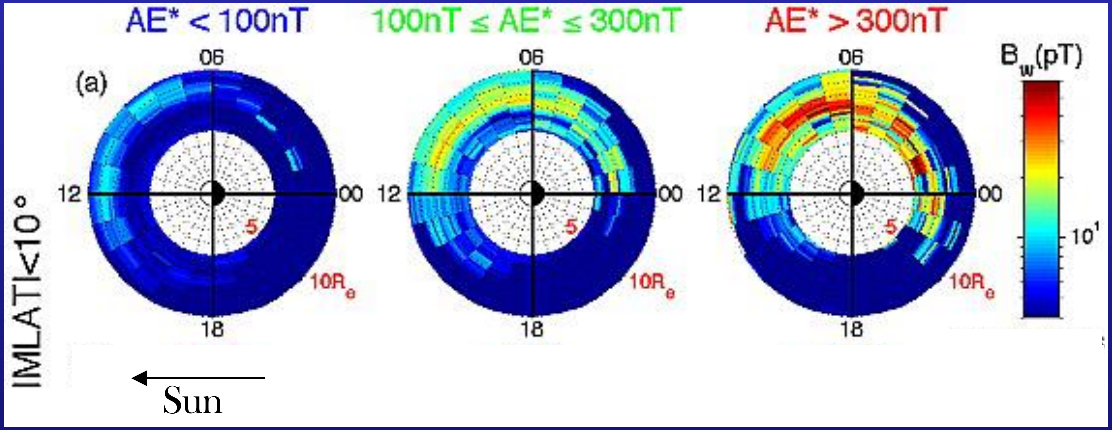
Lower-band Chorus - Equatorial Observations



CRRES observations (1990-1991)

Meredith et al. (2003), *Geophys. Res. Lett.*, 10.1029/2003GL01769.

Average equatorial lower-band chorus magnetic field **intensities** (pT^2) as a function of *L*, MLT.



THEMIS observations (2007-2009)

Li et al. (2009), *Geophys. Res. Lett.*, 10.1029/2009GL03759.

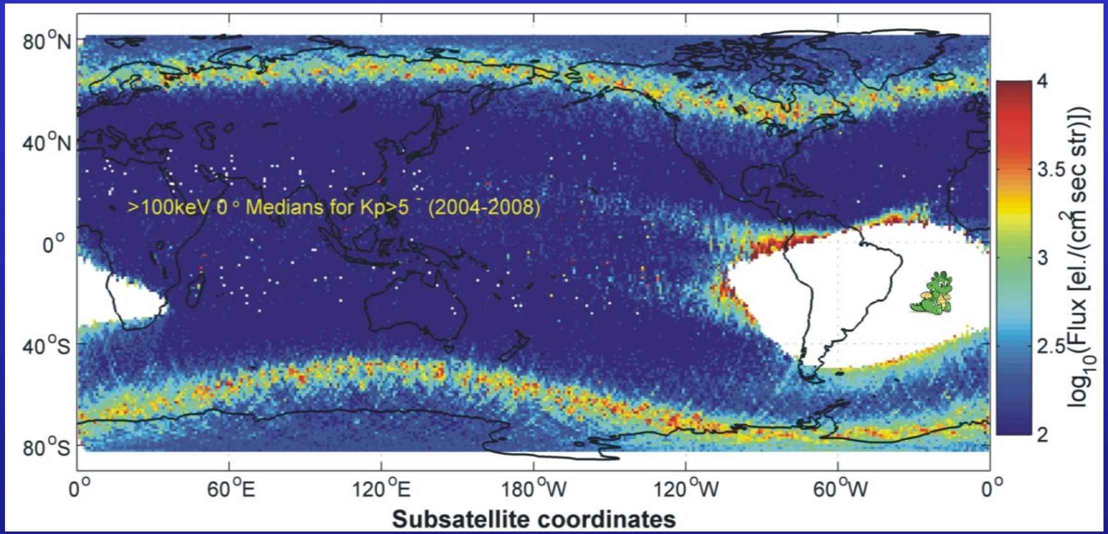
Equatorial chorus magnetic field RMS wave **amplitude** (pT).

Both CRRES and THEMIS suggest there is roughly a 2 order of magnitude difference in the chorus wave <u>intensities</u> between quieter and highly disturbed conditions.

Energetic Electron Precipitation at "Storm Times"

Look at world maps of >100keV EEP from MEPED/POES, and separate by geomagnetic storm conditions. Now take storm time conditions.

Rodger et al. (2013), *J. Geophys. Res.*, 10.1002/2013JA019439.



Map of the median >100keV precipitating fluxes over the time period 1 January 2004-31 December 2008 for disturbed/storm times (Kp>4.7).

Now no significant variations in longitude are observed, and no hemispheric bias is present either. **Strong Diffusion!**

So one approach to describe the variation of long term precipitation is through long term empirical fitting using a geomagnetic proxy.

And we do have a long lived precipitation dataset we can turn to

Orbit: ~835 km Sun synchronous.

While suffering from numerous limitations, the POES SEM-2 MEPED measurements are long lasting, observing inside the Bounce Loss Cone.

POES SEM-2 MEPED started in 1998 and data is still being produced!

Satellite	Orbital Sector	Data Availability	
NOAA 15	Morning	1st July 1998	Still Active
NOAA 16	Afternoon	10th January 2001	Dead Since June 2014
NOAA 17	Morning	12th July 2002	Dead Since April 2013
NOAA 18	Afternoon	7th June 2005	Still Active
METOP 02	Morning	3rd December 2006	Still Active
NOAA 19	Afternoon	23rd February 2009	Still Active
METOP 01	Morning	1 January 2013	Still Active

See Timo Asikainen's poster (#33) about the long-time period POES datasets.

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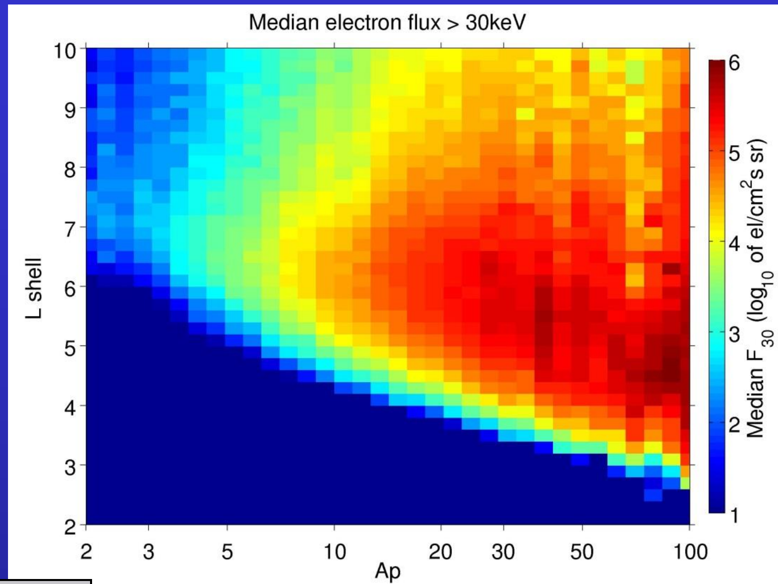
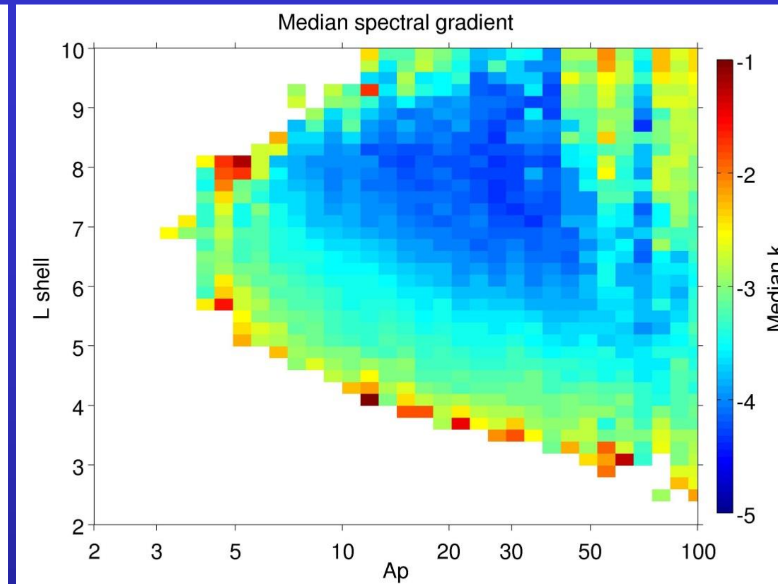
Empirical Data - EEP fitting to Ap





van de Kamp et al. (2016), *J. Geophys. Res. Atmos.*, 121, doi:10.1002/ 2015JD024212.

This is a combination of all the POES SEM-2 satellite data from 1998-2012 including NOAA-15, NOAA-16, NOAA-17, NOAA-19, NOAA-19, and MetOp-02.

This includes 19,949 satellite days of observations (i.e., >50 years).

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Improved Model for precipitation (not MLT-dependant)

- $$F_{30} = \frac{e^{T} e^{-A}}{e^{-b(S_{pp}-s)} + e^{c(S_{pp}-s)}}$$ → **>30keV electron flux magnitude**

  $T = 15.004$

  $A = 19.683 Ap^{-0.66696}$

  $b = 5.5619$

  $c = 0.61055$

  $s = 0.85072$

These are empirical fits to the experimental data (and thus not necessarily driven by physics).

- $$k = \frac{-1}{A\cosh\left(c(S_{pp}-s)\right)} - 1$$ → **energy spectral gradient**

  $A = 0.30180 + 2.0821 Ap^{-1.7235}$

  $c = 0.31955$

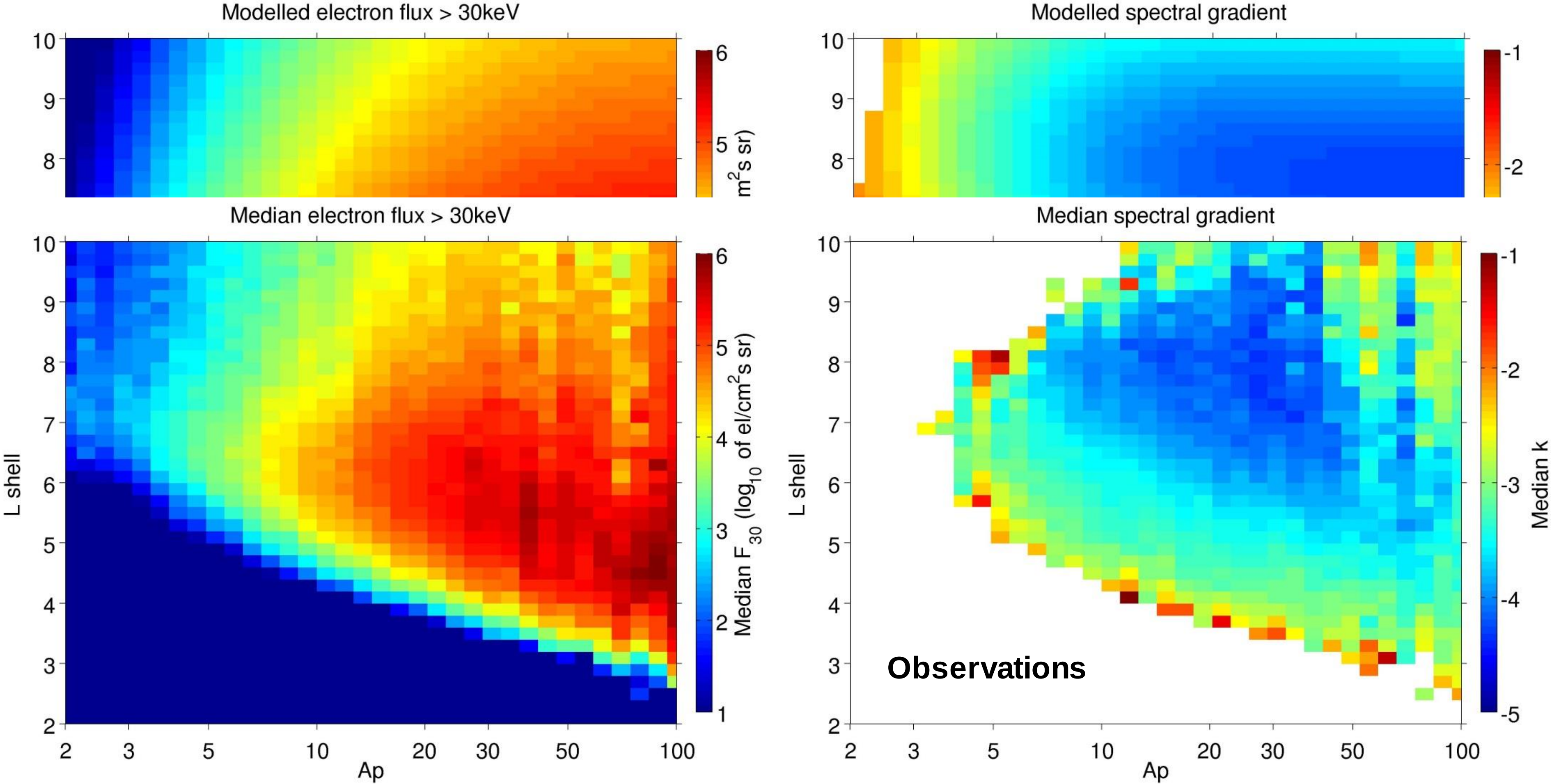
  $s = \ln(11.970 + 2.4824 Ap^{0.7340})$

- $S_{pp} = L - L_{pp}$ → **link to plasmapause location**
- $L_{pp} = -0.7430 \ln max_{-24,0} Ap + 6.5257$ [O'Brien and Moldwin, *Geophys. Res. Lett.*, 2003]
- $F_{30} = 0$ if $Ap = 0$, if $S_{pp} < -0.3$, or if $F_{30} < 10$

van de Kamp et al. (2016), *J. Geophys. Res. Atmos.*, 121, doi:10.1002/2015JD024212.

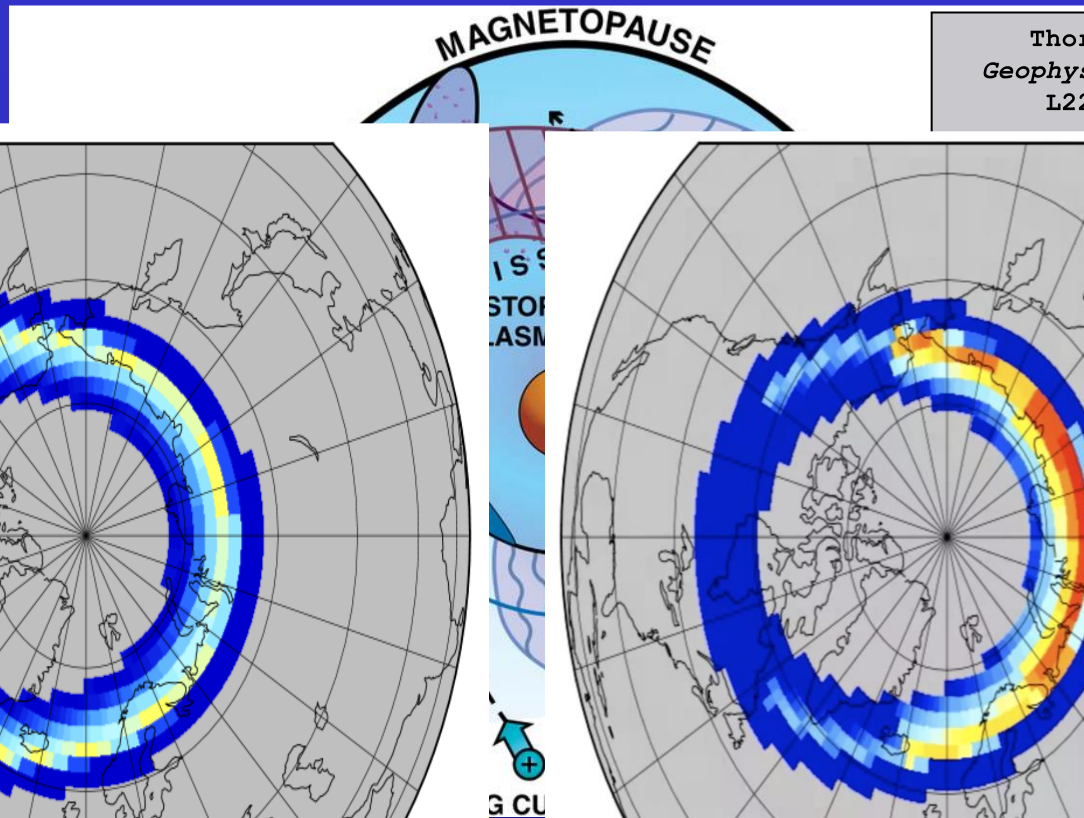
Model Results

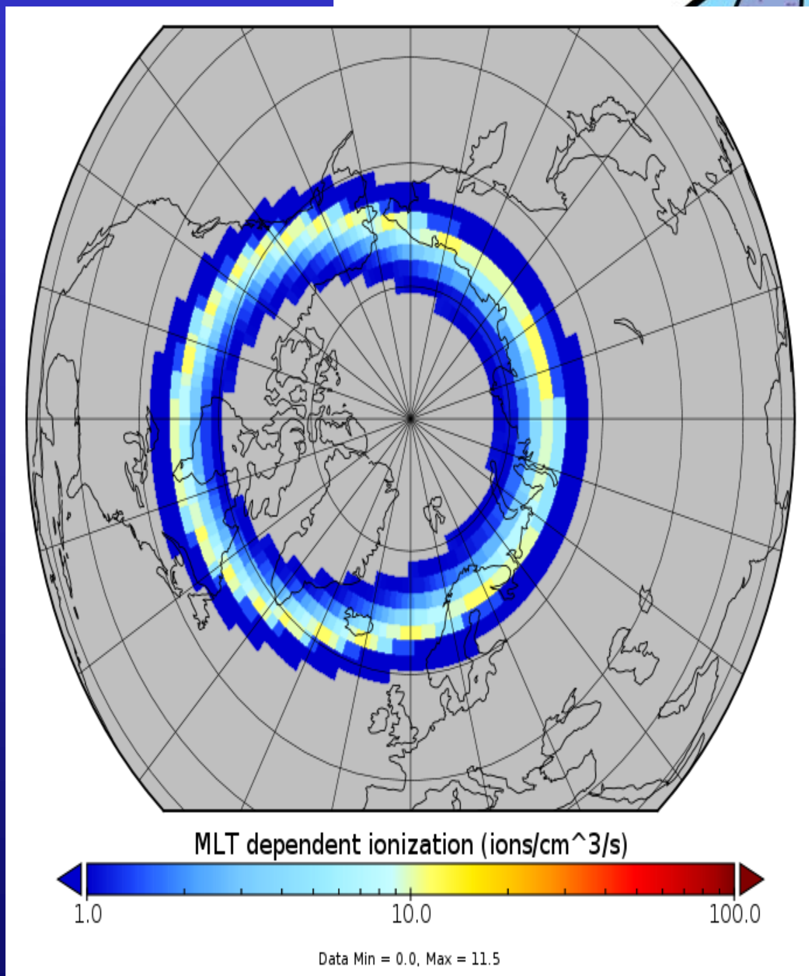
F_{30} and k as function of L and Ap (modelled):



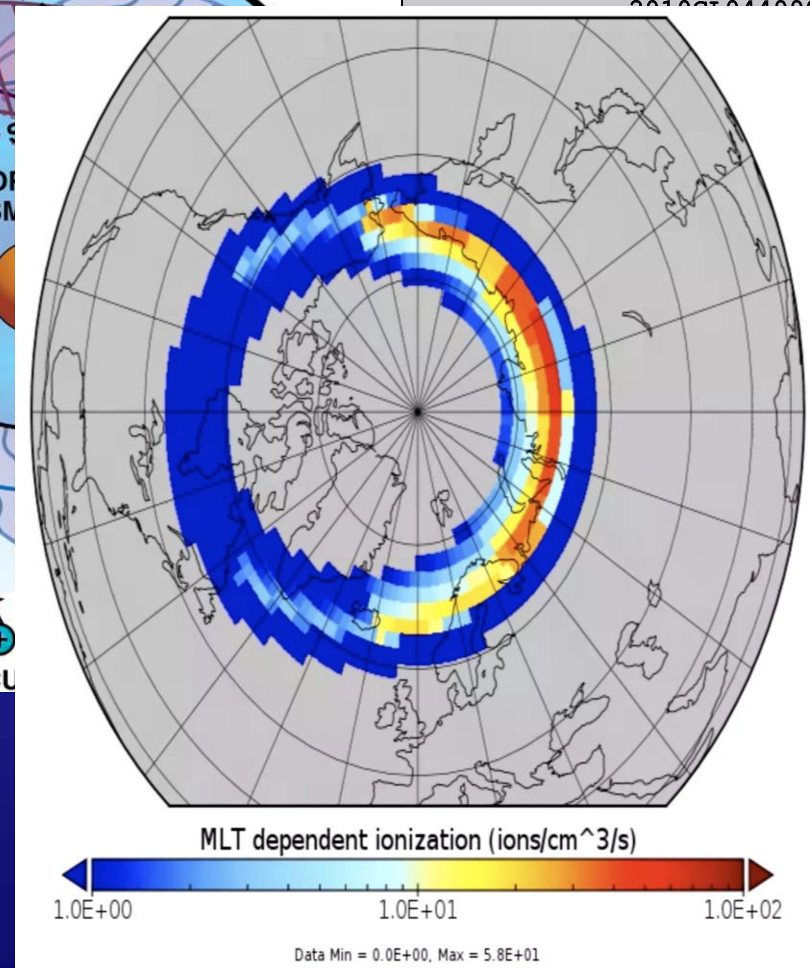
Can also work with a MLT dependent version

Thorne, R. M. (2010), *Geophys. Res. Lett.*, 37, L22107, doi:10.1029/





MLT Independent



MLT Dependent

Including MEE in climate modelling

In June 2017 a set of recommendations were published to include "solar forcing" in the Coupled Model Intercomparison Project Phase 6 (CMIP-6) of the World Climate Research Programme (WCRP). The CMIP processes develop and improve the models for the IPCC.

Due to the observed polar chemical changes, the "solar forcing" for CMIP-6 now includes medium energy electron precipitation (~10kev-1MeV)!!

Enables estimates of an EEP flux for any period of time for which Ap is available (i.e., 1932- or even earlier, if Ap estimates are used). This forcing is now being incorporated into climate models in the CMIP6 process.

Geosci. Model Dev., 10, 2247–2302, 2017
https://doi.org/10.5194/gmd-10-2247-2017

Geoscientific Model Development
Open Access
EGU

Solar forcing for CMIP6 (v3.2)

Katja Matthes[1,2], Bernd Funke[3], Monika E. Andersson[18], Luke Barnard[4], Jürg Beer[5], Paul Charbonneau[6], Mark A. Clilverd[7], Thierry Dudok de Wit[8], Margit Haberreiter[9], Aaron Hendry[14], Charles H. Jackman[10], Matthieu Kretzschmar[8], Tim Kruschke[1], Markus Kunze[11], Ulrike Langematz[11], Daniel R. Marsh[19], Amanda C. Maycock[12], Stergios Misios[13], Craig J. Rodger[14], Adam A. Scaife[15], Annika Seppälä[18], Ming Shangguan[1], Miriam Sinnhuber[16], Kleareti Tourpali[13], Ilya Usoskin[17], Max van de Kamp[18], Pekka T. Verronen[18], and Stefan Versick[16]

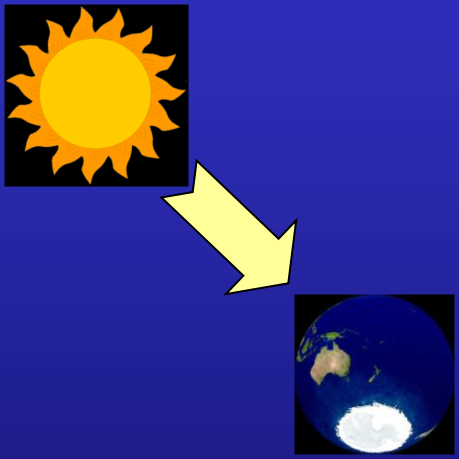
World Climate Research Programme

Including MEE in climate modelling

Enables estimates of an EEP flux for any period of time for which Ap is available (i.e., 1932- or even earlier, if Ap estimates are used).

The initial model can be improved a lot, but this is a start towards coupling the radiation belts to climate.

However, the strength of the model from a usability sense (it is driven by a simple parameter like Ap) is also one of its weaknesses - a geomagnetic proxy is used to estimate the true EEP magnitude and parameters. This approach is "good" for long term climate models, but is clearly missing physics.



- Physics I think we don't yet understand well enough.

In my opinion.

- More work on making quantifiably accurate electron loss observations from physics-based models is needed. This is not easy, but it should be done.

In my opinion.

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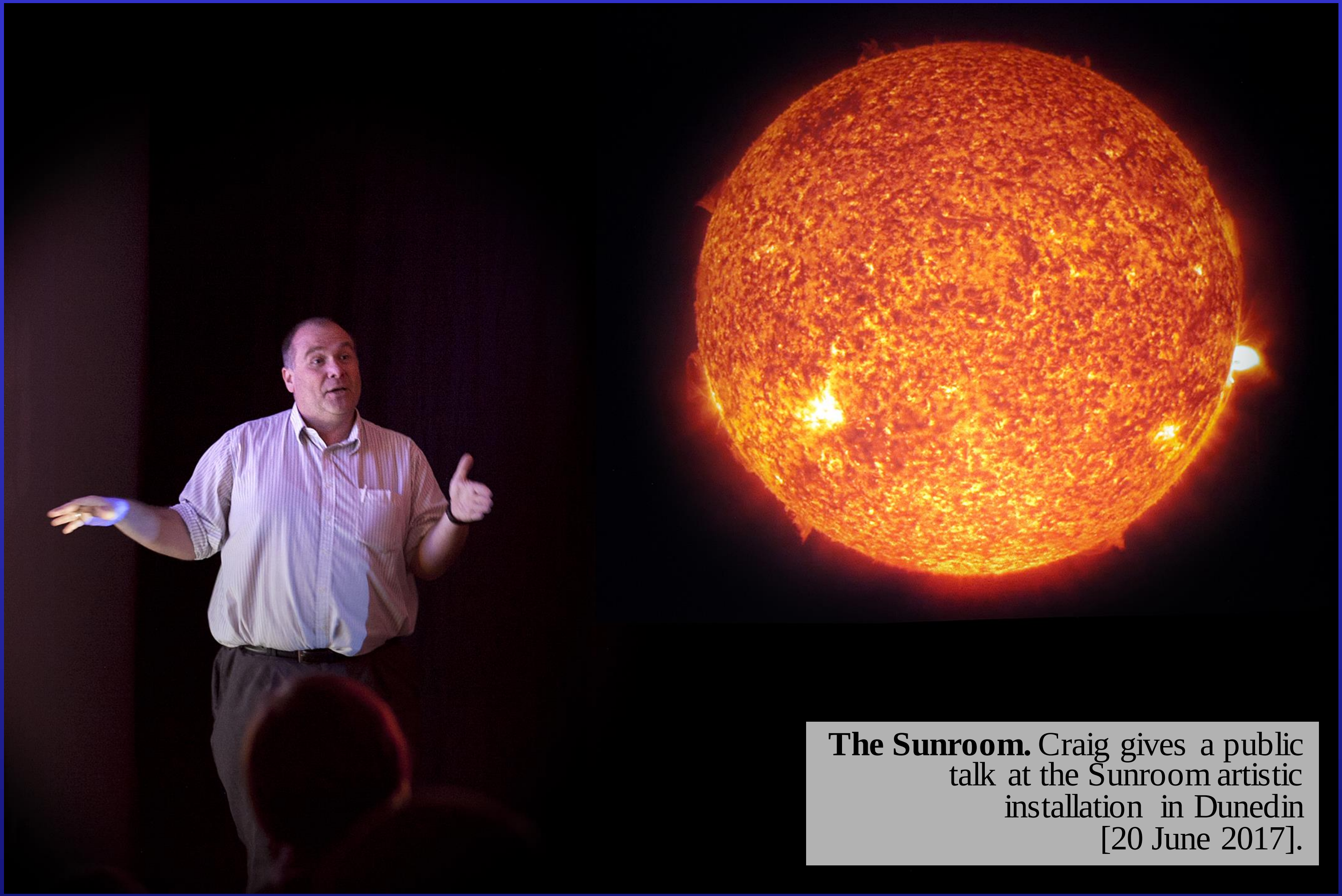
Summary

- Our understanding of the complex physical processes occurring in the radiation belts and their triggering has advanced significantly of late.
- While I did not focus on it, much of this comes from the current “golden age” for radiation belt research – multiple flagship missions. And now we have hope due to Cubesats.
- There are codes, some which even seem to work OK, providing short term prediction of changing radiation belt fluxes.
- We have a good quantitative understanding of how precipitation occurs, but our qualitative ability is still fairly limited.
- This limits our ability to understand long term precipitation and forcing of the atmosphere and climate – so empirical proxies have been used. **See tomorrows presentations for much more detail on the atmospheric linkages!!**



The Sunroom. Craig gives a public talk at the Sunroom artistic installation in Dunedin [20 June 2017].

Thankyou!

Are there any questions?

The team behind this work

Kathy Cresswell-Moorcock and Craig Rodger. Kathy and Craig are wearing their academic robes, as she had just had her Master of Science with Distinction conferred.

Mark Clilverd during a visit to the city of Dunedin.

Thankyou!

Are there any questions?

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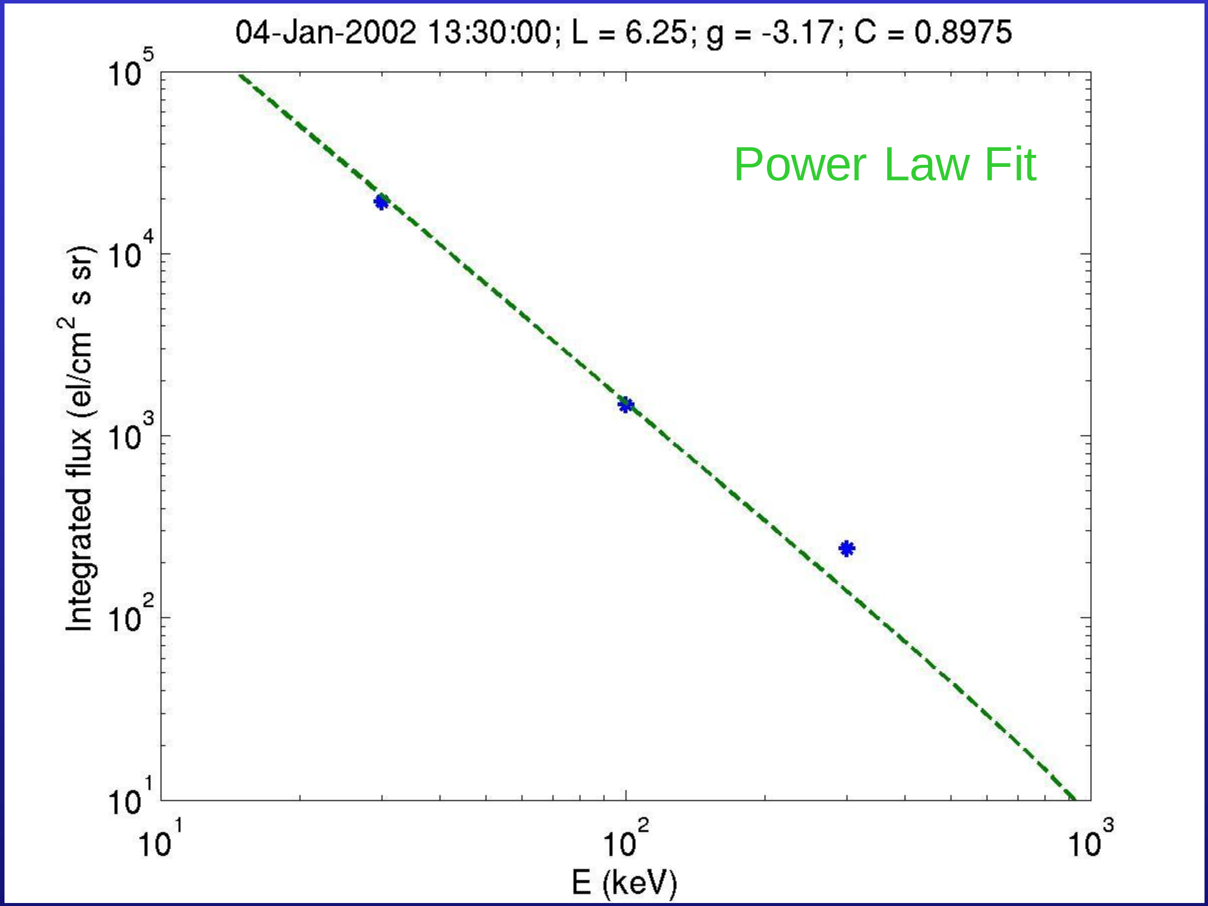
Most of the authors of this study, meeting in Cambirdge (UK) to talk about our EEP-impact work [29 March 2017]. **SORRY DAN!**

Thankyou!

Are there any questions?

Need to decide how to work with observations to make differential fluxes



Assume a power law and fit to get > 30 keV Flux (F_{30}) and gradient (k) as functions of L, and time (and in some versions, *MLT*).

[a power law is consistent with literature].