The role of plasmaspheric dynamics in electron precipitation occurrence

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Radiation Belt Dynamics and Remote Sensing of the Earth's Plasmasphere

11:00-12:30 The role of plasmaspheric dynamics in electron precipitation occurrence (**M. A. Clilverd**)

26-30 September 2022

Overview

- Why do we care about the plasmasphere?
- What is the plasmasphere?
- What are the main characteristics?
- How is the plasmasphere formed?
- How long does it take to reach equilibrium?
- Overall effect of a geomagnetic storm.
- What causes erosion from saturated levels?
- Models of the plasmasphere.
- What effect does the plasmasphere have on Radiation Belt processes?
- Electron precipitation occurrence.
- Electron precipitation modelling.
- Near the plasmapause…..
- And at the plasmapause.

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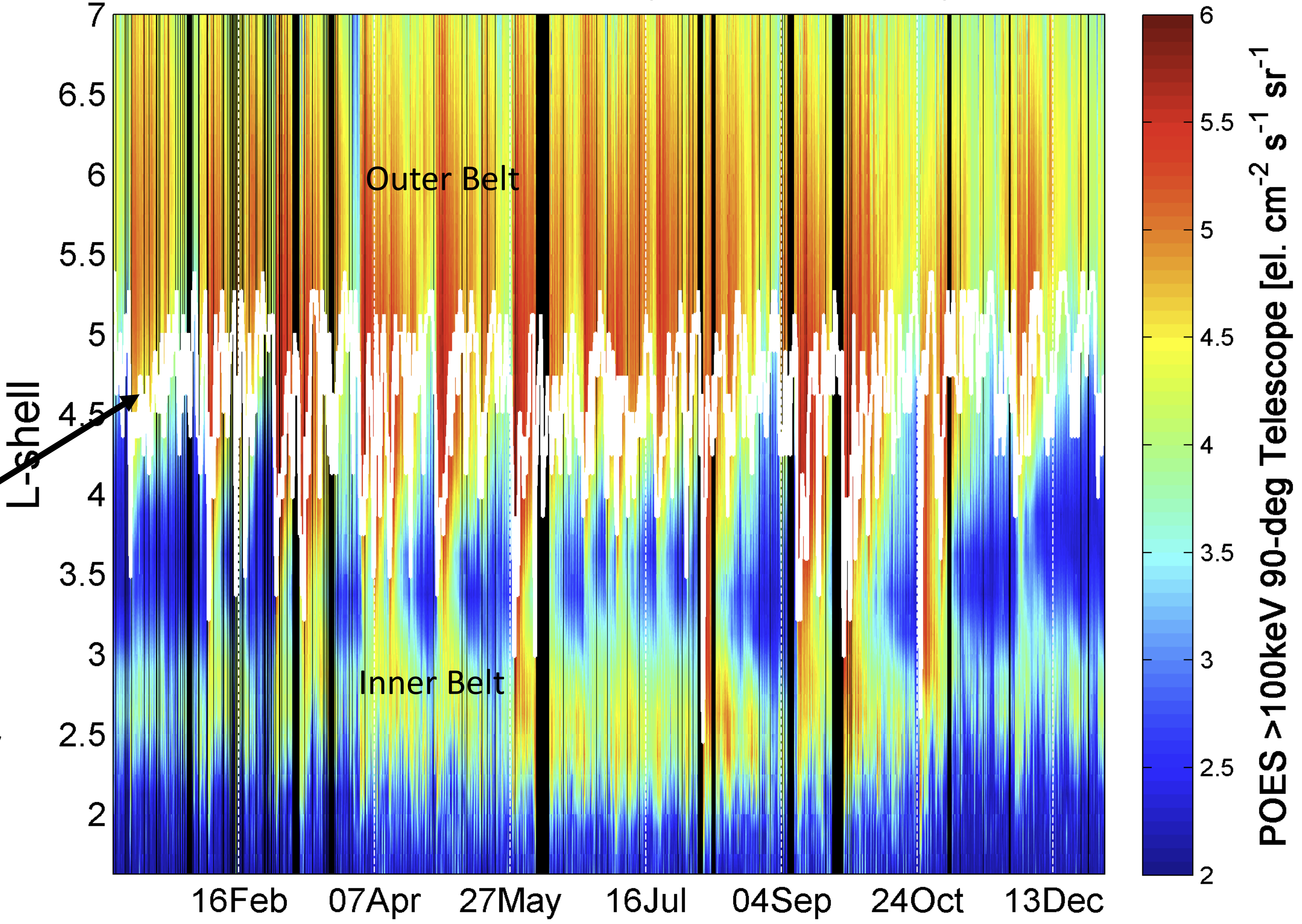
Focus on the 1st & 2nd Adiabatic Invariants

Why do we care about the plasmasphere?

As an example of its relevance, lets see how energetic electron fluxes are influenced by the background plasmasphere.

Plasmapause

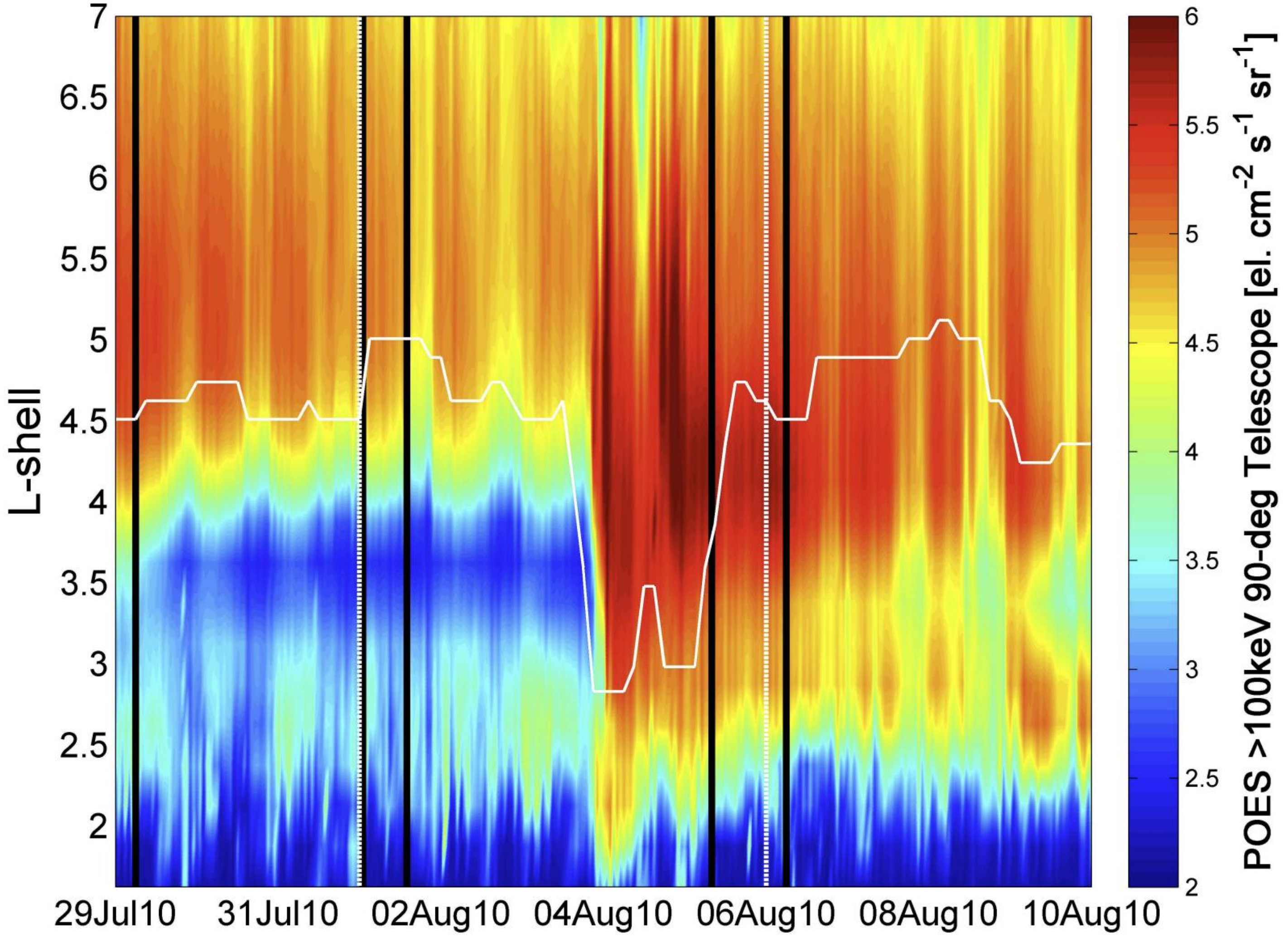


The location of the plasmapause is a good proxy for the inner boundary of the outer radiation belt.

Why do we care about the plasmasphere?

Even on short time periods there is a good relationship between plasmaspheric structure (plasmapause – white line) and radiation belt populations.

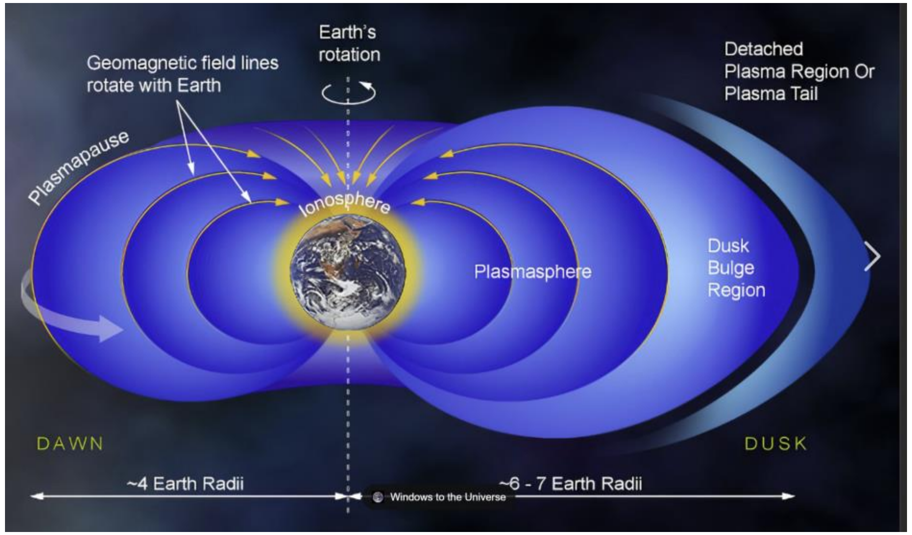
Periods of enhanced fluxes of electrons coincide with inward excursions of the plasmapause.



Lichtenberger, L., et al. (2013), The plasmasphere during a space weather event: First results from the PLASMON project, *J. Space Weather Space Clim.*, **3**, A23, doi:10.1051/swsc/2013045 .

What is the plasmasphere?

- The Earth's plasmasphere is an inner part of the magnetosphere. It is located just outside the upper ionosphere located in Earth's atmosphere. It is a region of dense, cold plasma that surrounds the Earth. Although plasma is found throughout the magnetosphere, the plasmasphere usually contains the coldest plasma.

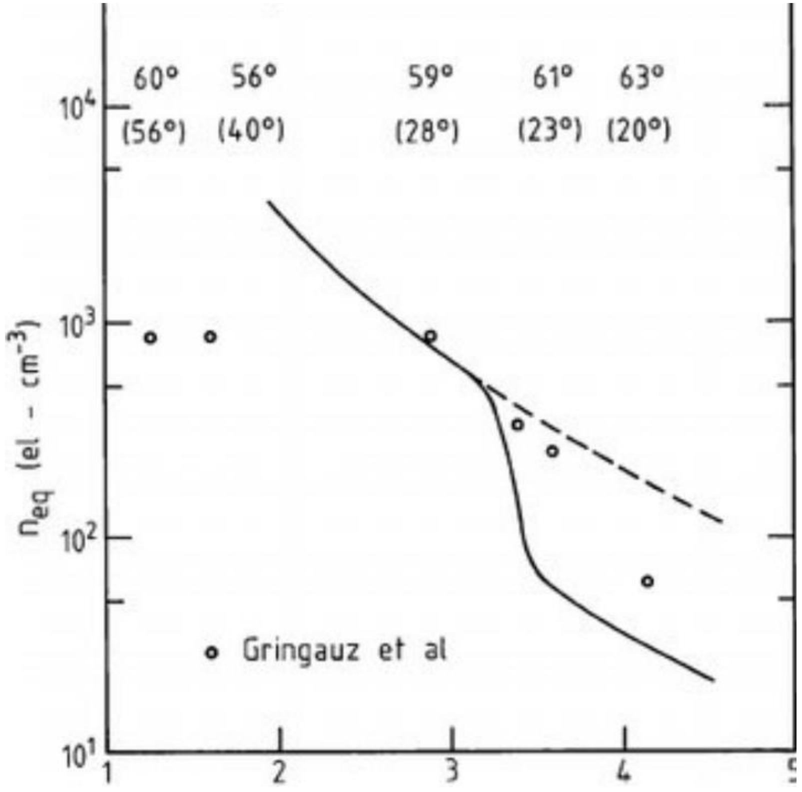


- This "donut shaped" region of cold (about 1 electron volt in energy) plasma encircling the planet is called the plasmasphere. [NASA]

What are the main characteristics?

- Four main characteristics:
  - Decreasing electron number density with L-shell.
  - Inner region of high density.
  - Outer region of low density.
  - Sharp gradient between the two regions.

Equatorial electron number density



L-shell (Re)

In 1963 Don Carpenter found a sharp drop in frequency dispersion of whistlers about 3 Earth radii out or 12,000 miles away from Earth. This represented a sharp drop in plasma in that region. About the same time Konstatin Gringauz made measurements of plasmaspheric electron density from the USSR space craft Luna 2.

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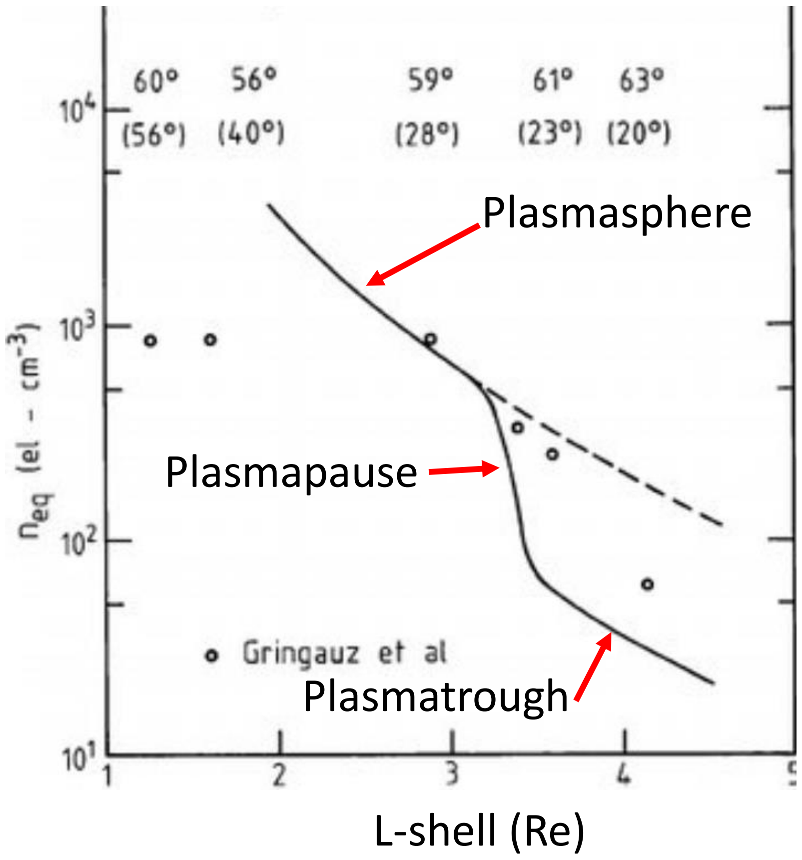
Equatorial electron number density



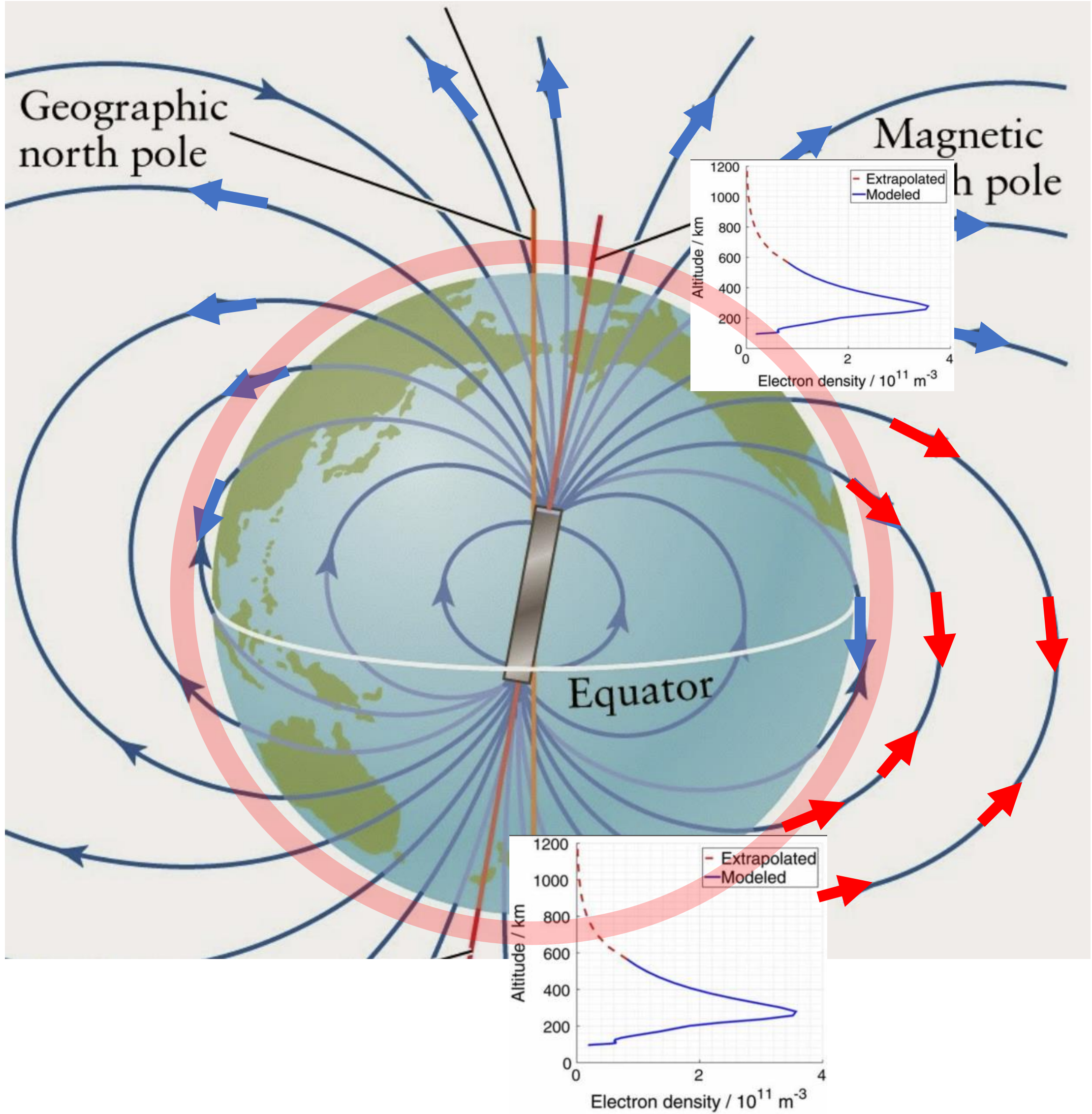
How is the plasmasphere formed?

- The plasmasphere is made up of plasma that diffuses up along magnetic field lines from the underlying ionosphere.
- Plasma diffuses up from both ends of the magnetic field line.
- It’s charge neutral, which means that ions and electrons diffuse up together. The lightest constituent of the ionosphere is Hydrogen, then Helium, then Oxygen.
- Hydrogen dominates the plasmasphere. To first order there are equal numbers of electrons as H^+ (for charge neutrality).
- Small amounts of He^+ and O^+ .

How is the plasmasphere formed?

Diffusion up from the ionosphere occurs in the **northern hemisphere and the southern hemisphere** on the same field-line.

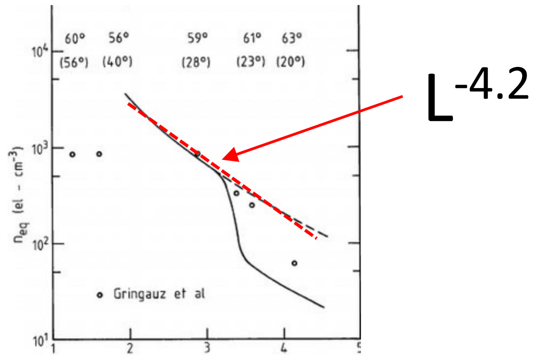
Given time the field-line comes into **diffusive equilibrium** with the ionosphere below.



To first order the underlying ionosphere is the same – especially over a range of latitude equivalent to L=2 – 6.

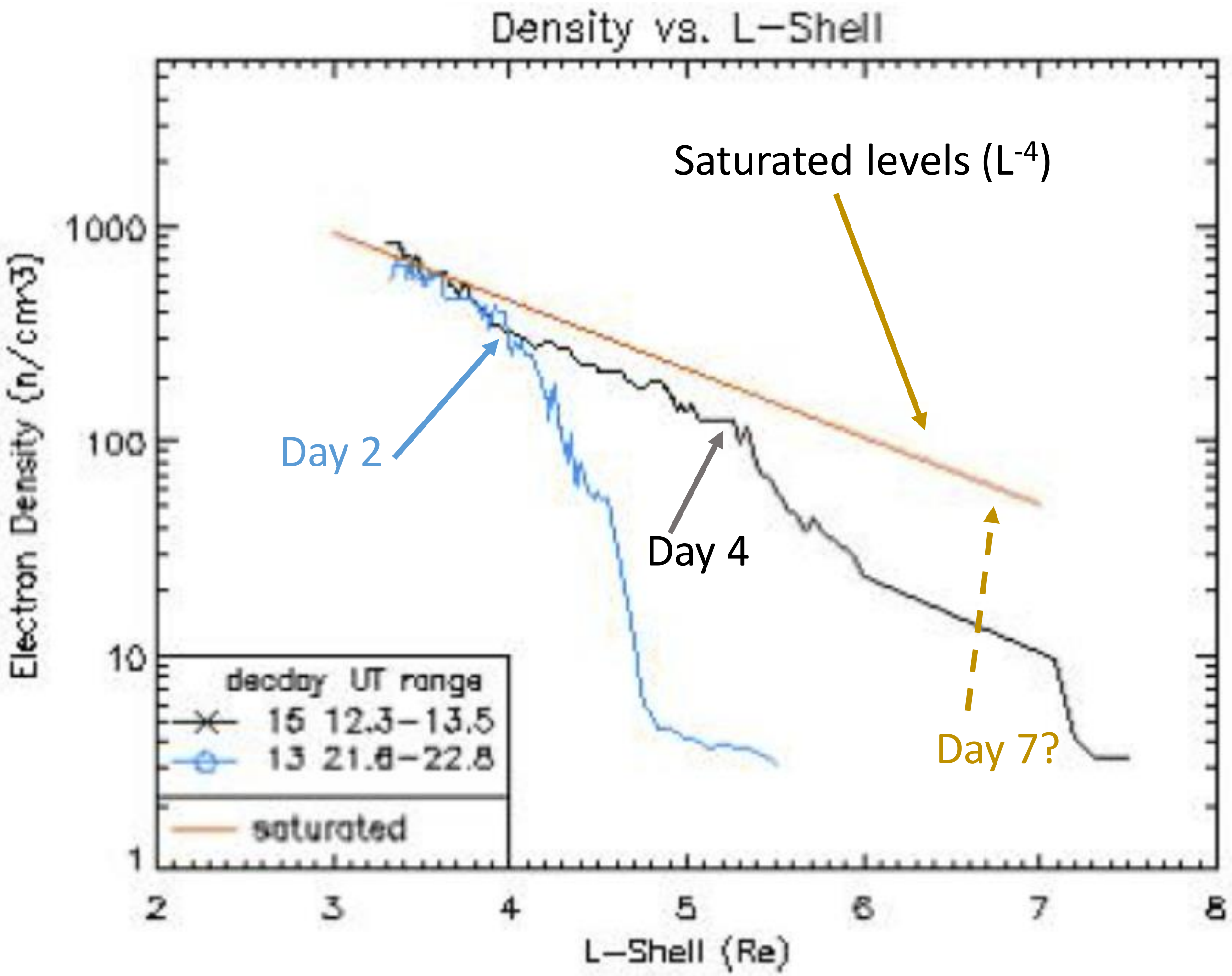
But the field lines are much longer at L=6 than L=2

So, same plasma but spread thinner: L^{-4} dependence



How long does it take to reach equilibrium?

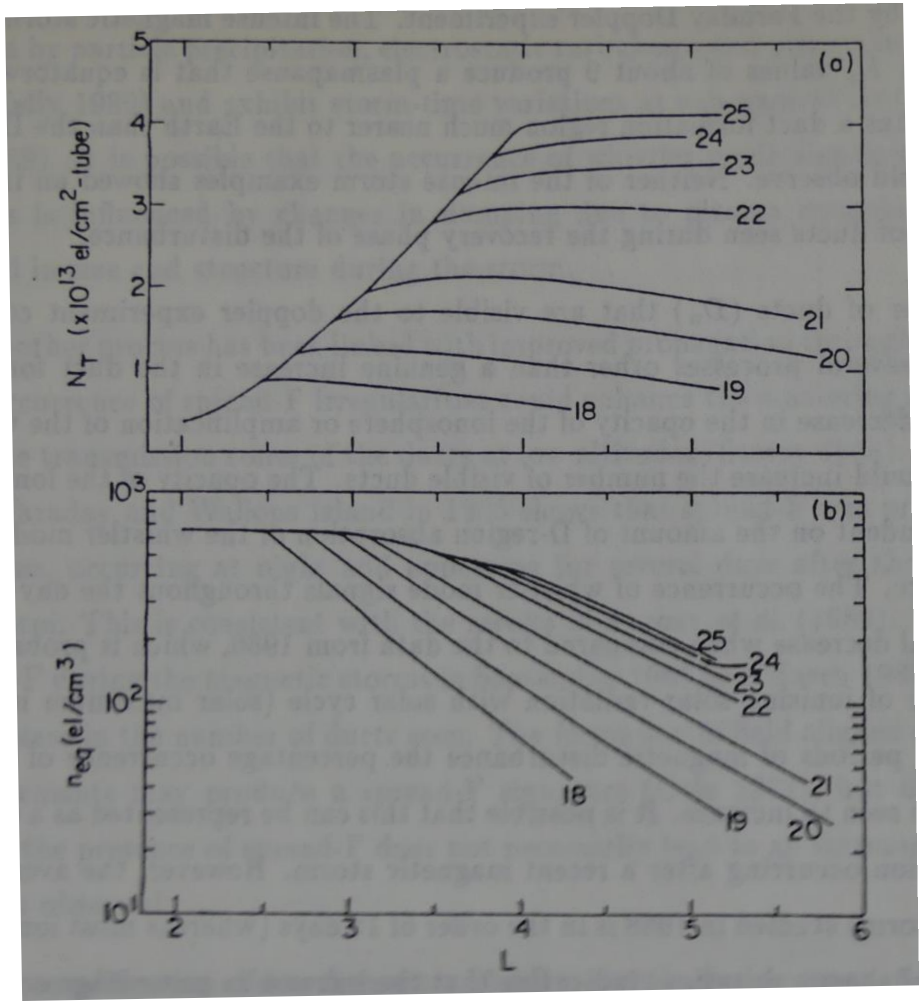
- It can take up to a week or so for the plasmasphere saturate (i.e., diffusive equilibrium) at the higher L-shells associated with the outer radiation belts.



Overall effect of a geomagnetic storm

Park (1974) analysed a storm which started on 15 June 1964, and peaked towards the end of 16 June 1965.

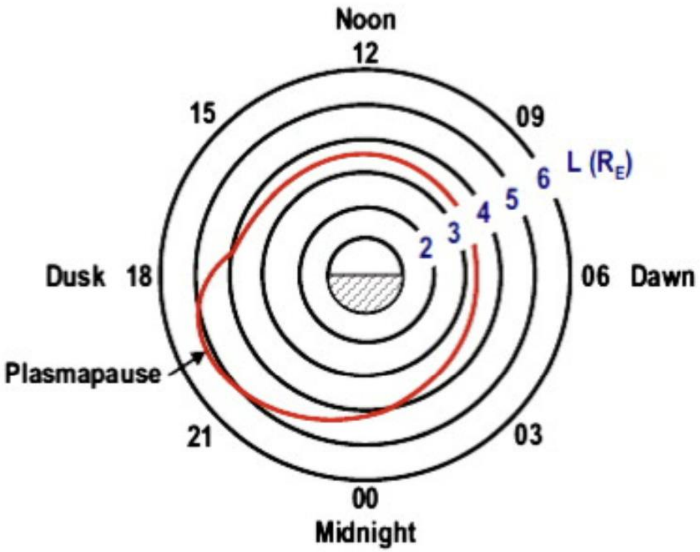
Both the **equatorial number density** and the field-line **tube content** showed recovery towards saturated levels over the next 10 days.

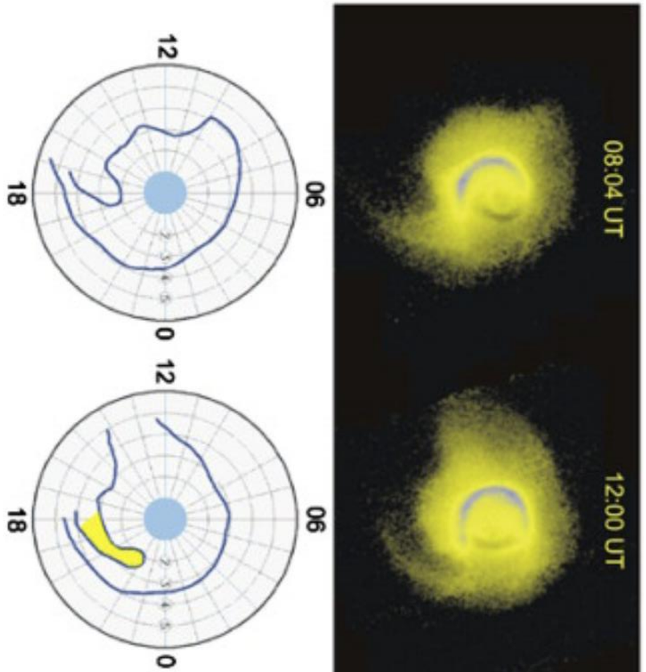


What causes erosion from saturated levels?

- The plasmasphere is influenced by the solar wind-induced convection electric field, which has a strong duskward component
- Sunward convection erodes the outer layers of the plasmasphere, removing plasma and creating a steep plasmapause boundary.
- A simple model of the plasmapause shape driven by combined corotation and convection electric fields suggests a teardrop shape with the dusk-side bulge.

The level of erosion is determined by the strength of the convection electric field, i.e., geomagnetic activity



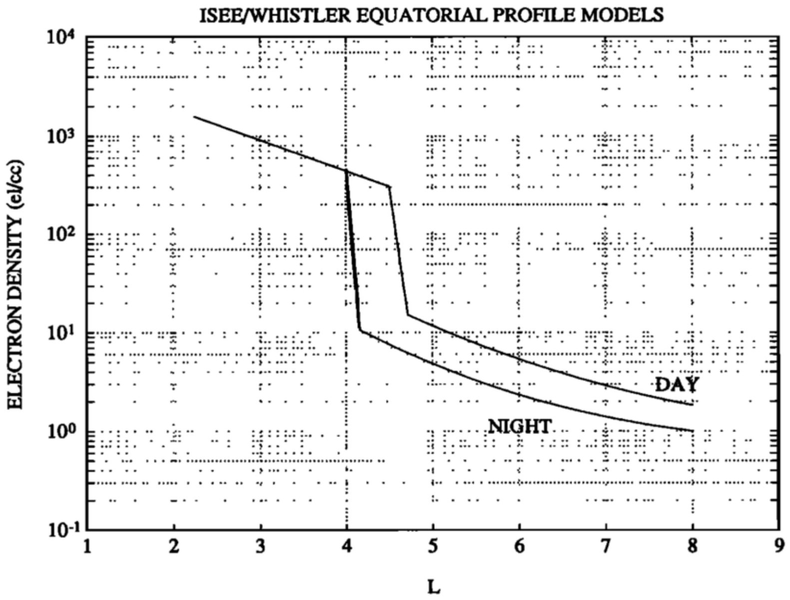


A.K. Singh, R.P. Singh, Devendraa Siingh,
State studies of Earth's plasmasphere: A review
Planetary and Space Science,
Volume 59, Issue 9,
2011,
Pages 810-834,
ISSN 0032-0633,
https://doi.org/10.1016/j.pss.2011.03.013.

Models of the plasmasphere

• (a) Carpenter and Anderson, 1992

- Developed an empirical model of equatorial electron density in the magnetosphere, covering the range $2.25 < L < 8$ using satellite and whistler data.
- The model describes 3 sections, i.e., the “saturated” plasmasphere, the region of steep plasmapause gradients, and the plasma trough.



The width of the plasmapause, Lppi to Lppo, is defined by the scale width in density across it. It is typically 0.1 – 0.2L.

Carpenter, D. L., and R. R. Anderson, An ISEE/whistler model of equatorial electron density in the magnetosphere, *J. Geophys. Res.*, **97**, 1097– 1108, 1992.

1. Plasmapause inner limit L_{ppi}, from (6):

$$L_{ppi} = 5.6 - 0.46\mathrm{Kp}_{max}$$

where Kp_{max} is the maximum Kp value in the preceding 24 hours.

Equatorial electron density: $n_e = n_e(L_{ppi}) \times 10^{-\frac{(L-L_{ppi})}{\Delta pp}}$

2. The saturated plasmasphere segment, from (1), (2), (3), and (4); $2.25 \le L \le L_{ppi}$:

$$\log n_e = (-0.3145L + 3.9043) + [0.15(\cos\frac{2\pi(d+9)}{365} - 0.5\cos\frac{4\pi(d+9)}{365}) + 0.00127\overline{R} - 0.0635]e^{-\frac{(L-2)}{1.5}}$$

3. The plasmapause segment, from (7); $L_{ppi} \le L \le L_{ppo}$:

$$n_e = n_e(L_{ppi}) \times 10^{-\frac{(L-L_{ppi})}{0.1}}, \qquad 00 \le t < 06 \text{ MLT}$$

$$n_e = n_e(L_{ppi}) \times 10^{-\frac{(L-L_{ppi})}{(0.1+0.011(t-6))}}, \qquad 06 \le t \le 15 \text{ MLT}$$

4. The extended plasma trough, from (5); $2.25 \le L \le 8$:

$$n_e = (5800 + 300t)L^{-4.5} + (1 - e^{-\frac{(L-2)}{10}}), \qquad 00 \le t < 06 \text{ MLT}$$

$$n_e = (-800 + 1400t)L^{-4.5} + (1 - e^{-\frac{(L-2)}{10}}), \qquad 06 \le t \le 15 \text{ MLT}$$

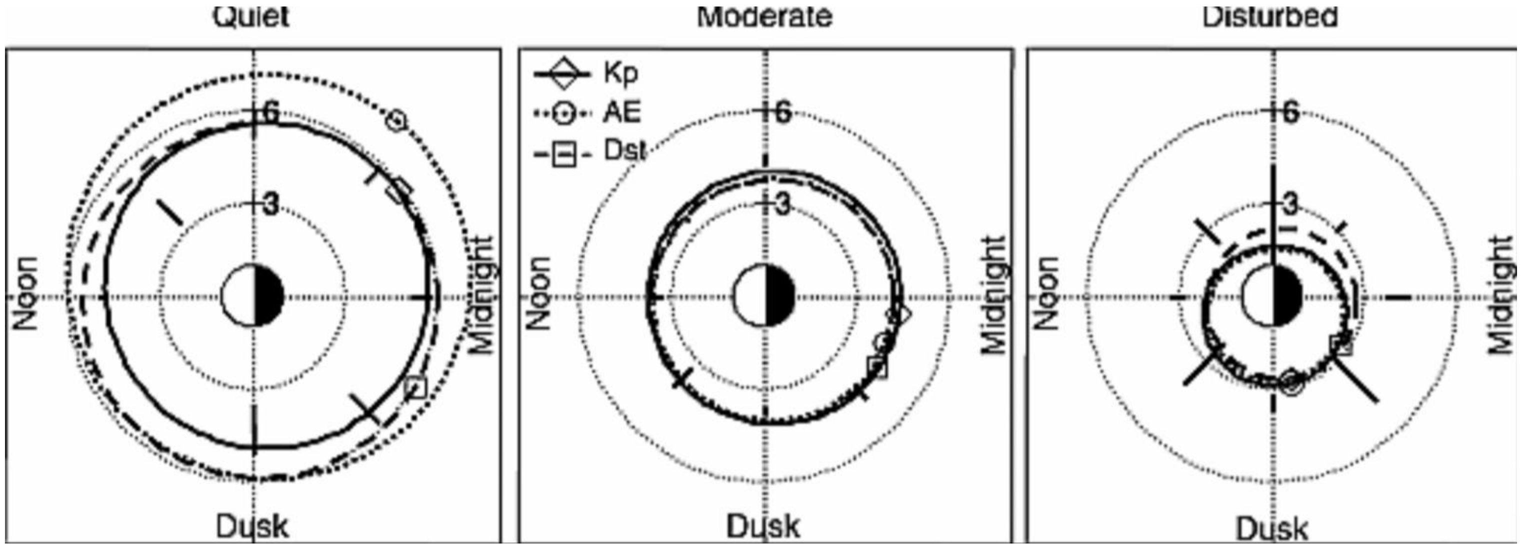
5. The plasmapause outer limit L_{ppo}, determined by solving simultaneously for the plasmapause segment and the extended plasma trough.

6. The plasma trough segment, from (6); $L_{ppo} \le L \le 8$:

$$n_e = n_e(L_{ppo}) \times (\frac{L}{L_{ppo}})^{-4.5} + (1 - e^{-\frac{(L-2)}{10}})$$

Models of the plasmasphere

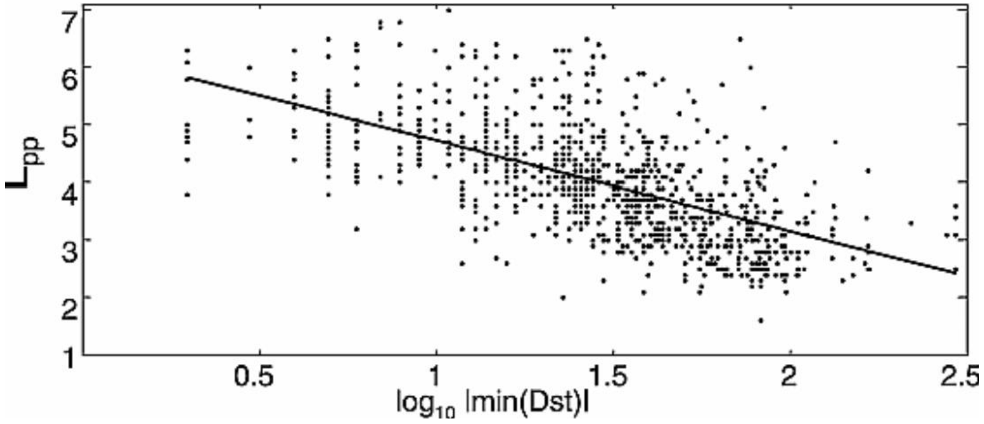
- (b) O'Brien and Moldwin, 2003
  - Used a database of 900 CRRES in situ observations of plasmapause crossings to build **empirical models of the plasmapause location** as a function of geomagnetic indices…. a recent maximum in *AE* or minimum in Dst provided a better model of the plasmapause radius than maximum *Kp*.



Used the form: $L_{pp} = aQ + b,$ where Q is the geomagnetic index term

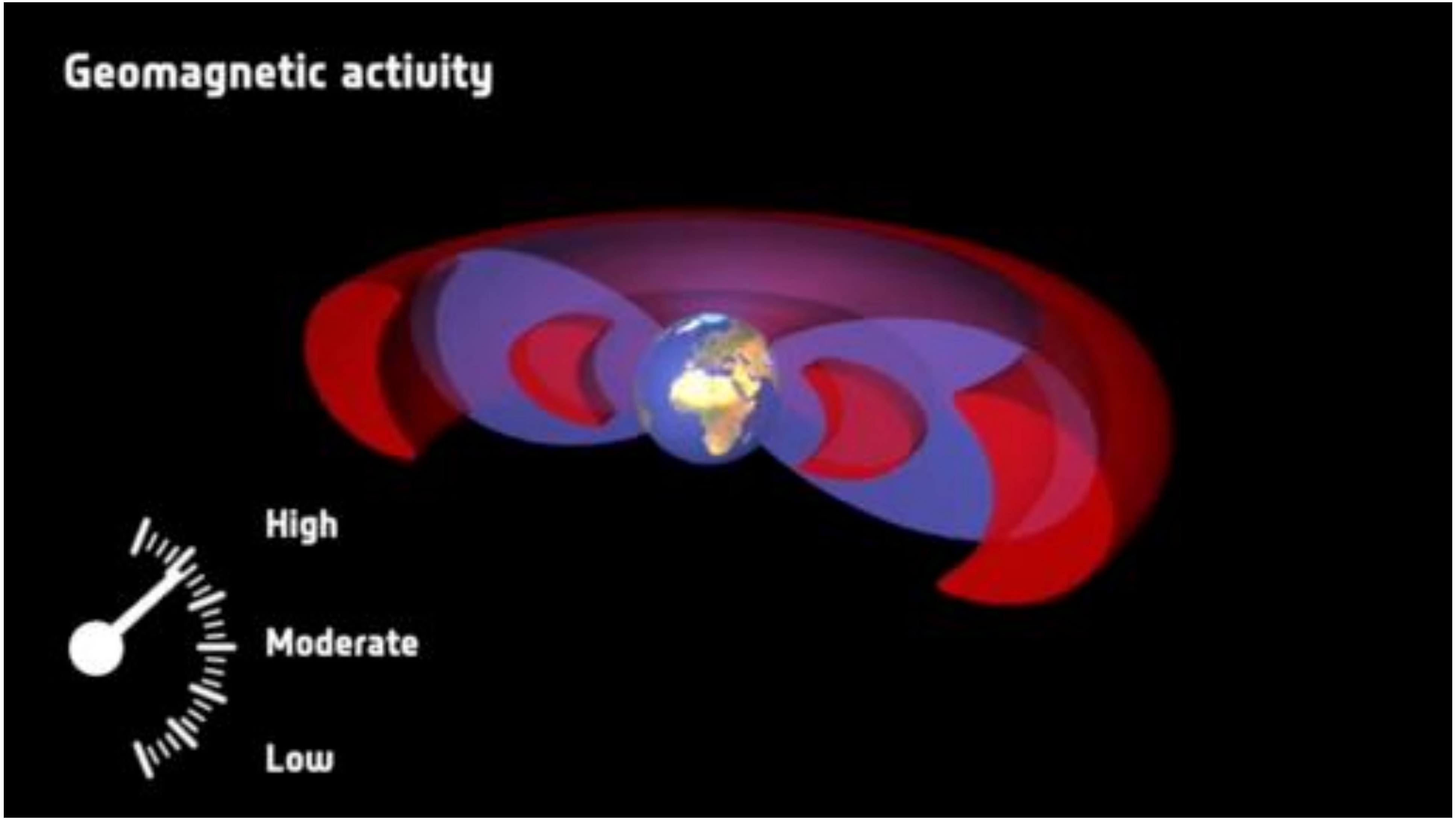
With a bulge described by: $\phi = 2\pi(mlt/24),$

Such that: $$L_{pp} = a_1[1 + a_{mlt}\cos(\phi - a_\phi)]Q + b_1[1 + b_{mlt}\cos(\phi - b_\phi)].$$



O'Brien, T. P., and M. B. Moldwin (2003), Empirical plasmapause models from magnetic indices, *Geophys. Res. Lett.*, **30**(4), 1152, doi:10.1029/2002GL016007 .

Plasmasphere and radiation belts - influenced by magnetospheric activity levels



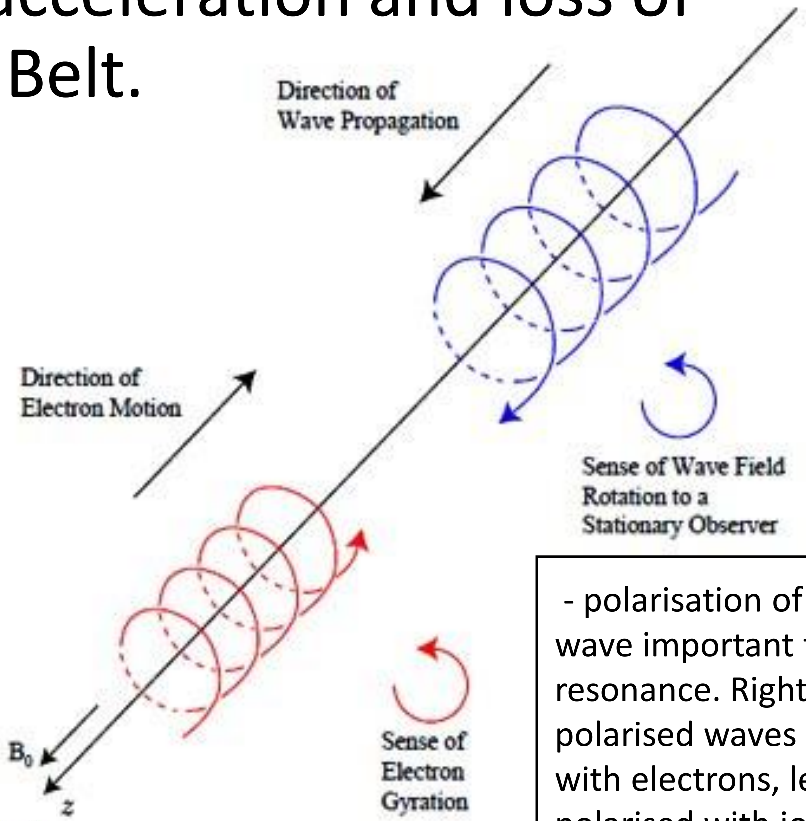
Plasmapause is the outer edge of the plasmasphere (blue).
Radiation belts showing in red.

Credits ESA - C. Carreau

What effect does the plasmasphere have on Radiation Belt processes?

- As we have heard this week, cyclotron resonance wave-particle interactions are a significant player in the acceleration and loss of energetic electrons in the Outer Radiation Belt.

Chorus waves can interact strongly with electrons over a wide energy range from ~100 eV up to several MeV via Doppler shifted cyclotron resonance [*Horne and Thorne*, 2003]. These cyclotron resonant interactions result in pitch angle diffusion of electrons into the loss cone (electron precipitation)… particularly in regions of low plasma density [*Horne et al.*, 2003].

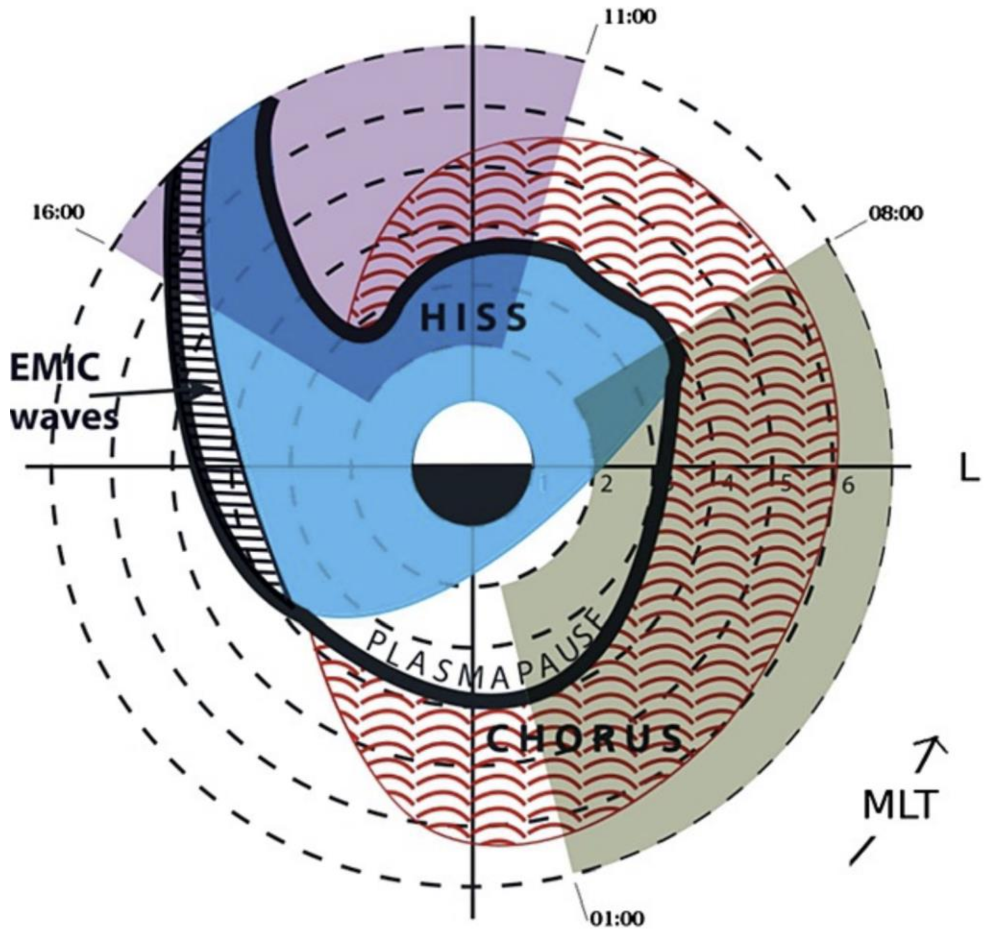


- polarisation of the wave important for resonance. Right hand polarised waves resonate with electrons, left hand polarised with ions.

Citation: Horne, R. B., T. Kersten, S. A. Glauert, N. P. Meredith, D. Boscher, A. Sicard-Piet, R. M. Thorne, and W. Li (2013), A new diffusion matrix for whistler mode chorus waves, *J. Geophys. Res. Space Physics*, *118*, 6302–6318, doi:10.1002/jgra.50594.

What effect does the plasmasphere have on Radiation Belt processes?

- There are several contender waves that could provide wave-particle interactions resulting in electron precipitation:
- VLF Chorus probably dominates the largest region. It is usually found outside the plasmapause.
- Plasmaspheric Hiss dominates inside the plasmapause, and into plasmaspheric plumes.

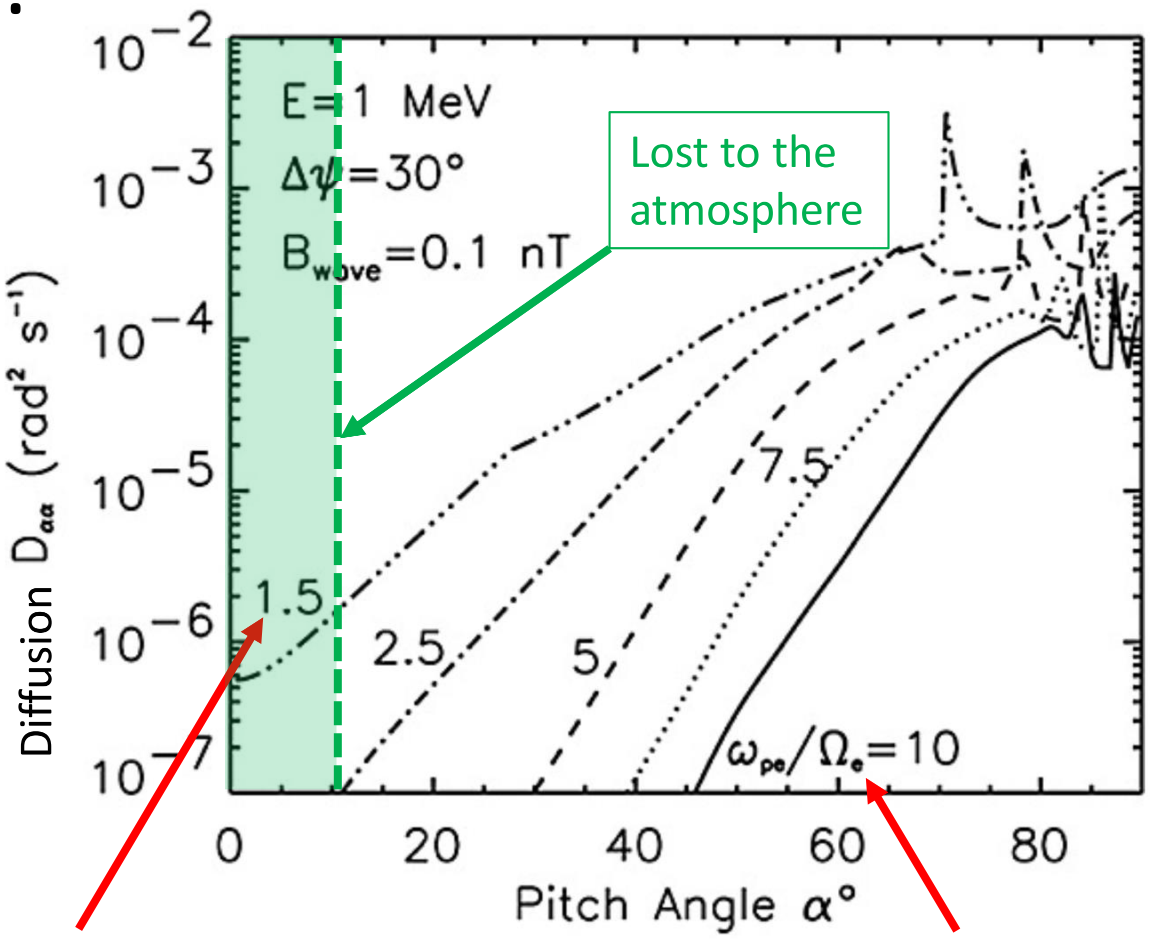


What effect does the plasmasphere have on Radiation Belt processes?

- Resonant diffusion by whistler-mode waves is most efficient when the ratio of the electron plasma frequency to the electron gyrofrequency is relatively low $\omega_{pe}/\Omega_e \sim 1$ [*Summers et al.*, 1998].

- This condition corresponds to regions just outside the plasmapause. During magnetic storms the plasmapause is compressed inside L = 4 reducing ω_{pe}/Ω_e in the region L = 4–5.

[More diffusion = more electron flux]



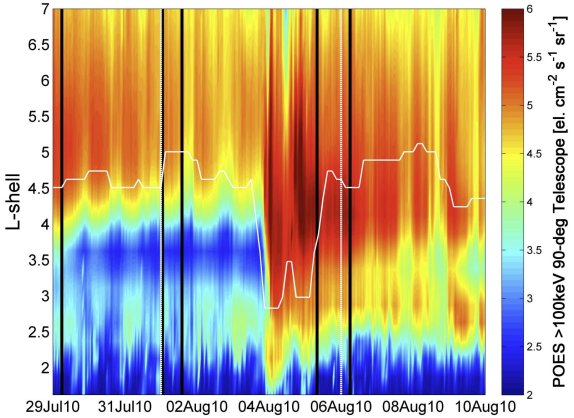
Horne, R. B., S. A. Glauert, and R. M. Thorne (2003), Resonant diffusion of radiation belt electrons by whistler-mode chorus, *Geophys. Res. Lett.*, *30*(9), 1493, doi:10.1029/2003GL016963.

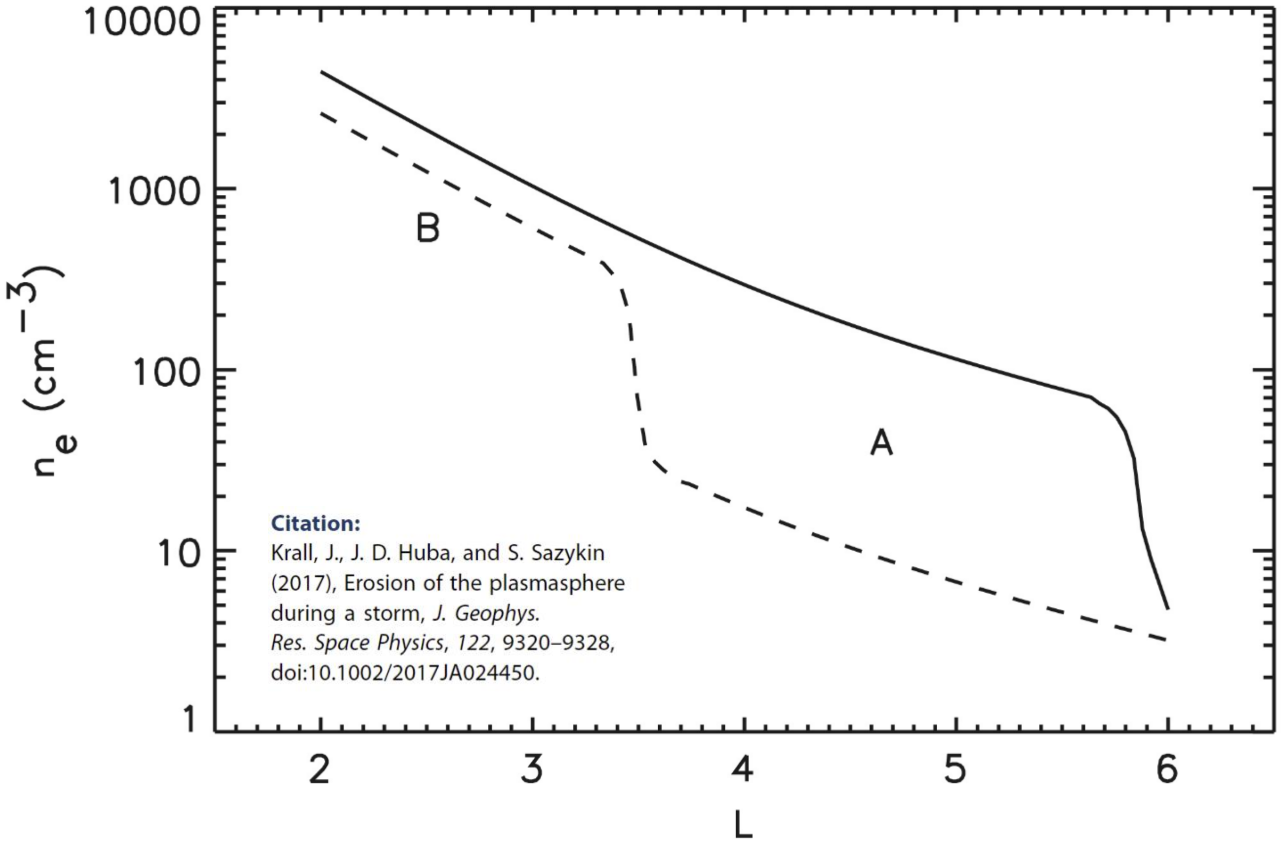
What effect does the plasmasphere have on Radiation Belt processes?

- Thus electron precipitation caused by wave-particle resonance interactions is more likely to occur from regions where plasmaspheric densities are low.

So when we are looking for **electron precipitation** from the Outer Radiation Belt we will need to take the **location of the plasmapause** into account.

[which is where we came in..]





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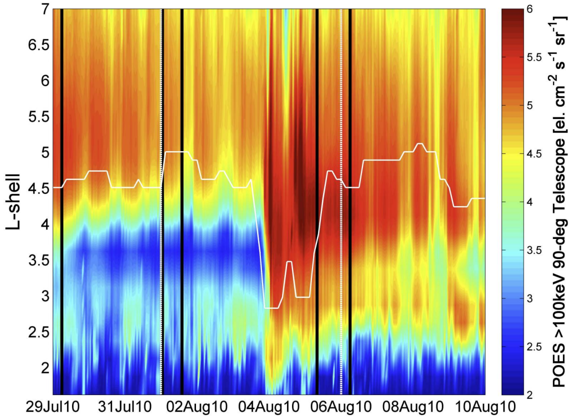
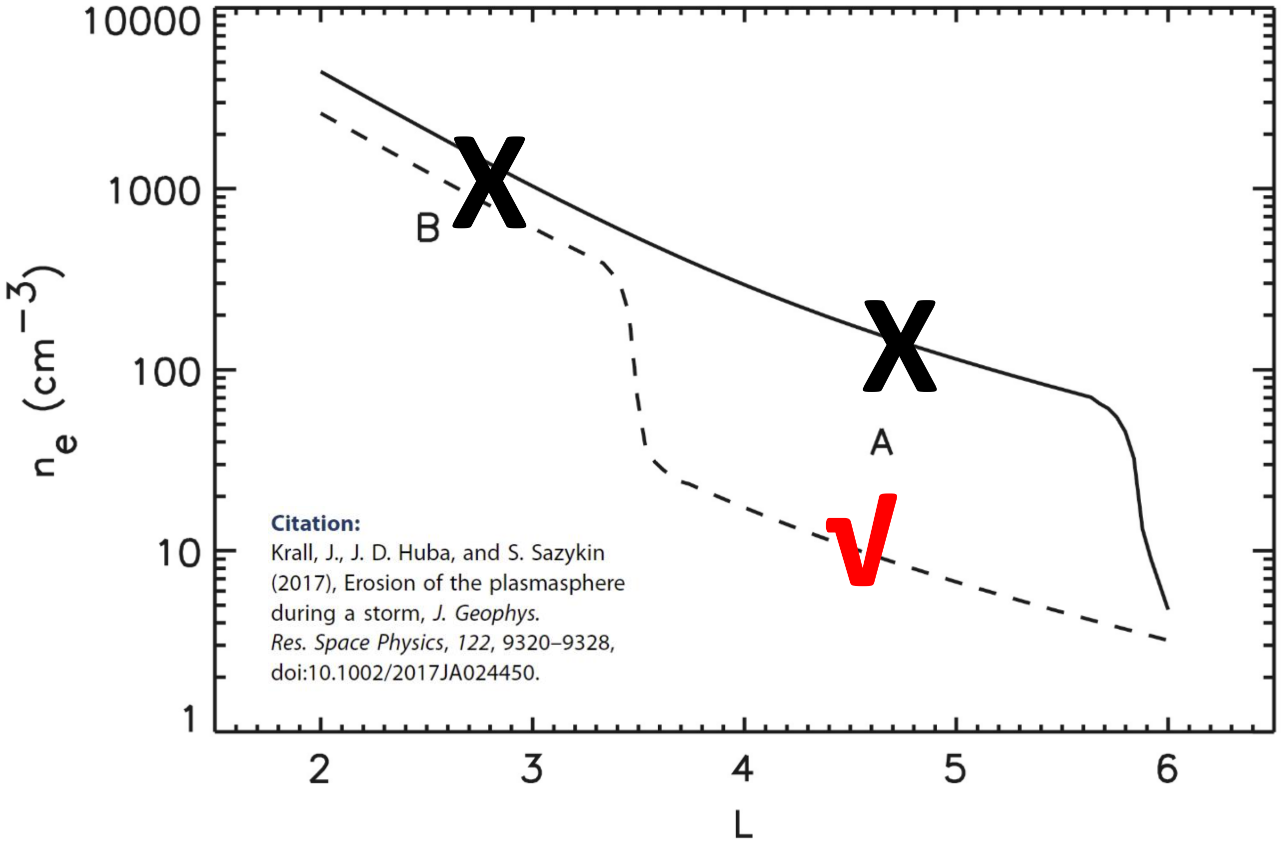




Citation:
Krall, J., J. D. Huba, and S. Sazykin (2017), Erosion of the plasmasphere during a storm, *J. Geophys. Res. Space Physics, 122*, 9320–9328, doi:10.1002/2017JA024450.

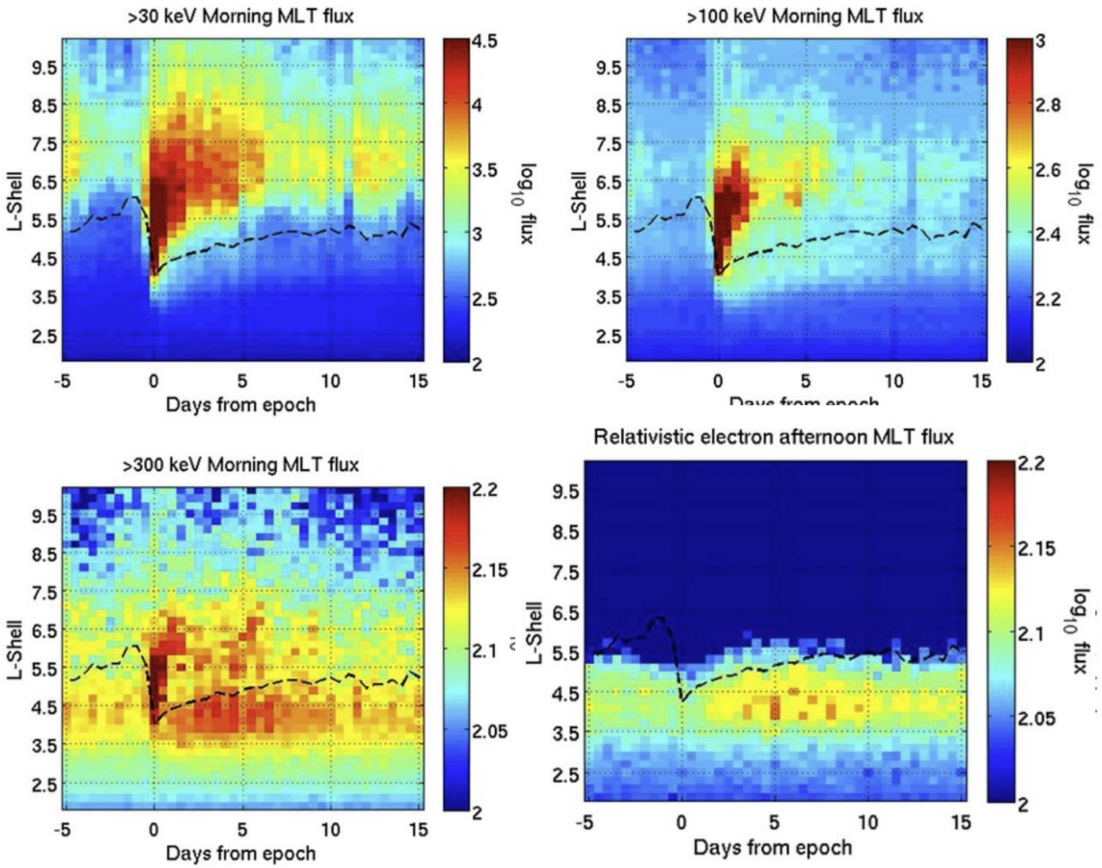
Electron precipitation occurrence

- Whittaker et al. [2014] used NOAA POES energetic electron precipitation measurements to investigate the role of the plasmapause on precipitation behaviour:

Superposing 103 storm start times showed how the majority of the low energy electron precipitation happened outside of the plasmapause.

At higher energies (>300 keV and >800 keV) the precipitation happened inside of the plasmapause, but with much lower flux.

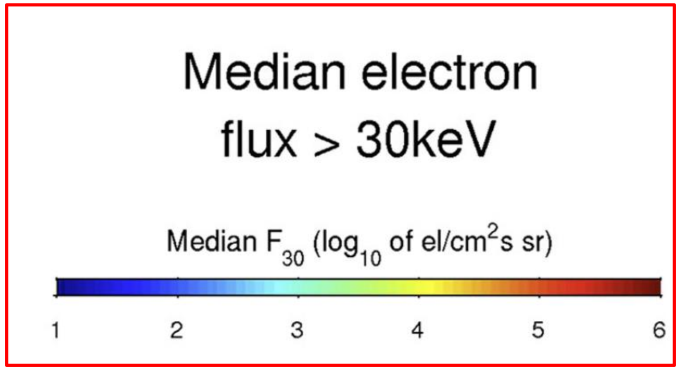
Here the plasmaspause location is identified by the O'Brien and Moldwin model (2003) driven by a 12-hour averaged Dst index.

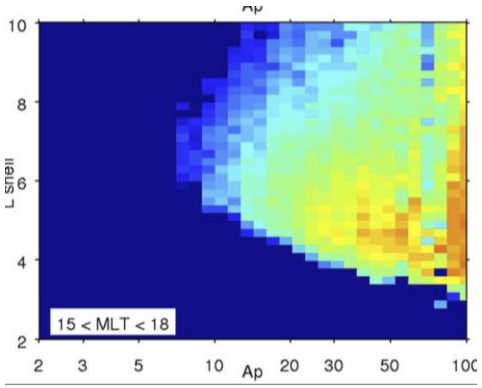


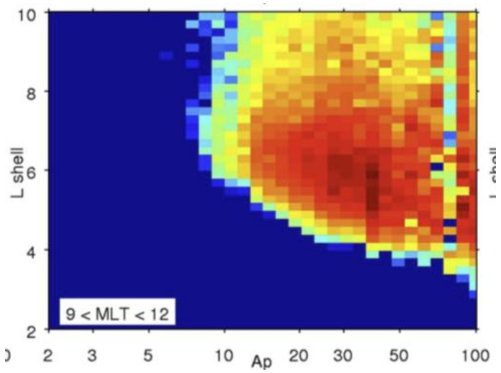
· Whittaker, I C, M A Clilverd, and C J Rodger, Characteristics of precipitating energetic electron fluxes relative to the plasmapause, J. Geophys. Res., 119, 8784–8800, doi:10.1002/2014JA020446, 2014.

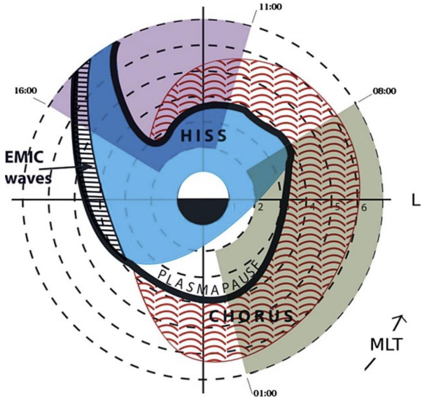
Electron precipitation occurrence

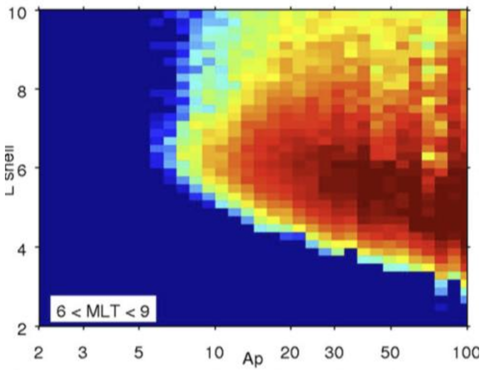
- Using POES >30 kev electron precipitation observations (0-deg detector) and binning by L-shell, MLT, and geomagnetic activity, Ap.



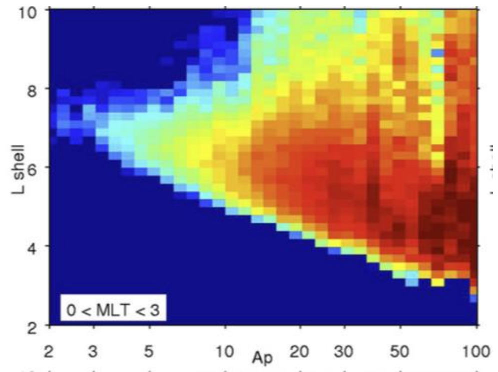








- Large fluxes in the morning sector, lower in the afternoon – chorus.
- Higher L-shell at lower Ap levels.
- Larger fluxes for higher Ap levels.



Citation:
van de Kamp, M., Rodger, C. J., Seppälä A., Clilverd, M. A., & Verronen, P. T. (2018). An updated model providing long-term data sets of energetic electron precipitation, including zonal dependence. *Journal of Geophysical Research: Atmospheres*, *123*, 9891–9915. https://doi.org/10.1029/2017JD028253

Electron precipitation modelling

- Precipitation outside of the plasmapause is well ordered relative to the plasmapause, with maximum fluxes at Lpp + 1-2 Re.

The location of peak fluxes is indicative of chorus-induced precipitation.

$$\mathrm{Flux}_{\mathrm{chorus}} = a(|Dst|).e^{-\left(\frac{S_{pp}-c(|Dst|)}{w(|Dst|)}\right)^2}$$

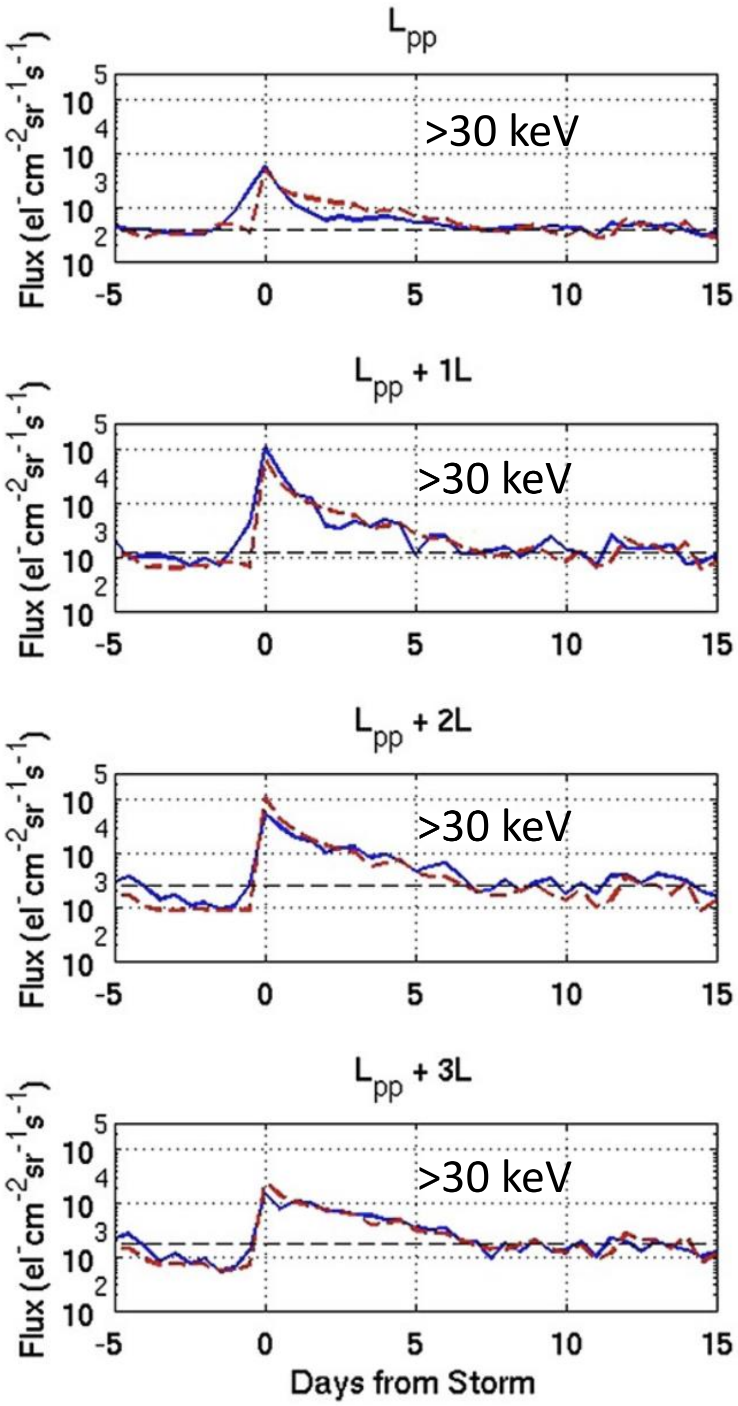
Where:

$$a(|Dst|) = 4.53|Dst|^{2.475}$$

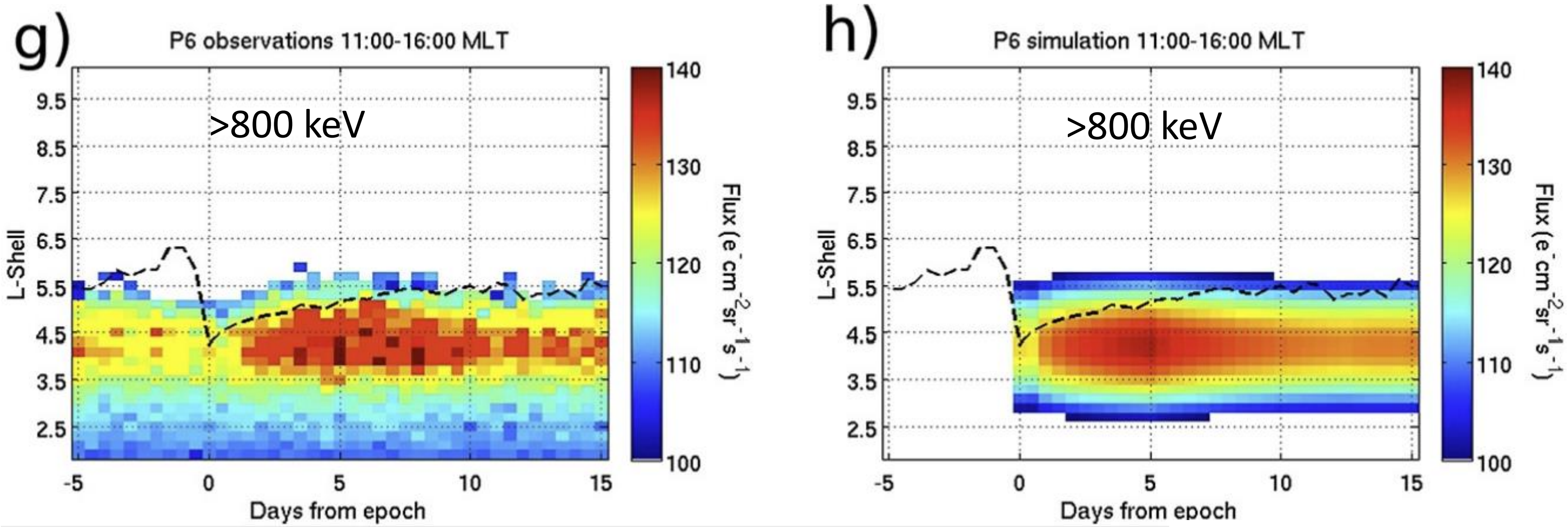
$$c(|Dst|) = 3.11|Dst|^{-0.14}$$

$$w(|Dst|) = 1.59.e^{-0.061|Dst|} + 0.95$$

$$S_{pp} = \text{distance from the plasmapause (in } L\text{)}$$



Electron precipitation modelling – inside Lpp



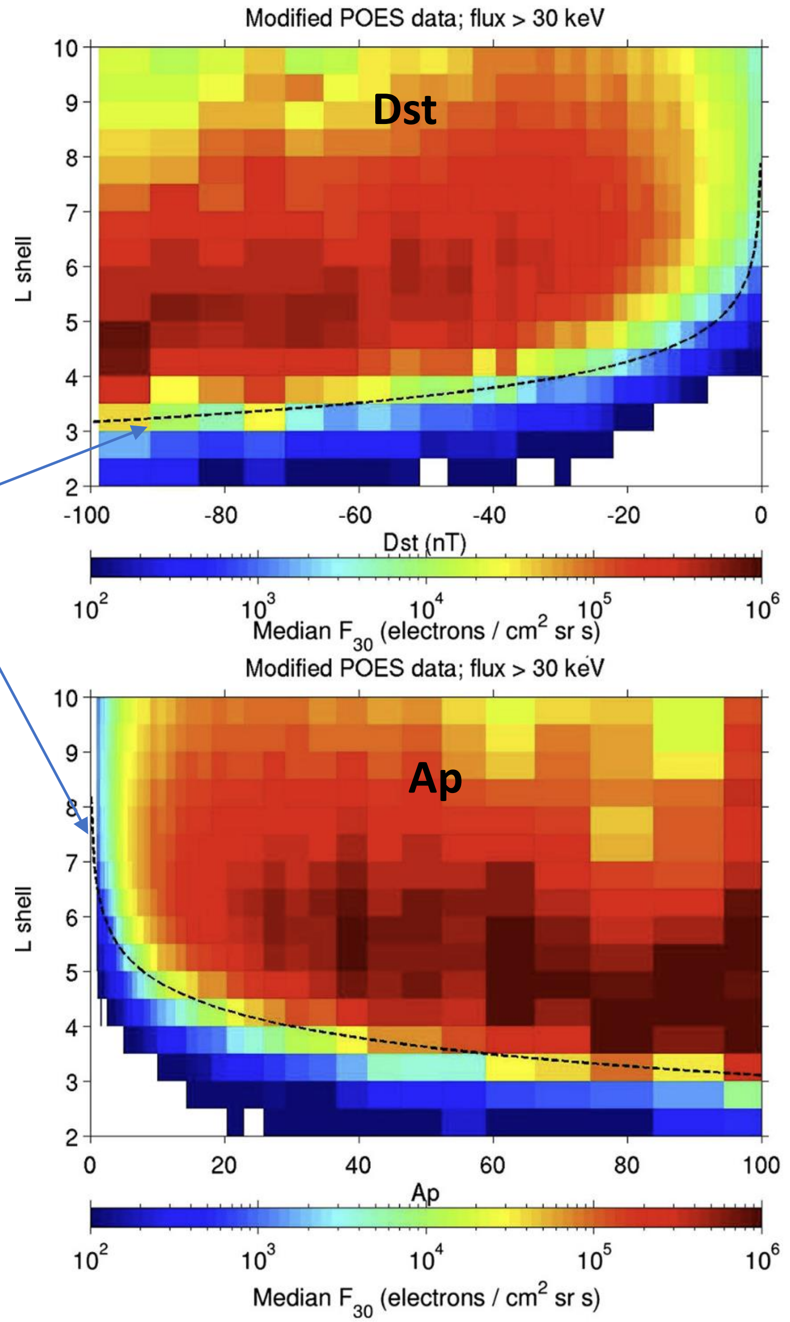
- Higher energy precipitation inside the plasmapause –indicative of plasmaspheric hiss
- 4-day average of Dst means less sensitivity to Lpp variations.
- Low flux levels!

$$\text{Flux}_{\text{hiss}>800} = a(L)|\overline{Dst}_{-120:-24}|^{0.055}$$

Where *a (L)* $= 114e^{-\left(\frac{L-4.2}{2.8}\right)^2}$

Geomagnetic activity influence:

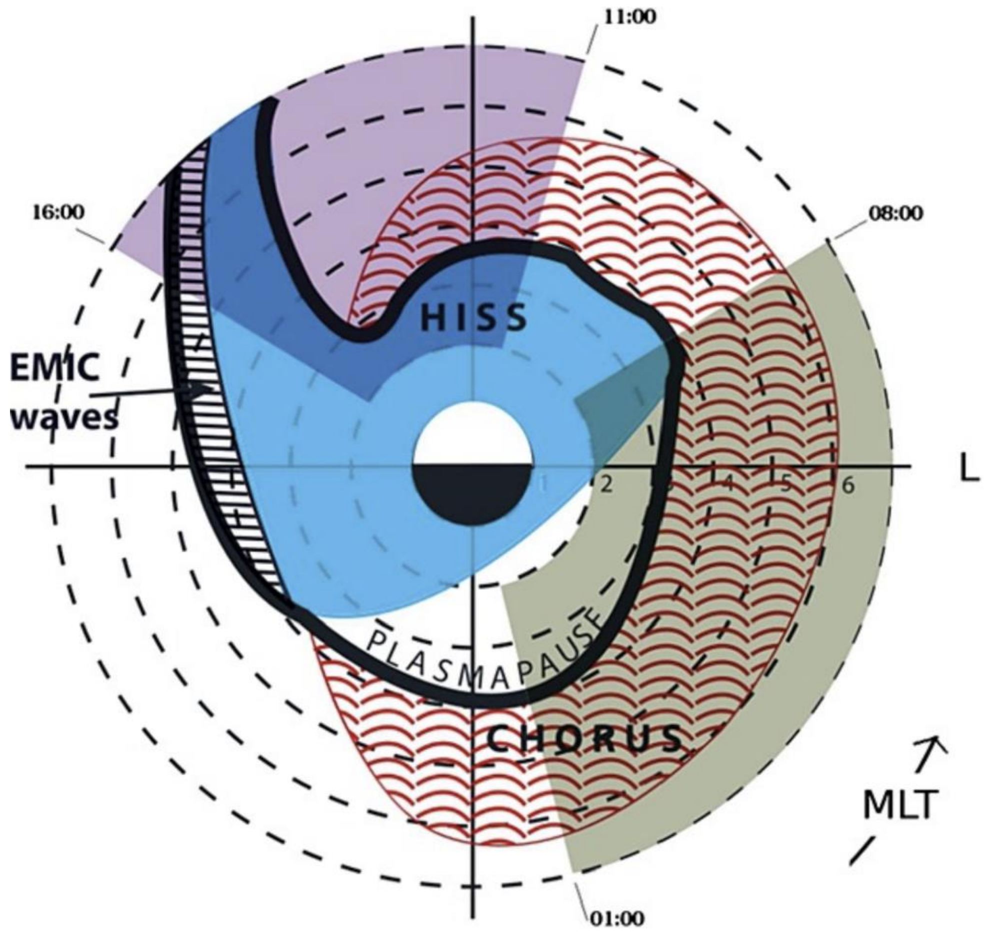
- Overall the majority of medium energy electron precipitation occurs **outside the plasmapause**.
- Precipitation **peak moves to lower L-shell** with increasing geomagnetic activity.
- Precipitation **fluxes increase** with increasing geomagnetic activity.
- The details in the precipitation behaviour differ slightly depending on geomagnetic **activity index used**.



- van de Kamp, M, A Seppälä, M A Clilverd, C J Rodger, P T Verronen, and I Whittaker, A model providing long-term datasets of energetic electron precipitation during geomagnetic storms, J. Geophys. Res., 121, 12,520-12,540, doi:10.1002/2015JD024212, 2016.

And near the plasmapause....

- We have discussed electron precipitation caused by Chorus and Hiss regions, i.e., large regions with large-scale zones of precipitation.
- The **plasmapause** is a smaller feature in terms of regional coverage, but it bounds many of the wave regions, and should therefore be important – you would have thought.



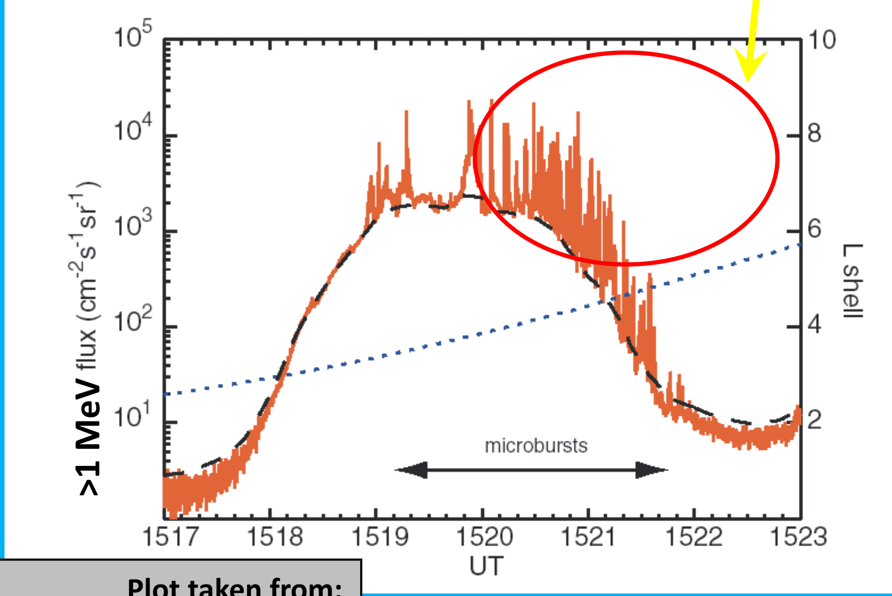
Lets look at Relativistic Electron Microbursts

- **>1 MeV** microbursts lasting <<1 s
- Each burst less than "several tens of gyro-radii" ($r_B \approx$ 0.2km) in L
- Thought to be associated with VLF chorus waves
  [*Blake et al.*, 1996; *Lorentzen et al.*, 2001]

Estimates of SAMPEX satellite observed fluxes suggest that microburst precipitation could essentially "flush out" the entire relativistic electron population during the main phase of the storm.

Individually small, but collectively important!

These pulses here!



Plot taken from:
Lorentzen et al. (2001), *Geophys. Res. Lett*, 28(13), 2573-2576.

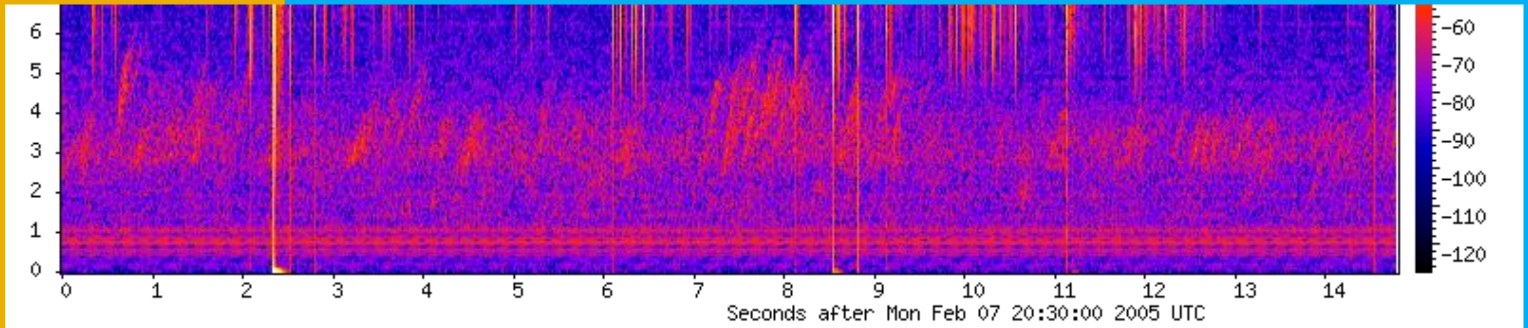
REP Microbursts & Chorus

REP microbursts are correlated with satellite observed VLF chorus wave activity:

* short duration of microbursts is similar to chorus elements
* similarity in MLT distributions

This has lead to the widely held assumption that REP microbursts are produced by wave-particle interactions with chorus waves.

However, this has yet to be confirmed, and a one-to-one correlation of REP microbursts and chorus elements has yet to be demonstrated.



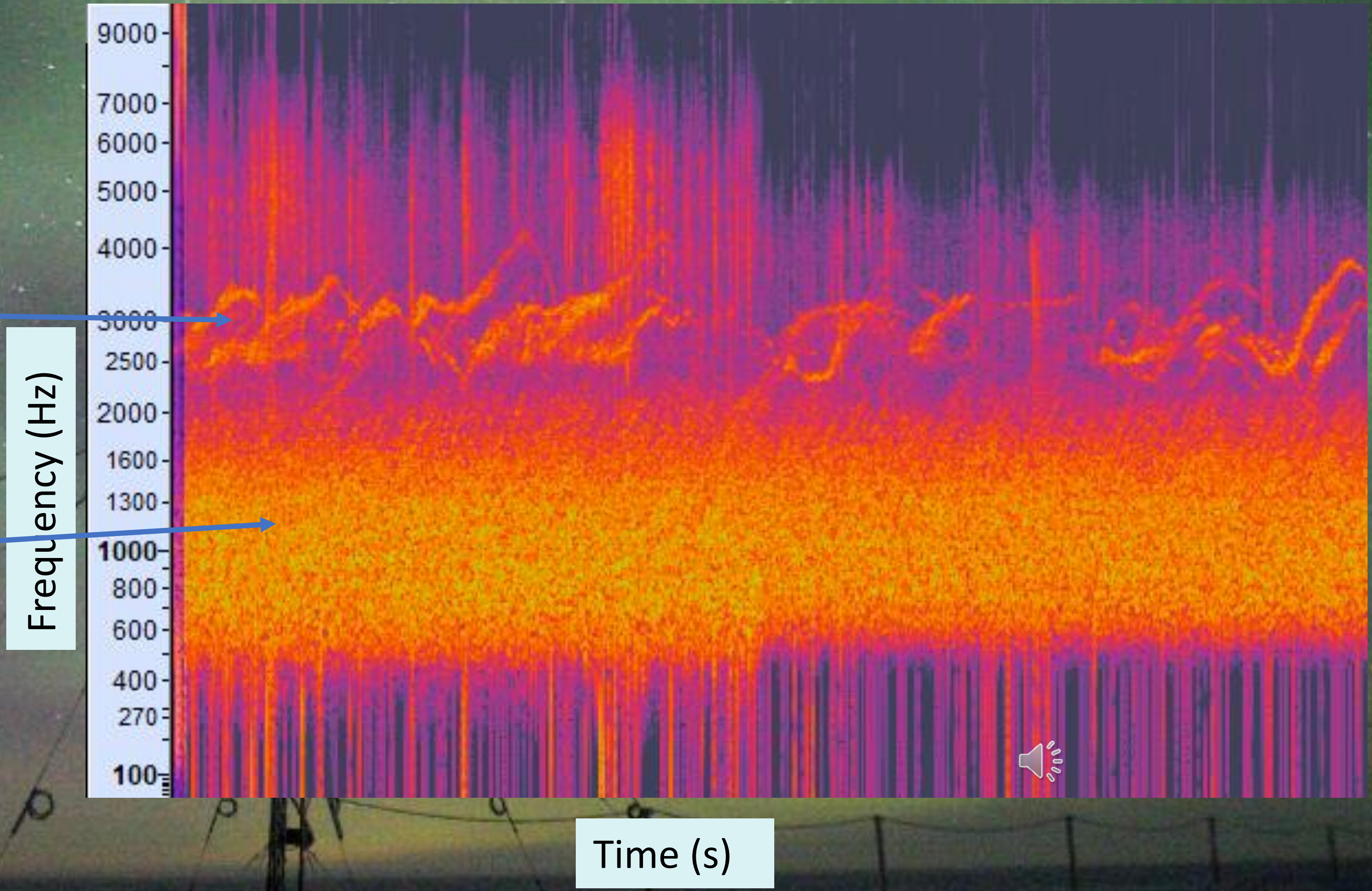
Chorus observed in Dunedin on 7 Feb 2005

Chorus observed at Halley, Antarctica

- **Two very important waves:**

- **VLF Chorus**
(non-linear plasma processes)

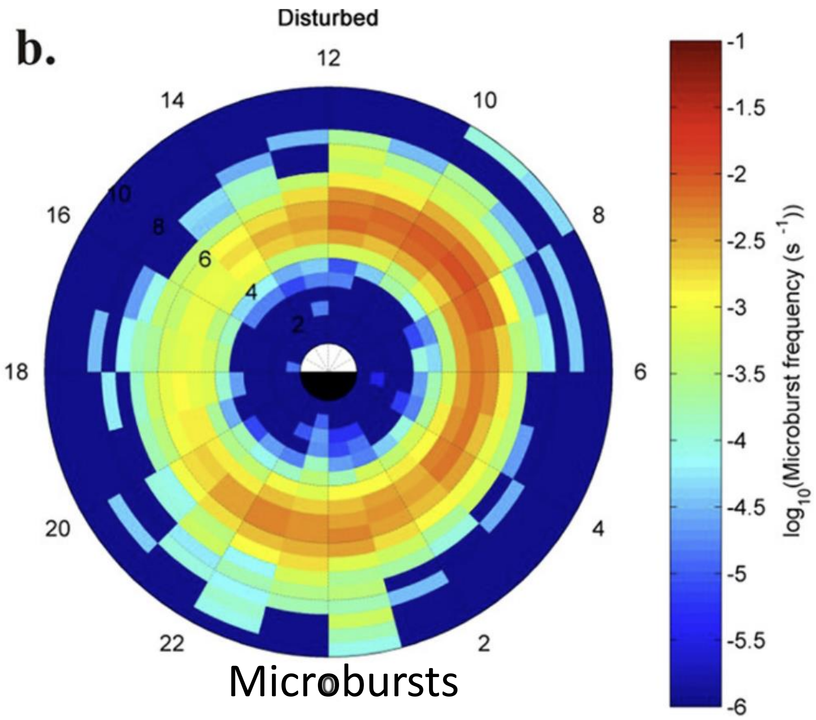
- **VLF Hiss**
(linear plasma processes)



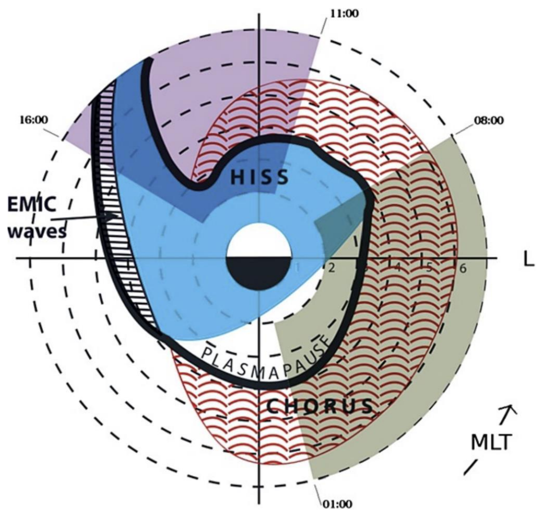
Where do microbursts occur?

These plots show that it is possible to automatically detect microbursts, thus providing a large database of events, and that they occur in the MLT morning side – just like chorus does.

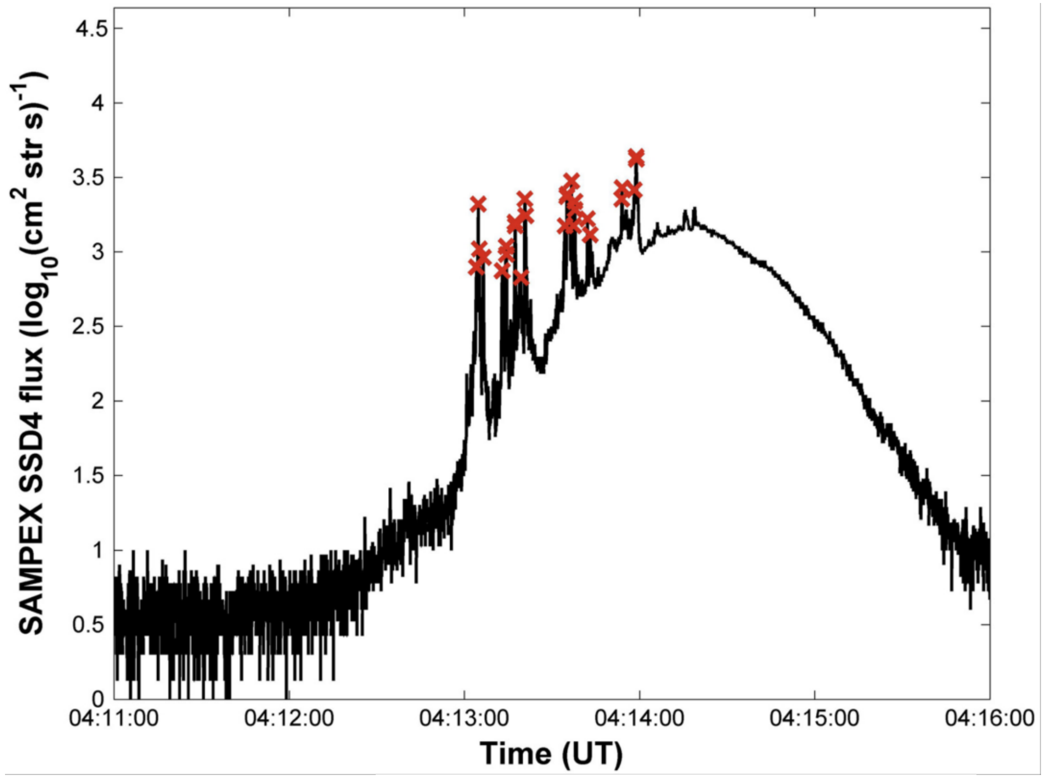
Not a lot going on in the MLT afternoon sector.



Microbursts



Waves



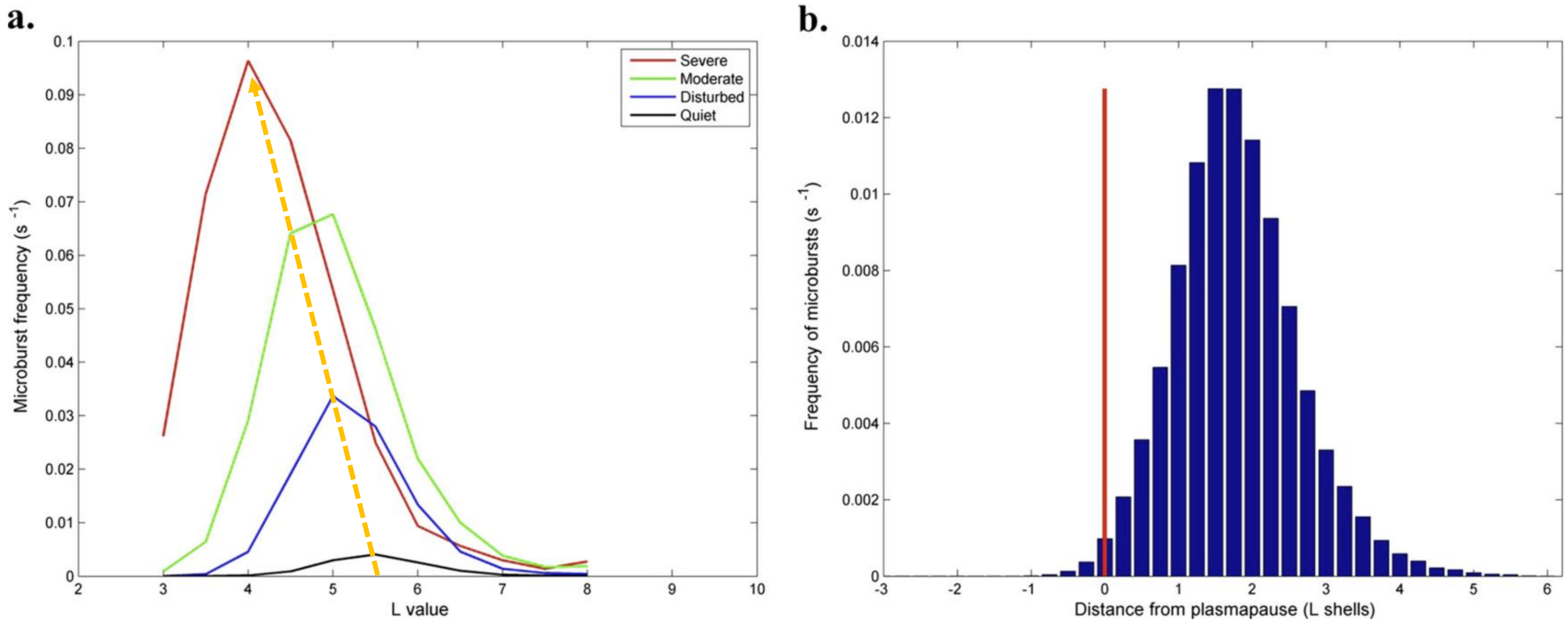
Citation:
Douma, E., C. J. Rodger, L. W. Blum, and M. A. Clilverd (2017), Occurrence characteristics of relativistic electron microbursts from SAMPEX observations, *J. Geophys. Res. Space Physics, 122*, 8096–8107, doi:10.1002/2017JA024067.

Where do microbursts occur?

These plots show that:

(a) the region where microbursts occur moves **inward in L-shell** as geomagnetic activity increases.

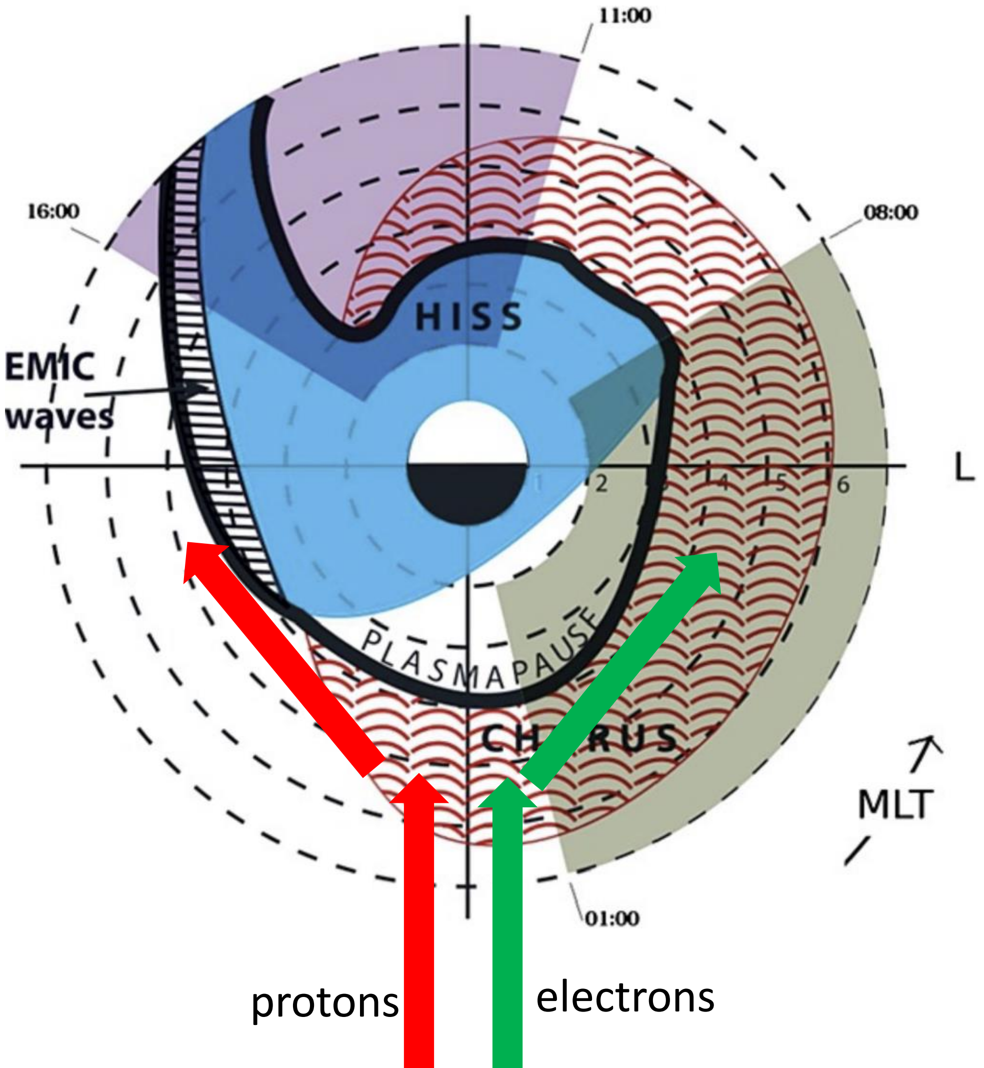
(b) When you sort the microburst locations out relative to the plasmapause you get a consistent picture of occurrence about 2 Re outside of the plasmapause.



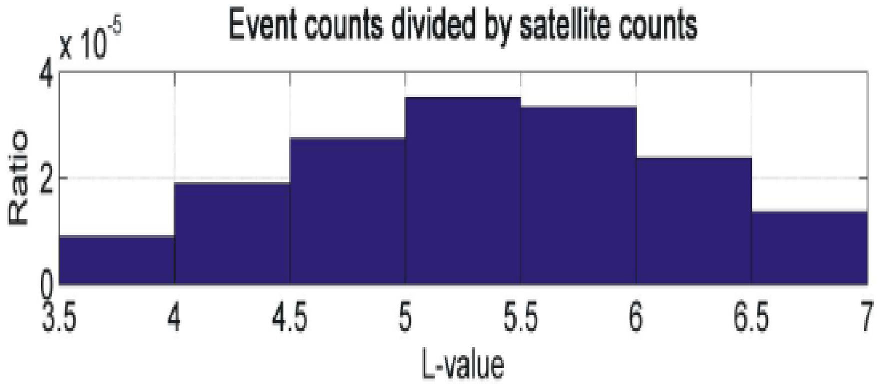
Citation:
Douma, E., C. J. Rodger, L. W. Blum, and M. A. Clilverd (2017), Occurrence characteristics of relativistic electron microbursts from SAMPEX observations, *J. Geophys. Res. Space Physics*, *122*, 8096–8107, doi:10.1002/2017JA024067.

And finally….on the plasmapause….

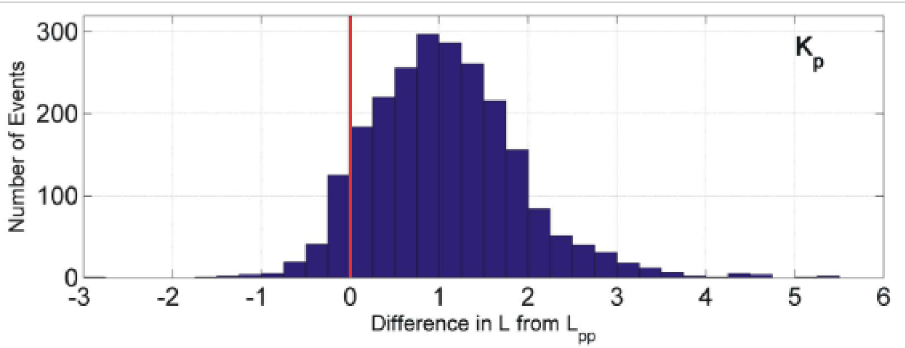
- We have discussed electron precipitation caused by Chorus and Hiss. What about **EMIC waves**?
- Electromagnetic ion-cyclotron waves **(0.1 – 2 Hz)** that cause precipitation on the plasmapause occur in the afternoon-evening MLT sector.
- This is because they are generated from **substorm-injected protons** drifting westwards from MLT midnight.



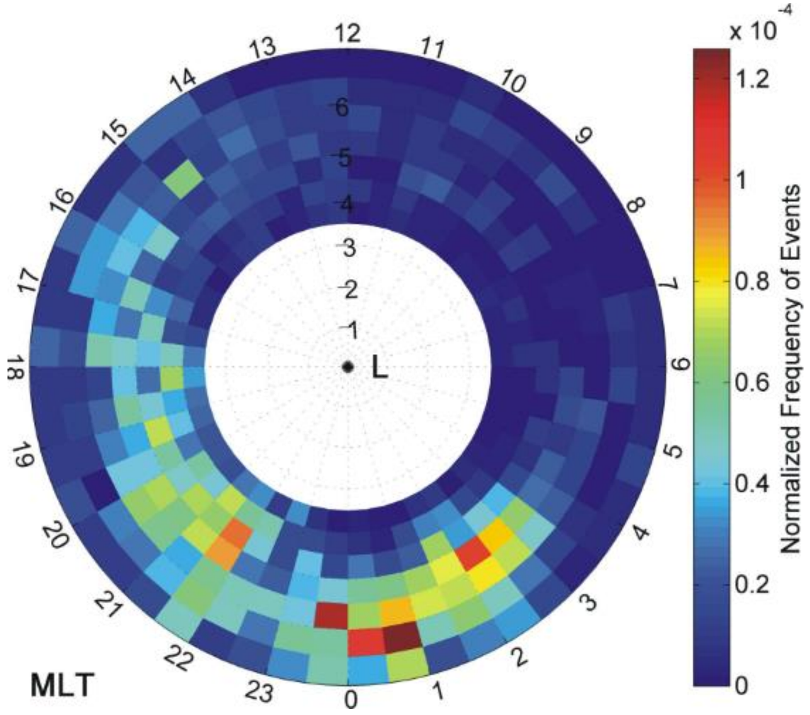
What are the characteristics of EMIC-induced electron precipitation?



Peak occurrence at L-4-6.5

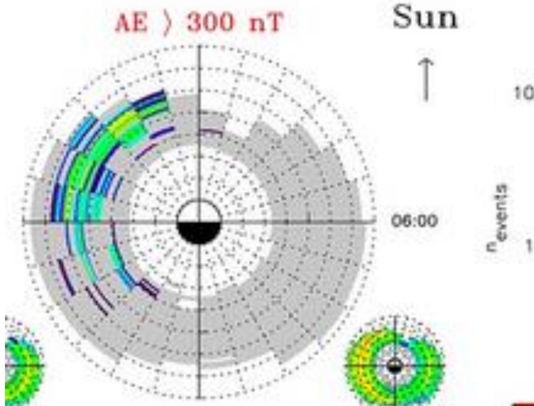


Typically found just outside of the plasmapause



Observed Afternoon – evening – morning sector

Meredith et al., 2014



Helium band

UNIVERSITY of OTAGO

SAPERE AUDE

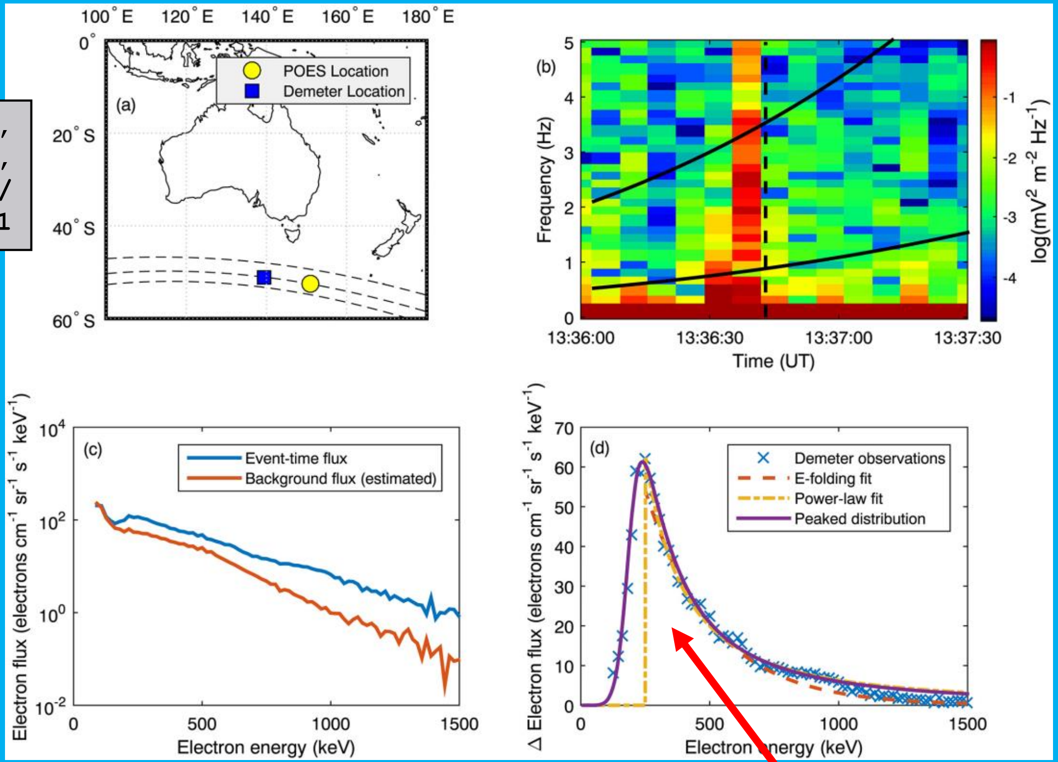
Te Whare Wānanga o Otāgo

NEW ZEALAND

EMIC electron precipitation spectra

Aaron Hendry was able to show that the vast majority of the EMIC-induced precipitation events (found close to the plasmapause) are well fitted by a peaked precipitating flux spectra.

Hendry et al.(2019), *Geophys. Res. Lett.*, 46, 7248– 7257, doi:10.1029/ 2019GL082401



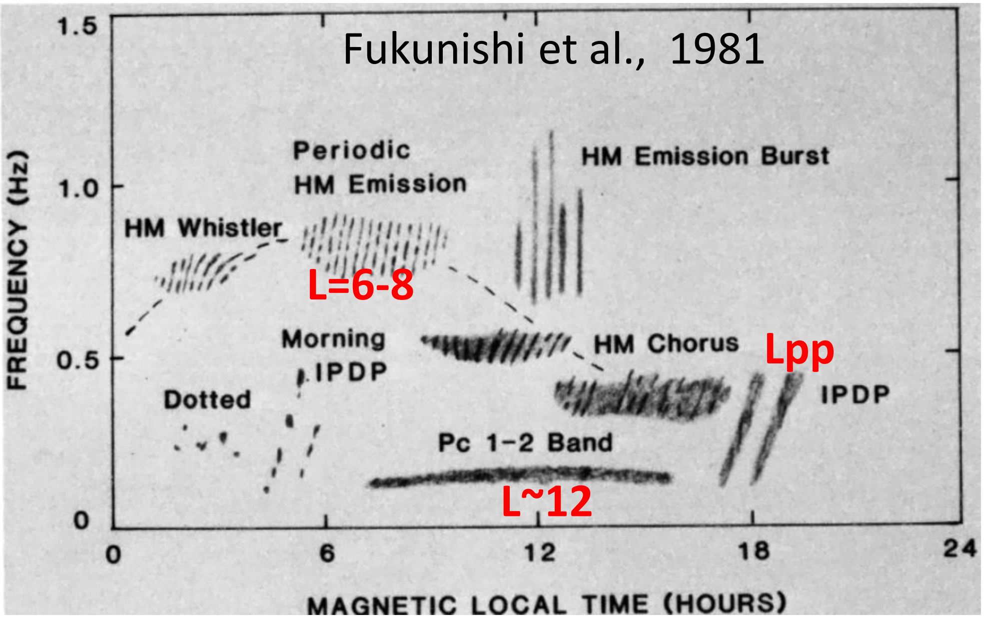
Citation:
Hendry, A. T., C. J. Rodger, and M. A. Clilverd (2017), Evidence of sub-MeV EMIC-driven electron precipitation, *Geophys. Res. Lett.*, *44*, 1210–1218, doi:10.1002/2016GL071807.

The surprise is that the EMIC-peak precipitation fluxes are **a few hundred keV**. Much work has shown that the energies should be MeV (maybe 2-10 MeV electrons)?

EMIC precipitation & waves

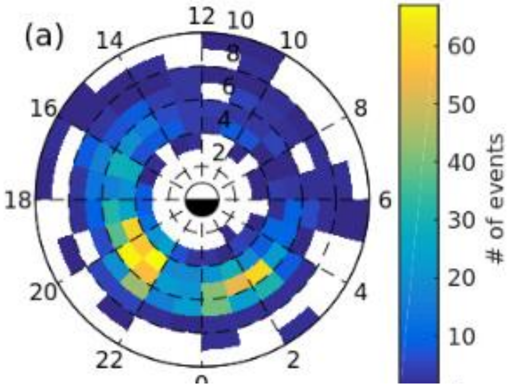
In a study of POES EMIC-precipitation triggers that occurred within ±15°longitude of the Halley station, Antarctica, magnetometer and within ±0.5L (including the magnetic conjugate point) the Halley magnetometer detected EMIC waves for **90% of the POES triggers.**

IPDP-type waves accounted for over 50% of all EMIC waves observed.



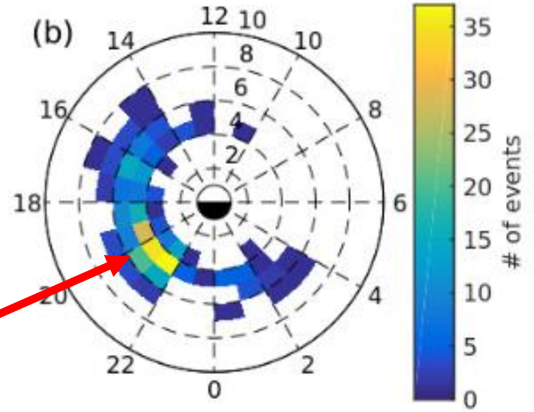
The majority (85%) of the POES precipitation associated EMIC waves observed in the Hendry studies occurred in the helium/oxygen bands.

All wave event times

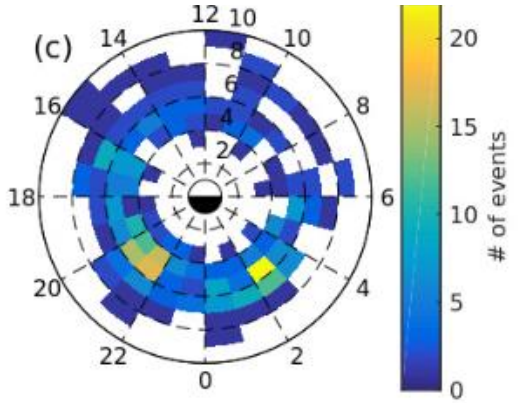


IPDP wave event times

Classic IPDP timing



Non-IPDP wave event times



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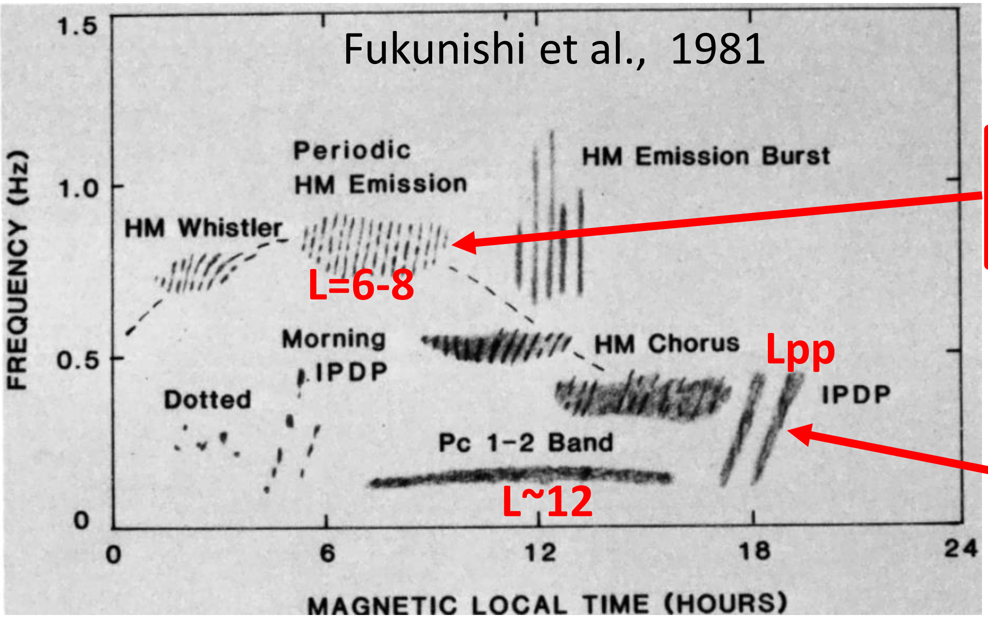
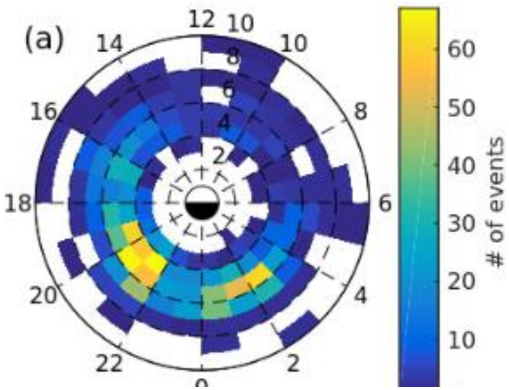


Ions involved in the ring current

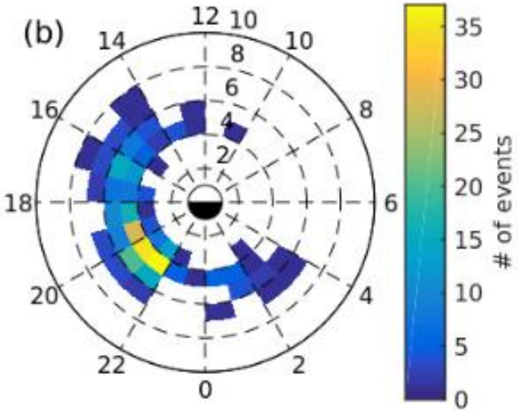
Ions injected by substorms

The majority (85%) of the POES precipitation associated EMIC waves observed in the Hendry studies occurred in the helium/oxygen bands.

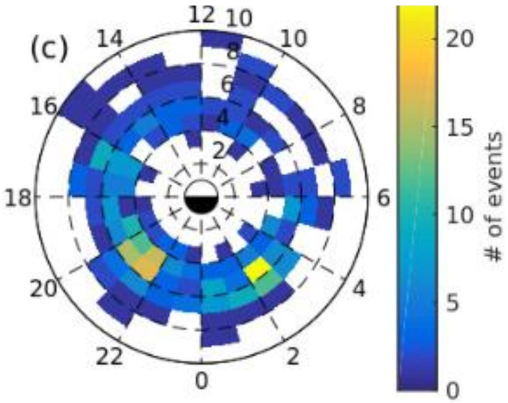
All wave event times



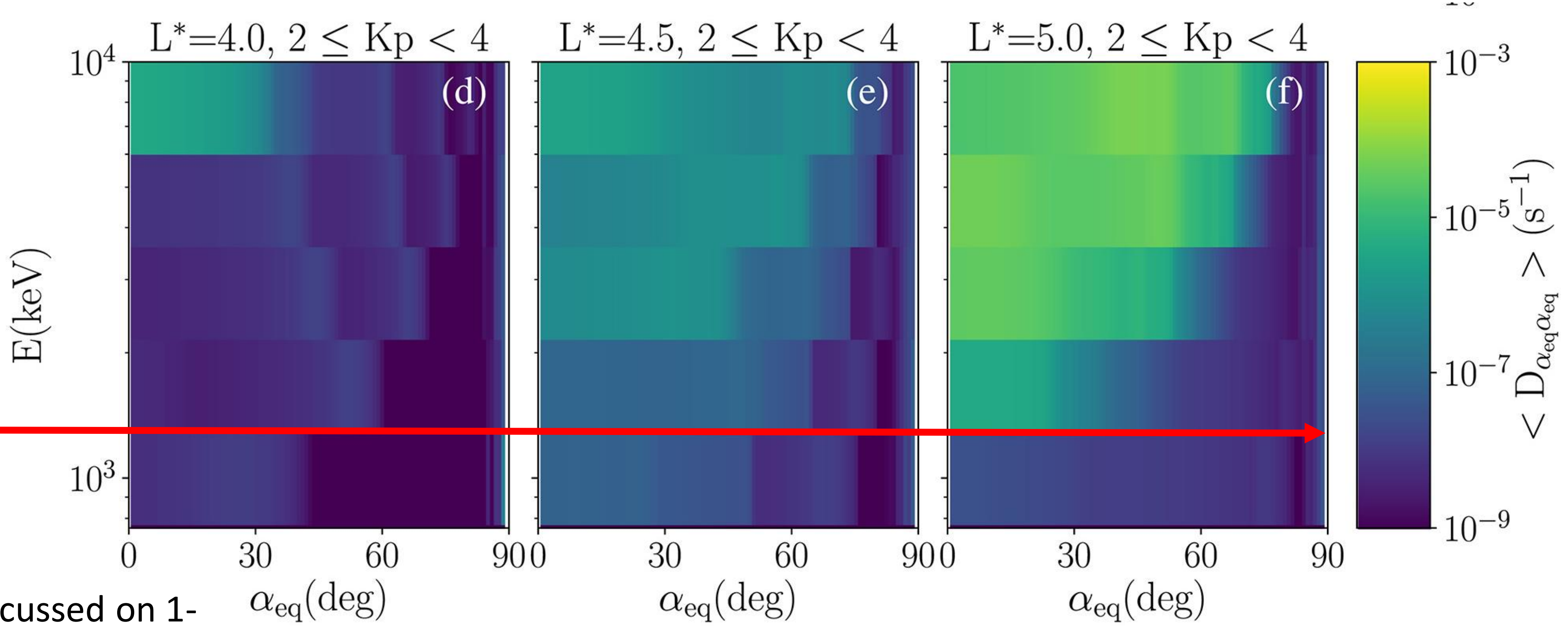
IPDP wave event times



Non-IPDP wave event times



The BAS RBM uses EMIC waves: as a loss mechanism for electrons



Model-based Diffusion tends to run out of puff below 1 MeV

Analysis is therefore focussed on 1-10 MeV electrons in the radiation belts – these are biased to **HM chorus/emission waves L=6-8, i.e., outside of the plasmapause and on the MLT dayside**

Ross et al., (2020). A New Approach to Constructing Models of Electron Diffusion by EMIC Waves in the Radiation Belts, *Geophys. Res. Lett.* 2020 DOI: 10.1029/2020gl088976

Summary

- The plasmasphere plays a significant role in constraining the occurrence and characteristics of electron precipitation.
- Electron precipitation depends on the presence of waves, and we particularly concentrate on wave-particle cyclotron resonance.
- All regions of the plasmasphere exhibit electron precipitation but the fluxes, and energy spectra are different.
- Low density regions, normally found outside of the plasmapause, contribute the most significant medium energy (10’s - 100’s keV) electron precipitation fluxes (through interactions with whistler-mode chorus).

Or…

- In a quiet backwater of the magnetosphere, not so far, far away there lies the plasmasphere.

- Some say it is cold, some say it is dull, some say ‘who cares?’.

- It turns out it is quite important as far as the Radiation Belts are concerned….

- ..particularly where it isn’t.

Thanks for listening.

Looking for the Elephant in the room……..

..turns out it wasn't even an Elephant