Electron precipitation from the radiation belts into the atmosphere

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Radiation Belt Dynamics & Earth's Plasmasphere

L'Aquila - Italy

09:00-10:30, Thursday 29 September 2022

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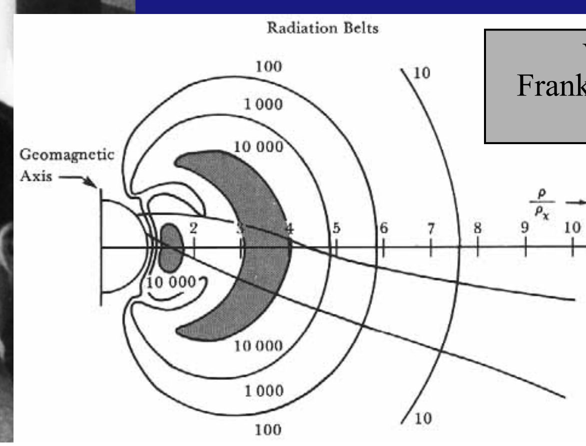
At the "Dawn of the Space Age"

Explorer 1 – post launch press briefing.

In 1958 the first US satellites were launched into orbit. These carried Geiger counters into space.

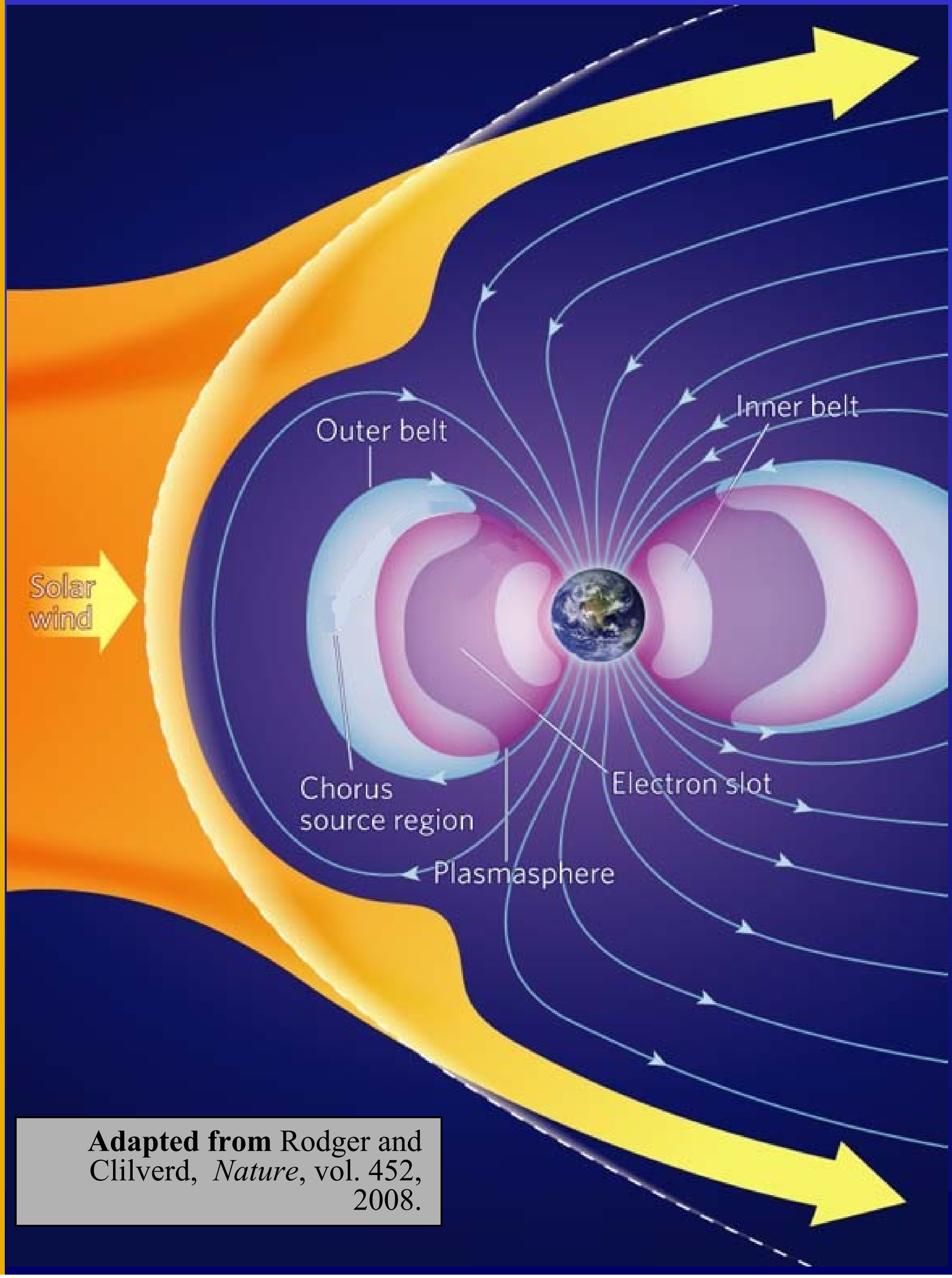
Explorer I and *Explorer III* discovered that the magnetic field of the Earth traps high energy particles – these have become known as the **Van Allen radiation belts**.



Van Allen and Frank, *Nature*, vol. 183, 1959.

EXPLORER 1

Basic structure of the Van Allen belts



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

Of course since the original observations, a lot more has been learnt, in particular, where the radiation belts are located relative to other parts of Geospace.

It may come as a surprise, however, to discover there are still fundamental open questions as to the Physics of the Radiation Belts.

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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.

POES >100keV trapped electrons

POLAR OPERATIONAL ENVIRONMENTAL SATELLITES

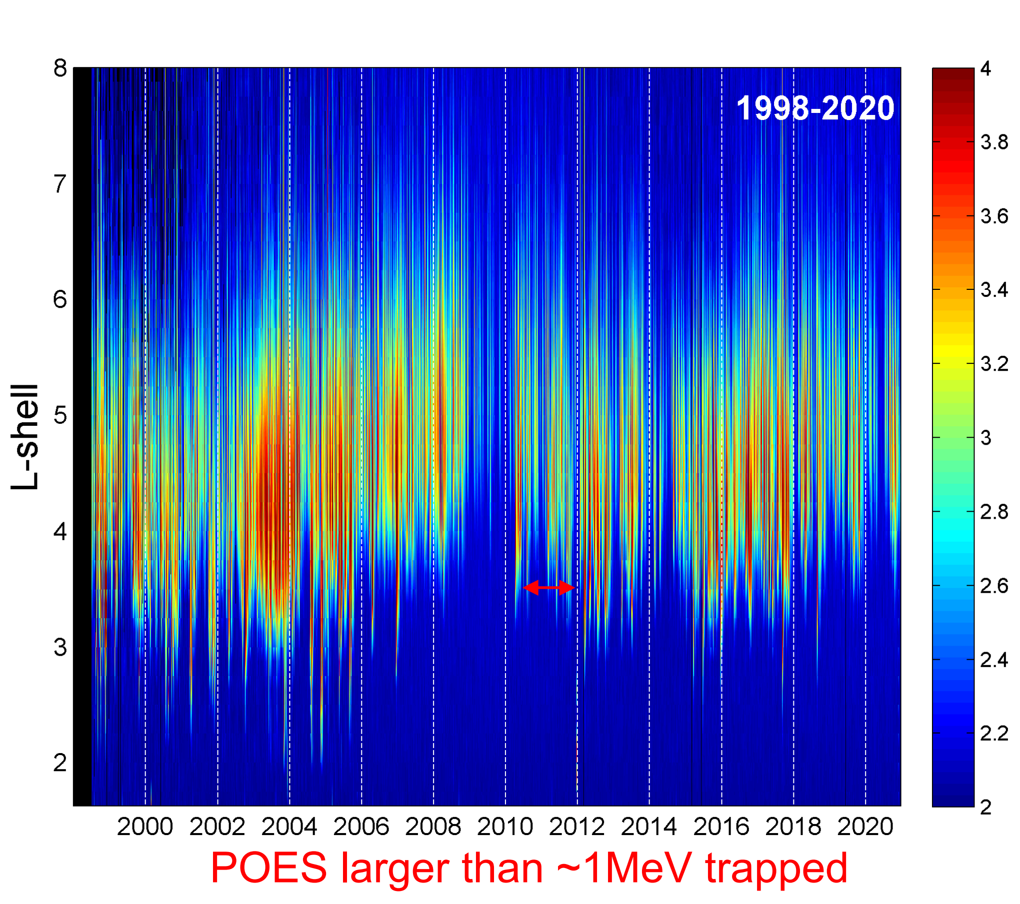
POES

NASA/NOAA

And especially "Killer Electrons"

When talking to the public we sometimes use the phrase “Killer Electrons”, which are those electrons with energies greater than about 1 MeV, which are clearly relativistic in energy.

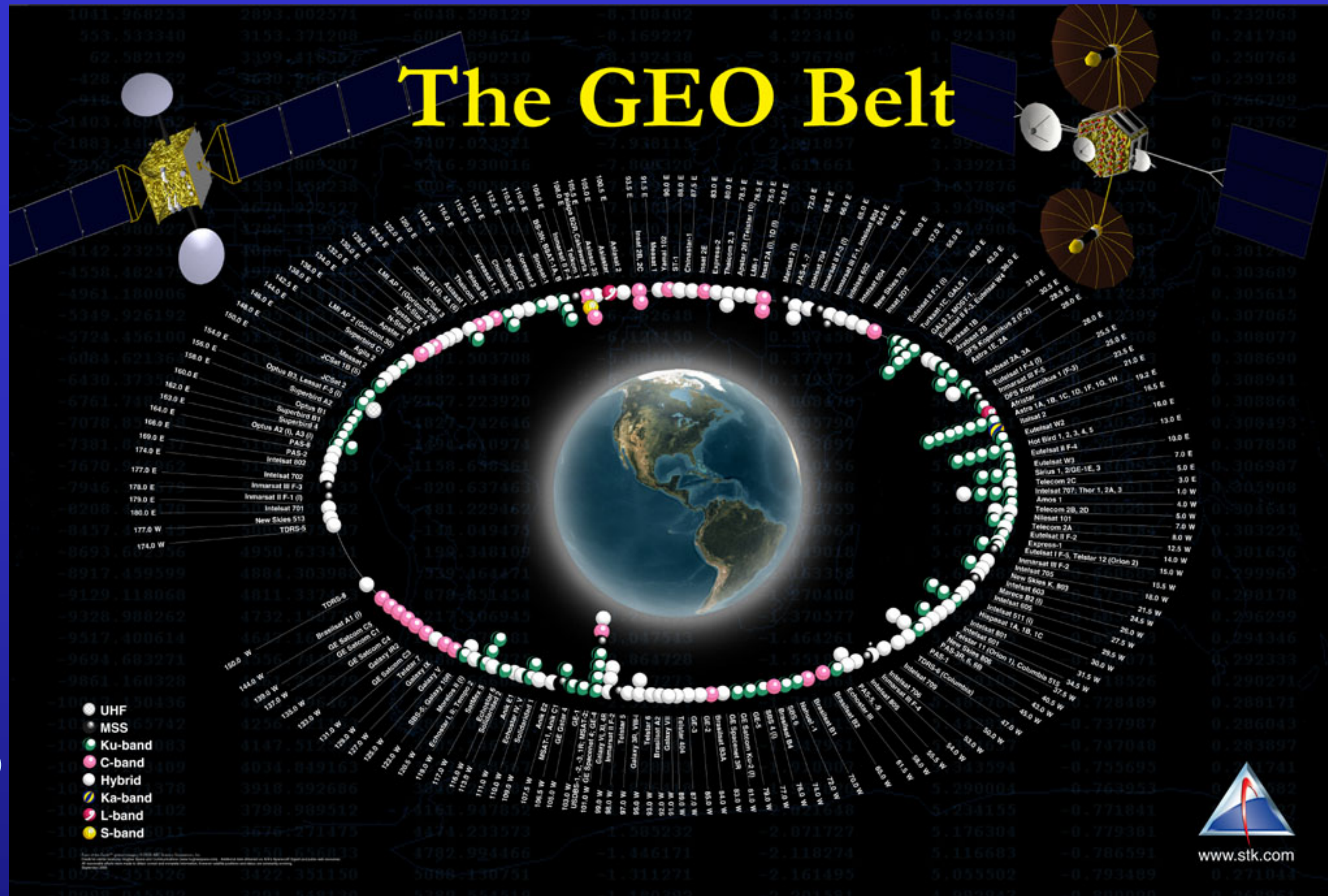
WHY KILLER? Their potential effect on satellites.



There are also many orders of magnitude changes occurring in the flux of “killer electrons” with time.

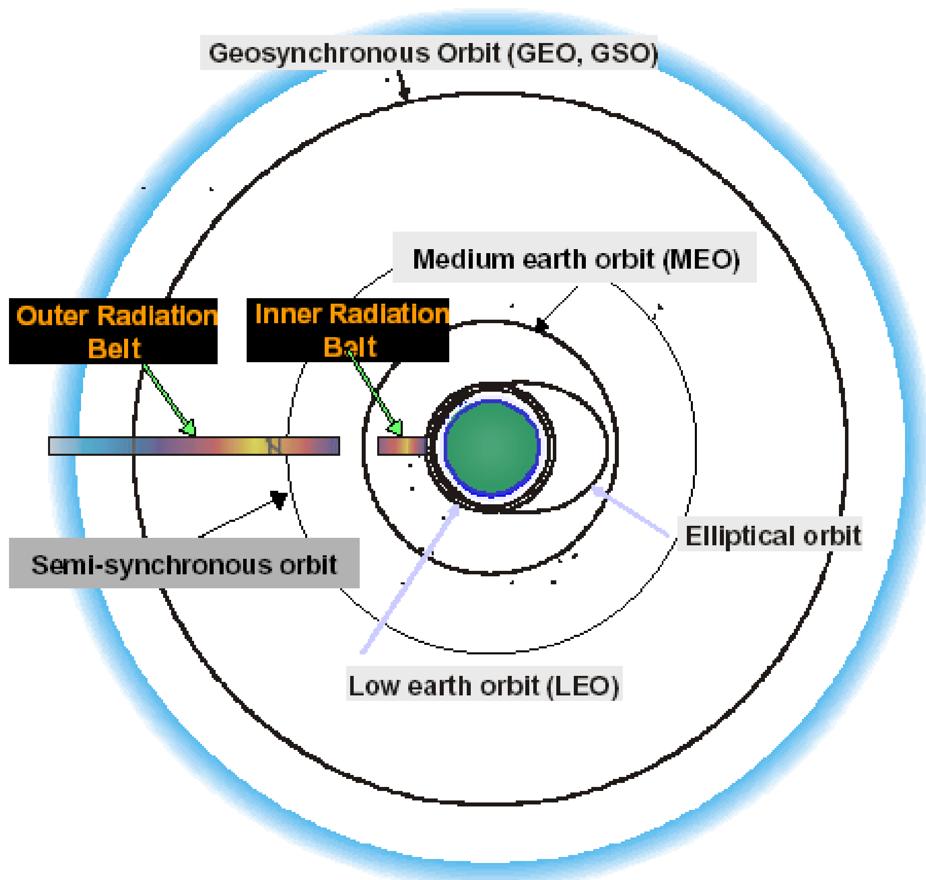
Roughly 565 operational satellites currently in GEOstationary Orbit.

UCS Satellite Database (April 2022)



- **Examples of Losses:** Intelsat K, Anik E1 & E2, Telstar 401, Galaxy-4, Galaxy-15 (twice, 2010 & 2022)
- **Costs:** ~$200M build, ~$300M launch to GEO.

SATELLITE MOTION THROUGH THE BELTS



Highly idealized depiction of natural radiation belts.
Inclination of each satellite orbit set to zero for display purposes.

LEO – inner belt (4700 satellites)

MEO – slot region (140 satellites)

GEO – outer belt (565 satellites)

Elliptical – mixed (60 satellites)

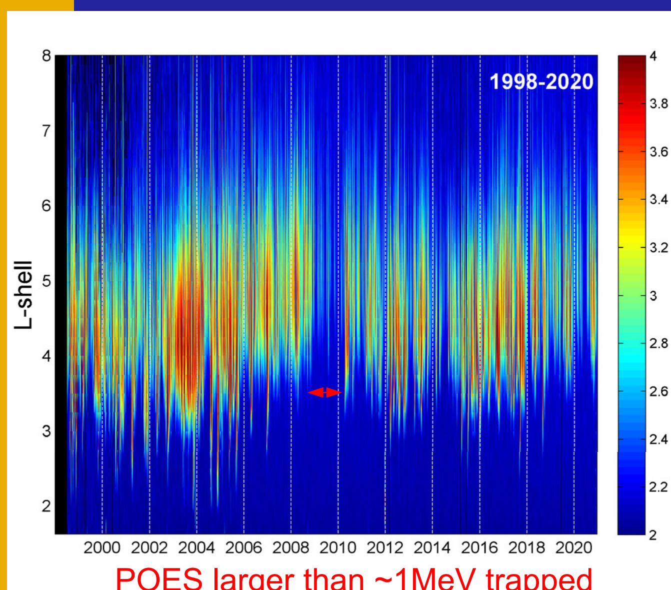
UCS Satellite Database

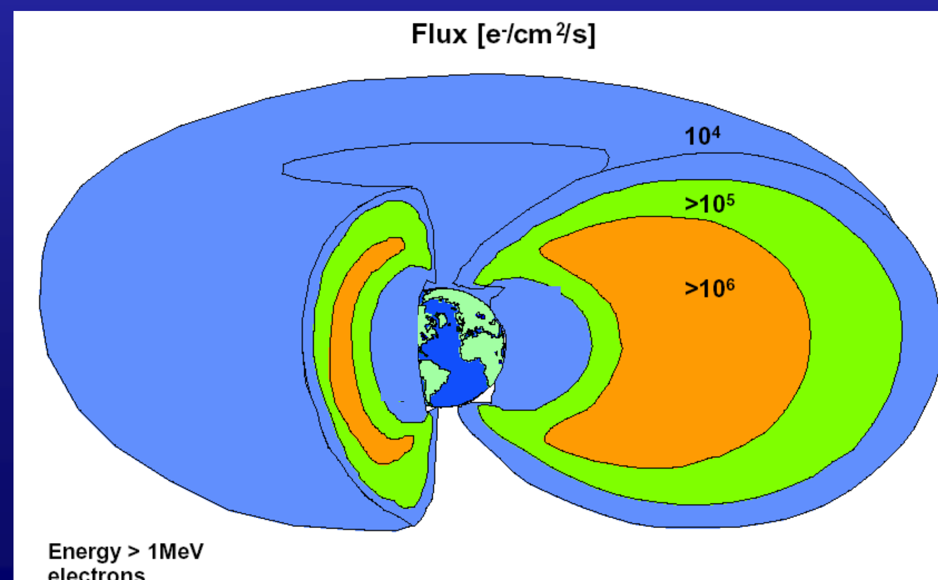
How to understand the Dynamic Changes?

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

The overall response of the Radiation Belts to geomagnetic storms are a "delicate and complicated balance between the effects of particle acceleration and loss" [*Reeves et al.*, GRL, 2003].

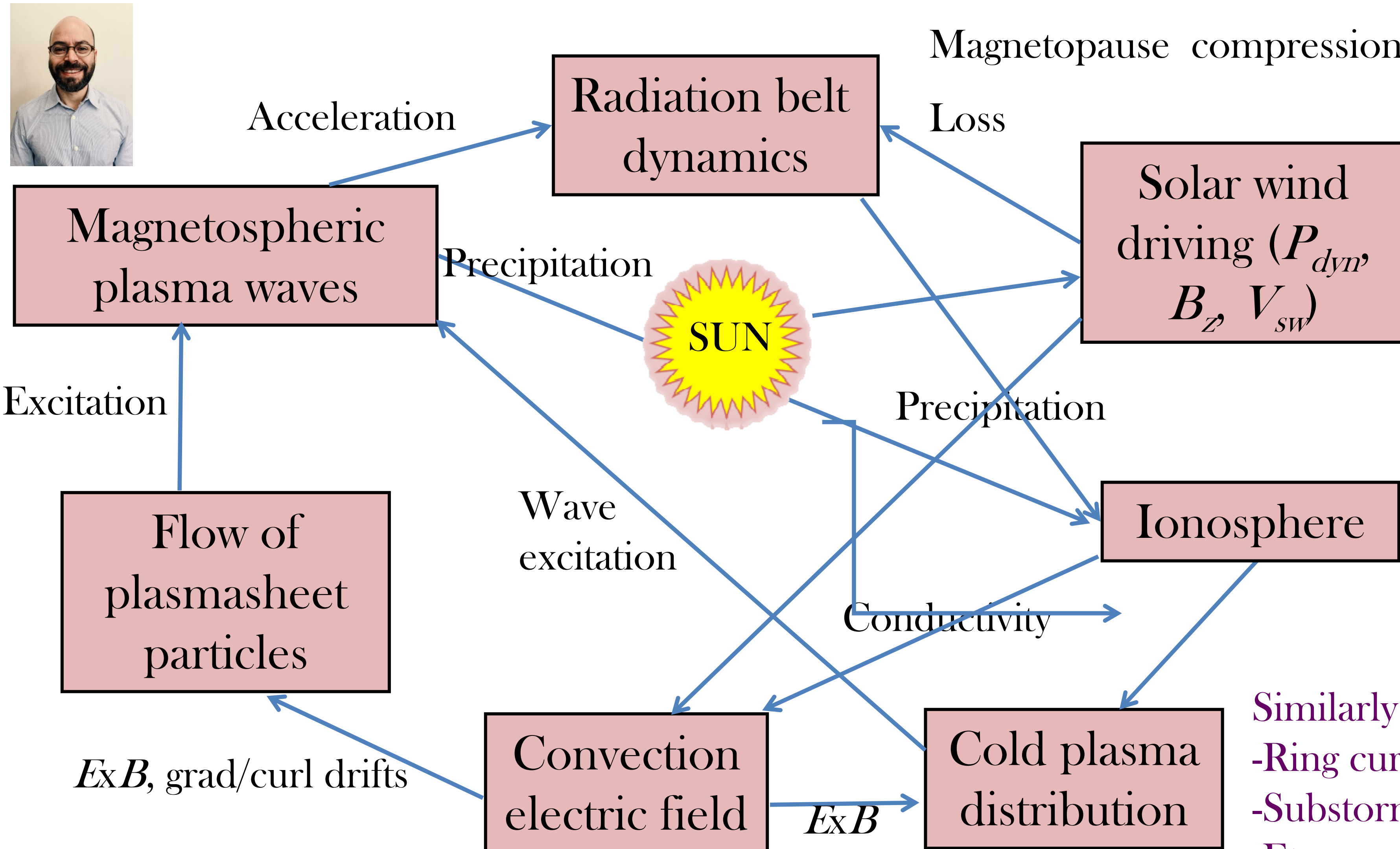
My group has focused on understanding the losses! There are many other groups working on the acceleration questions.





It's a complex system!

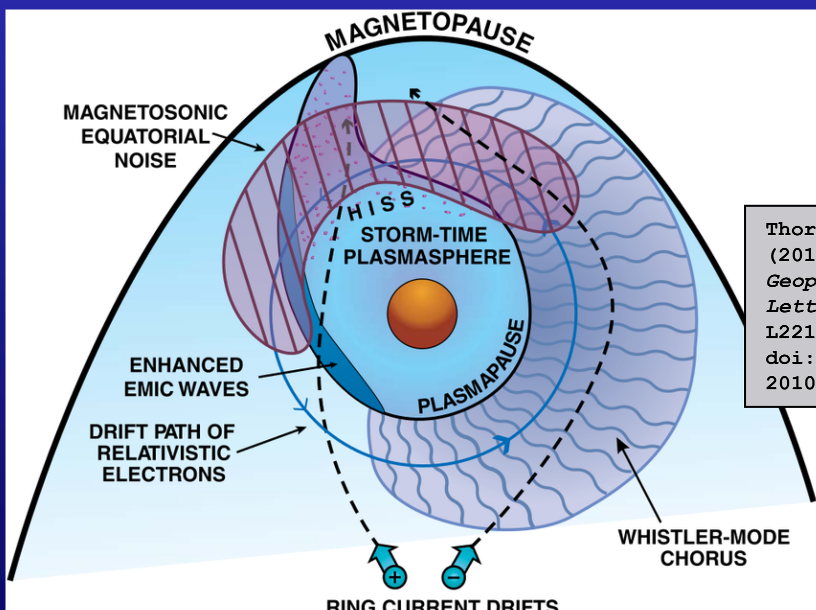
There is a lot of coupling and lots of observations from space and ground are needed to characterise the processes (remember, we span ~6-orders of magnitude in Energy).



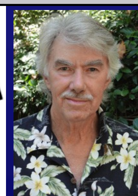
Similarly:
-Ring current
-Substorms
-Etc.

Primary Questions

- Why are the belts so dynamic?
- How can we predict the changing trapped electron fluxes in time and space?
- **What are the energy dependent losses into the atmosphere (in time and space) and how important are they?**

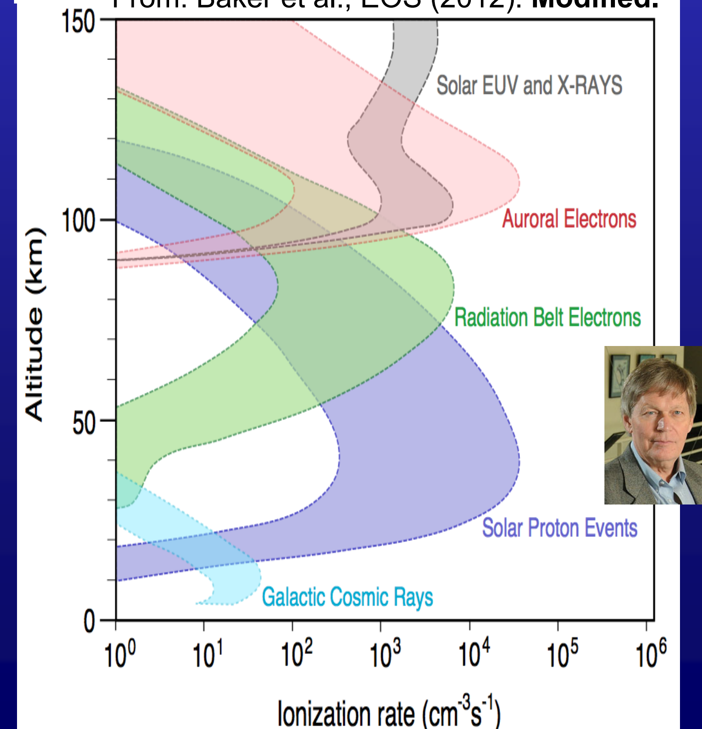


Thorne, R. M. (2010), *Geophys. Res. Lett.*, 37, L22107, doi:10.1029/2010GL044990.



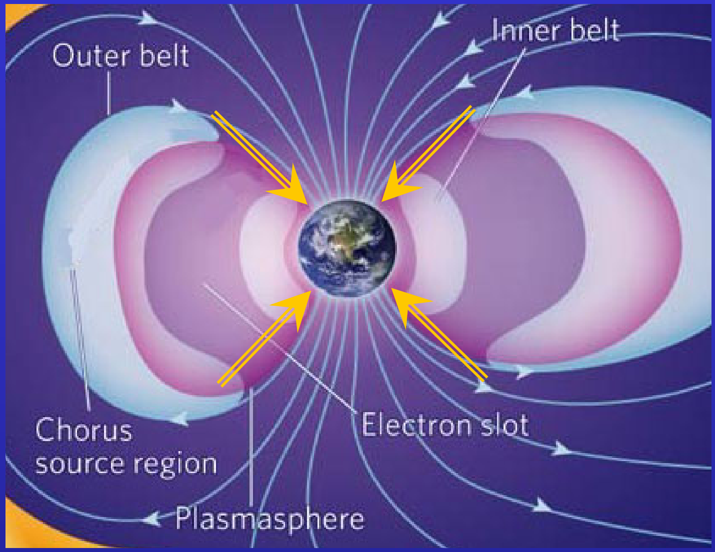
A ~1 MeV electron drifts around the world in ~10min, so the different processes occurring in Magnetic Local Time impact these electrons rapidly, causing a combined impact that can be hard to remove.

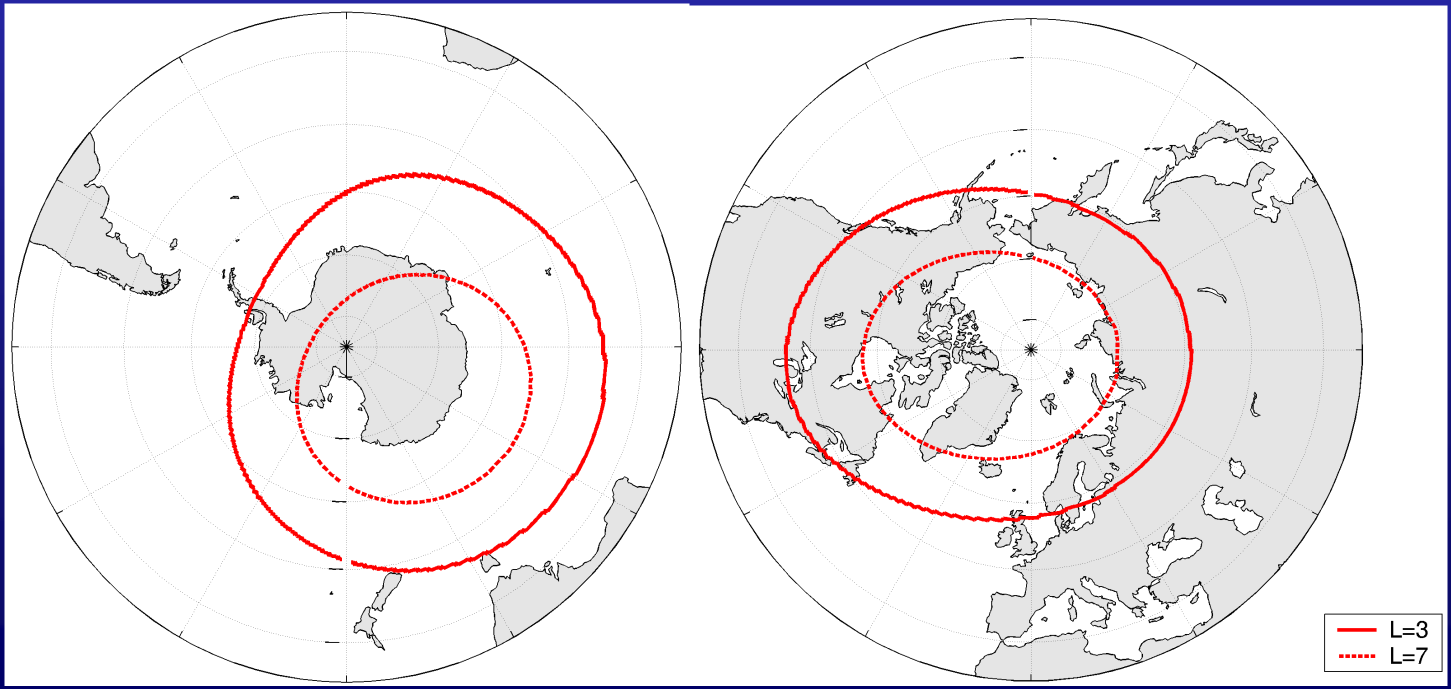
From: Baker et al., EOS (2012). **Modified.**



Particles are lost to the polar upper atmosphere

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

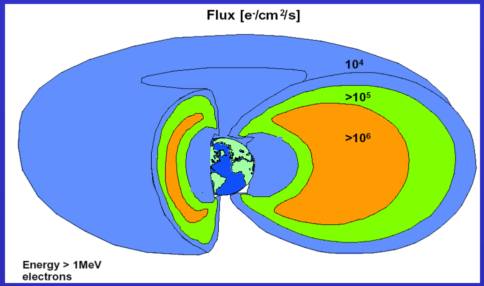




Radiation Belt Precipitation

Understanding the Radiation Belts - Particle Motion

A charged particle trapped in the Radiation Belt experiences three basic motions – **cyclical** (around the field line), **bounce** motion (between the hemispheres) and **drift** around the Earth.



Gyrofreq ~4 kHz
Bounce *T* ~1s
Drift *T* ~1 hour
drift for ~150keV e-

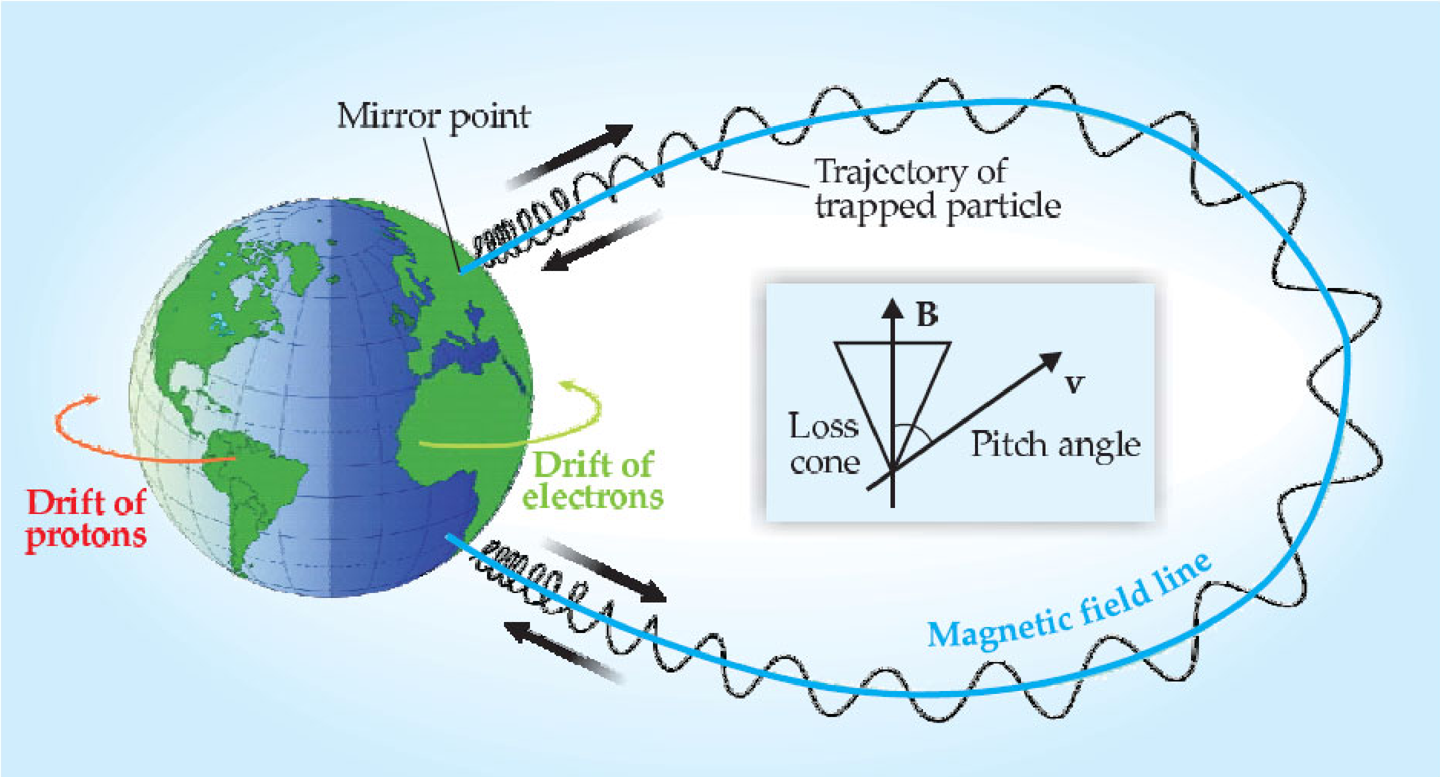


Figure 2.4: Schematic showing cyclotron, bounce and drift motion of geomagnetically trapped particles. Inset: equatorial pitch angle and loss cone definitions. Reproduced from *Day* (2008).

Understanding the Radiation Belts – The Importance of the Pitch Angle

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The long term fate of a radiation belt e^- is determined by the pitch angle (α) of a radiation belt particle at the geomagnetic equator. For example:

$\alpha = 90°$ is trapped at the geomag. equator.

$\alpha = 0°$ will strike the Earth's surface (and thus lost)

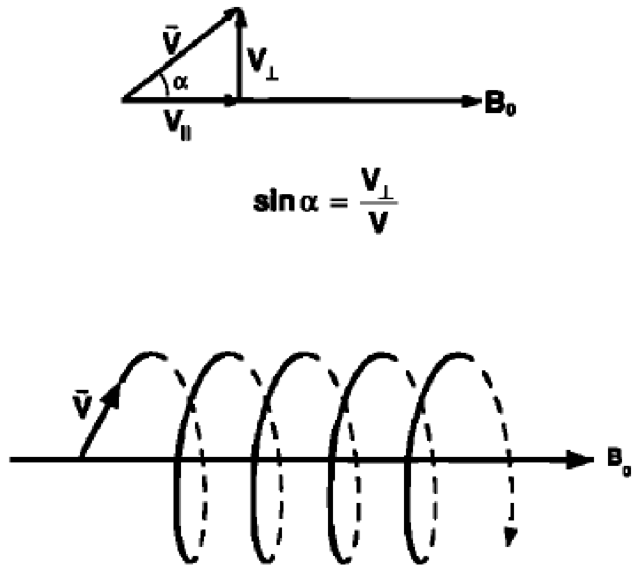


Figure 2.1: (Top) definition of pitch angle α, and (bottom) cyclotron motion of a charged particle in a homogeneous magnetic field. Reproduced from *Tsurutani and Lakhina* (1997).

Plots from Tsurutani & Lakhina (1997), *Rev. Geophys.*, doi:10.1029/97RG02200.

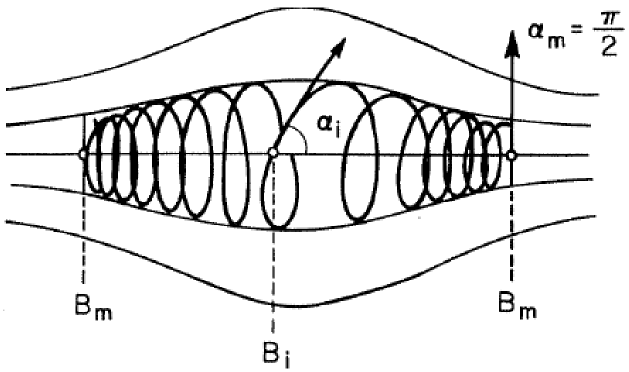
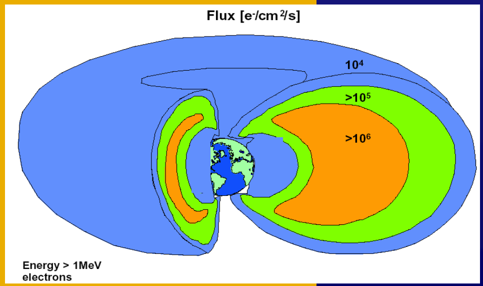


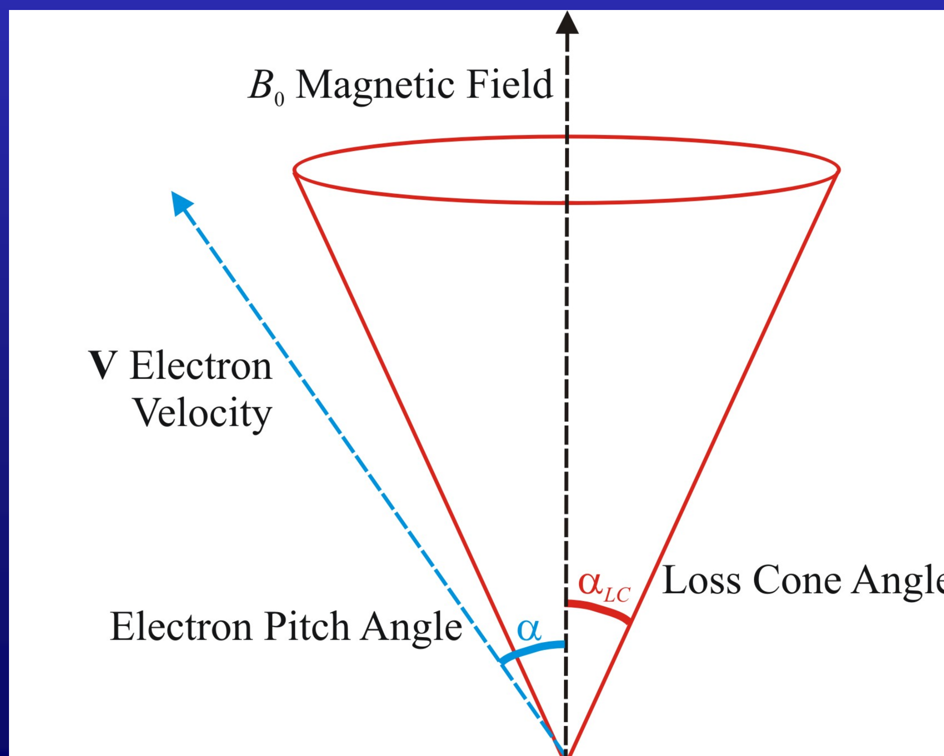
Figure 2.2: Bounce motion of a charged particle in magnetic field with $(\nabla B)_\parallel \neq 0$. Reproduced from *Jursa* (1985).



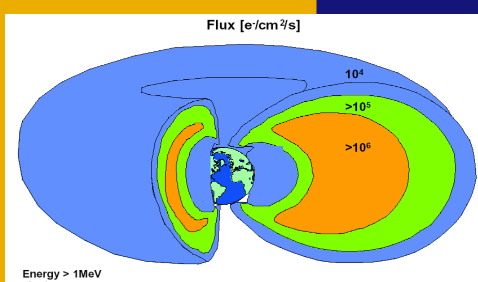
In reality, the majority of Radiation Belt electrons have pitch angles between this range (i.e. neither $\alpha = 0°$ nor $\alpha = 90°$), and so bounce from hemisphere to hemisphere passing through the geomagnetic equator.

Understanding the Radiation Belts - The Importance of the Pitch Angle

While an equatorial pitch angles of $\alpha = 0°$ would strike the Earth, an electron which should mirror at 1m above the ground would also be lost by colliding with the atmosphere. In practise there is a range of pitch angles which will be quickly lost through atmospheric collisions. The threshold is taken as ~100km altitude, and this range of pitch angles defines the loss cone with the outer edge the "loss cone angle", α_{LC}.



Any electron which starts with a pitch angle smaller than α_{LC} (or is scattered into that range) will be rapidly loss – within a few bounces at most.



Understanding the Radiation Belts - The Importance of the Pitch Angle

BUT the mirror height (and hence the width of the loss cone) depends on the strength of the magnetic field, and this is not constant at the surface of the Earth or at satellite altitudes.

Thus the width of loss cone angle, α_{LC}, varies with latitude, and longitude (and altitude, but we normally reference α to the geomagnetic equator).

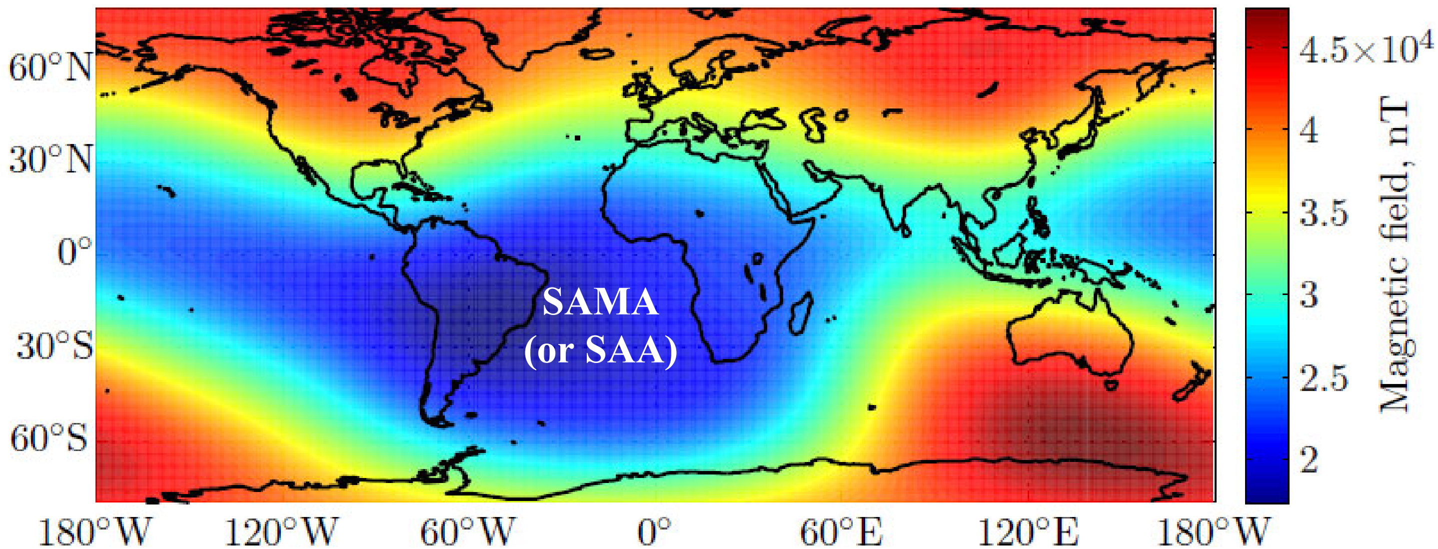
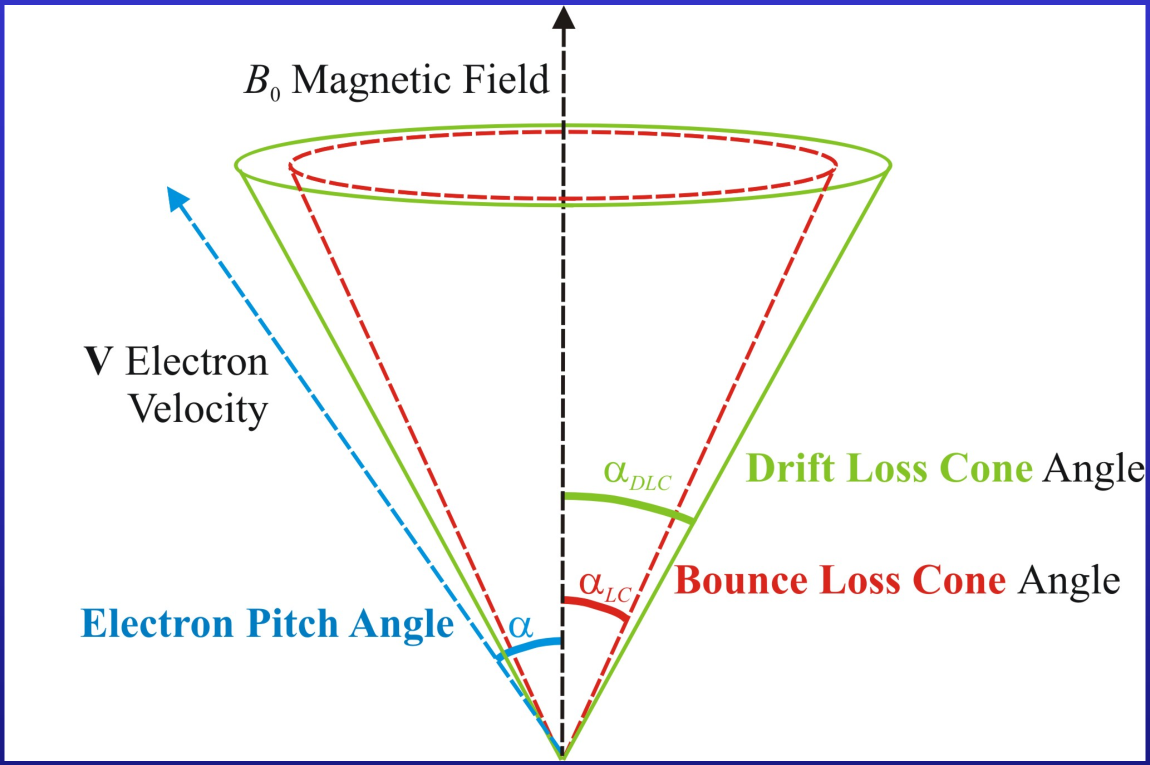


Figure 2.5: Geographic variation of IGRF-modelled geomagnetic field strength calculated at the altitude of the DEMETER satellite (710.5 km) for epoch 2005, showing the weak magnetic field in the SAMA region.

Understanding the Radiation Belts – The Importance of the Pitch Angle

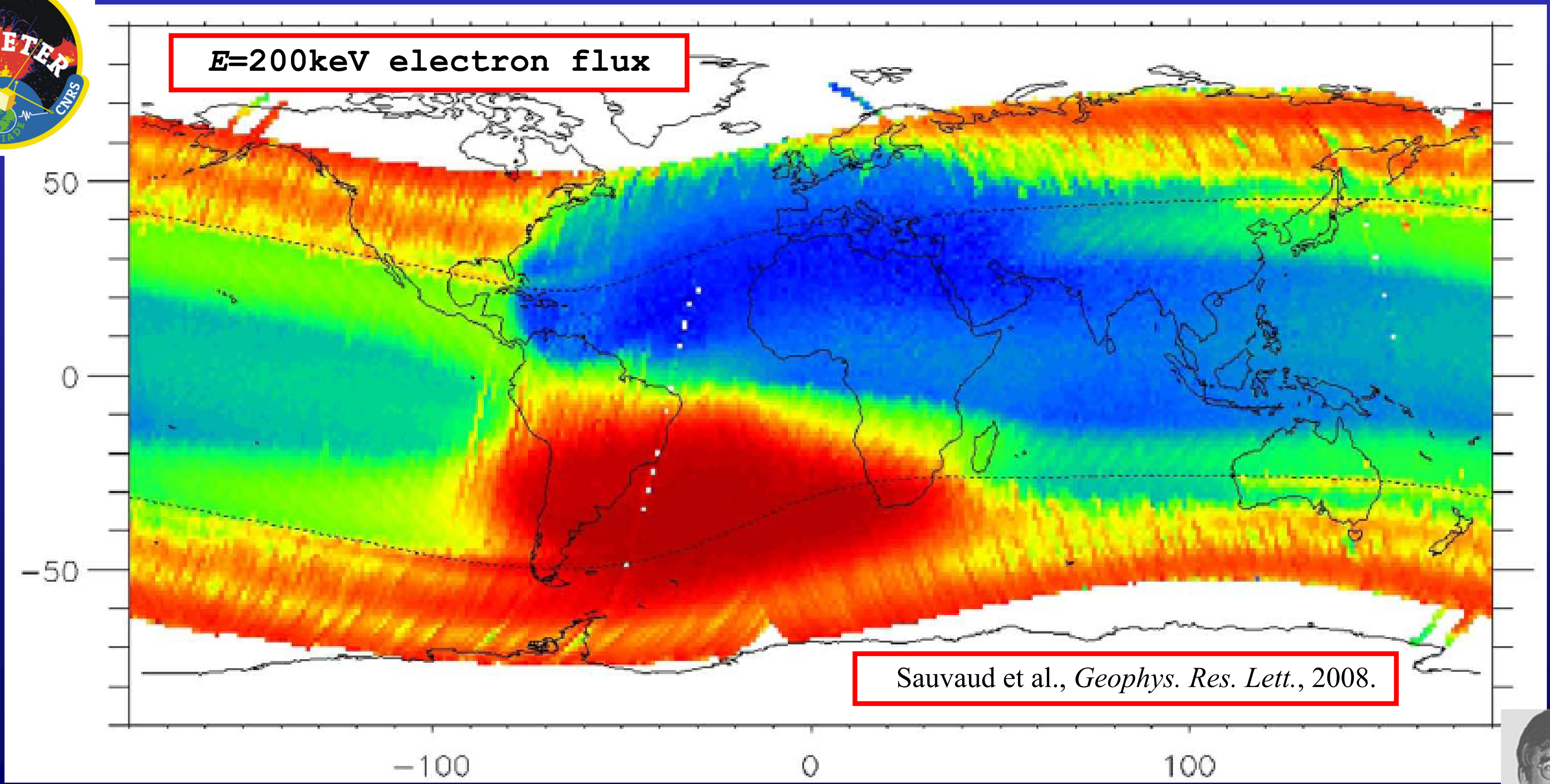


So in practise there are two loss cones at any given location – the "local" bounce loss cone α_{LC}, <u>and</u> the "drift" loss cone α_{DLC}, which is the maximum value of α_{LC} for a given magnetic drift shell (and thus L) and tends to be located in the South Atlantic-ish region.

Note that most LEO spacecraft are normally measuring pitch angles near the α_{DLC}. So these electrons are either certain to be lost <u>soon</u> or are not far off being scattered into the drift loss cone or bounce loss cone.

You can see the "signature" of the DLC in measurements made by some LEO spacecraft

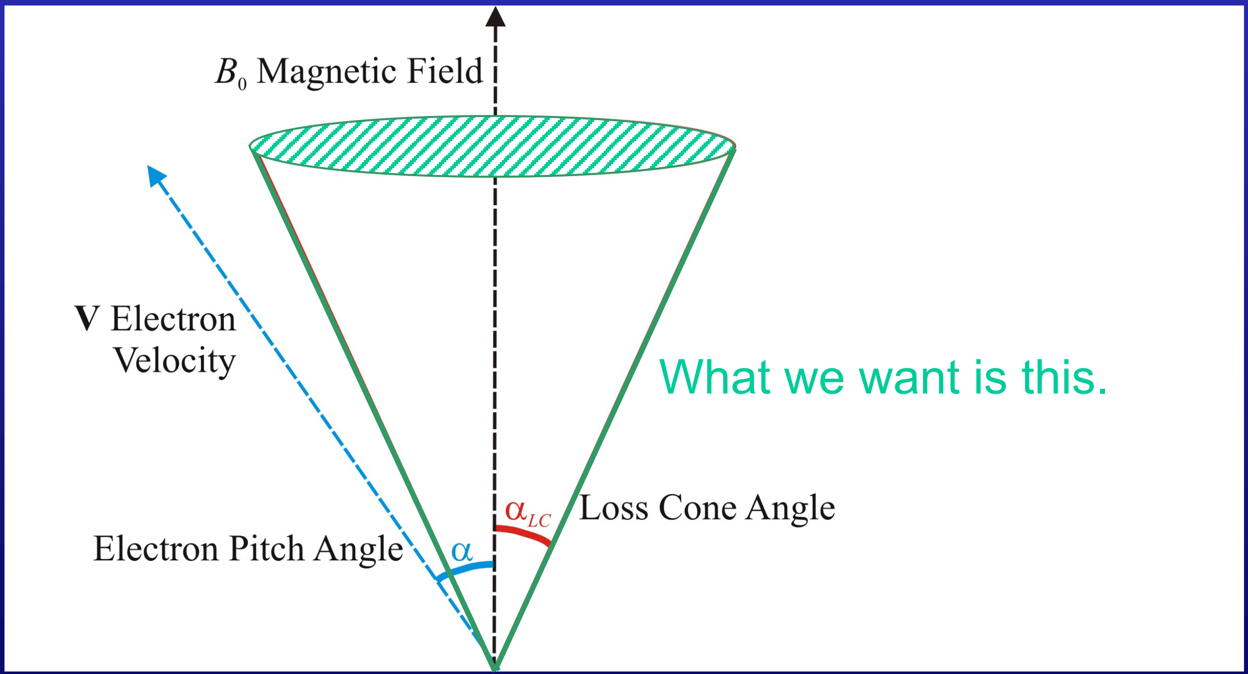
Drift Loss Cone electron fluxes at 200 keV as seen by DEMETER. The filling of the DLC and the sudden flux loss is very clear (as is the SAMA).

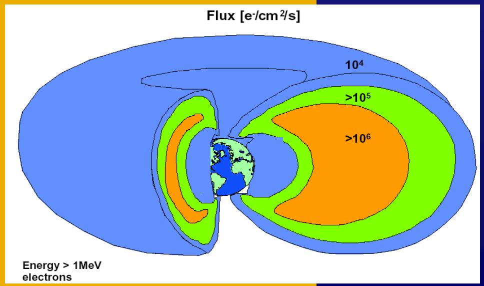


Observing the Bounce Loss Cone from Space

In order to measure energetic electrons lost from the radiation belts, our first urge is to use satellites. That is, measure from space the electrons being lost from space into the atmosphere.

In practise this does not work that well.



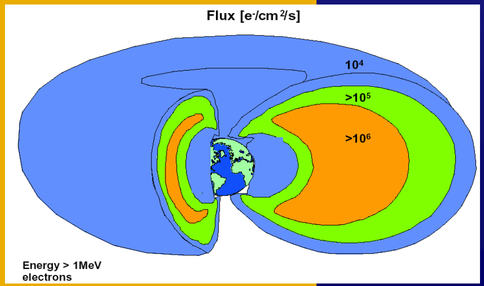


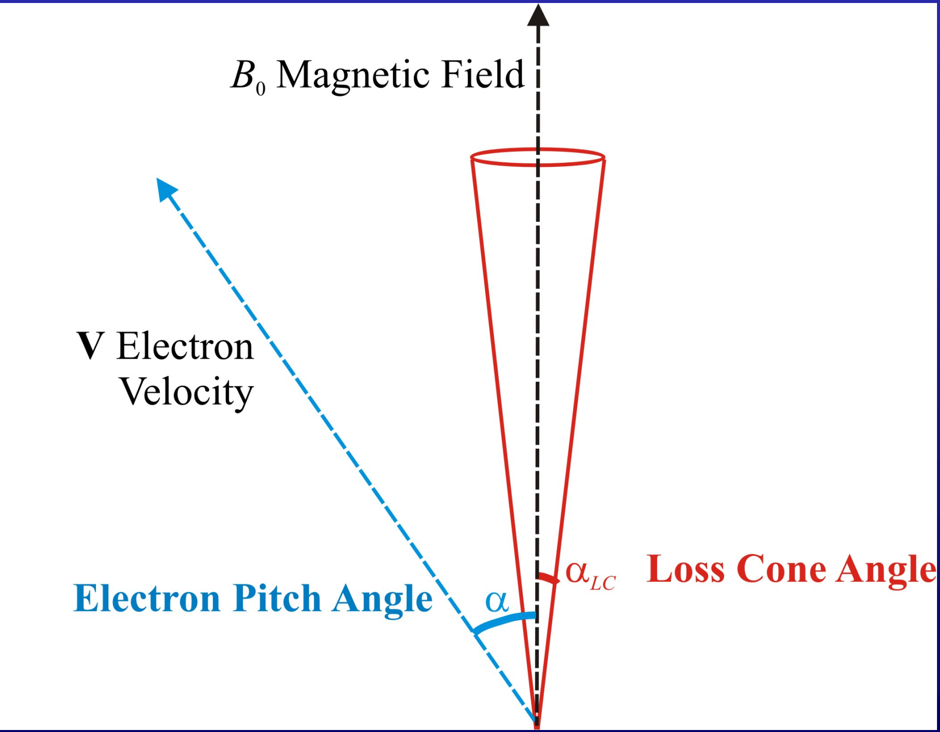
Observing the Bounce Loss Cone from Space?

In order to measure energetic electrons lost from the radiation belts, our first urge is to use satellites. That is, measure from space the electrons being lost from space into the atmosphere.

In practise this does not work well. At geostationary orbits the loss angle is very very small (just a few degrees wide). Its very challenging to build an instrument which can do this – so typically people have not done it.

Examples: GOES, LANL, RBSP



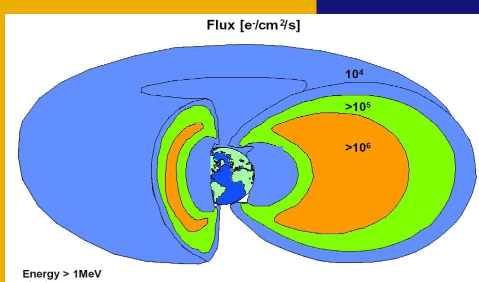


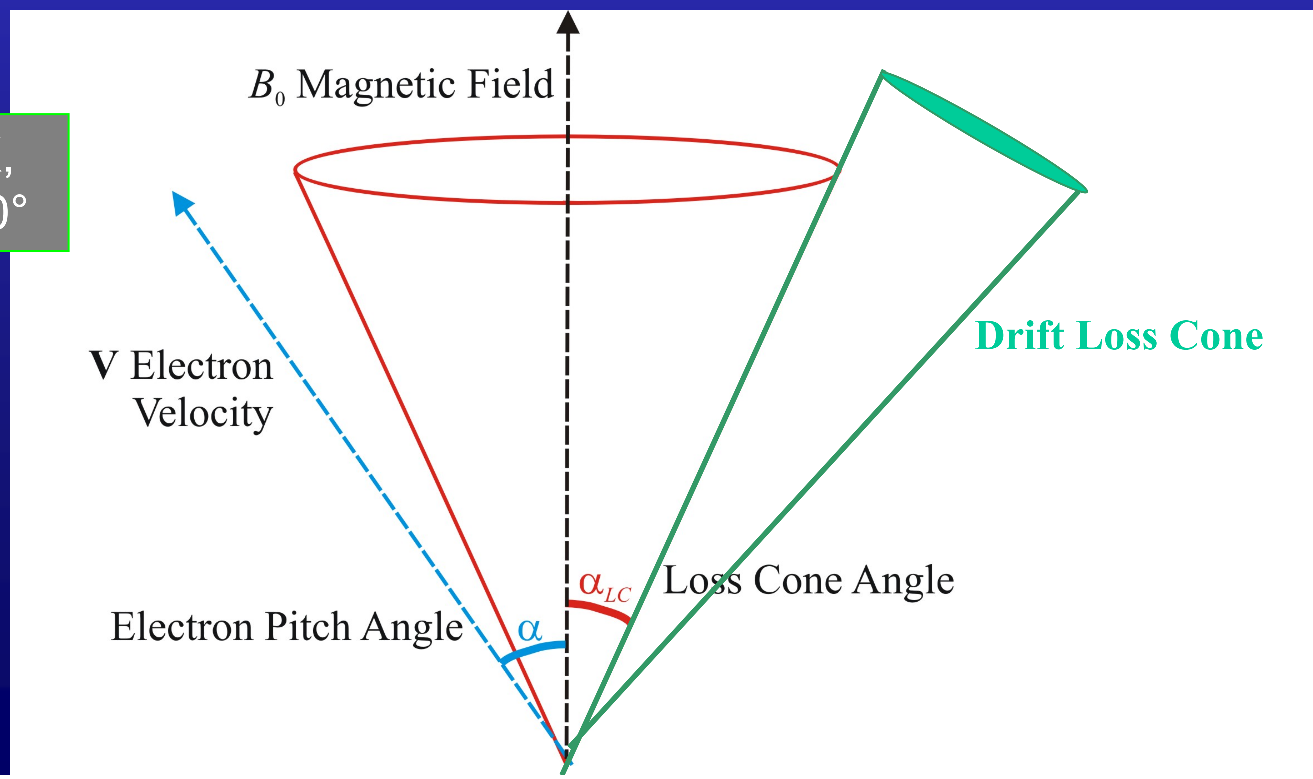
Observing the Bounce Loss Cone from Space?

In order to measure energetic electrons lost from the radiation belts, our first urge is to use satellites. That is, measure from space the electrons being lost from space into the atmosphere.

In practise this does not work well.
A lot of satellites we work with make measurements just outside the Bounce Loss Cone, as that turns out to much technically easier (and useful in its own way).

Examples: SAMPEX, DEMETER, POES 90°



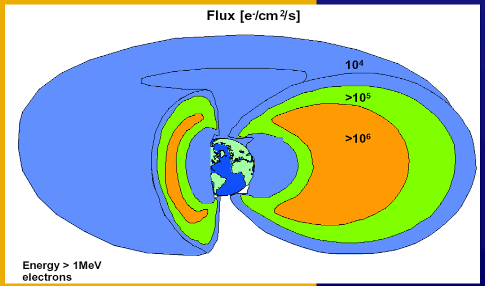


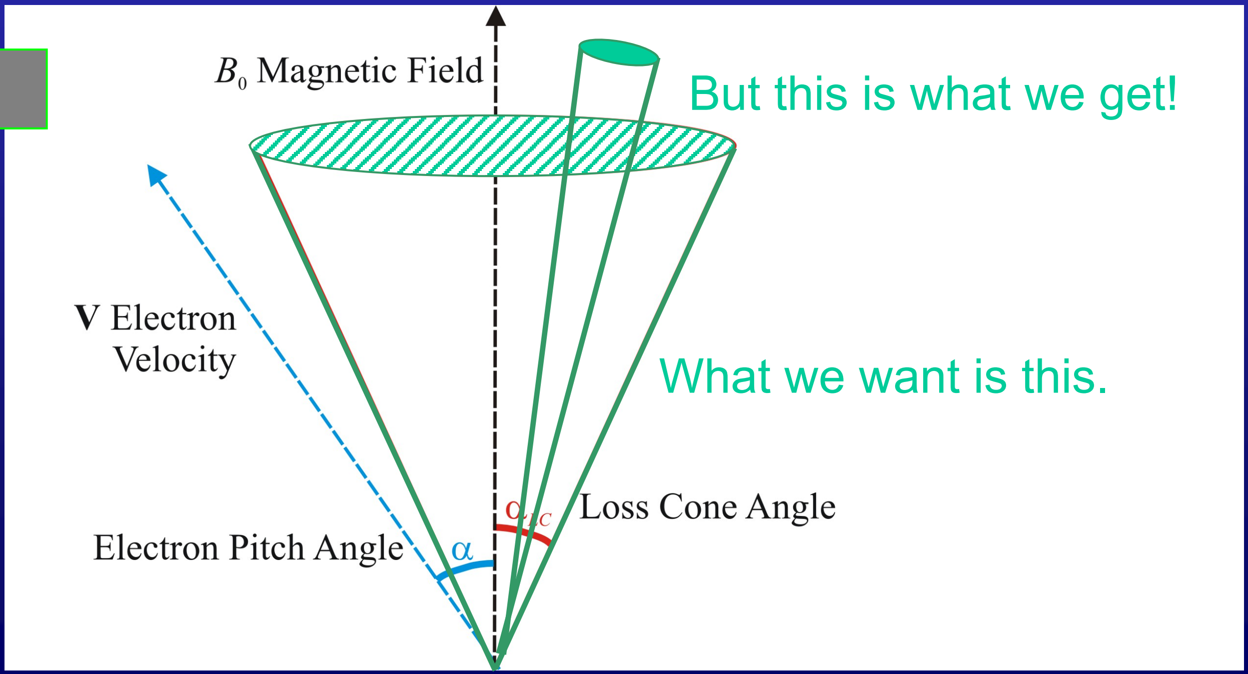
Observing the Bounce Loss Cone from Space!

In order to measure energetic electrons lost from the radiation belts, our first urge is to use satellites. That is, measure from space the electrons being lost from space into the atmosphere.

In practise this does not work well. The rare instruments which do sample inside the loss cone tend to only at a small portion of it. This leads to some issues but these measurements are the main space-based tools we have (and includes long-lived observations).

Examples: POES 0°





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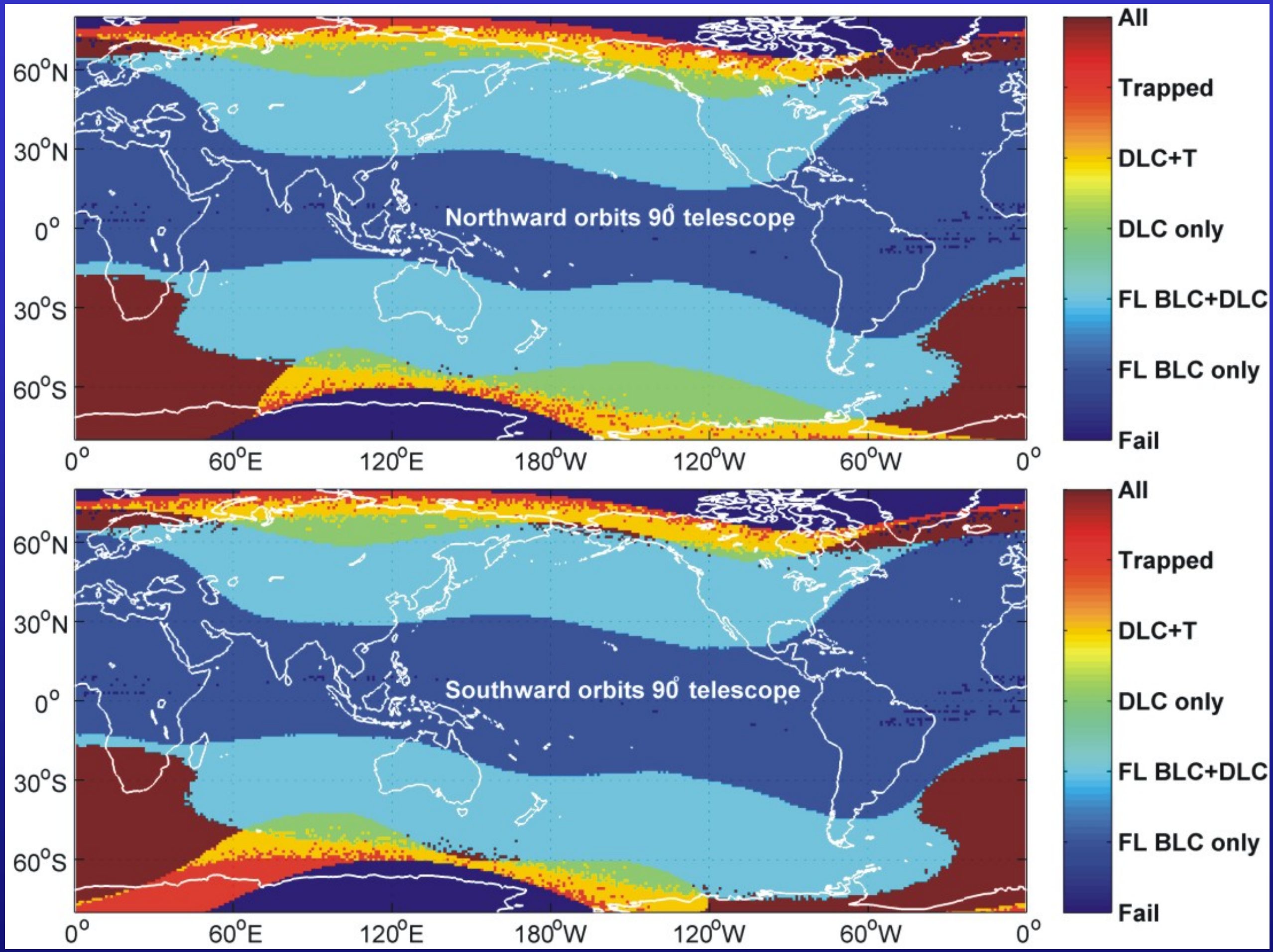
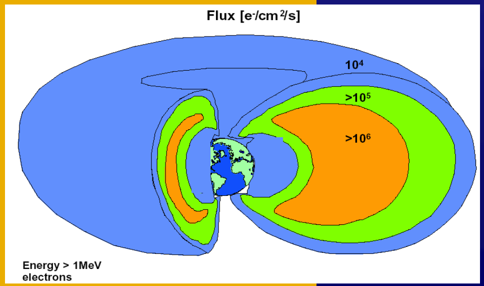
Observing Loss Cones from Space

From Rodger et al, *J. Geophys. Res.*, 115, A12208, doi:10.1029/2010JA015880, 2010.

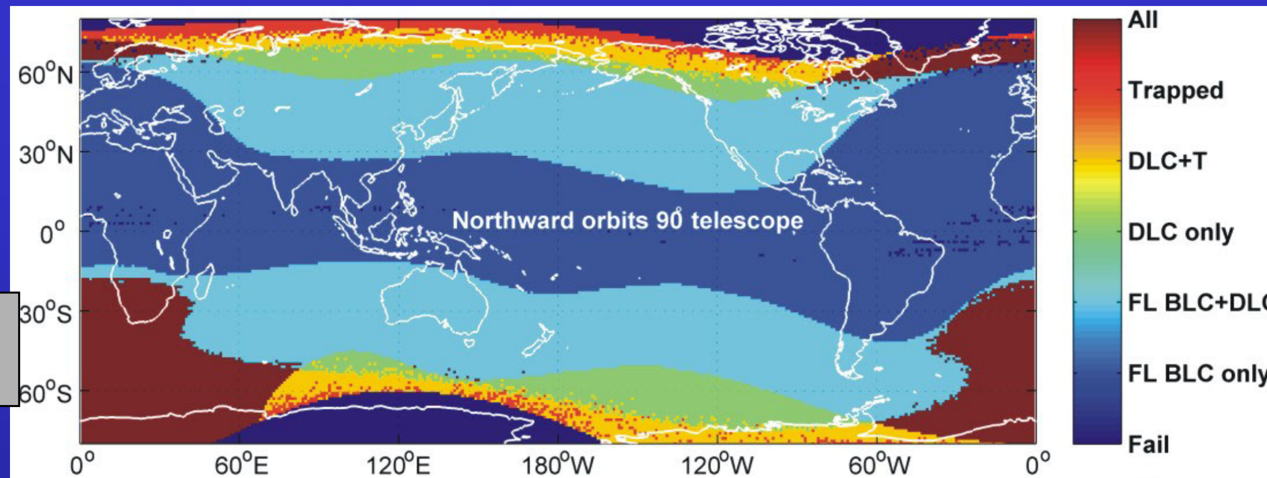
Examples: POES 90°, SAMPEX and DEMETER are similar





World map showing the changing radiation belt population observed by the 0° directed, ±15° wide MEPED telescopes onboard POES. Here "**T**" indicates **trapped flux**, "**DLC**" is **drift loss cone**, and "**FL BLC**" is **field line bounce loss cone**.

Observing Loss Cones from Space



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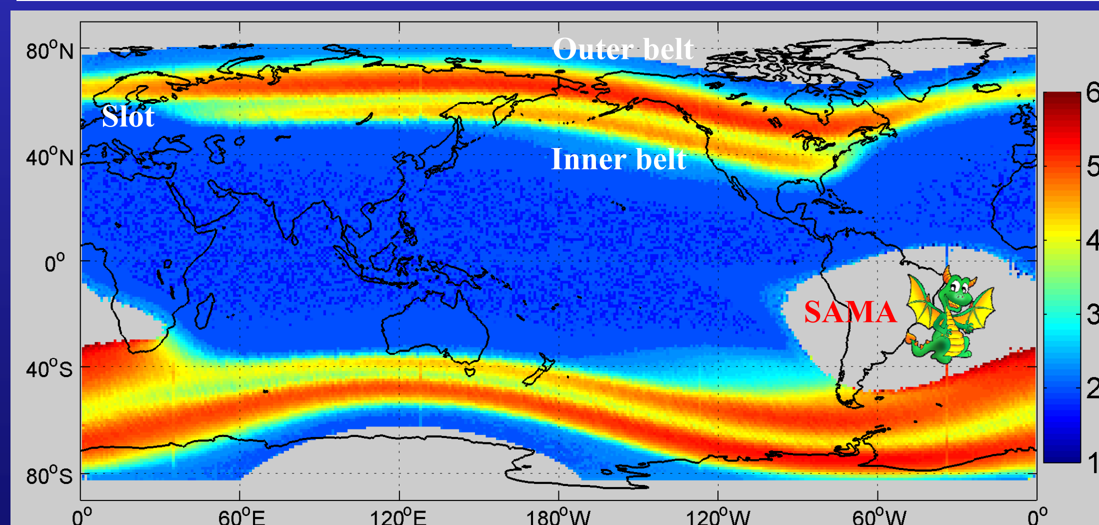

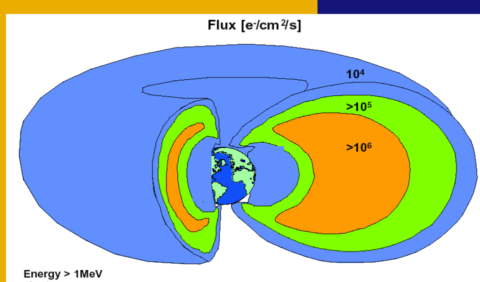

The lower panel is the median NOAA-15 >100 keV median flux for the 90-degree instrument (observations from 1999-2008), i.e., 10 years. The "signature" of the DLC is very clear when examined this way!

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Observing Loss Cones from Space

From Rodger et al, *J. Geophys. Res.*, 115, A12208, doi:10.1029/2010JA015880, 2010.

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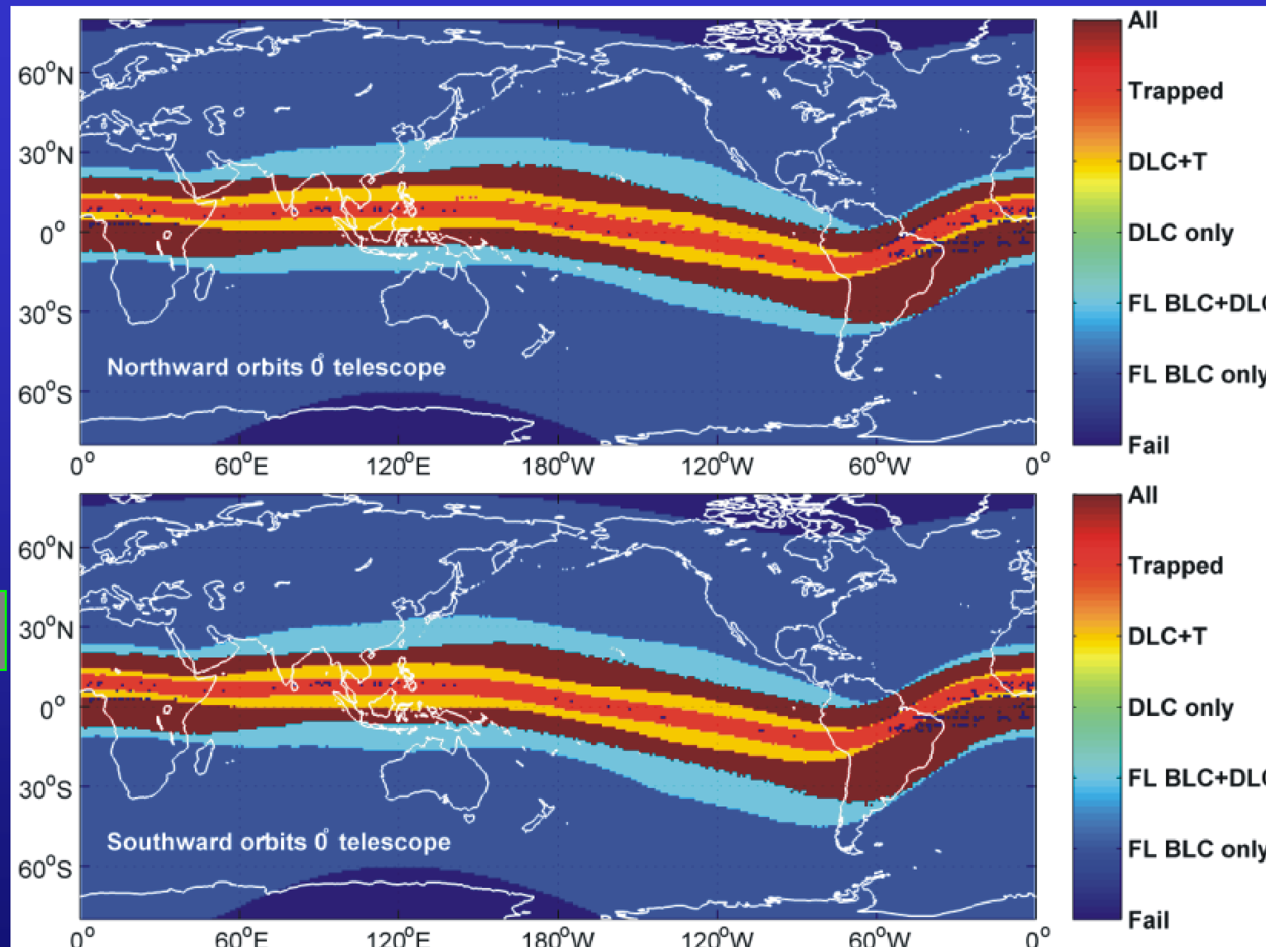

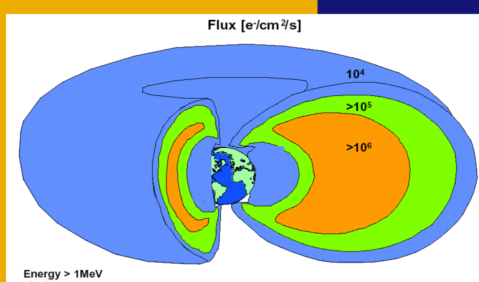

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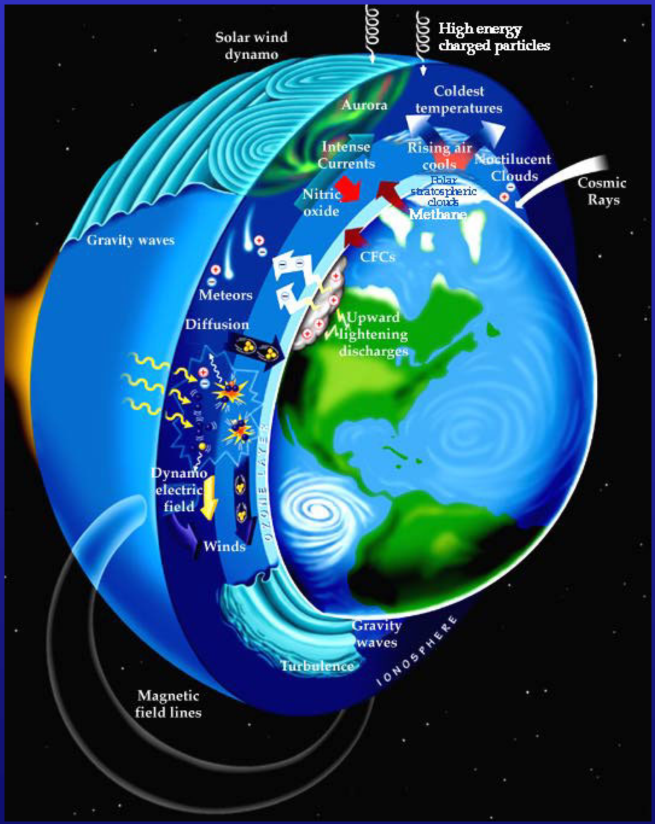
Energetic Particle Precipitation

<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.

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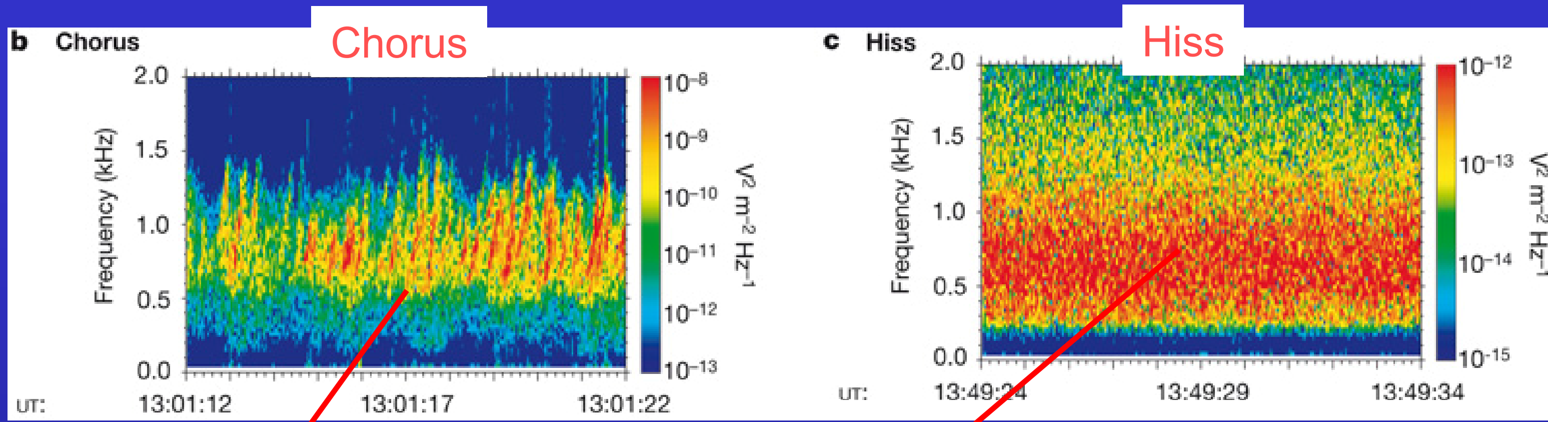
What causes precipitation? Plasma Waves! (of course)



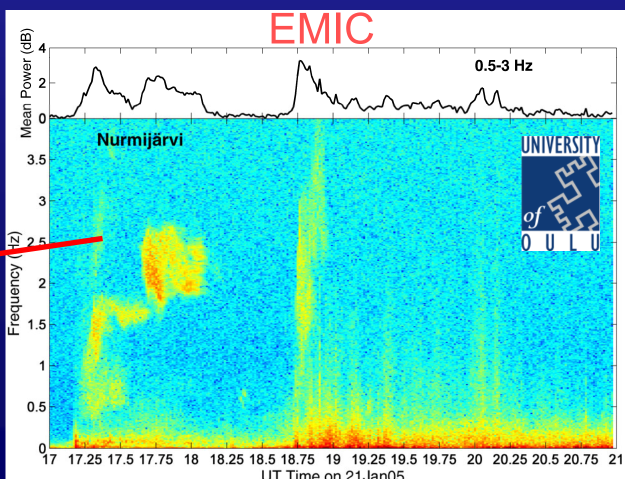
Adapted from Bortnik et al., *Nature*, vol. 452, 10.1038/nature06741, 2008.

W-M = "**whistler mode**"

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

W-M Plasmaspheric Hiss: Has long been suggested as the **reason the slot region exists** (so makes losses).

Electromagnetic Ion Cyclotron waves: long understood as a likely important loss mechanism (especially relativistic).



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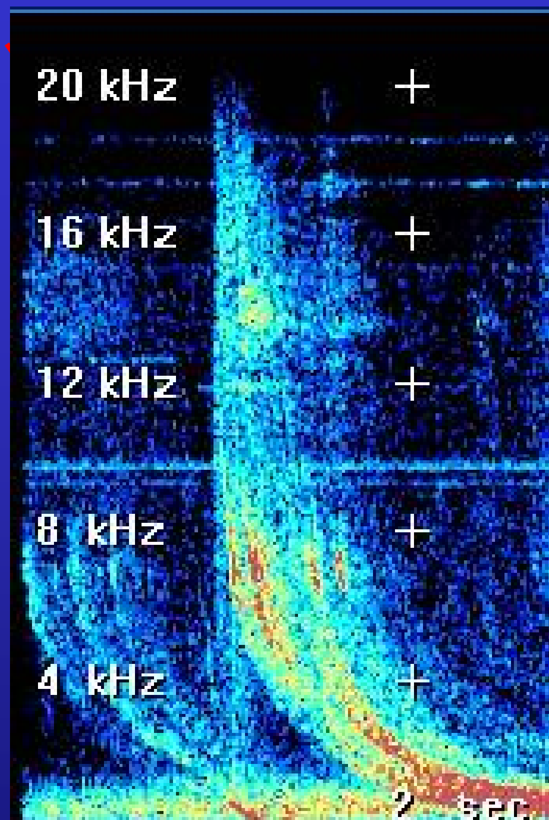
Getting our terminology right



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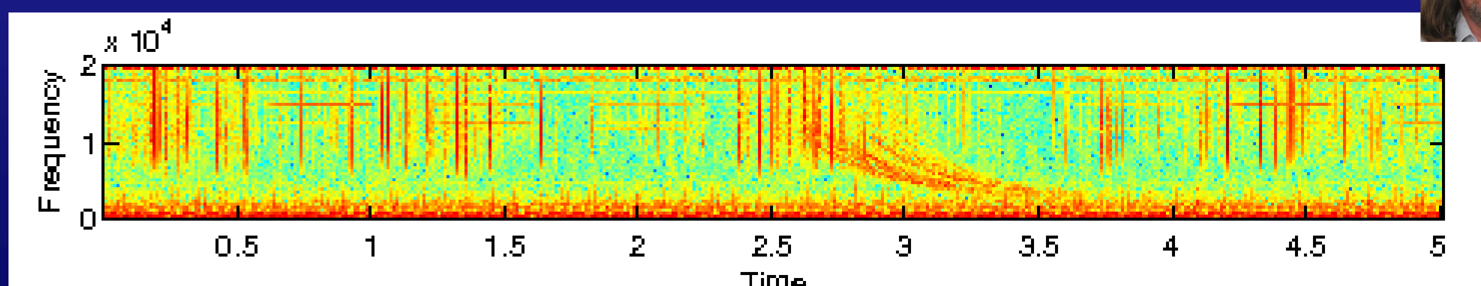
Whistler Waves

Produced by impulsive EM discharges in the atmosphere (i.e., lightning), after dispersion on propagation through a magneto-active plasma (i.e., the inner magnetosphere).



[these are examples of a whistler, otherwise you are likely talking about a whistler-mode wave (and probably you mean to say “chorus”)]

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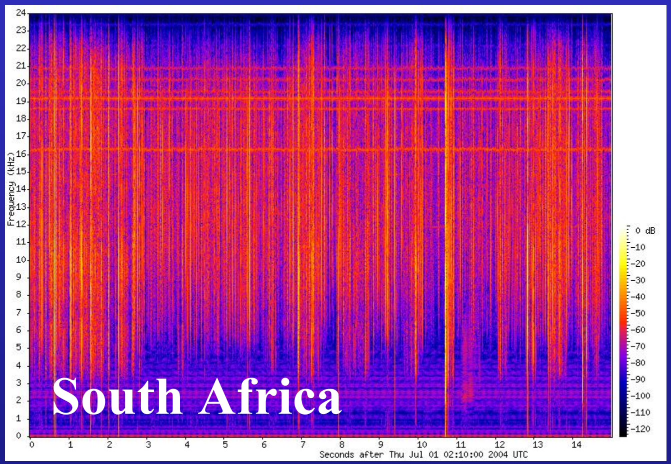
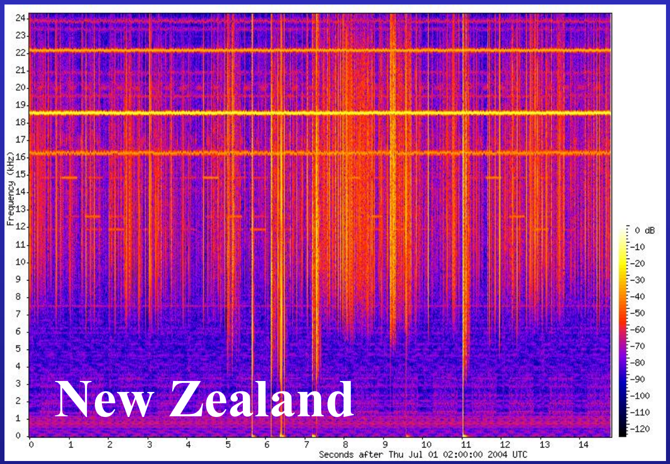
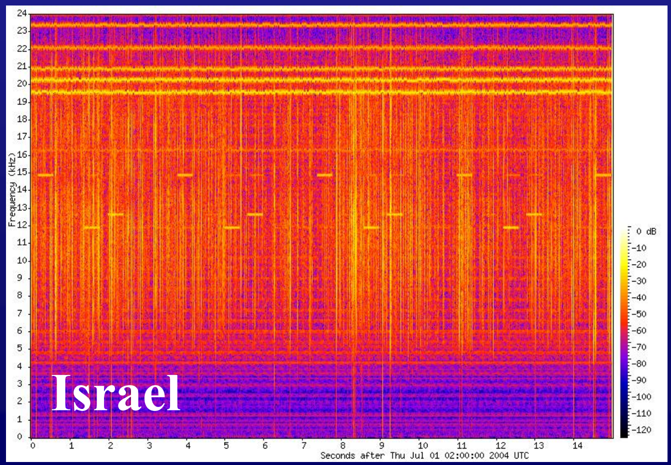
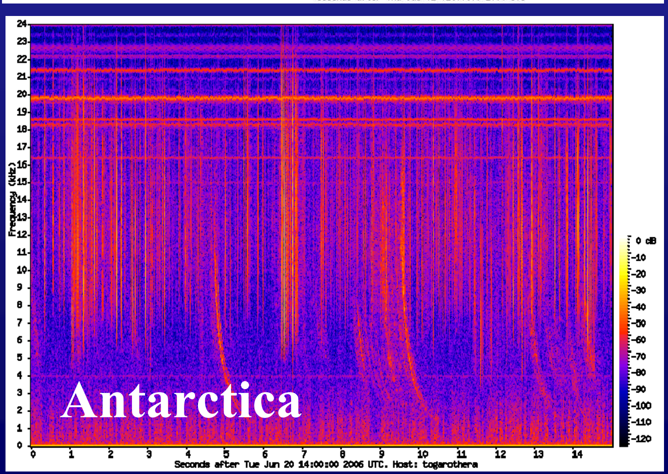
Lightning (Sferics) & Whistlers

The source of whistlers is incredibly common (44 lightning flashes per second on average across the globe) – the electromagnetic radiation from lightning in the VLF range is detectable everywhere in the world and is the dominant naturally occurring ELF/VLF radiation observed.



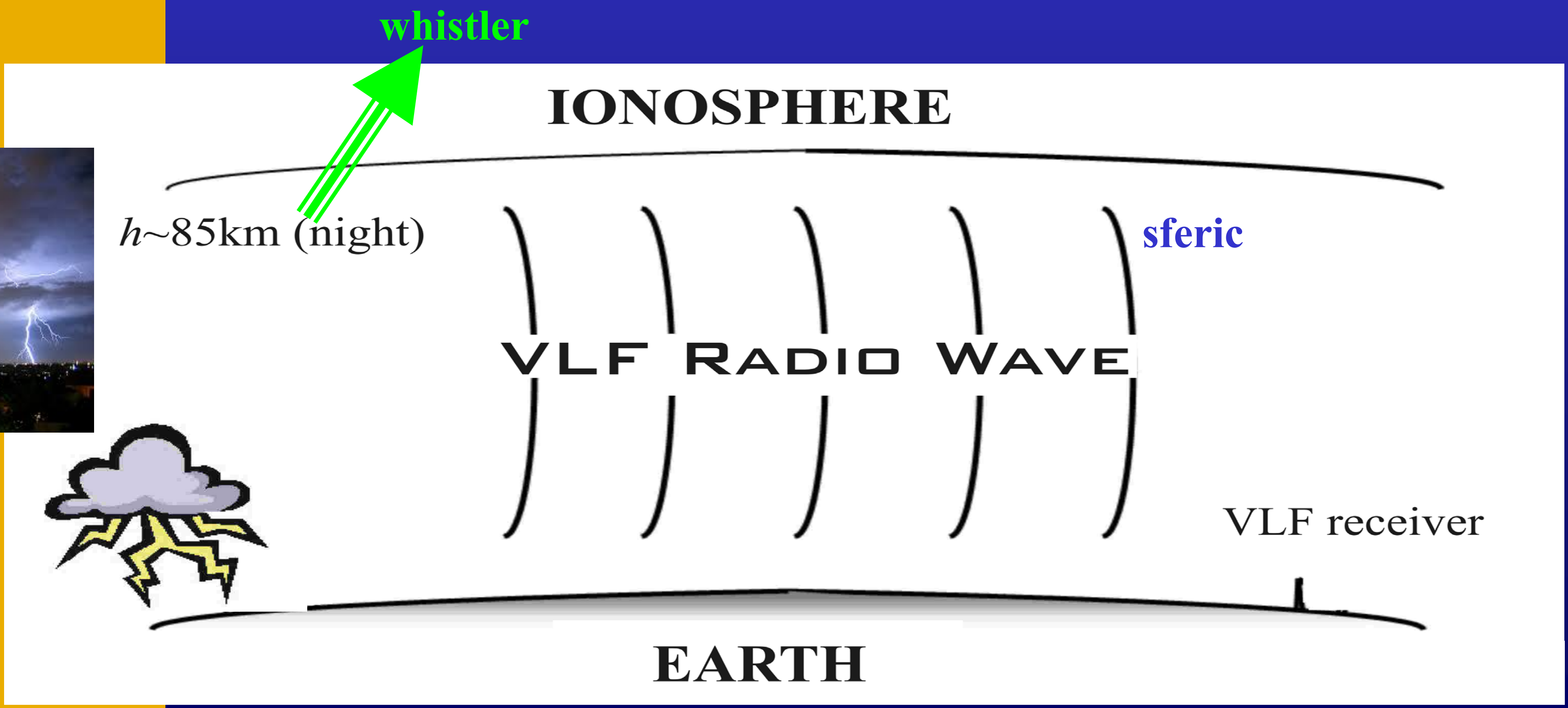






Lightning (Sferics) & Whistlers

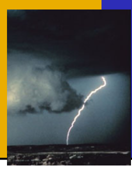
- The majority of the energy from VLF radio atmospherics ("sferics") propagates in Earth-ionosphere waveguide
- Lightning output powers are even more powerful than man made broadcasts in the ELF-VLF band
- Some fraction of the sferic energy leaks through the ionosphere, which makes the whistler

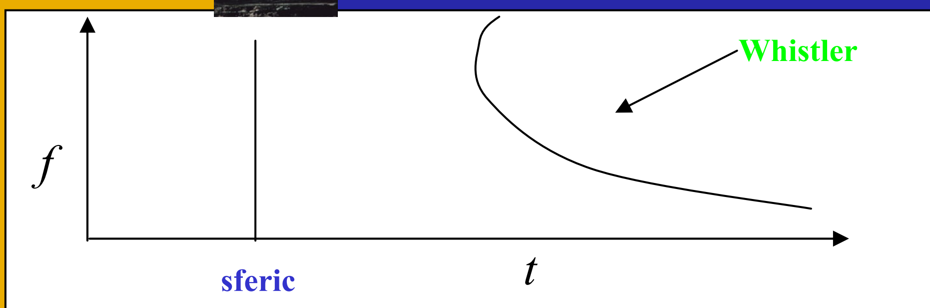


Lightning+Dispersion=Whistler

- Propagation of EM radiation in this situation well described by the Appleton-Hartree Equations
- Propagation velocity is dependent upon frequency, leading to the classic whistler shape (and "noise freq.)

$$v_g = \frac{c}{n_g} = \frac{2c\ f^{\frac{1}{2}}\left(f_B \cos\theta - f\right)^{\frac{3}{2}}}{f_p\ f_B \cos\theta}$$





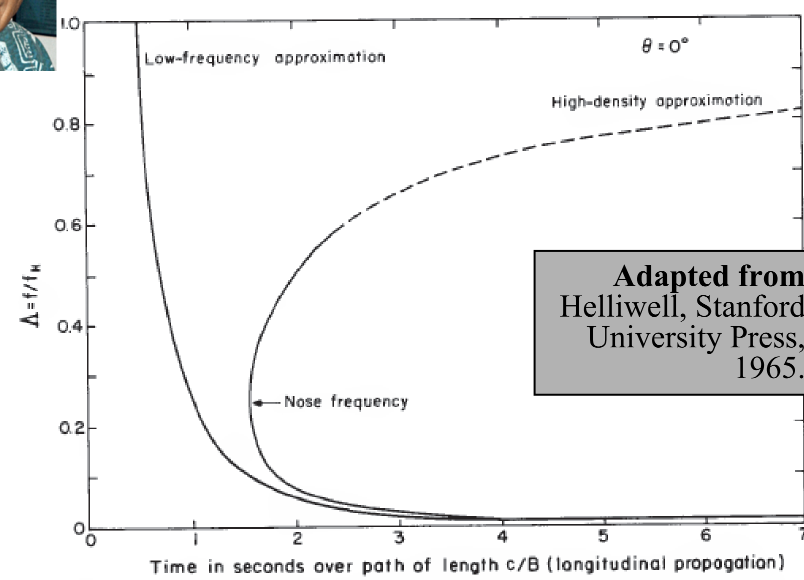


FIG. 3-5. Normalized frequency versus group delay for longitudinal propagation over a path of length c/B.

Adapted from Helliwell, Stanford University Press, 1965.

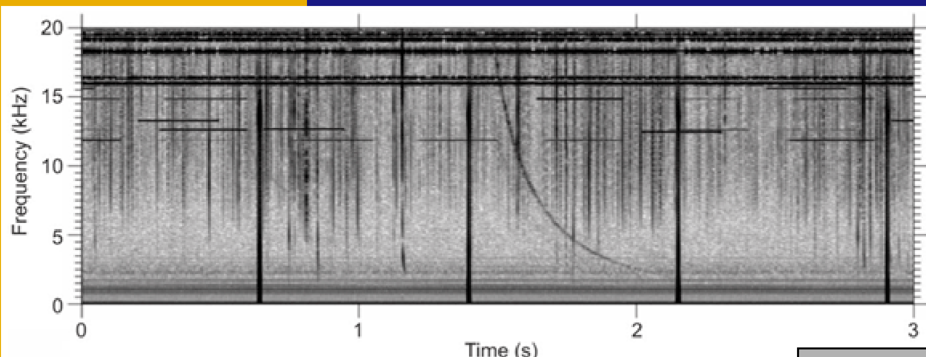


Fig. 1. Example of a whistler recorded at Tihany, Hungary, at 19:41 UTC on 22 January 2003.

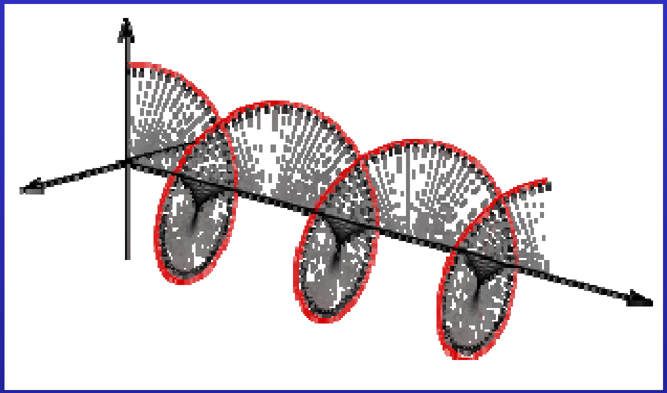
Adapted from Öster et al., *Sth. African J. Sci.*, 105(5-6), 2009,

Polarisation

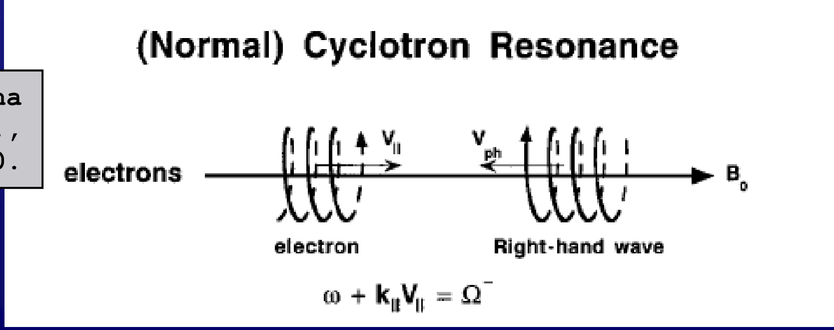
- Whistler waves are right-hand circularly polarised (from the point of view of the source), which is the same sense as an electron gyrating in a magnetic field

  $\Rightarrow$ **electron cyclotron mode**

And of course we now recognise all the other classes of "whistler mode waves" which propagate in the magnetosphere (and beyond) driven by the same Physics.



- This allows classic "cyclotron resonance" to occur, where a whistler **wave at a given frequency** can resonate with an **electron of a given energy**.



"Normal" cyclotron resonance occurs between counter-streaming waves and electrons (generally with energies of tens to hundreds of keV).

Tsurutani and Lakhina (1997), *Rev. Geophys.*, doi:10.1029/97RG02200.

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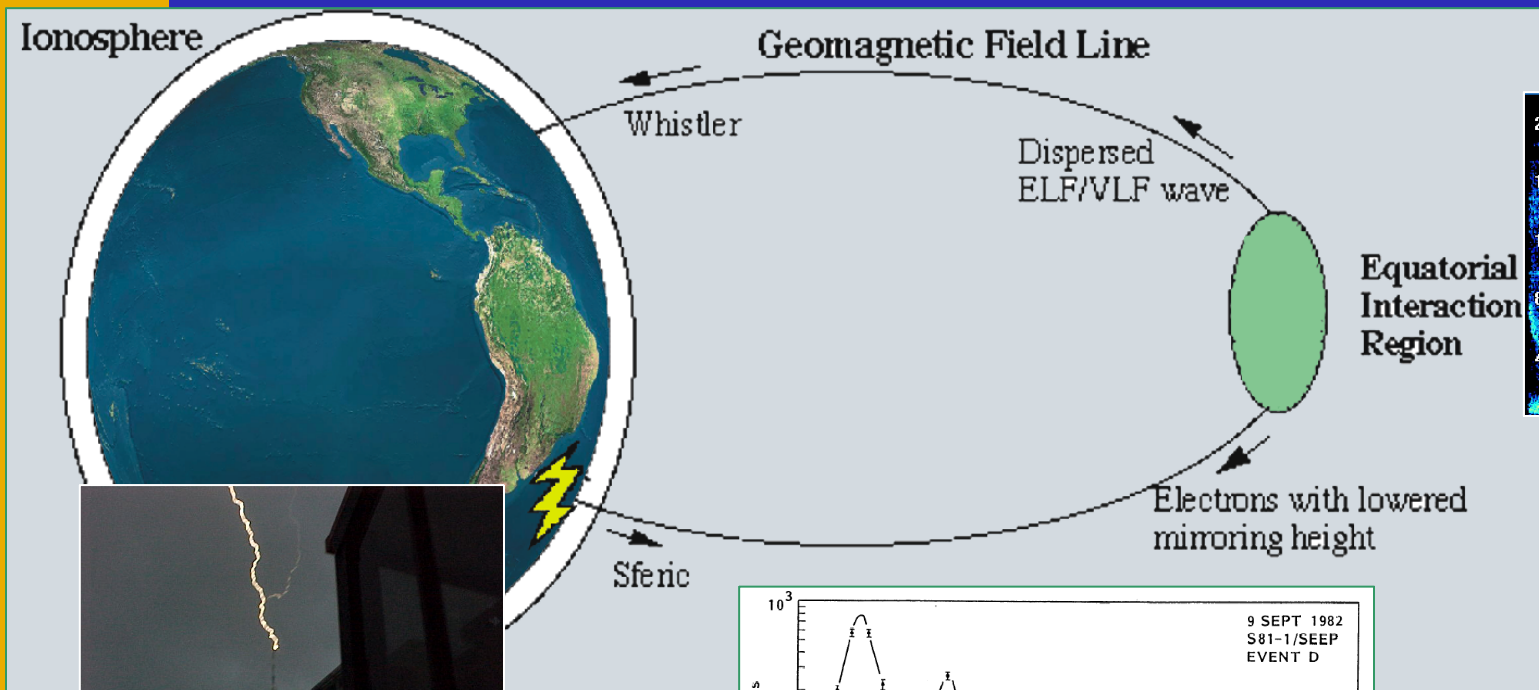
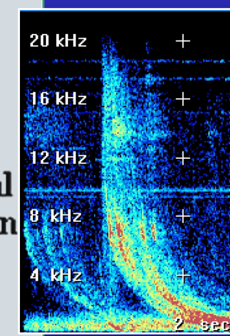
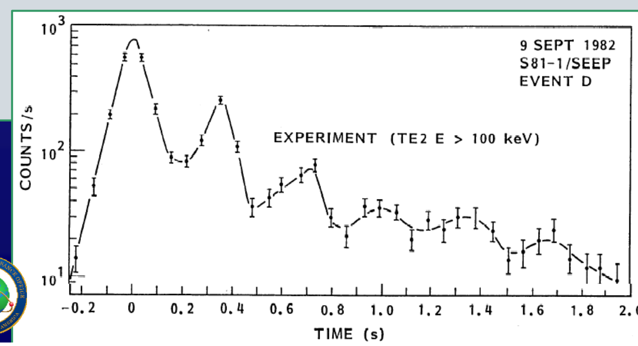
Lightning Generated Whistlers remove electrons from the Van Allen inner belt

It is well known that the amplification of *whistlers* through wave-particle interactions leads to a pulse of energetic electrons pitch-angle scattered into the loss cone

⇒ **whistler induced electron precipitation** (WEP)





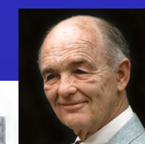


Voss et al., *J. Geophys. Res.*, vol. 103, 1998.

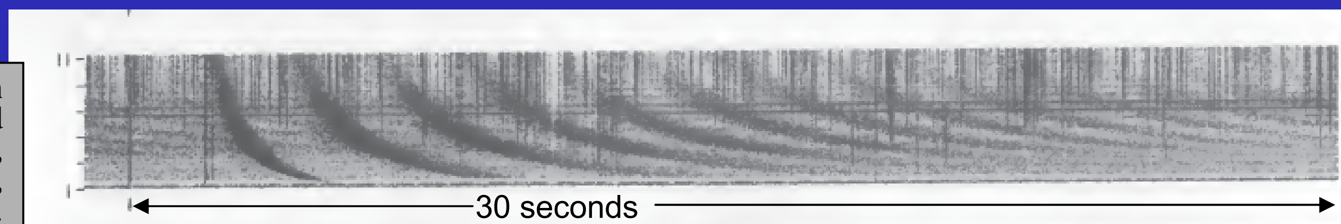
Electrons from the Van Allen belts needed to produce "whistler trains"

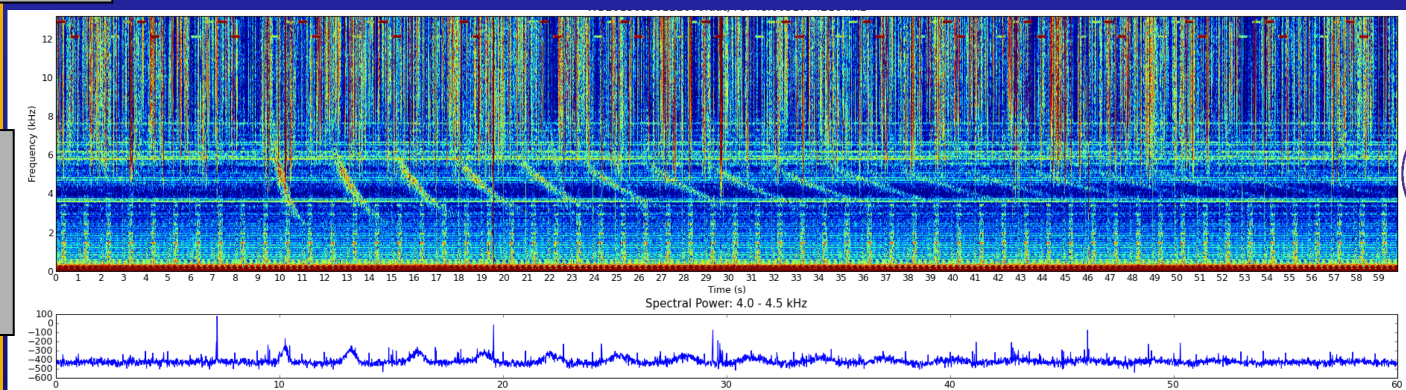
Wave-particle interactions with inner belt energetic electrons amplify the whistler on each pass through the belts, allowing a very long lived series of increasingly dispersed whistlers to be seen on the ground

⇒ **whistler echo train**

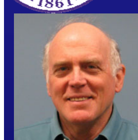


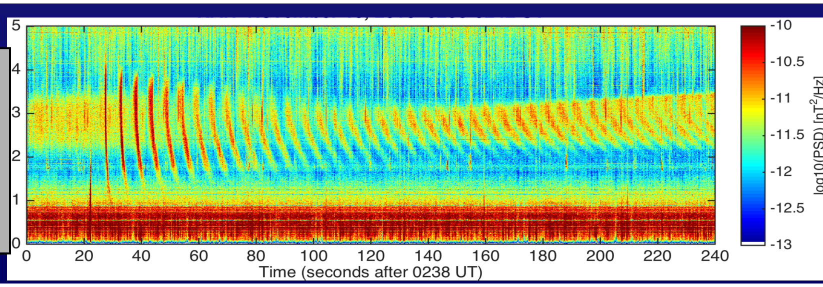
Adapted from Helliwell, Stanford University Press, 1965. 1 June 1958, Wellington (NZ).



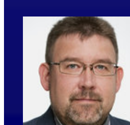


Echo Train courtesy of Bob Holzworth (U. Washington), observations from Forks (WA) in 2013.





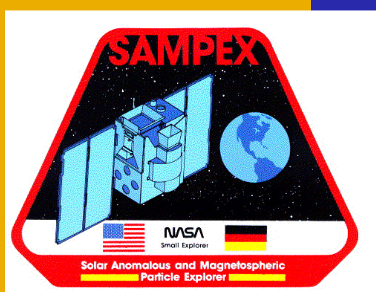
Echo Train courtesy of Jyrki Manninen (U. Oulu), observations from Kannuslehto (FIN) in 2016.



Do the whistler-driven losses from the RB matter?

Meredith et al. [2009] examined SAMPEX data for relativistic electrons fluxes in the slot region (L=2.4-3), and determined the lifetimes.

They found these lifetimes were an order of magnitude less than expected from hiss alone. These authors concluded that plasmaspheric hiss PLUS ducted whistlers were required, and were the dominant loss drivers.



Meredith et al., *J. Geophys. Res.*, vol. 114, doi:10.1029/2008JA013889, 2009.

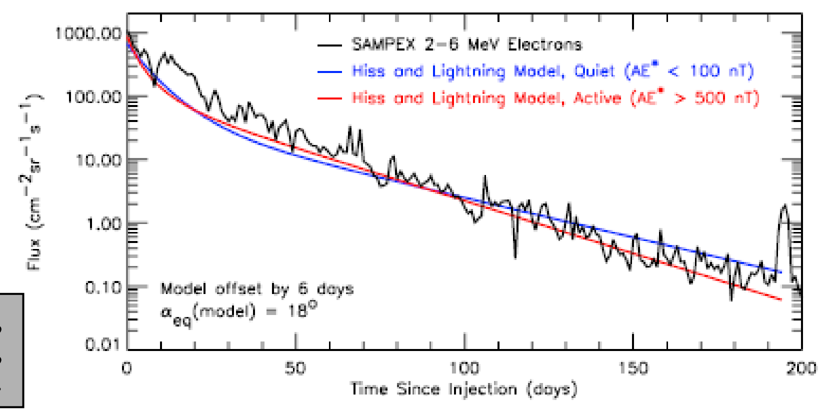


Figure 7. (top) Time evolution of 2–6 MeV electron flux (black) measured by SAMPEX at α_{eq} = 18°, starting on DOY 328, and the decay of the model distribution function due to the combined spectrum of plasmaspheric hiss and guided whistlers for (blue) quiet and (red) active conditions. (bottom) Time evolution of the models shifted in time by 6 days into the simulation.

While it has commonly thought that plasmaspheric hiss was the dominant driver for the slot, whistlers also play a role.

Variability of Global Lightning activity

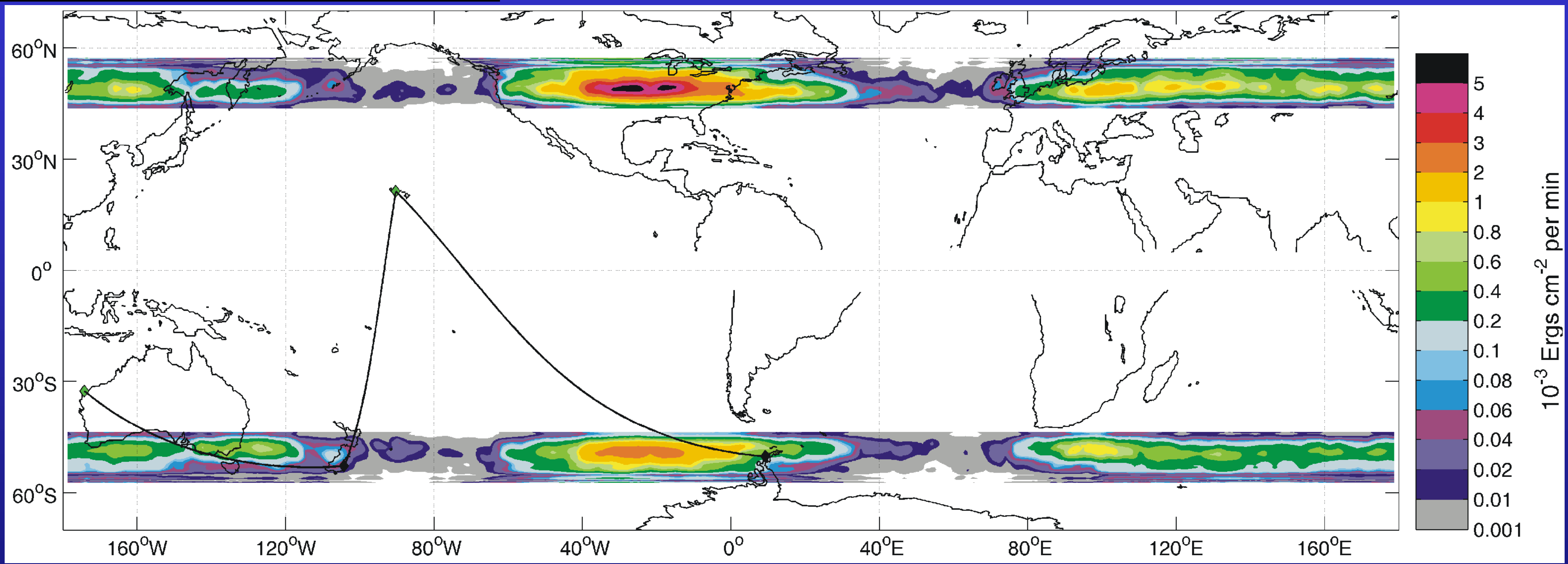
As whistlers are caused by lightning activity it seems reasonable that there should be a linkage between lightning activity levels and whistler detection. On this basis one would expect much higher whistler rates in some parts of the world when contrasted with others.

GEOMAGNETIC ACTIVITY DISTRIBUTION

Adapted from the LIS v1.0 Low Resolution Full Climatology dataset, shifted into CGM coordinates.

Expected global distribution in the rate of energy deposited by WEP into the atmosphere

From: Rodger et al. (2007), *Ann. Geophys.*, www.ann-geophys.net/25/1745/2007/ .



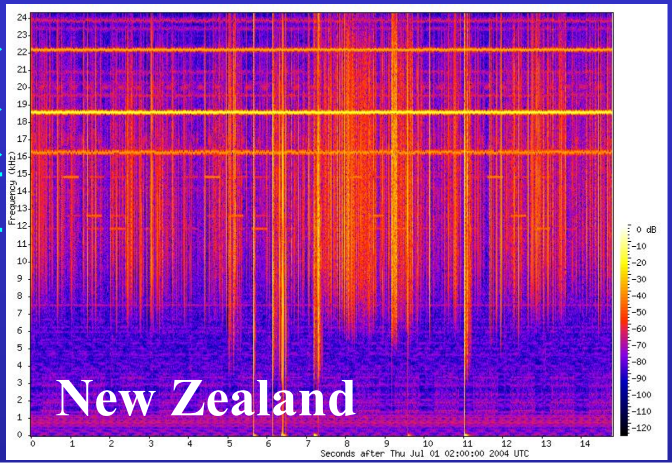
First pulse in WEP is into the lightning source hemisphere, and as lightning occurs more in the northern hemisphere more energy will be deposited in the north than south.

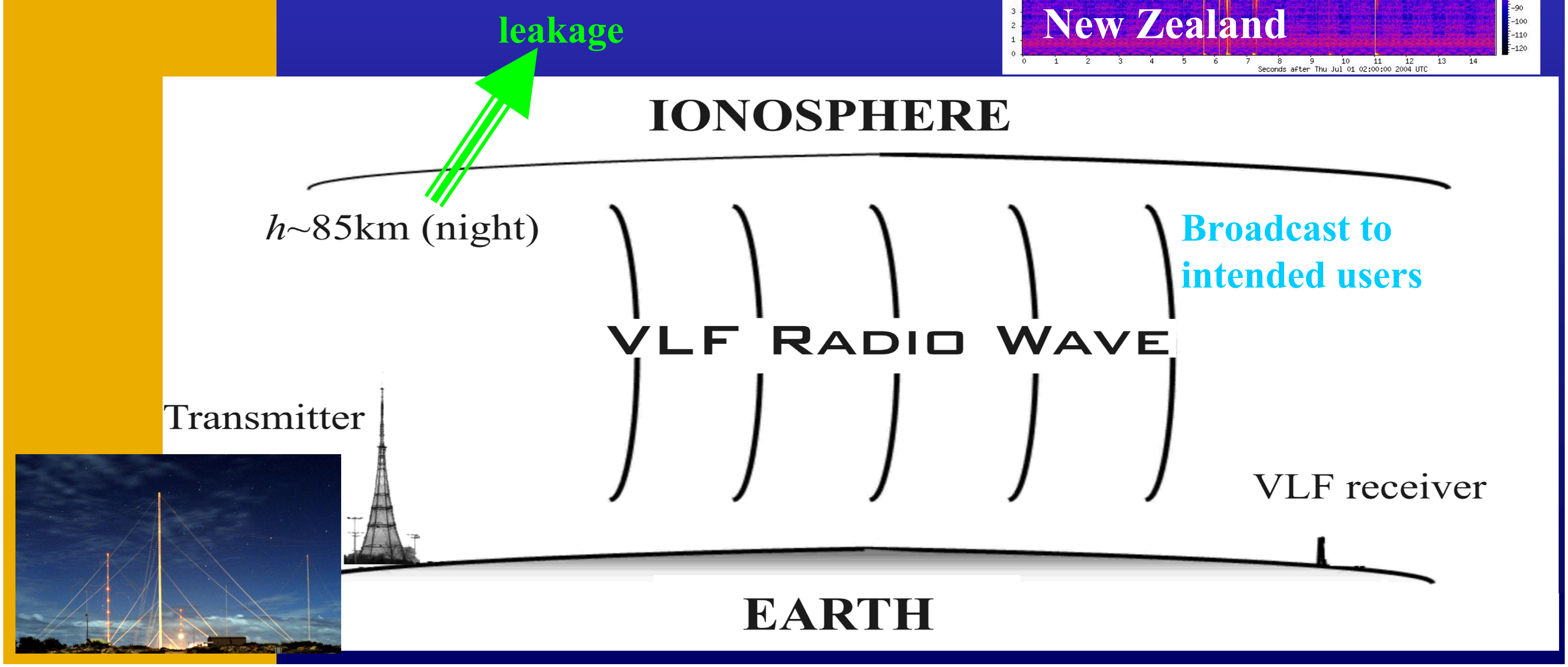
Peak is above North America, lowest energy depositions in oceans. This study suggested **WEP is a significant energy input into the lower ionosphere in some regions**, depending on the latitude/longitude and altitude (but is not significant to the neutral chemistry of the mesosphere).

What about Manmade VLF Transmitters?

All the spectra I showed earlier had strong fixed frequency signals in them, due to transmissions from manmade VLF transmitters.

These powerful transmissions should also leak out into the magnetosphere and act as a manmade source of whistler-mode waves.





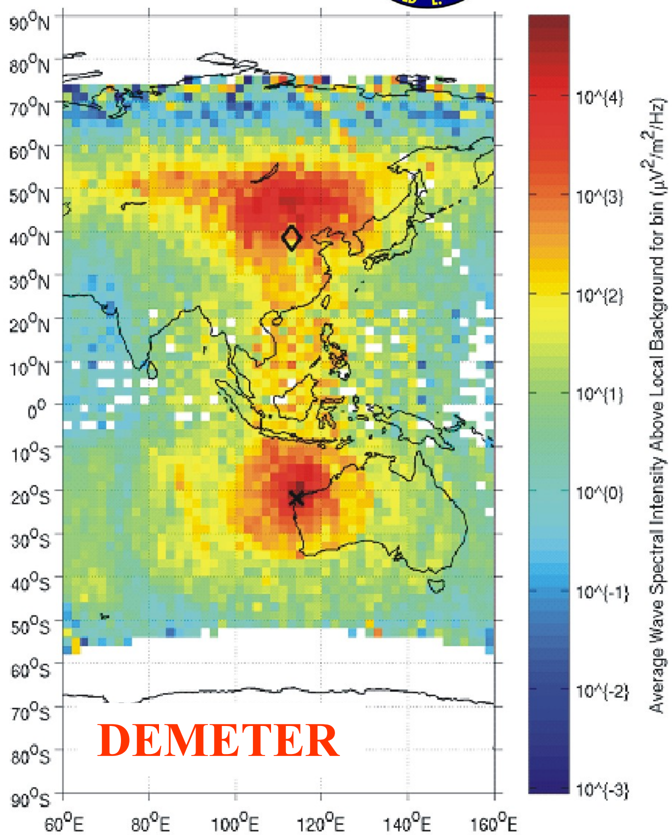
VLF transmitters

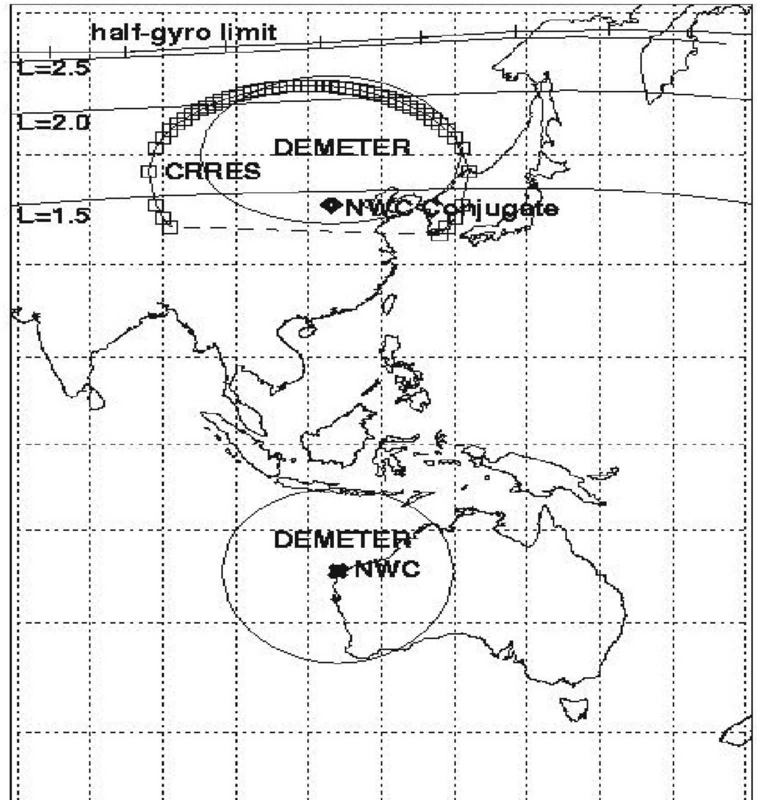
Primarily military communications transmitters. Very high output powers and near continuous operation.

Neil Thomson in front of the towers of the US Navy VLF transmitter at Lualualei, Hawaii (**NPM**). Radiated power of 500 kW at 21.4 kHz. Each tower is 460m high.

GoogleEarth view of the US Navy VLF transmitter **NAA** (Cutler, Maine). Radiated power of ~1 MW at 24.0 kHz.

NWC L=1.44





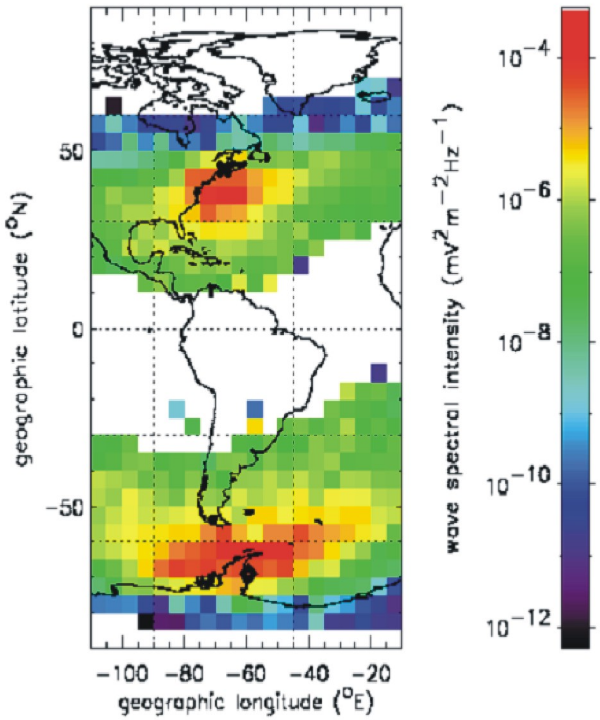
Adapted From: Clilverd et al. *J. Geophys. Res.,* 113, A04211, doi:10.1029/ 2007JA012602.

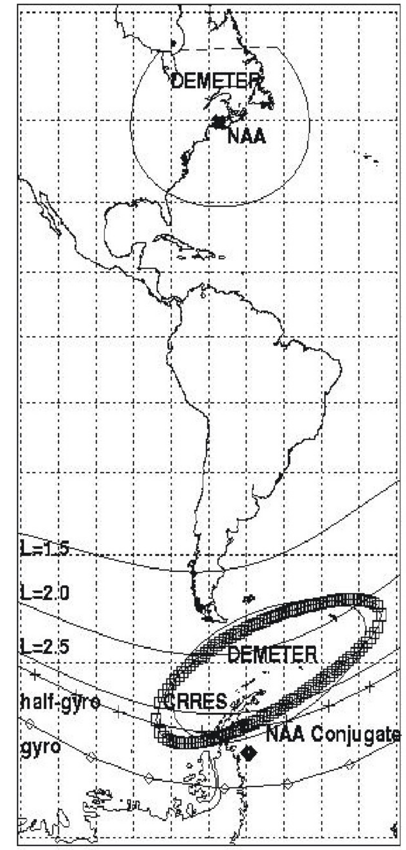
1 MW output power transmitter with call sign **NWC** broadcasts at a frequency of 19.8 kHz . One of the most powerful transmitters in the world.

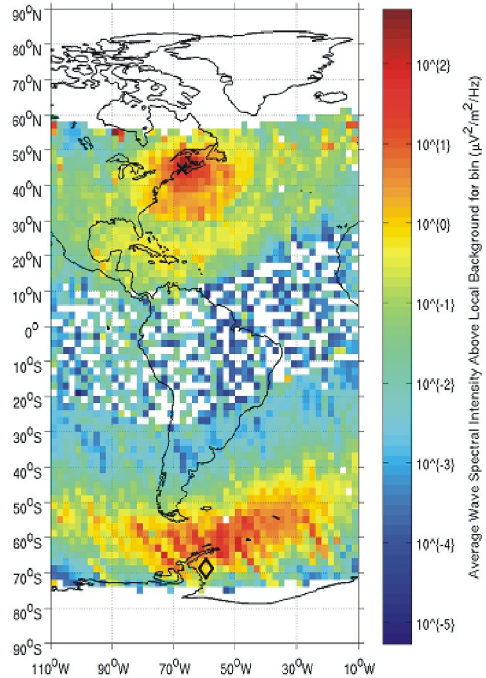
Shows very strong leakage above the transmitter, with energy in the conjugate region as well.

NAA L=2.93

CRRES







DEMETER

Adapted From: Clilverd et al. *J. Geophys. Res.*, 113, A04211, doi:10.1029/ 2007JA012602.

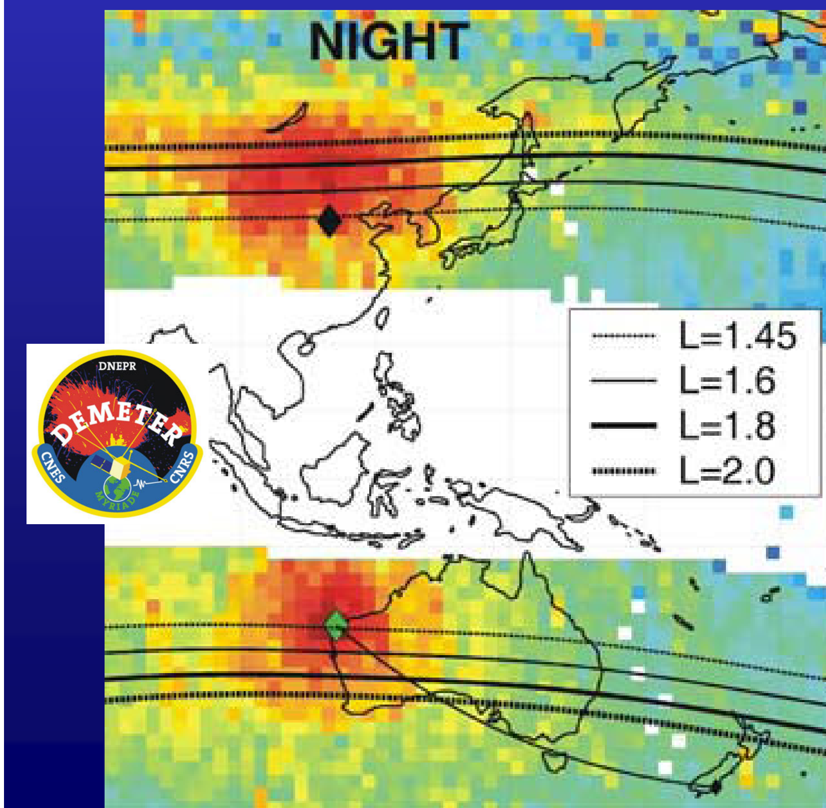
1 MW output power transmitter with call sign NAA broadcasts at a frequency of 24.0 kHz. Also one of the most powerful transmitters in the world.

Shows very strong leakage above the transmitter, with energy in the conjugate region as well.

NWC Transmitter

- US Naval VLF transmitter
- *L*=1.45
- Frequency: 19.8 kHz
- Signal strength is logged by VLF receiver in Dunedin (AARDDVARK network).

- Good candidate for observing the influence on inner belt energetic particles:
  - higher latitude VLF transmitters resonate with energies lower than DEMETER can detect
  - NWC is west of the SAMA
  - NWC is extremely powerful: **1000kW** radiated power



Identified as a strong source of ducted waves.

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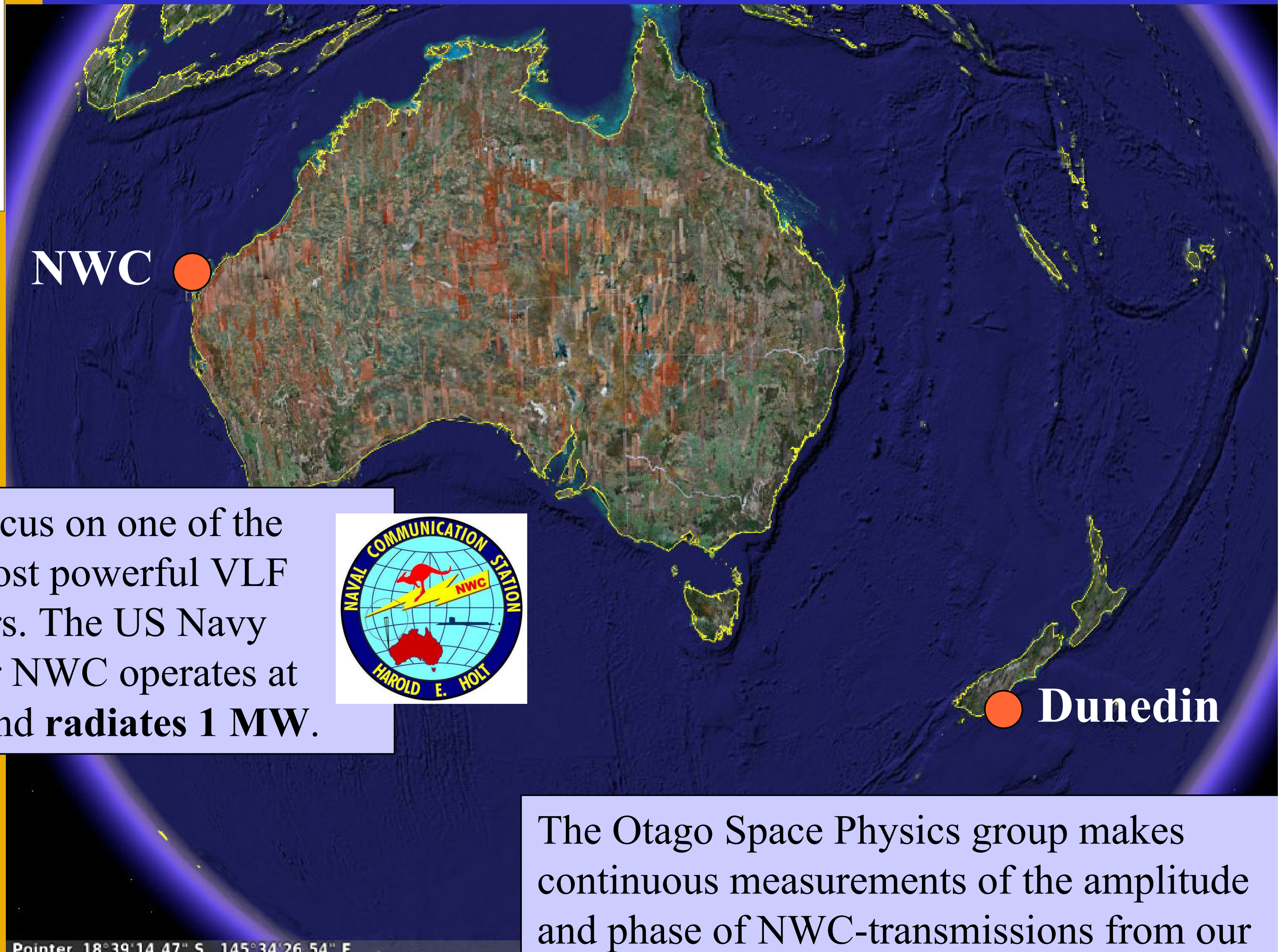
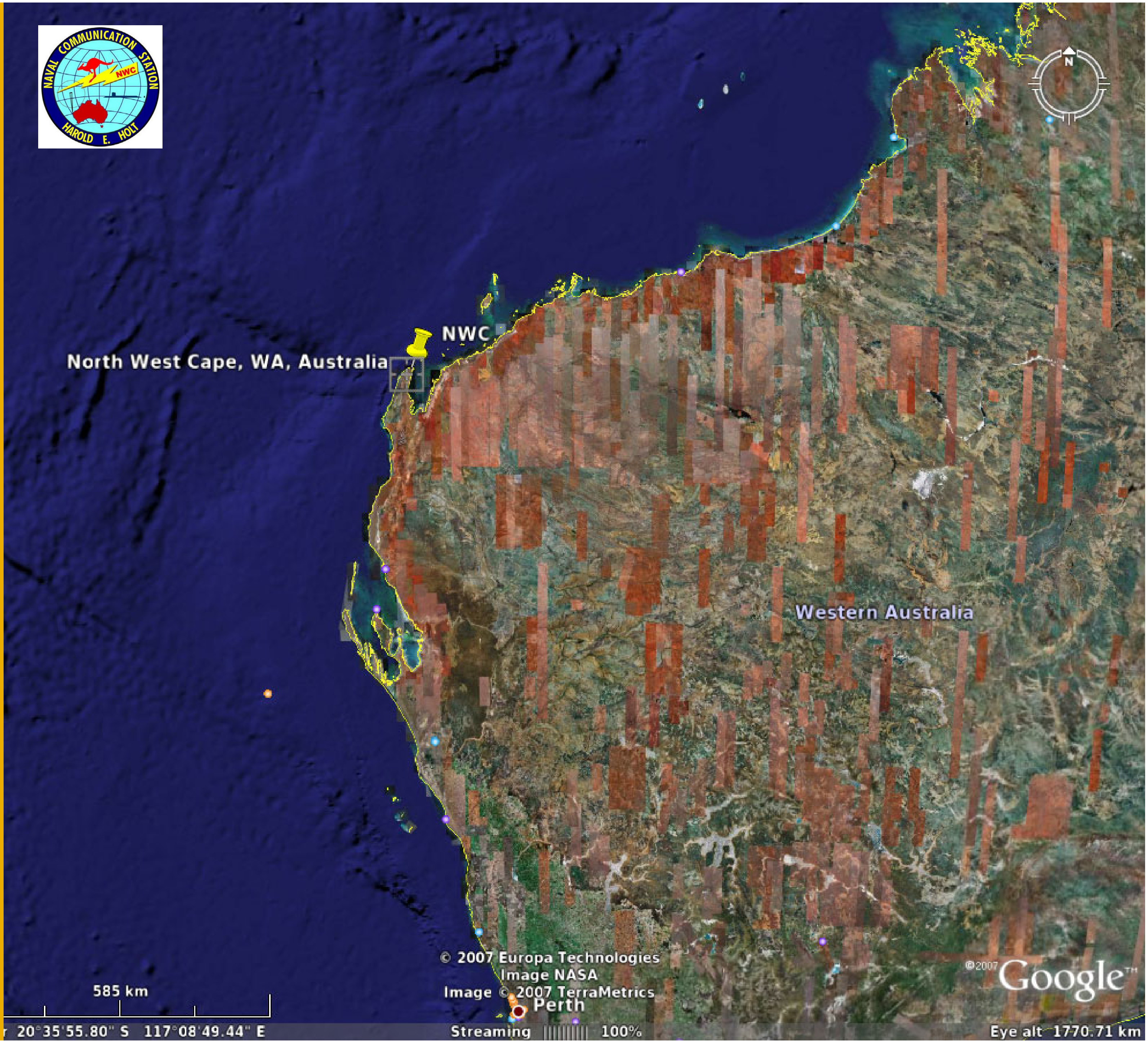
There is an example of strong Tx in my "backyard"



We will focus on one of the world's most powerful VLF transmitters. The US Navy transmitter NWC operates at 19.8kHz and **radiates 1 MW**.

The Otago Space Physics group makes continuous measurements of the amplitude and phase of NWC-transmissions from our antenna at Scott Base and also in Dunedin.

Altitude = 6200 km



Altitude
= 1800 km

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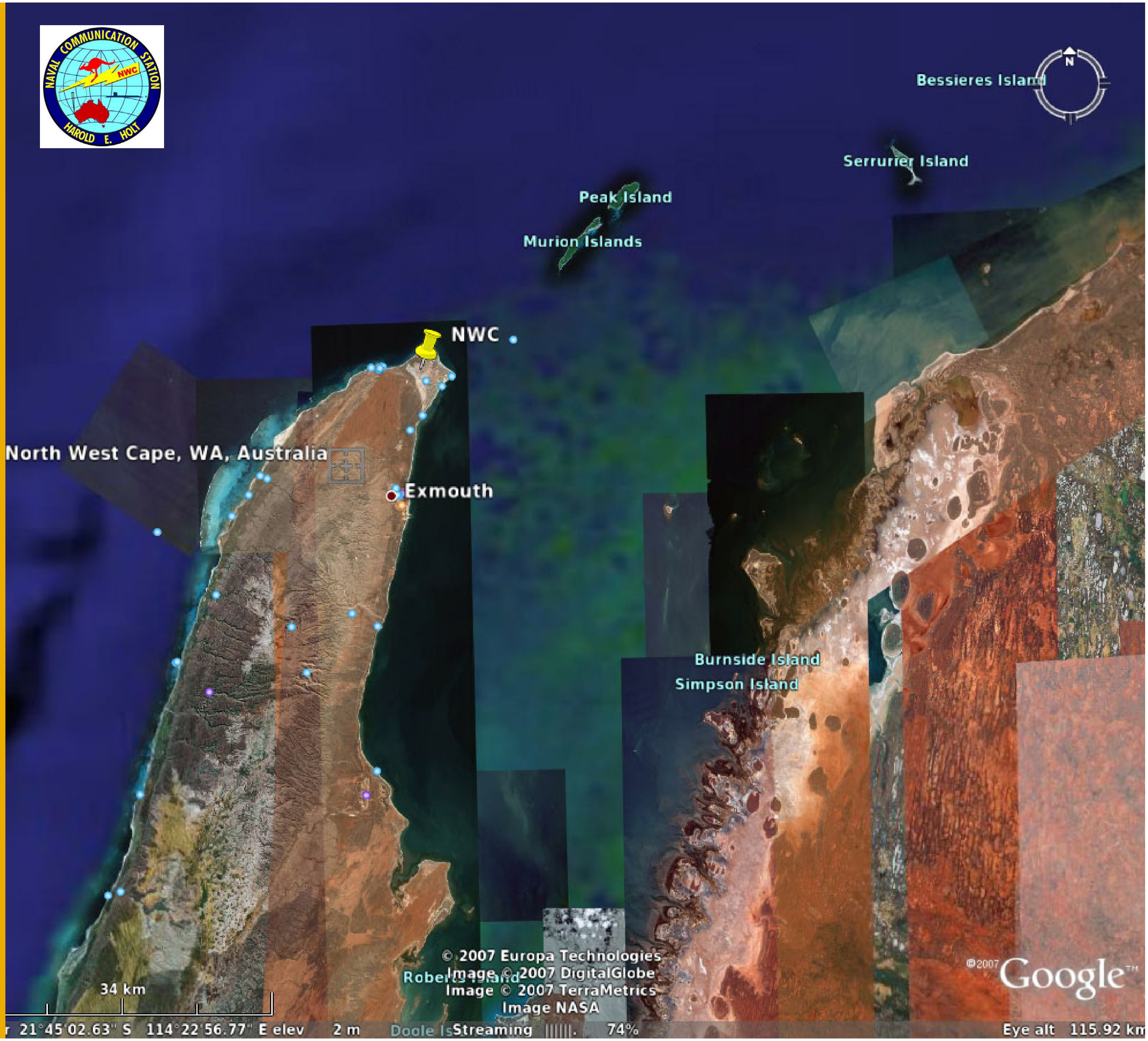
NAVAL COMMUNICATION STATION HAROLD E. HOLT NWC



Altitude
= 120 km

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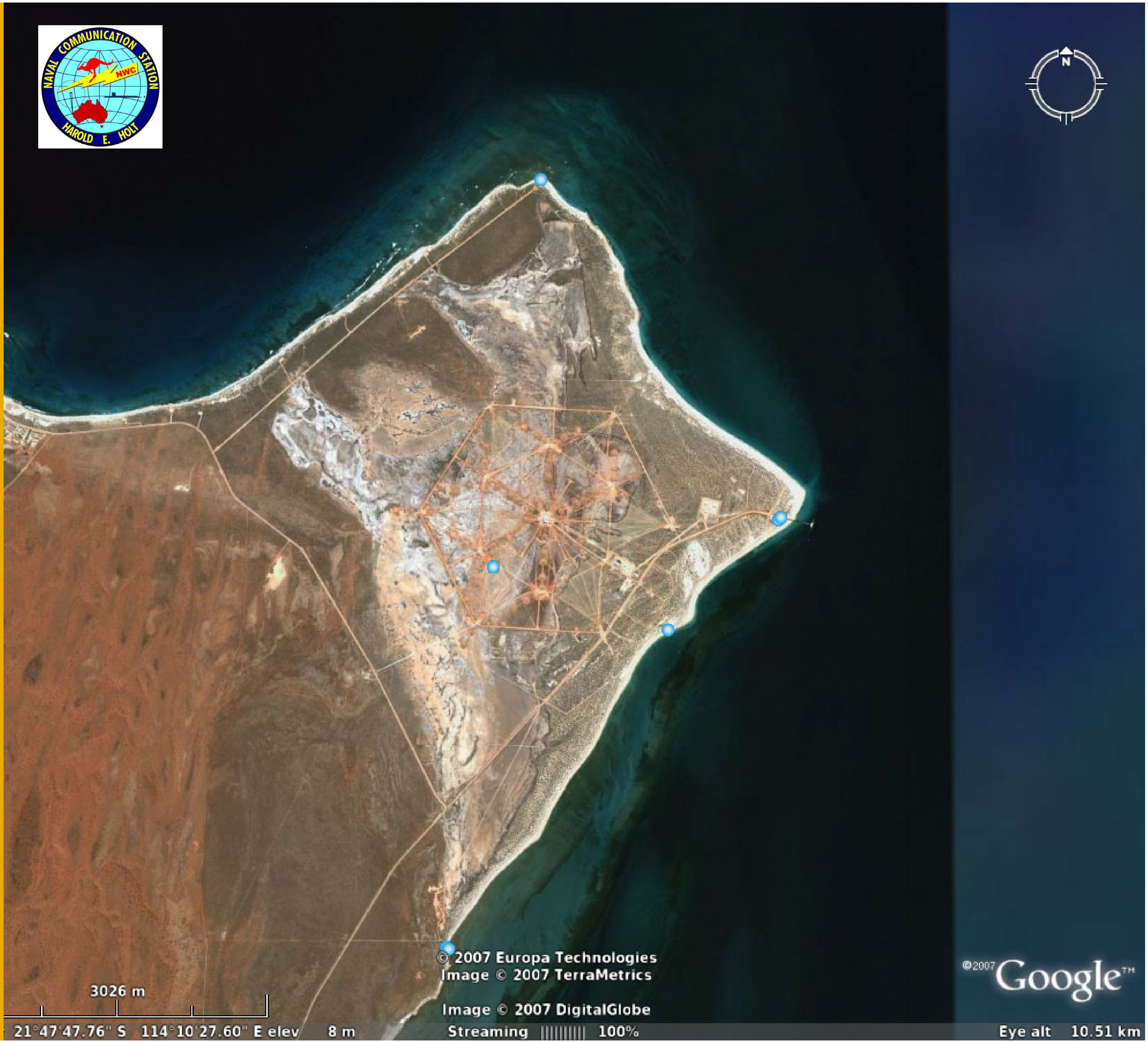

Altitude
= 11 km

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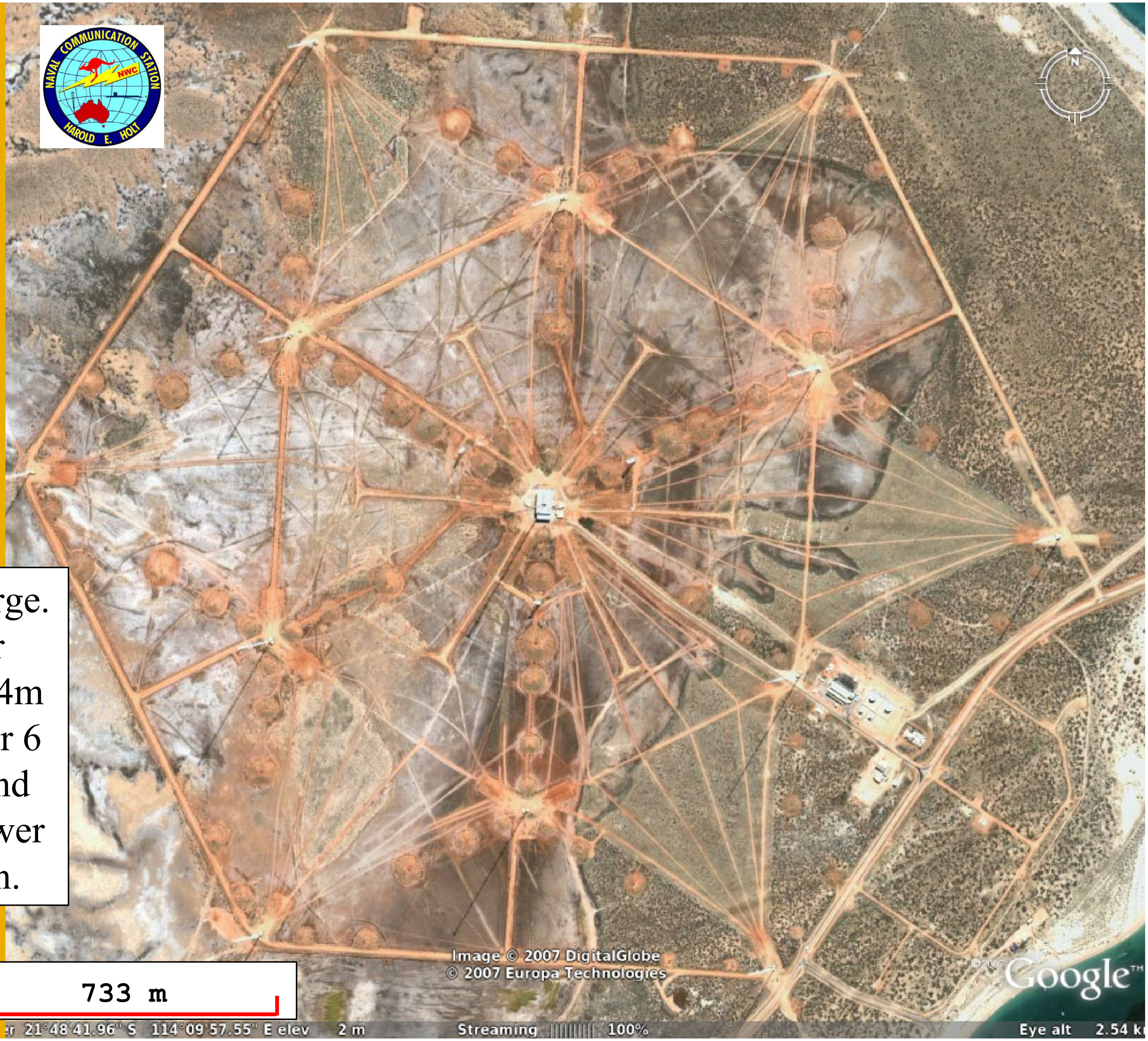
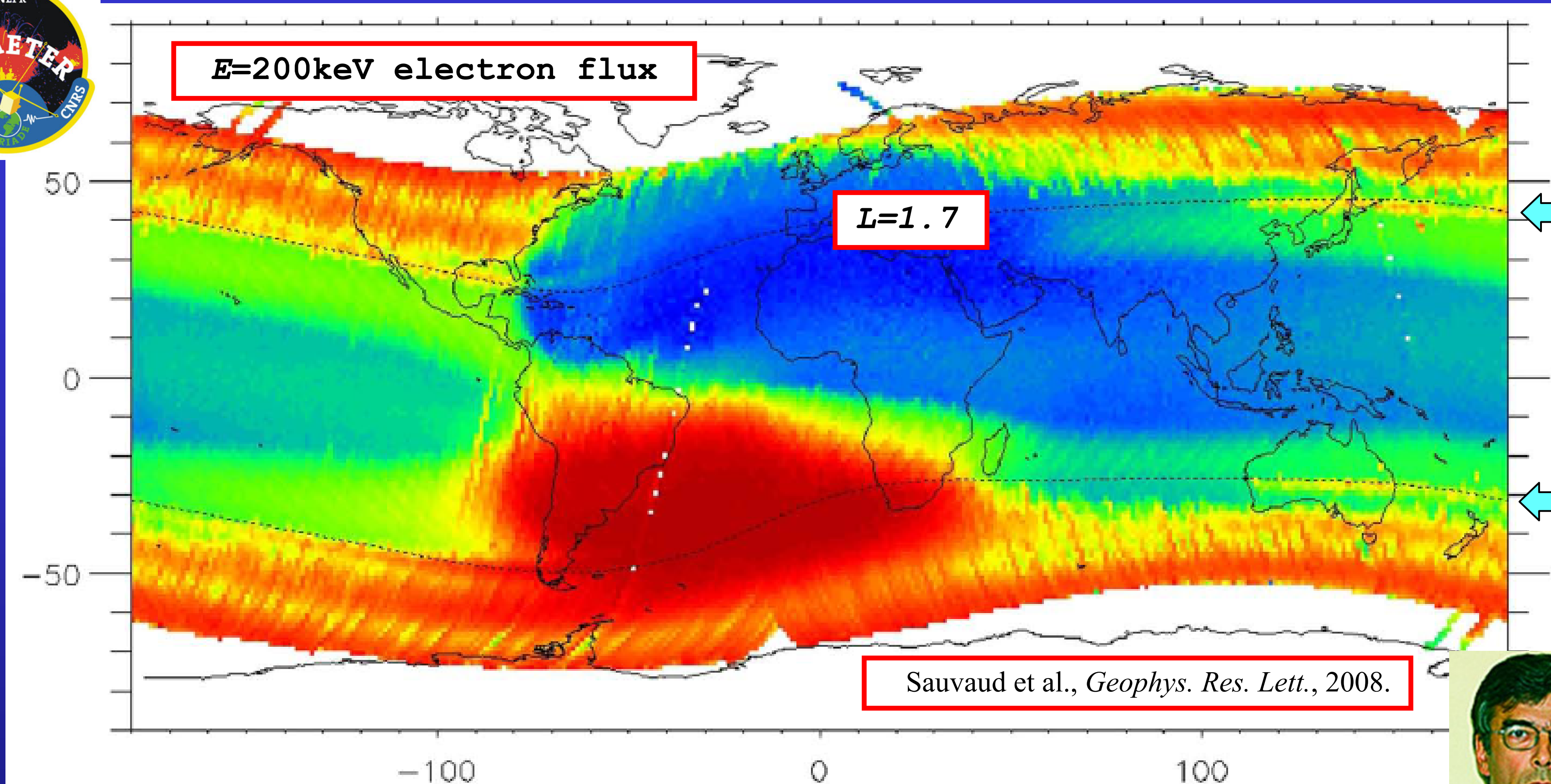


It is VERY large. The 6 outer towers are 364m high, the inner 6 are 304 m, and the central tower is 387m high.

Altitude = 3 km

733 m



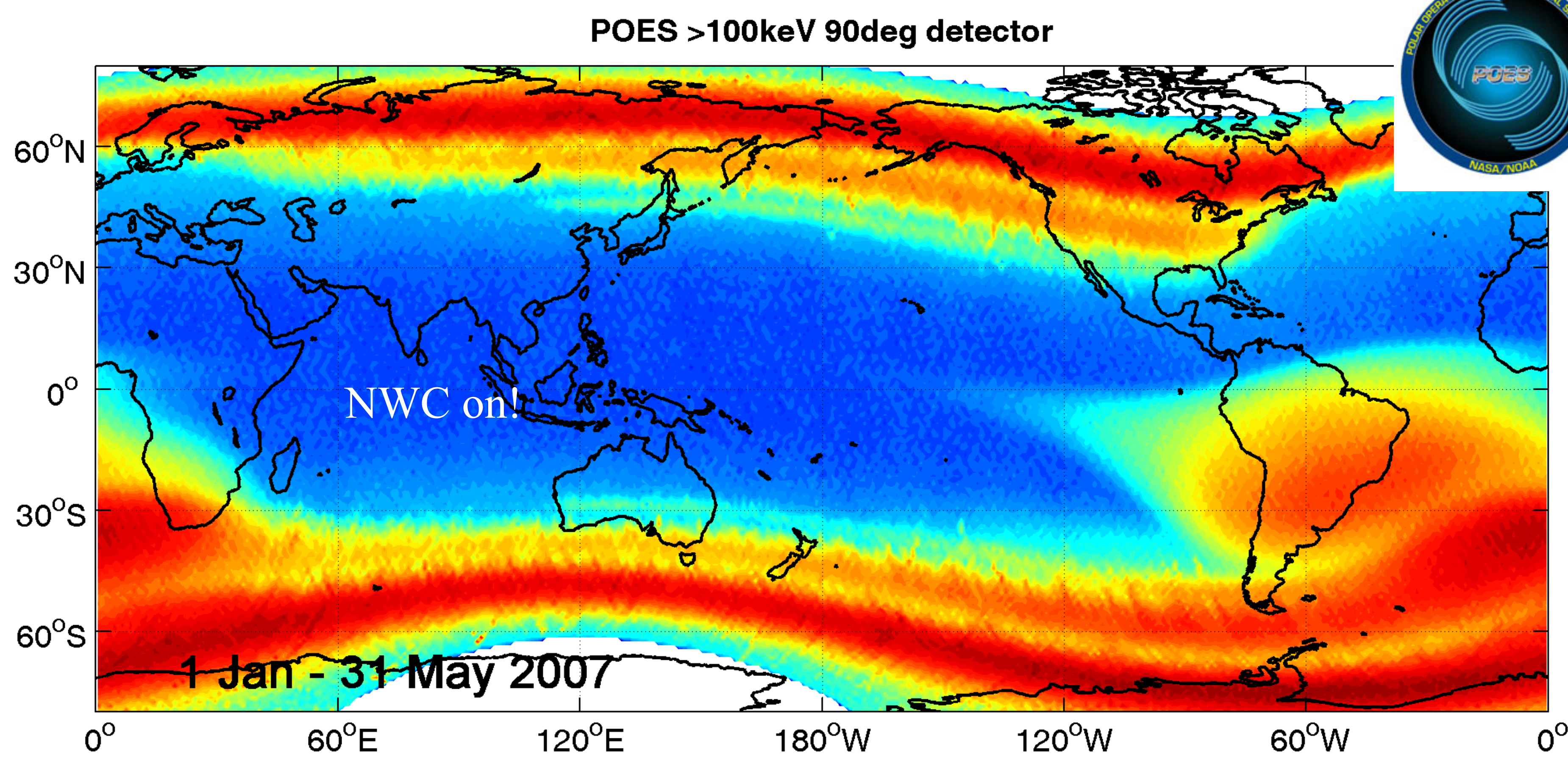
- **Drift Loss Cone** electron fluxes at 200 keV, as seen by DEMETER

- The structure associated with NWC is only detected eastward of the west coast of Australia, as expected from the electron drift motion.

- Structure in both hemispheres, from NWC across to the South Atlantic Magnetic Anomaly (SAMA) where the electrons precipitate into the atmosphere.

Effect of NWC on the fluxes

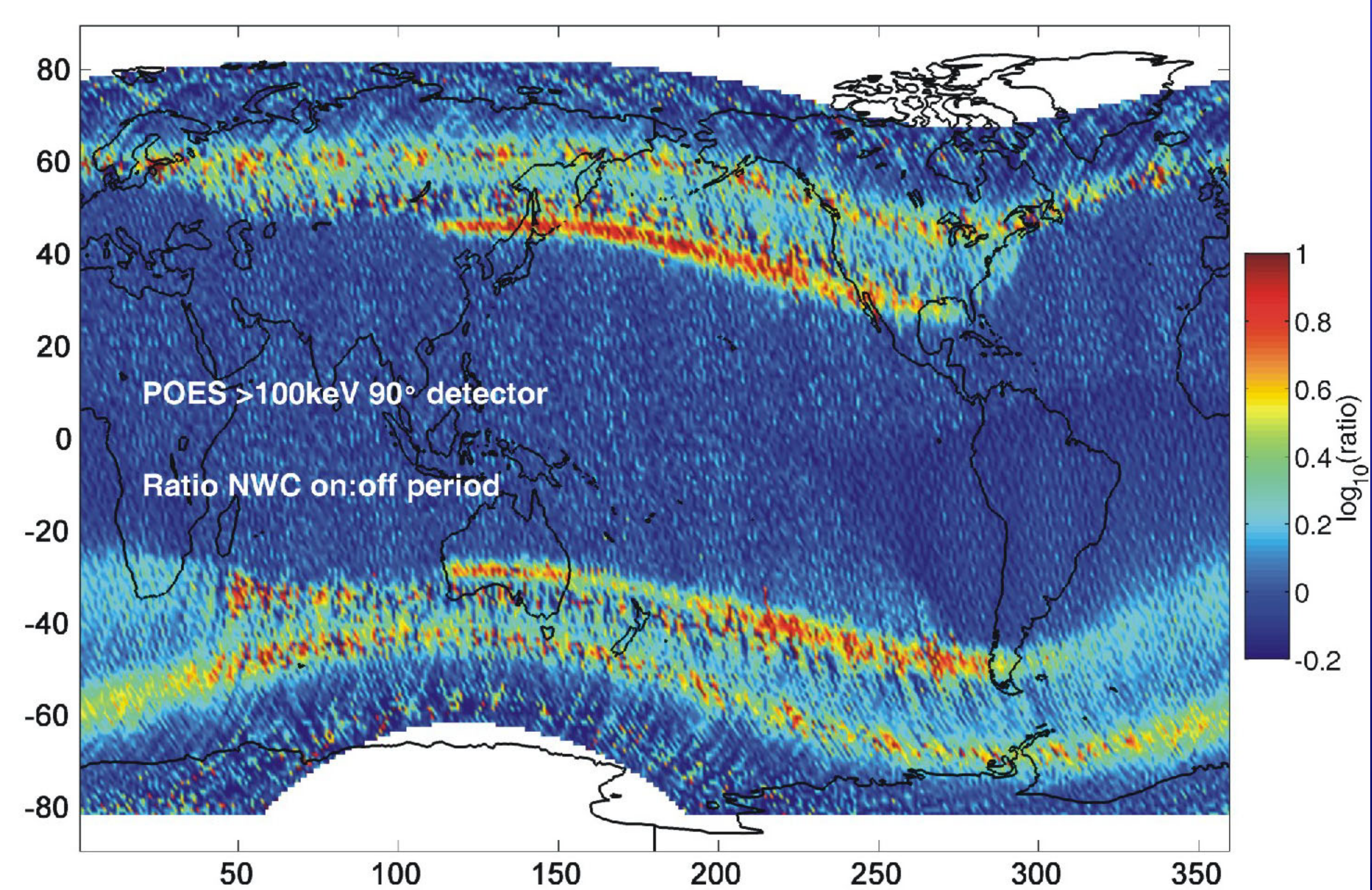
Here we combine 5 months of >100keV observations from the 4 NOAA POES spacecraft (N-15,-16,-17, & -18). This is the measurements from the 90º pointing instrument, which primarily responds to trapped/quasi-trapped flux (except very near the equator).

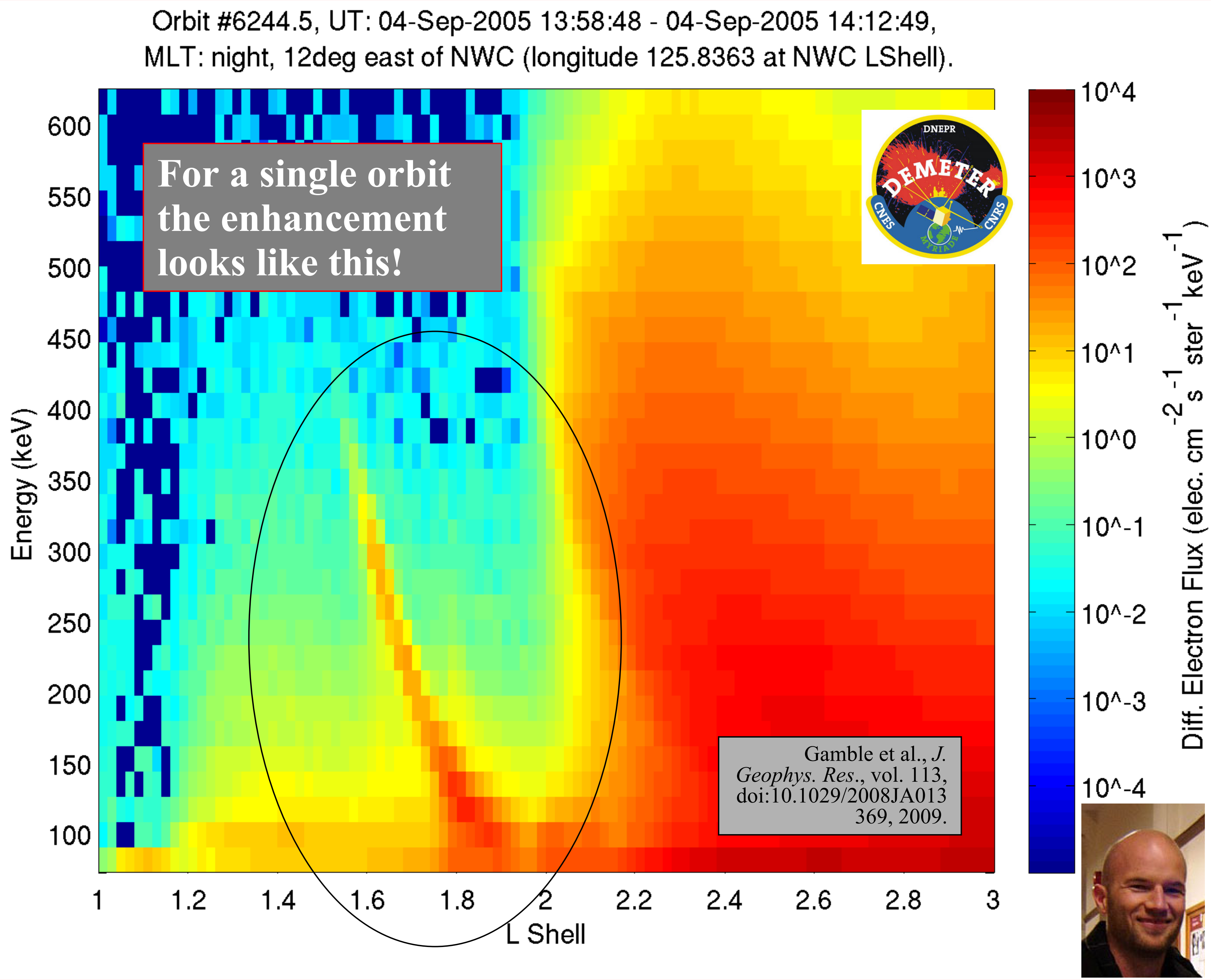


Despite NWC being **on**, the DLC scattering is not <u>super</u> clear here.

Effect of NWC on the fluxes

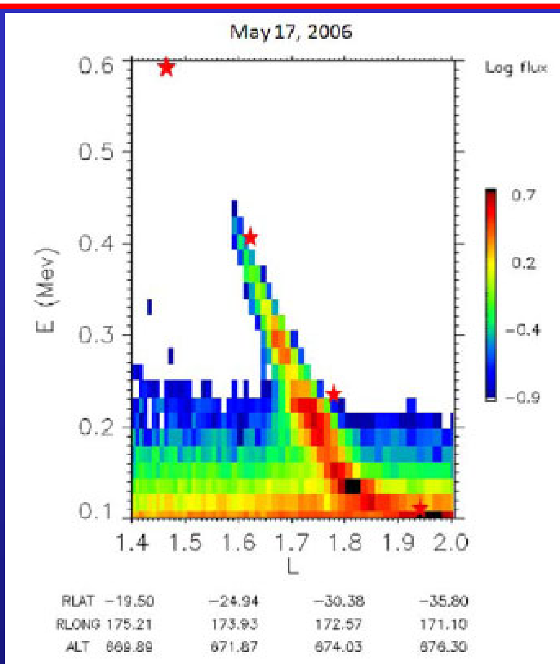
Here we take the ratio of 5 months of >100keV observations from the 4 NOAA POES spacecraft (N-15,-16,-17, & -18) when NWC was **ON** and 5 months when it was **OFF**. NOT such a subtle feature anymore!

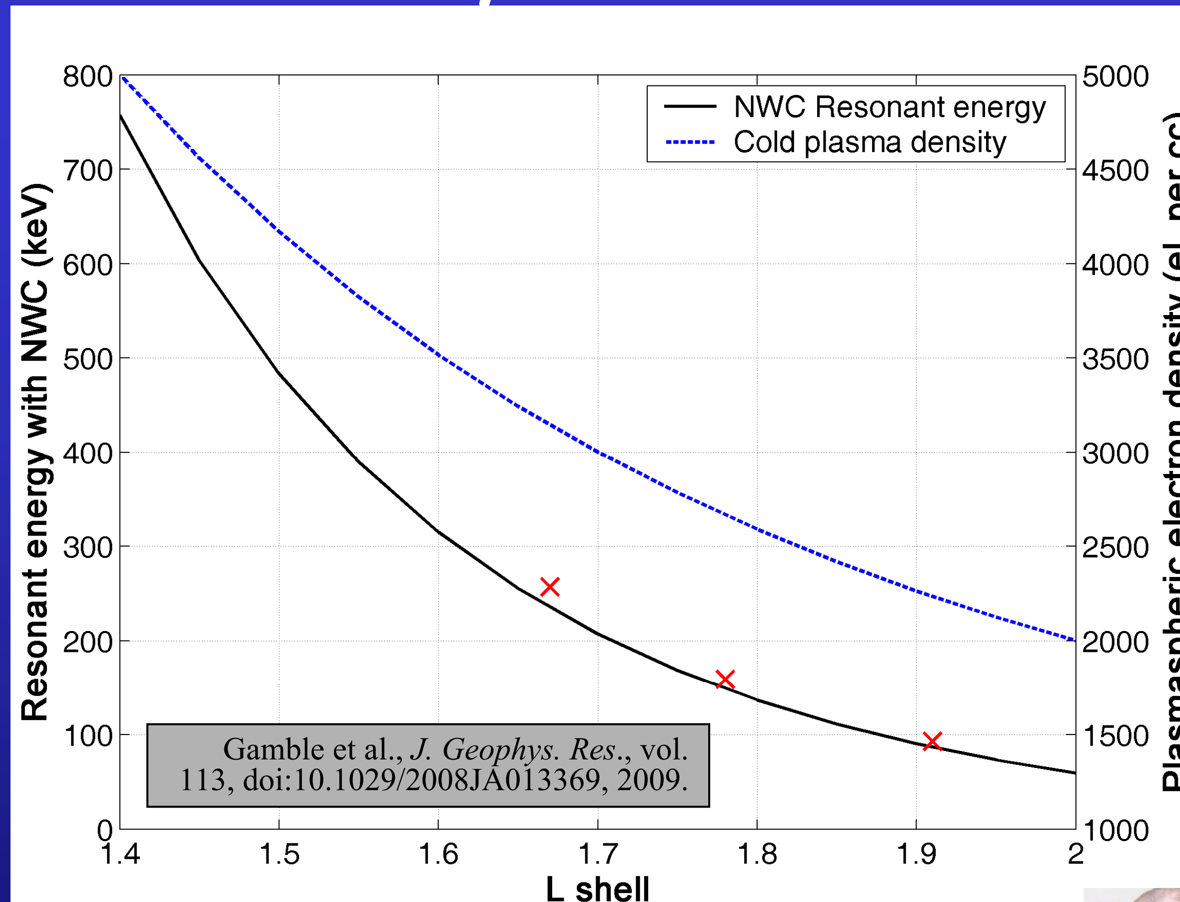



Orbit #6244.5, UT: 04-Sep-2005 13:58:48 - 04-Sep-2005 14:12:49,
MLT: night, 12deg east of NWC (longitude 125.8363 at NWC LShell).
For a single orbit the enhancement looks like this!
DNEPR
DEMETER
CNES
CNRS
MYRIADE
Gamble et al., J. Geophys. Res., vol. 113, doi:10.1029/2008JA013369, 2009.
Energy (keV)
600
550
500
450
400
350
300
250
200
150
100
1
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
2.8
3
L Shell
10^4
10^3
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-4
Diff. Electron Flux (elec. cm^-2 s^-1 ster^-1 keV^-1)

Contrast with First-order cyclotron Resonance

Sauvaud et al., *Geophys. Res. Lett.*, 2008.





Gamble et al., *J. Geophys. Res.*, vol. 113, doi:10.1029/2008JA013369, 2009.

The predicted variation with *L* of the first-order cyclotron resonant energy for electrons resonant at the geomagnetic equator with 19.8 kHz waves, compared with the experimentally derived data (× crosses).

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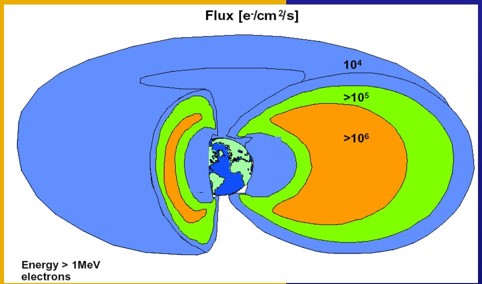
Do these transmitters "matter"?

For decades there have been claims that VLF transmitters are strong drivers of losses from the radiation belts. Al Vampola used to suggest that a transmitter near Moscow (UMS, now non-operational for >20 years) was a very significant loss mechanism.

At one point he concluded that VLF transmitters might be entirely response for the slot region.



That paper also pointed out that precipitation data in the slot region are inconsistent with the mechanism of Lyons et al. [1972] and may be entirely due to other ground-based VLF transmitters. That paper, together with the present results, indicate that the entire slot region may be an artifact of man's activities. If satellites replace VLF transmitters for both communication and navigation, we may have a chance to observe the slot refill and remain filled. If that happens, we will also see the inner zone become a very enhanced region, perhaps more enhanced even than during the post-Starfish period. We might have to continue to radiate VLF waves at high power levels in order to protect low altitude satellites.

Vampola (1983), *Geophys. Res. Lett.*, vol. 10, doi:10.1029/GL010i008p00619.

Do these transmitters "matter"?

Selesnick et al. (2013), *J. Geophys. Res.*, vol. 118, doi:10.1002/jgra.50095.

NWC produces the strongest clearest signal of experimentally observed energetic electron losses from the inner radiation belt, as seen by DEMETER and also POES drift-loss cone observations.

This plot is from modelling of NWC's effect on trapped electrons which reproduced the observed "wisp" signatures.

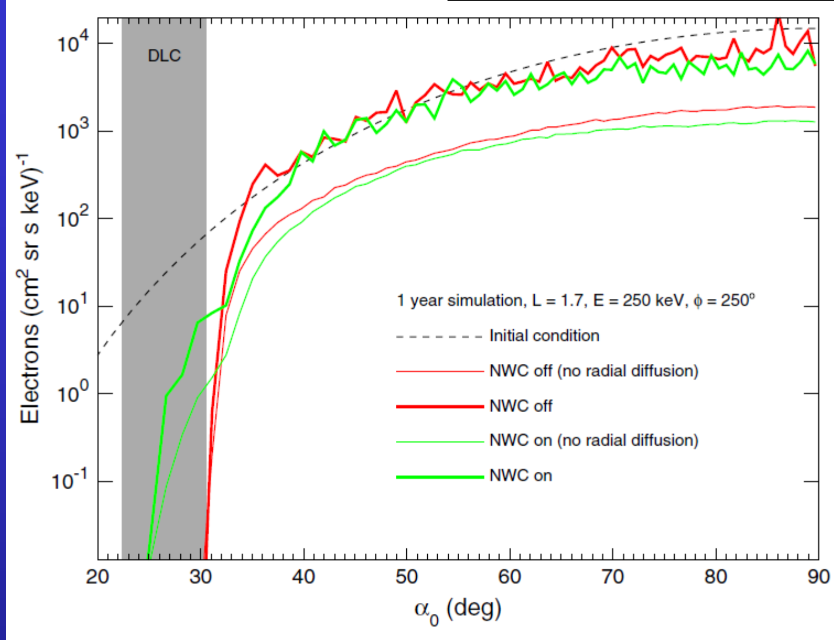


Figure 11. Model equatorial pitch angle distributions after evolving from the initial condition for 1 year, with NWC turned on or off, and with or without radial diffusion. The shaded region represents the drift loss cone.

However, this study concluded that "if NWC were shut down, the resulting increase in stably trapped electron intensity would be minimal".

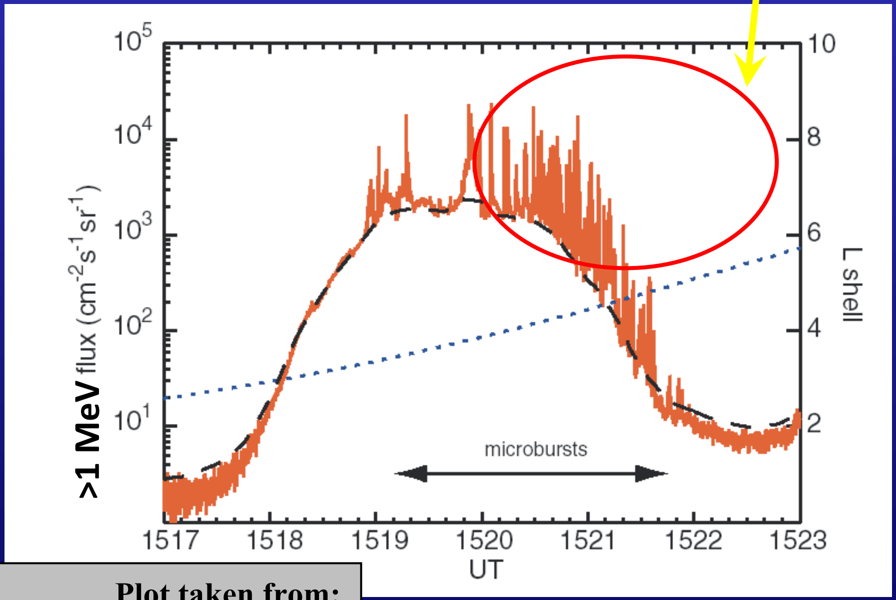
Selesnick et al. (2013), *J. Geophys. Res.*, vol. 118, doi:10.1002/jgra.50095.

Relativistic Electron Microbursts

- >1 MeV microbursts lasting <<1 s
- Typically observed at the outer edge of the outer radiation belt
- Observed at all local times, but predominantly in the morning sector
- 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]

These pulses here!

Early estimates from SAMPEX satellite observed fluxes suggested that microburst precipitation could essentially "flush out" the entire relativistic electron population during the main phase of the storm.



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

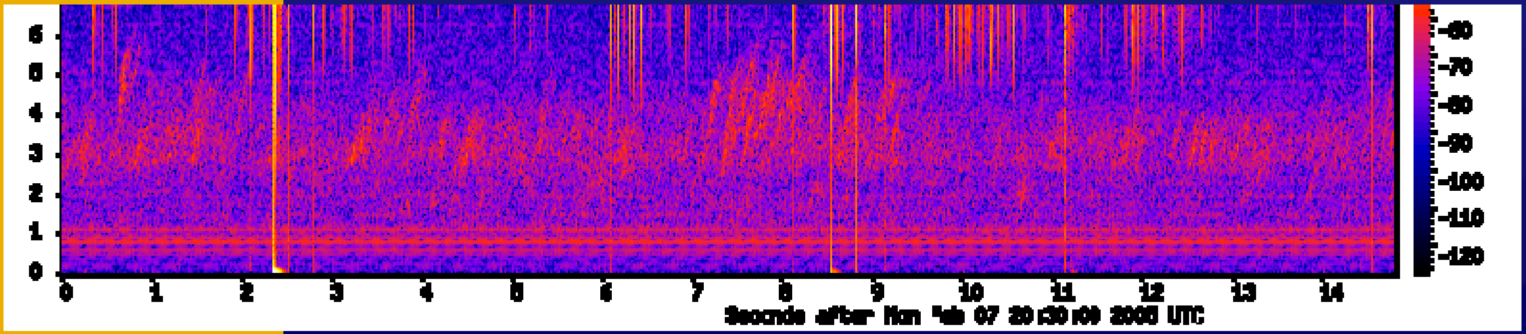
REP Microbursts & Chorus

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 hasn’t quite been demonstrated.



Chorus observed in Dunedin on 7 Feb 2005

REP Microbursts & Chorus: MLT & *L*

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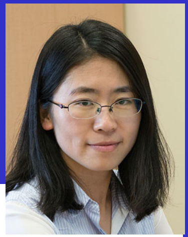
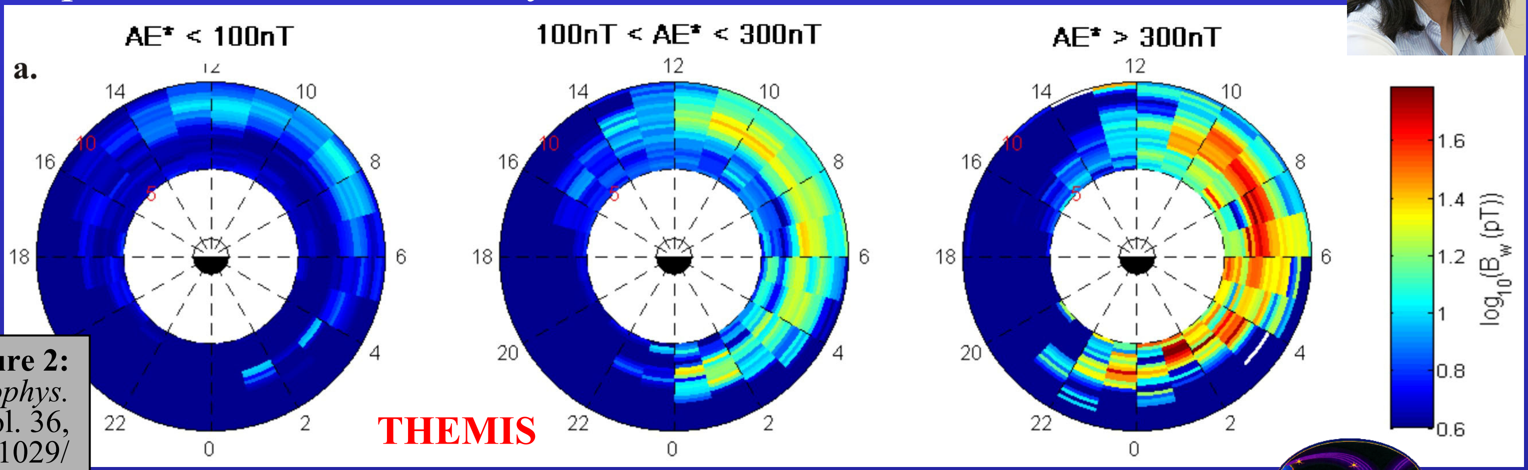


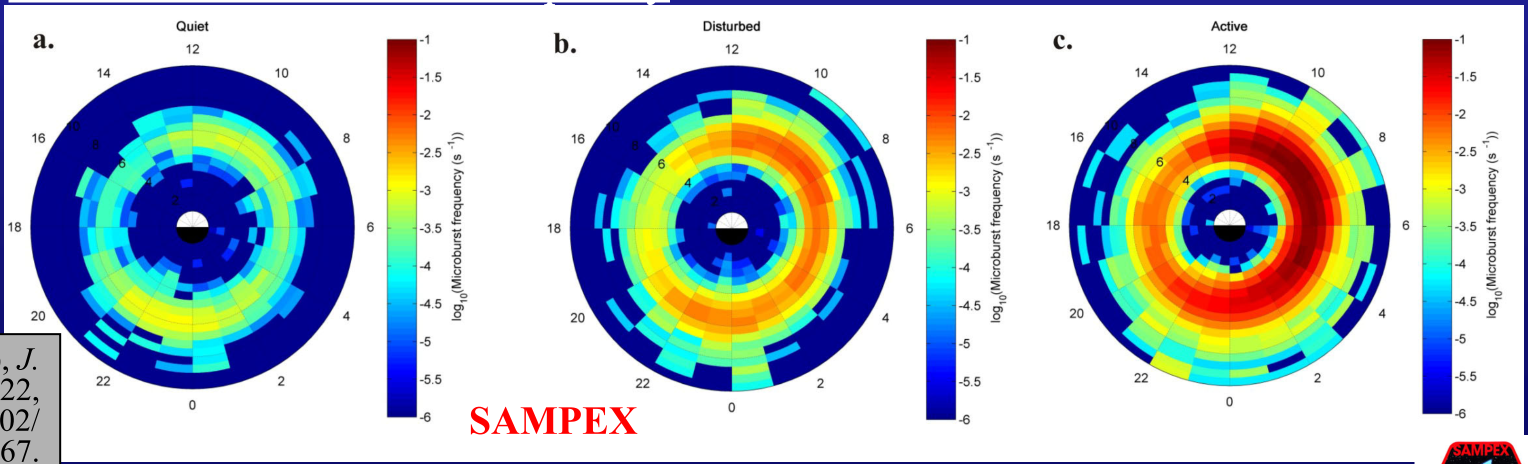
Equatorial Chorus Intensity



Adapted from Figure 2:
Li et al. (2009), *Geophys. Res. Lett.*, vol. 36, doi:10.1029/ 2009GL037595.

THEMIS

Microburst Occurrence Frequency



Douma et al. (2017), *J. Geophys. Res.*, 122, 8096– 8107, doi:10.1002/ 2017JA024067.

SAMPEX

Some similarity between the average MLT & *L* distributions.

REP Microbursts & Chorus: One to One?

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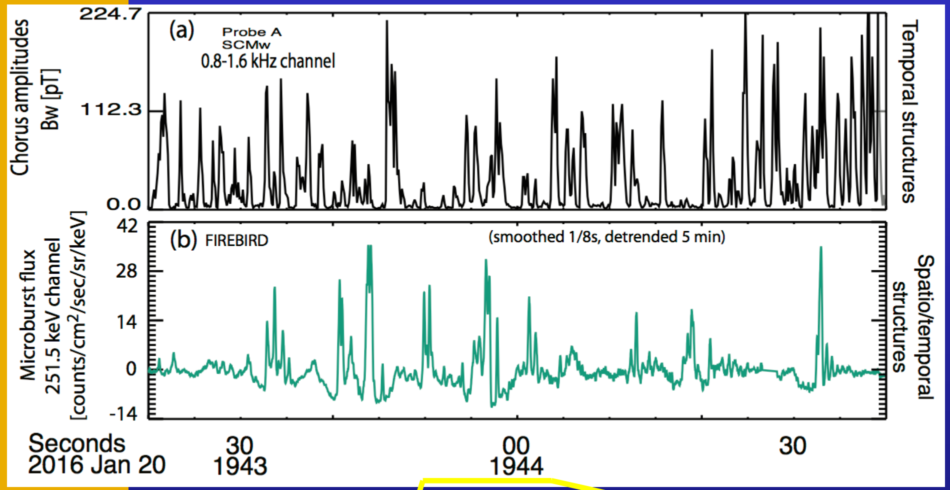
Aaron Breneman (U Minnesota) has shown strong evidence of <u>energetic and relativistic</u> microbursts AND chorus occurring in the same magnetic flux tube!

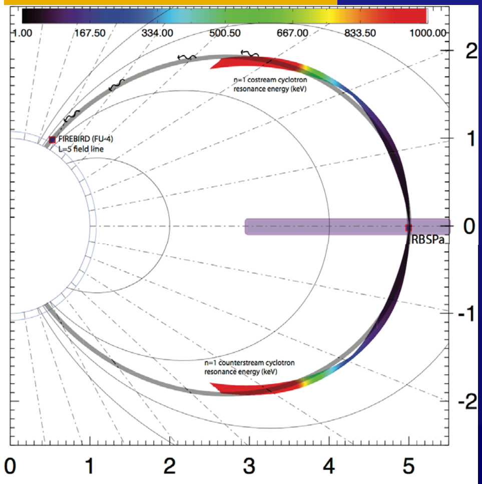
Breneman et al. (2017), *Geophys. Res. Lett.*, 44, 11,265-11,272. doi:10.1002/2017GL075001.

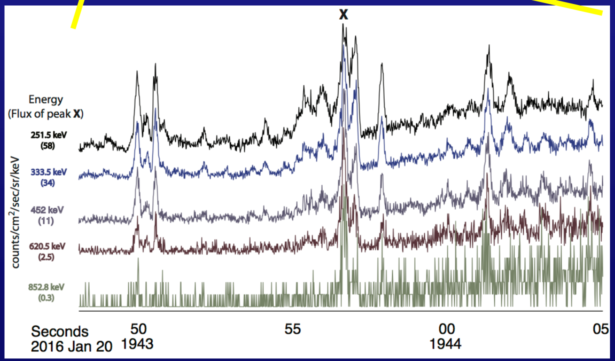


Evidence of lower band chorus in EMFISIS RBSP EFW peak detector amplitudes (8 s^{-1})

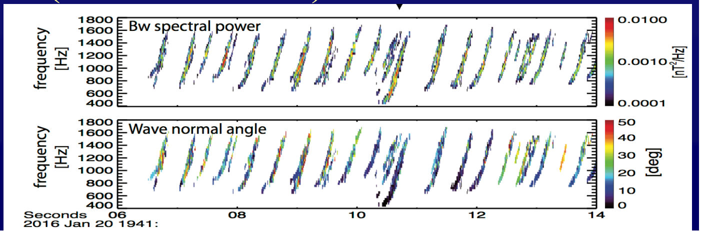
FIREBIRD microbursts

Not <u>quite</u> one to one, but this <u>easily</u> feels like some of the <u>strongest evidence to date</u>.





Chorus in EMFISIS burst mode (2.5 min earlier)



REP Microbursts Spectra

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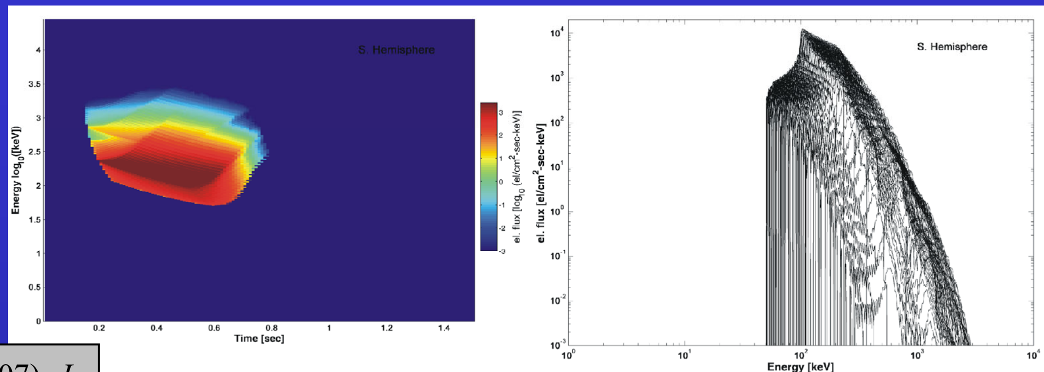
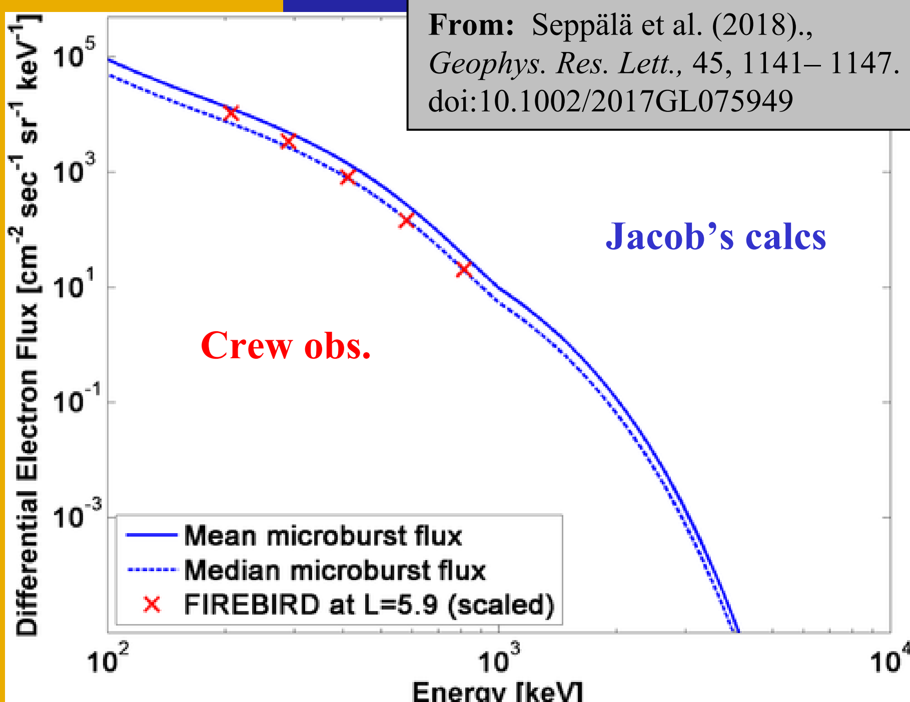


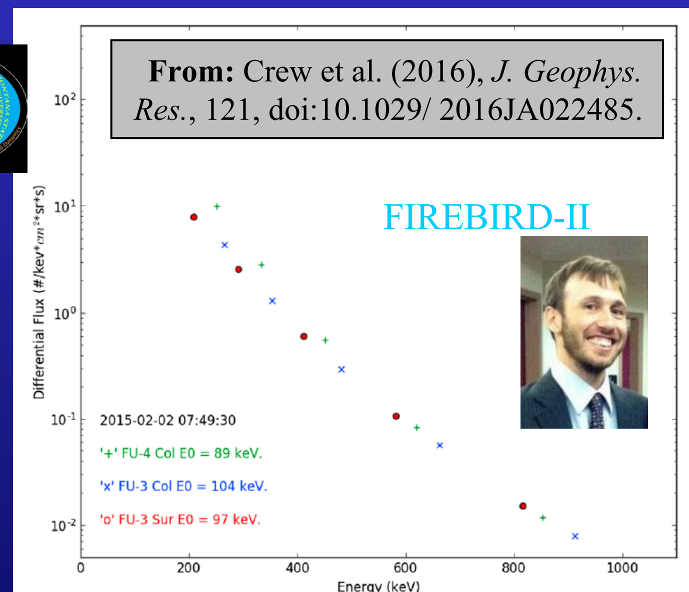
From: Rodger et al. (2007), *J. Geophys. Res.*, 112, doi:10.1029/ 2007JA012347.

Modelled Microburst due to whistler mode chorus

Jacob!



From: Seppälä et al. (2018)., *Geophys. Res. Lett.,* 45, 1141– 1147. doi:10.1002/2017GL075949



From: Crew et al. (2016), *J. Geophys. Res.*, 121, doi:10.1029/ 2016JA022485.

Impressive agreement between the shape of Jacob's calculation for a chorus driven microburst and the FIREBIRD-II precipitation observations.

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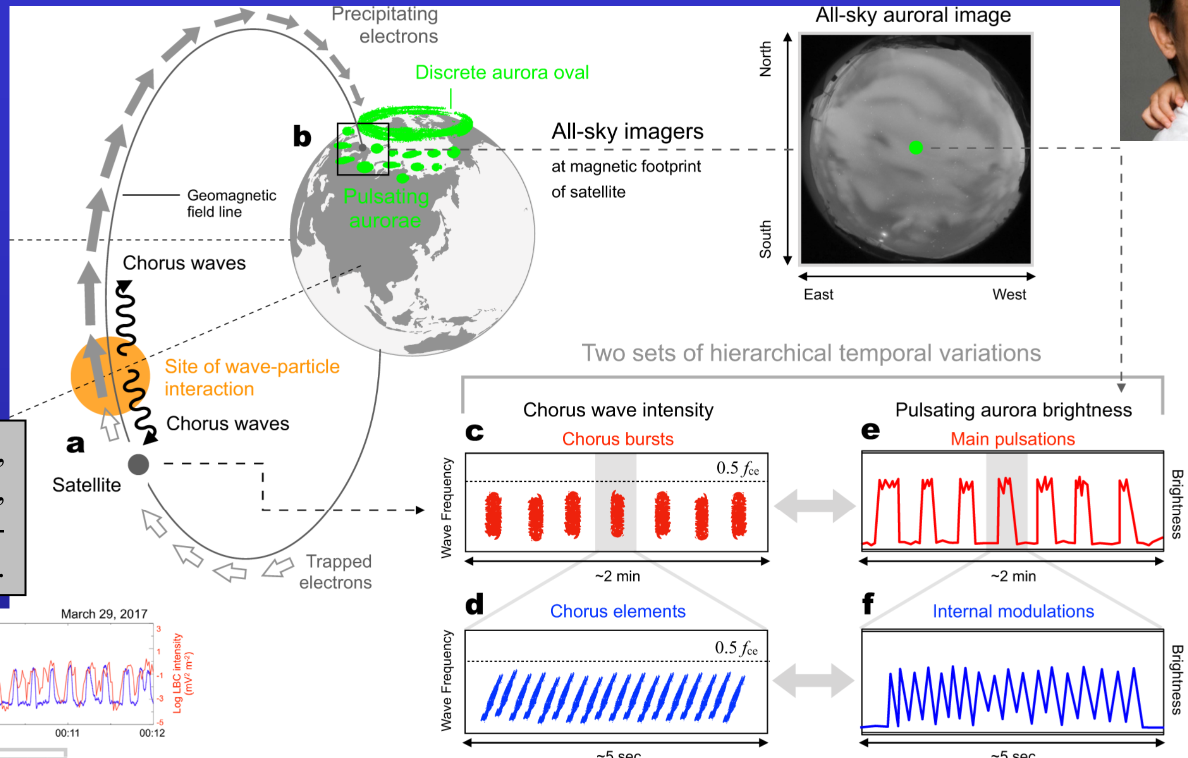
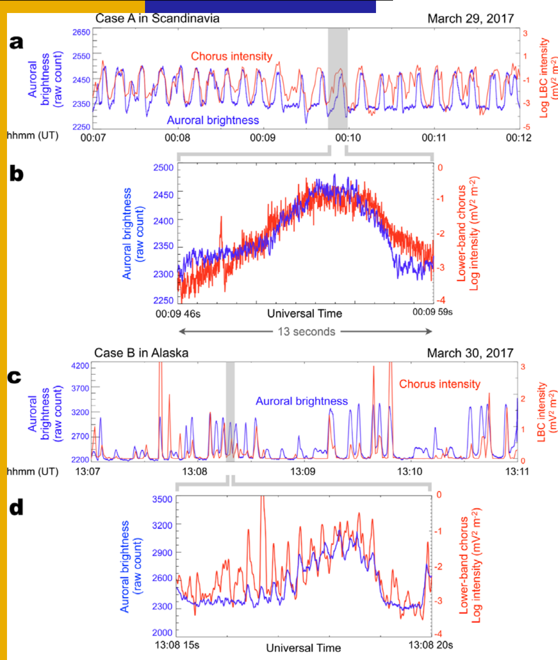
Pulsating Aurora



From: Hosokawa et al. (2020), *Sci Rep,* 10, 3380, doi:/10.1038/ s41598-020-59642-8.

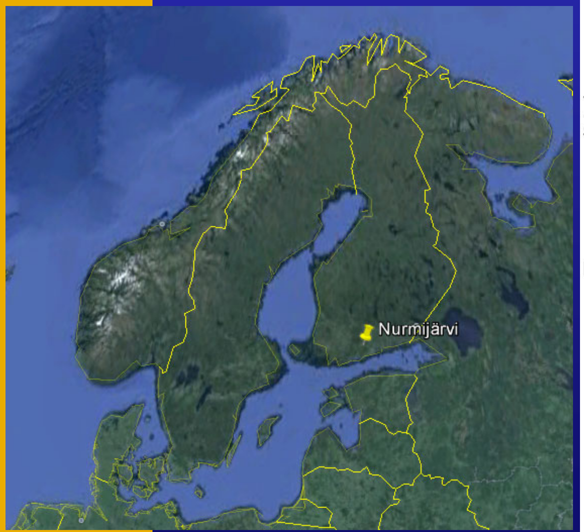


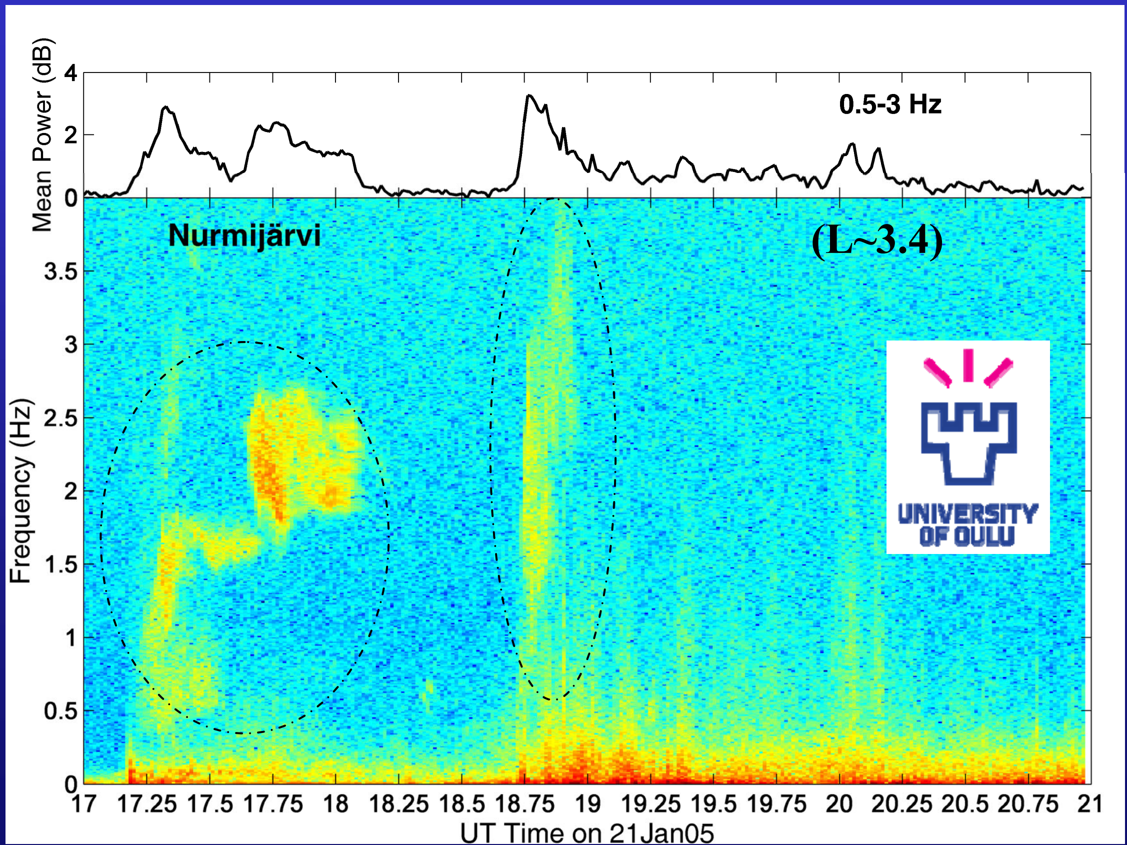
Also, the lowest energy electrons scattered by chorus (a few keV) is now strongly believed to be responsible for pulsating aurora.

Clearly, whistler mode chorus is a <u>very important</u> plasma wave!

EMIC Waves

It has long been recognised that losses can also be driven by scattering from ElectroMagnetic Ion Cyclotron (EMIC) waves. These propagate at frequencies below the proton gyrofrequency, and are thus in the ULF band.





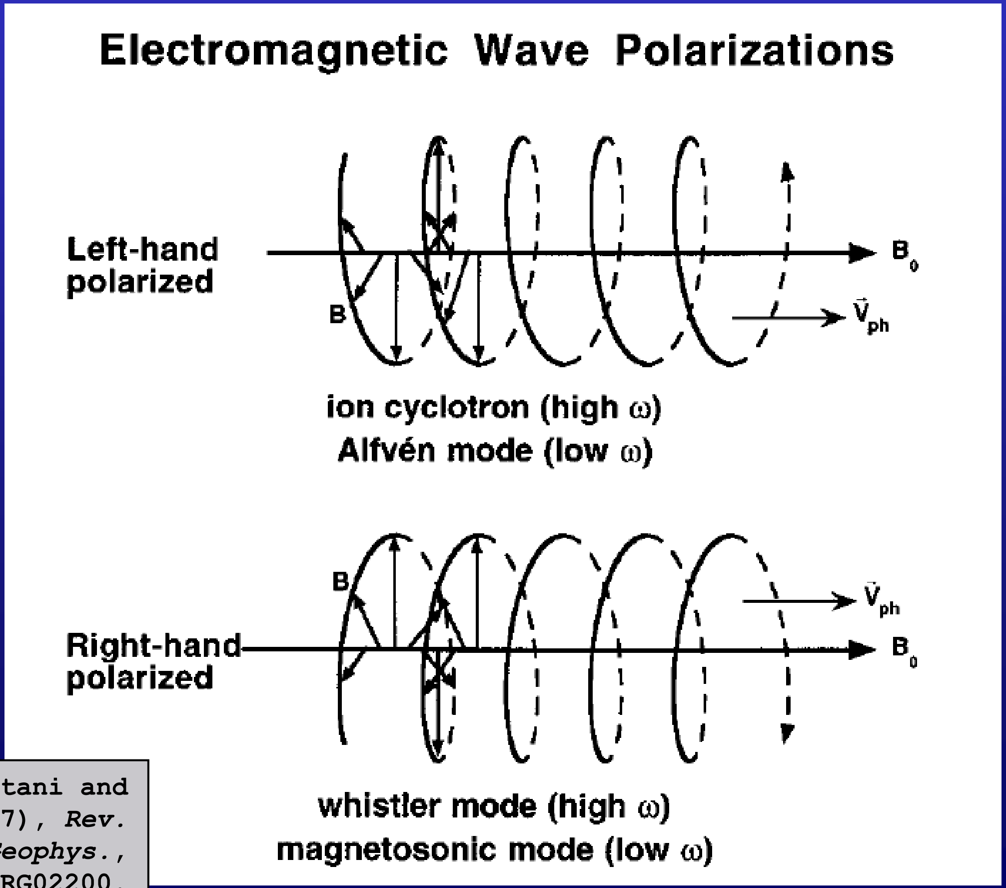
Example of EMIC waves during a highly disturbed geomagnetic period on 21 January 2005 after CME-linked solar wind pressure pulses struck the magnetosphere. Note this is a higher frequency event than typical.

EMIC Waves = ion-cyclotron waves

Charged particles in the geomagnetic field gyrate (from basic physics).

It turns out that the standard propagation modes for electromagnetic waves in plasma are (approximately) circularly polarised, with EMIC waves being LH polarised. **These waves are said to be in the ion cyclotron mode.**

EMIC = Electro-Magnetic Ion Cyclotron



Plot from Tsurutani and Lakhina (1997), *Rev. Geophys.*, doi:10.1029/97RG02200.

EMIC/ion cyclotron mode

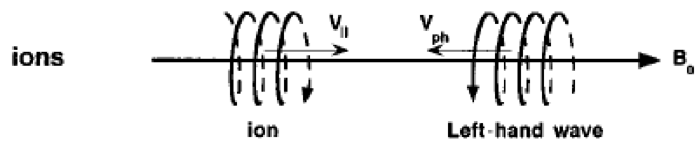
Examples: IPDP, bands, bursts, emissions.

Contrast the ion cyclotron mode with the whistler mode

Examples: whistlers, chorus, hiss.

Cyclotron Resonance for EMIC waves

(Normal) Cyclotron Resonance



$$\omega - \vec{k} \cdot \vec{V} = \Omega^{+}$$

$$\omega + k_{\parallel} V_{\parallel} = \Omega^{+}$$

The relative motion between the wave and particle Doppler shifts the wave up to the ion cyclotron frequency.

"Normal" cyclotron resonance occurs between counter-streaming waves and particles.

For the case of an ion-cyclotron wave like an EMIC wave, the normal resonance will be with protons with 10's to 100's keV energy.

Plots from Tsurutani and Lakhina (1997), *Rev. Geophys.*, doi:10.1029/97RG02200.

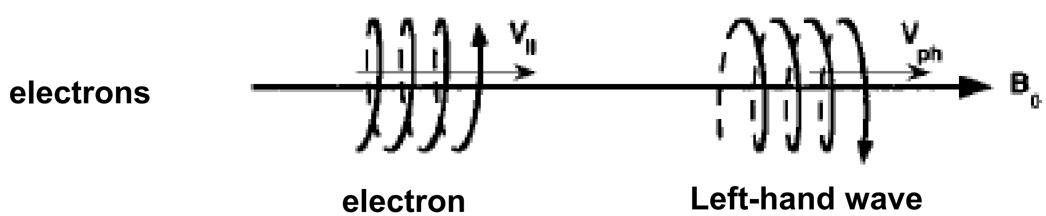


Figure 11. Schematic illustrating anomalous cyclotron resonance between electromagnetic circularly polarized waves and

"Anomalous" cyclotron resonance occurs when particles overtake the wave.

For the case of an EMIC wave, anomalous resonance is thought to be important for scattering relativistic electrons (~1 MeV).

Thorne and Kennel (1971) first suggested that EMIC wave scattering was likely a major loss mechanism for relativistic electrons.

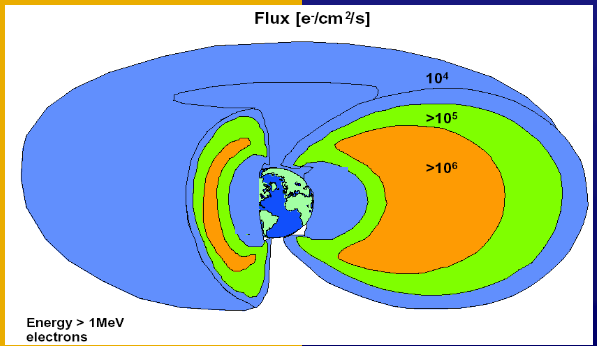
EMIC Waves – precipitation signature

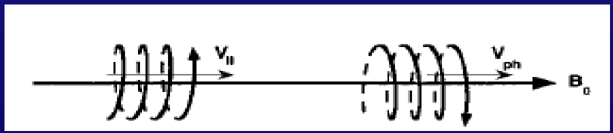
“normal” cyclotron resonance ⇒ **proton loss**

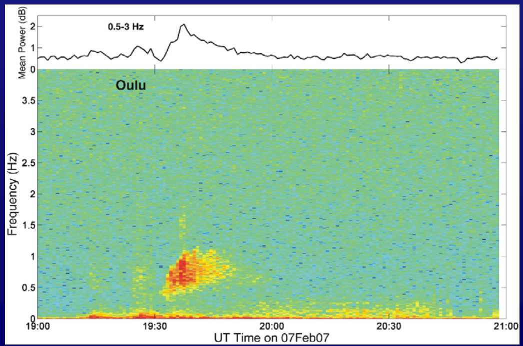
EMIC waves will regularly pitch angle scatter, and hence precipitate, protons of tens to hundreds of keV energy through first-order cyclotron resonance. These will deposit their energy into the atmosphere at altitudes above ~95 km.

“anomalous” cyclotron resonance ⇒ **electron loss**

EMIC waves can, under certain conditions pitch angle scatter, and hence precipitate, electrons with high hundreds to thousands of keV energy through first-order cyclotron resonance (i.e., ~1 MeV relativistic electrons). These will deposit their energy into the atmosphere at altitudes well below ~70 km.







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EMIC Wave-produced precipitation

As strange as this might seem, for a theoretical concept that goes back decades, experimental evidence for scattering and precipitation of energetic and relativistic electrons used to be quite rare in the scientific literature!

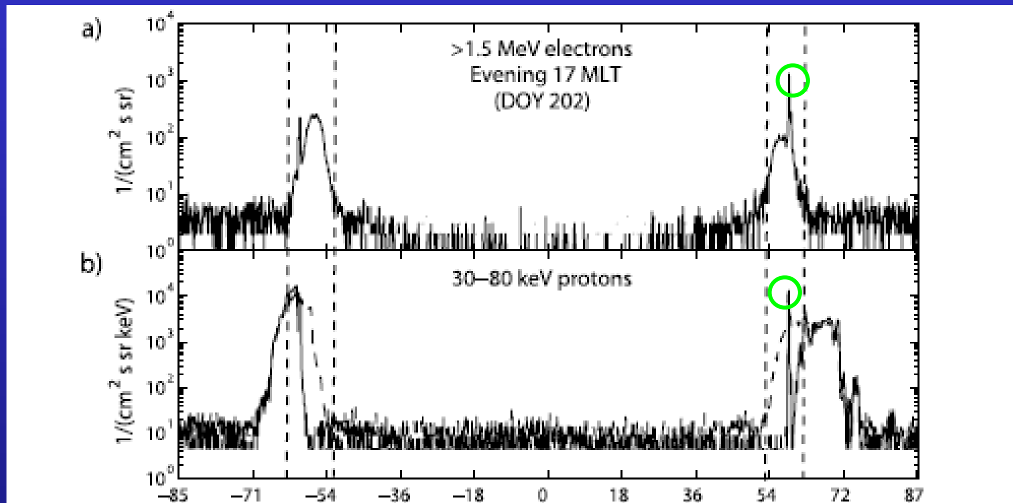

Figure 4. Particle data from NOAA-12 on 21 and 26 July 1998. The figure exhibits electrons >1.5 MeV and protons 30–80 keV, from the 90deg (dashed line) and 0deg detectors (a and b) from an eveningside pole-to-pole orbit on 21 July (1215–1305 UT) and (c and d) from an eveningside pole-to-pole orbit on 26 July (0700–0751 UT).

Example of suspected EMIC-scattering signature reported previously by *Sandanger et al.* [2007] (in this case from NOAA-12 data, i.e., an SEM-1 carrying satellite). Similar examples were reported by *Sandanger et al.* [2009].

Sandanger et al. (2007), *J. Geophys. Res.*, 112, doi:10.1029/2006JA012138.

Marit Sandanger reported simultaneous spikes seen in NOAA POES in the precipitating protons (ten's of keV) and also in the relativistic electron flux, which they claimed were probably caused by EMIC.

[My students have subsequently built up a database of thousands of these events following on from her examples]

Fluxes but no waves

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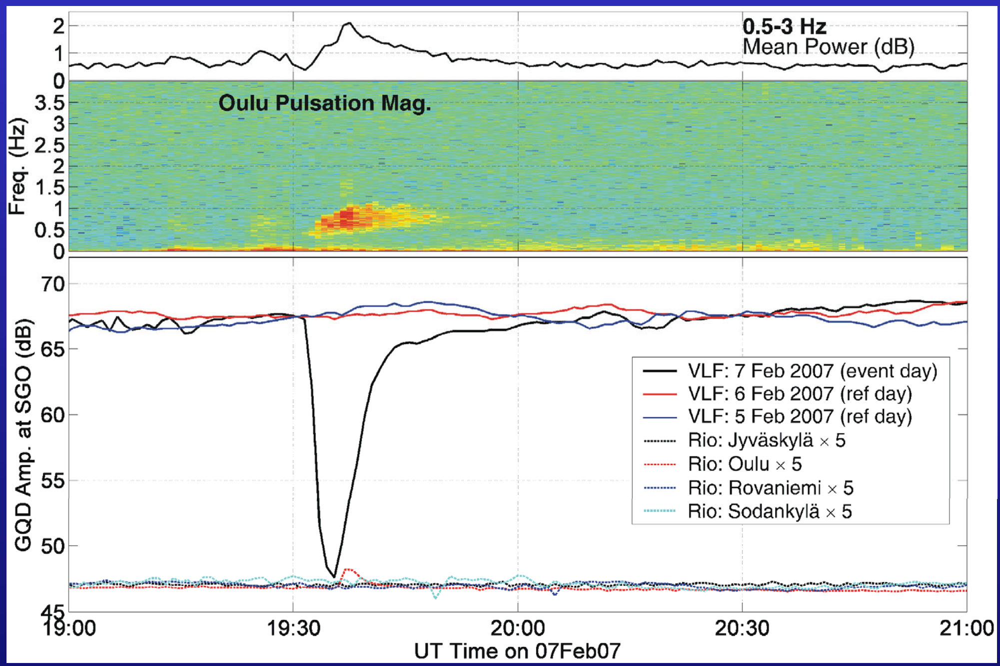
EMIC Wave-produced precipitation

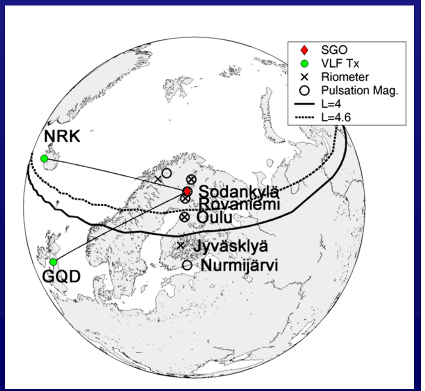
As strange as this might seem, for a theoretical concept that goes back decades, experimental evidence for scattering and precipitation of energetic and relativistic electrons used to be quite rare in the scientific literature!



Example of EMIC-scattering signature by *Rodger et al.* [2007], in this case all ground based. EMIC waves are see on the ground at the same time a subionospheric VLF propagation path responds very strongly to relativistic precipitation.

Rodger et al. (2008), *Geophys. Res Lett.*, 35, doi:10.1029/2008GL034804.

I had a set of 4 similar case studies of EMIC waves occurring and ground-based evidence for the precipitation.



Waves & D-region VLF but no fluxes

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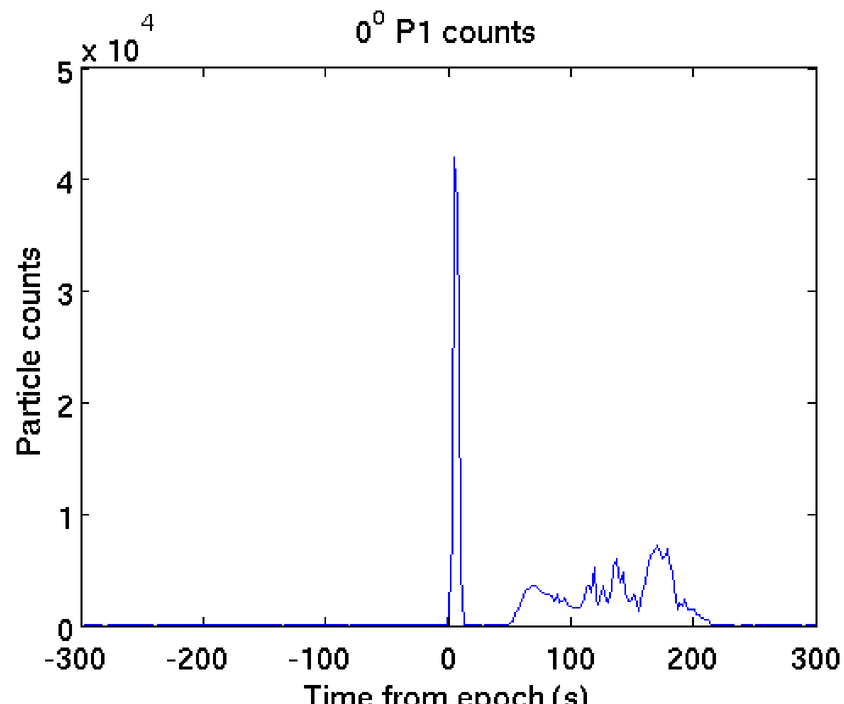
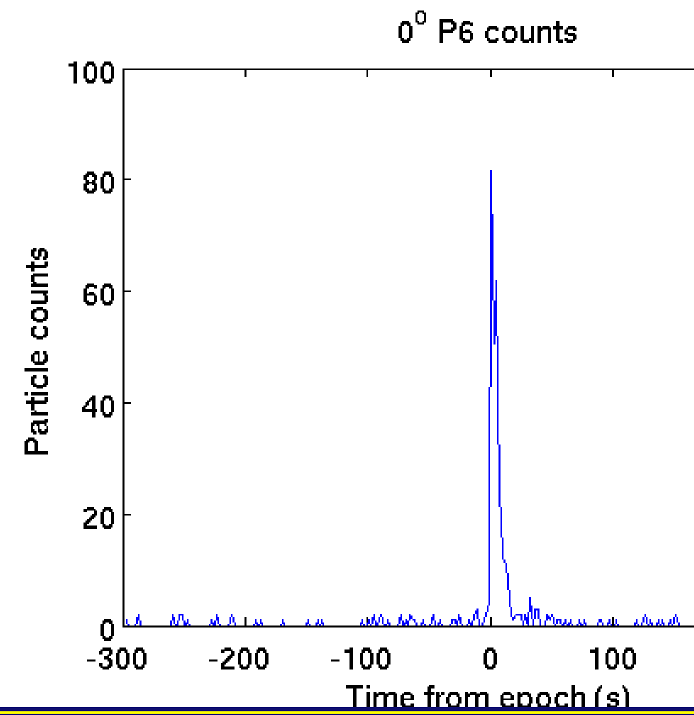
Searching for EMIC precipitation with POES

One of my MSc Students, Bonar Carson, made an EMIC precipitation detection algorithm to find the "spike" events seen in the *Sandanger et al.* [2007] and *Sandanger et al.* [2009] studies.

He scanned through 1998-2010 POES SEM-2 data and found 2331 triggers.





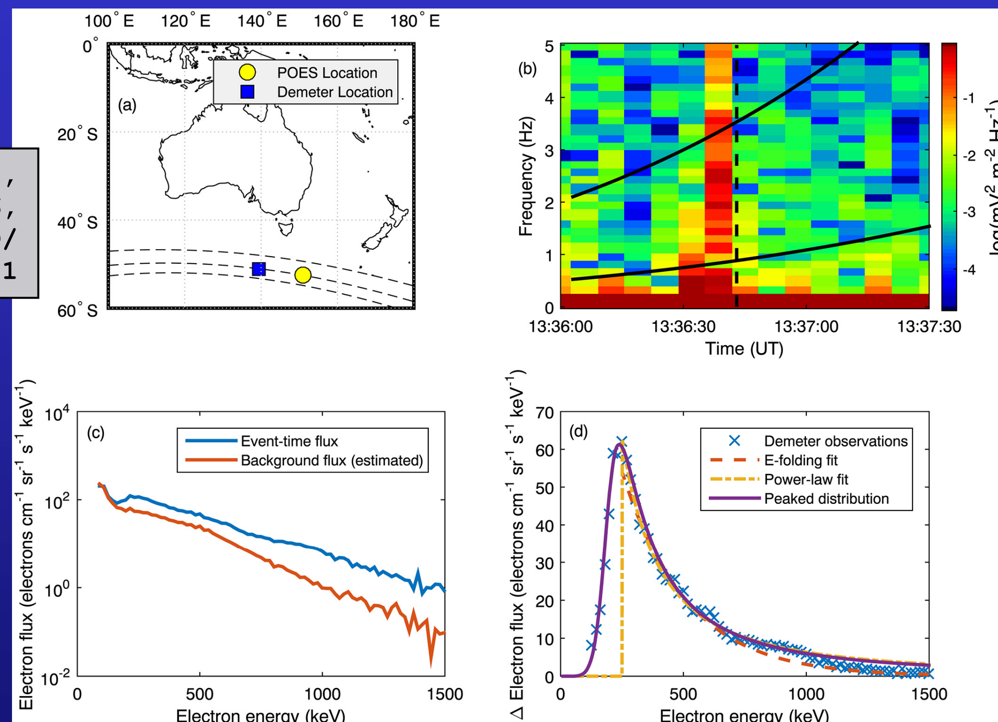
Algorithm described in: Carson et al., J. Geophys. Res., 118, 1-12, doi:10.1029/2012JA017998, 2013

Otago PhD student Aaron Hendry has used the algorithm on an extended dataset through to 2014 (plus included MetOp-01, -02, & -03 data) and found **5096 triggers**.

EMIC electron precipitation spectra

Aaron Hendry was able to show that the vast majority of the POES events are well fitted by a peaked precipitating flux events. Some of the POES EMIC triggers have associated nearby DEMETER observations (so much higher energy resolution), and DEMETER confirmed a peaked flux spectra.

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

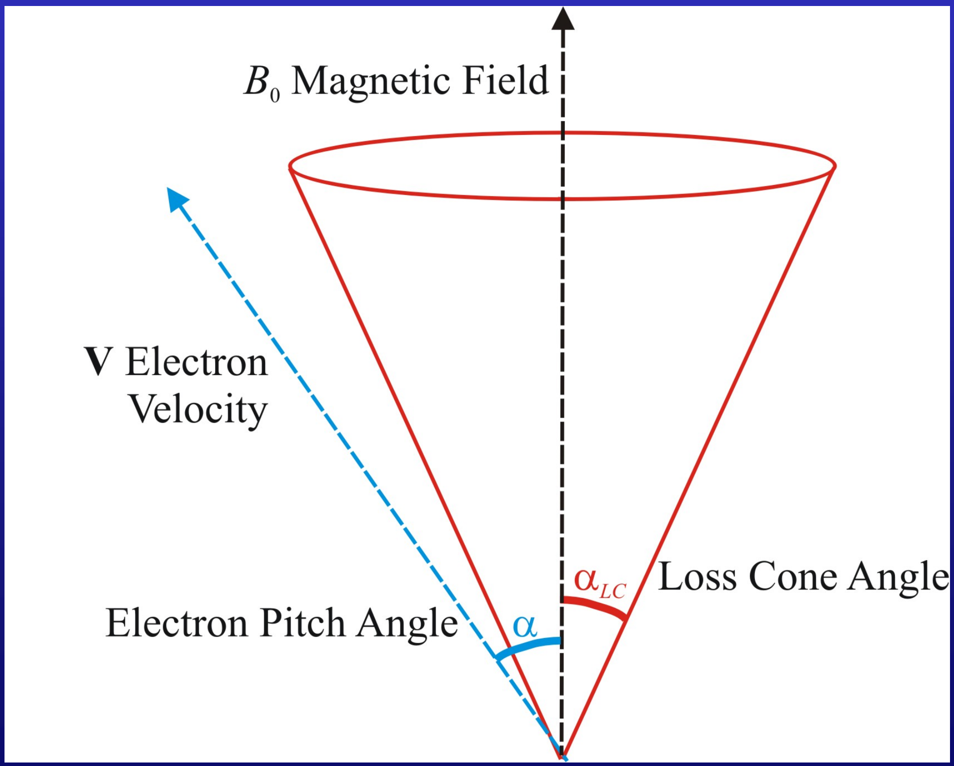


The surprise is that the peak EMIC precipitation fluxes are at a few hundred keV (not MeV), suggesting non first-order scattering is happening as well as relativistic scattering of MeV electrons. [energy range confirmed with FIREBIRD (Capannolo et al., *GRL,* 2021)]

More work to do here!

Observing the Bounce Loss Cone from Space

While an equatorial pitch angles of $\alpha = 0°$ would strike the Earth, an electron which should mirror at 1m above the ground would also be lost by colliding with the atmosphere. **In practise there is a range of pitch angles which will be quickly lost through atmospheric collisions.** The threshold is taken as ~100km altitude, and this range of pitch angles defines the loss cone with the outer edge the "loss cone angle", α_{LC}.



Any electron which starts with a pitch angle smaller than α_{LC} (or is scattered into that range) will be rapidly loss – within a few bounces at most.

But there are also a range of energies which are lost into the atmosphere!

Particle access to the upper atmosphere

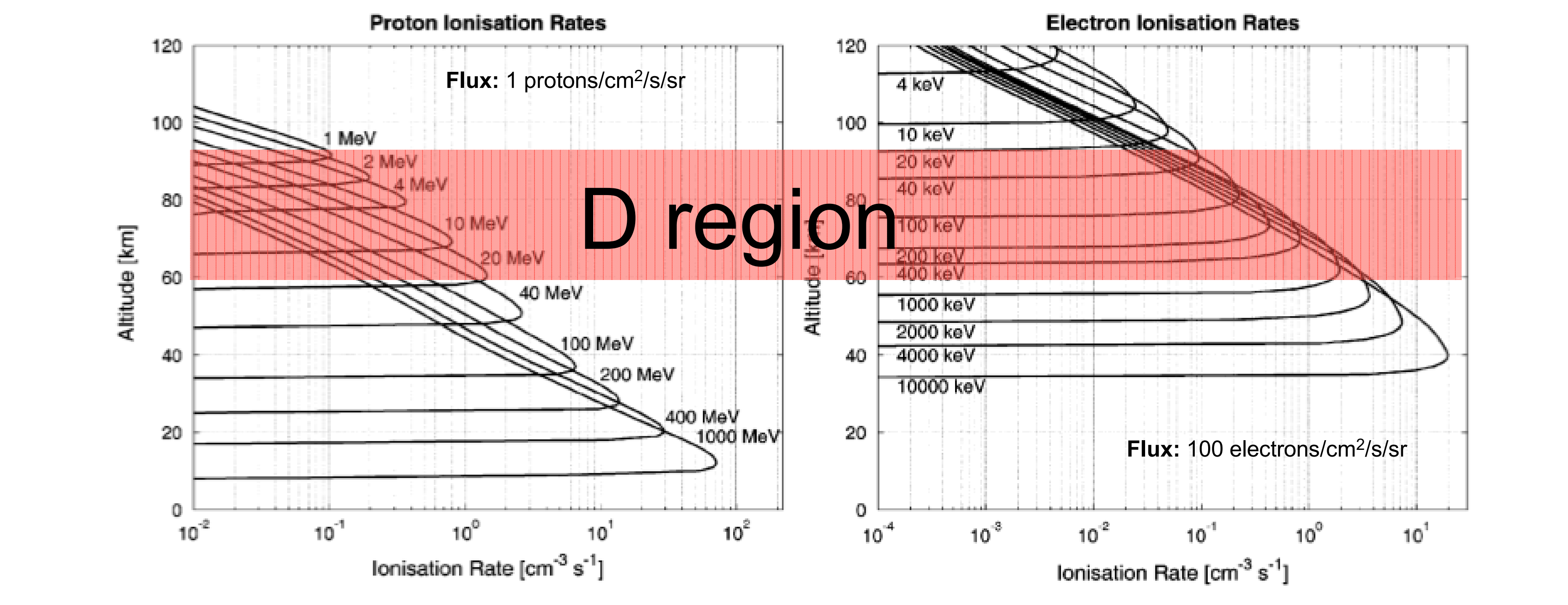


Fig. 3. Altitude versus ionisation rates for monoenergetic beams of protons 1–1000 MeV (left) and electrons 4–4000 keV (right).

Turunen et al., JASTP, 2009.

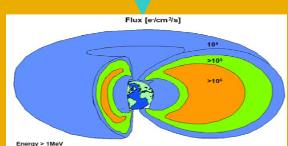
To produce 1 ion pair/cm^3/s at **60km** altitude

1 × 20MeV proton/cm^2/s

or **100** × 1MeV electrons/cm^2/s

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, <u>and</u> polar ozone levels, we need to know about the "natural" variation too!



Particle precipitation

↓

Production of NO_x and HO_x

↓

Destruction of mesospheric and upper stratospheric O_3

↓

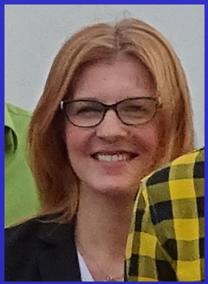
Change in dynamics mesosphere & <u>stratosphere</u> → "Climate"

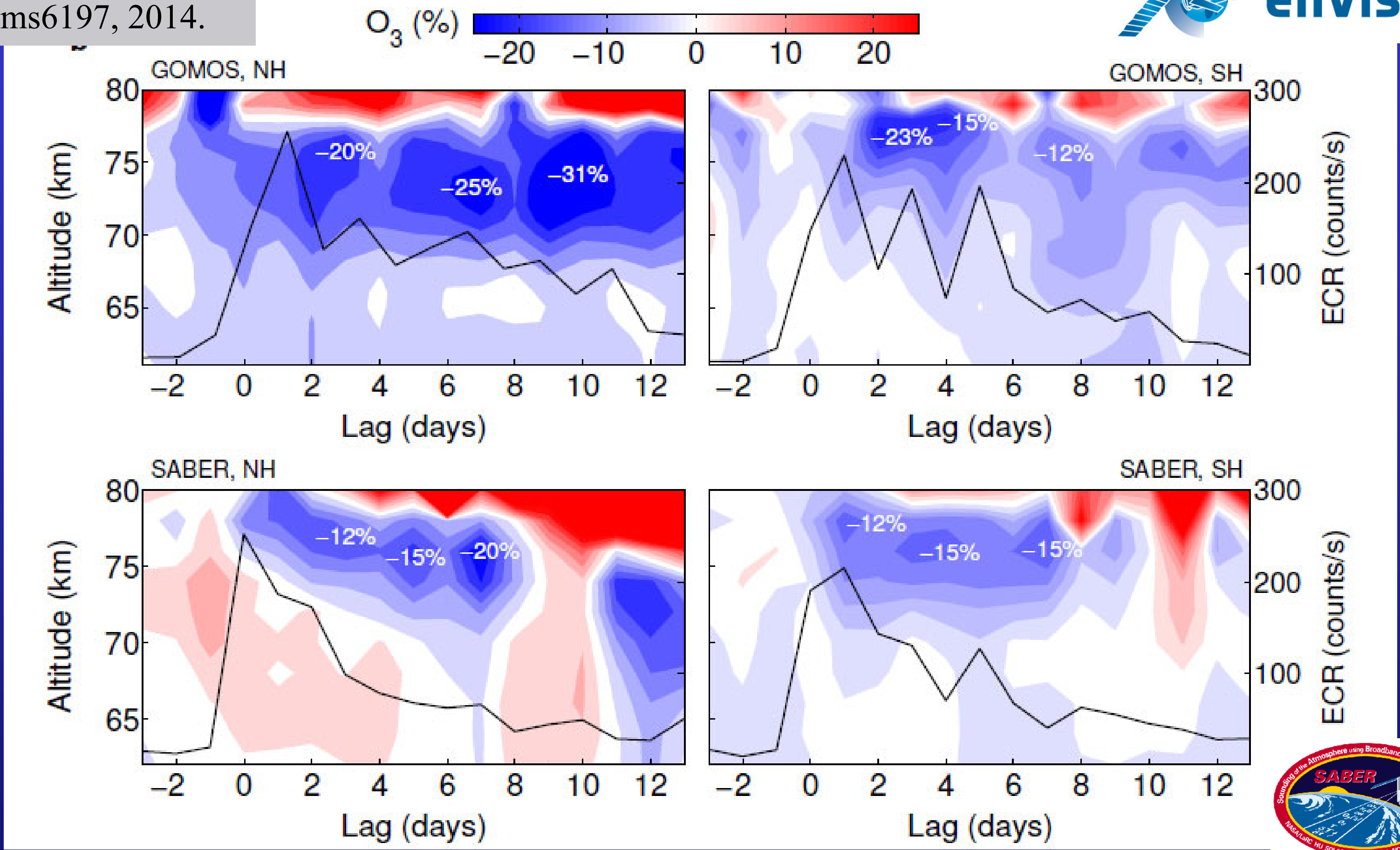
(Probably, at some level)

<u>Plus</u> of course the interest in precipitation from a strictly radiation belt physics viewpoint.

Observations of O_3 caused by EEP

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

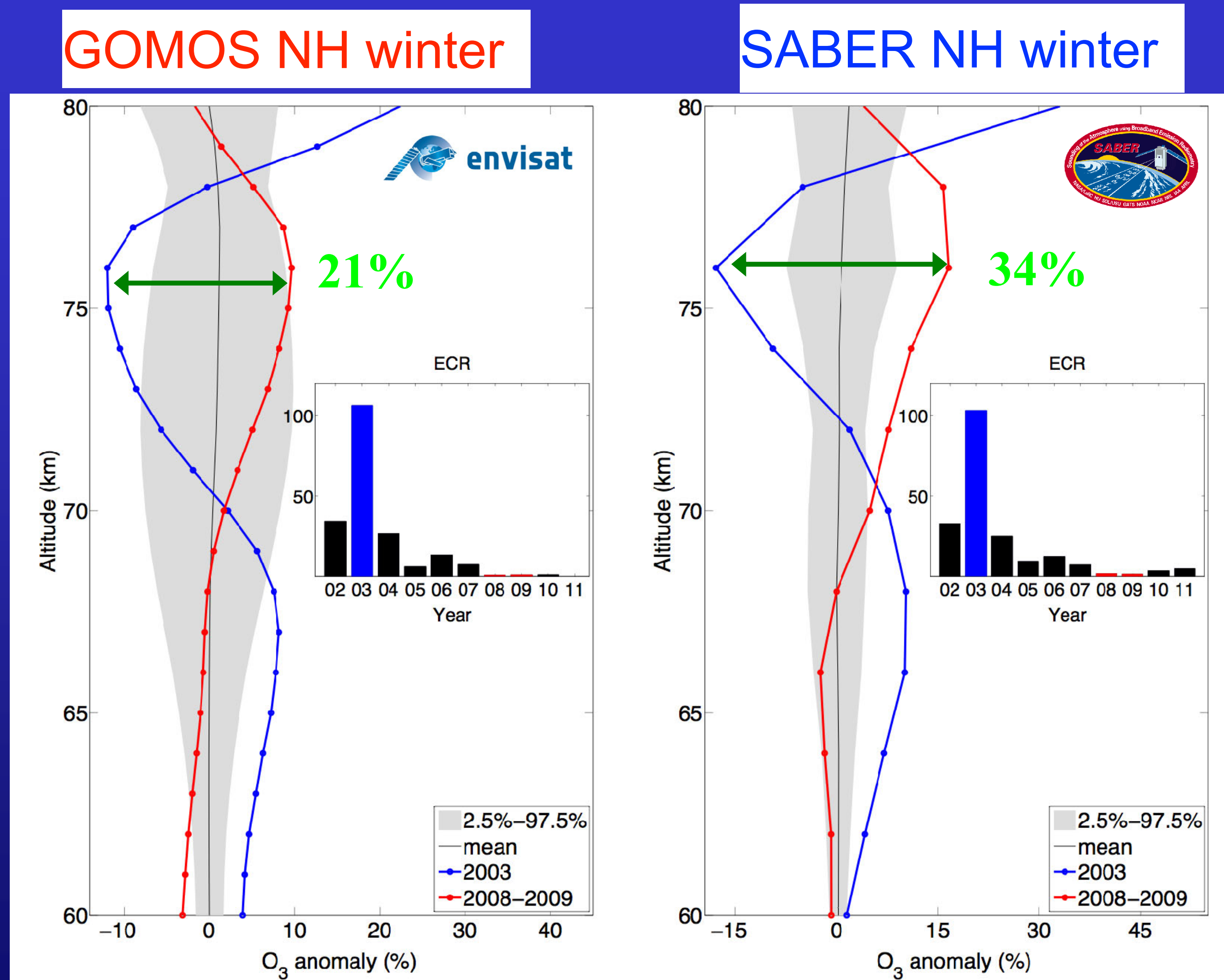




Superposed Epoch Analysis of mesospheric ozone observations from GOMOS and SABER after an EEP peak - **ozone does indeed decrease significantly** after strong precipitation events. The magnitude of the ozone decrease is similar to that from "large" Solar Proton Event, which are much less common occurrences!

Observations of EEP-O_3 effect on long timescales

Even though the EEP events only last days, they are common enough in high activity years to lead to long term changes in Ozone profiles.



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

Ozone anomalies (%) of deseasonalized daily means, averaged over the winter time. November to February in the Northern hemisphere showing years 2003 (**blue** line) and 2008–2009 (**red** line). Grey is the 95% confidence interval.

And a link to Climate?

Rozanov et al. [GRL, 2005] fed their chemistry-climate model (CCM) with NO_x changes calculated on a daily basis from particle fluxes reported by the NOAA/TIROS Space Environment Monitor (SEM-1) onboard the POES spacecraft for 1987. The two hemispheres were treated separately, and only "high latitude" data from *L*=5-10 was considered. They then looked at the change when EEP was included in the model run (relative to when it wasn't).

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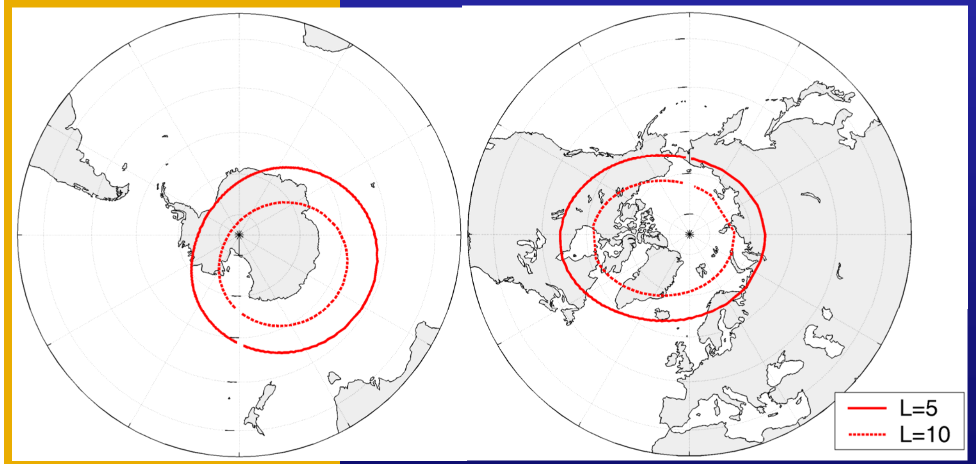


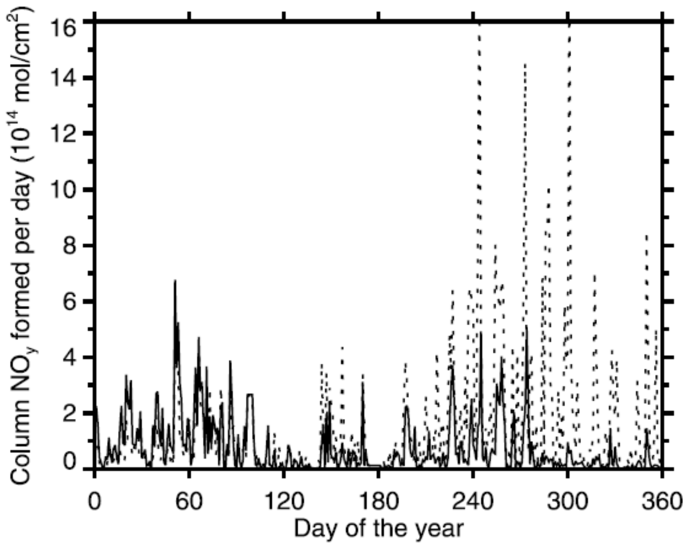


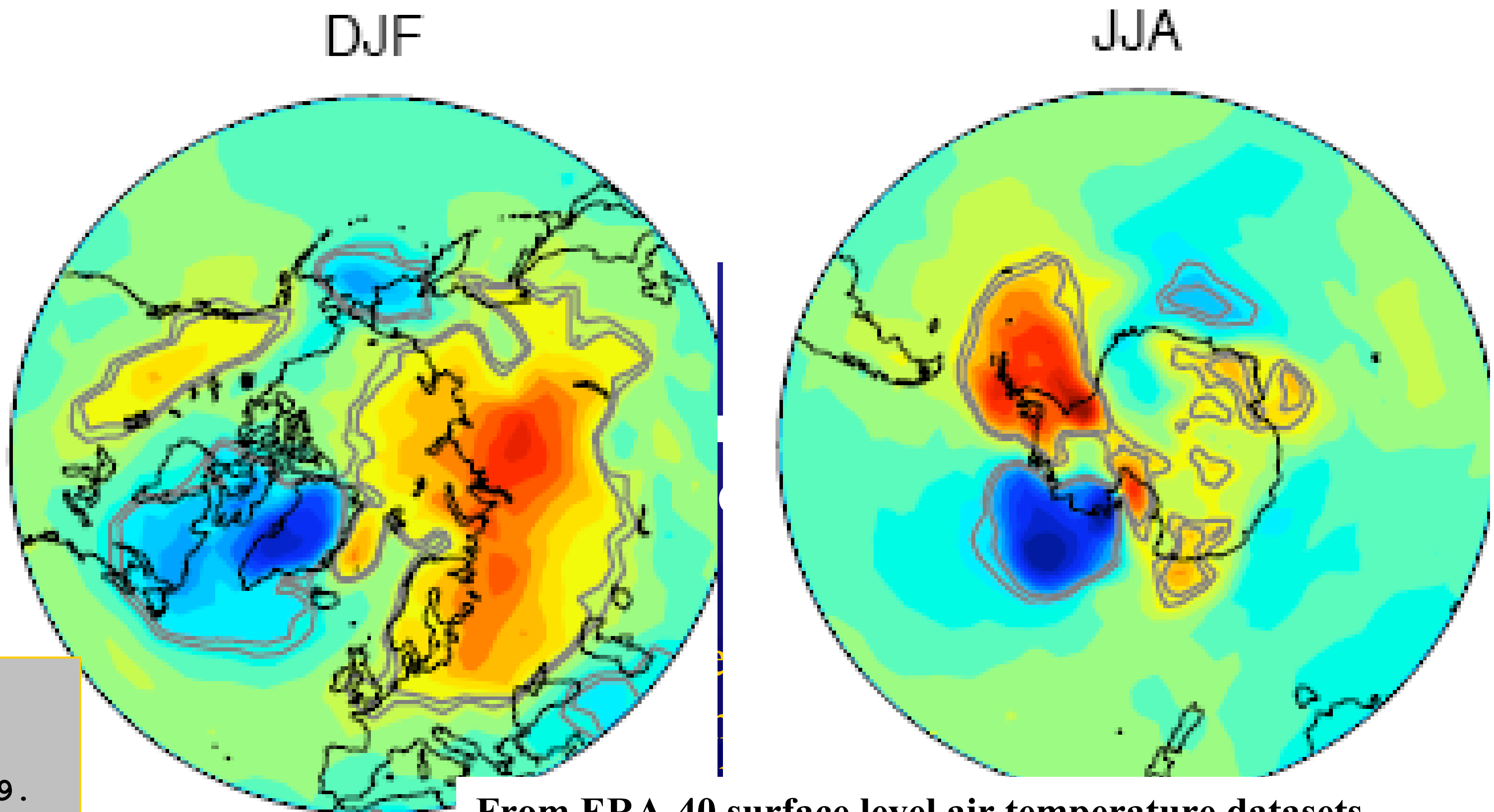
Figure 1. Daily formation of column NO_y during 1987 for the Northern (solid line) and Southern (dotted line) hemispheres between 60 and 90 km, and for values of the McIlwain parameter between 5 and 10.

Rozanov et al., *Geophys. Res. Lett.*, doi:10.1029/2005GL023041, 2005

We need to measure energetic particle precipitation, and examine EEP consequences, to see if it can explain the experimentally observed link between geomagnetic storms and polar surface temperatures.

The calculations presented in *Rozanov et al.* [GRL, 2005] lead to a particle precipitation driven surface air temperature variation of -0.5 to +2 K, relative to the no precipitation case.

Rozanov et al., *Geoph Res. Lett.*, doi:10.10 2005GL023041, 20



From ERA-40 surface level air temperature datasets

`Seppälä et al., J. Geophys. Res., doi:10.1029/ 2008JA014029, 2009.`

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How can we understand this link to climate?

The accepted route for understanding the way energetic electron precipitation couples to climate is to incorporate precipitation into chemistry climate models and explore the outputs as various physics is switched on and off.

Modelling has already reproduced the polar temperature variability through imposing an NOx source at mesospheric altitudes. But ideally, one would want to include EEP directly, and investigate the linkages. **People have been working on validating precipitation measurements so they can be used in chemistry climate models.**

Particle precipitation

↓

Production of NO_x and HO_x

↓

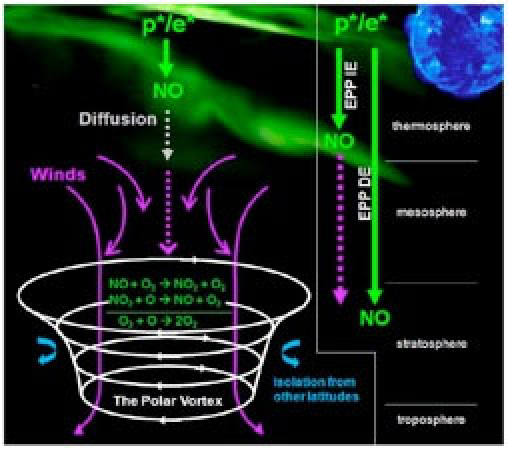
Destruction of mesospheric and upper stratospheric O_3

↓

Change in dynamics mesosphere & stratosphere

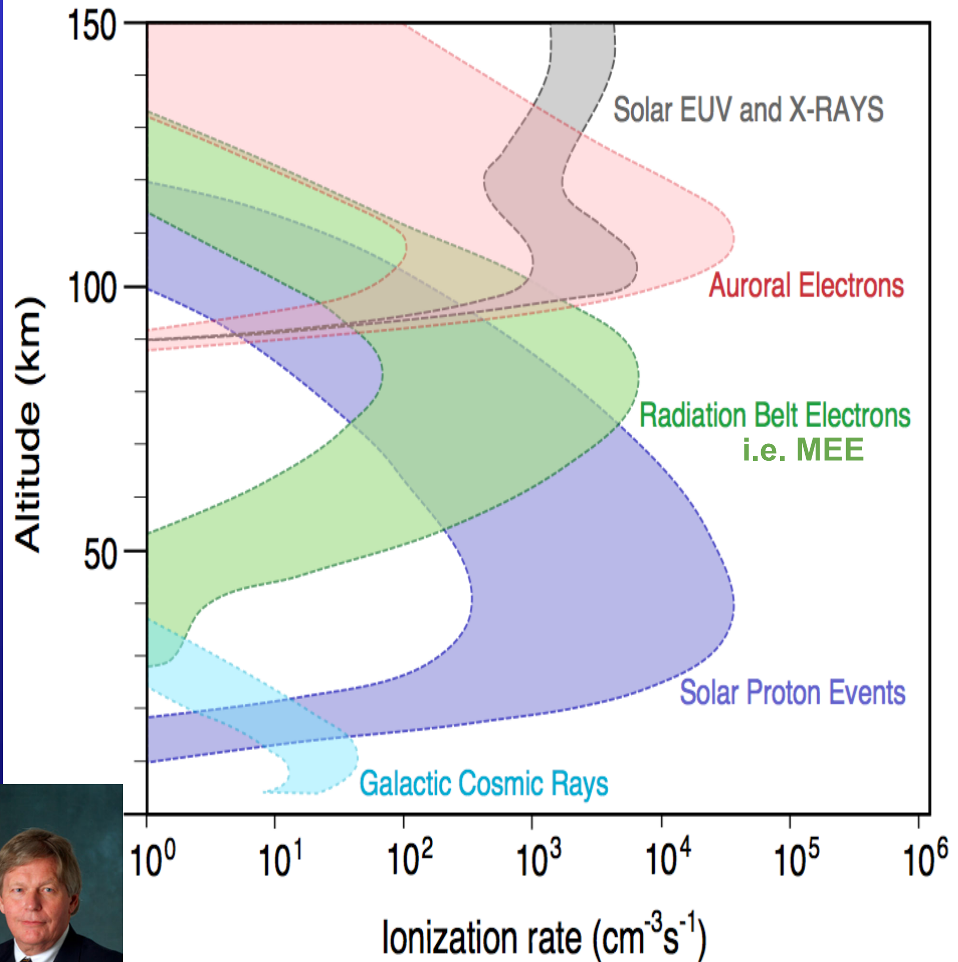
?→ "Climate" ?

(But how?)



Particle precipitation and the atmosphere

From:Baker et al., EOS (2012). **Modified.**



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.**

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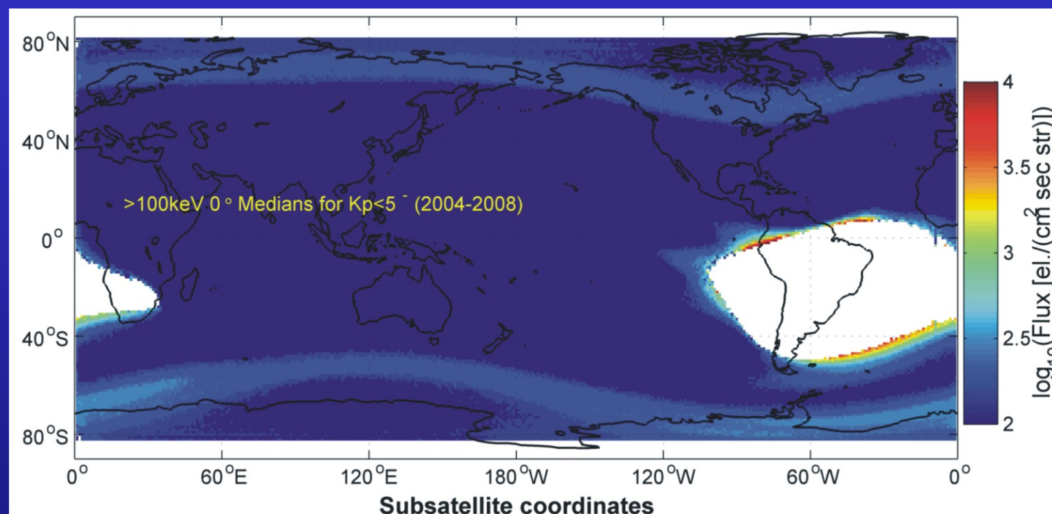
Rodger et al. (2013), *J. Geophys. Res.*, 10.1002/2013JA019439.



Map of the median >100keV precipitating fluxes over the time period 1 January 2004-31 December 2008 for quiet and mildly disturbed times (Kp≤4.7). Note that the dominant precipitation is in the Weddell Sea, south of the South Atlantic Magnetic Anomaly (SAMA). 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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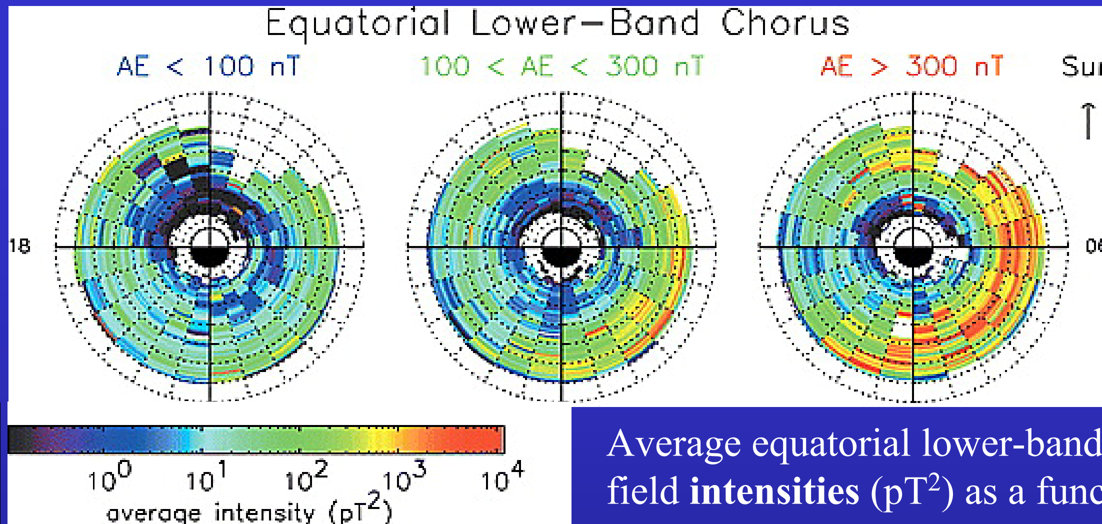
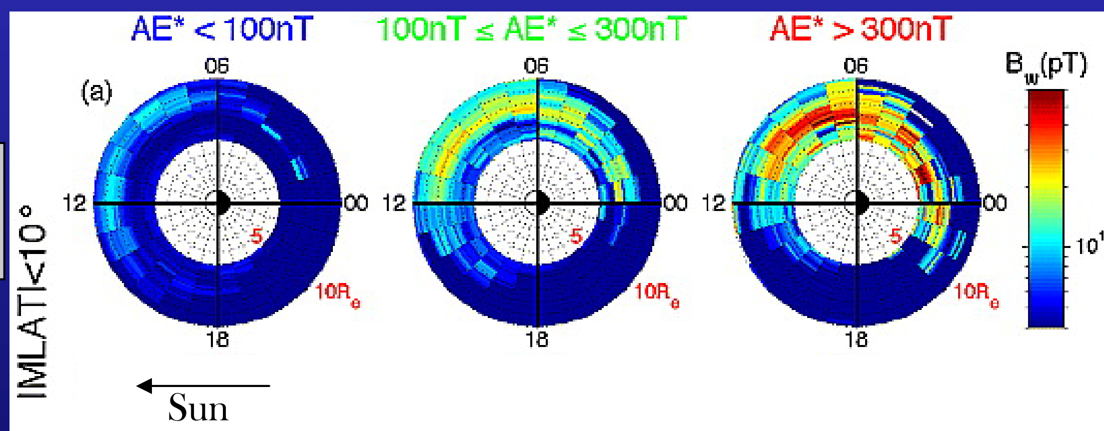
Lower-band Chorus - Equatorial Observations



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.

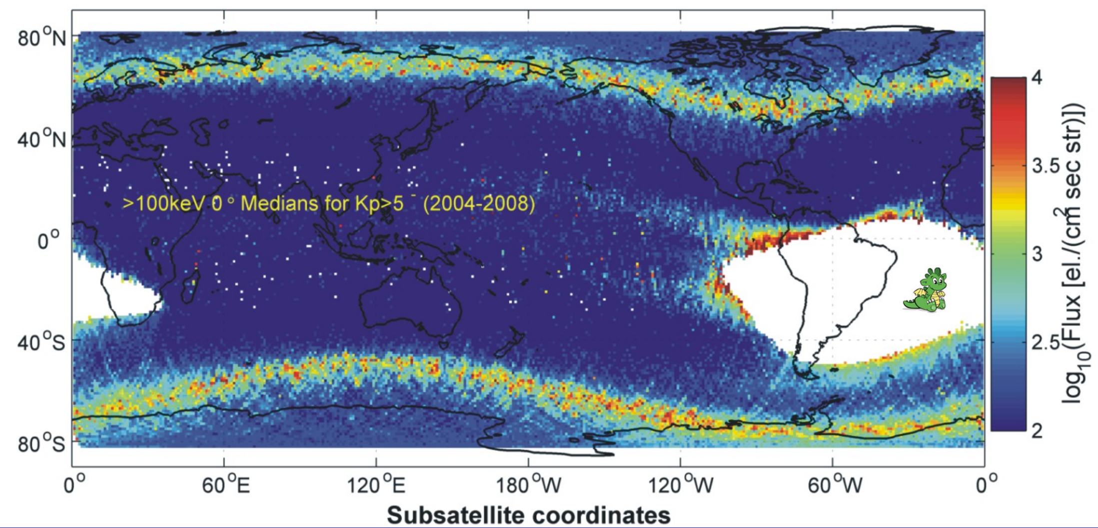
Equatorial chorus magnetic field RMS wave **amplitude** (pT).

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.



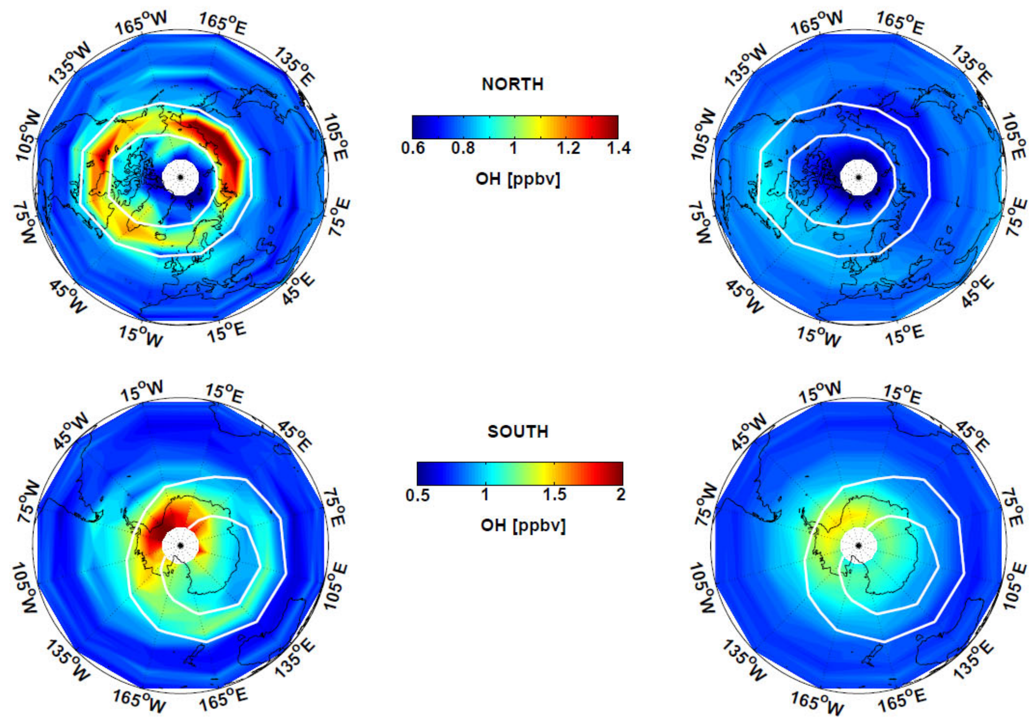
Map of the median >100keV precipitating fluxes over the time period 1 January 2004-31 December 2008 for disturbed/storm times (Kp>4.7).

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 geomagnetic proxies.

Observations of HOx caused by EEP

High EEP conditions = lots of precipitation and lots of HOx produced



Low EEP conditions = low levels of precipitation (into the DLC) and not much HOx produced.

From Andersson et al. (2014), Atmos. Chem. Phys., doi:10.5194/acp-14-1095-2014, 2014.

Fig. 4. Top panels: spatial distribution of OH medians in the NH calculated for the days with: (1) ECR> 100 counts/s (left panel) and (2) ECR< 5 counts/s (right panel) for the time period January 2005–December 2009 and altitude range 70–78 km. Bottom panels as top panels for the SH. Median values were calculated for each 5 (latitude) × 30 (longitude) degree bin between latitudes 82° N to 82° S and longitudes 180° W to 180° E. Approximate geomagnetic latitudes 55–72° N/S are indicated by superimposed white lines.

Observations of atmospheric HOx from MLS/Aura show that the HOx production is typically constrained by geomagnetic latitude and increases strongly during EEP events.

We think some of the longitudinal variation in the high EEP case is due to satellite sampling.

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

MetOp-03 is now operating too (since 2019), but the research work I am going to report on "only" used the earlier POES constellation data: NOAA-15 to NOAA-19 and MetOp-01 & MetOp-02.

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Te Whare Wānanga o Otāgo

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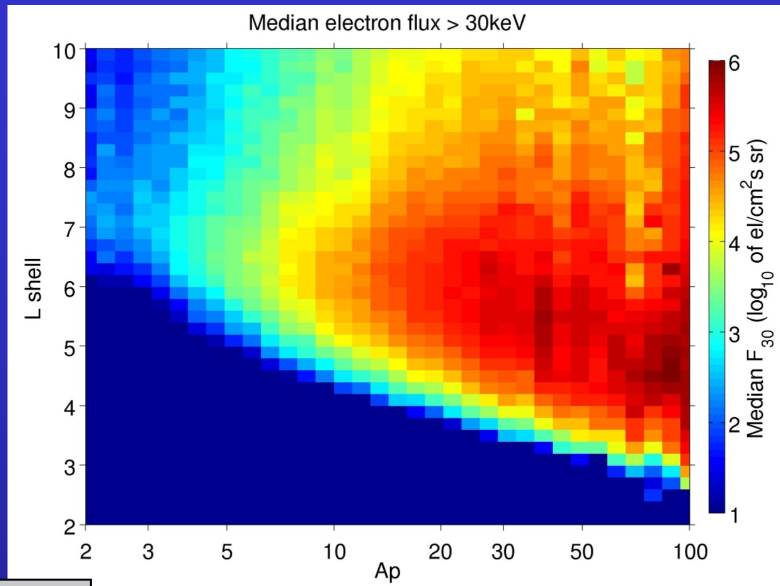
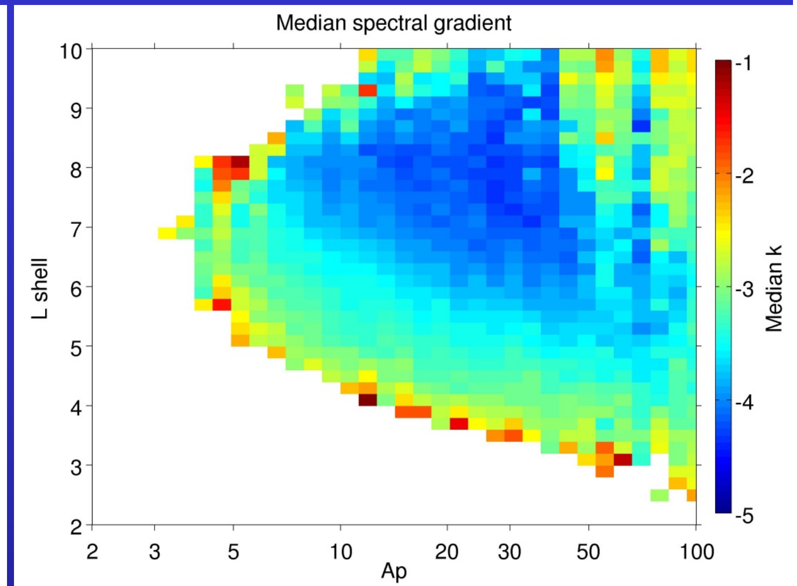
Empirical Data - EEP fitting to Ap





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

These fits are after 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).

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**

  $T = 15.004$

  $A = 19.683Ap^{-0.66696}$

  $b = 5.5619$

  $c = 0.61055$

  $s = 0.85072$

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

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

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

  $c = 0.31955$

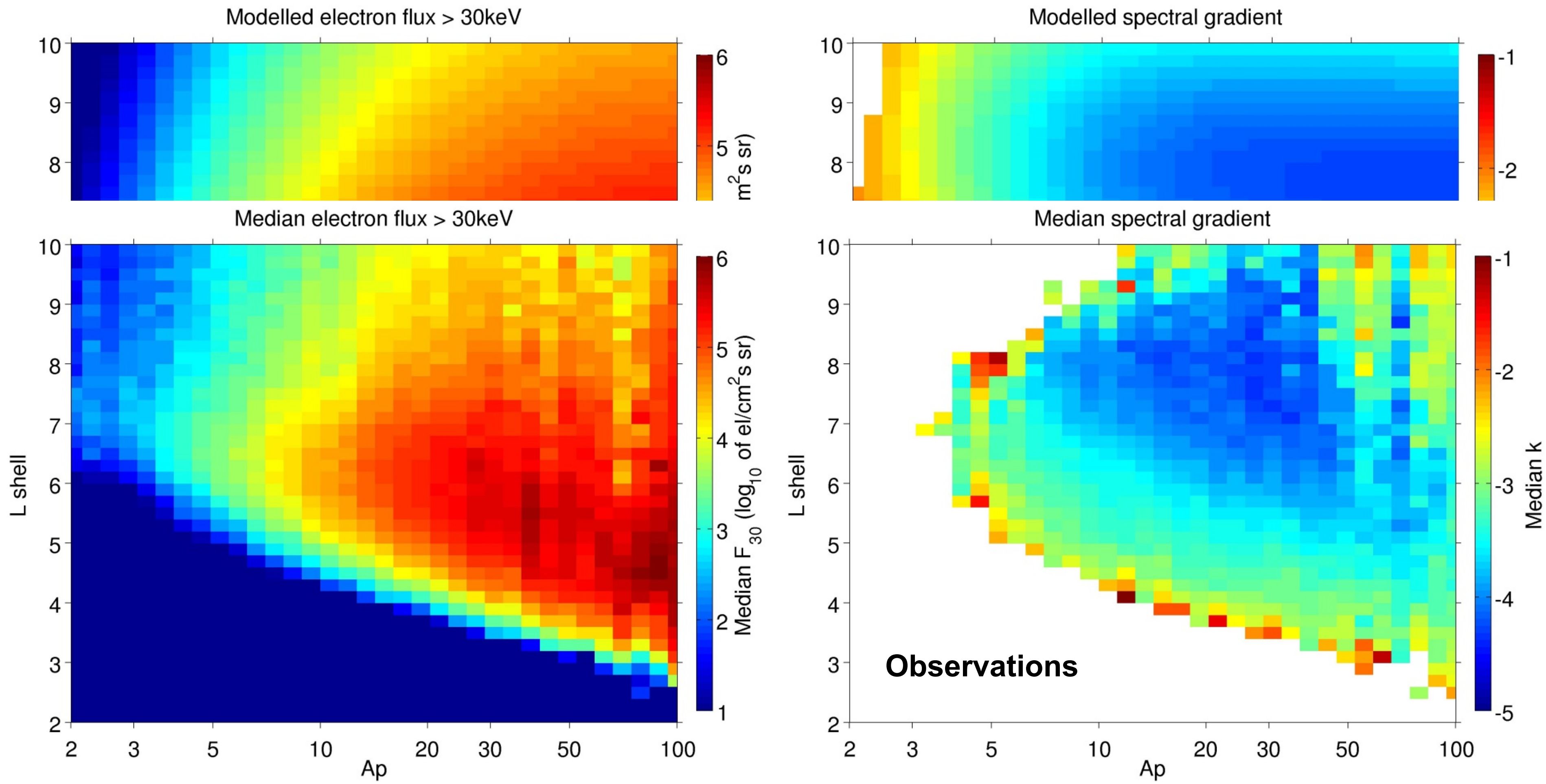
  $s = ln(11.970 + 2.4824Ap^{0.7340})$

- $S_{pp} = L - L_{pp}$ ➡ **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

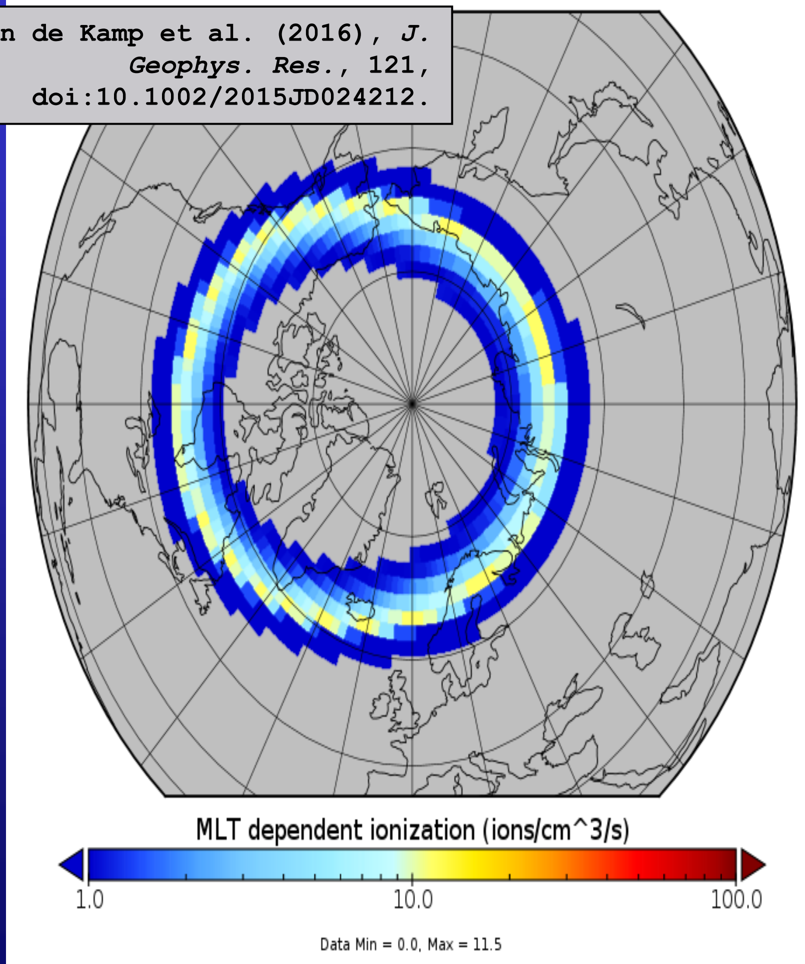
F_{30} and k as function of L and Ap (modelled):



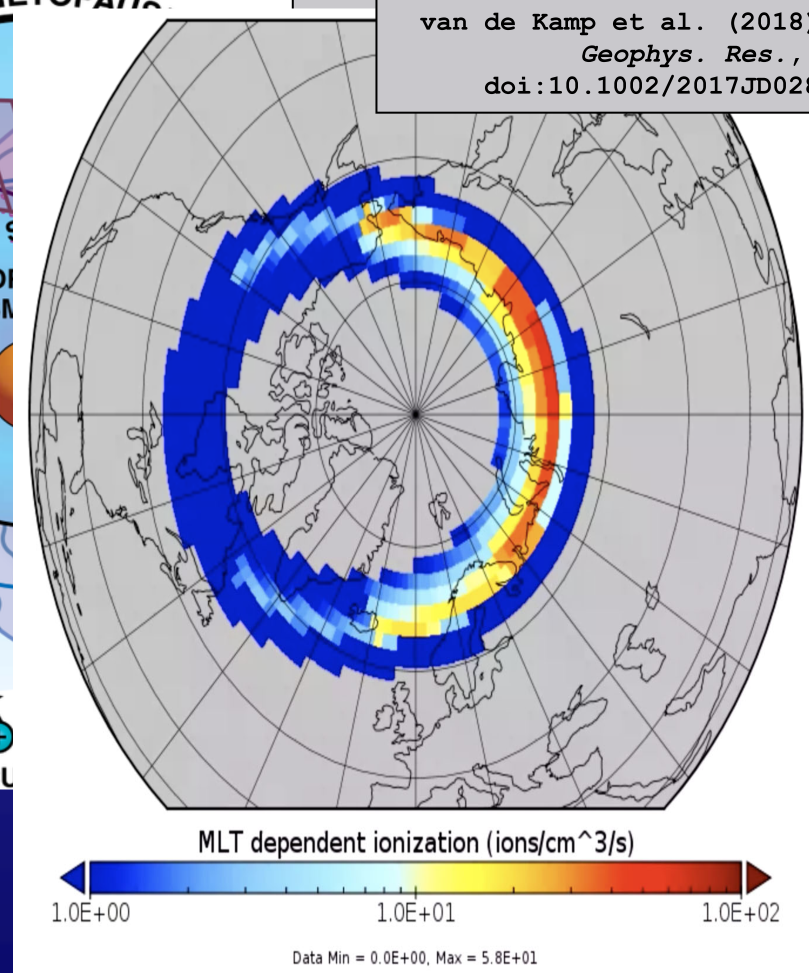
Can also work with a Magnetic Local Time dependent version

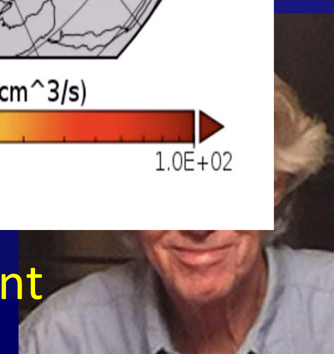
Thorne, R. M. (2010), *Geophys.*

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



van de Kamp et al. (2018), *J. Geophys. Res.*, 123, doi:10.1002/2017JD028253.





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

Matthes et al. (2017), *Geosci. Model Dev.*, 10, doi:10.1109/IVCNZ.2016.7804425.

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]

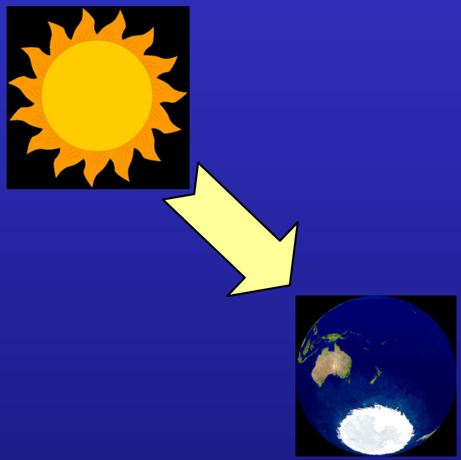
WCRP CMIP6
World Climate Research Programme

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 estimates of Ap derived from other observations 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 the physics.



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

In my opinion.

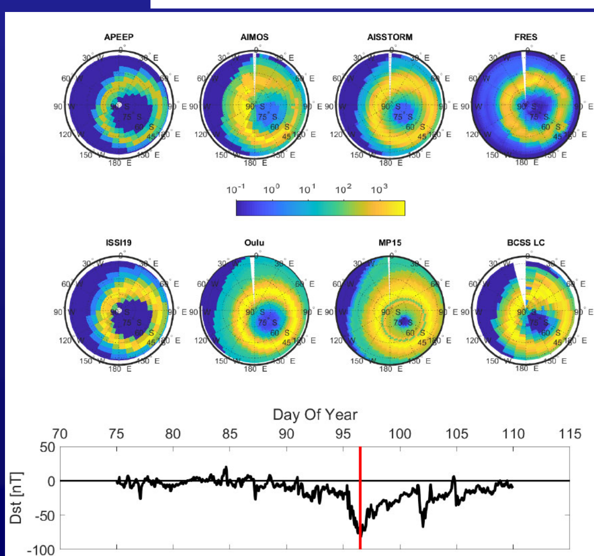
- ❖ More work is needed on making quantifiably accurate electron loss calculations from physics-based models. This is not easy, but it should be done.

In my opinion.

Including MEE in climate modelling - yet more options

MEE ionization rates	AIMOS	AISstorm	ApEEP	ISSI-19	FRES	Oulu	MP15	BCSS-LC
Low energy proton correction	*no*	*no*	*yes*	*yes*	*yes*	*yes*	*yes*	*yes*
Energy channels (keV)	>30 >100 >300	>30 >100 >300	>30 >100 >300	>30 >100 >300	>43 >114 >292 >756	>30 >100 >300	>30 >100 >300 >700	>43 >114 >292 >756
Upper energy limit	300 *keV*	300 *keV*	1000 *keV*	1000 *keV*	756 *keV*	1000 *keV*	1000 *keV*	756 *keV*
Telescopes	0°	0°	0°	0°	0°	0°&90°	0°&90°	0°&90°
Energy spectra	power law	power law	power law	power law	Maxwellian /exponential +power law	power law	Maxwellian/ exponential/ power law	PCHIP
Ionization rate calculation	Monte-Carlo* Wissing and Kallenrode (2009)		Equation of Transfer Fang et al. (2010)		Continuous loss Rees (1989)	Equation of Transfer Fang et al. (2010)		
Background atmosphere	HAMMONIA	HAMMONIA	MSIS	WACCM	CIRA	MSIS	WACCM	MSIS
MLT resolution	6H	0.25–1H	24H	24H	0.7H	24H	24H	0.7H

Nesse Tyssøy et al. (2021), *J. Geophys. Res.*, 126, doi:10.1029/2021JA029128.



Maps of the ionization rate in the Southern hemisphere at 0.01 hPa (~80 km) for 6 April 2010 during the peak of a moderate storm.

What Next?

I suggest that while we have a strong framework as to how we think losses are driven from the radiation belt, significant parts of this framework has not been fully confirmed, and the quantification is still lacking for many processes.

The clearest work has been done around lightning generated whistlers and ground-based transmitters and in the second case <u>large questions are still being raised</u> (by some people)!

Things to consider:

- is our modelling of precipitative losses in the outer radiation belt correct?

- what is the flux into the atmosphere, and over what energy range?

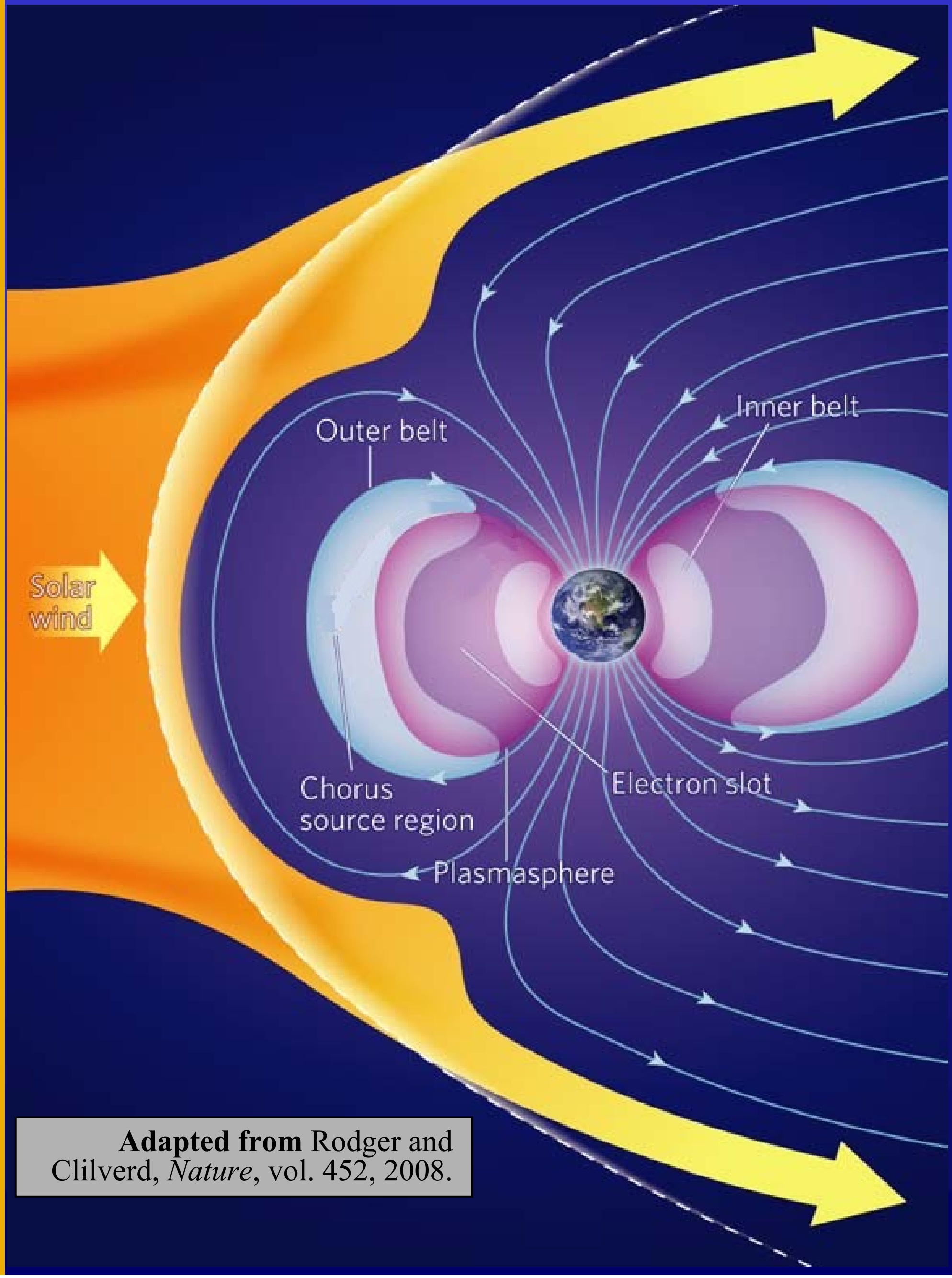
- can we show that the precipitation calculated is consistent with observations?

- can we get the precipitation spectra right, and confirm it experimentally?

- how important is precipitation to the radiation belts?

- how important is precipitation to the polar atmosphere and climate?

Remember the discovery of the Van Allen belts



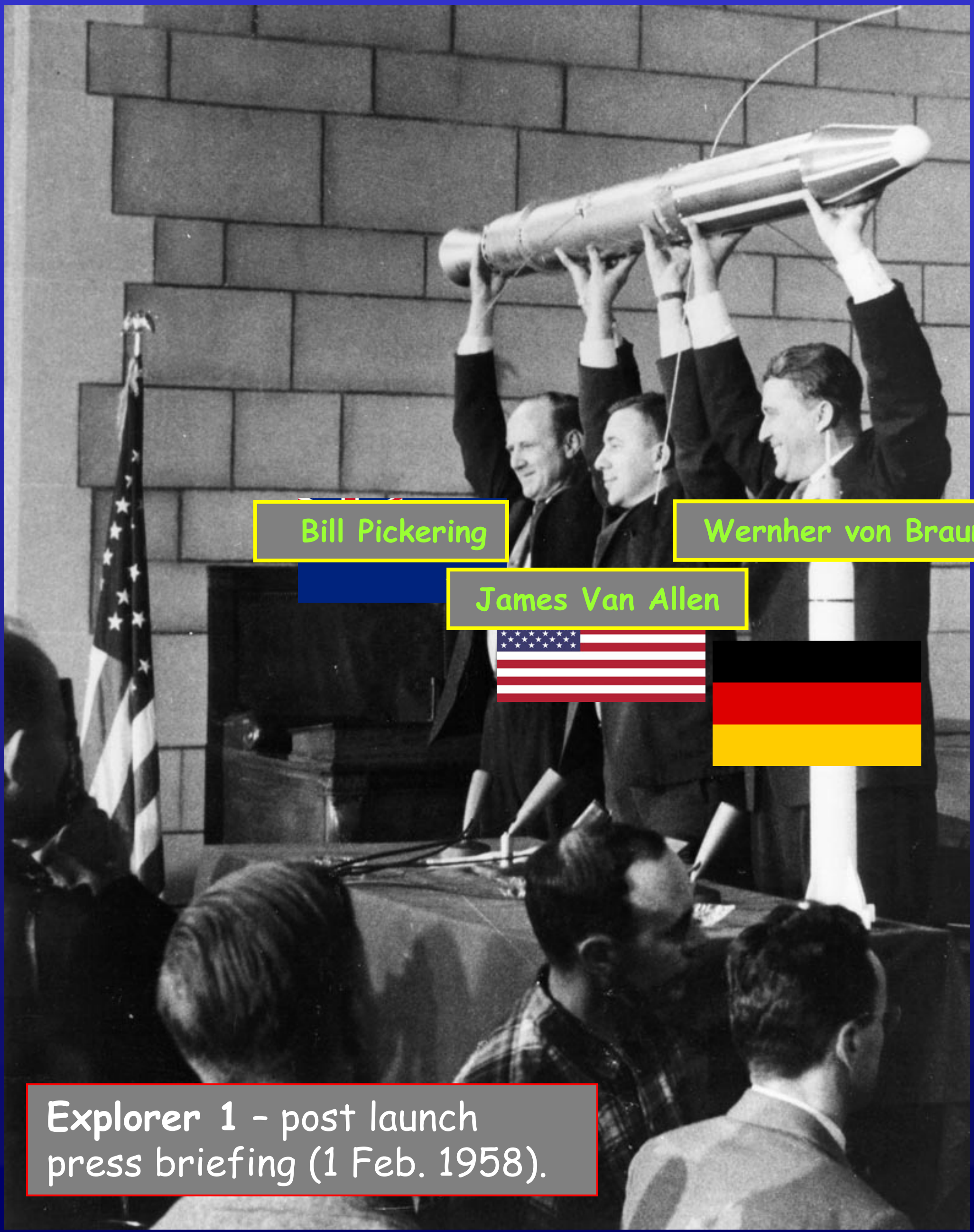
Adapted from Rodger and Clilverd, *Nature*, vol. 452, 2008.

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.

From the "Dawn of the Space Age" to Today



Explorer 1 – post launch press briefing (1 Feb. 1958).

The original discovery of the Radiation Belts, right at the start of the Space Age, was an example of research undertaken by international scientists from different backgrounds - and from across the world.

We are stronger when we do science together, with a diverse set of international collaborators.

EXPLORER 1

My groups primary support has come from:

UNIVERSITY of OTAGO
SAPERE AUDE
Te Whare Wānanga o Otāgo
NEW ZEALAND

MARSDEN FUND
TE PŪTEA RANGAHAU A MARSDEN

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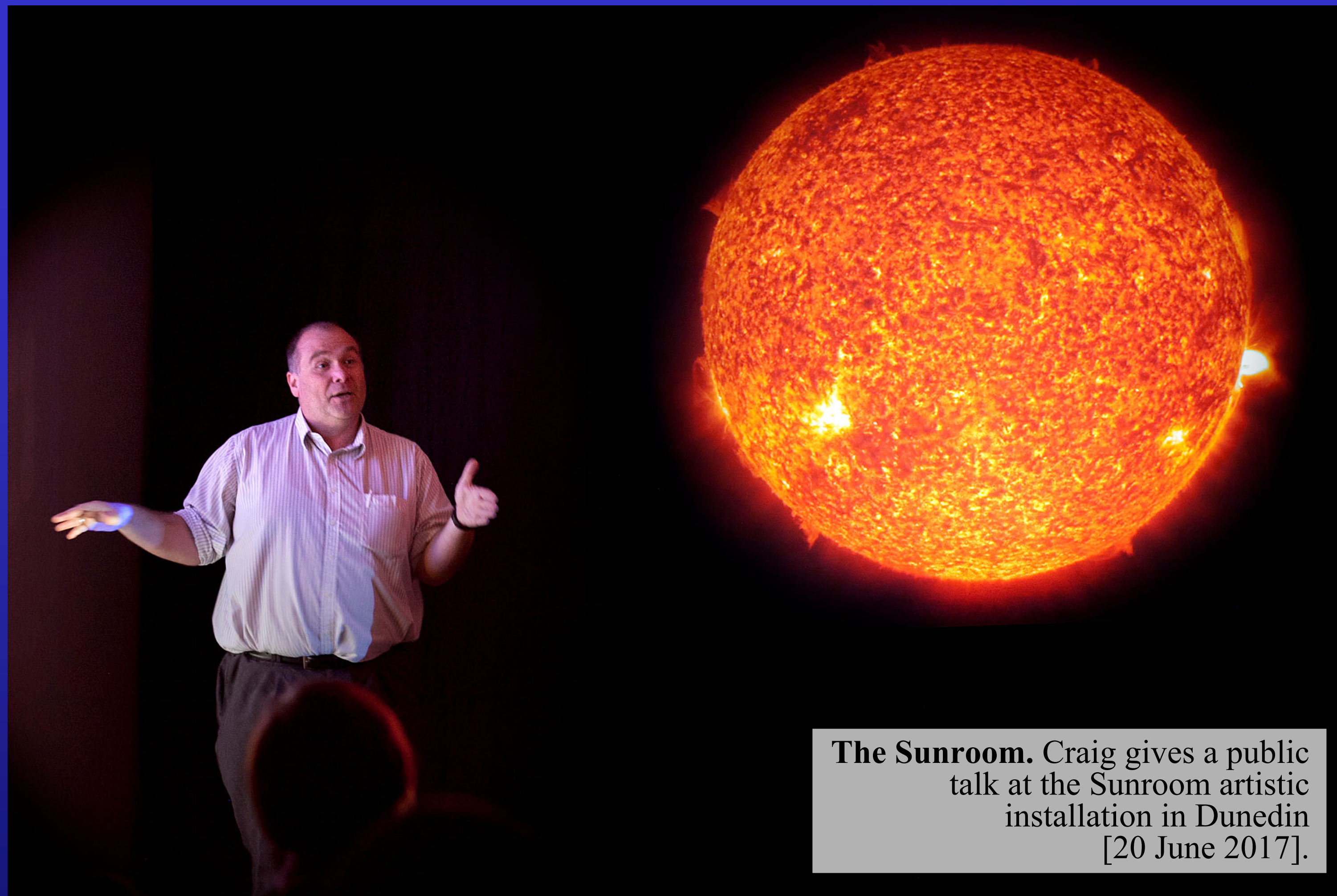

The Sunroom. Craig gives a public talk at the Sunroom artistic installation in Dunedin [20 June 2017].

Thankyou!

Are there any questions?