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The "Impenetrable Barrier" Revisited: Bursting the VLF Bubble.

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Outline

- ➢ The recent discovery of the so called “impenetrable barrier”
  - [see, *Baker et al., Nature, 2014*]
- ➢ Possible explanations
  - man made VLF waves Foster et al AGU, etc
  - Slow inward ULF wave radial diffusion on L-shells
  - Local acceleration outside the Lpp [see, *Baker et al., Science, 2014*]
- ➢ Our simulation results of the outer belt electron dynamics
- ➢ Summary/Conclusions

The Radiation Belts

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- Energies > 0.5 MeV
- Two belts
  - Inner belt stable <2 Re
  - Outer belt variable (~3 to ~6 Re)
- Focus here is on
  - >2 MeV electrons
  - Outer belt
  - 90^o e.p.a

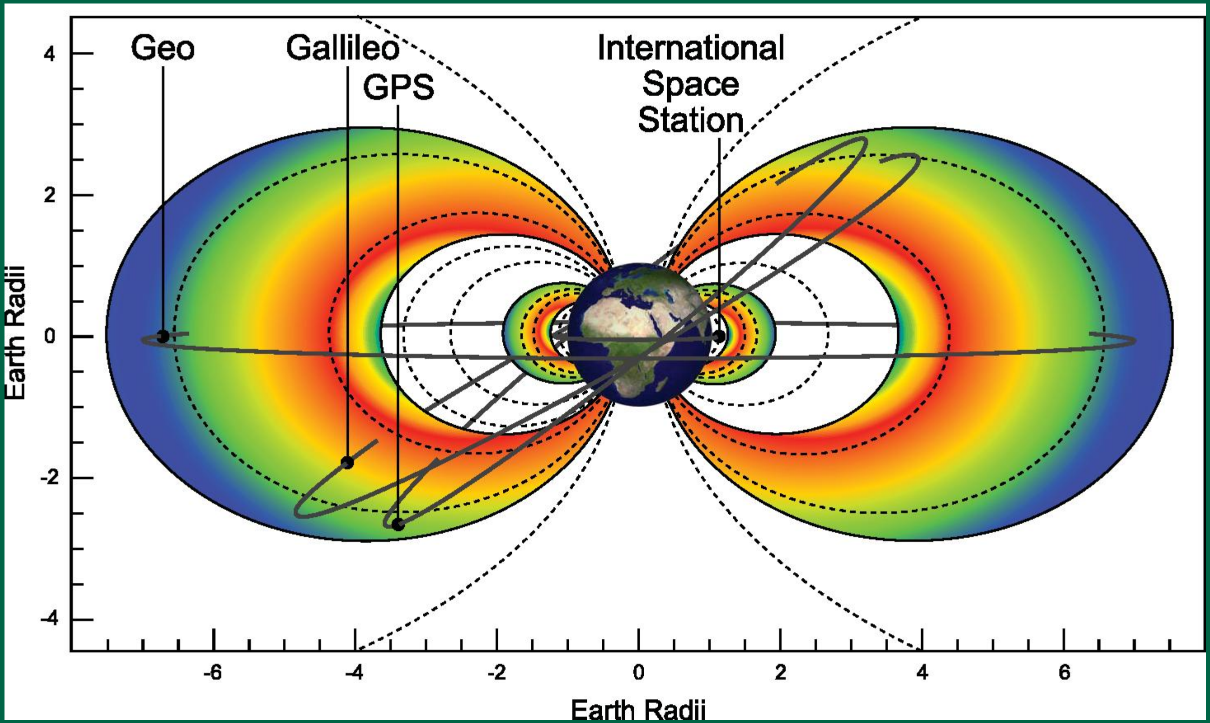

Image from Horne et al., SW, 2013

Van Allen Probes are 2 satellites designed to study these belts

- Apogee of 6 Re perigee 500 km, ~9 hr orbital period
- Lauched in 2012 with incl. ~18 degs

The Impenetrable Barrier

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- 7.5 MeV flux of electrons in the equatorial plane
- Sept 1-28, 2013, flux multiple orbit data from REPT-B.
- Sharp inner edge at 2.8 Re in the equatorial plane L=2.8, the so called *“impenetrable barrier”*

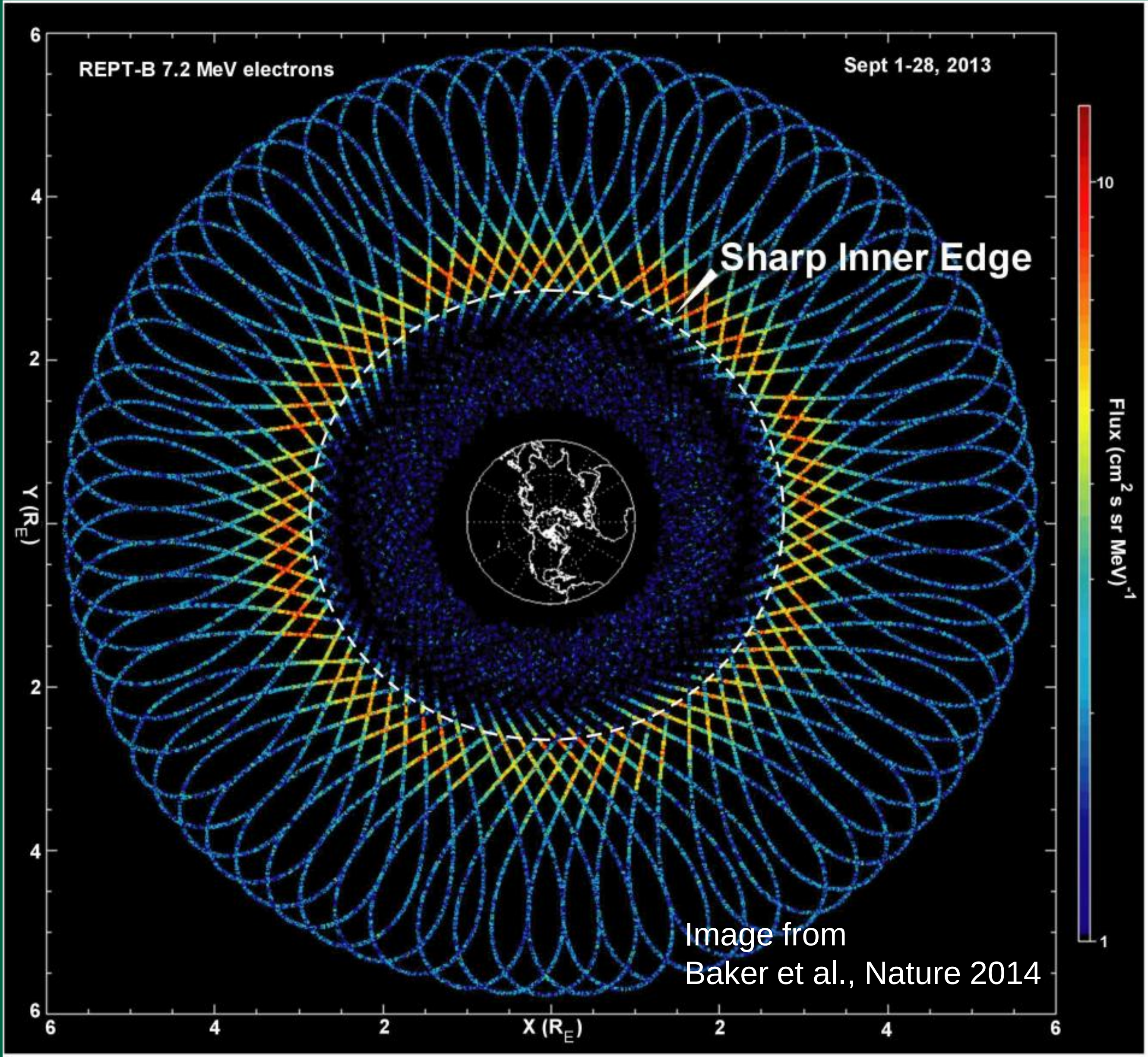


Image from
Baker et al., Nature 2014

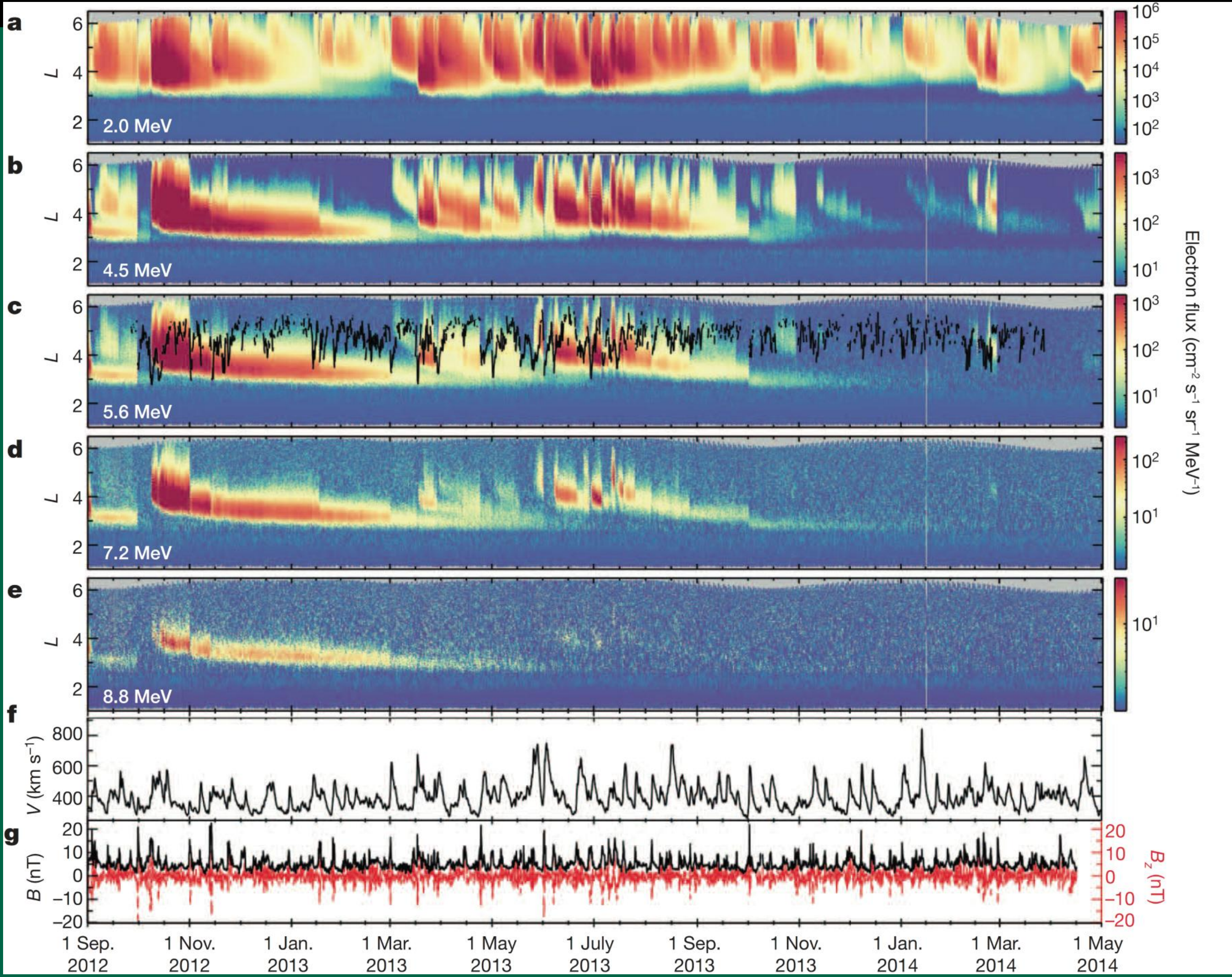
Ultra Relativistic Electron Flux

20 month time interval

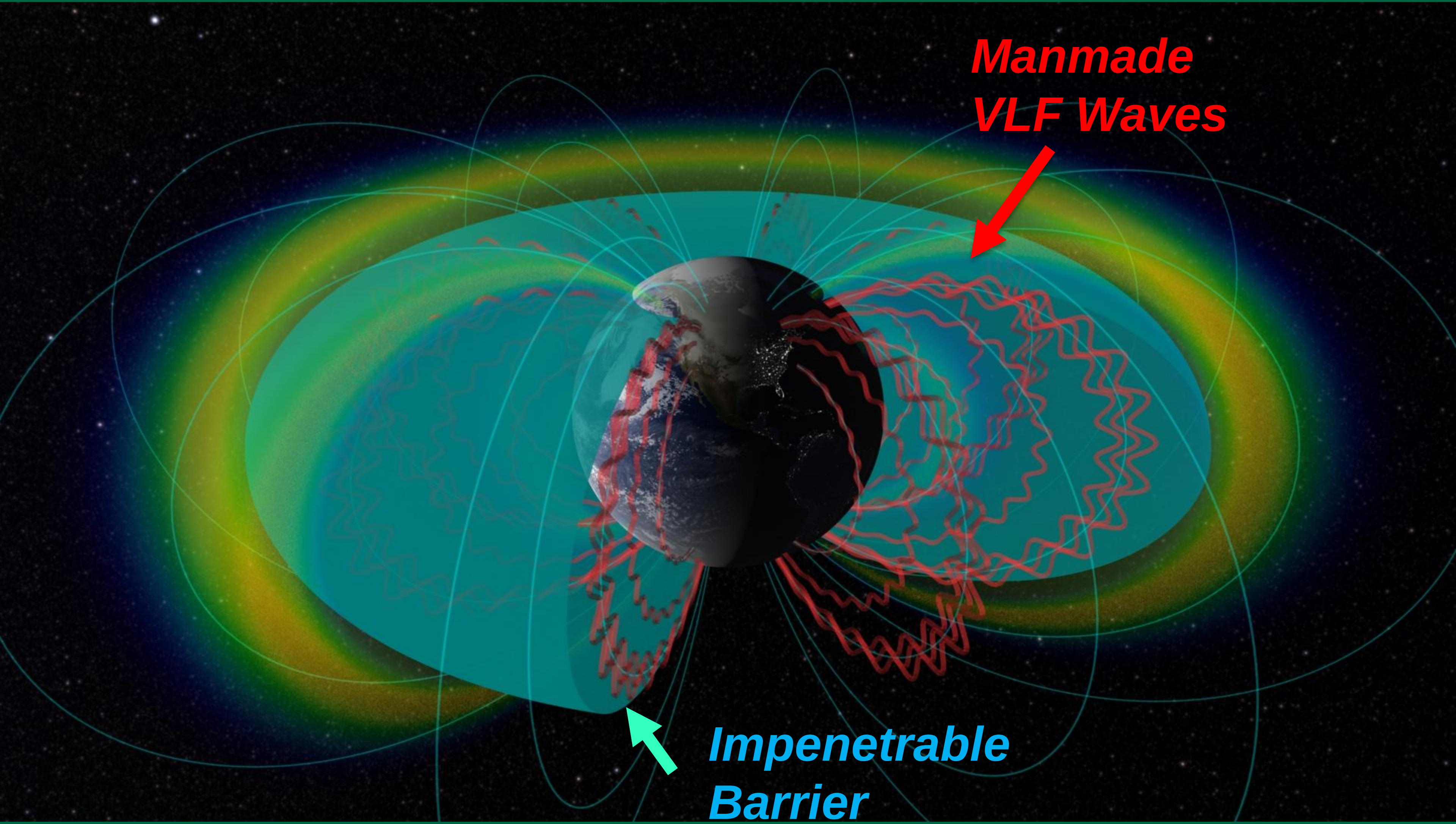
Wide range of geo. and solar wind conditions occurred

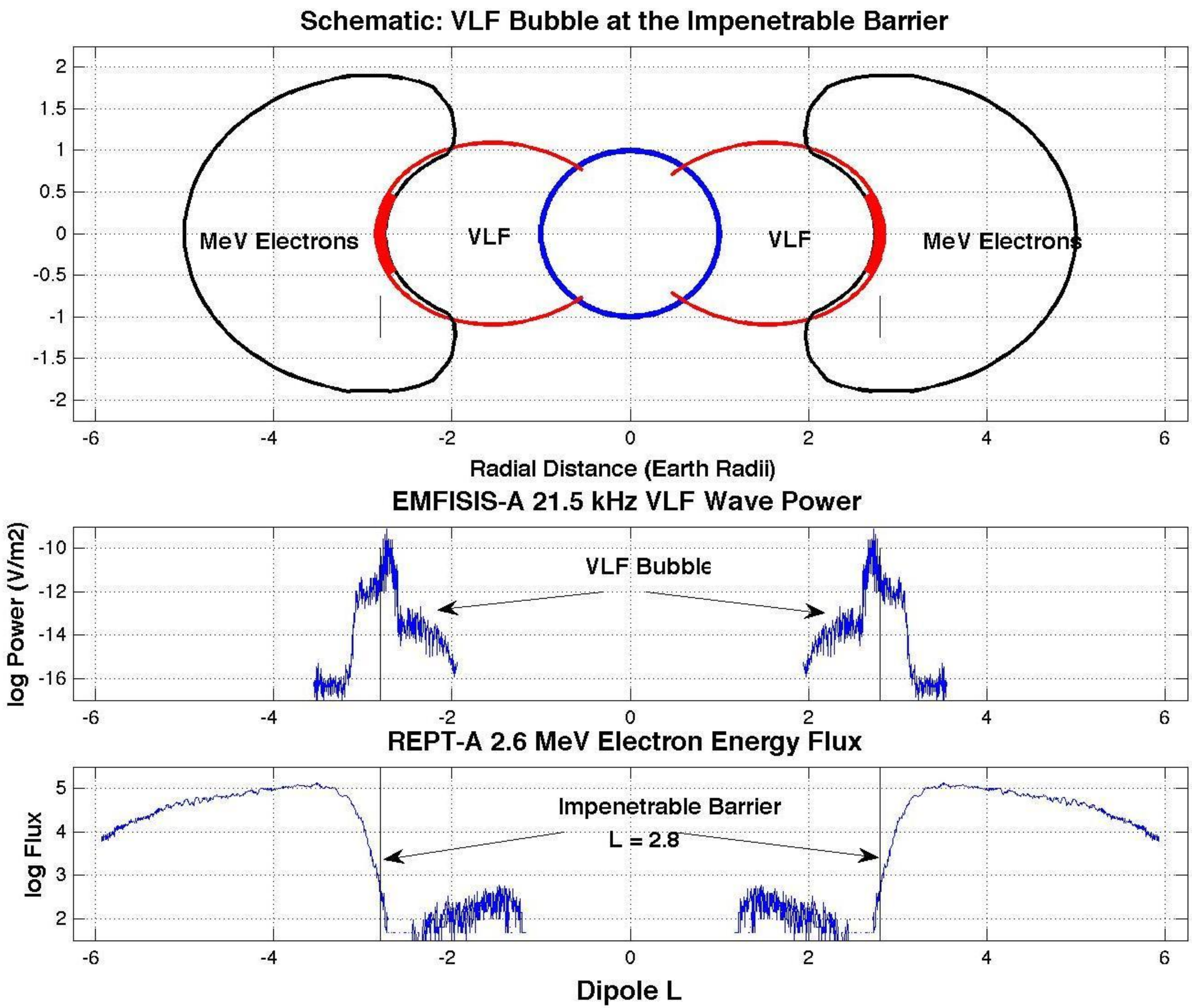
Kp max reached 7.7, lasted for 3 hrs

Kp average was 1.5



Possible Causes 1:The VLF Bubble





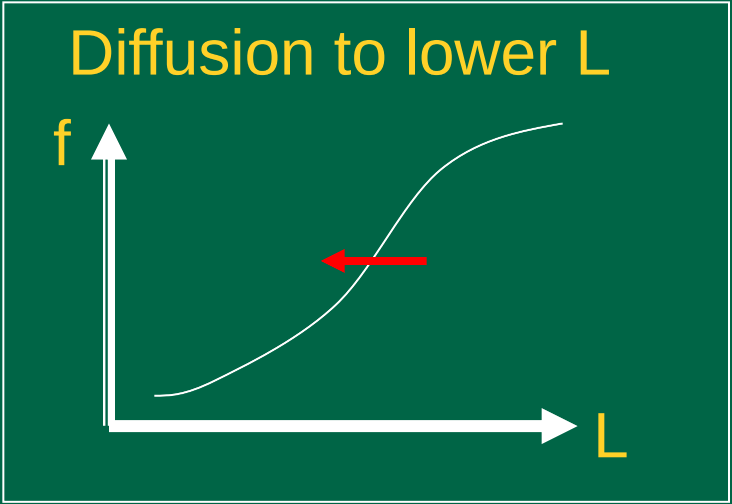
Schematic: VLF Bubble at the Impenetrable Barrier
MeV Electrons
VLF
VLF
MeV Electrons
Radial Distance (Earth Radii)
EMFISIS-A 21.5 kHz VLF Wave Power
log Power (V/m2)
VLF Bubble
REPT-A 2.6 MeV Electron Energy Flux
log Flux
Impenetrable Barrier
L = 2.8
Dipole L

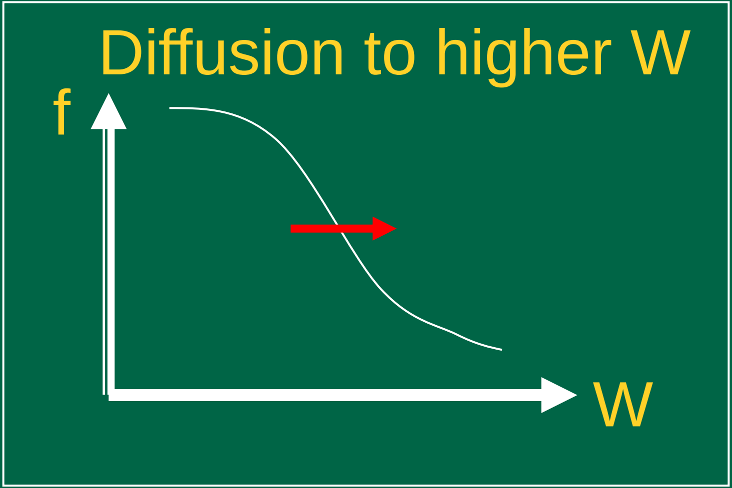
Possible Cause 2:
Slow Inward ULF wave radial Diffusion

- Diffusion of radiation belt electrons from high to low density is similar to diffusion in a gas.
- The radiation belt electrons are collision less
- The ULF waves play the role of collisions stochastically scattering the electrons
- As the electrons move inward/outward there energy increases/decreases.

$$\frac{W}{B} = \text{constant}$$

- On low L-shells diffusion is slow and loss to the ionosphere dominates due to pitch-angle scattering processes.





ULF Wave Radial Diffusive

(e.g., Falthammer 1965)

$$\frac{df}{dt} = L^2 \frac{\partial}{\partial L}\left(\frac{1}{L^2} D_{LL} \frac{\partial f}{\partial L}\right) - \frac{f}{\tau}$$

Transport
Acceleration term

Results from scattering of the electrons by ULF waves from high to low phase space density, f

$D_{LL} \propto$ ULF wave power in space

$D_{LL} = \langle \Delta L \rangle^2 / t$

Loss term

Results from pitch-angle scattering of electrons into the loss cone, e.g., from chorus and hiss waves.

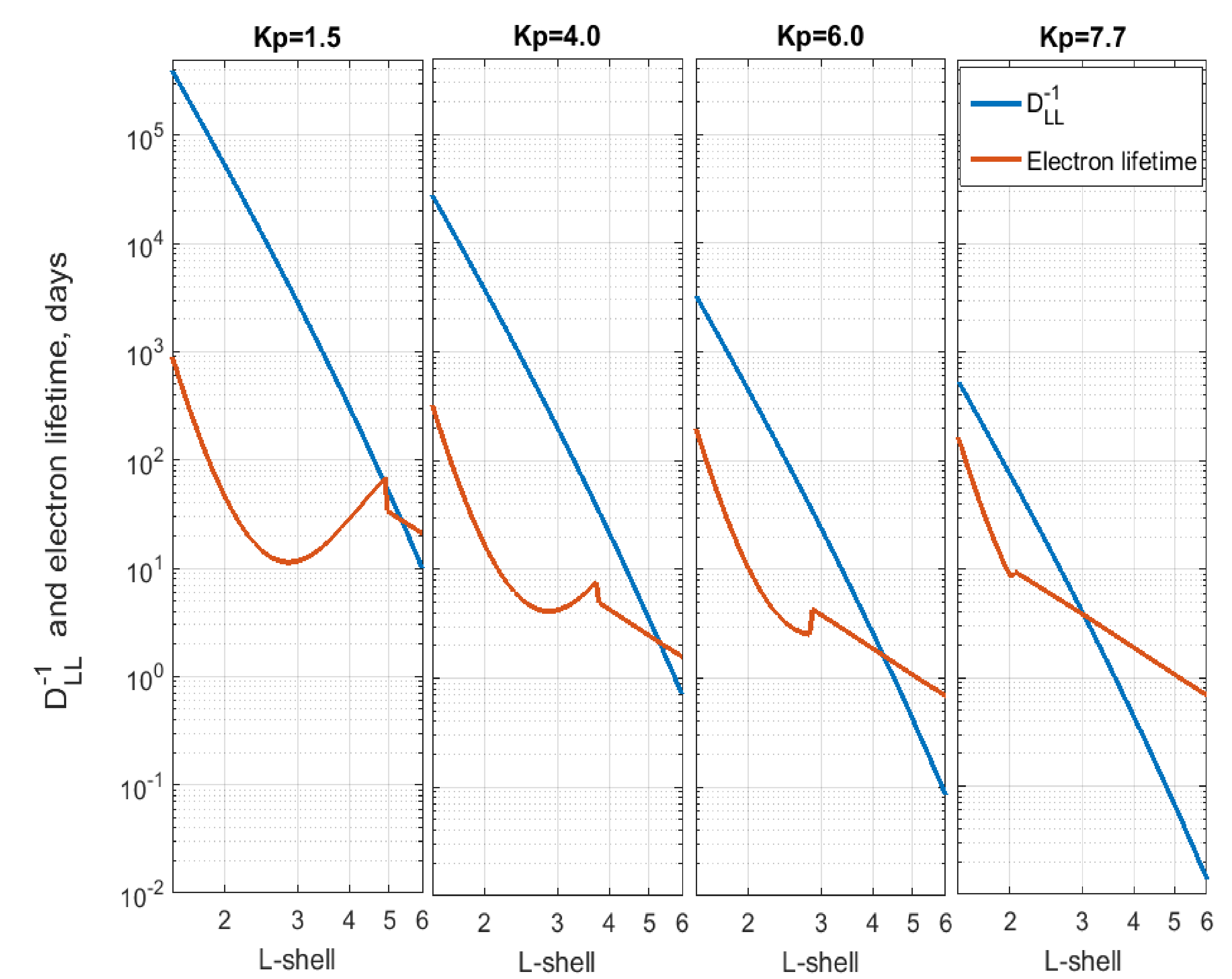
τ depends on the chorus & hiss wave power.

The initial condition, f(t=0) and the outer boundary condition f(L=6) are both derived from in-situ flux measurements.

Transport v Loss

- D_{LL} is a function of Kp & L. Faster at higher Kp & L.
- Kp=1.5 averaged conditions, at L<5 loss dominates
- Kp=7.7 the most geomagnetically active time, takes ~3 days to reach L=3 then loss dominates.
- Kp=7.7 conditions only last ~3 hrs over the 20 month interval examined in Baker et al., 2014

D_{LL}^{-1} is assumed ~ electron transport time in *Baker et al.*, 2014



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Baker et al 2014 states:

"*The radial transport of such electrons from the heart of the outer zone to L<2.8 is usually very slow* ***(on the timescale of years).*** *Thus, the electrons would be significantly depleted (by several orders of magnitude) by wave scattering during inward transport from the nominal plasmapause location at around four to five Earth radii*".

Based on these results *Baker et al., 2014* logically hypothesised that if ULF wave diffusion is too slow to transport the electrons inward to L=2.8 then another mechanism must be responsible, such as local acceleration by chorus waves.

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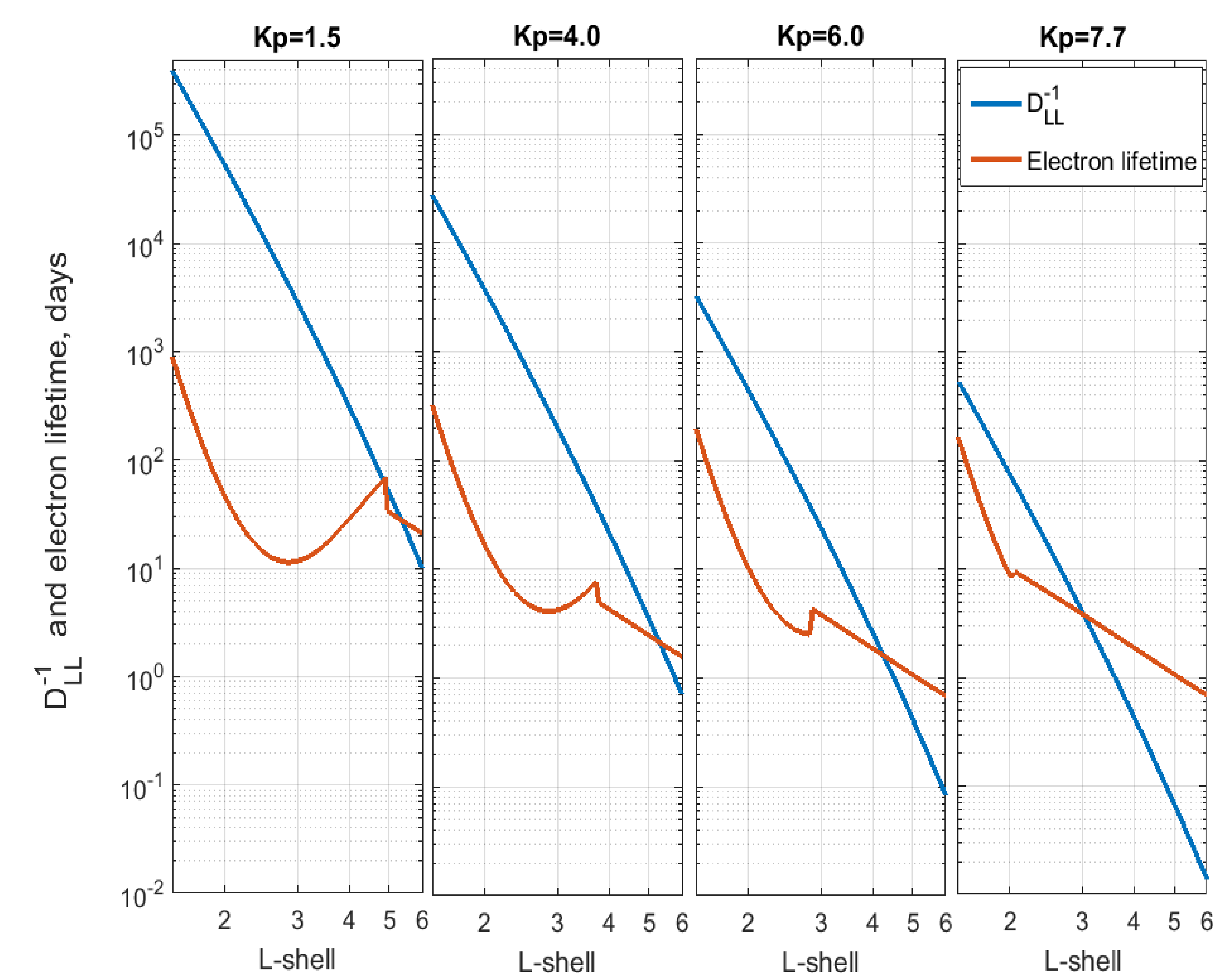
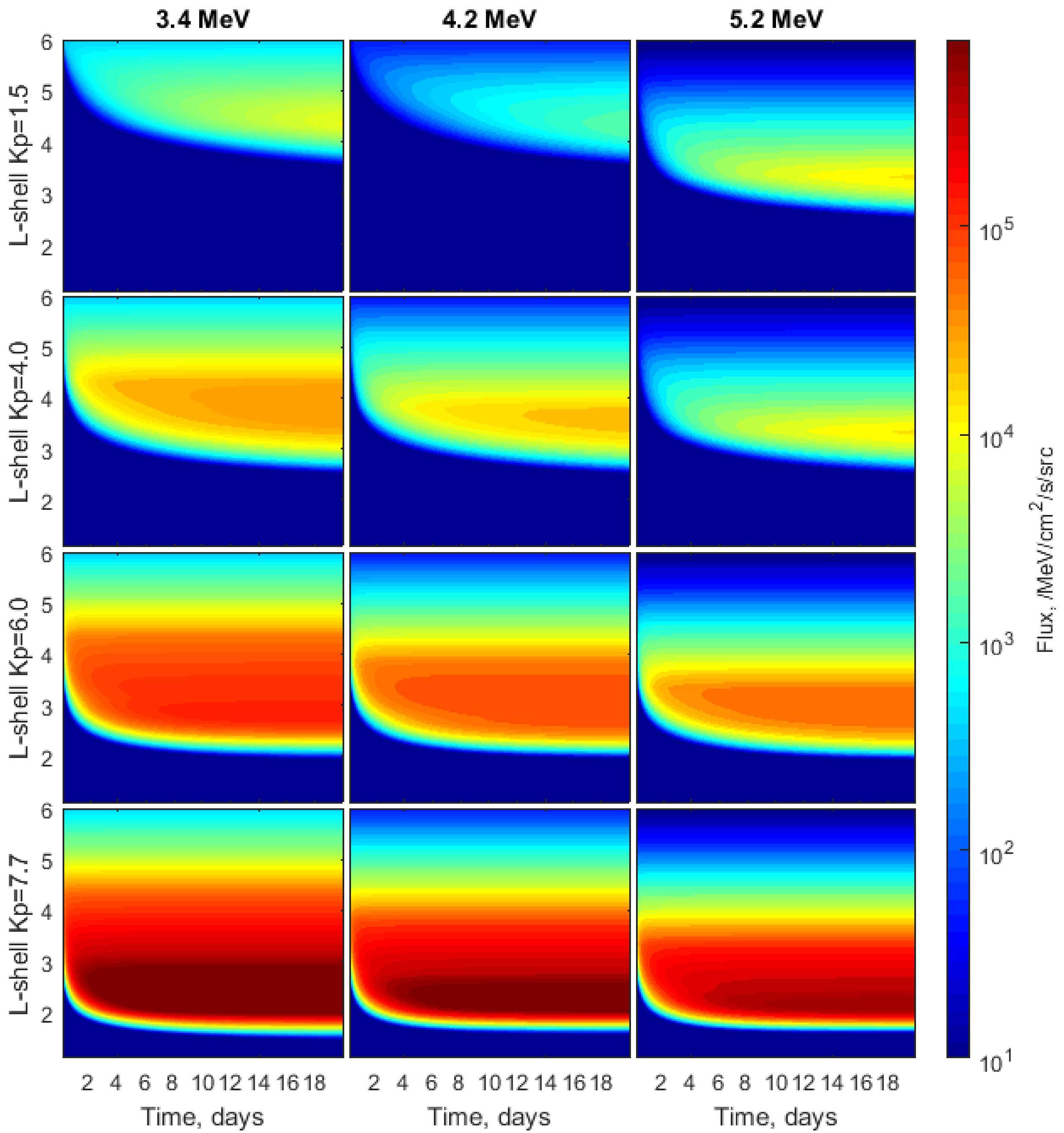


Our Flux Simulation Results

- Produced by solving the diffusion equation
- No local acceleration processes included
- No man-made VLF wave loss included.

Simulated Inward Flux Transport

- Fixed outer BC
- Kp is fixed in each simulation → constant ULF wave power.
- Plots show transport from L=6 to L~2.8 and lower is possible



Measured vs Simulated Flux

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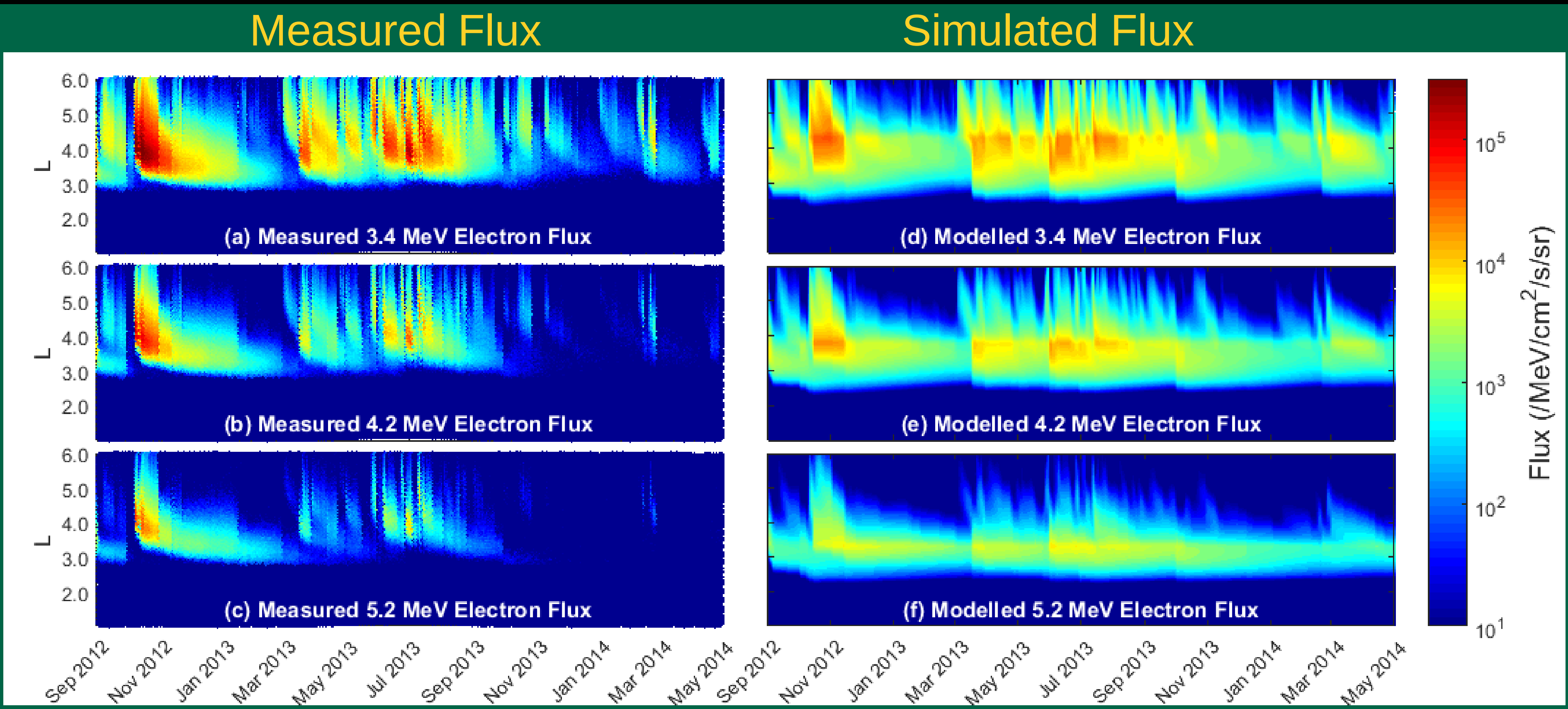

- Simulated flux more intense than that measured maybe due to loss mechanisms not being included EMIC waves magnetosonic waves or extinction events!
- Simulated and measured flux both stop at L~2.8
- No enhanced loss below L~2.8 such as from terrestrial VLF waves or local acceleration required in our model to reproduce the “impenetrable barrier”.

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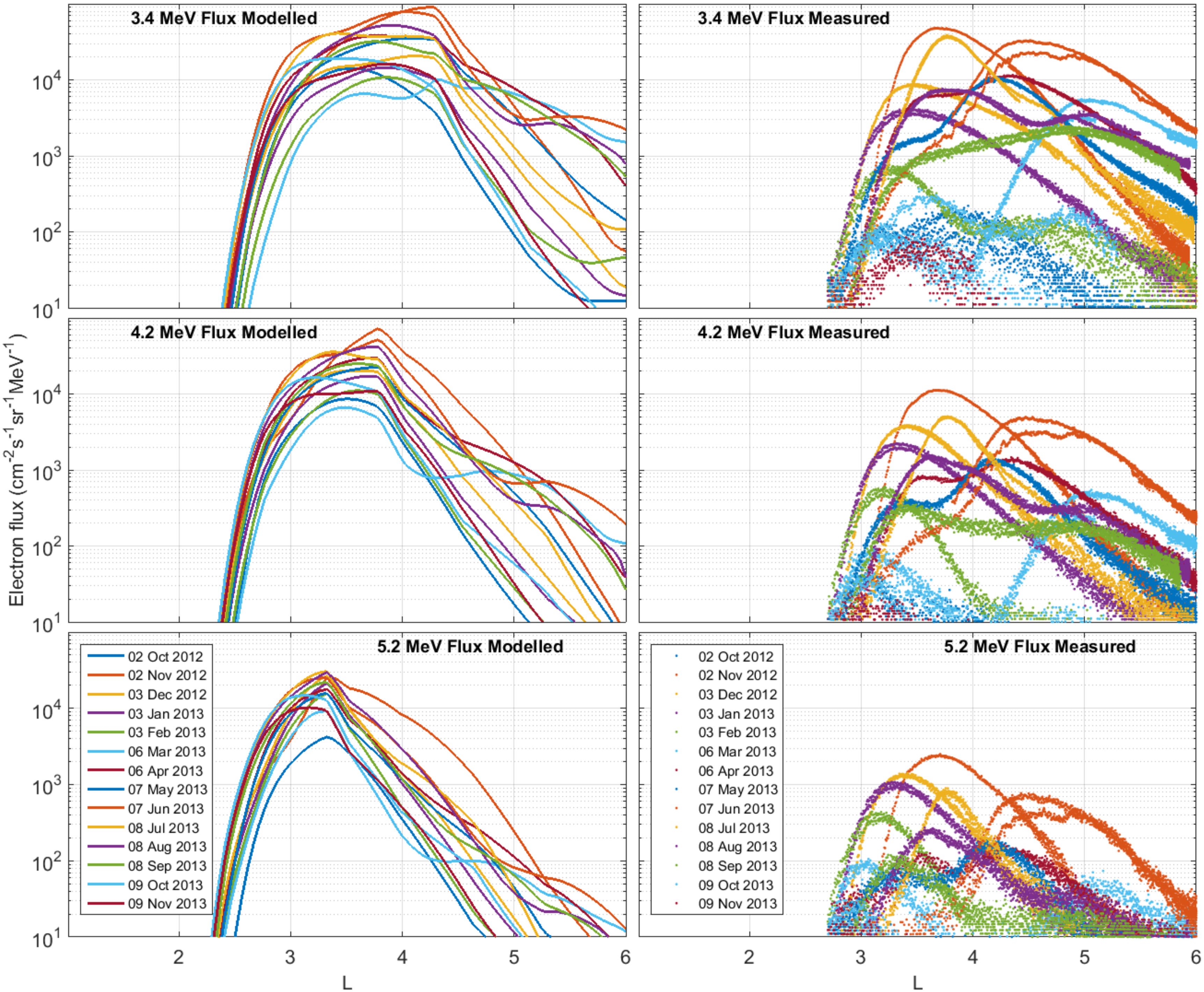
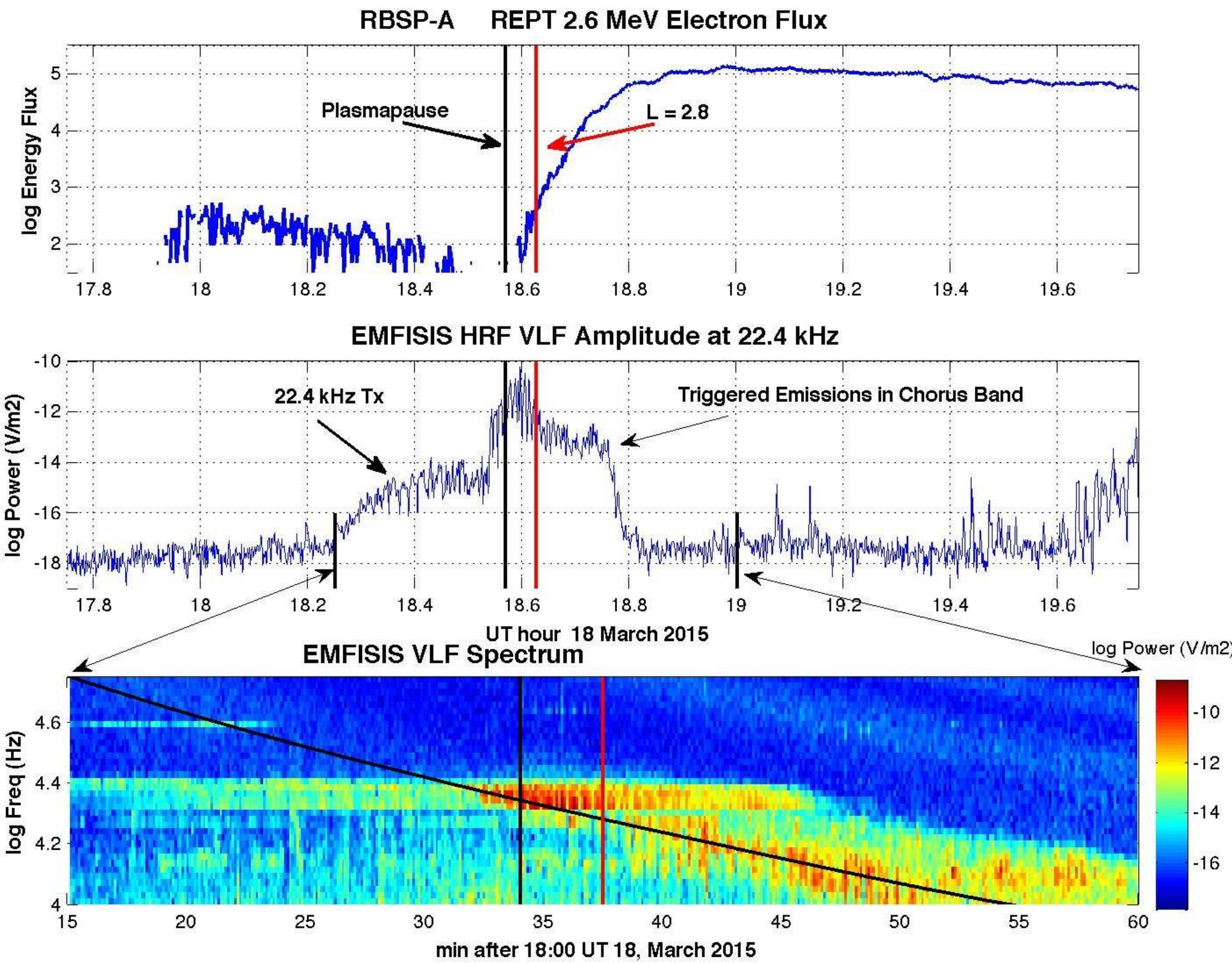
Summary/Conclusions

- 20 months of Van Allen Probe data, show that ultra relativistic electrons do not penetrate inward of L~2.8.
- Man made VLF transmitters have been suggested as creating a bubble of VLF waves out to L~2.8 which quickly scatter the electrons into the loss ionosphere.
- Here we show that inward radial diffusion by ULF waves coupled with loss due to naturally occurring chorus and hiss waves transports electrons to L~2.8, during the same 20 month time interval observed by the Van Allen Probes
- No local acceleration or man-made VLF waves required.
- This study highlights the importance of correctly specifying the radial diffusion transport times.

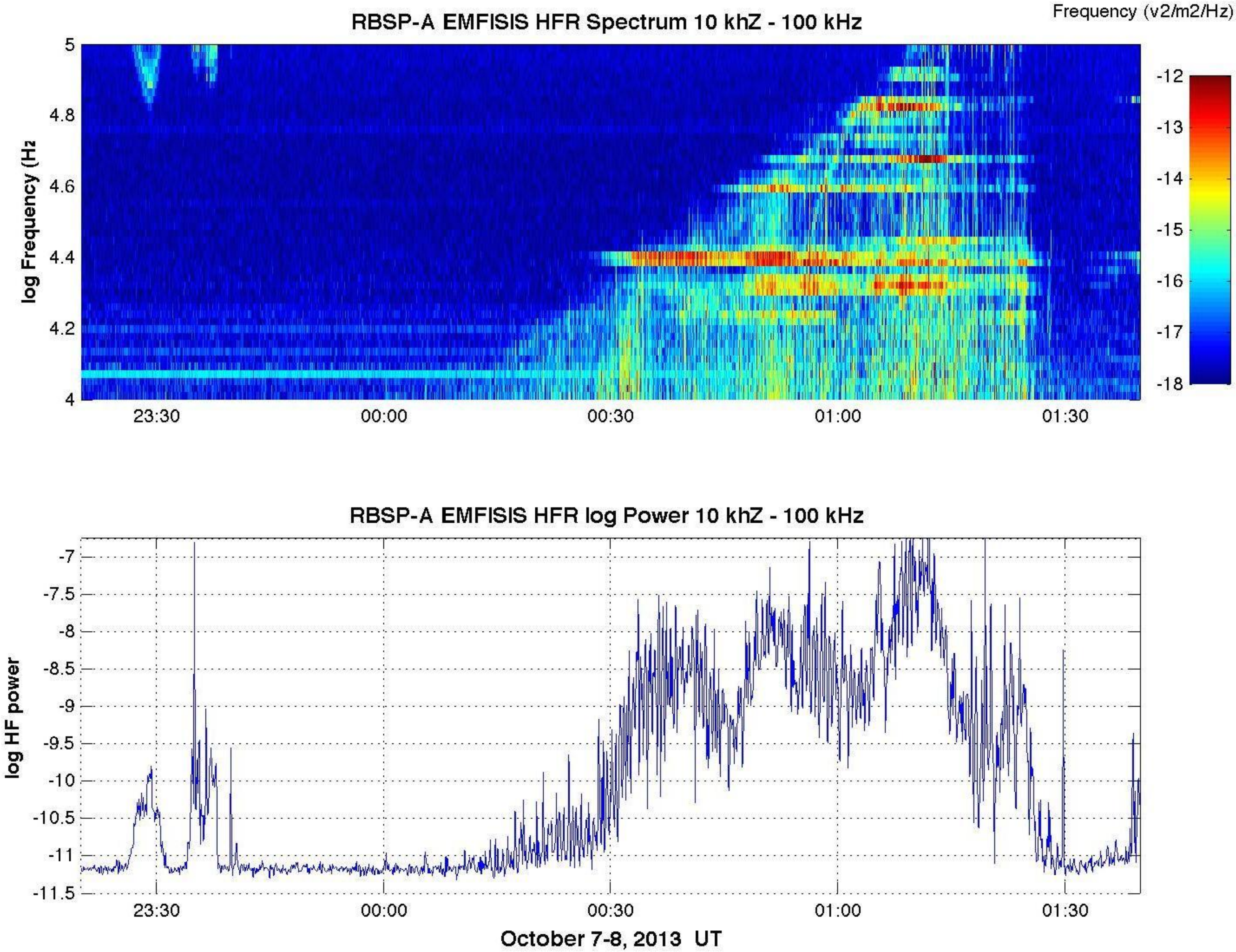
Extra Slides



3.4 MeV Flux Modelled
3.4 MeV Flux Measured
4.2 MeV Flux Modelled
4.2 MeV Flux Measured
5.2 MeV Flux Modelled
5.2 MeV Flux Measured
Electron flux (cm^{-2}s^{-1}sr^{-1}MeV^{-1})
10^1
10^2
10^3
10^4
L
2
3
4
5
6
02 Oct 2012
02 Nov 2012
03 Dec 2012
03 Jan 2013
03 Feb 2013
06 Mar 2013
06 Apr 2013
07 May 2013
07 Jun 2013
08 Jul 2013
08 Aug 2013
08 Sep 2013
09 Oct 2013
09 Nov 2013



Foster, Baker, Erickson,…(2015)



VLF Bubble in Inner

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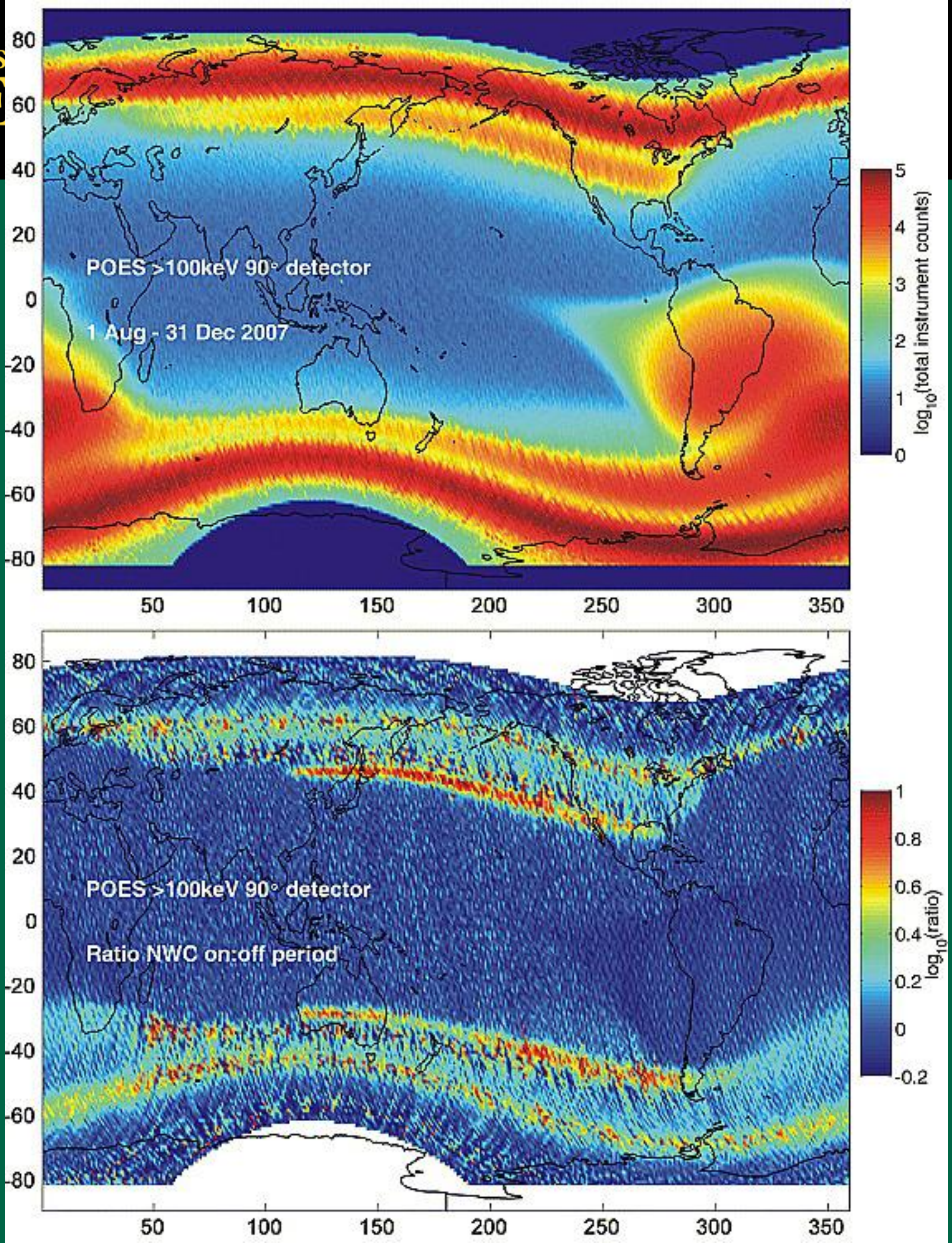

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 86, NO. A2, PAGES 640-648, FEBRUARY 1, 1981

Precipitation of Inner Zone Electrons by Whistler Mode Waves From the VLF Transmitters UMS and NWC

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The precipitation of energetic electrons which are commonly observed in the drift loss cone east of 60 ø east longitude between L ~ 1.6 and L ~ 1.8 can be accounted for by a Doppler-shifted cyclotron resonance between the electrons and nonducted whistler mode waves from high-power, ground-based VLF transmitters. A ray-tracing analysis using a diffusive-equilibrium model shows that 17.1-kHz waves starting with vertical wave normals between 23 ø and 31 o magnetic latitude cross the magnetic equator between L ~ 1.6 andf L ~ 1.8 with wave normals of approximately 63 o. A relativistic cyclotron-resonance analysis for the same model plasmasphere using the ray-tracing results gives an energy versus L shell dependence for the precipitated electrons which is in excellent agreement with the observed dependence. The primary VLF transmitter is most probably the UMS transmitter located near Gorki, USSR. It transmits on 17.1 kHz. VLF records covering this frequency band were available for only three of the time periods when electrons were observed. In two cases UMS was transmitting at the time required to account for the observations. In the third case a higher frequency is required to fit the data. At the time, the NWC transmitter at North West Cape, Australia was operating at 22.3 kHz. These data are consistent with a model in which weak pitch angle scattering by whistler mode waves from NWC does not completely fill the drift loss cone at the longitude of NWC.