Testing the theory behind ULF pulsation-related precipitation

I Jonathan Rae[1], Kyle R Murphy[2], Clare EJ Watt[3], Alexa J Halford[4], Andrew R Inglis[5], Ian R Mann[6], Louis G Ozeke[6], Mark A. Clilverd[7], Craig J Rodger[8], David G Sibeck[2], Alexander W Degeling[9] and Howard J Singer[10]

(1)MSSL/UCL, (2)NASA GSFC, (3)University of Reading, (4)Aerospace Corporation, (5)Catholic University of America, (6)University of Alberta, (7)British Antarctic Survey, (8)University of Otago, (9)Shandong University, (10)NOAA Boulder

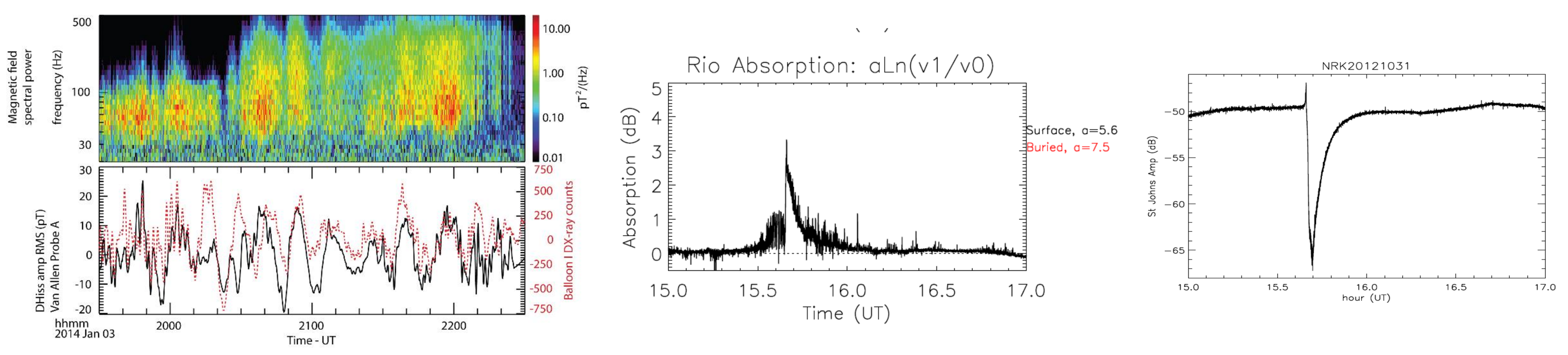
UCL

Abstract. We present a new mechanism for electron loss through precipitation into the ionosphere due to a direct modulation of the loss cone via *localized* compressional ULF waves. With localized ULF wave fields, modulation of the equatorial loss cone greatly exceeds the change in pitch angle through adiabatic motions leading to enhanced precipitation.

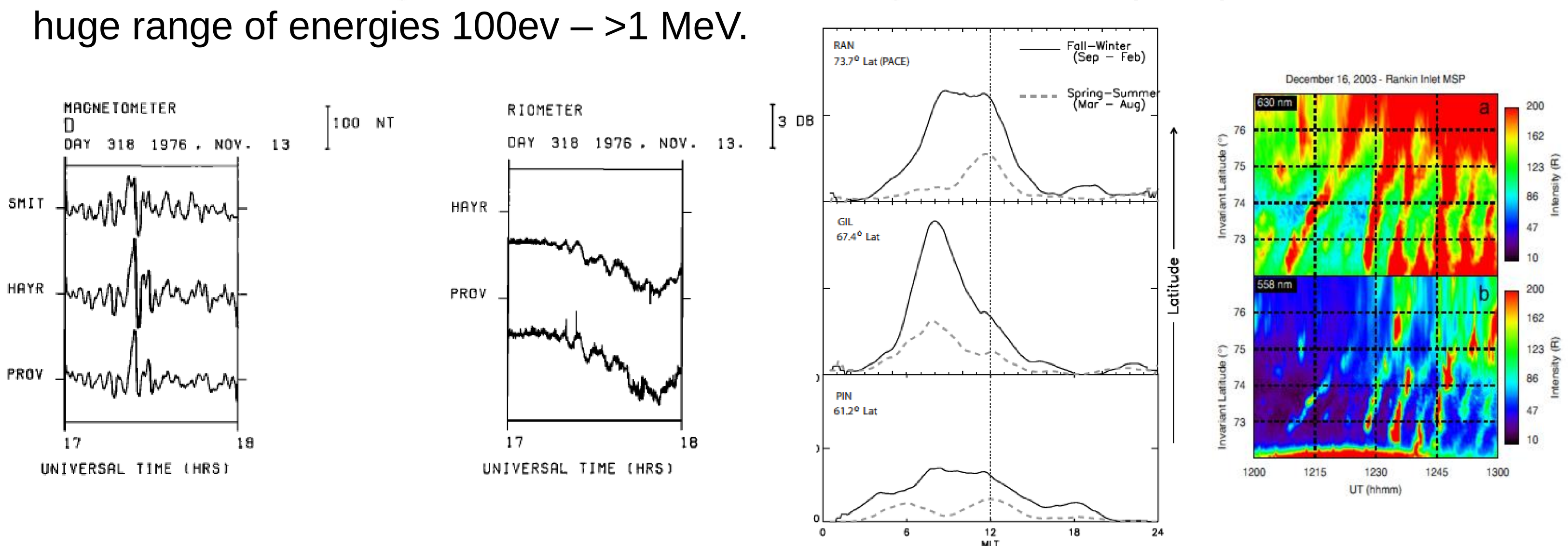
We further statistically investigate the relationship between compressional, poloidal and toroidal mode ULF waves and ULF-modulated ionospheric precipitation. We find no relationship between the amplitude of toroidal-mode ULF waves and ULF-modulated precipitation. However, we find a significant relationship between ULF wave modes that have a compressional component and ULF-modulated precipitation. This is true for compressional waves at any MLT. A similar relation is found for day-side poloidal mode ULF waves.

Current theory: compressional ULF wave fields modulate whistler-mode wave growth rates (Coroniti and Kennel, 1970; Breneman et al., 2015)

Does this explain all energetic electron precipitation?



- ULF waves have long been associated with energetic electron precipitation across a huge range of energies 100ev – >1 MeV.



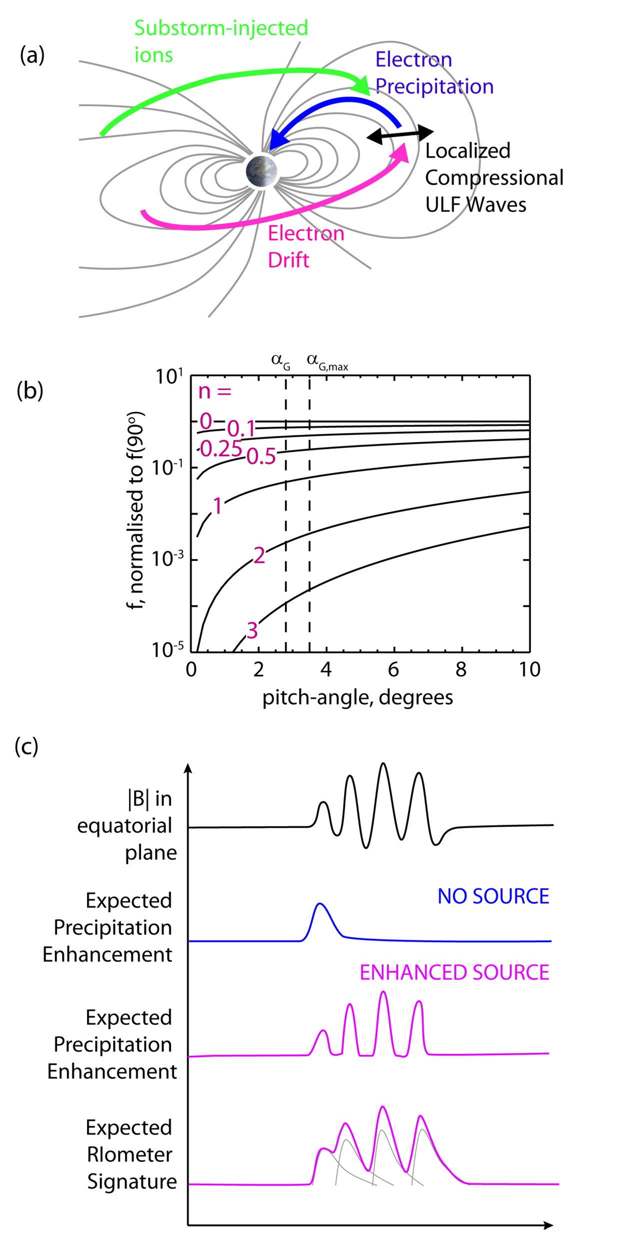
- ULF-modulated precipitation occurs at all MLTs in the heart of the Radiation Belts (e.g., Spanswick et al. 2005)
- ULF-modulated precipitation occurs for both compressional *and* non-compressional ULF waves (e.g., toroidal-mode FLRs; e.g., Rae et al., 2007 e

Do ULF waves simply modulate existing energetic electron precipitation or can they cause energetic electron precipitaton where otherwise there would be none?

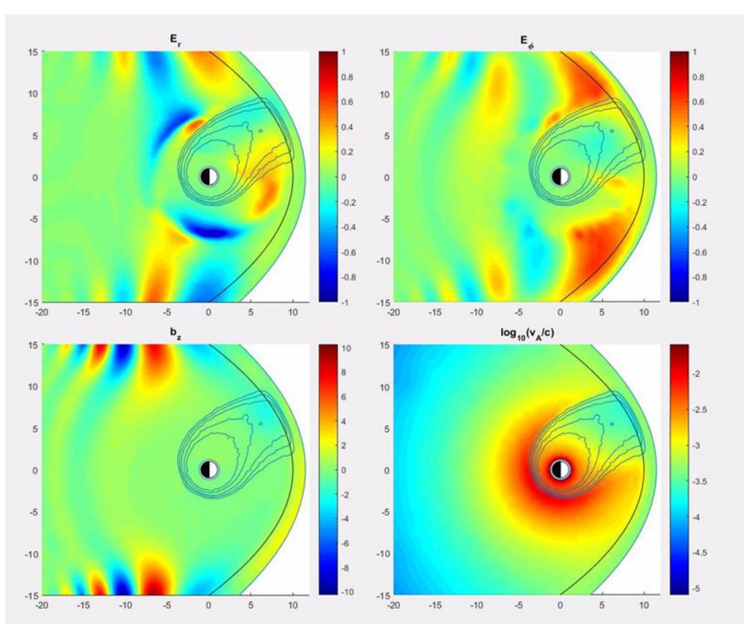
Traditionally we always assume ULF waves are everywhere and homogeneous. Is this ever true?

Additional precipitation mechanisms

- Modulation of electron drift paths (e.g., Brito et al., 2015) suggest not much
- ULF modulation of EMIC waves (e.g., Loto'aniu et al., 2009; Woodger et al., 2012) suggest yes in a specific energy range
- Kinetic-scale FLRs (Rankin, Samson, Rae etc) suggest yes in a specific energy range
- Modulation of local bounce loss cone (e.g., Rae et al., 2017) suggest yes across all energies with an energy dependence



Localisation, radial and azimuthal structuring, time variation, density gradients. Do we understand any of them?



(top) a thought experiment on the conservation of the first and second invariants and breaking of the third in response to a localised ULF wave field and it's resultant increase in precipitation on ULF wave timescales (Rae et al., 2017)

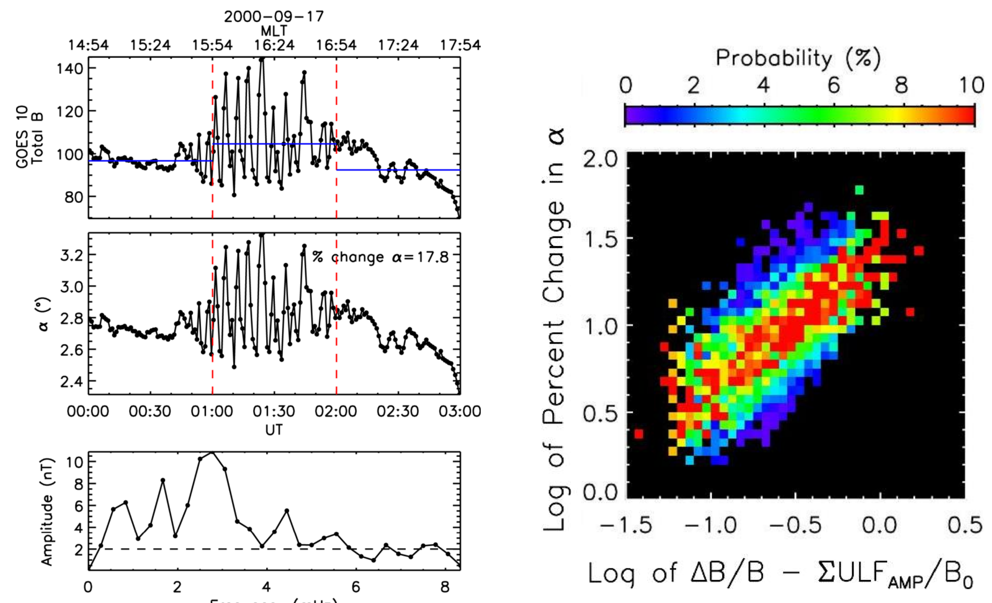
(left) simulations of ULF wave fields in the presence of a plasmaspheric density plume, demonstrating a significant change in ULF wave characteristics local to the dusk sector (Degeling et al., 2017)

Storm-time Pc5 waves: What are they and how big can they get?

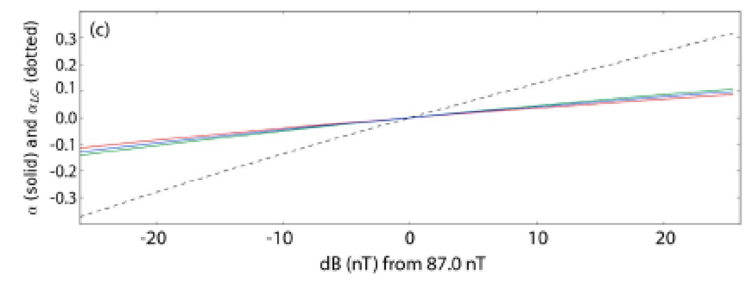
Storm-time Pc5 waves or poloidal-mode FLRs have a strong radial and azimuthal localisation and can be large amplitude in the afternoon sector (dB/B ~60%)

$$\sin^2 \alpha_{eq} = \frac{B_{eq}}{B_m}$$

If the change in loss cone is larger than the change in pitch angle due to the conservation of the 1st and 2nd invariants then more particles are able to precipitate



$$\sin \alpha_{eqf} = -\frac{L_f^{1/2} \cos^2 \alpha_{eq0}}{2 L_0^{1/2} \sin \alpha_{eq0}} + \frac{1}{2}\left(\frac{L_f \cos^4 \alpha_{eq0}}{2 L_0 \sin^2 \alpha_{eq0}} + 4\right)^{1/2}$$



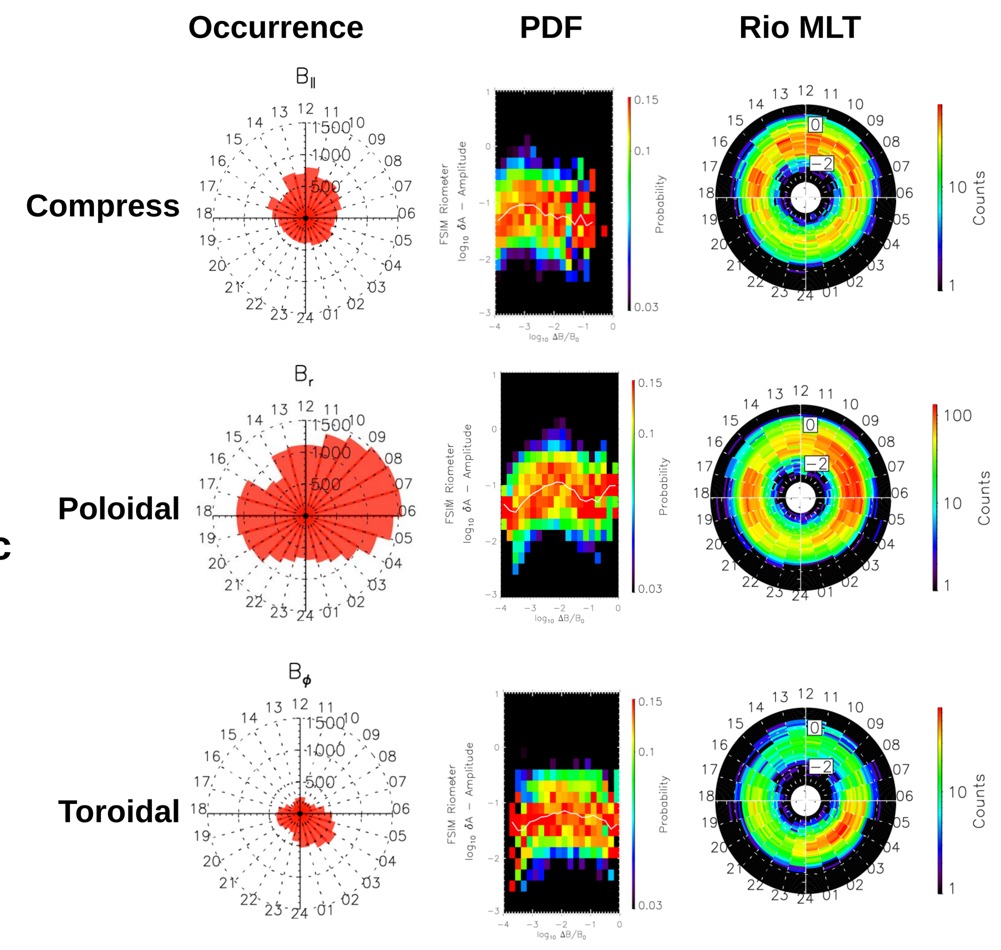
Changes in the loss cone outweigh the changes in pitch angle due to conservation of invariants (0.4° c.f., 0.1° in this case study)

Statistically, we find that the loss cone can change by 50%. Depending upon the shape of the PSD close to the loss cone, this would result in significantly more precipitation without requirement for any wave-particle interaction processes.

Storm-time Pc5 waves: Statistically linked to energetic electron precipitation?

Using novel technique (AFINO; Inglis et al., 2015) we analyse 12 years of GOES magnetic field data to find discrete, monochromatic wave packets

Oscillations classified as compressional ($B_\parallel$); poloidal/radial (B_r) and toroidal/azimuthal (B_ϕ)



Relationship between magnetic wave amplitude and riometer pulsation amplitude varies for different types of oscillation

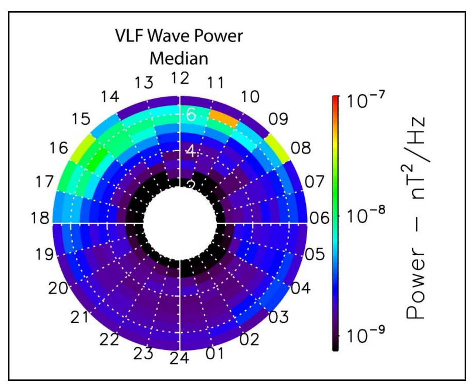
Poloidal (radial) oscillations have strongest relationship to riometer pulsations
Toroidal (azimuthal) oscillations have weakest relationship
Riometer response appears to saturate for all wave modes

Poloidal (radial) oscillations *frequently* result in strong riometer oscillations across most of the dayside.
Compressional oscillations *quite frequently* result in strong riometer oscillations across most of the dayside.
Toroidal (azimuthal) oscillations associated with riometer pulsations are only seen in the post-midnight sector

A provocative comparison to Van Allen Probes

Van Allen Probe whistler-mode wave powers variable across the dayside magnetosphere

Some evidence of more wave power in dusk than dawn, but does not cover all dayside MLTs



Summary and Conclusions

- ULF modulation of VLF growth rates can't explain all ULF modulated precipitation signatures
- Large precipitation signatures across 100s eV – MeV are observed in the post-noon sector
  - Do current mechanisms explain entire range of energies?
- We present a simple and additive mechanism that may be important to consider that can precipitate electrons across all energies
  - In fact all of these mechanisms work best in tandem

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