A Statistical Study of Energetic Particle Precipitation in the D-region Ionosphere

R. J. Irvin[1,2], R. H. Varney[1], A. S. Reimer[1], P. M. Reyes[1], and S. R. Kaeppler[3]

[1]Center for Geospace Studies, SRI International, Menlo Park, CA. [2]Department of Physics, Purdue University, West Lafayette, IN. [3]Department of Physics and Astronomy, Clemson University, Clemson, SC

Abstract

Energetic particles trapped in the inner magnetosphere can, as a result of wave-particle interactions, enter the loss cone and precipitate into the atmosphere. Only the most energetic of these particles can reach penetration depths in the D-region. Incoherent Scatter radars (ISR) can detect this enhanced D-region ionization.

Using Poker Flat Incoherent Scatter Radar (PFISR) D-region data from 2009-2018 we identify events of enhanced ionization caused by energetic particle precipitation, and observed how the frequency of these events scales with geomagnetic activity and MLT. We found that energetic particle precipitation is more frequently observed on the dawn side (0-12 MLT) and for higher global AE values (>250 nT).

Comparing our results with global distribution studies of some inner magnetospheric waves suggests that the MLT and AE distribution of Energetic Particle Precipitation (EPP) is similar to that of equatorial whistler-mode chorus waves

Introduction

- (EPP) refers to highly energetic particles that are accelerated into the atmosphere
- PFISR is an ISR at Poker Flat Research Range, Chatanika, AK and has been running D-region modes since 2007
- Only the most energetic electrons (>30 keV) make it to the D-region (Fang 2008)
- EPP → Enhanced Ionization which impacts Mesospheric chemistry
- Is there a relationship between EPP in the D-region and MLT or some Geophysical indices?

Observations and Data Processing

- Pulse to Pulse Spectra, 2ms IPP (250 Hz Nyquist), 256 point FFT, 449.3 MHz Tx Frequency, 13-baud Barker Code, 10μs baud (1.5km range resolution), 5μs sample rate, beam look directions shown in Fig. (1)
- Power spectral density (PSD) in collisional regime is Lorentzian (Kudeki 2011):

$$S(f) \approx \frac{2k^2 D_i}{(2\pi f - 2\pi f_o)^2 + (2k^2 D_i)^2} \quad (1)$$

Where f is the frequency, S(f) is the PSD, k is the bragg wavenumber, f_o is the radial doppler shift of the target, $D_i \propto 1/\upsilon_{in}$ is the ion diffusion coefficient and υ_{in} is the ion neutral collision frequency

- With decreasing altitude → Neutral density increases → ion collision rate increases → ion diffusion coefficient in Eq. (1) decreases → PSD narrows Fig (1)
- Spectral width becomes larger than the Nyquist frequency above 85km so the spectrum is aliased Fig (1)
- Noise estimation of spectra was made by averaging over 'dark' altitudes (52.5-57.5 km)
- EPP causes the ISR signal to be large enough in the D-region for the Lorentzian shape to be detectable by PFISR

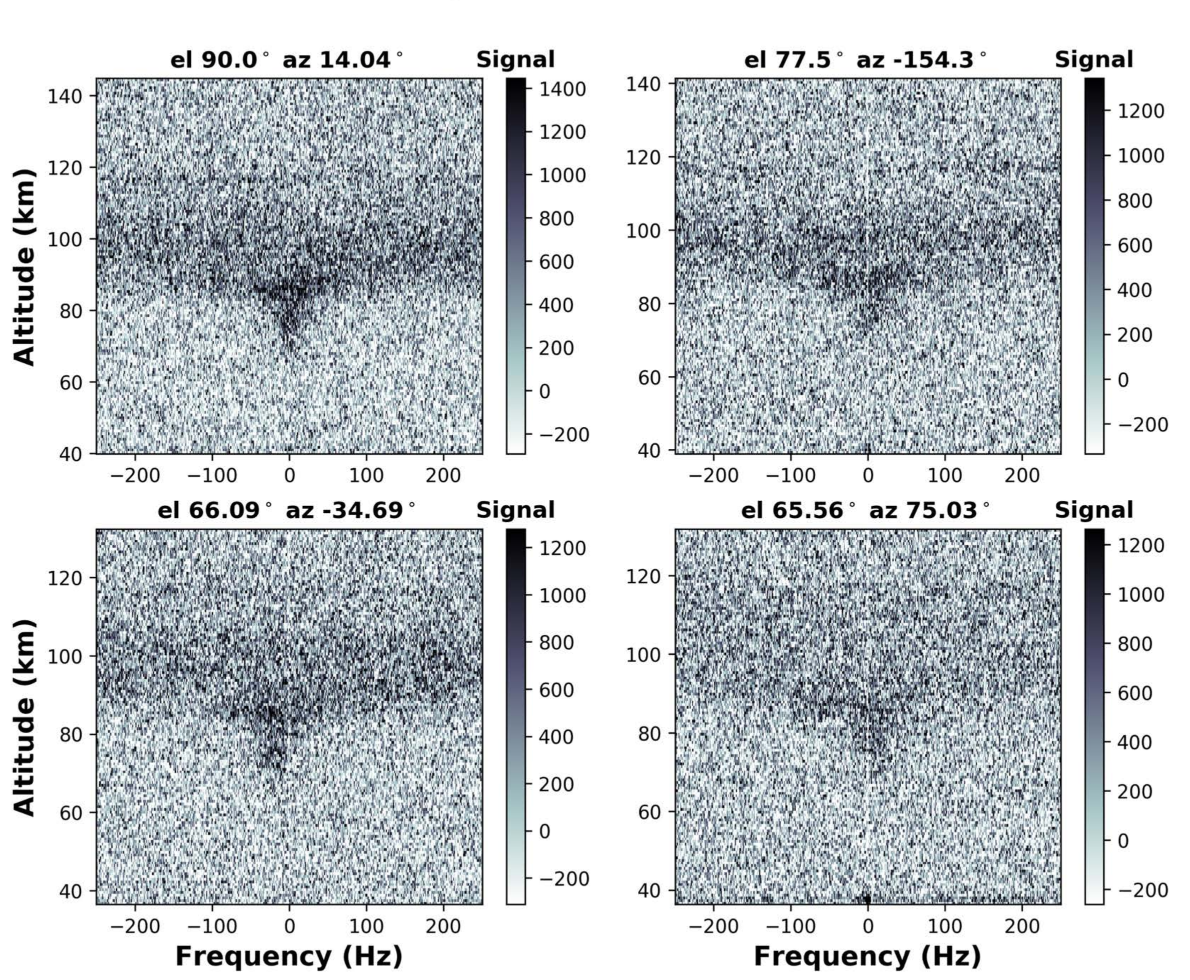

Fig. (1) 5 minute integrated D-region ISR spectra taken from PFISR experiment on May 8, 2017 at 1605 MLT

Methodology

- Non-linear fitting is a computationally expensive way to estimate spectral width
- We wanted a cheap method that could summarize the relevant details of PFISR D-region experiments as they pertain to EPP
- The first three moments of the PSD provide estimates of the power, radial doppler shift, and the square of the spectral width and are given in equations (2) through (4)

$$P = \int S(f)df \quad (2)$$

$$\bar{f} = \frac{\int fS(f)df}{P} \quad (3)$$

$$\triangle f^2 = \frac{\int (f-\bar{f})^2 S(f)df}{P} \quad (4)$$

- When spectra is aliased the spectral width saturates at 144 Hz

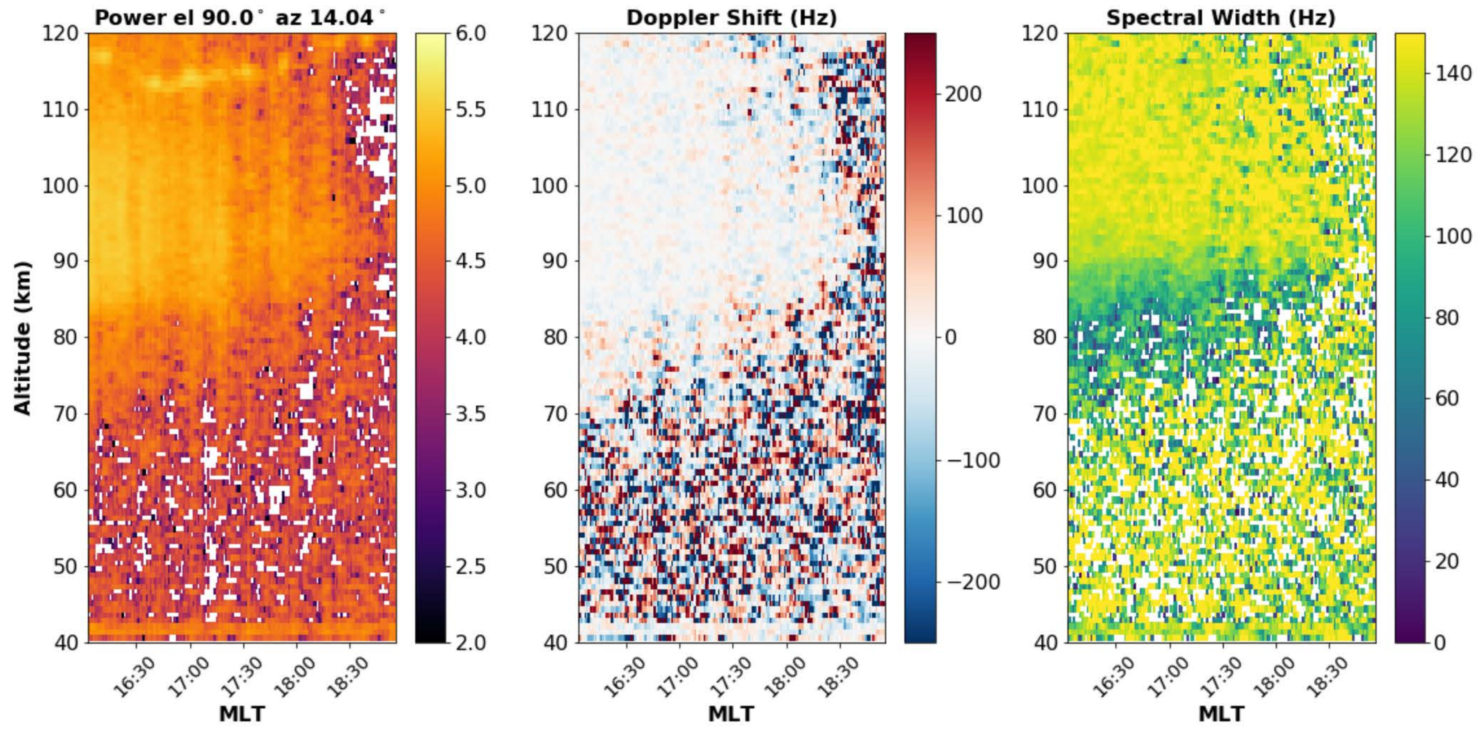

Fig. (2) 5 minute integrated D-region ISR spectra taken from PFISR experiment on May 8, 2017 at 1605 MLT for the up look direction.

- EPP was observed if spectral width decreased with altitude below 85 km
- Experiments were broken up into half hour bins. If EPP was observed in at least one beam then a 1 was assigned to that bin, else a 0 was assigned for no EPP, and data with significant interference was not included
- The 5 minute integrated spectra was used to resolve experiments in which EPP could not be determined from the spectral width and power plots alone (e.g. PMSE)
- These moment plots were generated, and this procedure repeated, for PFISR D-region experiments dating back to 2009. See Figure (3) for a monthly distribution of the data used
- Observed precipitation data was then plotted against MLT and some geomagnetic indices
- Hourly AE, KP, and Dst values were obtained from World Data Center for Geomagnetism, Kyoto

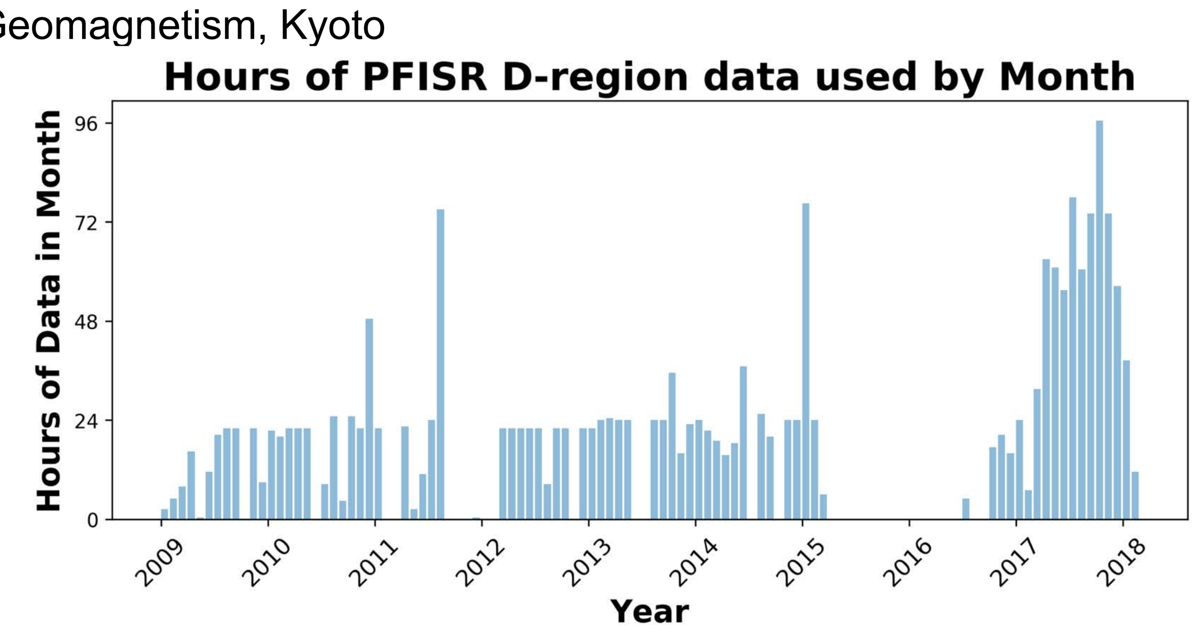

Fig. (3) A histogram displaying the hours of PFISR D-region data analyzed in this study by month. The 2015-2016 gap in this study is explained by a different D-region mode that was run during that period that has not been processed yet

Results

- Though our observed EPP data was recorded in 30 minute intervals, here we present our plots with one hour resolution to increase the sample size and confidence in each bin.
- In Figure (4) we see EPP is more frequently observed on the dawn side (0-12 MLT) and during periods of high geomagnetic activity (AE >250 nT, KP >4).

Bin	AE(nT)
1	0-30
2	30-50
3	50-100
4	100-250
5	250-1000

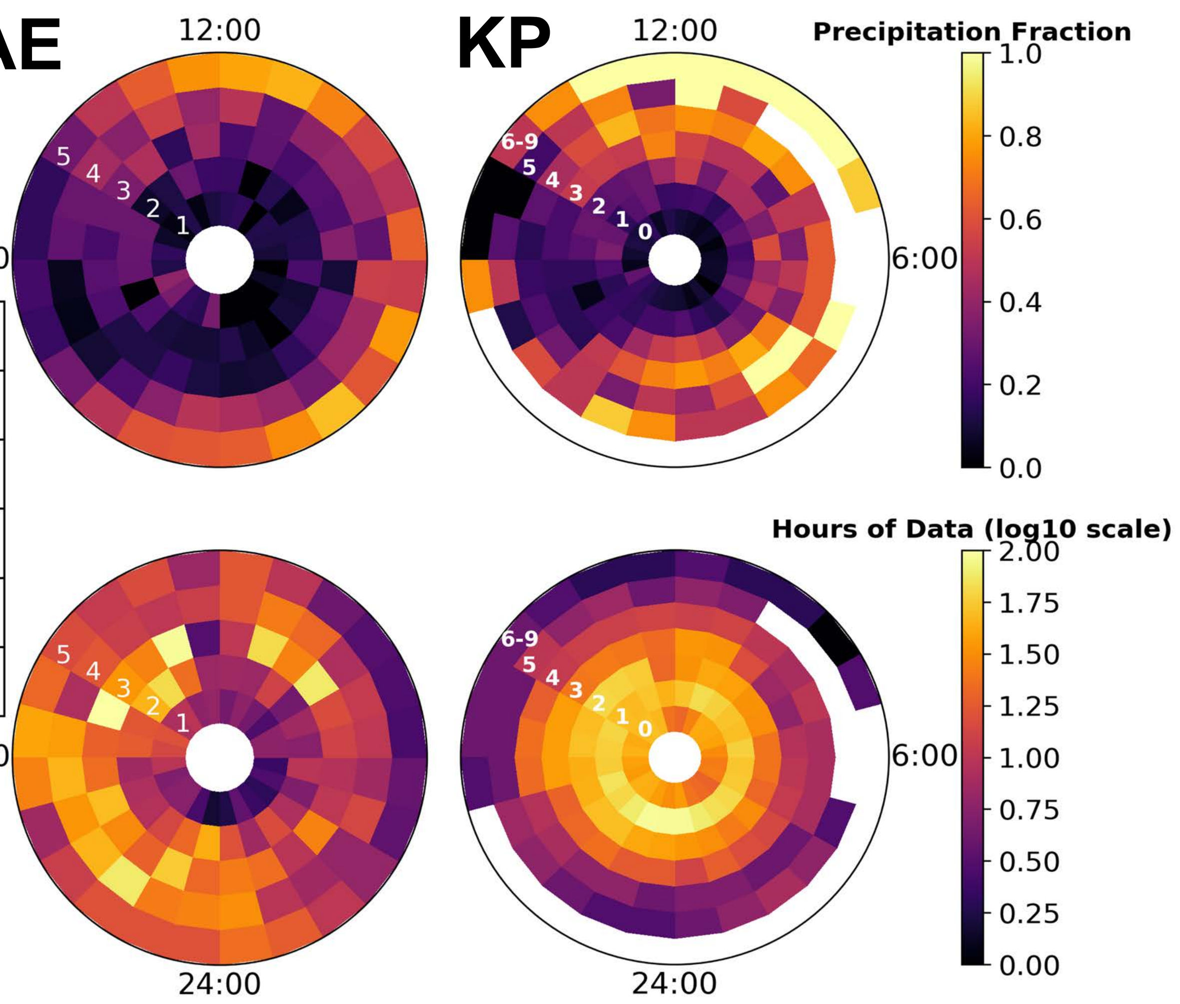

Fig. (4) Left: Precipitation Fraction and Hours of Data vs. AE (radial) and MLT (azimuthal). Right: Precipitation Fraction and Hours of Data vs. KP (radial) and MLT (azimuthal)

- Dst values < -20 exhibit a similar distribution to that of high AE and KP
- F10.7 displays a higher likelihood of observed EPP in the pre dawn and noon regions.
- In Figure (5) F10.7 we see EPP is more frequently observed in the pre-dawn and noon regions

Bin	Dst	F10.7
1	35 to 5	0-75
2	5 to -5	75-90
3	-5 to -10	90-120
4	-10 to -20	120-200
5	-20 to -50	
6	-50 to -110	

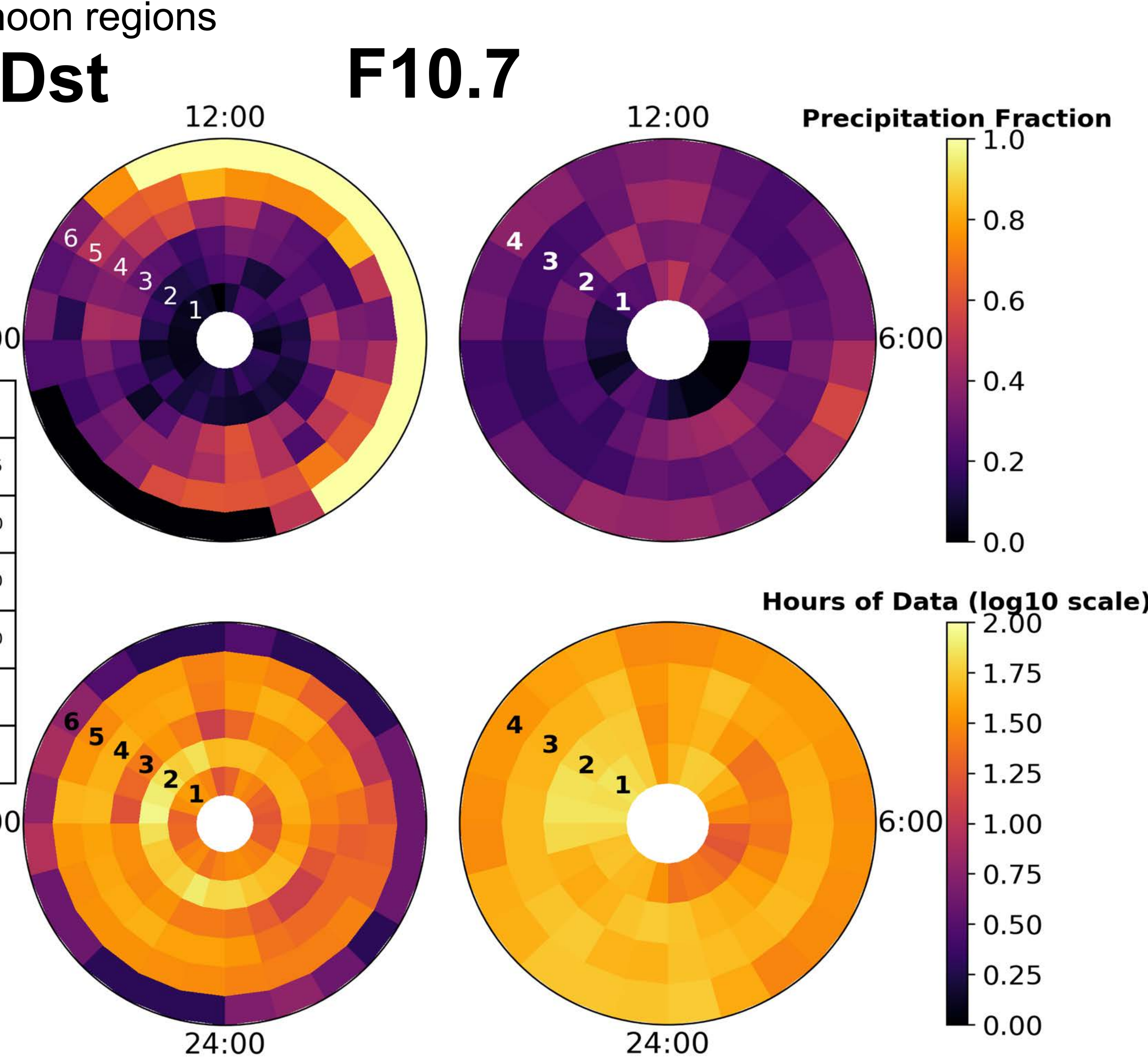

Fig. (5) Left: Precipitation Fraction and Hours of Data vs. instantaneous Dst (radial) and MLT (azimuthal). Right: Precipitation Fraction and Hours of Data vs. F10.7 (radial) and MLT (azimuthal)

- Chorus waves are generated and usually observed outside the plasmapause and occur over a broad frequency range
- In Fig. (6), Meredith used plasma wave data from 5 satellites to develop a global model of equatorial whistler-mode chorus

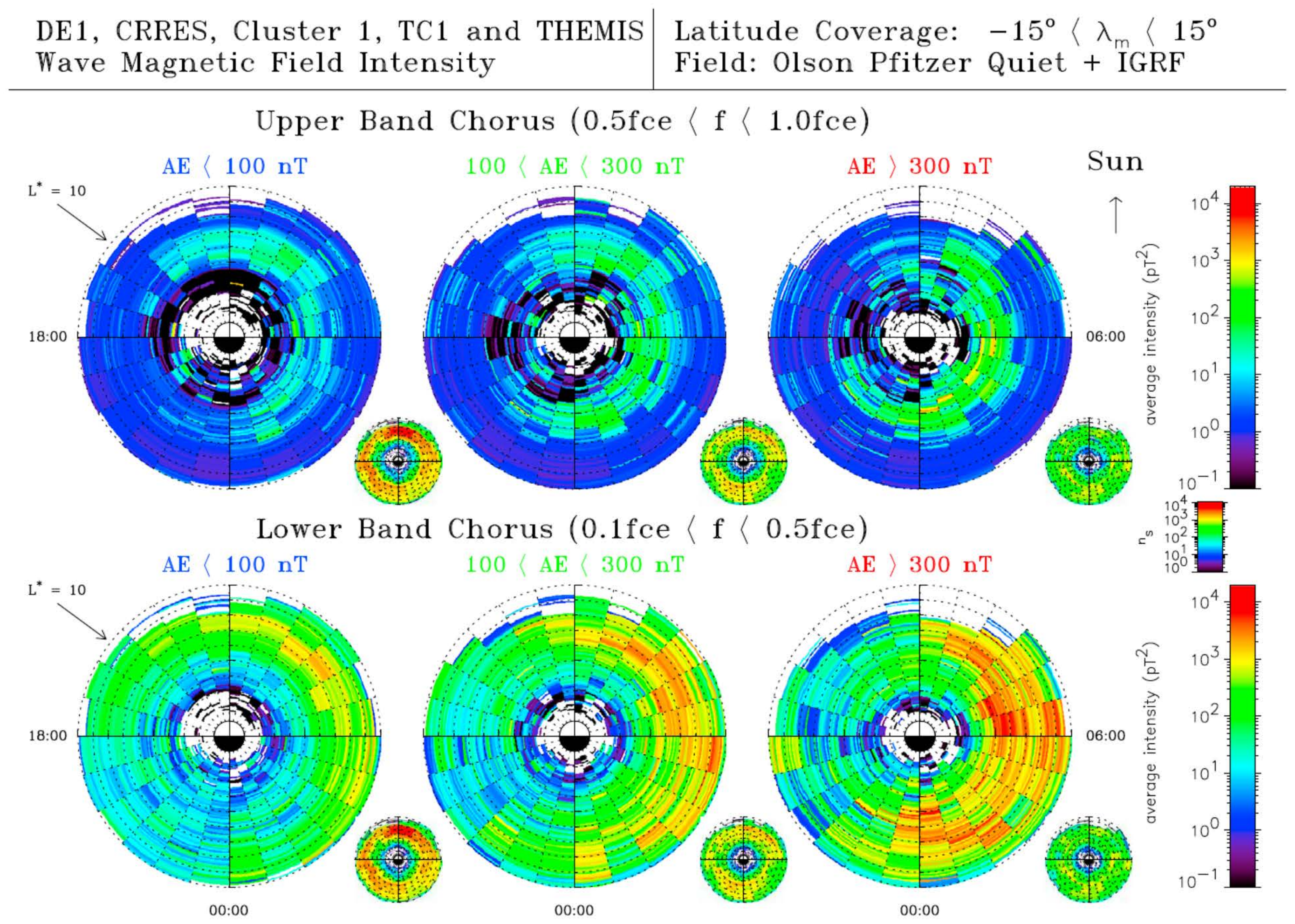

Fig. (6) Pulled from [Meredith 2012 et. al] global distribution of equatorial upper and lower band chorus waves as a function of L*, MLT, and AE. Their data is from this experiment/instrument.

Conclusions

- In a study of PFISR D-region data dating back to 2009 we were most likely to observe EPP on the dawn side (0-12 MLT) and during high geomagnetic activity (AE 250 nT, KP > 3, instantaneous Dst < -20)
- Comparing our results with global distributions of upper/lower band chorus waves [Meredith 2012] at PFISR's L^* (~5.0) we see similar distributions of observed EPP and equatorial whistler-mode chorus
- The next step is to implement an automated algorithm, either using the moments or non linear fitting the D-region ISR spectra, that can analyze the D-region data and provide more confidence in our results.

Acknowledgments

PFISR operations are supported by NSF cooperative agreement AGS-1133009 to SRI International, and data are available from http://amisr.com/database or http://isr.sri.com/madrigal. Hourly AE, Dst, and KP data are provided by the Kyoto World Data Center for Geomagnetism http://wdc.kugi.kyoto-u.ac.jp/

References

Fang, X., C. E. Randall, D. Lummerzheim, S. C. Solomon, M. J. Mills, D. R. Marsh, C. H. Jackman, W. Wang, and G. Lu (2008), Electron impact ionization: A new parameterization for 100 eV to 1 MeV electrons, *J. Geophys. Res.*, 113, A09311, doi: 10.1029/2008JA013384.

Kudeki, Erhan & Milla, Marco. (2011). Incoherent Scatter Spectral Theories—Part I: A General Framework and Results for Small Magnetic Aspect Angles. Geoscience and Remote Sensing, IEEE Transactions on. 49. 315 - 328. 10.1109/TGRS.2010.2057252.

Meredith, N. P., R. B. Horne, A. Sicard-Piet, D. Boscher, K. H. Yearby, W. Li, and R. M. Thorne (2012), Global model of lower band and upper band chorus from multiple satellite observations, J. Geophys. Res., 117, A10225, doi: 10.1029/2012JA017978.