Sluggishness of the Ionosphere: Characteristic time-lag in Response to Solar Flares

S. Chakraborty*[1], J. M. Ruohoniemi[1], J. B. H. Baker[1], S. M. Bailey[1], R. A. D. Fiori[2], and K. A. Zawdie[3]

[1]Center For Space Science and Engineering Research, Virginia Tech, Blacksburg, USA
[2]Geomagnetic Laboratory, Natural Resources Canada, Ottawa, Ontario, Canada
[3]US Naval Research Laboratory, Washington DC, USA

shibaji7@vt.edu

URSI GASS, 2020

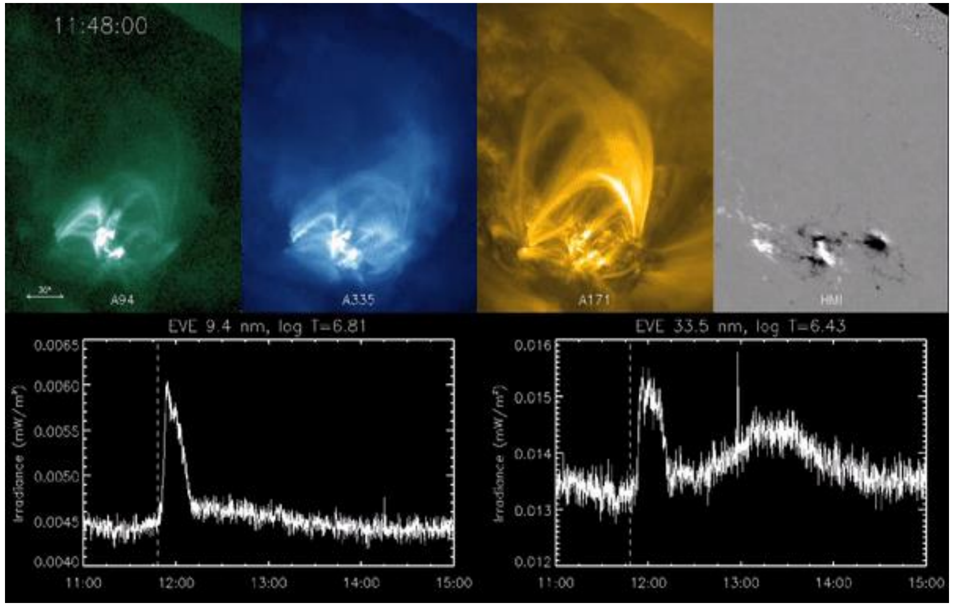
Rome, Italy

Outline

- Introduction & Motivation
  - Characterizing ionospheric Sluggishness during solar flare
- Dataset & Methodology
  - Riometers & SuperDARN HF radars
  - Alternative definition of ionospheric Sluggishness.
- Results
- Discussion and Conclusion

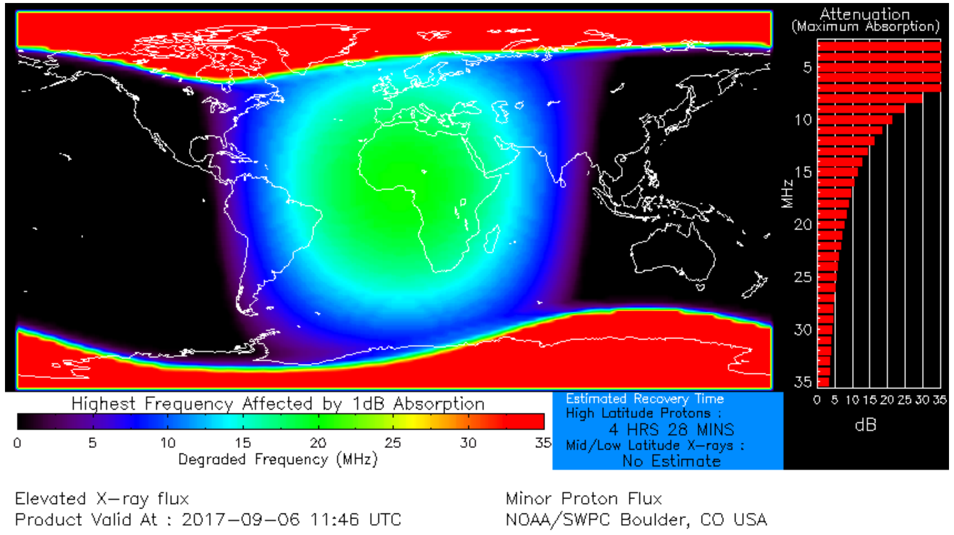
Introduction: Solar Flare, SWF & Sluggishness

- <u>Solar Flares:</u> Sudden enhancement of solar EUV & X-rays.
- <u>Short-Wave Fadeout (SWF):</u> Sudden disruption in HF radio waves traveling through ionosphere in response to a solar flare. One of the following two features are explored in this study:
  - <u>Absorption:</u> Increased attenuation of HF signals due to sudden enhancement in ionospheric electron density.
  - **<u>Sluggishness:</u> Delay in ionospheric response to change in solar flux.**



SDO **AIA** Observations Left to right 94,331,171nm & HMI

SDO **EVE** Observations Left to right 9.4 – 33.9 nm



Estimation of HF Absorption Using **DRAP2** Model

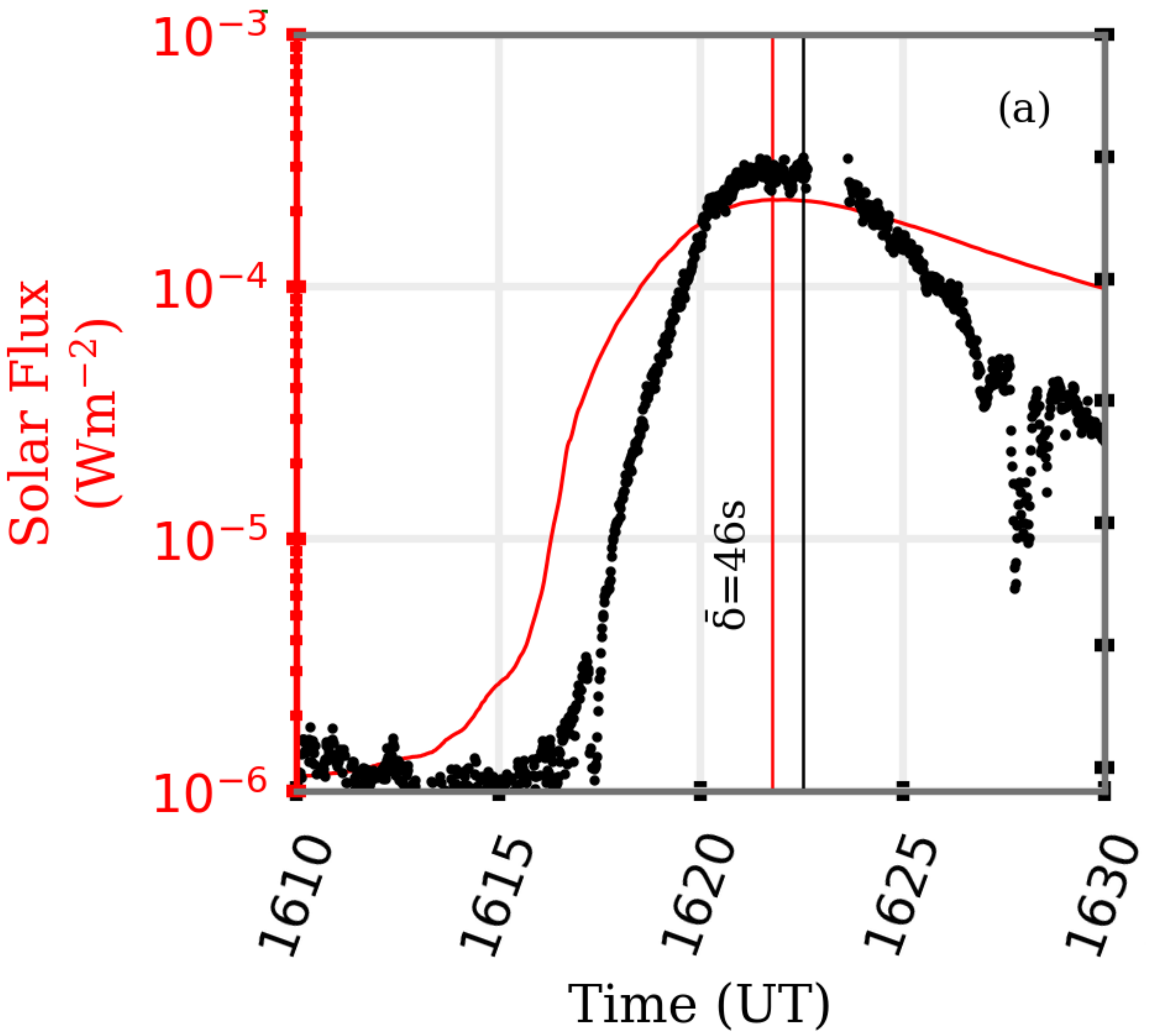
Introduction: What is Ionospheric Sluggishness?

- Sluggishness is the time delay between maximum electron density in the ionosphere following the time of maximum flux during a solar flare.

$$\delta = T_{n_e^{max}} - T_{I_\infty^{max}}$$

- Sluggishness depends on latitude, longitude, and height of the ionosphere [Appleton, 1953] and redefine measured sluggishness as time delay between maximum HF absorption following the time of maximum flux

$$\bar{\delta} = T_{\beta^{max}} - T_{I_\infty^{max}}$$

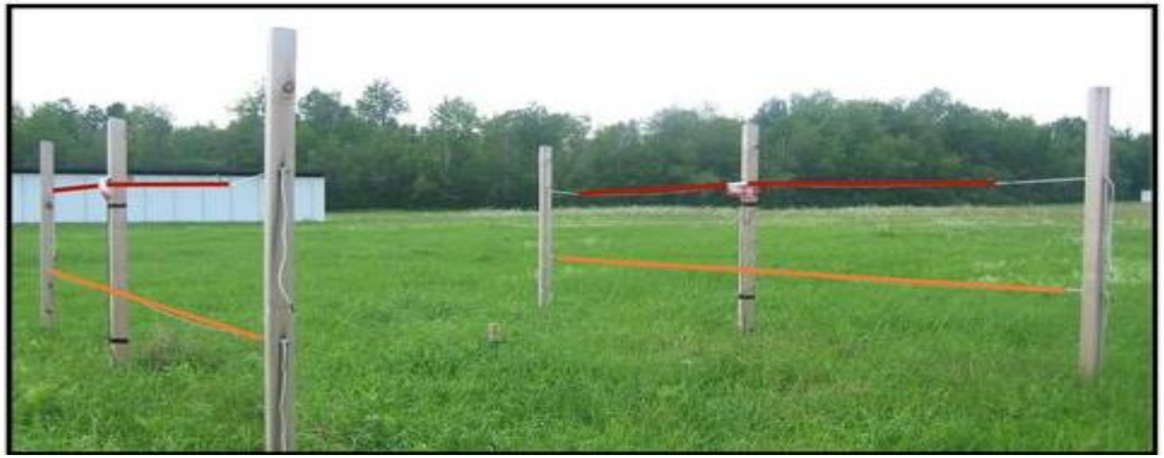


Introduction: Previous studies & our objectives

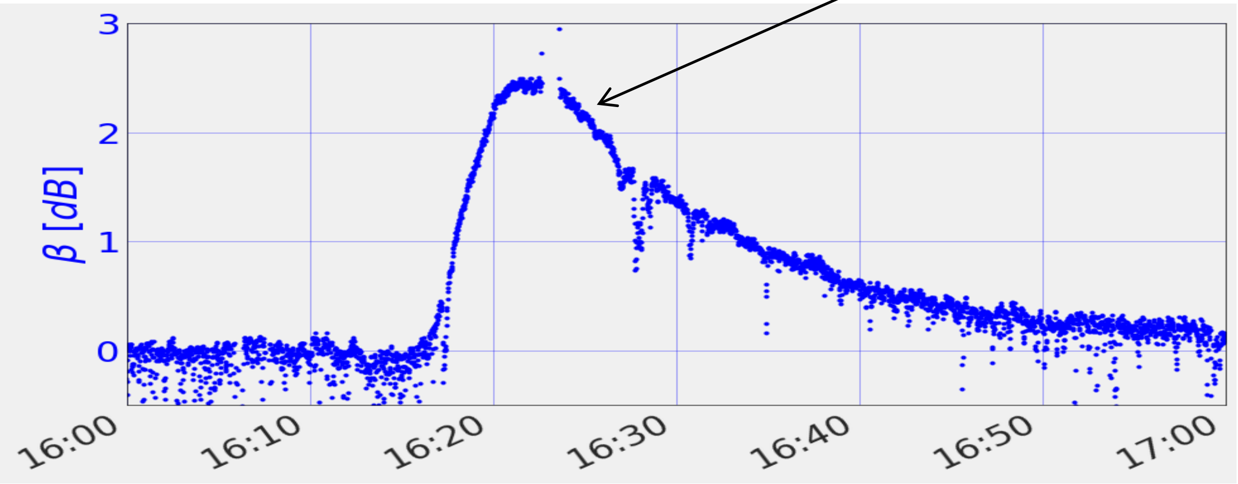
- Inversely proportional to electron density and recombination rate (Appleton, 1953).
- Sluggishness provides information about ionospheric electron density and effective recombination coefficient (α_{eff}), where (α_{eff}) is controlled by atmospheric anions and heavier positive ions (cluster ions).
- Varies linearly with solar zenith angle (Basak et al., 2013).
- Only considered soft X-ray peak time as reference to estimate sluggishness.
- Complicated variation with height (Palit et al., 2017).
- All previous observational studies have done using VLF and reported a typical value of sluggishness 3-10 minutes (e.g. Zigman et al., 2007).
- Objectives, 1) use HF instruments to study ionospheric sluggishness, 2) demonstrate soft X-ray peak time can be used as reference, and 3) do a validation of the theory by observations.

Relative Ionospheric Opacity Meter (Riometer)

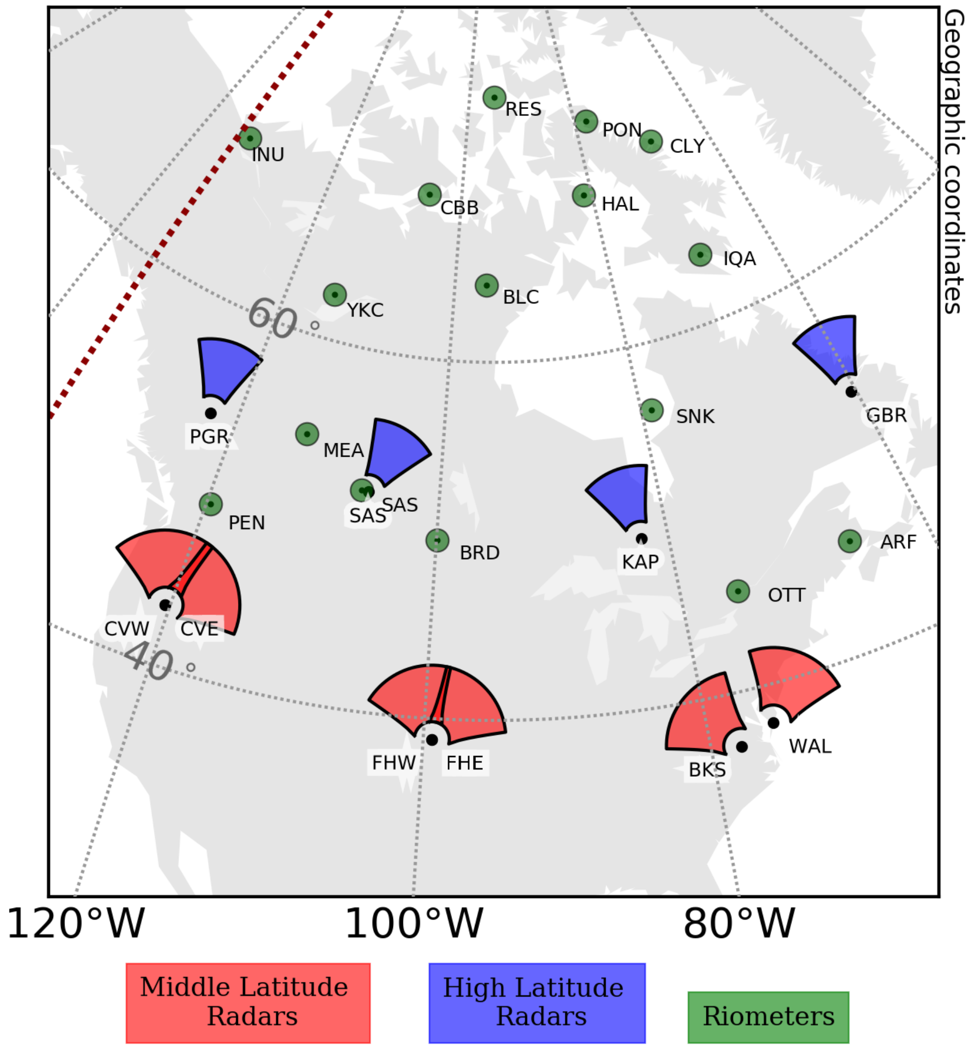
- Relative Ionospheric Opacity Meter (Riometer): A passive radio receiver which provides information about HF absorption in the ionosphere by measuring variations in cosmic radio noise.



Ottawa Riometer response to a solar flare on 2015-3-11

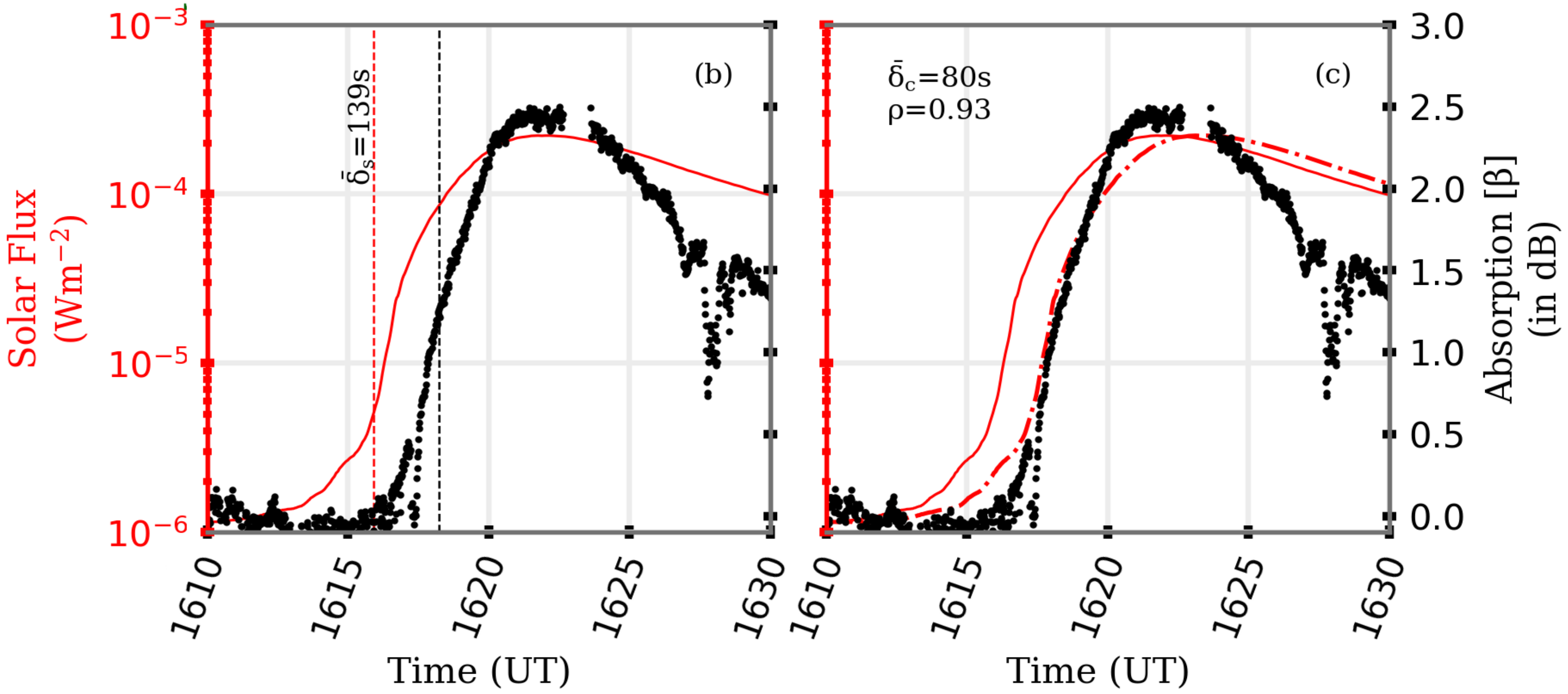


Instruments: Riometers & SuperDARN



- In this study, we used riometer and SuperDARN data from stations showed in the map.

Alternative Methods to Estimate Sluggishness



Why do we need alternative methods?

- Not all the events produces good observational data.
- Due to dynamic range, SuperDARN radars undergo a flat peak (saturation effect) during a solar flare event (example next slides).

- We defined sluggishness as the time difference between peak slope in these two curves:

$$\bar{\delta}_s = T_{\beta^{slope_{max}}} - T_{I_\infty^{slope_{max}}}$$

- Sluggishness as the time delay in solar X-ray flux which produces maximum correlation between in these two curves:

$$\bar{\delta}_c = \max_{\bar{\delta}} \rho \left[\beta, I_\infty^{\bar{\delta}}\right]$$

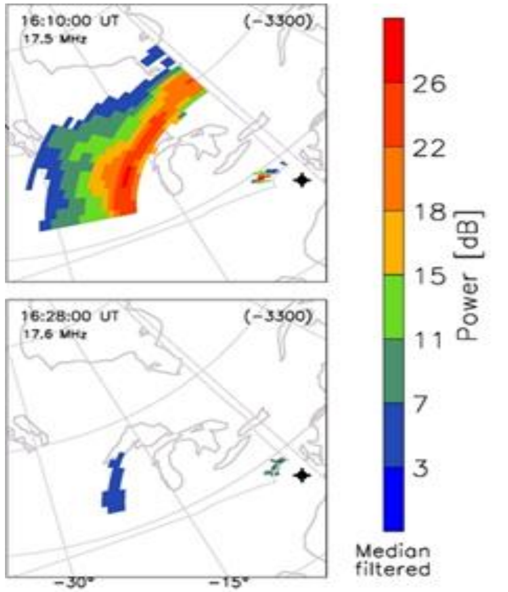
Ionospheric Sluggishness: Recorded in SuperDARN

- An example showing ionospheric sluggishness in SuperDARN observations during a solar flare on 11th March 2015.

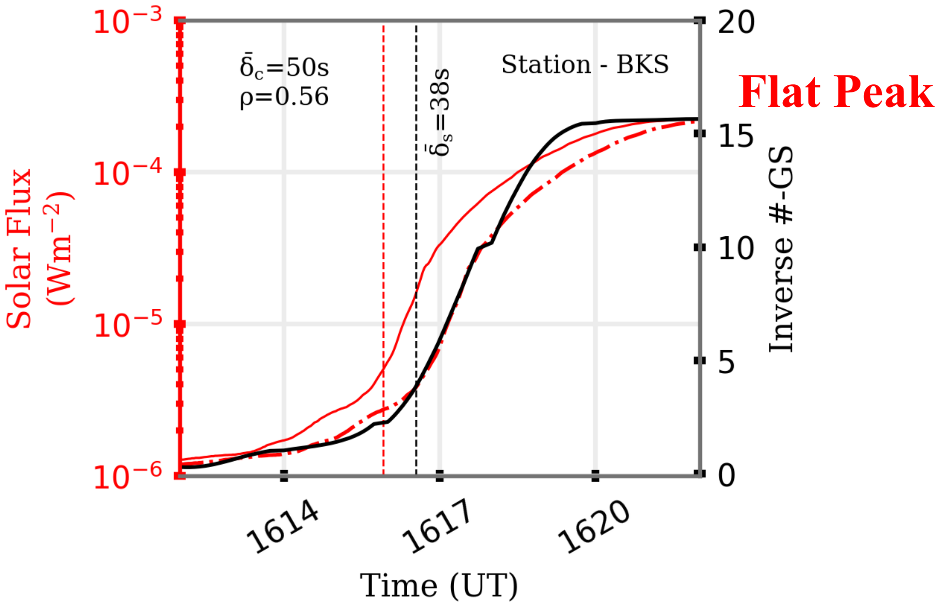
- We define parameter “Inverse Ground-Scatter Count” by subtracting instantaneous (flare time) ground-scatter (bottom panel) count from the background ground-scatter (top panel) count.

$$IGSC(t) = GS_{bg} - GS^{*}_{inst}(t)$$

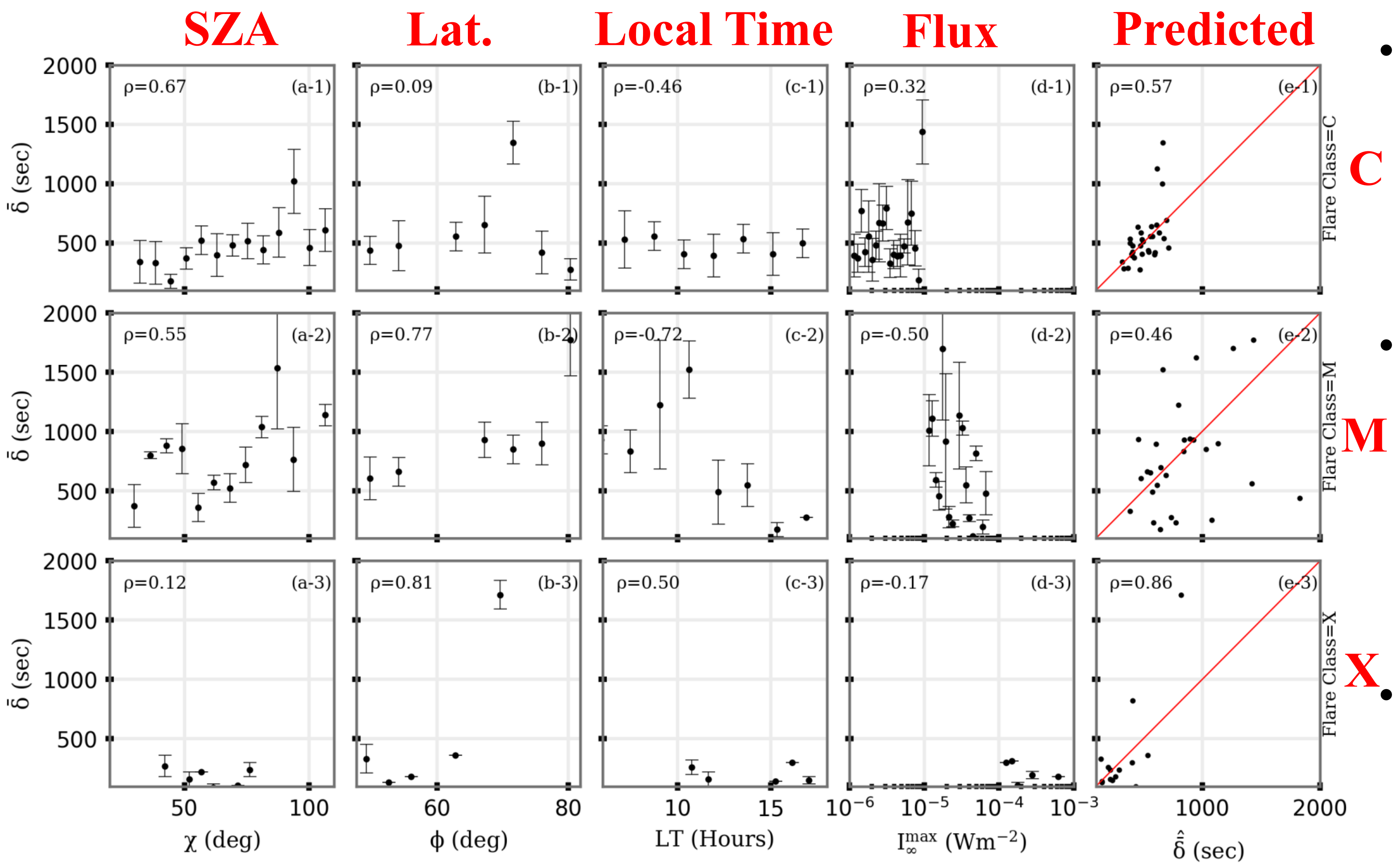
- Example of ionospheric sluggishness in SuperDARN Blackstone radar ground scatter measurements during a solar flare event on 11 March 2015. Measured $\bar{\delta}_s$38=s and $\bar{\delta}_c = 50$s



GS is higher in the top panel than lower panel



Correlation Analysis of Sluggishness ($\bar{\delta}$)



Riometer measurements for C, M & X class flares between 2006-2017

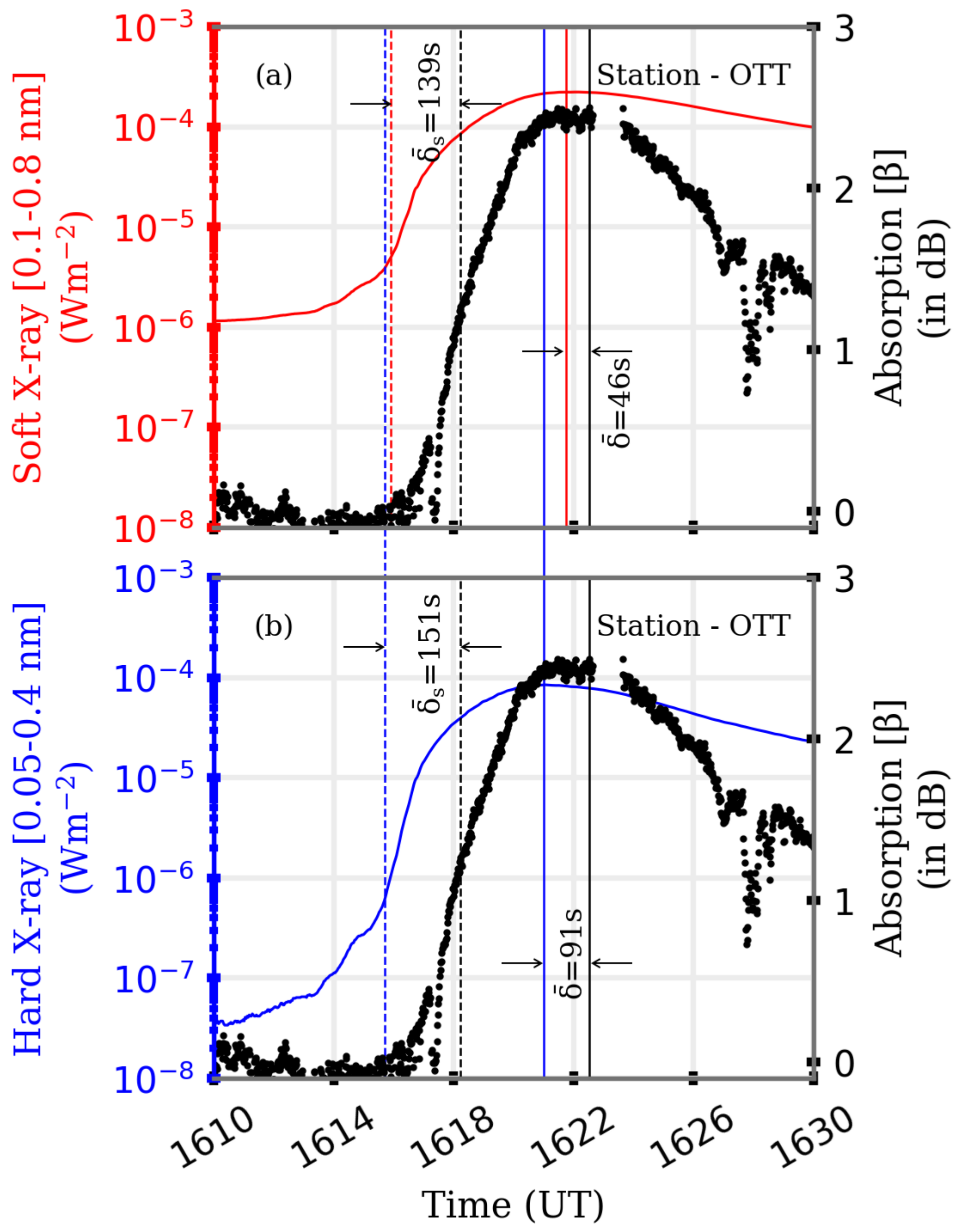
- $\bar{\delta}$ has a high positive correlation with χ, ϕ, and a negative correlation with I_{∞}^{max}.
- High positive correlation with χ and negative correlation with I_{∞} is due to variations in electron density.
- High positive correlation with φ is might be due to variations in electron density and ionic chemistry [Amemiya, 1996].

Sluggishness considering Hard X-ray as reference

- Ottawa riometer measurements during a solar flare event on 11 March 2015. Comparing sluggishness measurements considering (a) soft X-ray and (b) hard X-ray as reference.

- Peak in solar radiations at different wavebands during a solar flares occurred at different times [Yanshi, 2013].

- Refer to the ionizing solar radiation waveband, corresponding to the optical depth of that waveband, where usually see the maximum absorption.



Ionospheric Sluggishness: Simulation Study on effective reaction rate coefficient (α_{eff})

- From the basic understanding of D region chemistry, defined by GPI (Gulkov-Pasko-Inan) model -

$$\boldsymbol{\alpha_{eff}} = \left[\frac{(\boldsymbol{\beta} - \boldsymbol{\gamma\lambda})}{\boldsymbol{n_e}} + \boldsymbol{\alpha_d^c}\frac{\boldsymbol{n_x^+}}{\boldsymbol{n_e}} + \boldsymbol{\alpha_d}\right] = \left[\boldsymbol{\alpha_{eff}^{n^-}} + \boldsymbol{\alpha_{eff}^{n_x^+}} + \boldsymbol{\alpha_{eff}^{n^+}}\right]$$

$$= [\text{Anionic chemistry}(10^{-11}) + \text{Cluster ion chemistry } (10^{-11}) + \text{Simple ion chemistry } (10^{-13})]$$

- From the basic understanding of sluggishness [Appleton, 1953] $\delta = \frac{1}{2n_e^{max}\alpha_{eff}}$
- From Zigman et al, 2007 $\alpha_{eff} = \frac{3}{8\delta\left(n_e^{max} - \frac{I_\infty^{max} g m_{avg}\delta}{\rho ekT}\cos\chi\right)}$
- For unperturbed ionosphere $\alpha_{eff} \sim 10^{-11} - 10^{-12} m^3 s^{-1}$, Basak et al, 2013.

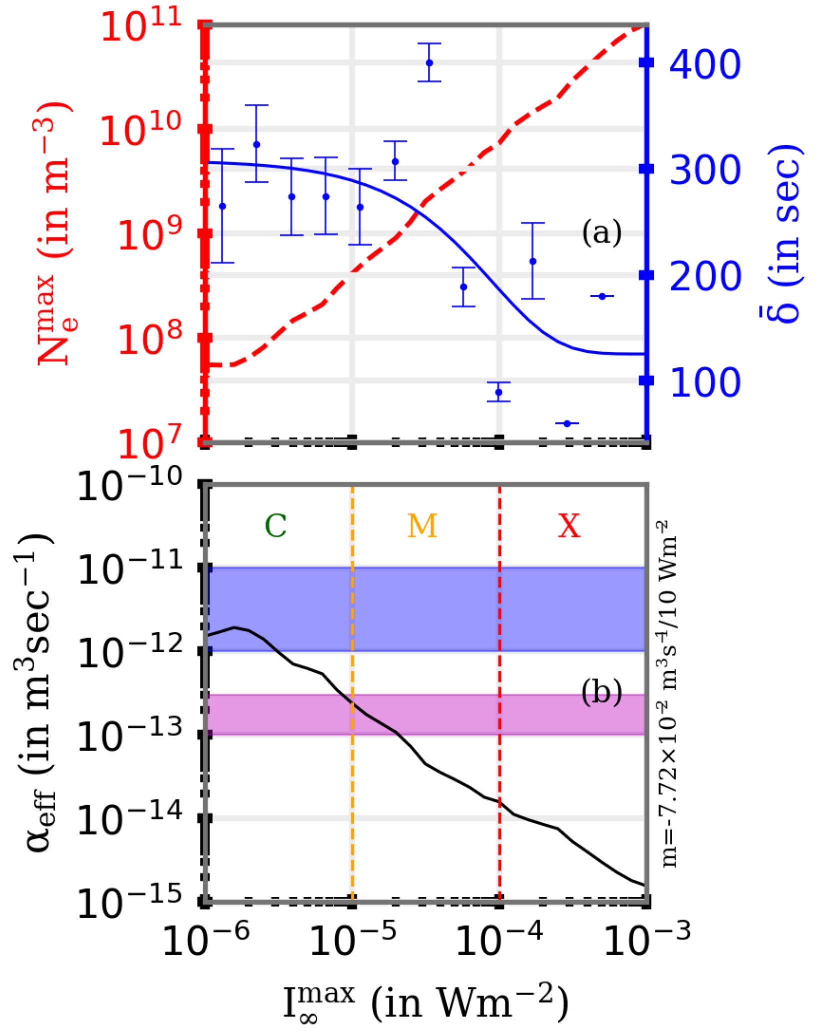
$\beta = electron\ attachment\ rate$
$\gamma = electron\ detachment\ rate$
$\lambda = \frac{n^-}{n_e} = negative\ ion\ ratio$
$\alpha_d^c = dissociative\ recombination\ for\ cluster + ve\ ion$
$\alpha_d = dissociateive\ recombination$
$n_e = electron, n_x^+ = +ve\ cluster\ ions, n^- = negative\ ion$
$n^+ = positive\ ions$

Ionospheric Sluggishness: Simulation Study on effective reaction rate coefficient (α_{eff})

- Assumption – D region is one thin layer of plasma, and sluggishness in riometer measurements coming from the D region, and use the following equation to estimate α_{eff}

$$\alpha_{eff} = \frac{3}{8\delta\left(n_e^{max} - \frac{I_\infty^{max} g m_{avg} \delta}{\rho e k T}\cos\chi\right)}$$

- $\bar{\delta}$ shown in the figure is the mean sluggishness observed in riometer for all events for $\chi \sim 50^o - 60^o$.
- From simulation study we found α_{eff} decreases rapidly with increasing I_∞^{max} .
- Infer: Most likely among three types of reaction rates coefficients $\boldsymbol{\alpha_{eff}^{n^-}}$ ***and*** $\boldsymbol{\alpha_{eff}^{n_x^+}}$ decreases under solar energetic radiation.



Discussions

- This is the first attempt of characterization of sluggishness using riometers and SuperDARN HF radars.

- We found the measured sluggishness varies significantly with the measuring techniques. Estimation of sluggishness using the modified definition is greater than that using standard definition. **Reason**: Enhanced electron density during the peak of solar flare event than before the peak.

- Sluggishness is estimated considering peaks in soft X-ray as reference [Appleton, 1953; Ellison, 1954]. We consider hard X-ray as reference then estimation changes. **Reason**: Peak in solar radiations at different frequencies during a solar flares occurred at different times [Yanshi, 2013].

- We found α_{eff} a few orders of magnitude, typically between $10^{-11} - 10^{-15} m^3 s^{-1}$ .The estimated domain matches with pervious studies [Schunk, 2009; Mitra, 1992; Zigman 2007; Palit, 2015]. **Reason**: Enhancement in electron density and in electron detachment rate under the influence of energetic radiations, changes α_{eff} [Verronen et al, 2009].

Conclusions

- Choice of ionospheric sounding technique effects the measurement of sluggishness.

- Statistical study shows sluggishness is –
    - Anti-correlated with solar EUV radiation intensity.
    - Positively correlated with latitude.

- Ionospheric effective recombination rate coefficient $\boldsymbol{\alpha}_{eff}$ varies a few orders of magnitude, typically between 10^{-15} - 10^{-11} m^3s^{-1} with peak solar irradiance.

- Observation and simulation study infer ionospheric sluggishness <u>might</u> influenced by the ionic (anion and positive cluster ions) photochemistry.

Thank You!

Questions and Comments

email: shibaji7@vt.edu

Manuscript submitted to JGR: Space Physics