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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

- **Solar Flares**: Sudden enhancement of solar EUV & X-rays.
- **Short-Wave Fadeout (SWF)**: 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:
  - **Absorption**: Increased attenuation of HF signals due to sudden enhancement in ionospheric electron density.
  - **Sluggishness**: Delay in ionospheric response to change in solar flux.

SDO AIA Observations
Left to right
94,331,171 nm & 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 ($\alpha_{eff}$), where ($\alpha_{eff}$) 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
In this study, we used riometer and SuperDARN data from stations showed in the map.
Alternative Methods to Estimate Sluggishness

- We defined sluggishness as the time difference between peak slope in these two curves:
  \[ \bar{\delta}_s = T_{\beta \text{slope max}} - T_{I_{\infty \text{slope max}}} \]

- Sluggishness as the time delay in solar X-ray flux which produces maximum correlation between in these two curves:
  \[ \bar{\delta}_c = \max_{\delta} \rho\left[ \beta, I_{\infty \delta} \right] \]

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

\[ \bar{\delta} \] has a high positive correlation with $\chi$, $\phi$, and a negative correlation with $I_{\max}^\infty$.

High positive correlation with $\chi$ and negative correlation with $I_{\max}^\infty$ is due to variations in electron density.

High positive correlation with $\phi$ is might be due to variations in electron density and ionic chemistry [Amemiya, 1996].

Riometer measurements for C, M & X class flares between 2006-2017
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 ($\alpha_{eff}$)

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

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

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

- From the basic understanding of sluggishness [Appleton, 1953] $\delta = \frac{1}{2n_{e}^{\text{max}} \alpha_{eff}}$

- From Zigman et al, 2007 $\alpha_{eff} = \frac{3}{8\delta \left( n_{e}^{\text{max}} - \frac{m_{\text{avg}}^{\text{max}} g \delta}{\rho ekT} \cos \chi \right)}$

- For unperturbed ionosphere $\alpha_{eff} \sim 10^{-11} - 10^{-12} m^3 s^{-1}$, Basak et al, 2013.

$\beta = \text{electron attachment rate}$
$\gamma = \text{electron detachment rate}$
$\lambda = \frac{n^-}{n_e} = \text{negative ion ratio}$
$\alpha_c^d = \text{dissociative recombination for cluster + ve ion}$
$\alpha_d = \text{dissociative recombination}$
$n_e = \text{electron, } n_x^+ = \text{+ve cluster ions, } n^- = \text{negative ion}$
$n^+ = \text{positive ions}$
Ionospheric Sluggishness: Simulation Study on effective reaction rate coefficient ($\alpha_{eff}$)

- 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 $\alpha_{eff}$

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

- $\bar{\delta}$ shown in the figure is the mean sluggishness observed in riometer for all events for $\chi \sim 50^\circ - 60^\circ$.

- From simulation study we found $\alpha_{eff}$ decreases rapidly with increasing $I_{\infty}^{max}$.

- Infer: Most likely among three types of reaction rates coefficients $\alpha_{eff}^{n-}$ and $\alpha_{eff}^{n+}$ 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 $\alpha_{eff}$ 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 $\alpha_{eff}$ [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 $\alpha_{\text{eff}}$ varies a few orders of magnitude, typically between $10^{-15} - 10^{-11}$ m$^3$s$^{-1}$ with peak solar irradiance.

- Observation and simulation study infer ionospheric sluggishness might influenced by the ionic (anion and positive cluster ions) photochemistry.
Thank You!

Questions and Comments
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