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

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Abstract

The term "sluggishness" is used to describe the time delay between maximum radio absorption in the ionosphere following the time of maximum irradiance during a solar flare. Sluggishness is one of the characteristic properties that can be used for studying lower ionospheric (D-region) and mesospheric chemistry. In this study, we propose a novel approach to estimate the ionospheric sluggishness from riometer and SuperDARN radar observations following a solar flare. In addition, we analyze sluggishness observed in riometer data. We find that sluggishness is anti-correlated with the peak solar X-ray flux and positively correlated with solar zenith angle and geographic latitude.

1 Introduction

Solar EUV and X-ray radiations are primary sources for producing the ionosphere. The characteristic ionospheric response to sudden intense solar X-ray bursts, also known as solar flares, has been studied since the early 1900s [1]. Flare-driven HF absorption, also known as shortwave-fadeout (SWF), is a well-understood phenomenon. However, the initial time delay of the ionospheric response following a solar flare, also known as "sluggishness", is not yet fully understood [2]. E. V. Appleton first defined the term sluggishness as the time delay between the peak ionospheric electron density and peak electron-ion production rate at local solar noon [3]. We now understand sluggishness as an inertial property of the ionosphere that is dependent on latitude, longitude, and height of the ionosphere, as described in equation (1).

$$\Delta t(\theta,\phi,h) = T_{N_e^{max}} - T_{q^{max}} \tag{1}$$

where: $T_{N_e^{max}}$, and $T_{q^{max}}$ are the times of peak electron density and peak electron-ion production rate, respectively. Appleton and his contemporaries tried to measure and characterize sluggishness in terms of the time delay between peak radio wave absorption (β) in the ionosphere and peak solar irradiance (I_∞) [1, 3], as described in equation (2).

$$\Delta\bar{t}(\theta,\phi) = T_{\beta^{max}} - T_{I_\infty^{max}} \tag{2}$$

where: $T_{\beta^{max}}$ and $T_{I_\infty^{max}}$ are the times of peak HF absorption and peak solar irradiance, respectively. We propose an alternative definition of sluggishness as the time difference between the peak slope in β and peak slope in I_∞, as described in equation (3).

$$\Delta\bar{t}^*(\theta,\phi) = T_{\beta^{max\_slope}} - T_{I_\infty^{max\_slope}} \tag{3}$$

where: $T_{\beta^{max\_slope}}$ and $T_{I_\infty^{max\_slope}}$ are the times of peak slope in absorption and peak slope in solar irradiance, respectively.

Note that both $\Delta\bar{t}$ and $\Delta\bar{t}^*$ represent time delays between a change in solar irradiance and an ionospheric response. Specifically, $\Delta\bar{t}$ represents the time delay between the peaks of the event, whereas $\Delta\bar{t}^*$ represents the time delay when both solar irradiance and ionospheric response are changing rapidly (during peak slope). Although the three different time delays defined in equations (1)-(3) have different reference times, measurement and estimation techniques, all of them are indicative of the inertial property of the ionosphere. Our proposed definition in terms of peak slopes is advantageous for characterizing the response of the ionosphere to impulsive events events such as flares.

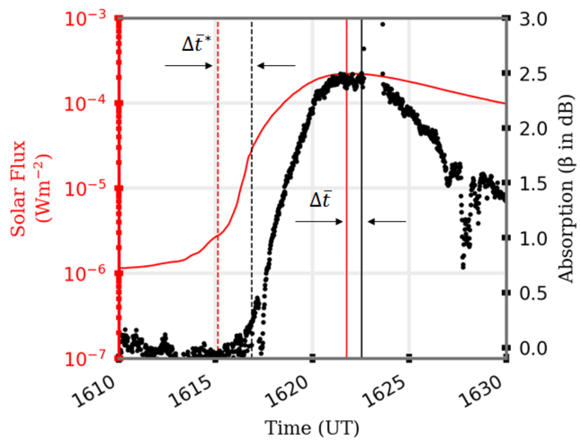

Figure 1. Example of ionospheric sluggishness in Ottawa riometer measurement during a solar flare event on 11 March 2015. Measured $\Delta\bar{t}$ = 47s and $\Delta\bar{t}^*$=56s.

Figure 1 presents an example of height integrated ionospheric sluggishness ($\Delta\bar{t}$) and modified sluggishness ($\Delta\bar{t}^*$) observed in Ottawa riometer data during a solar flare on 11 March 2015. The red curve and and black dots indicate increase in solar soft X-ray (.1-.8 nm) irradiance from a GOES satellite and cosmic noise absorption (CNA) from a riometer, respectively. The solid and dashed vertical lines indicate peaks and maximum slope in X-ray irradiance (red) and CNA data (black), respectively. The differences in the timings indicated by the solid and dashed vertical lines show $\Delta\bar{t}$ = 47s and $\Delta\bar{t}^*$ = 56s, for this event, respectively.

Sluggishness measurements are useful because they provide information about the ionospheric electron density and the effective recombination coefficient (α_{eff}) [3]; the latter being controlled by the atmospheric (negative ions, e.g. O^-, O_2^-, NO_3^-, CO_3^-, HNO_3^- etc and their hydrates) and heavier positive ions (cluster ions, e.g. $H^+(H_2O)_n$) [2, 4, 5]. Specifically, α_{eff} defines the effective loss rate of electrons due to cascading photochemical reactions following electron production due to photoionization [6]. Understanding sluggishness thus provides insight into D-region and mesospheric photochemistry. Furthermore, sluggishness measurements can be used to validate D-region models.

Ever since Appleton described sluggishness, experimental studies have used very low frequency (VLF, 3-30 kHz) receivers to understand its variations with solar zenith angle (χ), I_∞ [1, 2]. The sluggishness recorded using VLF instruments are defined as the time difference between the peak in VLF amplitude (A^{max}) and peak in I_∞, as described in equation (4).

$$\Delta t^{VLF} = T_{A^{max}} - T_{I_\infty^{max}} \qquad (4)$$

VLF Studies reported a typical value of sluggishness (Δt^{VLF}) is 3-10 minutes [2, 7]. Most of these studies reported variability of sluggishness during M and C class flares but did not try to explain the chemical processes that manifest the sluggishness.

Here we report on the first attempt to understand the basic characteristic of sluggishness using both passive and active high frequency (HF, 3-30 MHz) instruments, namely riometers and SuperDARN HF radars, respectively. We present a statistical characterization of ionospheric sluggishness following X class flares and report on the variations of $\Delta\bar{t}$ with χ, I_∞, and latitude (ϕ). We also discuss the physical basis of sluggishness and its variability with the factors under consideration.

2 Instrumentation & Datasets

The primary datasets used in this study are ground-based riometers, SuperDARN radars, and solar flare data from the Geostationary Operational Environmental (GOES) 15 satellite's X-ray sensor. A riometer is a ground-based passive radio receiver that provides information about HF absorption in the ionosphere by measuring variations in the cosmic radio noise at 30 MHz frequency [8]. SuperDARN is a global network of HF radars, operating between 8 and 18 MHz [9], that is used to study ionospheric plasma motion. SuperDARN observations primarily consist of backscatter from the surface roughness of the Earth and from ionospheric density structures, namely, ground and ionospheric scatter, respectively. Due to vertical gradients in refractive index the HF rays transmitted by the radar refracted downward in the bottom-side ionosphere. The ground scatter is generated when the rays bends toward the ground and are reflected from surface roughness and return back to the radar following the same path. This is equivalent to a complete one-hop ground-to-ground HF communication link, with passes through the absorptive D region 4 times. Perturbations in D region electron density will impact the ground scatter observation through altered propagation and absorption. Ionospheric scatter is due to reflection of signal from ionospheric plasma density irregularities at F region altitude and is not relevant to this study.

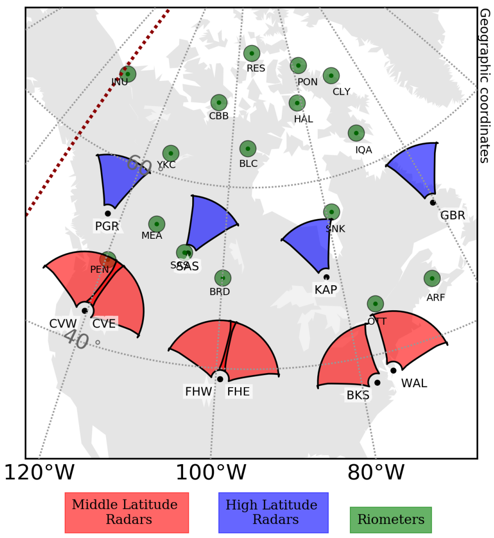

Figure 2. Location of the various instruments used in the study. The red line at -135.3^o longitude indicates the longitudinal location of the GOES 15 satellite. Red, blue and green colors represent middle, high latitude SuperDARN radars and riometers, respectively.

Bands of ground scatter are a persistent feature of the daytime observations in SuperDARN radars. The number of ground scatter echoes can be taken as a proxy of ionospheric propagation condition pertaining to absorption [10]. Specifically, we use the time history of the inverse ground scatter count, evaluated as the difference between the number of echoes following a flare event and the number of echoes prevailing before the event, to estimate the sluggishness observed by SuperDARN HF radars. Figure 2 presents the location of the instruments used in this study. Figure shows two latitudinal radar chains and riometers across the North American sector.

3 Results

In this section, we describe our method of extracting sluggishness estimates from SuperDARN observations, and present a statistical analysis of sluggishness observed by riometers.

3.1 Sluggishness in SuperDARN Data

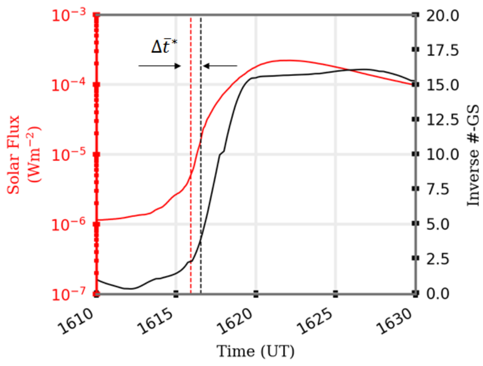

Figure 3. Example of ionospheric sluggishness in SuperDARN Blackstone radar ground scatter measurements during a solar flare event on 11 March 2015. Measured $\Delta\bar{t}^{*}$=41s.

Figure 3 presents a time series of inverse ground scatter count data from the SuperDARN Blackstone radar (black) in response to sudden increase in solar flux due to a solar flare (red) on 11 March 2015. The difference in peak slope times, indicated by the red and black vertical dotted lines, represents the modified sluggishness, which in this case is $\Delta\bar{t}^{*}$ = 41s. This compares with the values obtained from the riometer measurement using the standard and alternative definitions of $\Delta\bar{t}$ = 47s and $\Delta\bar{t}^{*}$ = 56s, respectively (see Figure-1).

3.2 Statistical Analysis

To characterize statistically the behavior of ionospheric sluggishness ($\Delta\bar{t}$) we analyzed 12 X class solar flare events between 2006 to 2017. Each solar flare event affects four riometers on average and 40 absorption events were collectively observed by riometers.

Figure 4 presents the statistical analysis correlating the $\Delta\bar{t}$ seen by riometers with χ, ϕ, and I_∞ (panels a-c), while panel (d) shows a multiple linear regression of $\Delta\bar{t}$ versus the three factors. The correlation coefficients are listed inside each panel. This analysis shows the typical range of $\Delta\bar{t}$ is 45s-130s, which is in contrast from the 3-10 minutes (Δt^{VLF}) reported by previous studies [2, 11]. It can also be seen that $\Delta\bar{t}$ has a high positive correlation with χ, negligible correlation with ϕ, and a negative correlation with I_∞. The negligible correlation with ϕ is unexpected because anionic chemistry should impact $\Delta\bar{t}$, and it has strong variation with latitude.

4 Discussion

In this study we have defined an alternative method to estimate ionospheric sluggishness ($\Delta\bar{t}^{*}$) using both riometers

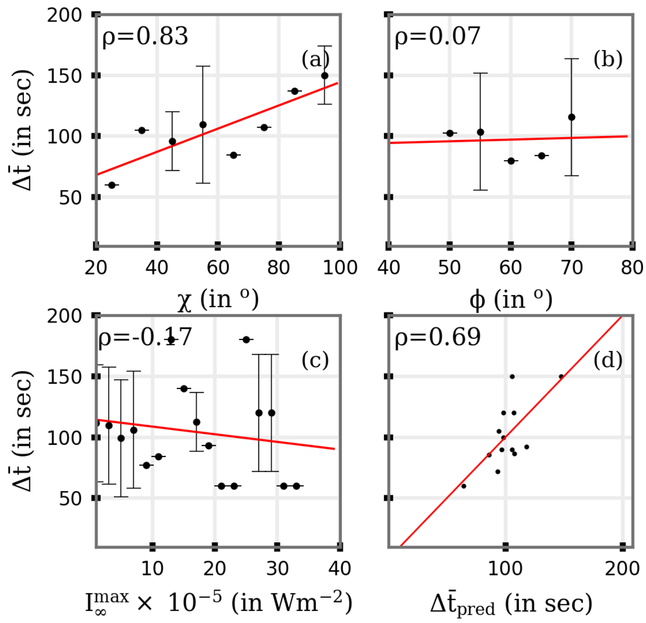

Figure 4. Association between $\Delta\bar{t}$ with (a) solar zenith angle (χ), (b) latitude (ϕ), (c) peak solar irradiance (I_∞), respectively, and (d) multiple linear regression analysis of $\Delta\bar{t}$ and the three factors under consideration. Black dots in panels (a)-(c) represent mean $\Delta\bar{t}$ over 5^o χ, 5^o ϕ, and 5×10^{-5} Wm^{-2} I_∞ bins. The error bars represent one standard deviation.

and SuperDARN radars. In addition, this is the first attempt of characterization of $\Delta\bar{t}$ using riometers following 12 X-class flares that occurred 2006-2017. In this section, we summarize the findings and discuss their relationship to the physical processes that produce ionospheric sluggishness.

Sluggishness is an inertial property of the ionosphere [1, 7]. Early studies claimed that sluggishness is related to recombination processes and inversely proportional to the product of electron density and α_{eff}, where α_{eff} is relatively constant for a particular latitude, local time and height. If this were the case sluggishness would only be a function of electron density [2]. However, in this study we found the measured sluggishness varies significantly with the measuring techniques (see Figure 1). We also found the estimation of sluggishness using the modified definition (equation 3) is greater than that using standard definition (equation 2). One reason might be, larger electron density during the peak of solar flare event than before the peak. This infers ionospheric sluggishness is indeed inversely proportional to electron density, but does not confirm α_{eff} is a constant. Furthermore, this explanation does not fit the reasoning for the smaller values of sluggishness from SuperDARN observation using the modified definition (refer Figure 3). The probable cause might be the difference of the ionospheric sounding techniques between the instruments. The SuperDARN rays traverse the D region 4 times and at lower operating frequency, hence, they are more sensitive to the D region perturbations. Taking all these factors together we can conclude the choice of ionospheric sounding techniques can impact the sluggishness measurement.

From the statistical study (Figure 4), we found sluggishness ($\Delta\bar{t}$) is positively associated with decreasing solar radiation intensity, and increasing solar zenith angle, which is consistent with previous VLF studies [2, 7] that found an inverse relationship between sluggishness and electron density. With decrease in radiation intensity and increase in solar zenith angle the photoionization rate decreases, which leads to an increase in ionospheric sluggishness. Figure-4(b) shows there is no significant variations of sluggishness with latitude. This is contrary to the explanation that sluggishness should vary with latitude, mainly due to change in α_{eff} which varies with anionic chemistry at higher latitudes [12]. There are two possible explanations for this. First we are only considering a handful of events and so the statistics are relatively poor. Second, we only consider X class flares which might impact the ionosphere at all the latitudes approximately similarly. Further detailed analysis and modeling of sluggishness during various geophysical events and across latitudes may provide further insights into the D region ion chemistry and to the underlying physics of sluggishness.

5 Conclusion

In this study, we found the choice of ionospheric sounding technique effects the measurement of sluggishness. We also found that ionospheric sluggishness is anti-correlated with solar EUV radiation intensity and suggest anionic chemistry under the influence of EUV and X-ray flux is the major determinant of sluggishness. Specifically, ionospheric sluggishness might influenced by the anionic photochemistry. Future work will further examine how sluggishness depends on ionospheric sounding techniques, high latitude chemistry and geomagnetic activity.

6 Acknowledgements

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