ISSI International Team Proposal 2024 - Part A

The Impact of Solar Flare Irradiance on the Earth's Ionosphere

1. Abstract

Variations in solar irradiance are known to influence the composition and dynamics of the Earth's atmosphere, which can impact modern technologies such as radio communication, GPS accuracy, and satellite drag. However, the consequence of increases in solar radiation during solar flares on the Earth's ionosphere is still not fully understood. Our team will comprise experts in solar flares and ionospheric aeronomy, two interconnected areas that have been studied quite separately historically. We will determine how the ionosphere responds to flares of different magnitudes, spectral properties, locations, at different times of year and solar cycle. This will help us understand how and why ionisation rates, particle temperatures and densities vary during ionospheric disturbances caused by solar flares. To comprehensively study this solar-terrestrial connection, we will combine solar flare observations from a range of space-borne instruments, as well as spectral irradiance and radiative hydrodynamic models, with ionospheric measurements and theoretical predictions. Our findings will piece together the physical mechanisms responsible for producing geoeffective emission during flares and the impact those emissions have on various layers of the Earth's ionosphere. Obtaining a comprehensive understanding of the relevant physical processes, and improving our predictive capability, is increasingly important in space weather research.

2. Scientific Rationale

The influence of solar flares on the Earth's ionosphere and their possible effect on space weather, communication, and navigation systems, remains an outstanding issue in solar-terrestrial physics. Solar flares result in a broadband enhancement to the Sun's radiative output, from both spectral lines and continua. During a solar flare, X-ray photons of wavelengths <1nm can penetrate to depths as low as the ionospheric D-region (~60-90 km in altitude), resulting in an increase in the ionisation of O_2 and N_2 molecules (Mitra, 1974). In the E-layer (~90-150 km), soft X-rays (1-10nm) and far-UV photons are primarily absorbed by O_2, N_2, and N, while in the F-layer (>150 km), extreme ultraviolet (EUV) photons (10-100nm) are the dominant source of ionisation of O (Watanabe et al. 2021). Therefore, this sudden increase in solar irradiance causes dynamical and compositional changes in the entire dayside ionosphere of the Earth. An interdisciplinary analysis of the cause of changes in solar irradiance and its effect on the ionosphere is required to deepen our understanding of the solar-terrestrial relationship.

Flares of comparable X-ray magnitudes can have vastly different EUV signatures (Greatorex et al. 2023). While the X-ray emission generally comes from hot (~10^7 K) plasma confined to coronal loops, EUV emission during the initial "impulsive" phase comes predominantly from the loop footpoints rooted in the solar chromosphere (~10^4-10^5 K). As the X-ray emitting plasma cools through the "gradual" phase, there can also be successive coronal EUV emission at intermediate temperatures (~10^5-10^6 K), as well as additional enhancements from the EUV late phase (Woods et al. 2011). Therefore, the EUV component of a given flare can depend upon the heating (and cooling) rate, location on the solar disk (opacity effects), flare duration, solar background, etc. The current solar cycle is providing us with rich datasets of spectrally and temporally resolved X-ray and EUV emission from flares of various magnitudes (e.g. SDO/EVE, GOES-R/EXIS, SORCE/SOLSTICE and XPS, PROBA2/LYRA)[1]. These allow us to study detailed changes in the solar

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[1] Solar Dynamics Observatory/EUV Variability Experiment; Geostationary Operational Environmental Satellite/EUV and X-ray Irradiance Sensor; SOlar Radiation and Climate Experiment/SOLar-STellar Irradiance Comparison Experiment and XUV Photometer System; PRoject for OnBoard Autonomy 2/Large Yield RAdiometer

(spectral) irradiance during a range of events of different magnitudes and timescales. The properties of the accelerated electrons responsible for driving (impulsive) increases in irradiance can be diagnosed from hard X-ray measurements (e.g. RHESSI, *Fermi*, Solar Orbiter/STIX)[2], which be used to drive radiative hydrodynamic models (e.g. RADYN) that can point to how and where X-ray and EUV emission is generated on the Sun.

The current accuracy of forecasting ionospheric dynamics under the influence of natural disturbances is insufficient. A large amount of experimental data and theoretical estimates on the behaviour of ionospheric components during solar flares is now available and can be utilised to address this problem. Sudden ionospheric disturbances caused by solar flares can significantly affect the propagation of radio waves. For example, variations in the lower ionosphere electron concentration, N_e, disturb the amplitude and phase of very low frequency waves (VLF; 3-30 kHz) propagating in the Earth-ionosphere waveguide. This makes VLF data a valuable tool for studying the response of the lower ionosphere to variations in X-ray radiation which ionises the D-region (Bekker and Korsunskaya, 2023). Similarly, changes in electron concentration during a flare causes a delay in GPS signals, so data from global navigation satellite systems can be used to estimate the increase in the total electron content (TEC) in the Earth's ionosphere (Yasyukevich et al., 2018). Moreover, temporal variations of TEC can be an experimental source of information about the impact of geoeffective solar radiation at different phases of a flare.

Figure 1 shows X-ray and EUV lightcurves (from selected emission lines) from GOES and SDO/EVE (top panel), respectively, along with the associated predicted emission from the Flare Irradiance Spectral Model (FISM, Chamberlin et al., 2007, 2008, 2020; middle panel) during the X2.8 solar flare on 3 November 2011. FISM is commonly used as an input to many ionosphere/thermosphere models, although it has been shown to under-estimate the EUV component in flares of comparable magnitudes (Greatorex et al. 2023). The bottom panel of Figure 1 shows the associated change in TEC, which was calculated by averaging data from 956 illuminated GPS stations (blue curve), as well as the amplitude dynamics of a dayside VLF signal (red curve).

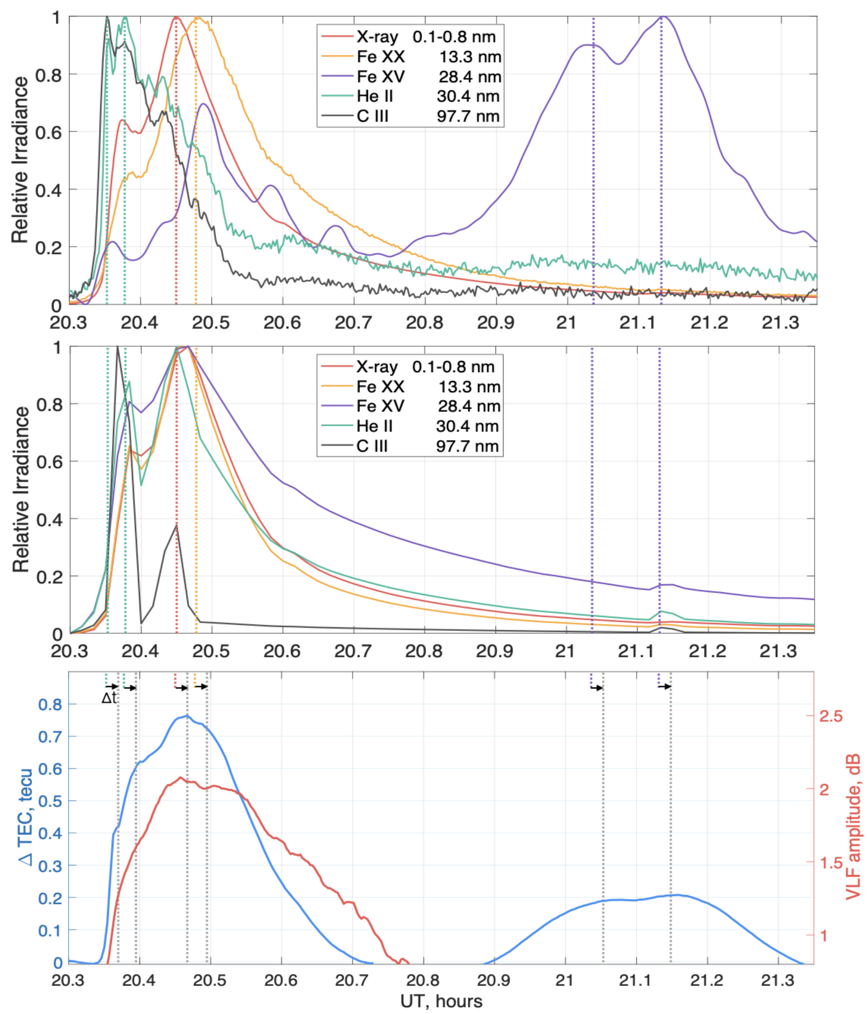

Figure 1: Top panel: Solar flare lightcurves in X-rays and selected EUV emission lines from GOES and SDO/EVE, respectively. Middle panel: The same flare emission as predicted by FISM. Bottom panel: Measured response of TEC (blue) and amplitude of VLF signal (red).

[2] Ramaty High-Energy Solar Spectroscopic Imager; Spectrometer/Telescope for Imaging X-rays

The TEC curve reacts initially to the peaks of cool, chromospheric emission (He II and C III) during the impulsive phase of the flare (dotted vertical green lines), then to the peaks of hot coronal X-rays (0.1-0.8nm) and Fe XX (~10^7K) emissions (red and yellow dotted vertical lines, respectively). The approximate delay in the TEC response to the radiation maxima is Δt=1 min, which is a typical delay time of the most ionised layer of the ionosphere, the F-region. Reflection of VLF signals occurs at altitudes of the ionospheric D-region, which is mostly ionised by X-ray radiation during a flare. This is why the amplitude of VLF signal reacts to the flare later than TEC, as can be seen from the bottom panel. In the EUV late phase of the flare the increased Fe XV emission generates a secondary two-peak response in the TEC (dotted vertical purple lines). There was no VLF data available during the later phase of this event. *This figure demonstrates the relevance of synchronous analysis of data on solar radiation fluxes and variations in TEC for the qualitative and quantitative study of solar-terrestrial connections during flares.*

The increased temporal and spectral resolution of solar flare observations, advances in modelling efforts since Solar Cycle 24, along with recent developments in atmospheric response measurements and predictions, now allows for a comprehensive study of changes in the solar irradiance and how this influences the composition and dynamics of the Earth's ionosphere.

Main goal and scientific questions

The overarching goal of this project is to understand how solar flares with differing spectral properties, X-ray magnitudes, durations, heliographic locations, etc, affect the dynamics, composition, and recovery times of the Earth's ionosphere. To achieve this goal, the combined expertise of the proposed team will aim to address the following science questions:

1. *How do different phases of solar flares impact the ionosphere?*

Much modern research is devoted to assessing TEC changes during the impulsive phase of a flare. To date there is only a single estimation of the TEC response to the late phase of a solar flare, which can be much longer than the impulsive phase and consequently can be energetically comparable (Liu at al., 2024). As shown in the bottom panel of Figure 1, there is a noticeable N_e response to the late phase of the flare which is almost a third of the N_e reaction to the impulsive phase. The frequency and magnitude of the impact of this late phase emission requires additional investigation. Moreover, as evident from the middle panel of Figure 1, FISM fails to predict this late phase emission in the Fe XV line (28.4 nm), which has a measurable effect on changes in electron concentration in the ionosphere. Consequently, models that rely on FISM as an input would then fail to predict corresponding TEC response. Therefore, further analysis is necessary to identify the model weaknesses and improve its predictive capabilities.

2. *How do flares with various spectral properties and locations on disk influence the ionosphere under different background conditions (such as season, geographical location, background ionisation)?*

Changes in different solar emission lines lead to non-uniform increases in electron concentration at different ionospheric altitudes. Therefore, solar flares with different spectra will result in different vertical distributions of charged particles in the ionosphere. Additionally, a limb flare will have a larger fraction of X-ray emission and a lower fraction of EUV emission relative to a disk flare due to opacity effects (Qian et al., 2010, Milligan 2021). This will mostly affect the electron concentration in the ionospheric E and D regions. The extent of the flare impact on the ionosphere also depends on factors such as background ionisation (caused by stage of the solar cycle and magnetic activity), season, latitude, longitude, and solar zenith angle in the point of observation. Consideration of different solar and geophysical conditions will allow us to understand the complex nature of ionospheric reactions to variations in solar irradiance.

3. *What are the mechanisms by which geoeffective emission is generated during solar flares?*

During a flare's impulsive phase, EUV emission emanates primarily from the loop footpoints during heating via non-thermal electrons, while additional emission can come from the corona as plasma cools from X-ray temperatures during the gradual phase. However, the precise mechanism responsible (including opacity effects) and the originating layer(s) of the solar atmosphere are not fully understood. Quasi-periodic pulsations are also commonly observed in solar flares (primarily coronal X-rays) that can induce similar oscillations in the D-region of the ionosphere, as well as affecting the electron density in this region (Hayes et al., 2017). Similar pulsations have been observed across a range of wavelengths, including in EUV and UV emission originating in the chromosphere during flares (Milligan et al. 2018), although their underlying nature and effect on the ionosphere, if any, is unknown.

3. Project Work Plan

We propose to have two five-day long meetings at ISSI-Bern. Before Meeting One the team will identify several geoeffective flares with coincident solar and ionospheric datasets and begin preliminary analysis. Meeting One will be held in late 2024 and will be devoted to scientific discussion, selection of approaches, and delegation of individual tasks within the project. Between meetings the team will actively work on projects initiated in Meeting One with monthly online meetings coordinated by the team leaders. Meeting Two will be held ~12-18 months later, reviewing the progress of the project, accumulating the findings made, and finalising a plan for publication and dissemination of results.

The work plan for addressing the three science questions above is as follows:

1. We shall compare changes in the solar irradiance over the EUV and X-ray wavelengths (using high-cadence observations from SDO, GOES, PROBA2, etc), along with predictions from FISM, and compare these with the response of the Earth's ionosphere using ground-based data of GPS stations, VLF receivers and magnetometers.

2. Solar spectral irradiance datasets will be analysed to determine the changes in wavelengths of emission from flares and compared with ground based ionospheric observations to determine the most geoeffective emission lines. Terrestrial atmospheric responses shall then be modelled (using GAIA and TIE-GCM)[3] to determine the different altitude ranges above the Earth and chemical compositions at which each emission line has the most impact on electron density.

3. Hard X-ray data (from RHESSI, *Fermi*, Solar Orbiter/STIX) will also be used to establish the parameters of the electron distribution responsible for generating the initial changes in irradiance and can be used to drive the RADYN models of geoeffective emission lines. These observations can also be used to elucidate the nature of any quasi-periodic pulsations detected in the EUV observations (e.g. acoustic waves, MHD, episodic reconnection), and whether they have an appreciable impact on the ionosphere.

4. Expected Outputs

The findings that result from this collaboration shall be published in high-impact, peer-reviewed journals, (e.g. Space Weather, The Astrophysical Journal, Astronomy & Astrophysics, Journal of Geophysical Research) and presented at relevant international conferences and workshops (e.g. American Geophysical Union meeting, European Space Weather Week, etc). By addressing the above science questions our findings will prepare the solar community for future irradiance observations expected in Solar Cycle 25, such as Solar-C/Solar Spectral Irradiance Monitor (SoSpIM; currently entering phase C/D). By identifying key areas for improvements, the findings from this team will help guide future iterations of the FISM model, as well as help steer policy decisions on Space Weather impacts.

5. Financial support requested

We require in-kind support for two 1-week meetings with 12 core members for a total of 24 person weeks at ISSI Bern.

[3] Ground-to-topside Atmosphere Ionosphere model for Aeronomy; Thermosphere Ionosphere Mesosphere Electrodynamics General Circulation Model

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