The Role of Solar Flares in Space Weather: Risks and Implications for Earth

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Abstract - This paper discusses the active nature of solar flares and coronal mass ejections (CMEs) in determining the space weather during Solar Cycle 25 and the effects on the ionosphere of the earth and the technological systems. We use real-time data from GOES satellites, GNSS, and GOLD to examine the unparalleled rise of X-class solar flares across 2024, with detailed case studies of major events in February, May, and October. It is found that solar bursts cause instant short-term increases in ionosphere total electron content (TEC) caused by intensified soft X-ray and extreme ultraviolet (EUV) radiation, whereas geomagnetic storms caused by CMEs result in long-term electrodynamic and thermospheric changes, resulting in losses of TEC on a large scale and restructuring of equatorial ionisation anomalies. Examples of these coupled processes were the TEC variations (rapid and radiative) that occurred quickly in February and the profound, lingering TEC depletions (after the Mother's Day superstorm in May). We find the interaction of radiative and electrodynamic drivers important in the development of ionospheric variability, showing the need to persist with solar monitoring and prediction modelling to protect technological infrastructure. The discoveries help us learn more about the effects of space weather forecasts; things are making modern society stronger and more resilient.

Key words: Solar Flares, Coronal Mass Ejections (CMEs), Space Weather, Ionosphere, Total Electron Content (TEC)

I. INTRODUCTION

Space weather refers to the changing physical characteristics of the near-space environment of Earth, primarily caused by solar emissions and the solar wind. Among the key causes of space weather are the solar flares that release a significant amount of radiation and considerable energy within a relatively short period of time. Active processes in the outer atmosphere of the Sun create these phenomena, known as sunspots. They are very extreme phenomena, which occur in cases when magnetic energy is suddenly emitted in the process of magnetic reconnection, pushing charged particles and heating the solar plasma to tens of millions of degrees [1], [2]. Solar flares produce energy in the entire electromagnetic spectrum, including radio waves, X-rays, and gamma rays. Depending on their size and complexity, they may require several hours or even a few minutes. The strongest solar flares may induce hazardous imbalances in the space environment in the vicinity of planet Earth and hamper the operations of satellites, radio communications, and even the navigation system. Moreover, they are also critical to the safety of the astronauts as well as high-altitude aviation, as they expose them to the solar radiation [3], [4].

The flares of the sun are classified based on the brightness, which is determined by the intensity of the X-ray in a wavelength of 18A as monitored by the GOES satellite. The classification of the flares is represented as A, B, C, M, and X, with each level signifying a one-order-of-magnitude increase in severity. Each class has been further divided on a linear scale from 1 to 9 (e.g., M2, X5). The most hazardous ones are the X-class flares and can produce severe technological effects [5]. CMEs (coronal mass ejections) are enormous releases of both solar matter and magnetic energy that likely occur alongside flares, as the two often happen in association with sunspots. The combination of these solar events causes effects that lead to space weather since they affect the dynamical processes of the magnetosphere, ionosphere and thermosphere on Earth [6]. There can be extensive effects of solar flares and other outer space weather events. They could produce geomagnetic storms, which lead to the energetic events of particles and a series of effects on space-based and ground-based technological

infrastructures. The scenario of geomagnetic storms, which can generate dangerous currents through power grids and lead to the destruction of transformers and massive power cuts, is highlighted. Strong levels of solar activity distort or render radio communications and navigation systems (e.g., GPS) useless. The swelling of the atmosphere can also cause the satellites to be vulnerable to breakdowns and orbital decay, and the electronic devices are also quickly deteriorating. Moreover, high-energy particle propagation also takes place in isolated cases, which is also another threat to the health and safety of astronauts and airline passengers on polar flights [7], [8].

These processes are also separately coupled with the solar cycle, which is a cyclic process of solar activity with a period of about 11 years, which is regulated by the magnetic field of the Sun. It is known as the solar cycle and is responsible for accelerating and declining the intensity and frequency of solar flares and CMEs; it is most significant at the solar maximum and weakens at the solar minimum [9]. It is in Solar Cycle 25, which began in December 2019 and is estimated to peak in the end of 2024 or early 2025. Interestingly, this cycle has already registered more sunspots than expected, suggesting that it will have significant impacts on space weather. The technological industry is becoming reliant on a significant portion of the society, and therefore, continued studies and real-time observation of the space weather and solar flares will be necessary to reduce risks, provide early alerts, and preserve the existing infrastructure [8], [6].

Solar Cycle 25 was a significant year during which there were notable milestones in solar activity and saw a record number of occurrences of high-energy events, including X-class solar flares. Based on the data received, 54 X-class solar flares were recorded during the year, and thus, it was the most active year of X-class solar flares observed since at least 1996 [10]. The strongest types in the GOES scale of classifications are X-class, which are capable of releasing energy up to 10^{-4} W/m² in the 1-8 Å X-ray band. Such energetic activities tend to disrupt high-frequency (HF) radio activities, impair satellite activities, and, when related to coronal mass ejections (CMEs), may cause geomagnetic storms that pose threats to power grids and navigation systems [11]. These observations prove that Solar Cycle 25, which was initially predicted to be a humble one, has surpassed predictions as far as flare productivity is concerned [12]. The X-class events, especially those that are produced by individual active regions, are clustered, which indicates magnetic reconnection processes are complex in sunspot groups with magnetic configurations. These bursts yield useful information for space weather modelling and the necessity of further solar observations and prediction capabilities as contemporary society grows more dependent on space-based and land-based infrastructure that is prone to a space weather occurrence. The most impressive application of the low-latitude influence of geomagnetic storms in 2024 was the case of May, when auroras were seen in the areas where they do not occur at all. The information shows how deep the magnetic field had been compressed and how much energy was delivered into the magnetosphere of the earth, and this forced the oval of the aurora to go out of position to a position much farther on the equator.

This paper is organised as follows. Part 1 follows with the background and importance of solar flares in the cause of space weather by enforcing their capability of causing interference in communication, navigation, and power infrastructure. Section 2 describes the data sources, which were the GOES records of solar flares and the Dst geomagnetic index, and the analysis procedure of the relationship between them and ionospheric reactions. The results are found in section 3 and indicate the major solar flares of 2024 and the subsequent geomagnetic effects predicted by Dst in the form of a short-term gain and long-term loss of the ionospheric TEC. Section 4 explains these findings using the earlier literature, which includes the technological implications and reveals the importance of the solar flare and Dst observations as the auxiliary tool for measuring the ionospheric variability. Finally, Section 5 concludes by summarising the key findings, conclusion and relevance of this study in improving space weather monitoring and prediction capabilities besides safeguarding vulnerable technology infrastructure.

II.DATA SET

The main data source used in this study was the GIRO Digital Ionosonde Database (DIDbase) (https://giro.uml.edu/didbase/scaled.php) which has given the vertical Total Electron Content (TEC) measurements of the identified solar flare and CME. The low-latitude station, WA619 (19.29^0 N, 166.64^0 E), was chosen to record the TEC data at a frequency of 5-15 minutes between these periods to realize the finer details of ionospheric reactions. Data on solar index (soft X-ray flux, geomagnetic indices like Dst) was obtained through the OMNI database (http://omniweb.gsfc.nasa.gov) to make it possible to correlate the ionosonde measurements with time. All datasets were handled and analysed in Microsoft Excel to clean up the data, synchronise it, analyse the trend, and graphically visualise data to have a clear evaluation of the rapid flare-induced TEC increment and the long-term depletion in the case of the CME.

<center>III. RESULT</center>

3.1. Event 1: 8–10 February 2024 –

Figure 1 illustrates the simultaneous development of solar flares, geomagnetic responses, and ionospheric variability. M-class flares were moderate and reached their peaks on February 9, and the SXR flux improvement promoted further ionisation. The Dst index was not intense (-20 +25 nT), which indicated only slight current systems and no storm level. TEC fluctuations were dramatic: on 8 February the values fell to about 75 TECU, then to 20 TECU at night, and on 9 February they rose again to about 78 TECU before becoming erratic on 10 February. These variations demonstrate the importance of flare-induced radiation even in the case of no significant geomagnetic forcing in the occurrence of intense diurnal variations (>60 TECU).
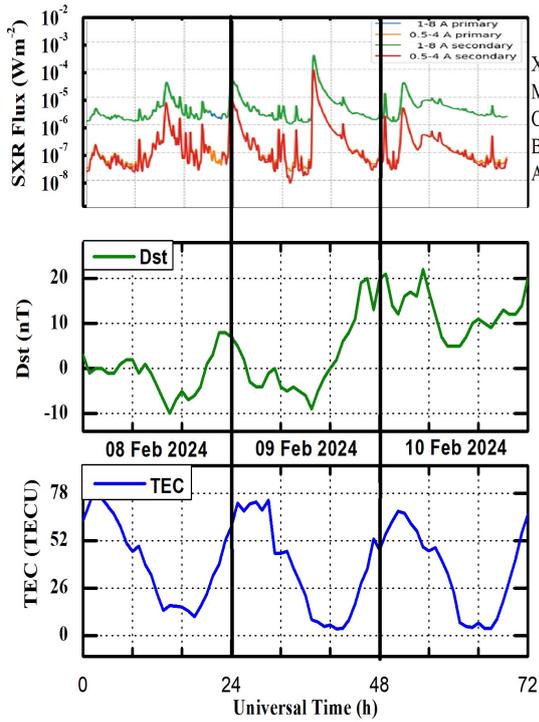

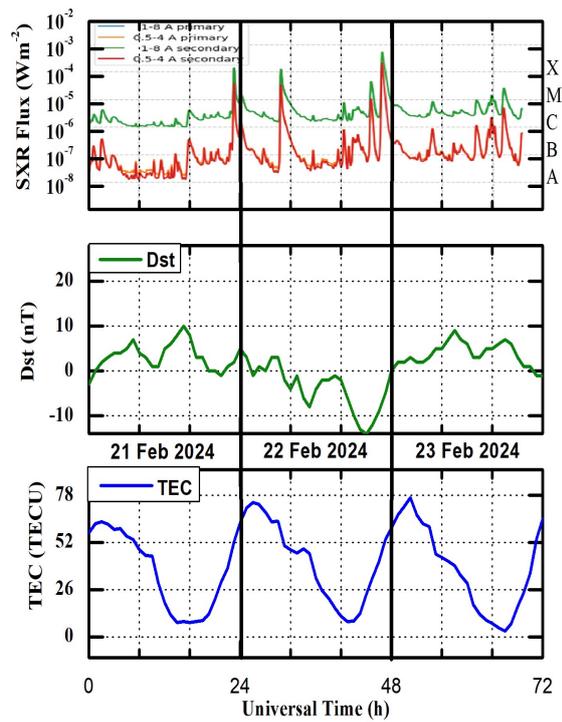Figure 1: Solar flares, Dst, and TEC for the period of Feb 8 to 10, 2024.

Figure 2: Solar flares, Dst, and TEC for the period of Feb 21 to 23, 2024

3.2. Event 2: 21–23 February 2024 –

The C- to M-class flares on 21-23 February generated individual flayers (figure 2), with the greatest flayers on 22 February, as the mid-M-class activity was the highest. There were no significant geomagnetic events, and Dst was dropped briefly and only once to -18 nT and then recovered. However, there were significant day-night variations in ionospheric TEC, with values up to 70-75 TECU during the day and 10 or less during the night. The outcome was the variability of over 60 TECU, which once again highlighted the ionosphere's sensitivity to flare radiation, regardless of slight geomagnetic interference.

3.3. Event 3: 9–11 May 2024 –

The period around 9–11 May was one of the most intense disruptions of Solar Cycle 25 (figure 3). Several X-class flares were accompanied by Earth-directed CMEs, which resulted in instant radiative effects as well as very severe geomagnetic activity. GOES detected some strong bursts on 9-10 May, resulting in extensive radio blackouts. The Dst index, which remained stable at 0 nT on May 9, dropped to -430 nT on May 10, which was a favourable confirmation of a superstorm. It was only on 11 May that recovery was partial, and values were still at about -200 to -250 nT. The ionosphere was dramatically depleted: TEC decreased from 55 to 60 TECU to 5 to 10 TECU around the centre of the storm and then recovered to a range of 72 TECU on May 11. This sequence indicates the duality of the geomagnetic forcing by the flare radiation and CME in the cause of extreme variability in the ionosphere.
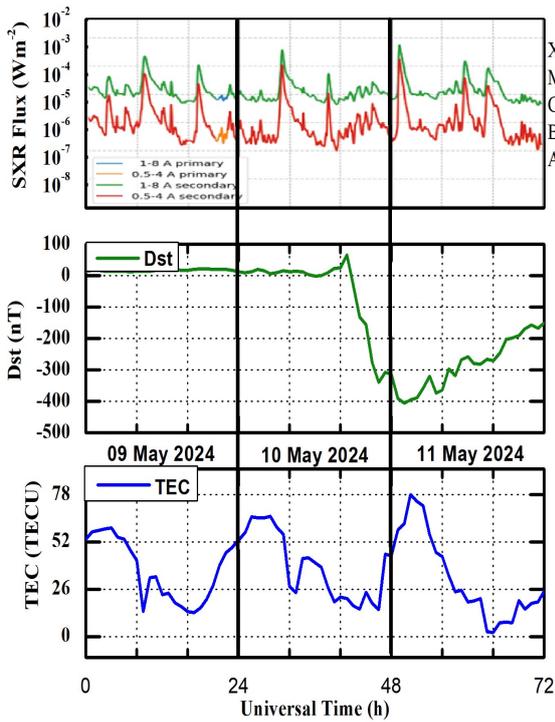
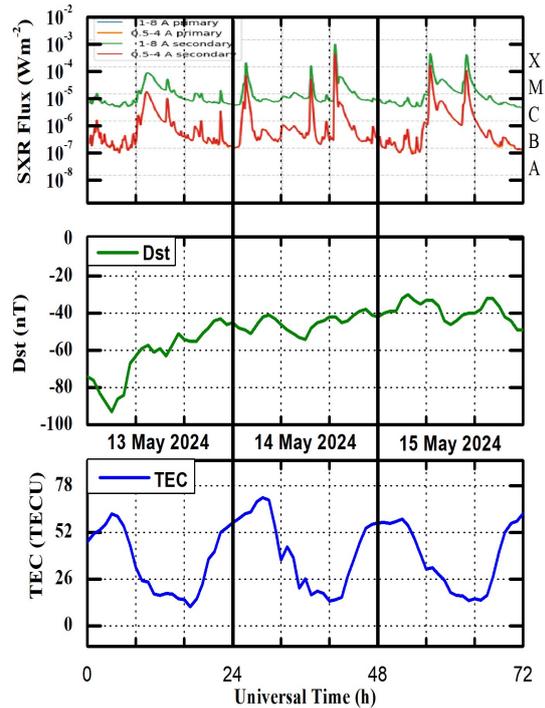Figure 3: Solar flares, Dst, and TEC for the period of May 9 to 11, 2024

Figure 4: Solar flares, Dst, and TEC for the period of May 13 to 15, 2024

3.4. Event 4: 13–15 May 2024 –

There were residual disturbances (figure 4) following the May superstorm. A number of M-to X-class flares were not accompanied by new CMEs, and thus, no new major storms were formed. The Dst index reached a low of -95 nT on 13 May and slowly rose to -40 nT on 15 May, which is in line with the decay of the ring current. TEC, though, was extremely fluctuating: it rose up to approximately 60 TECU at the beginning of 13 May, decreased sharply to approximately 15-20 TECU in the middle of the day, and again dropped, followed by a secondary recovery on 15 May. These oscillations depict the electrodynamics of storm times, such as the penetration of electric fields and the equatorial activity of the anomaly even in the recovery stage.

3.5. Event 5: 1–3 October 2024 –

One of the most geoeffective periods of the year was during 1–3 October (figure 5), when there was an X7.1 flare (1 October) and an X9.0 flare (3 October) generated by NOAA AR 3842. Although the October 1 event did result in temporary ionisation enhancements, the October 3 flare was at night, and it did not have much direct impact. CME interaction was the overriding cause: on 2 October, the Dst index recorded a storm onset (+20 nT), and on 3 October, further positive deflections were associated with magnetospheric compression instead of the development of ring currents. The ionosphere responded very violently: on 2 and 3 October, TEC was down to around 20 and 78 TECU, respectively, 60-70 per cent depleted. These modifications were associated with the electrodynamic effects of CME, such as disturbed winds and sudden penetration of electric fields.
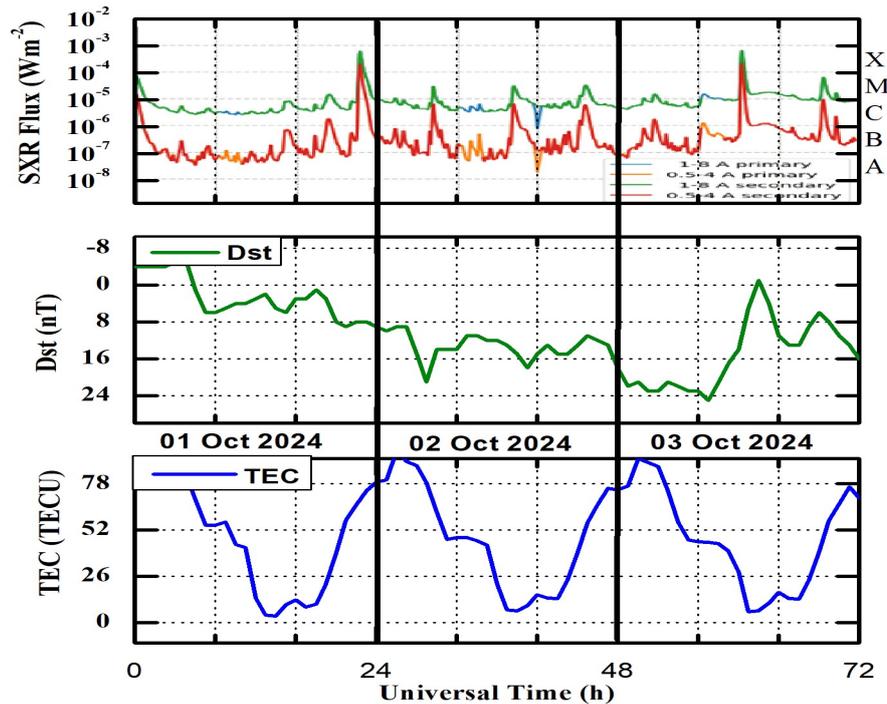
Figure 5: Solar flares, Dst, and TEC for the period of Oct 1 to 3, 2024

IV. DISCUSSION

The intervals of 8–10 February and 21–23 February 2024 distinctly illustrate how various forms of solar activity produce unique signatures in the ionosphere. In the absence of geomagnetic storms, solar flares still release significant quantities of radiative energy into the upper atmosphere. Elevations in soft X-ray and EUV fluxes enhance photoionisation rates in the F-region, resulting in pronounced daytime increases in TEC [13], [14]. In February 2024, diurnal swings exceeding 60 TECU were observed, highlighting the strong influence of flare-driven ionisation. These enhancements developed within seconds to minutes, bypassing magnetospheric processes, which explains why large TEC variability occurred even though Dst changes remained relatively small.

Recent machine learning methodologies, including LSTM-based forecasting, demonstrate that flare-induced alterations can match the variability typically observed during minor geomagnetic storms [15]. By contrast, the May 10–11, 2024, "Mother's Day" superstorm highlights the much stronger role of CME-driven processes. A powerful southward IMF combined with elevated solar wind pressure triggered intense magnetic reconnection, which in turn energised the ring current and drove the Dst index below –400 nT [7], [16]. These conditions elicited immediate penetration and disruption of dynamo electric fields, resulting in the redistribution of plasma across low and mid-latitudes [17]–[19]. Observations from GOLD and GNSS confirmed major changes in the equatorial ionisation anomaly, including crest merging and the formation of depletion zones [20]. Events driven by both flares and CMEs also revealed strong thermosphere–ionosphere coupling.

Intensified Joule heating at high latitudes induced equatorward winds that altered plasma transport, while nocturnal recombination reduced TEC to below 20 TECU [21], [22]. Collectively, these cases demonstrate the multi-scale variability of Solar Cycle 25. Flares induce swift, radiative ionisation, whereas coronal mass ejections (CMEs) create prolonged electrodynamic and thermospheric disruptions—phenomena that are increasingly being monitored due to robust GNSS networks and advancements in AI-based forecasting [23], [24].

V. CONCLUSION

The previous solar cycles have demonstrated the impact of solar activity on the ionosphere in two aspects. Solar flares, however, occur in a very short duration of time. They produce rapid but transient ionisation spikes through an augmentation in the soft X-ray and EUV emission. Storms due to CMEs, on the other hand, lead to changes in thermosphere and electrodynamics that last longer and alter the distribution of plasma on a global

level. This is indicated by the difference between the flare activity in February 2024 and the superstorm of May 2024, the Mother of Days. Short-term alterations are primarily caused by the radiative processes, and long-term alterations are primarily caused by the CME dynamics. These effects can now be seen and predicted on the ground in real time due to the advances in GNSS tracking, space-based imaging and AI-driven prediction. This ability to unite things not only makes communication systems and navigation systems more reliable but also allows us to understand more about the process of interaction between the Sun and the Earth. Simultaneously, using radiative and electrodynamic factors enables better understanding of the entire spectrum of ionospheric variability and the subsequent enhancement of space weather resilience methods, among other benefits.

REFERENCES

[1] A. O. Benz, *Flare Observations*, 2017.

[2] H. S. Hudson, "Solar flares, microflares, nanoflares, and coronal heating," *Solar Physics*, vol. 273, no. 1, pp. 69–75, 2011.

[3] D. N. Baker, "Effects of the Sun on the Earth's environment," *Journal of Atmospheric and Solar-Terrestrial Physics*, vol. 62, no. 17–18, pp. 1669–1681, 2000.

[4] A. Pulkkinen, "Space weather: Terrestrial perspective," *Living Reviews in Solar Physics*, vol. 4, no. 1, pp. 1–60, 2007.

[5] NOAA SWPC, "Solar flares: Classification and impacts," 2024.

[6] C. J. Schrijver and G. L. Siscoe, *Heliophysics: Space Storms and Radiation: Causes and Effects*, Cambridge University Press, 2010.

[7] W. D. Gonzalez, J. A. Joselyn, Y. Kamide et al., "What is a geomagnetic storm?" *Journal of Geophysical Research: Space Physics*, vol. 99, no. A4, pp. 5771–5792, 1994.

[8] D. N. Baker, E. Daly, T. G. Onsager, and J. Allen, "Space weather effects on technology," *Space Weather*, vol. 6, S01D03, 2008.

[9] D. H. Hathaway, "The solar cycle," *Living Reviews in Solar Physics*, vol. 12, no. 1, p. 4, 2015.

[10] SpaceWeatherLive.com, "X-class flares in Solar Cycle 25," 2024.

[11] H. S. Hudson, "Solar flares, the X-ray flare class system, and their technological impacts," *Solar Physics*, vol. 133, pp. 357–369, 1991.

[12] NOAA, "Solar Cycle 25 update," 2024.

[13] B. T. Tsurutani, O. P. Verkhoglyadova, G. S. Lakhina, and S. Yagitani, "Solar flares, particle acceleration, and ionospheric effects," *Journal of Geophysical Research: Space Physics*, vol. 114, A00A17, 2009.

[14] L. Qian, A. G. Burns, P. C. Chamberlin, and S. C. Solomon, "Solar flare impacts on the thermosphere and ionosphere," *Journal of Geophysical Research: Space Physics*, vol. 115, A09311, 2010.

[15] V. Dass, R. Yadav, and M. Sharma, "AI-based prediction of flare-driven TEC variability using LSTM," *Space Weather*, vol. 23, e2025SW003456, 2025.

[16] R. Kataoka and D. Shiota, "Extreme space weather and the May 2024 storm," *Earth, Planets and Space*, vol. 76, 2024.

[17] B. G. Fejer, E. R. de Paula, S. A. Gonzalez, and R. A. Heelis, "Global equatorial ionospheric electric fields during geomagnetic storms," *Journal of Geophysical Research*, vol. 84, pp. 5797–5802, 1979.

[18] M. C. Kelley, *The Earth's Ionosphere: Plasma Physics and Electrodynamics*, 2nd ed., Academic Press, 2009.

[19] B. G. Fejer, A. J. Mannucci, and S. Basu, "Storm-time electrodynamics in the low-latitude ionosphere," *Journal of Atmospheric and Solar-Terrestrial Physics*, vol. 234, 2024.

[20] D. Karan, R. A. Heelis, and S. Basu, "GNSS and GOLD observations of equatorial ionization anomaly during May 2024," *Geophysical Research Letters*, vol. 51, e2024GL123456, 2024.

[21] M. Blanc and A. D. Richmond, "The ionospheric disturbance dynamo," *Journal of Geophysical Research*, vol. 85, no. A4, pp. 1669–1686, 1980.

[22] S. Imtiaz, P. Prasad, and R. Singh, "Thermosphere–ionosphere coupling during solar flare–CME events," *Annales Geophysicae*, vol. 43, pp. 55–70, 2025.

[23] Y. Gordiyenko, A. Afraimovich, and O. Shumeiko, "GNSS monitoring of ionospheric variability during Solar Cycle 25," *Advances in Space Research*, vol. 75, pp. 2250–2265, 2025.

[24] D. Bojilova, P. Vellante, and T. Farges, "AI-enhanced forecasting of ionospheric disturbances," *Space Weather*, vol. 23, e2025SW003498, 2025.