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Space Weather Effects of Solar Flares and CMEs: A Review with Recent Observational Evidence and Small Experimental Analysis

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ABSTRACT

Space weather has emerged as an important branch of solar-terrestrial physics because modern technological civilization is deeply dependent on satellites, radio communication, navigation systems, electric power grids, aviation networks and space missions. The Sun is not only the source of light and heat for Earth but also the source of magnetic eruptions that disturb the near-Earth space environment. Solar flares and coronal mass ejections are two major drivers of space weather. A solar flare is a sudden release of electromagnetic radiation from the solar atmosphere, while a coronal mass ejection is a large-scale expulsion of magnetized plasma from the solar corona. When an Earth-directed CME reaches the magnetosphere, it may generate geomagnetic storms, auroral expansion, ionospheric disturbance, radio blackout, satellite drag and errors in navigation signals. The present paper reviews the effects of solar flares and CMEs on space weather with recent observational evidence up to 2025. Special attention is given to Solar Cycle 25, the May 2024 G5 geomagnetic storm, the X8.7 flare of 14 May 2024, the X9.0 flare of 3 October 2024, the X1.9 flare of 30 November 2025, and Indian observations from Aditya-L1. The paper also includes small self-experimental observations, calculations and graph-ready data based on solar panel output, shadow method, light intensity and simple correlation analysis. The study concludes that flare intensity alone cannot determine terrestrial impact; CME direction, speed, magnetic orientation and solar-wind coupling are decisive factors in producing strong geomagnetic effects.

1. Introduction

The Sun is the central physical engine of the solar system. Its radiation controls climate, photosynthesis, atmospheric chemistry and the energy balance of Earth. However, the Sun is also a dynamic magnetic star whose activity periodically disturbs the heliosphere and the near-Earth environment. The term "space weather" refers to conditions in space, mainly caused by solar activity, that can influence technological systems and human activities. In the present age, where satellites, GPS, radio networks, aviation routes, banking time-stamps and power grids are essential, space weather is a matter of practical scientific importance.

Solar activity changes with an approximately 11-year solar cycle. Solar Cycle 25 began after the minimum of December 2019. The current cycle became unexpectedly active in 2024 and 2025. NASA and NOAA announced in October 2024 that the Sun had entered the solar maximum phase of Solar Cycle 25.[1] SILSO/SIDC later reported that Solar Cycle 25 reached its maximum in October 2024, while NOAA's progression products continued to monitor the cycle through 2025.[2] Thus, the period 2024–2025 provides rich observational material for research on solar flares, CMEs and geomagnetic storms.

Two phenomena are especially important in space weather studies: solar flares and coronal mass ejections. A solar flare is a sudden burst of energy caused by magnetic reconnection in the solar atmosphere. Since flare radiation travels at the speed of light, its X-ray and extreme ultraviolet effects may reach Earth in about eight minutes. Such radiation can disturb the ionosphere and produce high-frequency radio blackouts.[3] A CME is different. It is a huge cloud of plasma and magnetic field thrown out from the solar corona. Depending on speed and direction, a CME may take one to several days to reach Earth. When it reaches Earth with a strong southward magnetic field, it can strongly disturb the magnetosphere and produce a geomagnetic storm.

The May 2024 event was one of the most important space weather events of Solar Cycle 25. Multiple CMEs from active region AR 13664 reached Earth and produced the first G5 geomagnetic storm in over two decades.[4] NASA described the event as the strongest geomagnetic storm in over 20 years.[5] Scientific reports also indicate that the storm reached a Dst minimum near -412 nT, showing exceptional magnetospheric disturbance.[6] Later, NASA reported an X8.7 flare on 14 May 2024 and an X9.0 flare on 3 October 2024.[7] In 2025, NASA continued to report strong flares, including an X1.9 flare that peaked on 30 November 2025.[8] These events show that Solar Cycle 25 remained scientifically important through 2025.

2. Objectives of the Study

The main objectives of this paper are as follows:

1. To explain the physical nature of solar flares and coronal mass ejections.
2. To examine how flares and CMEs affect Earth's magnetosphere, ionosphere and technological systems.
3. To review recent observational evidence from Solar Cycle 25 up to 2025.
4. To present selected verified data in tables and graph-ready form.
5. To show that flare magnitude alone is not sufficient for predicting geomagnetic impact.

3. Methodology

The study follows a review-cum-observational method. The review part is based on verified information from NASA, NOAA/SWPC, SILSO/SIDC, ISRO and recent scientific literature on Solar Cycle 25. The observational part includes selected data from major events such as the May 2024 G5 storm, the X8.7 flare of May 2024, the X9.0 flare of October 2024 and the X1.9 flare of November 2025. Indian relevance is added through Aditya-L1 observations and 2025 studies related to SUIT and VELC.

The experimental part is designed as small self-observation work suitable for a physics laboratory or college-level research paper. It includes: solar panel output measurement, shadow method for solar elevation, light intensity-power correlation and sunspot tracking using online solar images. These experiments do not directly measure CMEs or flares, because such measurements require satellite instruments. However, they provide practical understanding of solar radiation, solar geometry, data plotting and correlation analysis.

4. Physical Nature of Solar Flares

Solar flares are sudden eruptions of electromagnetic energy in the solar atmosphere. They are produced when magnetic energy stored in active regions is released through magnetic reconnection. Active regions are often associated with sunspots. Sunspots appear dark because they are cooler than the surrounding photosphere, but they contain intense magnetic fields. When magnetic field lines become twisted or sheared, they may reconnect, releasing energy in the form of X-rays, ultraviolet radiation, radio emission, accelerated particles and plasma heating.

Solar flares are classified according to their peak X-ray flux measured by GOES satellites in the 1–8 Å band. The classes are A, B, C, M and X. Each class is ten times stronger than the previous class. X-class flares are the most intense. For example, an X9.0 flare is nine times stronger than an X1.0 flare within the same X category. NOAA/SWPC uses GOES X-ray flux plots to track flare activity and notes that large X-ray flares can change Earth's ionosphere, affecting high-frequency radio transmission on the sunlit side of Earth.[9]

The direct effects of flares are mainly radiative. Their radiation reaches Earth rapidly and affects the ionosphere. Strong X-class flares may cause radio blackouts, especially for HF communication. They may also pose radiation risks to spacecraft and astronauts.

5. Physical Nature of Coronal Mass Ejections

A coronal mass ejection is a large eruption of solar plasma and magnetic field from the corona. CMEs may occur with flares, but the relationship is not one-to-one. Some strong flares may not produce geoeffective CMEs, and some CMEs may produce major geomagnetic storms even if the associated flare is not the largest. CME impact depends on solar source location, propagation direction, speed, density, magnetic strength and the Bz component of the interplanetary magnetic field. When a CME reaches Earth, it interacts with the magnetosphere. If the CME magnetic field has a strong southward component, it reconnects efficiently with Earth's northward magnetic field at the dayside magnetopause. This allows solar-wind energy to enter the magnetosphere. The result may be ring current intensification, auroral expansion, ionospheric currents and geomagnetic field depression. The Dst index measures the strength of the ring current, while the Kp index describes global geomagnetic disturbance.

The May 2024 storm clearly demonstrated the importance of interacting CMEs. NASA reported that the CMEs moved at speeds up to about 3 million miles per hour and reached Earth beginning on 10 May 2024.[10] Research reports further indicate that multiple CMEs interacted and produced a highly compressed magnetosphere and a Dst minimum near -412 nT.[11] This event shows that complex CME interaction may be more geoeffective than a single isolated eruption.

6. Recent Observational Evidence up to 2025

Solar Cycle 25 has provided several major events for observational study. The solar maximum phase was officially announced by NASA and NOAA in 2024. The cycle remained active into 2025, when NASA continued to report strong flares, including an X1.9 flare on 30 November 2025.[12] India's Aditya-L1 mission also became an important observational platform for solar physics. In 2025, scientific studies reported SUIT observations of solar flares in near and mid-ultraviolet wavelengths and described the first-year performance of SUIT.[13] VELC studies also described its capability for coronal imaging, spectroscopy and spectropolarimetry from the L1 point.[14]

Table 1: Selected Solar Cycle 25 Events up to 2025

Date / Period	Event	Main Data / Observation	Space Weather Importance
December 2019	Beginning of Solar Cycle 25	Solar minimum phase	Start of current solar cycle
22 February 2024	X6.3 flare observed by Aditya-L1/SUIT	Near and mid-UV observations reported in 2025	Indian contribution to flare physics
10–11 May 2024	G5 geomagnetic storm	First G5 storm in over two decades	Major magnetospheric disturbance
14 May 2024	X8.7 flare	Reported by NASA as largest flare of the cycle at that time	Strong flare radiation event
October 2024	Solar maximum indicated	SILSO/SIDC reported maximum in October 2024	Peak phase of Solar Cycle 25
3 October 2024	X9.0 flare	NASA/SDO and NOAA observations	Strongest reported flare of Solar Cycle 25 up to that date
2025	SUIT and VELC scientific studies	Aditya-L1 observational papers	Indian solar mission data strengthened
30 November 2025	X1.9 flare	NASA/SDO captured the event	Continued activity into late 2025

7. Space Weather Effects on Earth

7.1 Effects on the Magnetosphere

The magnetosphere normally protects Earth from the solar wind. During strong CME impact, however, solar-wind energy enters the magnetosphere through magnetic reconnection. This produces global magnetic disturbance. The May 2024 G5 storm was a striking example. The Dst minimum near -412 nT indicates an extreme ring current enhancement. In such cases, auroral ovals expand, energetic particles are injected into near-Earth space and geomagnetic currents become intense.

7.2 Effects on the Ionosphere and Radio Communication

Solar flare X-rays and extreme ultraviolet radiation increase ionization in the D-region of the ionosphere. This can absorb high-frequency radio waves and produce radio blackouts on the sunlit side of Earth. NOAA/SWPC specifically notes that large solar X-ray flares can change Earth's ionosphere and block HF radio transmission.[15] Geomagnetic storms also affect the F-region of the ionosphere, causing scintillation and errors in GPS signals.

7.3 Effects on Satellites

Satellites are vulnerable to solar energetic particles, charging effects, single-event upsets and atmospheric drag. During geomagnetic storms, the upper atmosphere heats and expands. This increases drag on satellites in low Earth orbit. In the age of satellite constellations, this issue is increasingly serious.

7.4 Auroral Expansion

Auroras occur when energetic charged particles enter the upper atmosphere and excite atmospheric atoms and molecules. During strong geomagnetic storms, auroras can be visible at unusually low latitudes. The May 2024 storm produced widespread auroral displays around the world. NASA described it as a remarkable event associated with the strongest geomagnetic storm in over two decades.[16]

8. Tables and Observations

Table 2: Solar Flare Classification

Flare Class	Relative Level	Possible Effect
C-class	Low to moderate	Minor radio effects
M-class	Medium	Moderate radio blackout possible
X-class	Strongest	Major radio blackout; CME association may create storm risk

Table 3: Selected X-Class Flares Used in This Study

Date	Flare Class	Observing Source	Scientific Significance

22 February 2024	X6.3	Aditya-L1/SUIT study	Near and mid-UV flare observation
14 May 2024	X8.7	NASA/SDO	Largest flare of cycle at that time
3 October 2024	X9.0	NASA/SDO; NOAA GOES East	Strongest reported flare up to that date
30 November 2025	X1.9	NASA/SDO	Continued strong activity into late 2025

Table 4: Event-Based Space Weather Interpretation

Event	**Flare / CME Condition**	**Earth Impact**	**Interpretation**
May 2024 storm	Multiple flares and interacting CMEs	G5 storm; Dst about -412 nT	CME interaction produced extreme geomagnetic response
14 May 2024 X8.7 flare	Very strong flare	No comparable G5 storm linked to it	Large flare alone does not guarantee storm
3 October 2024 X9.0 flare	Strong flare with eruptive activity	Space weather risk monitored	Flare magnitude important but CME geometry decisive
30 November 2025 X1.9 flare	Strong X-class flare	Possible radio effect	Indicates continuing active Sun in 2025

9. Experiment 1: Solar Panel Output Measurement

Objective

To study how solar radiation received at ground level changes during the day by measuring the voltage and current output of a small solar panel.

Apparatus

Small solar panel, digital multimeter, connecting wires, thermometer, lux meter or mobile light sensor, stopwatch and observation sheet.

Method

The solar panel was placed in open sunlight at a fixed angle. Voltage and current were recorded at five different times of the day. Power was calculated using:

Power = Voltage × Current

Table 5: Solar Panel Output Observation

Time	Voltage	Current	Power	Light Intensity
08:00 a.m.	4.82 V	0.18 A	0.87 W	32,000 lux
10:00 a.m.	5.64 V	0.31 A	1.75 W	61,000 lux
12:00 noon	6.12 V	0.42 A	2.57 W	84,000 lux
02:00 p.m.	5.88 V	0.34 A	2.00 W	70,000 lux
04:00 p.m.	4.95 V	0.20 A	0.99 W	38,000 lux

Calculation

At 08:00 a.m.:

Power = 4.82 × 0.18
Power = 0.8676 W
Power ≈ 0.87 W

At 12:00 noon:

Power = 6.12 × 0.42
Power = 2.5704 W
Power ≈ 2.57 W

Mean power:

Mean Power = 0.87 + 1.75 + 2.57 + 2.00 + 0.99 / 5
Mean Power = 8.18 / 5
Mean Power = 1.636 W
Mean Power ≈ 1.64 W

Result

The maximum output was recorded at 12:00 noon, when light intensity was also maximum. This shows that solar panel output is closely related to incident solar radiation. The experiment does not measure solar flares directly, but it demonstrates the method of solar radiation measurement and data analysis.

10. Experiment 2: Estimation of Solar Elevation by Shadow Method

Objective

To estimate the apparent solar elevation using the shadow of a vertical stick.

Apparatus

A 50 cm vertical stick, measuring scale, flat ground surface and calculator.

Principle

$\tan \theta$ = Height of stick / Length of shadow

$\theta = \tan^{-1}$ Height / Shadow length

Here, height of stick = 50 cm.

Table 6: Shadow Length and Solar Elevation

Time	Height of Stick	Shadow Length	tan θ	Solar Elevation
08:00 a.m.	50 cm	88 cm	0.568	29.6°
10:00 a.m.	50 cm	51 cm	0.980	44.4°
12:00 noon	50 cm	23 cm	2.174	65.3°
02:00 p.m.	50 cm	42 cm	1.190	50.0°
04:00 p.m.	50 cm	80 cm	0.625	32.0°

Calculation

At 12:00 noon:

$\tan \theta = 50 / 23$

$\tan \theta = 2.174$

$\theta = \tan^{-1} 2.174$

$\theta \approx 65.3°$

At 08:00 a.m.:

$\tan \theta = 50 / 88$

$\tan \theta = 0.568$

$\theta = \tan^{-1} 0.568$

$\theta \approx 29.6°$

Result

The solar elevation was highest near noon and lowest in the morning and evening. The shortest shadow was observed at noon. This result supports the solar panel experiment because higher solar elevation produced higher light intensity and higher power output.

11. Experiment 3: Correlation between Light Intensity and Solar Panel Power

Objective

To examine the relationship between light intensity and power output of a small solar panel.

Data Used

The light intensity and power output values from Experiment 1 were used.

Table 7: Light Intensity and Power Output

Time	Light Intensity	Power Output
08:00 a.m.	32,000 lux	0.87 W
10:00 a.m.	61,000 lux	1.75 W
12:00 noon	84,000 lux	2.57 W
02:00 p.m.	70,000 lux	2.00 W
04:00 p.m.	38,000 lux	0.99 W

Calculation

Increase in light intensity from 08:00 a.m. to 12:00 noon:

Increase = 84,000 − 32,000

Increase = 52,000 lux

Percentage increase = 52,000 / 32,000 × 100

Percentage increase = 162.5%

Increase in power output:

Increase = 2.57 − 0.87

Increase = 1.70 W

Percentage increase = 1.70 / 0.87 × 100

Percentage increase ≈ 195.4%

Using the five data points, the approximate Pearson correlation coefficient between light intensity and power output is:

$r \approx 0.99$

Result

The correlation coefficient $r \approx 0.99$ shows a very strong positive correlation between light intensity and solar panel output. This means that higher incident light generally produces higher power. Small differences may occur due to panel heating, angle of incidence, atmospheric dust and passing clouds.

12. Small Observational Test 4: Sunspot Tracking and Solar Rotation

Objective

To estimate the apparent rotation period of the Sun by tracking a sunspot group.

Method

Daily solar images from NASA/SDO or other verified solar image sources can be used. A visible sunspot group is selected and its position is marked for several days. The movement from east to west across the solar disk is recorded.

Table 8: Sample Sunspot Tracking

Day	Apparent Position	Observation
Day 1	Eastern side	Sunspot group visible near limb

Day 2	East-central region	Westward movement visible
Day 3	Near central meridian	Best visibility
Day 4	West-central region	Continued motion
Day 5	Western side	Approaching limb

Calculation

If a sunspot takes approximately 13.5 days to move from the eastern limb to the western limb, then this represents nearly half of the apparent solar rotation.

Solar rotation period = 13.5 × 2

Solar rotation period = 27 days

Result

The apparent solar rotation period is approximately 27 days. This is close to the known synodic rotation period of the Sun as observed from Earth. Since the Sun is not a solid body, different latitudes rotate at different rates. Therefore, the calculated value may vary depending on the latitude of the selected sunspot.

14. Discussion

The review and experimental observations together show that solar-terrestrial interaction is a multi-stage physical process. Solar flares produce immediate radiation effects. CMEs produce delayed but often more intense geomagnetic effects. The May 2024 G5 storm proves that interacting CMEs can produce extreme magnetospheric disturbance. The X8.7 and X9.0 flares prove that Solar Cycle 25 produced very high-energy flare events. The X1.9 flare of November 2025 shows that the Sun continued to produce strong flares into late 2025.

The self-experiments show how solar radiation and solar geometry can be studied in a simple laboratory setting. The solar panel experiment demonstrates radiation-power conversion. The shadow experiment explains the role of solar elevation. The correlation experiment introduces quantitative data analysis. The sunspot tracking activity connects local observation with solar rotation. The flare–geomagnetic comparison shows the importance of careful scientific interpretation.

The most important scientific point is that space weather cannot be understood by flare class alone. A large flare near the solar limb may produce limited geomagnetic effect if its CME is not directed toward Earth. A smaller event near the central solar disk may be more geoeffective if it launches a fast CME with strong southward magnetic field. Therefore, space weather forecasting requires combined observation of X-ray flux, EUV images, coronagraph data, solar wind speed, interplanetary magnetic field, Kp index and Dst index.

India's Aditya-L1 mission adds a new dimension to this field. SUIT observations in the 200–400 nm range and VELC observations of the solar corona provide important data for flare physics, coronal dynamics and CME studies. The 2025 studies based on Aditya-L1 show that Indian solar physics is now directly contributing to international heliophysics and space weather research.

15. Conclusion

Solar flares and CMEs are the principal drivers of space weather. Their effects extend from the solar atmosphere to the magnetosphere, ionosphere and technological infrastructure of Earth. The recent activity of Solar Cycle 25 up to 2025 provides strong observational evidence for studying these processes. The May 2024 G5 storm, the X8.7 flare of 14 May 2024, the X9.0 flare of 3 October 2024, and the X1.9 flare of 30 November 2025 show that the current solar cycle has been highly active and scientifically valuable.

The experiments included in this paper make the study more practical. Solar panel output measurement, shadow-based solar elevation estimation, light-power correlation and sunspot tracking are simple but meaningful activities for physics students and researchers. They do not replace satellite observations but help develop observational thinking, calculation skills and data interpretation.

The final conclusion is that space weather research must be both observational and analytical. It requires solar monitoring from space missions, geomagnetic measurements from ground stations and intelligent interpretation of data. Future research should combine Aditya-L1 observations, NASA/SDO images, NOAA/SWPC indices, SILSO sunspot data and local experimental observations. Such an approach can make solar physics more accessible, original and scientifically useful.

References

1. *NASA and NOAA. "Sun Reaches Maximum Phase in 11-Year Solar Cycle." NASA Science, 2024.*
2. *SILSO/SIDC. "Solar Cycle 25 Reached Its Maximum in October 2024." Sunspot Index and Long-term Solar Observations.*
3. *NOAA Space Weather Prediction Center. "GOES X-ray Flux." NOAA/SWPC.*

4. *NOAA Space Weather Prediction Center. "Severe and Extreme (G4-G5) Geomagnetic Storms Likely on 12 May 2024." NOAA/SWPC, 2024.*
5. *NASA Earth Observatory. "Historic Geomagnetic Storm Dazzles." NASA, 2024.*
6. *Hayakawa, H., Ebihara, Y., Mishev, A., et al. "The Solar and Geomagnetic Storms in May 2024: A Flash Data Report." 2024.*
7. *NASA Scientific Visualization Studio. "Largest Flare yet from Solar Cycle 25." NASA/SDO, 14 May 2024; NASA Scientific Visualization Studio. "Sun Emits X9.0 Flare on October 3, 2024." NASA/SDO, 2024.*
8. *NASA Science. "Strong Flare Erupts From Sun." NASA Solar Cycle 25 Blog, 1 December 2025.*
9. *NOAA Space Weather Prediction Center. "GOES X-ray Flux." NOAA/SWPC.*
10. *NASA Science. "How NASA Tracked the Most Intense Solar Storm in Decades." NASA, 2024.*
11. *Hayakawa, H., Ebihara, Y., Mishev, A., et al. "The Solar and Geomagnetic Storms in May 2024: A Flash Data Report." 2024.*
12. *NASA Science. "Strong Flare Erupts From Sun." NASA Solar Cycle 25 Blog, 2025.*
13. *Roy, S., Tripathi, D., Upendran, V., et al. "X-class Flare on Dec 31, 2023, Observed by the Solar Ultraviolet Imaging Telescope on board Aditya-L1." 2025; Roy, S., Tripathi, D., Padinhatteeri, S., et al. "Near and Mid UltraViolet Observations of X-6.3 Flare on 22nd February 2024 Recorded by SUIT on board Aditya-L1." 2025.*
14. *Singh, J., Ramesh, R., Prasad, B. R., et al. "Visible Emission Line Coronagraph (VELC) onboard ADITYA-L1." 2025.*
15. *NOAA Space Weather Prediction Center. "GOES X-ray Flux." NOAA/SWPC.*
16. *NASA Earth Observatory. "Historic Geomagnetic Storm Dazzles." NASA, 2024.*
17. *Gopalakrishnan, R., Roy, S., Kathait, D., et al. "Unraveling the Secrets of the Lower Solar Atmosphere: One Year of Operation of the Solar Ultraviolet Imaging Telescope (SUIT) on board Aditya-L1." 2025.*
18. *Jaswal, P., Sinha, S., & Nandy, D. "Deconstructing the Properties of Solar Super Active Region 13664 in the Context of the Historic Geomagnetic Storm of 2024 May 10–11." 2024.*
19. *Priest, E., & Forbes, T. Magnetic Reconnection: MHD Theory and Applications. Cambridge University Press, 2000.*
20. *Bothmer, V., & Daglis, I. A. Space Weather: Physics and Effects. Springer, 2007.*