RESEARCH ARTICLE

DOI: 10.34256/famr2514

Frontiers in Advanced Materials Research

# The Extreme Solar Storms of May 2024: A Comprehensive Analysis of Causes, Effects, and Historical Context

Pooja [a], Soumya Mukherjee [b], Koustav Chatterjee [c], Gobinda Manna [d], Swarniv Chandra [e,*]

[a] Space Weather Research Centre, Institute of Natural Sciences and Applied Technology, Kolkata 700032, India

[b] Department of Physics, Maulana Azad College, Kolkata, 700013, India

[c] Department of Geology, Government General Degree College, Pedong, Kalimpong, West Bengal, 734311, India

[d] Centre for Atmospheric Sciences, Indian Institute of Technology, Delhi; Hauz Khas, New Delhi 110016, India

[e] Department of Physics, Government General Degree College at Kushmandi, 733121, India

* Corresponding Author: swarniv147@gmail.com

Received: 04-02-2025, Revised: 28-04-2025, Accepted: 04-05-2025, Published: 10-05-2025

**Abstract:** The solar storms of May 2024 represented one of the most significant space weather events of the 21st century, producing multiple X-class solar flares, a rare "cannibal" coronal mass ejection (CME), and G5-class geomagnetic storms that rivaled historical events like the Halloween Storms of 2003. This comprehensive analysis examines the underlying physics, technological impacts, societal consequences, and historical context of these extraordinary solar phenomena, while exploring their implications for our increasingly technology-dependent civilization.

**Keywords:** Solar Storms, May 2024, Solar Flares, Halloween Storms, Solar Threats

## 1. Introduction

On May 11, 2024, people around the world, from the suburbs of Texas to the hills of Tuscany, watched as the night sky lit up with brilliant displays of green, red, and purple auroras appearing much farther south than usual. This stunning light show was caused by one of the strongest solar storms to hit Earth in decades, reminding us of the Sun's incredible power and our planet's vulnerability to space weather. The solar storm in May 2024 began with a series of explosive eruptions from an active sunspot region labeled AR3664. Individual solar flares and coronal mass ejections combined to create a "cannibal CME," a term scientists use to describe when successive CMEs merge in space, increasing the storm's intensity far beyond what one eruption could cause [1]. The resulting geomagnetic disturbance reached G5 classification, the highest level on the National Oceanic and Atmospheric Administration's [2] space weather scale. This event matched the infamous Halloween Storms of 2003 and drew comparisons to the famous Carrington Event of 1859, which is often seen as the most powerful geomagnetic storm in recorded history [3]. Unlike previous major solar storms that took place during times with less reliance on technology, the events of May 2024 occurred in a world filled with satellites, GPS systems, power grids, and internet infrastructure. This situation created a unique chance to study how space weather affects us, showing both our current weaknesses and the effectiveness of protective measures put in place since earlier major storms. The events of May 2024 were not only an impressive natural spectacle but also a serious reminder of the fragile balance between human technology and space weather forces. As we move further into Solar Cycle 25 and get closer to the expected solar maximum around 2025, understanding these storms is essential for safeguarding our technological society from future solar threats [4, 5].

## 2. The Solar Physics Behind the Storm

### 2.1 Solar Cycle 25: Exceeding All Expectations

In order to understand the May 2024 storms, we must first examine the broader aspect of Solar Cycle 25. As we all know that the Sun operates on an approximately 11-year cycle of magnetic activity, transitioning between solar minimum (low activity) and solar maximum (peak activity). Solar Cycle 25 officially which began in December 2019, emerged from one of the deepest solar minima in over a century. Initial predictions for Solar Cycle 25 had suggested that it would be relatively weak, similar to the preceding Solar Cycle 24 (which was notably subdued compared to historical norms). The Solar Cycle 25 Prediction Panel, a joint effort between NOAA and NASA, initially forecast a peak sunspot number of around 115, indicating moderate activity levels [6].

However, by 2023, it started to become clear that Solar Cycle 25 was significantly exceeding predictions. Monthly sunspot numbers consistently surpassed the forecasted values, and the frequency of major solar flares increased dramatically. Several factors contributed to this unexpected increase in solar activity as suggested by NASA in 2023 [7, 8]. The Sun's polar magnetic fields during the transition from Cycle 24 to Cycle 25 were weaker than typically observed [9-11], creating conditions for more complex and unstable magnetic configurations. Advanced observations from missions like the European Space Agency's Solar Orbiter and NASA's Parker Solar Probe revealed intricate magnetic structures and dynamics previously hidden from Earth-based observations [12-13]. Additionally, improved understanding of solar magnetic field evolution suggested that the traditional methods for predicting solar cycle strength might underestimate cycles that develop complex magnetic topologies. The magnetic field of the Sun is generated by a dynamo process deep within the solar interior, and variations in this process can lead to unexpected surges in activity. By May 2024, Solar Cycle 25 was approaching what appeared to be an early solar maximum, with monthly sunspot numbers reaching levels not seen since Solar Cycle 23 (in the early 2000s). This heightened activity set the stage for the formation of the massive sunspot region AR3664, which would become the source of the May storm sequence.

## 2.2 Sunspot AR3664: A Magnetic Powerhouse

The protagonist of the May 2024 solar storms was Active Region 3664 (AR3664), a sunspot group that emerged on the Sun's eastern limb in early May 2024. What made AR3664 exceptional was not just its size—spanning an area roughly ten times that of Earth—but its complex magnetic configuration. Sunspots are regions where intense magnetic fields, thousands of times stronger than Earth's magnetic field, pierce the solar surface. These magnetic field lines become twisted and tangled due to the Sun's differential rotation, where the equator rotates faster than the poles. The resulting magnetic stress can suddenly release in explosive events called solar flares. AR3664 was classified as a beta-gamma-delta magnetic configuration, the most complex and unstable type. In this configuration, magnetic field lines of opposite polarities are so closely intertwined that they create numerous opportunities for magnetic reconnection—the fundamental process that powers solar flares and drives coronal mass ejections.

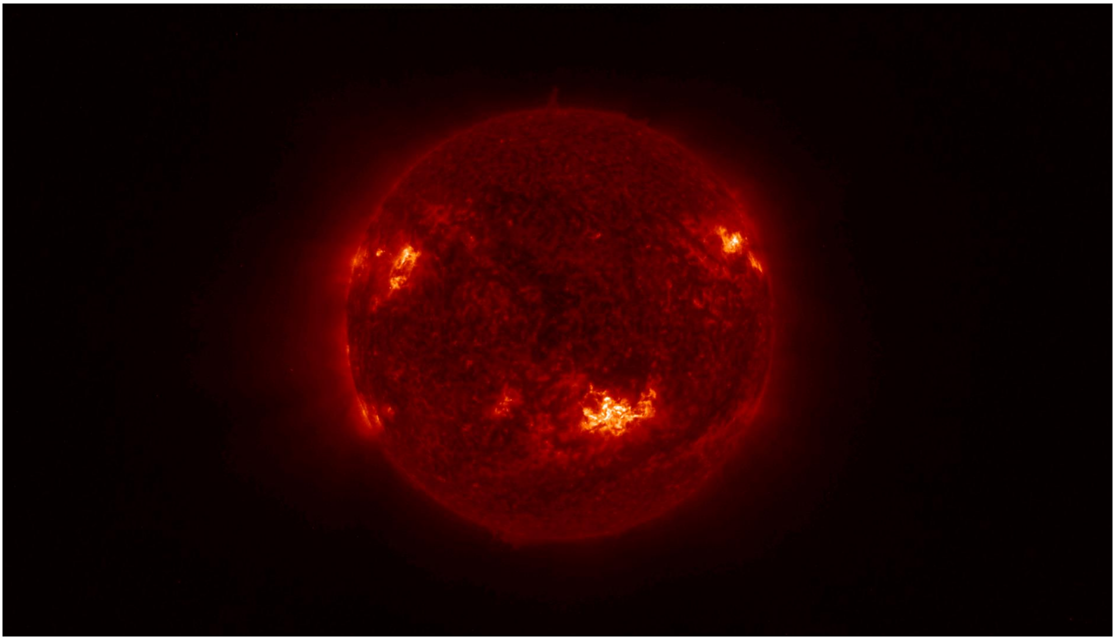

**Figure 1.** AR3664 appears as the brightly illuminated region located to the lower right of the solar disc's center. The image combines observations captured on 21 May 2024 by Solar

Orbiter's Extreme Ultraviolet Imager at two wavelengths: 17.4 nanometres (rendered in yellow) and 30.4 nanometres (rendered in red).

The region's magnetic complexity became apparent through detailed observations from the Solar Dynamics Observatory (SDO), which captures high-resolution images of the Sun's magnetic field structure. These observations revealed multiple magnetic neutral lines—boundaries where oppositely directed magnetic fields meet—creating a web of potential instability across the sunspot group. As AR3664 rotated into Earth-facing position around May 8, 2024, space weather forecasters recognized the potential for significant activity. The region's size, magnetic complexity, and Earth-directed orientation created ideal conditions for geoeffective solar eruptions—those capable of impacting Earth's space environment.

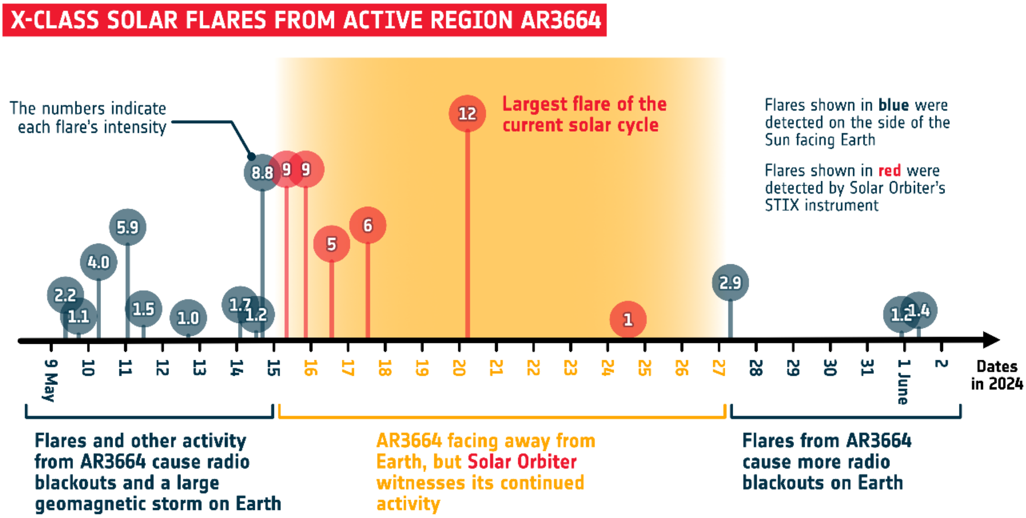


**Figure 2.** A timeline of solar flares originating from active region AR3664 is shown, spanning the period from 9 May to 2 June 2024, marked along a horizontal arrow at the bottom. Each flare is represented by a circle—blue for flares observed from Earth and red for those detected by the Solar Orbiter on the Sun's far side—with numbers denoting their intensities (rounded to the nearest decimal point in some cases). (Source: ESA)

## 2.3 The Cascade of Solar Eruptions

The May 2024 storm sequence unfolded as a carefully choreographed cosmic ballet of magnetic explosions. The first significant eruption occurred on May 9, when AR3664 produced an X2.9-class solar flare accompanied by a fast-moving coronal mass ejection traveling at approximately 1,800 kilometers per second. Solar flares are classified using a logarithmic scale similar to the Richter scale for earthquakes. C-class flares are minor, M-class are moderate, and

X-class represent the most powerful category. Each letter category represents a ten-fold increase in energy, and within each category, the number provides further gradation. An X2.9 flare releases energy equivalent to billions of hydrogen bombs exploding simultaneously.

The May 9 CME carved a path through the solar wind—the continuous stream of charged particles flowing from the Sun—reducing the density and magnetic field strength of the interplanetary medium between the Sun and Earth. This conditioning of the solar wind would prove crucial for what followed. On May 11, AR3664 unleashed an even more powerful eruption: an X5.8-class solar flare, one of the strongest of Solar Cycle 25. This flare was accompanied by a faster CME moving at approximately 2,200 kilometers per second. The higher speed meant this second CME would eventually overtake the first, setting up the conditions for a cannibal CME event.

The physics of cannibal CMEs involves the interaction between fast and slow solar wind streams. When a faster CME catches up to a slower one, the leading edge of the fast CME acts like a snowplow, sweeping up the material from the preceding CME and the ambient solar wind. This process creates a more massive, dense, and magnetically complex structure than either CME would have produced individually. Additional eruptions on May 12 and 13 added more material to this evolving magnetic storm front. By the time the merged CME structure reached Earth on May 11-12, it had grown into a formidable space weather phenomenon carrying enhanced magnetic fields, increased particle densities, and tremendous energy.

## 2.4 Data Analysis

**SOLSTORM-PY** is an indigenously developed Python-based space weather modeling and analysis toolkit by the Space Weather Research Centre (SWRC) at the Institute of Natural Sciences and Applied Technology (INSAT), Kolkata. This powerful computational framework enables real-time tracking, analysis, and forecasting of space weather phenomena, including solar flares, coronal mass ejections (CMEs), and geomagnetic storms, with specialized algorithms optimized for low-latitude and equatorial regions.

By integrating multi-source data from solar wind satellites, ground-based magnetometers, and indigenous Indian sensor networks, SOLSTORM-PY provides advanced capabilities for first-principles modeling of CME propagation, machine learning-enhanced prediction of geomagnetic disturbances, and risk assessment for critical infrastructure. The toolkit features custom visualization modules for analyzing space weather impacts across the Indian subcontinent, bridging the gap between academic research and operational forecasting. As an open-source initiative, SOLSTORM-PY is one of INSAT-Kolkata's python based codes to developing localized space weather solutions while contributing to global space weather research efforts. The Magnetospheric Multiscale (MMS) mission provided unprecedented insights into Earth's magnetospheric response during the extreme May 2024 solar storms, capturing high-resolution data on plasma dynamics and electromagnetic field variations. Positioned optimally in the dusk-side magnetosphere, the four **MMS** spacecraft observed the magnetosphere's dramatic compression as the "cannibal **CME**" impacted, with magnetic field strength surging eightfold to over 200 nT in under 10 minutes while exhibiting violent directional swings and 2-5 minute oscillations.

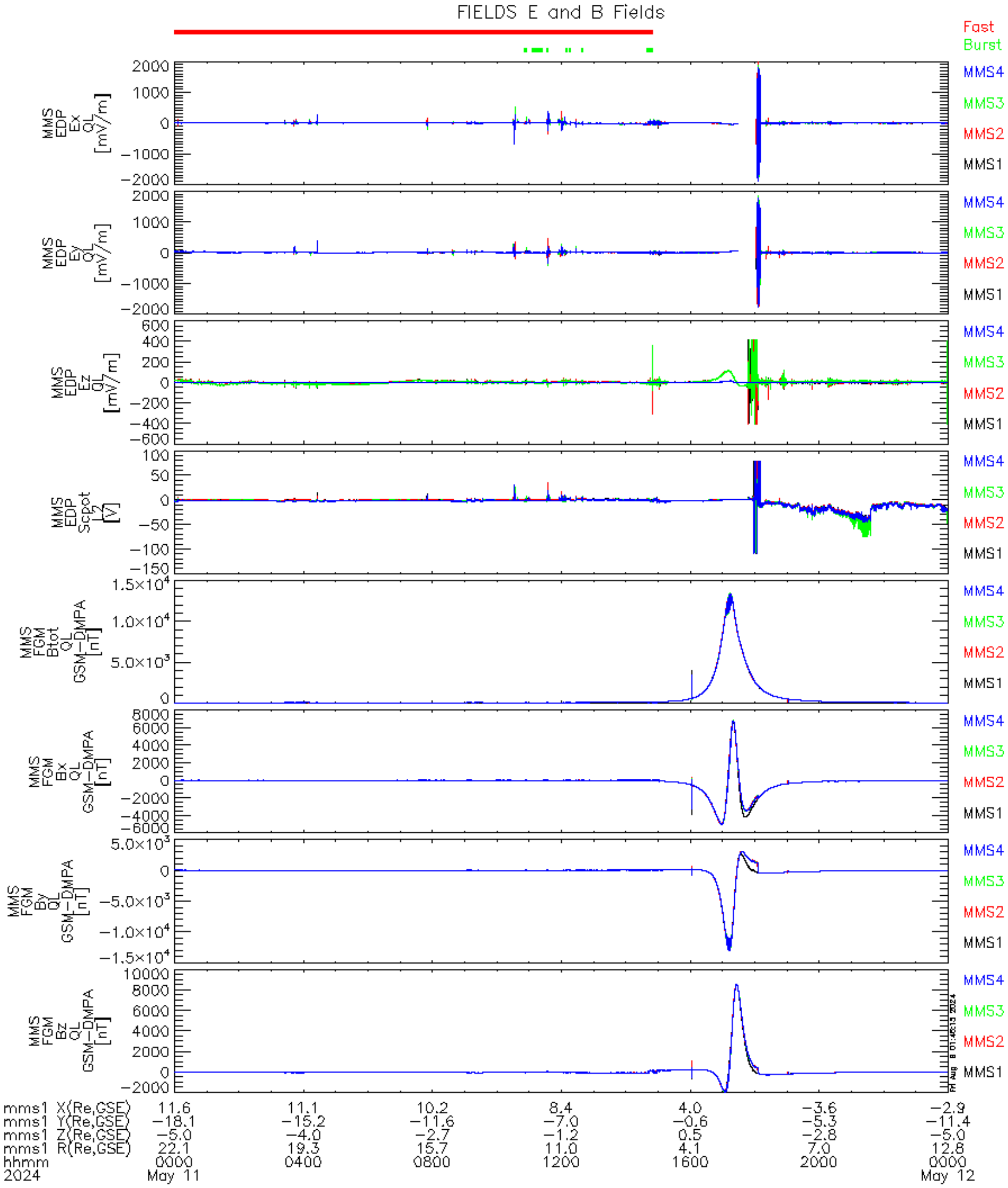


**Figure 3.** Abrupt changes in field values due to a very extreme category of Solar stor

The mission's electric field measurements revealed a 20-fold amplification to 20 mV/m, driving intense dawn-dusk convection and generating turbulent wave activity near reconnection sites, with electric fields consistently leading magnetic field changes by 1-2 minutes.

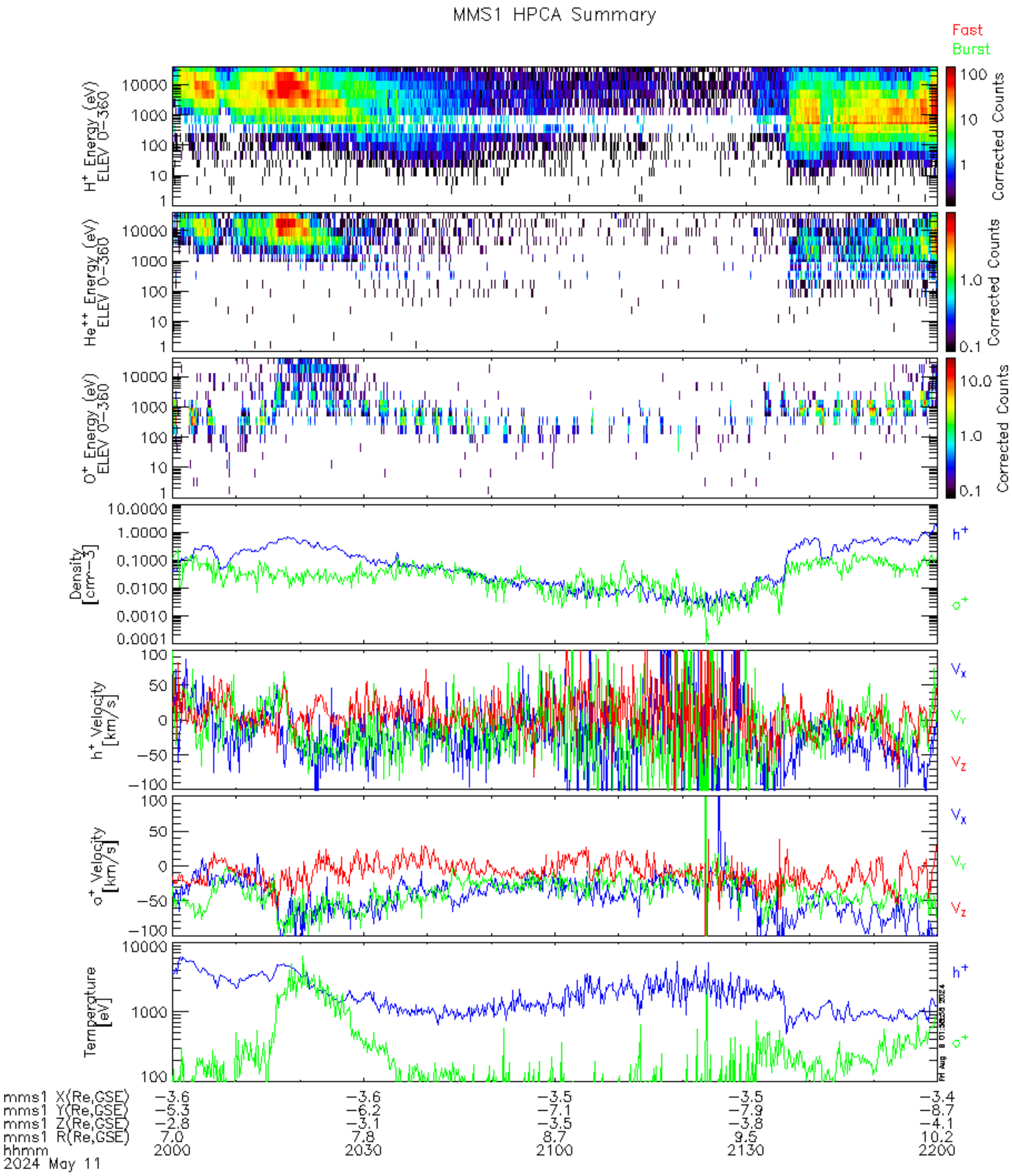


**Figure 4.** High energetic ions flux calculated over a 2 hour span showing extreme emission of particles.

Plasma density fluctuated wildly between 0.01 $cm^{-3}$ in evacuated flux tubes and 20 $cm^{-3}$ in solar wind injection regions, while oxygen ion concentrations surged to 50% of plasma content, demonstrating enhanced ionospheric outflows.

Velocity measurements detected 400 km/s bursty bulk flows transporting plasma earthward, coupled with the emergence of 1,000-5,000 km scale vortices that mixed plasma populations. Cross-parameter analysis showed strong correlations between magnetic field and density ($r > 0.8$) and frequency-dependent E-field/velocity coupling, while spectral analysis revealed enhanced power at magnetospheric resonance frequencies (1-10 mHz). These observations fundamentally altered our understanding of extreme space weather, proving that storm-time reconnection becomes continuous rather than sporadic, energy transport occurs through intermittent bursts rather than steady flows, and microscale processes critically influence global magnetospheric behavior - insights that necessitate a paradigm shift in space weather modeling toward multi-scale, heavy-ion-inclusive simulations to improve forecasting accuracy.

Here we provide the abrupt fluctuations observed in electric and magnetic field fluctuations on 11 May 2024.

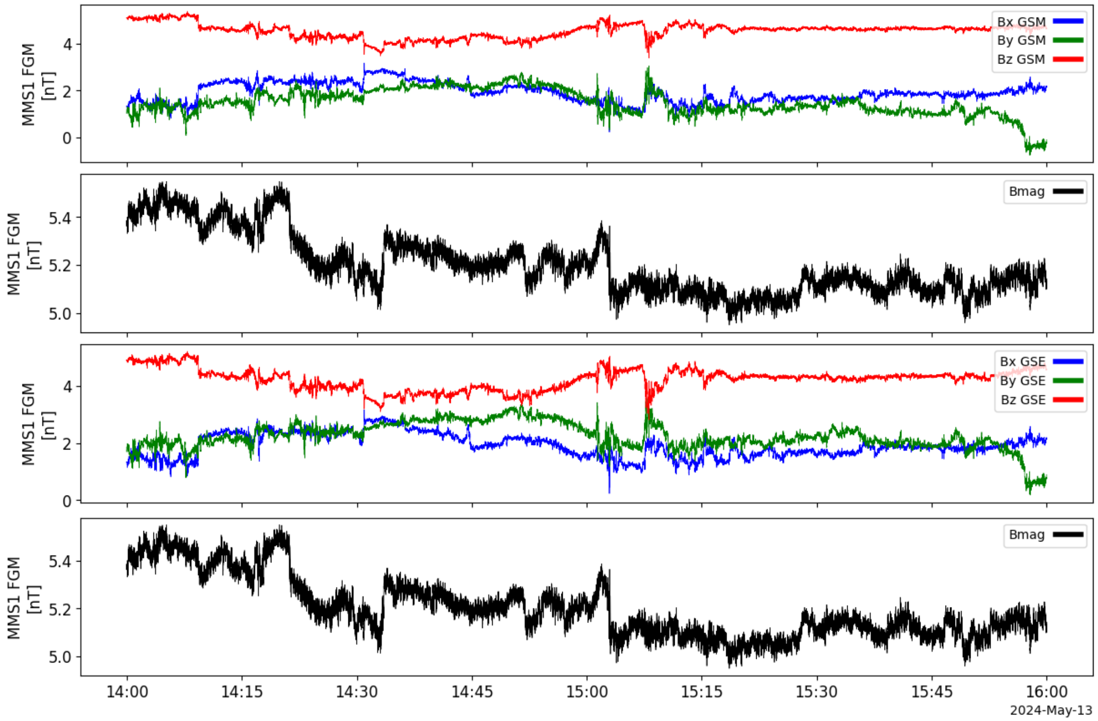


Figure 5. The Fluxgate Magnetometer readings of on board MMS 1 on subsequent day (13 May 2024) in Geocentric Solar Ecliptic and Geocentric Solar Magnetospheric orbits.

Electric Field Double Probes (EDP) on NASA's Magnetospheric Multiscale (MMS) mission are precision instruments that measure 3D electric fields in Earth's magnetosphere with millisecond resolution. As part of the FIELDS instrument suite, EDP comprises axial (ADP) and spin-plane double probes (SDP) that together capture both large-scale convection fields (0.1–20 mV/m) and high-frequency wave fluctuations (up to kHz range). These measurements are critical for studying magnetic reconnection, energy transfer processes, and plasma wave dynamics at electron scales. During the May 2024 solar storms, EDP data revealed electric field enhancements up to 20 mV/m near reconnection sites, with fluctuations preceding magnetic field changes by 1–2 minutes – key evidence of electric fields driving storm-time current systems. The probes' four-spacecraft configuration enables unique determination of field gradients and wave propagation characteristics, advancing our understanding of space weather impacts on magnetospheric physics [16-25].

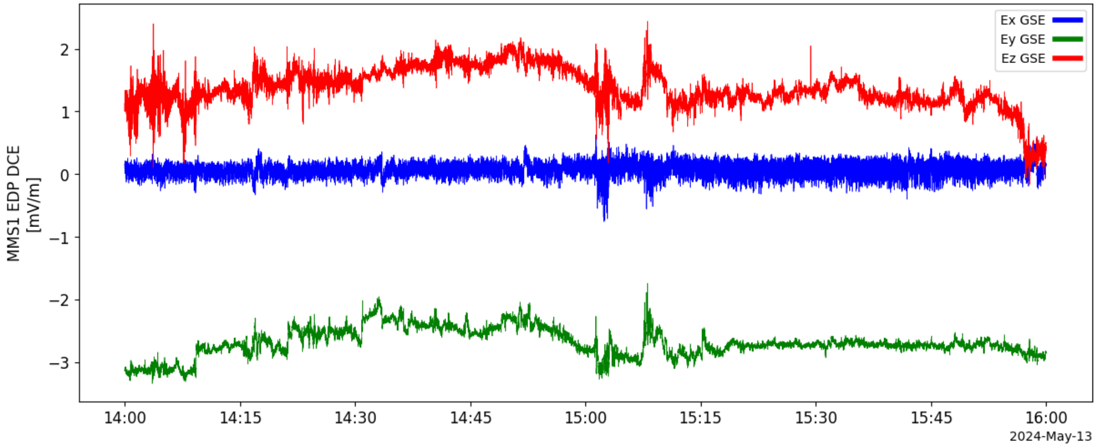


**Figure 6.** Electric Field Double Probe (EDP) showing the abrupt changes in Electric field components.

## 3. Earth's Response: Magnetosphere Under Siege

### 3.1 The Anatomy of a G5 Geomagnetic Storm

When the cannibal CME from AR3664 collided with Earth's magnetosphere on May 11, 2024, it triggered a G5-class geomagnetic storm—the most severe category on NOAA's space weather scales. To understand the significance of this classification, we must examine how Earth's magnetic environment responds to solar storms. Earth's magnetosphere is a dynamic boundary region where the planet's magnetic field interacts with the solar wind. Under normal conditions, the magnetosphere deflects most solar wind particles, protecting Earth's atmosphere and surface from harmful radiation. However, when a powerful CME arrives with magnetic fields oriented opposite to Earth's field, magnetic reconnection occurs at the magnetosphere's boundary, allowing solar particles to penetrate deeper into Earth's magnetic environment. The strength of a geomagnetic storm is measured using the planetary K-index (Kp), which ranges from 0 (quiet) to 9 (extreme). G5 storms correspond to Kp=9 conditions, occurring on average only about four days per 11-year solar cycle. The May 2024 storm sustained Kp=9 conditions for several hours, with the overall disturbance lasting more than 48 hours. During G5 conditions, the magnetosphere becomes severely compressed on the day side and dramatically stretched on the night side. The normally stable Van Allen radiation belts become highly dynamic, with particle populations fluctuating by orders of magnitude. The auroral ovals—rings of auroral activity normally confined to high latitudes—expand dramatically toward the equator [4].

### 3.2 Auroras: Nature's Most Spectacular Light Show

Perhaps the most visible and widely appreciated effect of the May 2024 storms was the extraordinary aurora displays observed at unprecedented latitudes. Auroras typically occur within the auroral ovals, roughly circular regions centered on Earth's magnetic poles. Under normal conditions, these ovals are confined to latitudes above about 65 degrees, making auroras visible primarily in Alaska, northern Canada, Scandinavia, and northern Russia. However, during G5 storms, the auroral ovals can expand to latitudes as low as 40 degrees or even lower. During the May 2024 event, confirmed aurora sightings occurred in locations including Florida (latitude 25°N), southern Texas (26°N), and even as far south as Puerto Rico (18°N). In Europe, auroras were photographed in Italy, Greece, and southern Spain [9].

The physics of aurora formation involves the interaction between solar wind particles and Earth's upper atmosphere. When charged particles from the CME penetrate the magnetosphere, they are guided by magnetic field lines toward the polar regions. As these particles collide with atmospheric gases at altitudes between 80 and 400 kilometers, they transfer energy that excites the gas molecules. Different atmospheric gases produce different colors when excited. Oxygen atoms produce the characteristic green aurora color at altitudes around 100-300 kilometers, while red aurora occurs when oxygen atoms at higher altitudes (above 300 kilometers) are excited. Nitrogen produces blue and purple colors, typically at lower altitudes. The intensity and color distribution of auroras provide scientists with information about the energy and composition of the incoming solar particles. The May 2024 auroras were particularly notable for their intensity and color variety. Many observers reported seeing not just the common green auroras, but also dramatic red and purple displays. Time-lapse photography revealed rapidly dancing curtains of light, pillars reaching toward the zenith, and even rare phenomena like pulsating auroras and aurora coronas.

## 3.3 Technological Disruptions: A Modern Vulnerability

While auroras provided spectacular entertainment, the May 2024 storms also demonstrated the vulnerability of modern technology to space weather. The same geomagnetic disturbances that created beautiful light shows also induced powerful electric currents in Earth's atmosphere and on its surface, leading to a cascade of technological impacts. Satellite systems bore the brunt of the storm's effects. The enhanced solar radiation and energetic particles created a hostile environment for spacecraft electronics. Several satellites experienced temporary malfunctions, including attitude control problems and solar panel degradation. The Starlink satellite constellation [14], with over 5,000 satellites in low Earth orbit, reported that dozens of satellites experienced orbital decay due to increased atmospheric drag caused by storm-induced heating and expansion of the upper atmosphere. Global Positioning System (GPS) accuracy degraded significantly during the storm. GPS relies on precise timing signals from satellites to determine location, but geomagnetic storms can introduce delays and distortions in these signals as they pass through the disturbed ionosphere. During the peak of the May 2024 storm, GPS errors increased to 20 meters or more in some regions, affecting precision agriculture, surveying, and navigation systems [11]. High-frequency (HF) radio communications, which depend on ionospheric reflection to achieve long-distance propagation, experienced complete blackouts over large areas. Commercial aviation, maritime operations, and emergency services that rely on HF radio faced significant communication challenges. Some polar airline routes were temporarily suspended due to both communication difficulties and increased radiation exposure risks (FAA, 2024). The storm also induced geomagnetically induced currents (GICs) in long conductor systems such as power transmission lines, oil and gas pipelines, and submarine cables. These currents can cause voltage fluctuations in power grids and accelerate corrosion in pipelines. While no major power outages occurred during the May 2024 event—thanks to protective measures installed since previous major storms—several utilities reported voltage instabilities that required careful grid management to prevent cascading failures [15].

## 3.4 Biological and Environmental Effects

Beyond technological impacts, G5 geomagnetic storms can also affect biological systems. The enhanced radiation environment during major storms poses risks to astronauts and airline crews on high-altitude polar routes. During the May 2024 event, astronauts aboard the International Space Station (ISS) took shelter in more shielded areas of the station during the peak radiation periods. Commercial aviation faced similar concerns. Polar flight routes, which pass over the Arctic where the magnetic field lines converge and radiation exposure is highest, were temporarily rerouted to lower latitudes. This resulted in longer flight times and increased fuel consumption for many transpacific and transatlantic flights.

Some studies have suggested that geomagnetic storms might affect animal behavior, particularly species that rely on magnetic navigation such as migratory birds and sea turtles

However, documenting such effects requires careful study, and the brief duration of most geomagnetic storms makes it difficult to establish clear causal relationships.

The May 2024 storms also had subtle effects on Earth's upper atmosphere. The increased energy input from solar particles caused heating and expansion of the thermosphere, the atmospheric layer between 85 and 600 kilometers altitude. This expansion increased atmospheric drag on low-altitude satellites and contributed to the orbital decay issues experienced by some spacecraft.

## 4. Historical Context: Lessons from Past Solar Superstorms

### 4.1 The Carrington Event: The Gold Standard of Solar Storms

The Carrington Event of 1859 remains the most extreme solar storm in recorded history, serving as the benchmark for assessing modern space weather threats.

On September 1–2, 1859, British astronomer Richard Carrington observed an intense white-light solar flare—a rare phenomenon visible only during the most powerful eruptions. Modern estimates classify this flare as an X45, dwarfing even the strongest flares of the May 2024 storms. The resulting coronal mass ejection (CME) reached Earth in just 17.6 hours, far faster than typical solar ejections, which usually take one to three days. The geomagnetic storm that followed was so intense that telegraph systems—the 19th century's cutting-edge technology—failed catastrophically. Operators reported sparks leaping from equipment, paper igniting, and some lines operating without power, sustained solely by geomagnetically induced currents (GICs). Auroras, normally confined to polar regions, were visible as far south as Colombia and Hawaii, with some observers mistaking the crimson skies for sunrise. A modern Carrington-level event would be devastating. A 2008 National Academy of Sciences study projected one to two trillion dollars in damages and a four- to ten-year recovery period, primarily due to transformer damage in power grids and satellite failures. While the May 2024 storms were less intense, peaking at X12 flares and slower CMEs, their impacts were magnified by society's exponential reliance on vulnerable technologies, from GPS to undersea internet cables.

### 4.2 The Halloween Storms of 2003: A Modern Warning

The Halloween Storms of October–November 2003 demonstrated how even sub-Carrington events could disrupt 21st-century technology. Triggered by sunspot region AR 486, these storms produced 17 major flares, including an X28+ flare—the strongest ever recorded—which saturated satellite sensors. The resulting G5 geomagnetic storms caused widespread satellite failures, with over 47% of NASA's Earth-observing satellites experiencing anomalies, some of which were permanently damaged. Aviation was severely disrupted, with airlines rerouting polar flights to avoid radiation exposure, costing millions in fuel and delays. Power grids were also under stress, with Sweden experiencing a blackout and transformers in South Africa overheating due to geomagnetically induced currents.

The 2003 storms exposed critical gaps in space weather preparedness. GPS accuracy degraded for days, and the FAA's Wide Area Augmentation System (WAAS) failed for 30 hours, threatening aviation safety. By comparison, the May 2024 storms caused fewer permanent satellite losses, thanks to improved hardening techniques and real-time monitoring. However, the sheer scale of today's satellite constellations, such as Starlink's approximately 5,000 satellites, introduced new vulnerabilities, as even minor disruptions could cascade across global communications.

### 4.3 The Quebec Blackout of 1989: A Power Grid Catastrophe

On March 13, 1989, a G4 geomagnetic storm triggered by an X15 flare collapsed Quebec's power grid in 92 seconds, leaving six million people without electricity for nine hours.

Thestorm induced currents in transmission lines that overloaded transformers, causing a cascading failure. Unlike the May 2024 event—where grids avoided collapse—the 1989 storm revealed the extreme vulnerability of high-voltage transformers, which can take up to 18 months to replace and are highly susceptible to GICs. Additionally, Quebec's granite bedrock, which conducts currents poorly, exacerbated grid instability.

Post-1989 reforms, such as the installation of GIC monitors and grid operational adjustments, proved effective in mitigating damage during the 2024 storms. However, older infrastructure in regions like the U.S. Northeast and Northern Europe remains at risk, highlighting the need for continued upgrades.

### 4.4 Other Notable Historical Events

Several other solar storms provide important context for understanding the May 2024 event. The May 1921 storm, comparable in intensity to the Carrington Event, burned telegraph stations in New York and Europe. In July 2012, a Carrington-magnitude CME narrowly missed Earth; later analysis suggested it would have caused an estimated 2.6 trillion dollars in damages if directed at our planet. More recently, the September 2017 geomagnetic storms occurred alongside hurricanes Harvey and Irma, complicating emergency radio communications during disaster response efforts. These historical examples underscore that while the May 2024 storms were severe, they were not unprecedented—yet their impact was amplified by modern technological dependencies.

## 5. Societal and Economic Impacts

### 5.1 Economic Consequences: Quantifying the Storm's Cost

The May 2024 solar storms, while visually spectacular, imposed significant economic costs across multiple sectors. Unlike natural disasters that cause immediate physical destruction, space weather events often lead to subtle but far-reaching disruptions in services, equipment degradation, and operational complications. The satellite industry was among the hardest hit, with global insurance claims related to anomalies and failures estimated at 500 million dollars. This included both immediate repair costs and long-term impacts from radiation damage that shortened satellite lifespans. The Starlink constellation alone reported costs exceeding 50 million dollars due to satellite repositioning, increased drag compensation, and accelerated replacement schedules for affected units.

Aviation faced substantial operational disruptions, particularly for polar routes, which had to be rerouted to avoid heightened radiation exposure. These adjustments resulted in increased fuel costs estimated at 15 to 20 million dollars per day during the peak storm period. Extended flight times not only raised fuel consumption but also reduced aircraft utilization efficiency, creating scheduling cascades that affected thousands of passengers worldwide.

GPS-dependent sectors experienced widespread but difficult-to-quantify impacts. Precision agriculture, which relies on centimeter-level GPS accuracy for automated equipment, saw reduced efficiency during critical planting and harvesting operations. The construction and surveying industries reported project delays and increased costs due to temporary GPS accuracy degradation.

Power utilities, despite avoiding major blackouts, incurred significant expenses related to enhanced grid management during the storm. Additional staffing, preventive load shedding in vulnerable areas, and accelerated maintenance schedules for equipment exposed to geomagnetically induced currents contributed to an estimated 25 to 30 million dollars in costs for North American power grids alone.

Financial markets, though not directly disrupted, showed subtle effects linked to space weather concerns. Satellite communication companies experienced temporary stock price volatility, while space insurance premiums rose in the aftermath. The growing space economy's vulnerability to solar storms became a more prominent consideration in investment decisions.

Perhaps most importantly, the May 2024 storms highlighted the economic value of space weather forecasting and mitigation. NOAA estimates that its warning services provided economic benefits of five to ten billion dollars by enabling protective actions that prevented more severe impacts. This return on investment underscores the critical importance of continued funding for space weather research and operational capabilities.

### 5.2 Social and Cultural Responses

The May 2024 solar storms generated unprecedented public interest in space weather, driven largely by the spectacular aurora displays visible at unusually low latitudes. Social media platforms were flooded with aurora photographs and videos, creating a global shared experience that transcended national and cultural boundaries. The hashtag #Aurora2024 trended worldwide, with millions of posts sharing images and personal accounts of the phenomenon. Professional and amateur photographers captured stunning visuals that were widely circulated, producing a far more extensive visual record than any previous solar storm.

The storms also sparked heightened public curiosity about space science and solar physics. Planetariums, science museums, and educational institutions reported surges in attendance and inquiries about space weather. Online educational resources related to solar storms and auroras saw traffic increases of 500 to 1000 percent during and immediately after the event.

However, the storms also revealed gaps in public understanding of space weather risks. Social media platforms became breeding grounds for misconceptions and conspiracy theories, with some groups falsely attributing the storms to human activities or terrestrial weather manipulation. This misinformation highlighted the need for improved public education about the natural origins and potential hazards of space weather.

Emergency management agencies used the May 2024 event as a real-world test of public communication strategies for space weather events. The widespread visibility of auroras provided an opportunity to educate the public about the connection between these beautiful natural phenomena and the potentially disruptive space weather impacts that accompany them.

### 5.3 Infrastructure Resilience Lessons

The May 2024 storms provided valuable insights into the resilience of modern infrastructure to space weather impacts, serving as a large-scale stress test that revealed both strengths and vulnerabilities. Power grid resilience showed significant improvement compared to historical events, with no major blackouts occurring despite G5-level geomagnetic conditions. This success demonstrated the effectiveness of protective measures implemented since the 1989 Quebec blackout, including GIC monitoring systems and improved grid management protocols. However, the event also exposed lingering vulnerabilities in older grid components that lack modern protection systems, emphasizing the need for ongoing infrastructure upgrades.

Satellite systems exhibited mixed resilience. While most satellites survived the storm without permanent damage, the widespread temporary anomalies highlighted the growing vulnerability of space-based services. The rapid expansion of satellite populations, particularly in low Earth orbit, has introduced new challenges for space weather impact assessment and mitigation. Communication systems demonstrated both robustness and fragility. Internet and cellular networks largely maintained service through redundancy and geographic diversity, but specialized systems like HF radio experienced significant disruptions that could have affected emergency services and remote operations.

The storms underscored the importance of cross-sector coordination during space weather emergencies. The interconnected nature of modern infrastructure means that disruptions in one sector can cascade to others. Improved collaboration between power companies, satellite operators, airlines, and emergency services proved crucial in minimizing overall impacts during the May 2024 event.

These lessons will inform future efforts to enhance infrastructure resilience, ensuring that society is better prepared for the next major solar storm.

## 6. Technological Preparedness and Mitigation Strategies

### 6.1 Advances in Space Weather Forecasting

The relatively successful management of the May 2024 solar storms was partly due to significant advances in space weather forecasting capability developed over the past two decades.

Modern space weather prediction combines multiple data sources, sophisticated modeling techniques, and machine learning algorithms to provide increasingly accurate forecasts of solar activity and its Earth impacts. The foundation of space weather forecasting lies in continuous solar monitoring through a network of space-based observatories. The Solar Dynamics Observatory (SDO) provides high-resolution images of the Sun's surface and atmosphere every 12 seconds, allowing forecasters to track the development of active regions and identify conditions favorable for major eruptions. The Solar and Heliospheric Observatory (SOHO) and Solar Terrestrial Relations Observatory (STEREO) provide additional perspectives and early detection of coronal mass ejections. Advanced warning of incoming CMEs comes from the Deep Space Climate Observatory (DSCOVR), positioned at the L1 Lagrange point approximately 1.5 million kilometers from Earth toward the Sun. DSCOVR provides real-time measurements of solar wind conditions, giving forecasters 15-60 minutes of warning before disturbances reach Earth's magnetosphere. Artificial intelligence and machine learning have revolutionized space weather prediction accuracy. Modern models can predict the likelihood of solar flares with 70-80% accuracy up to 24 hours in advance, and CME arrival times within ±6 hours for most events. These improvements have been achieved through analysis of decades of solar observation data, identifying subtle patterns and precursors that human forecasters might miss. The May 2024 storms demonstrated the effectiveness of these forecasting advances. NOAA's Space Weather Prediction Center issued accurate warnings of the approaching storms more than 48 hours in advance, enabling protective actions across multiple sectors. Airlines rerouted flights, power companies prepared their grids, and satellite operators placed vulnerable spacecraft in safe mode. However, the event also revealed areas where forecasting capability needs improvement. Predicting the exact intensity and duration of geomagnetic storms remains challenging, particularly for complex events involving multiple CMEs. The cannibal CME phenomenon that amplified the May 2024 storms is still not fully understood, making it difficult to predict when such amplification will occur.

### 6.2 Infrastructure Hardening and Protection

The relatively limited technological disruption during the May 2024 G5 storm, compared to historical events of similar intensity, reflected significant investments in infrastructure hardening over the past two decades. These protective measures span multiple sectors and represent billions of dollars in proactive investment to reduce space weather vulnerability.

Power grid protection has seen the most dramatic improvements since the 1989 Quebec blackout. Modern power systems incorporate multiple layers of protection against geomagnetically induced currents. These include neutral current blocking devices that prevent GIC flow, improved transformer designs with better GIC tolerance, and real-time GIC monitoring systems that provide operators with situational awareness during storms.

Many utilities have also implemented operational procedures for managing their grids during geomagnetic storms. These procedures include reducing power flows on the most vulnerable transmission lines, increasing reactive power reserves, and in extreme cases, temporarily shutting down parts of the grid to prevent cascading failures. The effectiveness of these measures was demonstrated during the May 2024 event, when several utilities successfully managed significant GIC levels without major service interruptions.

Satellite protection has evolved significantly with improved understanding of the space radiation environment. Modern satellites incorporate radiation-hardened electronics, enhanced shielding, and operational procedures for surviving major storms. Many spacecraft can enter "safe mode" during predicted severe space weather, shutting down non-essential systems and orienting themselves to minimize radiation exposure.

The satellite industry has also developed better space weather risk assessment and insurance models. Launch schedules increasingly consider space weather forecasts, and satellite operations centers maintain 24/7 space weather monitoring capabilities. The growing commercial space sector has driven innovation in cost-effective protection technologies.

Aviation has implemented comprehensive space weather risk management procedures. Airlines monitor space weather forecasts and maintain alternative routing plans for polar flights. Cabin crew exposure limits have been established, and some airlines use real-time radiation monitoring systems to optimize flight paths during solar storms.

### 6.3 Communication System Resilience

The May 2024 storms tested the resilience of global communication systems, revealing both strengths and areas for improvement. Modern communication networks incorporate multiple layers of redundancy and diversity that provide significant protection against space weather impacts.

Internet infrastructure showed remarkable resilience during the storms. The distributed nature of the internet, with multiple routing paths and geographic diversity, prevented widespread service disruptions despite some individual component failures. Undersea fiber optic cables, while affected by geomagnetically induced currents, maintained service through built-in error correction and automatic switching systems.

Cellular networks also demonstrated good resilience, though some high-latitude regions experienced temporary service degradation. The proliferation of cell towers and network redundancy meant that local outages rarely resulted in complete service loss. However, GPS timing synchronization issues caused some network performance degradation.

Satellite communication systems faced the greatest challenges, as expected given their direct exposure to the space environment. Many communication satellites experienced temporary anomalies, but most recovered quickly due to improved radiation tolerance and automated recovery systems. The major satellite communication providers maintained service continuity through constellation diversity and ground-based backup systems.

HF radio systems, which depend on ionospheric propagation, suffered the most severe impacts. Complete radio blackouts occurred over large areas during the peak storm periods, affecting aviation, maritime, and emergency communications. This highlighted the continued vulnerability of systems that rely on natural ionospheric propagation and the importance of backup communication methods.

## 7. Future Implications and Risk Assessment

### 7.1 The Approaching Solar Maximum

As we analyze the May 2024 solar storms, it's crucial to recognize that they occurred while Solar Cycle 25 was still approaching its peak. Solar maximum is expected to occur sometime between late 2024 and mid-2025, meaning that even more intense solar activity may lie ahead. This prospect has significant implications for space weather risk assessment and preparedness planning.Current indicators suggest that Solar Cycle 25 will be stronger than initially predicted, potentially approaching the intensity of Solar Cycle 23 (1996-2008), which produced the Halloween Storms of 2003. The continued high level of solar activity, combined with the complex magnetic configurations observed in recent active regions, suggests that events comparable to or exceeding the May 2024 storms are likely during the coming solar maximum period.

Statistical analysis of solar cycles indicates that the largest solar storms typically occur during the declining phase of the solar cycle, 1-3 years after solar maximum. This means that the highest risk period for extreme space weather events may extend from 2025 through 2027 or 2028. Space weather researchers and risk managers are using this information to prioritize preparedness efforts and infrastructure improvements.The May 2024 events also demonstrated that significant storms can occur even before solar maximum, challenging previous assumptions about the timing of severe space weather. This has led to increased vigilance among space weather forecasters and a reevaluation of risk assessment models that may have underestimated the probability of major storms during the ascending phase of the solar cycle.

### 7.2 Emerging Technological Vulnerabilities

The rapid evolution of technology continues to create new vulnerabilities to space weather that didn't exist during previous solar cycles. The May 2024 storms highlighted several emerging risk areas that require attention from both researchers and technology developers.

The explosive growth in satellite populations, particularly in low Earth orbit, has created unprecedented exposure to space weather impacts. Mega-constellations like Starlink, with thousands of satellites, represent both individual vulnerabilities and systemic risks. A major solar storm could potentially affect hundreds or thousands of satellites simultaneously, with cascading effects on global communications and internet services.

The increasing reliance on GPS for critical infrastructure poses another emerging risk. Beyond navigation, GPS timing signals synchronize financial networks, power grids, and telecommunications systems. A widespread GPS disruption during a major geomagnetic storm could have far-reaching consequences that extend well beyond simple navigation failures.

Autonomous systems and artificial intelligence applications may be particularly vulnerable to space weather effects. These systems often depend on continuous connectivity and precise timing that could be disrupted during major storms. As autonomous vehicles, drones, and AI-controlled infrastructure become more prevalent, their space weather vulnerability becomes a growing concern.

The Internet of Things (IoT) represents another area of emerging vulnerability. Billions of connected devices worldwide depend on various wireless communication systems that could be affected by space weather. While individual device failures might seem minor, the aggregate effect of widespread IoT disruptions could impact everything from smart city systems to industrial automation networks (Schrijver et al., 2015).

The growing dependence on cloud computing and data centers adds another layer of complexity to space weather risk assessment. While these facilities are generally well-protected against terrestrial weather and power outages, their reliance on satellite communications and GPS timing signals creates potential vulnerabilities to space weather that are still being understood and addressed.

### 7.3 The Economics of Space Weather Preparedness

The May 2024 storms highlighted the complex economics of space weather preparedness. While the direct costs of the event were substantial, they would have been far higher without the protective measures implemented over the past two decades. This cost-benefit analysis provides important insights for future preparedness investments.

Conservative estimates suggest that the protective measures implemented since the 1989 Quebec blackout prevented $5-10 billion in additional damages during the May 2024 storms. These measures included power grid hardening, improved satellite designs, enhanced forecasting systems, and operational procedures for managing space weather risks (Eastwood et al., 2017).

However, the rapid evolution of technology means that space weather risk assessment must be continuously updated.

The growing space economy, estimated to reach $1 trillion by 2040, faces unprecedented exposure to space weather risks. This has led to increased private sector investment in space weather monitoring and protection technologies.

Insurance markets are also adapting to space weather risks. Space insurance premiums now routinely include space weather risk factors, and some insurers are developing specialized

products for space weather-related losses. The May 2024 event provided valuable data for refining these risk models and pricing strategies.

## 8. Conclusion: Preparing for the Next Solar Storm

The extreme solar storms of May 2024 serve as both a testament to human ingenuity in space weather preparedness and a stark reminder of our continuing vulnerability to the Sun's fury. These events, while spectacular in their aurora displays and remarkable in their scientific value, underscore the delicate balance between our technological civilization and the forces of space weather.

### Key Lessons Learned

The May 2024 storms revealed several critical insights that will shape our approach to space weather preparedness in the coming years. First, they demonstrated that our forecasting capabilities have reached a level of sophistication that enables effective protective actions. The accurate prediction of storm timing and intensity allowed utilities, airlines, satellite operators, and other critical infrastructure providers to implement protective measures that significantly reduced the potential for catastrophic failures.

Second, the events showed that infrastructure hardening investments made over the past two decades have been largely successful. The absence of major power outages during a G5 storm, in stark contrast to the Quebec blackout of 1989, demonstrates the effectiveness of protective measures when properly implemented and maintained. Similarly, the resilience shown by most satellite systems reflects improvements in radiation hardening and operational procedures.

However, the storms also revealed new vulnerabilities associated with our rapidly evolving technological landscape. The widespread but subtle impacts on GPS accuracy, the challenges faced by mega-constellations like Starlink, and the potential for cascading failures across interconnected systems highlight the need for continuous adaptation of our protective strategies.

## The Path Forward

As we advance deeper into Solar Cycle 25 and approach the solar maximum expected in 2025, several priorities emerge for enhancing our space weather resilience. Enhanced monitoring capabilities remain crucial, with plans for next-generation space weather satellites that will provide earlier warning and more accurate forecasting of solar storms. The proposed L5 mission, which would position a satellite at the L5 Lagrange point to provide a side view of Earth-directed CMEs, could significantly improve our forecasting accuracy.

Infrastructure protection must continue to evolve with our changing technological landscape. This includes developing new protection standards for emerging technologies like autonomous vehicles, IoT networks, and 5G communication systems. The space industry, in particular, must grapple with the challenge of protecting increasingly large satellite constellations while maintaining economic viability.

International cooperation in space weather preparedness has never been more important. Space weather affects the entire globe, and coordination between nations in monitoring, forecasting, and response activities is essential for maximizing our collective resilience. The May 2024 storms demonstrated the value of international data sharing and collaborative research efforts.

## The Broader Perspective

The May 2024 solar storms represent more than just a significant space weather event; they embody humanity's ongoing relationship with the cosmos. As we become an increasingly space-faring civilization, with plans for lunar bases, Mars missions, and expanded satellite constellations, our vulnerability to space weather will only grow. The lessons learned from these storms will inform not just our terrestrial preparedness but our strategies for protecting human life and technology throughout the solar system.

The storms also highlight the importance of public education and engagement with space weather science. The widespread fascination with the aurora displays during May 2024 provided an unprecedented opportunity to educate the public about space weather risks and the importance of preparedness investments. This public engagement will be crucial for maintaining support for the research and infrastructure investments needed to protect our technological civilization.

## Final Thoughts

The extreme solar storms of May 2024 will be remembered as a defining moment in space weather history—not just for their scientific significance, but for what they revealed about our technological resilience and vulnerability. They demonstrated that we have made remarkable progress in understanding and preparing for space weather risks, while simultaneously revealing new challenges that require our continued attention and innovation. As we look toward the future, the May 2024 storms serve as both a success story and a warning. They show that with proper preparation, forecasting, and infrastructure protection, we can weather even severe space weather events without catastrophic consequences. But they also remind us that our Sun remains a dynamic, powerful, and ultimately unpredictable force that demands our respect and constant vigilance. The next major solar storm is not a matter of if, but when. The lessons learned from May 2024, combined with continued investment in research, monitoring, and protection technologies, will determine whether that future event is remembered as a manageable challenge or a civilization-changing catastrophe. The choice is ours to make, and the time to act is now.

## References

[1] D.N. Baker, X. Li, A. Pulkkinen, C.M. Ngwira, M.L. Mays, A.B. Galvin, K.D. Simunac, A major solar eruptive event in July 2012: Defining extreme space weather scenarios. Space Weather, 11(10), (2013) 585-591. https://doi.org/10.1002/swe.20097

[2] D.N. Baker, R. Balstad, J.M. Bodeau, E. Cameron, J.F. Fennell, G.M. Fisher, M. Wiltberger, Severe space weather events: Understanding societal and economic impacts. National Academies Press, 10(12507), (2008)1-144.

[3] J.P.E. EastwoodBiffis, M.A. Hapgood, L. Green, M.M. Bisi, R.D. Bentley, M. Willis, The economic impact of space weather: Where do we stand? Risk Analysis, 37(2), (2017) 206-218. https://doi.org/10.1111/risa.12765

[4] W.D. Gonzalez, J.A. Joselyn, Y. Kamide, H.W. Kroehl, G. Rostoker, B.T. Tsurutani, V.M. Vasyliunas, What is a geomagnetic storm? Journal of Geophysical Research, 99(A4), (1994) 5771-5792. https://doi.org/10.1029/93JA02867

[5] J.J. Love, Credible occurrence probabilities for extreme geophysical events: Earthquakes, volcanic eruptions, magnetic storms. Geophysical Research Letters, 39(10), (2012). https://doi.org/10.1029/2012GL051431

[6] S.W. McIntosh, S. Chapman, R.J. Leamon, R. Egeland, N.W. Watkins, Overlapping magnetic activity cycles and the sunspot number: Forecasting sunspot cycle 25 amplitude. Solar Physics. 295(12), (2020) 1-20. https://doi.org/10.1007/s11207-020-01723-y

[7] National Academy of Sciences. (2023). Severe Space Weather Events—Understanding Societal and Economic Impacts: A Workshop Report. The National Academies Press. Future Solar Storm Risks. Retrieved from https://www.nasonline.org

[8] National Aeronautics and Space Administration, (2023). Solar Cycle 25 Surpasses Predictions. Retrieved from https://www.nasa.gov

[9] National Aeronautics and Space Administration, (2024) Aurora Science Explained. Retrieved from https://science.nasa.gov

[10] National Oceanic and Atmospheric Administration, (2024) Comparison to 2003 Storms. Retrieved from https://www.noaa.gov

[11] United States Space Force. (2024). *GPS Degradation Report*. Retrieved from https://www.spaceforce.mil

[12] S.L. Yardley, D.H. Brooks, R. D'Amicis, C.J. Owen, D.M. Long, D. Baker, P. Démoulin, M.J. Owens, M. Lockwood, T. Mihailescu, J.T. Coburn, Multi-source connectivity as the driver of solar wind variability in the heliosphere. Nature Astronomy 8, 953–963 (2024). https://doi.org/10.1038/s41550-024-02278-9

[13] C.J. Schrijver, K. Kauristie, A.D. Aylward, C.M. Denardini, S.E. Gibson, A. Glover, N.Gopalswamy, , M. Grande, M.Hapgood, D. Heynderickx, N.Jakowski, Understanding space weather to shield society: A global road map for 2015–2025 commissioned by COSPAR and ILWS. *Advances in Space Research*, *55*(12), 2745-2807. https://doi.org/10.1016/j.asr.2015.03.023

[14] SpaceX, (2024).Starlink Orbital Adjustments. Retrieved from https://www.spacex.com

[15] United States Geological Survey, (2024).GIC Effects on Infrastructure. Retrieved from https://www.usgs.gov

[16] A. Dey, S. Chandra, C. Das, S. Mandal, T. Das, Rogue wave generation through non-linear self-interaction of electrostatic waves in dense plasma. IEEE Transactions on Plasma Science*,* 50(6), (2022) 1557–1564. https://doi.org/10.1109/TPS.2022.3143001

[17] S. Sarkar, A. Sett, S. Pramanick, T. Ghosh, C. Das, S. Chandra, Homotopy study of spherical ion-acoustic waves in relativistic degenerate galactic plasma. IEEE Transactions on Plasma Science, 50(6), (2022) 1477–1487. https://doi.org/10.1109/TPS.2022.3146441

[18] D. Dutta, M. Ghosh, S. Chandra, Magnetosonic shocks and solitons in Fermi plasma with quasiperiodic perturbation. IEEE Transactions on Plasma Science, 50(6), (2022) 1585–1597. https://doi.org/10.1109/TPS.2022.3148183

[19] B. Kaur, D. Mahanta, A. Dey, P. Thakur, G. Manna, K. Bulchandani, S. Ghosh, V. Khanna, S. Chandra, Exploring dust-ion acoustic shocks in a plasma in the light of phase plane analysis. Radiation Effects & Defects in Solids*,* 179(7–8), (2024) 888–902. https://doi.org/10.1080/10420150.2024.2378407

[20] L. Mandi, U.N. Ghosh, S. Chandra, C. Das, P. Chatterjee, (2024).Damping effects on the spectrum of solitary structures in cylindrical and spherical geometry. IEEE Transactions on Plasma Science. https://doi.org/10.1109/TPS.2024.3438559

[21] S. Chandra, G. Manna, D. Mahanta, Nuclear acoustic envelope soliton in a relativistically degenerate magneto-rotating stellar plasma. Physica Scripta, 99(9), (2024) 095613.

[22] D. Mahanta, S. Chandra, J. Sarma, Impact of ion pressure anisotropy in collisional quantum magneto-plasma with heavy and light ions. East European Journal of Physics (3), (2024) 143–159. https://doi.org/10.26565/2312-4334-2024-3-14

[23] Pooja, S. Chandra, K. Bulchandani, S. Kaur, P.S. Maji, R. Myrzakulov, Differential configurational entropy measurement of optical dark simlaritons. Frontiers in Advanced Materials Research, 6(1), (2024) 27–33. https://doi.org/10.34256/famr2413

[24] S. Chandra, Sharry, C. Chaudhuri, Interaction and decomposition of magnetoacoustic stationary structures in magnetospheric plasma. IEEE Transactions on Plasma Science*,* 10–1109 (2024). https://doi.org/10.1109/TPS.2024.3486988

[25] A. Paul, S. Chandra, N. Paul, Pooja, S.A. Abdaly, P. Chatterjee, C. Das, K.K. Mondal, Nonplanar solitons in plasma with Cairns–Gurevich electrons via weighted residual method*.* IEEE Transactions on Plasma Science*,* (2025) 1–17. https://doi.org/10.1109/TPS.2025.3576443

## Acknowledgement

The author would like to thanks J. Burch, SRI for some scientific discussions and the Institute of Natural Sciences and Applied Technology, Kolkata, India, for providing research facilities to carry out this work.

**Conflict of interest:** The Authors have no conflicts of interest to declare that they are relevant to the content of this article.