Journal of Physics:
Conference Series

PAPER • OPEN ACCESS

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To cite this article: T Khumlumlert *et al* 2025 *J. Phys.: Conf. Ser.* **2934** 012007

Journal of Physics: Conference Series **2934** (2025) 012007 doi:10.1088/1742-6596/2934/1/012007

An analysis of the solar flare event and space weather at the peak of solar cycle 23–25

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Abstract. The potential impact of space weather violence on Earth was forecasted following a solar flare on March 23, 2024, with an X-ray class of X1.1, which occurred on the peak of the 25th solar cycle. Although a resulting geomagnetic storm with an 8 Kp index was expected to disrupt Earth on March 24, 2024, it proved to be short-lived, resulting in no significant disturbances or reported impacts. This causes people to be interested and observe the effects of space conditions. Our study focused on analyzing solar flares and X-ray class intensity across the 23rd to 25th solar cycles, aiming to compare their distribution of solar energetic particles affecting Earth's space weather during peak solar activity. We observed the highest X-ray classes recorded as X40+, X9.96, and X6.3 for the 23rd, 24th, and 25th solar cycles, respectively. The 23rd solar cycle had five solar flares exceeding X20 and five exceeding X10, while the 24th cycle had only two flares exceeding X10, and occurred at the end of the cycle. We conducted an analysis of solar energetic particle propagation for specific events within each solar cycle, along with space weather using the diffusion transport equation. We resolved these problems using the numerical technique of the finite difference method. Our investigation showed that solar cycle 23 showed greater severity and strength compared to cycles 24 and 25.

1. Introduction

A solar flare is a sudden and intense burst of electromagnetic radiation within the solar atmosphere, associated closely with the 11-year solar cycle. These events are thought to arise from the interaction of accelerated charged particles with plasma, leading to the emission of high energy X-ray radiation. Solar flares frequently occur alongside other solar phenomena such as coronal mass ejections (CMEs) and solar particle events. Powerful solar flares, known as X-class flares, can significantly impact Earth. They can disrupt the planet's magnetic field and create issues for satellites, communication equipment, and even power grids. These flares pose risks to astronauts in orbit and can affect both the magnetosphere environment around Earth and ground-based communication systems. X-ray solar flares are monitored by various satellites like the Geostationary Operational Environmental Satellites (GOES), which play a crucial role in solar monitoring. These events, caused by twisted magnetic fields typically above sunspots, are essential in the study of space physics and space weather. Tracking the solar cycle involves monitoring the number of sunspots. At the start of the cycle, during solar minimum, the Sun exhibits minimal sunspot activity. As time progresses, solar activity and the number of sunspots increase, reaching a peak known as solar maximum in the middle of the cycle. As the cycle concludes, solar activity decreases back to solar minimum, marking the beginning of a new cycle. Throughout this cycle, significant solar eruptions like solar flares and coronal mass ejections become more frequent and intense. The current solar cycle started in 2019, and it will reach its peak around 2024 or 2025, followed by a decline in solar activity leading into the early 2030. The rate and intensity of solar activity during the solar cycle significantly impact satellite operators. Sometimes, violent solar flares occur during the solar minimum, but the solar energetic particles (SEPs) they release are weaker and have minimal impact on Earth. This research focuses to investigates solar flares and space weathers occurring during various solar cycle peaks to analyze the movement of high-energy particles reaching Earth and the intensity of their effects on Earth.

Our study aimed to analyze the occurrence of solar flares and X-ray intensities during the 23rd to 25th solar cycles. Our focus was on comparing how these events distribute solar energetic particles, which influence Earth's space weather during peak solar activity. Data were collected using instruments aboard the ACE spacecraft (Advanced Composition Explorer). We conducted a detailed analysis of solar energetic particle propagation during specific events within each solar cycle, employing the diffusion transport equation to study space weather phenomena. Our approach involved resolving these issues using the numerical method.

2. Solar cycle, solar flare and space weather

The Sun follows a repeated pattern of activities called the solar cycle or sunspot cycle, where the number of sunspots varies in a regular, approximately 11–year cycle. Solar cycle 25, which spans from 2019 to 2030, is currently underway and represents the 25th cycle since systematic recording of solar sunspot activity began in 1755. The solar cycle includes two main phases: the solar maximum, marked by peak solar activities, and the solar minimum, a phase characterized by decreased or sometimes minimal solar activities. The solar cycle revolves around the Sun's magnetic field undergoing a periodic shift where the positions of its north and south poles interchange approximately every 11 years. This process leads to heightened solar activity midway through the cycle. The solar cycle impacts solar activity on the Sun's surface, particularly sunspots, which arise from shifts in the Sun's magnetic fields. Changes in the magnetic field correlate with fluctuations in solar surface activity. During the solar cycle, there is an increase in significant solar events such as solar flares and CMEs. These events emit powerful bursts of energy and particles into space. Such activity can affect Earth, leading to phenomena such as auroras, interruptions in radio communications, and disturbances to electricity grids.

A solar flare is a powerful burst of radiation caused by the rapid release of magnetic energy associated with sunspots. These events are the largest explosions in the solar system, appearing as bright regions on the Sun that can last from minutes to hours. Solar flares emit photons across the entire electromagnetic spectrum and accelerate particles such as electrons, protons, and heavier ions. They occur when magnetic energy stored in the solar atmosphere is suddenly released, resulting in an incredibly intense burst of energy. The intensity of a solar flare varies with the solar cycle and is categorized based on its brightness in X-ray wavelengths. Solar flares erupt when accumulated magnetic energy in the solar atmosphere becomes unstable.

Space weather refers to the conditions originating from the sun that extend through the solar wind, magnetosphere, ionosphere, and thermosphere. These conditions have the potential to impact the performance and reliability of both space-based and ground-based technological systems, and they can also pose risks to human life and health. The sun serves as the primary source of space weather, occasionally undergoing turbulent eruptions that explosively propagate into the surrounding solar wind. These eruptions include sudden releases of plasma and magnetic field structures known as CMEs, as well as bursts of radiation called solar flares. These events can induce powerful currents in wires, disrupt power grids, and even lead to widespread blackouts on Earth. In addition to these effects, the sun emits energetic particles, primarily protons and electrons, along with heavier ions, which can damage satellites crucial for commercial communications, global positioning, intelligence gathering, and weather forecasting. Accurate space weather forecasts are essential because radiation from solar particles associated with significant solar flares poses hazards to astronauts, airplane passengers, and satellites lacking adequate protection. Despite these risks, not all outcomes of space weather are negative; phenomena such as aurorae are beautiful natural phenomena caused by space weather.

Solar Energetic Particles (SEPs) are high-energy particles emitted from the Sun, including protons, electrons, and heavy ions ranging in energy from tens of keV to GeV. These particles are closely associated with solar eruptions such as solar flares, filament eruptions, and CMEs. The intensity of SEPs is influenced by factors such as the speed of CMEs and their magnetic connectivity to Earth. SEPs play a critical role in space weather and traverse the interplanetary medium, largely guided by the interplanetary magnetic field (IMF). They are particularly concerning due to their potential dangers to life and technology in space. SEPs originate from two primary processes: energization at the site of a solar flare or through shock waves associated with CMEs.).

3. Methodology

In this research, we examined data on space weather and the propagation times of SEPs derived from simulations of significant solar events and X-ray class intensities spanning solar cycles 23 to 25. Our objective was to assess how these SEPs distribute and impact Earth's space weather during periods of heightened solar activity. The data utilized was gathered by instruments aboard the ACE spacecraft. Additionally, we utilized the transport equation developed by Ruffolo (1998) to simulate the movement of particles from solar flares and to compute the time profiles of particle injections from the Sun to Earth. Ruffolo's transport equation presents a challenge as it involves a complex partial differential equation (PDE) with numerous independent variables, making direct solution difficult. Nonetheless, leveraging the known boundary conditions and the nature of the PDE, the Finite-differences method provides a viable approach to obtaining solutions. In this study, we employ numerical methods to solve the equation and compute the particle flux over time, accounting for varying mean free paths that describe particle movement along irregular magnetic fields. Following the particle motion simulation results, we will analyze the trajectories of high-energy particles and compare them with spacecraft data. Utilizing the linear least squares fitting technique, we aim to determine the mean free path and evaluate injection times using the FWHM (Full Width at Half Maximum) method.

Considering the effects and changes induced by particle intensity reaching Earth, we have identified specific solar events for analysis. Specifically, we have chosen the 7 most powerful solar flares based on their X-ray class during solar cycles 23–25, comprising 2 significant events per cycle. Furthermore, for solar cycle 24, we focused on 3 notable solar flares: 2 occurring at the cycle's peak and 1 particularly strong event on September 6, 2017, during the solar cycle minimum. Hence, we will analyze the connection between space weather and solar flares at the peak of the solar cycle to forecast and salve future incidents in time. The chosen solar events along with their corresponding physical details for each solar cycle are outlined in table 1.

Table 1. Physical details of powerful solar events for solar cycle 23–25.

Solar event/ solar cycle	X-ray class	Injection time (min)	Eruption position	CME
Nov 4, 2003/23	X40	37	S17W75	yes
Dec 5, 2006/23	X12.95	27	S06E72	yes
Aug 9, 2011/24	X9.96	20	N18W68	yes
Nov 5, 2013/24	X4.93	8	S09E74	no
Sep 6, 2017/24	X13.37	17	S08E62	yes
Feb 22, 2024/25	X6.3	35	N18E26	no
Feb 9, 2024/25	X3.38	39	S35W97	yes

4. Results

This study investigated the anticipated effects of space weather disturbances on Earth following a solar flare of X1.1 class on March 23, 2024, coinciding with the peak of the 25th solar cycle. Despite forecasts suggesting a geomagnetic storm with an 8 Kp index would disrupt Earth on March 24, 2024, the event was brief and ultimately resulted in no significant disturbances or reported impacts. This work focused on analyzing solar flares and the intensity of X-ray classes across the 23rd to 25th solar cycles, aiming to compare their distribution of solar energetic particles impacting Earth's space weather during periods of peak solar activity. The highest X-ray classes observed were X40+ for the 23rd solar cycle, X9.96 for the 24th solar cycle, and X8.79 for the 25th solar cycle. During the 23rd solar cycle, there were five solar flares exceeding X20 and five exceeding X10. In contrast, the 24th solar cycle obtained only two flares exceeding X10, occurring towards the cycle's end. The most recent solar flare in the 25th solar cycle, on May 14, 2024, reached an X-ray class of X8.79.

Table 2. The simulation results of the release of helium particles from the Sun to Earth during the solar event at the beginning of the 25th solar cycle.

Solar event/ solar cycle	Mean free path (AU)	Injection duration (min)	Solar event details
Nov 4, 2003/23	0.4-1.5	48-1,346	The largest flare observed to date originates from a region located on the Sun's limb, as viewed from Earth, positioned to the right and pointing away from us.
Dec 5, 2006/23	0.37-1.32	409-977	Despite occurring on the eastern side of the Sun, a shock wave was produced, resulting in an impact on Earth, despite the event occurring towards the end of the solar cycle.
Aug 9, 2011/24	0.31-0.68	42-47	The solar event of interest had minimal impact from the space environment. Therefore, during the peak of the solar cycle, the injection time of particles from the Sun to Earth was similar to the injection time observed at the Sun itself.
Nov 5, 2013/24	0.7-1.3	103-624	In a single day, the Sun produced three significant flares. According to NASA, an X2 flare is twice as intense as an X1 flare, and an X3 flare is three times as intense. However, no geomagnetic disturbance is anticipated from these events.
Sep 6, 2017/24	0.48-1.53	113-359	The kp-index for this flare is 4, indicating it did not affect global systems. In contrast, another solar event from the same sunspot region caused the kp-index to rise to 8 on September 7 to 8, 2017. This event resulted in auroras visible in several countries, including the United States, France, Kazakhstan, and Australia, and affected satellites, GPS systems, and power grids.
Feb 22, 2024/25	0.37-1.32	1280-2135	Solar flares themselves do not directly affect infrastructure on the ground.
Feb 9, 2024/25	0.17-1.31	1151-1644	Shortwave radio blackouts were observed across South America, the Southern Atlantic, and Africa.

Table 2 displays the computed injection function of particles traveling from the Sun to the Earth (minutes), determined using the fitting method. It includes data from spacecraft observations, simulation results of particle propagation considering the optimal mean free path (AU), a compare on between spacecraft data and simulation results from the fitting process, and the injection function of helium ranging from 4.03 to 34.77 MeV/n. The impacts of these chosen solar events and space weather on Earth were acquired and are also detailed in table 2.

5. Conclusion

This research examined space weather during the peak of the 23rd to 25th solar cycles, focusing on physical phenomena such as solar surface outbursts. It analyzed the movement of high-energy particles using distribution data acquired from the ACE spacecraft. Particles that travel along magnetic field lines with a longer mean free path experience shorter injection times. This occurs because these particles encounter less scattering (lower diffusion), enabling them to reach Earth more quickly. Conversely, particles with a shorter mean free path, influenced by magnetic field line distortions from solar wind effects, undergo greater scattering (higher diffusion) and thus require more time to reach Earth.

The solar flare with a higher X-ray intensity (X40) traveled from the Sun to Earth more rapidly compared to the solar flare with lower X-ray intensity. Solar flares occurring on August 9, 2011, November 4, 2003, and February 9, 2024 had injection times from the Sun to Earth closely matching the X-ray emission's injection time on the Sun. This synchronization occurred because these solar events originated from explosion positions situated on the western side of the Sun. Since the solar flare erupted from N18E26 on the east side, the plasma cloud was pointed away from Earth, and there was no impact on the Earth. The severity of space weather affecting the intensity of solar flares reaching Earth includes factors such as the solar flare's position on the Sun, detected X-ray intensity, and coronal mass ejections (CMEs). An analysis of solar flare severity, classified by X-ray class, indicates that solar cycle 23 exhibited greater intensity and strength compared to cycles 24 and 25.

Acknowledgments
The authors would like to extend our heartfelt gratitude to Prof. Dr. David Ruffolo of Mahidol University, Bangkok, Thailand, for providing the transport equation and simulation program. Additionally, we express our deep appreciation to Falculty of Science, Naresuan University for funding this research endeavour.

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