Short Communication

Need to recognize the vagaries of space weather

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Introduction

There is a Maasai community in southern Kenya and northern Tanzania. One of the famous tales of this community is that the Sun and Moon are husband and wife. Unfortunately, Sun is a wife beater and engages in domestic violence. He has scratched the face of Moon and plucked out one of her eyes. So, we see the spots owing to the beating done by the Sun. Interestingly, Moon is no less, a very short-tempered woman, she responded vehemently and wounded the Sun's forehead. Owing to the embracement the Sun drifted from the Moon. Sun wanted to hide his defaced face hence decided that he is going to shine so hard that people will not be able to even look at him.[1] Now this angry behaviour of the Sun is at times causing solar storms, solar wind, and other phenomena. The mood of the Sun is known to be changing after every eleven years and we can call that as a Sunspot cycle.

Now since the Sun is misbehaving since then and there are problems with our satellites. The recent example is during Feb 2022, 49 Starlink satellites were launched and very next-day, a geomagnetic storm increased the density of the atmosphere, unexpectedly increasing the drag force on the satellites and owing this 40 would 49 satellites became unusable.[2] During May 2024 there was much impact for satellite systems owing to the biggest geomagnetic storm due to solar activity in two decades. The earlier such storm was witnessed during 2003. May 2024, Starlink, the satellite arm of Elon Musk's SpaceX, warned on Saturday of a "degraded service" as the Earth is battered by the biggest geomagnetic storm due to solar activity in two decades. Elon Musk said in a post on X that Starlink satellites were under a lot of pressure due to the geomagnetic storm, but were holding up so far.

Aspects of space weather

Space weather is an issue for conducting various space missions. It is important to mention that there is a difference between the space weather and the way we perceive our terrestrial weather and its effects. Space weather can even impact the weather systems on Earth too. In the vacuum of space, there is no water or air, and thus there is also no precipitation. The commonly used terminologies like solar wind should not be confused with the concepts of the terrestrial weather. Here wind is not related to any presence of air, but it is a stream of energy and plasma, or charged particles, from the Sun. Mostly, the 'storms' involving the space weather are invisible, but still impact Earth.

The term space weather likely first appeared in the scientific literature in 1968. By that time, the scientific community had begun to realize that certain activities occurring in space could have an impact on the instruments used on Earth. They tried to understand some events in the past by corelating them with now what was being discussed as a space weather. It was realised that, the concept of space-related phenomena affecting Earth goes back much further. In 1806, the explorer and naturalist Alexander von Humboldt (1769–1859) described the erratic behaviour of his compass during an auroral event. Humboldt coined the term magnetic storm to refer to a global magnetic disturbance. He produced five volumes of Kosmos, an encyclopaedic account that covered a wide range of scientific fields.[3] While he did not use the term space weather specifically, his work extensively discussed phenomena related to the Sun, sunspots, geomagnetism, and auroras, all of which align with what we now consider part of space weather.

A cluster of oddly large sunspots appeared on the Sun's surface, concluding in what is widely regarded as the largest geomagnetic storm in recorded history on September 2, 1859. This event, known as the "Carrington Storm," was marked by bright and vibrant auroral displays visible across much of the globe. During the storm, many anomalies were documented, mainly related to telegraph communications. These included large voltages at the ends of telegraph wires, which led to fires and the burning of the lines. These disturbances were attributed to the effects of auroral electricity flows. Moreover, carbon-14 isotope data from tree rings suggest that a similar event occurred in 774 BC, with similar-sized storms occurring every few millennia.[4]

The Sun gives off electromagnetic energy in many wavelengths, including visible light, radio waves, ultraviolet, high-energy X-rays, and more. The Sun also emits a stream of radiation in the form of charged particles (plasma) that make up the solar wind. Occasional energy bursts resulting from huge explosions on the Sun send plasma and radiation hurtling through our solar system, sometimes in the direction of Earth. Solar flares, coronal mass ejections (CMEs), and solar prominence events are examples of solar phenomena that can release these energy bursts toward Earth and create space weather storms. So, there are geomagnetic storms which are caused by coronal

[1]The Maasai Legend of the Sun and the Moon — Google Arts & Culture, accessed on Dec 12, 2024

[2]Dozens of Starlink satellites from latest launch to reenter after geomagnetic storm - SpaceNews, accessed on Dec 24, 2024

[3]Aurora represents the glow or light produced when electrons from space flow down Earth's magnetic field and collide with atoms and molecules of the upper atmosphere and Magnetic Storms and Kristian Schlegel, "Space Weather and Alexander von Humboldt's Kosmos", Jan 05, 2006, https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2005SW000166, accessed on Dec 30, 2024

[4] "What is space weather and how does it affect us down on Earth?", January 13, 2023, What is space weather and how does it affect us down on Earth? | Zurich Insurance, accessed on Jan 05, 2025

mass ejections (CMEs), there are Solar flares which are there because of huge explosions on the sun that release high energy particles and radiation. There is Atmospheric drag because of such storms that can cause a gradual reduction in the altitude of satellites LEO. Also, there is major interference in radio signals. There could be damage to long-distance transmission lines. At times, Radiation exposure can affect aircraft passengers and crew to radiation, particularly on polar routes.[5]

Space weather is the result of activity on the Sun's surface, which can impact both Earth and the rest of the solar system. Notwithstanding the vast distance about 150 million km between the Sun and Earth, space weather can still cause significant impacts on satellites and mainly communications systems on the Earth. Massive damage satellites could happen and even there is a possibility of electrical blackouts on Earth. This space weather can reach Earth since the Sun constantly emits gas and particles (solar wind), from its hot outer atmosphere called the corona. These charged particles travel toward Earth at great (millions of km/h) speeds. The solar wind carries these particles through space, and on reaching Earth, they interact with the Earth's magnetic field and atmosphere. Luckily, Earth is protected since magnetosphere shields it from any harmful solar and cosmic particle radiation. But, at time some particles slip through and collide with the atmosphere. The visual manifestation of this impact becomes visible via the stunning light displays known as auroras.[6] Such weather phenomenon is generally harmless but impact the electronics of various space based and Earth based instruments put in use by the humans during solar storms. These storms, caused by intense magnetic activity on the Sun, can send powerful solar winds and radiation toward Earth. Solar flares and CMEs can damage satellites, disrupt power grids, and pose risks to astronauts in space and even to airliners.

One the most important events, which needs greater understating from the point of view of securing artificial satellite systems is CMEs. They are massive expulsions of plasma and magnetic fields from the Sun's corona. Unlike solar flares, which travel at the speed of light and reach Earth in about 8 minutes, CMEs move slower and can take around 15 to 18 hours, some slower CMEs can even take several days. CMEs can disrupt power grids, telecommunication networks, satellites, and pose radiation risks to astronauts. Coronal mass ejections (CMEs) form when the Sun's magnetic field twists and realigns, a process known as magnetic reconnection, according to National Oceanic and Atmospheric Administration (NOAA). This tangling of magnetic field lines creates CMEs which are strong, localized magnetic fields that can break through the Sun's surface in active regions.

CMEs typically occur around sunspot groups and are often accompanied by solar flares, CMEs, like solar flares, are most common during the Sun's solar maximum, a period of heightened activity in its 11-year cycle. If a CME is large and fast enough, it can generate a shock wave that accelerates charged particles, further disrupting space weather and intensifying geomagnetic storms. Large CMEs can cause significant technological disruptions, particularly for the 21st century world. Occasionally, CMEs are known to impact the global navigational systems like the GPS. This constellation is especially vulnerable to ionospheric disturbances, which can cause GPS coordinates to drift by tens of feet. Since GPS signals pass through the ionosphere, there charged plasma bends the signal's path. Mostly GPS systems can usually adjust for this, but severe CME disruptions can overwhelm the system, leading to inaccurate position calculations.[7]

Most extreme solar storms are very rare. Solar storms of different types are caused by disturbances on the Sun, most often from CMEs and solar flares from active regions. Rarely may they originate from coronal holes. Earth has long experienced solar storms, with some being powerful enough to trigger stunning auroras far beyond their usual polar range. Scientists have tried to decode the past in regards to the solar storms that occurred before the advent of modern technology. They have found means to know if a storm of unprecedented magnitude hit thousands of years ago. Various ancient trees have told them the secrets of the storm in the past centuries. A team from the University of Arizona, has been analysing tree rings to uncover evidence of rare solar storms called Miyake Events. These events are so rare that only six have been detected in the past 14,500 years, the most recent occurring between 664 and 663 BCE. Researchers caution that if such an event happened today, it would have catastrophic effects on communication technologies.

Miyake events,[8] first identified in 2012 by Japanese physicist Fusa Miyake, are marked by sharp increases in carbon-14 levels in tree rings. Carbon-14, a radioactive isotope formed when cosmic radiation interacts with nitrogen in the atmosphere, is absorbed by trees during photosynthesis. This increase in carbon-14 serves as a signature for these extreme solar storms, providing valuable insights into past space weather.

Space weather hazards

Following[9] are some recognized significant space weather related problems which could impact the space operations

a) Geomagnetic storms driven by CMEs are a major concern for various space operations. These storms can impact the electrical power grid, with the potential damage depending on the storm's strength and timing. Such storms are known to affect the grid significantly.

b) Geomagnetic storms, solar flares, and solar radiation storms can disrupt high-frequency radio communication (3-30 MHz), affecting a wide range of people and businesses, including airlines, disaster response agencies, and amateur radio operators.

c) Solar activity can cause disturbances in satellite navigation services, impacting aviation, road transport, shipping, and any other activities that rely on precise positioning. It also affects military targeting systems.

d) Space weather can harm satellites in orbit by degrading their communications, performance, and overall reliability. For instance, solar activity can impact the functioning of solar panels that convert sunlight into electrical power on most spacecraft, reducing power generation and thus affecting satellite performance.

[5]What Is Space Weather and How Does It Affect the Earth? | Center for Science Education, accessed on Dec 27, 2024

[6]What Is Space Weather? | NASA Space Place – NASA Science for Kids, accessed on March 23, 2025

[7]Coronal mass ejections: What are they and how do they form? | Space, accessed on March 21, 2025

[8] 'Cataclysmic' solar storm hit Earth around 2,687 years ago, ancient tree rings reveal | Space, accessed on March 22, 2025

[9]"Space weather forecasting and impacts: what you need to know", a conversation with NOAA space scientist Rob Steenburgh, Apr 7, 2023, Space weather forecasting and impacts: what you need to know and 'What is space weather? - Met Office, accessed on Feb 28, 2025

e) Radiation storms and ionospheric disturbances can interfere with space systems' ability to operate and communicate. Additionally, orbital drag caused by space weather can shorten the lifespan of satellites in Low Earth Orbit (LEO) and, in some cases, render them inoperable.

f) Astronauts in space are also at-risk during space radiation events, which can have serious health implications.

g) Space weather can damage and disrupt ground infrastructure, including power distribution networks, pipelines (by increasing corrosion), and radio communications.

h) Sunspots—dark areas on the Sun's surface—contain strong, shifting magnetic fields. These spots can be as large as Earth. They form and dissipate over days or weeks, with an 11-year sunspot cycle. Sunspot activity is also known to influence weather patterns on Earth.

Observing weather activity in space

Observing weather activity in space comprises mainly monitoring the Sun's activity. This includes watching solar flares, CMEs and observing sun spot related activities. The atmosphere is composed of layers based on temperature and any activity over the solar surface impacts these layers hence there is a need to observe the physical and phenomenological state of the natural space environment including magnetosphere, ionosphere, and thermosphere, and their interactions with Earth. Space agencies across the world are trying to study the space weather and for that purpose some of them have invested in both hardware and software for the purposes of studying the Sun. Some important ongoing projects in this regard are explained below:

The Solar and Heliospheric Observatory (SOHO, 1995) is a collaborative project between ESA (European Space Agency) and the US space agency NASA meant for studying the Sun. Its mission spans the Sun's interior, outer corona, and the solar wind. Together with ESA's Cluster mission, SOHO delivers valuable understandings into the Sun-Earth interaction from multiple perspectives. The observatory's accessible, stunning data and advanced scientific results have enchanted the understanding of both the space science community and the general public. SOHO was designed to address three fundamental scientific questions about the Sun: the structure and dynamics of the solar interior, knowledge about the solar corona and how is it heated to temperatures of around 1,000,000°C and origin and activities of solar wind.

Till date, SOHO has provided wealth of information about the Sun, including its interior, dynamic atmosphere, and solar wind. This data has increased the human knowledge about the Sun, manifold leading to some significant discoveries. This has led to scientists undertaking the most detailed measurements of the Sun's temperature structure, its internal rotation, and gas flows. They have succeed in the identification of the source regions and acceleration mechanisms for the fast solar wind, located in the magnetically "open" regions at the Sun's poles. Also, there is a discovery of new dynamic solar phenomena, including coronal waves and solar tornadoes.[10]

Following[11] is the list of important solar missions launched during the first two decades of the 21st century

Mission Name	Launch Year
STEREO	2006
Hinode (Solar-B)	2006
SDO	2010
IRIS	2013
Solar Orbiter	2020
Parker Solar Probe	2018

There are few important missions which have happened in recent past and they are discussed below:

The Indian Space Research Organisation (ISRO) has launched a satellite called Aditya-L1 on September 2, 2023. In Sanskrit language which is an old Indian language Aditya means Sun. Subsequently, after undertaking four orbit raising manoeuvres on January 6, 2024 this satellite has successfully completed halo-orbit insertion. Now, Aditya-L1 is operating from its final destination, the Lagrangian point 1 (L1) of the Sun-Earth system, around 1.5 million km from the Earth. This spacecraft will operate for around five years, with an uninterrupted view of the Sun.

This spacecraft has seven scientific payloads, which have been developed by various ISRO centers and scientific institutes. Out of seven, three sensors are for in-situ measurements of the solar wind and magnetic field and for plasma analysis. The remaining four sensors include soft and hard X-ray spectrometers, solar ultraviolet imaging, sensors used for spectropolarimetry and spectroscopy, and for assessment of the characteristics of the Sun's corona. Broadly, this spacecraft will investigate the dynamics of the Sun's outer layers. The idea is to understand the chromospheric and coronal dynamics of the Sun.[12]

On December 5, 2024, ISRO has launched spacecraft called Proba-3 into a highly elliptical orbit for the European Space Agency (ESA). The Proba-3 satellite is actually a set of two spacecraft operating as a single unit. The design of this system is such that it blocks the Sun's glare, enabling continuous observation of the corona. This mission is meant for knowing more about solar dynamics. It is expected to increase knowledge about the forces driving CMEs and the solar wind. This mission is also about demonstrating precise formation flying by the satellites. These crafts are known as the Coronagraph Spacecraft (CSC) and the Occulter Spacecraft (OSC). They were launched in a stacked configuration.

There was about four-month commissioning period for this system. The system became operational after the two satellites separated on January 14, 2025, and began their formation flying manoeuvres, with the operational phase including corona observations starting in early 2025. Proba-3 consists of an occulter and a telescope (coronagraph), with each unit being a separate spacecraft. An occulter spacecraft weighs 240 kilograms, and a coronagraph spacecraft is about 310 kg in weight. These spacecraft are positioned 150 meters apart. This formation ensures that the occulter blocks the intense rays from the Sun, while the telescope can study the Sun's edges more clearly. ASPIICS (Advanced Solar Plane Instrument for Imaging and Coronagraphic Studies), an instrument on-board Proba-3, has been developed by various European groups, mainly the teams of scientists from Spain, Switzerland, Poland, Italy, and Belgium. It helps to study the Sun's corona in unprecedented detail. The technique employed over here is a dual-disc system for effectively offsetting stray light.

[10]https://soho.nascom.nasa.gov/about/about.html, accessed on March 24, 2025
[11]https://www.jagranjosh.com/general-knowledge/how-many-solar-missions-have-been-launched-since-2000-1693569595-1, accessed on March 24, 2025
[12]https://www.thespacereview.com/article/4720/1, accessed on March 20, 2025

This system comprises a primary 1.4-metre occulting disc, made from carbon fibre-reinforced plastic. The private sector is involved in making these sensors, mainly Airbus in Spain. This disc works in tandem with a smaller central disc to block diffracted light waves and thus allows sharper observations of the Sun's corona.[13]

The observations collected by all these space based systems are used for forecasting the space weather. Actually, issuing such forecasts is a very challenging. Over the years, significant progress has been made in this field. Presently, the Space Weather Prediction Center (SWPC) of NOAA issues regular space weather forecasts 24/7, year-round. The NASA Advanced Composition Explorer (ACE) satellite helps the SWPC provide early warnings of geomagnetic storms. NASA's Solar Terrestrial Relations Observatory (STEREO) mission tracks solar wind, magnetic fields, and energetic particles. NASA's SOHO monitors Coronal Mass Ejections (CMEs), while other satellites like the Solar Dynamics Observatory (SDO) and NOAA's Geostationary Operational Environmental Satellite (GOES) R-series detect solar storms and solar wind changes. ACE, positioned at Lagrange point 1, analyses solar, interplanetary, and galactic particles, helping us understand the Sun, its interaction with Earth, and the solar system's evolution.[14]

[13] Proba-3: Why studying Sun, space weather have become imminent – Firstpost, accessed on March 23, 2025

[14] NOAA / NWS Space Weather Prediction Center and few other websites, accessed on Dec 12, 2024

Conclusion

For centuries, space weather has been known as a low-probability, high-impact phenomenon. There have been incidences where space weather has negatively affected the operations of space-based systems and, occasionally, even systems on the ground. The space community has long been aware of the challenges posed by space weather, leading to targeted investments by major space agencies to better understand it. Space weather forecasting has been ongoing for several decades, but with the rapid increase in human activities in space (leapfrogging in satellite launching) in recent years, the need to better understand the behaviour of the Sun has become more crucial.

Space weather has now become a critical component of global space situational awareness (SSA) frameworks. However, much more needs to be done in this field, and there is a need for a unified global structure for monitoring and analysing space weather. Continuous international collaboration is essential for improving forecast accuracy and mitigating the risks associated with space weather. Both the public and private space sectors must collaborate to develop the necessary infrastructure for space weather monitoring. Moving forward, better preparedness and a deeper understanding of space weather will be crucial in safeguarding critical infrastructure both on ground and in space.