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EDITORIAL

Solar Storms and the Geomagnetic Field

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What is a Solar Storm?

Solar Storms have been in the news recently. So what are they and how do they affect us?

Solar storms occur due to changes in the Sun. This 1.4 million km diameter gaseous ball of plasma is an average sized, middle aged star among billions of stars in the Milky Way galaxy, in its yellow dwarf stage. It is powered by nuclear fusion reactions converting hydrogen to helium in its core where temperature is about 15 million degree Celsius; when all the hydrogen is consumed after several billion years the Sun will, over the next few billion years go through the phases of star death. This star is the centre of our Solar System and represents more than 99% of the mass (*https://coolcosmos.ipac.caltech.edu/ask/15-Will-the-Sun-ever-stop-shining-*; *https://www.planetary.org/worlds/the-sun*).

The Sun rotates on its axis in the counter clockwise direction once every 27 Earth days. In reality, the star experiences complex differential rotation: the poles rotate slowly, once in every 35 Earth days, compared to the equatorial regions. Further, the core inside rotates much faster than the outer surface. The resultant motion produces 'tangles' in the magnetic field lines of the Sun, which can generate very strong localized magnetic fields manifested as *sunspots* on its surface, of the size of the Earth Solar and Heliospheric Observatory page, (*https://www.nasa.gov/science-research/heliophysics/esa-nasas-soho-reveals-rapidly-rotating-solar-core/*). These cause the magnetic pressure in the region to increase, which inhibits the flow of hot, new gas from the Sun's interior to the surface and lowers the temperature relative to its surroundings. Hence sunspots appear relatively dark because they may be 4000^{o} C cooler than their surroundings. The solar magnetic system drives an approximately 11-year activity cycle on the sun, during which the number of sunspots increase and decrease. We are now entering the peak or maximum phase of the 25th solar cycle.

Reports of sunspots are recorded in early literature from China and Greece; a resurgence of interest by natural philosophers like Christoph Scheiner, Galelio Galilei and Benedetto Castelli is known since early seventeenth century after the invention of the telescope. Systematic daily observations of sunspots began in 1749 at the Zurich Observatory, Switzerland. Sunspots host extremely large explosions or solar storms, usually at the dividing line between areas of oppositely directed magnetic fields within it. Bursts of plasma are injected out from the Sun in the form of a *solar flare* or a *coronal mass ejection* (CME). A solar flare is a brilliant flash of light emitting x-rays and magnetic fields, whereas a CME is an immense cloud of magnetized particles hurled into space. They emanate outward across the heliosphere, affecting the entire Solar System, including Earth and its geomagnetic field. With every eruption, the Sun's magnetic field smooths out slightly until progressively it reaches its simplest state, when solar explosions are least frequent (SpaceWeather.com; Liu et al., 2021 and references therein). This stage is known as the solar minimum. Over the next months and years, the Sun's magnetic field grows more complicated until it peaks at solar maximum, some 11 years after the previous solar maximum (Fig.1). The Aditya L1 mission, launched in September 2023, has the objectives to study the dynamics of the Sun's chromosphere and corona in more detail.

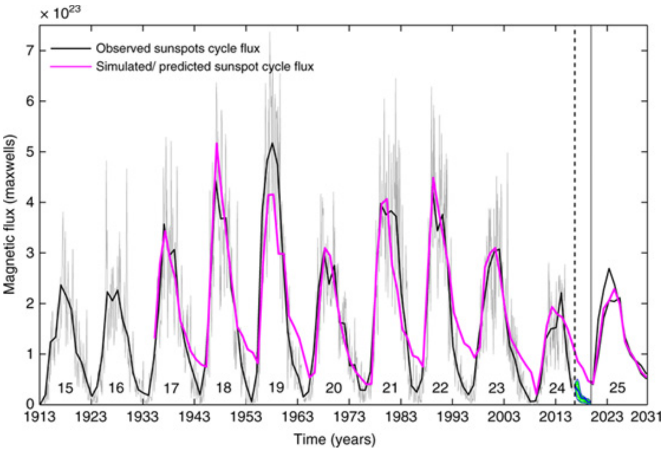

Fig. 1. Variations of sunspot cycle flux over the last century. Solar dynamo simulated sunspot cycles (magenta curve) compared with the observed sunspot cycle (unsigned magnetic flux; black curve), where both quantities are yearly averaged. The light grey curve in the background represents monthly averaged unsigned sunspot flux. (Bhowmik and Nandy, 2018)

How do these Storms Interact with the Geomagnetic Field?

The convective motion of conducting material in the liquid outer core of the Earth, driven by strong thermal inequalities, subjected to the Coriolis force due to Earth's rotation, give rise to Earth's ambient magnetic field, commonly referred as the *geomagnetic field*. At the surface of the earth, this field is equivalent to that produced by a N-S oriented magnetic dipole located near the centre of the Earth. Interaction and impact of continuous flow of solar wind, carrying charged particles from the Sun, confines the magnetic field of planet Earth into a large envelop, called *magnetosphere*. On the sunside, magnetospheres extends from the surface to about 10 Earth radii while on the nightside it stretches up to a few hundred Earth radii (Fig.2).

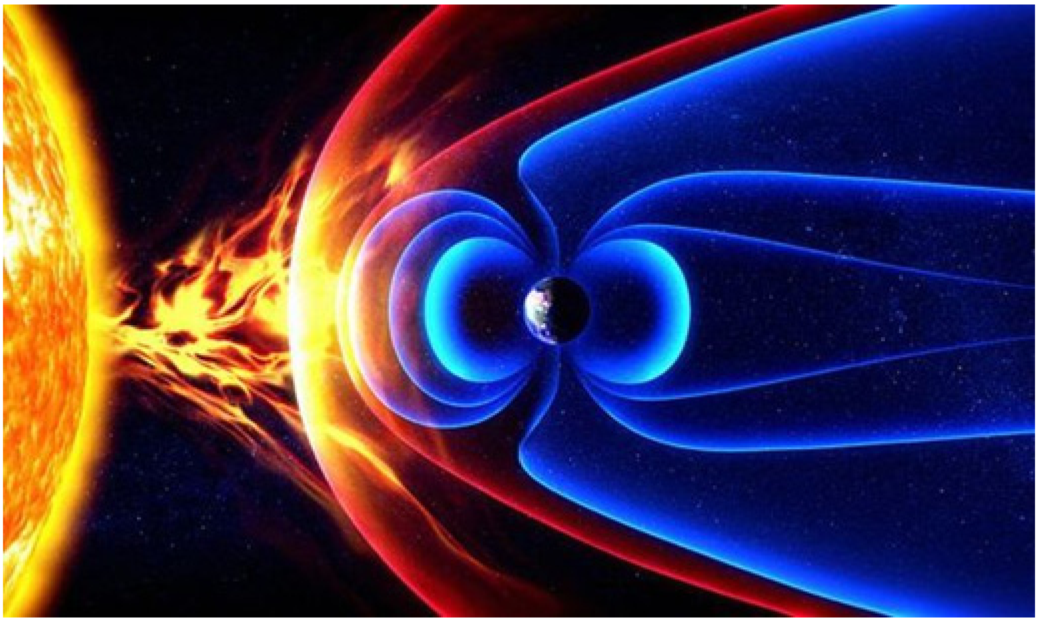

Fig. 2. Visualization of the Sun and the Earth enveloped by its magnetosphere, a CME emerging from the Sun is hitting the Earth's magnetosphere (Image: Getty, not to scale)

The Sun is the source of all life on Earth's surface. Radiation and particles from the Sun and other cosmic sources can also destroy the Earth's atmosphere and all life forms. It is the magnetosphere, which protects Earth from such destructive external forces. Solar flares bombard the Earth within minutes of the solar explosion and is the cause of rapid space weather changes. When a strong enough flare occurs, charged electrons in the upper atmosphere can temporarily absorb radio waves on the side of Earth that is facing the Sun and cause blackouts. Large increase in photoionization of the polar ionosphere leads to weak Joule heating of the Earth's upper atmosphere and changes in magnetospheric convection. CMEs take about 12-15 hours to reach the Earth's magnetosphere. The degree of magnetic disturbance from a CME depends not only on the quantum of the ejection but also on the alignment of the CME's magnetic field with the Earth's. If the CME's magnetic field is aligned with Earth's magnetic field, pointing from south to north the CME will pass on by with little effect. However, if the CME is aligned in the opposite direction to the Earth's geomagnetic field lines, they "merge" or "reconnect" at the dayside of Earth's magnetopause. As this occurs, plasma seep through the funnel-like openings over Earth's North and South Poles and penetrate to low altitudes, along the geomagnetic field lines. This is the *first/initial phase* of a *geomagnetic storm*.

In the next phase, charged particles get pushed into the inner magnetosphere close to the Earth and energizes the Van Allen radiation belts encircling the Earth within the magnetosphere. Positive ions gradually rotate clockwise while negative electrons rotate counter-clockwise, which creates an electric current in the near Earth environment "*ring current*" that circulates clockwise around the Earth. As the flow of charged particles increases, the ring current expands. This expansion can last from 3 hours to 12 hours on an average. This is the second, or *main phase*, of a geomagnetic storm, which depresses the normal geomagnetic field and produces a distinct signature on the magnetogram.

The ring current decays as the charged particles leave the Earth's magnetosphere and returns to its previous "quiet state." This is the third and *last phase* of storm growth. Such recovery normally takes 2-3 days. On rare occasions, such as the February 1986 storm, recovery may take up to a month. Figure 3 shows schematics of geomatic storms as recorded in the data, during such events in the solar maximum and minimum phases. Geomagnetic storms are categorized on a scale of 1-5 from weakest to strongest, as in table 1.

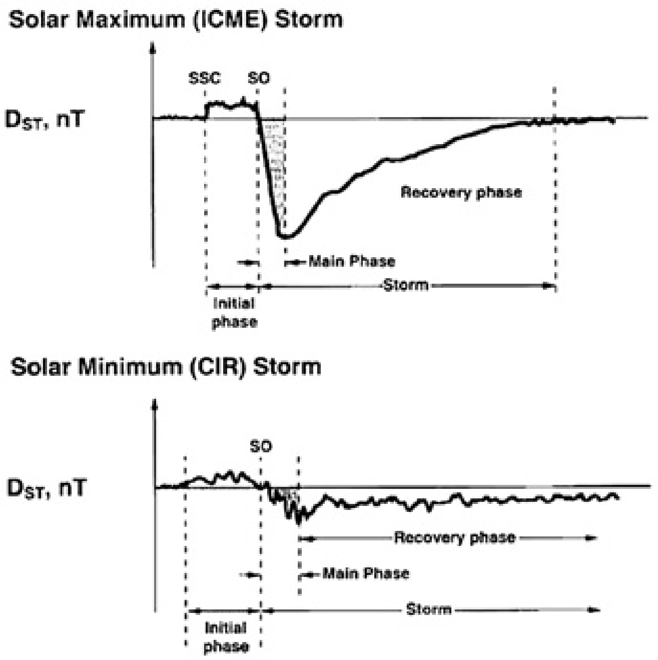

Fig.3. Schematic diagrams of geomatic storms as recorded in the data, during such events in the solar maximum and minimum phases (from Tsurutani, 2000)

Table 1. Classification of Geomagnetic storms

Scale	Description	Average Frequency (1 cycle = 11 years)
G 5	Extreme	4 per cycle (4 days per cycle)
G 4	Severe	100 per cycle (60 days per cycle)
G 3	Strong	200 per cycle (130 days per cycle)
G 2	Moderate	600 per cycle (360 days per cycle)

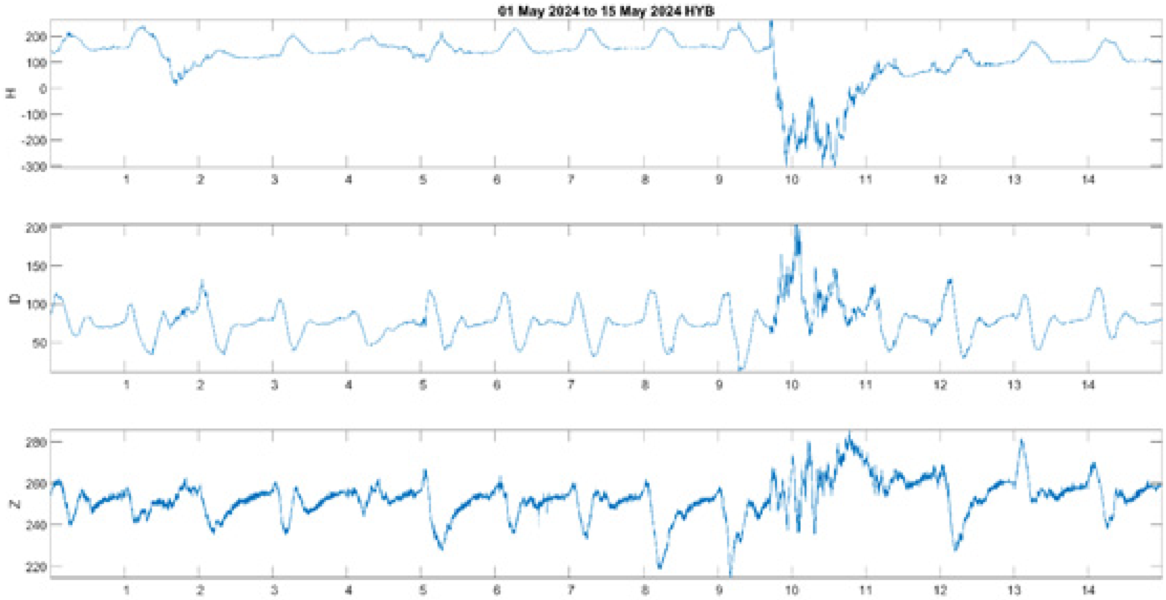

Fig.4. Geomagnetic storm as recorded in the three components of data of Hyderabad magnetic observatory (HYB), on 10th May, followed by recovery phase over next 5 days.

Solar Cycles Over the Last Century

Solar cycles (SC) vary in their durations and intensities of activity (as shown from the 15th recorded SC in Fig.1). While SC 18 and particularly 19, during 1943-53 and 1953-63 were intense, SC 20 was much weaker in activity. SC 21 and 22 picked up in strength and SC 23 and 24 have been less and less intense. The current cycle, SC 25 started on Christmas Eve in December 2019 and is in its ascending phase, expected to peak around July 2025. Although it was expected to be a fairly weak cycle, over the last several months, the remarkably strong performance of young SC 25 has surprised the scientific community; the number of sunspots have been increasing rapidly. Largest group of 17 sunspots were recorded during late November to early December 2020. In 2021, the first G3 storm occurred in May and X class flares in July and October; a G4 storm was triggered by a series of CMEs in November. In 2022 the CMEs in January burnt up 38 Starlink satellites. Activity spiked in 2023; February saw a storm as well as X class flares, CMEs created G4 storms in March, April, May, June, September, October, November, December. The trend continued to 2024 with G4 storm on 24 March, quadruple solar flares on 23rd April (Science.nasa.gov; SpaceWeather.com).

The Recent Solar Storm of SC 25

From May 3-9, 2024, 82 notable solar flares were reported by NASA, from two active regions on the Sun called AR 13663 and AR 13664. From May 7 – 11, multiple strong solar flares and multiple CMEs blasted toward Earth, arriving on May 10, created a long-lasting geomagnetic storm (Fig.4) that reached a rating of G5 and intensities that hasn't been seen since October 2003. Brilliant auroras were seen around the globe even visible at unusually low latitudes, including the southern U.S. and northern India, at Hanle, Ladakh. A gigantic solar flare - an X8 Category blast from giant sunspot AR3664, was further detected on May 14th. Extreme ultraviolet radiation from the flare ionized the top of Earth's atmosphere and caused a deep shortwave blackout over the large parts of the world. To add to the excitement, Sunspot AR3664, which caused the historic May 10th superstorm, returned on May 27th after a two-week trip around the far side of the Sun and emitted an X2.8 class solar flare (SpaceWeather.com). By current indications SC 25 may turn out to be of unprecedented strength. The implications, if this was to come true, would be very significant in terms of potential hazards from space weather.

How do Solar Storms Affect Us?

The areas that are most susceptible to geomagnetic storms are power systems, spacecraft operations and other systems like satellite navigation and radio frequency disruptions. Changes in the ionosphere during geomagnetic storms interfere with high-frequency radio communications and Global Positioning System (GPS). The storms induce currents in electrical systems on Earth, making power grids vulnerable during these times. Large scale studies on how solar events influence Earth's upper atmosphere is crucial in assessing impact on satellites, crewed missions, high altitude flights and Earth and space based infrastructure. Storms are not known to be dangerous to human bodies on the Earth's surface, but recent reports have noted forms of mood swings, headaches, increase in blood pressure in some people from possible effects on the cardiac and neurological systems (Alabdulgader, 2018; Liu et al., 2021; Zilli et al., 2022).

Efforts to predict solar cycles have not yet led to consistent outcomes and there are ongoing debates regarding the strength of SC 25 (Su et al., 2023). As nearly everything the modern world relies on, could fail if disabled by an intense solar storm, leading to huge loss of infrastructure and pushing progress back by decades, this remains a high priority area of research for the scientific community.

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