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Solar Flares and Their Impacts

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ABSTRACT
Solar flares are the most prominent events with the strongest magnetic field in Solar activity and are mostly associated with energetic particles (electron, neutron, proton, and heavy nuclei), coronal mass ejections, and shock waves. As the shock waves travel between the planets, they also accelerate the particles in their path. When these high-energy charged particles reach the Earth's magnetosphere, they cause geomagnetic storms and aurora. Solar flares can also cause adverse effects around the Earth. For example, if satellites are exposed to high-energy particles, major damage can occur to their systems. Satellite orbits can be destabilized, and even astronauts on and off the satellite may be exposed to these life-threatening high-energy particles. Therefore, the prediction of flares that may occur on the Sun is very important in this context. Here, solar flares, their effects on space weather and satellites will be discussed in detail.
Keywords: Sun, Sunpots, Solar Flares, Coronal Mass Ejections (CMEs), Solar Storms

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1. What causes solar activity?

Since the discovery of the magnetic field in the Sun (Hale, 1908), the role of the magnetic field in solar activity has been extensively investigated. The Skylab mission (1973 - 1974) first conducted a detailed study of the corona from space using a soft X-ray telescope and revealed the strong magnetic correlation of the bright regions in the soft X-ray. It is now widely accepted that the magnetic field provides the main source of energy for solar activity, including flares. Solar activity includes sunspots and other structures on the solar surface. Sunspots are cooler than their surroundings due to the magnetic field (Figure 1). The magnetic field suppresses convection and prevents plasma from penetrating into sunspots.

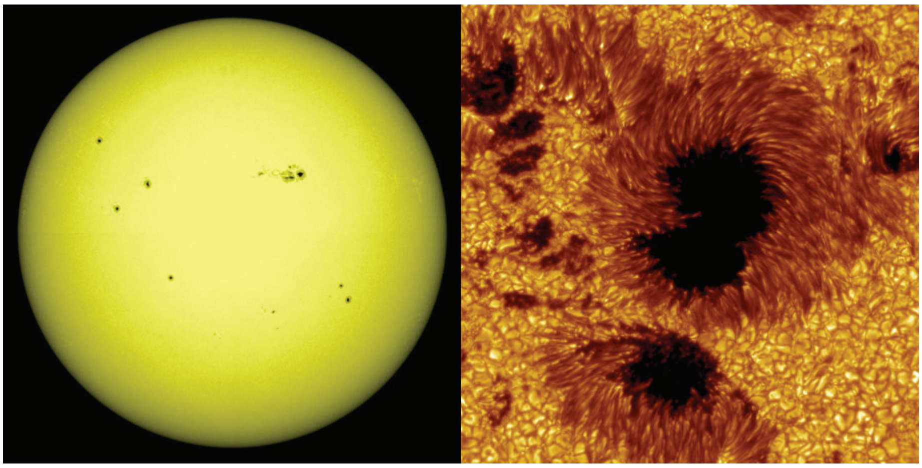

Figure 1. Many sunspots on the solar disk (left) and a close-up view of a sunspot group in an active region observed by the Swedish Solar Telescope (right). ©NASA/SDO and the AIA, EVE, and HMI science teams (left) and Royal Swedish Academy of Sciences (right)

Solar activity changes over time, and one of the most striking changes is the solar cycle or solar magnetic activity cycle with a nearly periodic 11-year change in terms of variations in the number of observed sunspots on the solar surface. During the solar cycle, the sunspot count rises and falls, and the magnetic field of the Sun associated with sunspots completely reverses polarity; the north and south poles of the Sun switch places.

1.1. Solar Flares

Flares are usually defined as the rapid release of magnetic energy stored in the corona because of the bending, rupture, and reconnection of magnetic field lines. The released energy during a flare is typically in the order of 10^{28} ergs (equivalent to 160 billion megatons of TNT) while in major flares, it can be up to 10^{32} ergs.

This enormous energy is released in the solar atmosphere in just a few tens of seconds. The duration of a flare and the amount of energy emitted depend on the spatial size of the flare. The emitted radiation covers all ranges of the electromagnetic spectrum: radio, visible, UV, X-ray, and gamma ray.

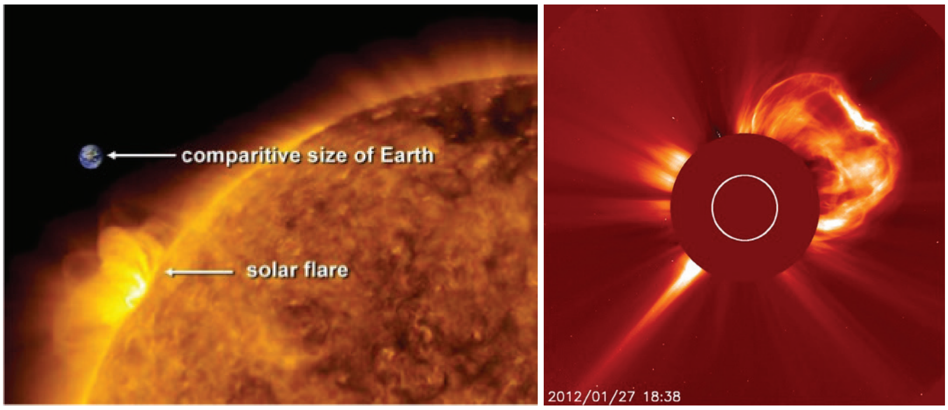

Figure 2. EUV image of a solar flare ©NASA/SDO (left) and an image of a CME (upper right) associated with an X1.8 class solar flare ©SOHO (right)

Historically, flares were first observed in the photosphere (Carrington, 1859; Hodgson, 1859). After spectroheliographs were developed, and an H*α* filter was invented, flares could be observed more frequently in H*α*. The H*α* image of a flare shows two ribbons, usually consisting of bright patches, and the distance between these ribbons increases with time. For a long time, flares were considered as the chromospheric event observed in H*α*. The discovery of coronal radio and X-ray emissions from a flare region revealed that the flares were actually coronal events.

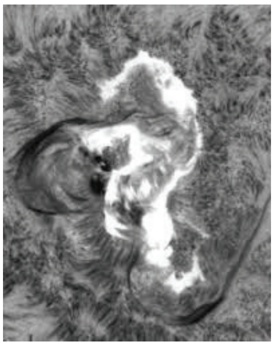

Figure 3. Hα image of a flare with (spreading) two ribbons of emission from the chromosphere ©BBSO

Solar flares occur over a wide range of spatial and temporal scales and the energy they emit. For this reason, it is classified depending on various parameters. The most commonly used flare classes are based on H*α* and X-ray observations. The H*α* classification system uses both the intensity and the size of flare area in H*α* spectral line while X-ray classification of flares uses the letters A, B, C, M, and X, according to their brightness in the wavelength range 1 to 8 Angstroms as measured at the Earth by the GOES spacecraft. Each category has nine subsections like M1-9.

The formation rate of solar flares also follows solar cycle; the frequency of flares occurs around maximum of solar cycles. There are 15,239 flares reported during the 24^{th} solar cycle from the GOES data archive. The distributions of the monthly total numbers of flares and X-ray flare classifications by years are given in Figure 4 and listed in Table 1. The figure also shows the distribution of the monthly total number of sunspots according to years on the same graph (left side), created by the SILSO (Sunspot Index and Long-term Observations) data of the 24^{th} cycle. It can be clearly seen from the figure that the variation of the flare and sunspot numbers over time during the cycle are similar (Atasoy, 2020).

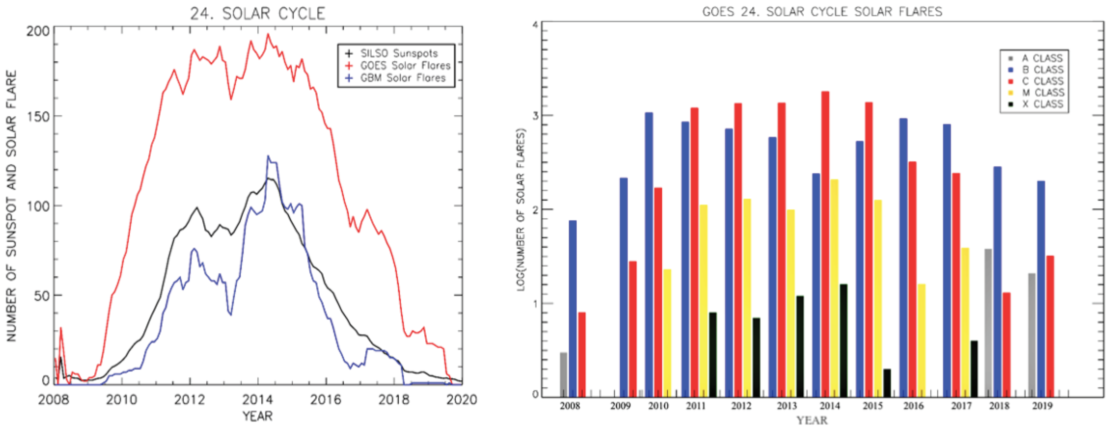

Figure 4: Distributions of monthly total numbers of sunspots (black line) and flares (red line) over the solar cycle (left), and also X-ray flare classes over the last solar cycle (right)

Table 1. Distribution of flare classes observed in the 24th solar cycle by years.

Years	GOES X-ray Classes					
	A	B	C	M	X	TOTAL
2008	3	76	8	1	0	88
2009	1	216	28	0	0	245
2010	0	1,068	170	23	0	1,261
2011	1	851	1,200	111	8	2,171
2012	0	717	1,337	129	7	2,190
2013	0	584	1,357	99	12	2,052
2014	0	240	1,797	207	16	2,260
2015	0	530	1,377	125	2	2,034
2016	0	923	321	16	0	1,260
2017	0	804	243	39	4	1,090
2018	38	284	13	0	0	335
2019	21	200	32	0	0	253
TOTAL	64	6,493	7,883	750	49	15,239

1.2. Coronal Mass Ejections

Flares are mostly associated with energetic particles (electron, neutron, proton, and heavy nuclei), mass ejections, and shock waves. Shock waves accelerate particles on their ways while propagating in interplanetary space. Coronal Mass Ejection (CME) is an outward release of enormous size solar plasma (billions and sometimes trillions of tons of matter). CMEs move outward from the Sun at speeds ranging from 250-3000 kilometers per second. Fast Earth-directed CMEs can reach our planet in 15-18 hours while slower CMEs can take several days to arrive. The formation rate of CMEs generally follows the solar cycle, and more intensive CMEs occur more frequently around maximum of solar cycles. Large Earth-directed CMEs can cause intense geomagnetic storms.

2. Impacts on the Earth

Solar flares, especially when combined with CMEs, have a powerful impact on Earth's geomagnetic field and space weather. Changes in solar activity cause changes in the shape of the Earth's magnetosphere and in Earth's radiation levels. These events can trigger magnetic storms and aurora and cause major changes in some properties of Earth's upper atmosphere. In particular, in the altitude range of 200-1,000 km, the temperature and mass density of the Earth's atmosphere can vary several times. Additionally, these phenomena have short-term and long-term impacts on infrastructure that includes failures of electronic system and equipment, disruptions in telecommunications and navigational systems, and corrosion problems in buried oil and gas pipelines, etc.

Shock waves associated with flares with CME accelerate particles on their path as they travel interplanetary medium. The Earth's magnetosphere, which extends to approximately 10 Earth diameters in the direction of the Sun, can be compressed by these high-energic charged particles coming by the solar wind. Satellites may be exposed to intense radiation by staying out of the magnetic belt, and severe damage may occur to their systems. When conditions get worse, satellites often switch to a safe mode to protect their systems. The lifetime of satellites can be significantly affected. Satellite-orbits may be out of balance, and even astronauts operating in and out of satellites may be exposed to these high-energy life-threatening particles.

3. Highlights in History

3.1. The Carrington Event on September 1, 1859

It was the most intense solar flare following by CME event on record. It was named after British amateur astronomer Richard Christopher Carrington, who observed the huge flare (along with Richard Hodgson who independently recorded the observation of the flare) and was the first to figure out the link between solar flares and geomagnetic disturbances on Earth. The flare-related major CME reached Earth in a record short time of 17.5 hours,which means energetic particles were moving at 8.5 million kilometers per hour. Then, they caused a violent magnetic storm on 1-2 September 1859.

Telegraph communication was failed for hours in North America and Europe. There were reports of sparks from telegraph machines, igniting papers, and shocking operators in telegraph offices. Auroras were seen at night at unusually low latitude areas such as Rome, Havana, Hawaii, southern Japan and China, and even the equator, such as in Colombia. Although Sun-Earth relationships were poorly understood at the time, the Carrington event was the first evidence to show that solar flares are the main cause of geomagnetic storms. Maynard et al. (2013) analyzed the risks posed by a Carrington-scale event to the US power grid today and found that 20-40 million people could be without power for up to two years, and the economic cost will be $0.6-2.6 trillion.

3.2. The Event of May 1921

It was another extraordinary geomagnetic storm caused by a powerful solar flare with CME. The magnetic storm of 1921 was associated with a large sunspot in the center of the disk, visible to the naked eye. A series of coronal mass ejections (CMEs) hit Earth between 13 and 16 May 1921. These CMEs produced several geomagnetic activities. The most intense geomagnetic storm among them occurred between 14-15 May 1921. This storm caused a series of short circuit events that resulted in fires. It also damaged submarine cables, power lines, and telephone lines on both sides of the Atlantic. An intense aurora event caused great currents in telegraph circuits and failed telegraph communications in England, Scotland, and Ireland. Strong magnetic storm effects have also been experienced on telegraph and radio communication systems in New Zealand. The impacts of these extreme geophysical conditions on contemporary technologies are major concerns today. The event of May 1921 provides useful information in taking precautions against the risks arising from such events (Hapgood, 2019).

3.3. The Quebec Event of March 13-14, 1989

It was the largest magnetic storm of the twentieth century and caused widespread impacts on technology. It was related a complex sunspot region across the face of the Sun from 6–18 March 1980 (Figure 5). During that time, 11 X-class flares occurred, and potentially related CMEs accompanying the flares blasted off into space. On 13 March, magnetometers on the ground recorded a sudden jump in the magnetic field showing the large magnetic storm with multiple substorms at higher latitudes that caused the most dramatic impacts on the space and ground-based infrastructure of modern society. It is the first large-scale catastrophe with an estimated total loss of $6 billion.

The magnetic storm blacked out Hydro-Quebec power grid resulting in six million people in province of Québec, Canada without power for 9 hours. Failure of transformers and blackouts occurred also in the USA and Europe (England). One of the most dangerous events was the failure of a massive $10 million transformer at the Salem Nuclear Power Plant in New Jersey. None of the power outages or infrastructure damage resulted in a major disaster, but the event caused significant financial losses and made clear the scale of the danger posed by adverse space weather (Marov and Kuznetsov, 2015).

These magnetic storms caused auroras down to unusually low latitudes, such as Florida and Cuba. Radio communications and the US space navigation system were disrupted (Allen et al., 1989; McEwan, 1992; Rich & Denig, 1992; Yeh et al., 1992). Also, satellites and orbital debris in low Earth orbit experienced increased atmospheric drag resulting in 2500 space objects being “lost” temporarily by tracking systems (Joselyn, 1990; Burke, 2018; Boteler, 2019).

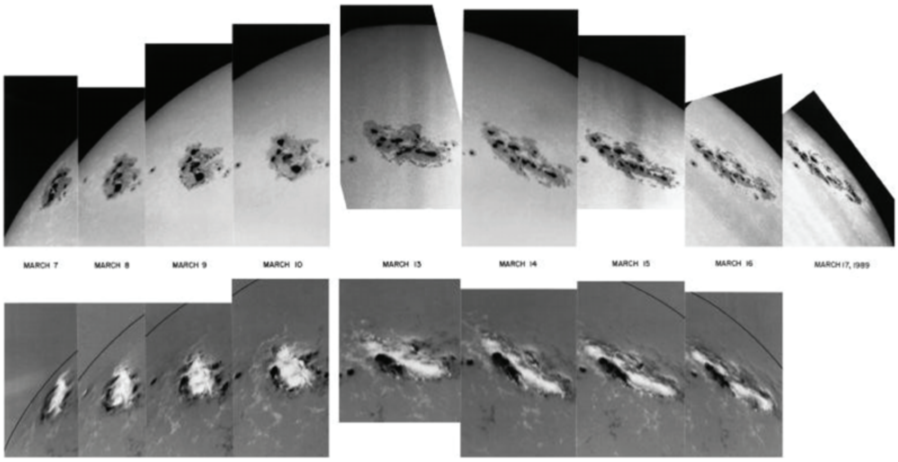

Figure 5. White light images (top) and solar magnetograms (bottom) showing the passage of the sunspot active region across the face of the Sun between 7 and 17 March 1989. The solar magnetograms show the line-of-sight magnetic flux density on the active region. White (Black) color indicates a field of positive (negative) polarity. Images from the Kitt Peak Observatory

3.4. The Halloween event, 2003

Between October-November 2003, eleven large X-class flares with CMEs occurred in the Sun. A powerful solar flare (X17 class) linked to a large sunspot group occurred on 28 October 2003. An hour after the following CME, solar energic particles hit the Earth and caused dangerous radiation conditions in the Earth's environment and produced violent and unusually long magnetic storms (also known as the Halloween event) between 28 October and5 November 2003. This caused radio blackouts and degradation of the ozone layer at the poles. The next day, on October 30, when the geomagnetic field barely recovered after the first storm, the plasma cloud of the second CME ejected from the same active region again struck Earth, causing another powerful magnetic storm. Solar particles accelerated in the second solar event continued to intrude into the deteriorating Earth's magnetosphere and reached the orbit of the International Space Station. Fortunately, the station was on the other side of the Earth at the time.

More than 50% of the records in the 2003 report of anomalies of satellite systems are related to this event. The SOHO satellite failed temporarily, and the Advanced Composition Explorer (ACE) was damaged by the solar activity. A Japanese satellite was lost. Numerous other spacecraft were damaged or experienced downtime due to various issues (Marov and Kuznetsov, 2015).

4. Concluding Remark

Recently, Jyothi (2021) reported that a powerful solar superstorm today has the potential to cause a major disruption to the Internet lasting several months on the entire globe. Scientists estimate that the probability of a solar superstorm of sufficient strength to cause devastating disruption to Earth within the next ten years is between 1.6-12%. It is therefore obligatory to plan defenses against this danger.

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