Space Weather Effects on Critical Infrastructure

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Abstract

Gas pipelines, transmission lines, overhead wires, transformers, GNSS navigation, and telecommunication systems are part of critical infrastructure. Industry, transportation, service operations, farming, and everyday life highly depend on this infrastructure. However, these systems are very sensitive to solar activity. Therefore, all activities above are vulnerable and defenseless against the catastrophic changes in Earth's cosmic environment. The Solar System is dominated by the influence of our star. In the Solar System, all objects are bounded gravitationally and the Sun's radiation provides the energy par example for the terrestrial biosphere. A small fraction of the energy produced in the core of our star turns into a magnetic field and emits the constant high-velocity plasma flow, the solar wind. Solar magnetic activity produces radiation and ejects matter from the upper atmosphere of our star. The magnetic field frozen to the solar wind plasma interacts with the planetary magnetic fields and atmospheres. These phenomena, called Space Weather have a serious influence on the radiation environment of Earth where telecommunication, GNSS, meteorological, and other purpose satellites are located. The conductivity and transparency of the higher partly ionized atmospheric layer, the ionosphere also depend on solar radiation and activity. This fact makes the navigation and communication systems dependent on solar activity. Finally, the solar magnetic activity creates magnetic variations in the terrestrial magnetic field and induces currents in gas pipelines, transmission lines, overhead wires, and transformers. In this short briefing, we introduce the solar activity phenomena, and their influence on our planet's cosmic neighborhood and provide a detailed description of the Space Weather effects on critical infrastructure. Finally, we share and detail some methods to forecast the critical Space Weather effects and protect the infrastructure mentioned previously.

Keywords: Space Weather, Solar Activity, Geomagnetically Induced Currents, Telecommunication, Global Navigation Satellite System disturbances

1 Introduction

This paper is supposed to be a brief review of the cosmic phenomena that endangers our planet and civilization on planet Earth.

1.1 Definitions and clarifications

Here, the critical infrastructure (CI) means submarine internet cables, gas pipelines, transmission lines, overhead wires, transformers, Global Navigation Satellite System (GNSS) navigation, satellite telecommunication, and HF radio telecommunication systems. Submarine internet cables, gas pipelines, transmission lines, overhead wires, and transformers are long, conductive objects therefore they are sensitive to quickly varied magnetic fields. GNSS navigation, satellite telecommunication, and HF radio telecommunication systems depend on the transmission and reflection ability of the ionosphere (that is a conductive layer of the upper atmosphere at $\sim$120 km altitude).

The Space Weather (SW) term has two meanings. It is a new(er) name for the research of the solar-terrestrial relationship. Additionally, the expression covers the efforts to predict the conditions of the near-Earth cosmic environment, the ionosphere, and the surface of our planet [1].

1.2 Introduction to space weather

The main drive of the space weather in the Solar System is the Sun. All planets, moons and other objects are located in its extended and expanding atmosphere, the solar wind. The solar wind interacts with the magnetic field of our star.

1.2.1 The solar magnetic activity

We have an aggressive and dominant neighbor: the Sun (Fig. 1). During total solar eclipes the solar corona, this hot, extended and relatively faint part of the atmosphere of our star becomes visible. You can see filaments in the corona and its shape and extension varies depending the Sun's magnetic activity (Fig. 1, top left). In visible light you can see sunspot on the disc of the Sun (Fig. 1, top right). These regions have lower temperature than their neigbourhood therefore they look darker (Fig. 2). In the wavelength of H_α–line (656.28 nm) the granulation, the continious boiling (or convective) motion of the solar plasma is visible (Fig. 1, bottom). The energy produced in the solar interiour leaves our star by conductivity in it outmost layer. This conductive motion of the conductive solar plasma and the rotation of the Sun set up and moves the solar dynamo that produces strong magnetic field. The magnetivity of our star dominates the space nearly the Sun. This region of the space is called heliosphere (Fig. 6, bottom). The magnetic activity of the Sun makes serious disturbances in the navigation and the communication [1, 2].

Our star produces energy by thermonuclear fusion in its core. The produced energy flows out by radiation until ∼70 % of its radius. There the material of the Sun becomes convective. It means that the energy is transported by moving material and not by radiation. The Sun rotates quite quickly. The material of our star is in a so-called plasma state: its atoms lost their electrons and build up a quasi-neutral, highly conductive material. The convective and rotational motions of the highly conductive material set up a dynamo. Therefore the Sun has a very strong magnetic field. The magnitude of this magnetic field is 1 Tesla (T). The magnitude of Earth's magnetic field is from 25000 nT to 65000 nT. In a Magnetic Resonance Imaging (MRI) instrument the strength of the magnetic field is ∼1 T in a 0.5 m×0.5 m×0.5 m cube. On the Sun the diameter of the magnetic flux tubes are ∼13000 km (2 R_{Earth}) and their length could be a few hundred thousand km. Those solar magnetic structures consist of a vast amount of energy. It is only ∼1 % of the energy produced by the fusion in the solar core. However, the magnetic field and the magnetic activity of the Sun have a dominant influence on the nearby space around the Sun, to the heliosphere [1, 2].

1.2.2 Flares and coronal mass ejections

Sometimes two solar flux tubes with opposite direction situated close to each other and gradually forms an "X" shape configuration (Fig. 3). If these flux tubes are enough close to each other it becomes energetically better configuraton if half-half of the opposite tubes form a shorter bended structure (Fig. 3). Its phenomena is called reconnection and bursts huge amount of energy. This region of the solar atmosphere reaches 15-20 million K degree. (The temperature of the arbitrary defined solar surface is 6000 K and the solar core where the termonuclear fusion produces the energy is only 16 million K degree.) A bright flash in vissible light, X-ray and radio bursts are ejected. Charged particles are accelerated to high energy, these are the Solar Energetic Particles (SEPs). A jet is ejected to the solar surface and usually (but not always) a huge amount of hot plasma launched to the heliosphere. Its name is coronal mass ejection (CME) or solar storm (Fig. 4). The ejected plasma node remains connected magnetically to the Sun during its travel in the Solar System (Fig. 4, bottom). CMEs can also occur independently. A large CME could contain a billion tons of plasma that can be accelerated to several thousand km per seconds. Their size could be much larger than the diameter of the Sun. Therefore, solar material ejections fly through the interplanetary space, impacting any planet (Fig. 5) or spacecraft in its path [1, 2].

1.2.3 The solar wind and solar wind streams

The reason for all troubles in the heliosphere is the atmosphere of the Sun (Fig. 6, top left). The temperature of the photosphere is 6000 K. The temperature of the chromosphere which is above the photosphere is around 10000 K. Finally, the temperature of the corona which exists above the chromosphere is around 1000000 K. You can see that in the solar atmosphere, the outer layers have higher temperatures (Fig. 6, top left). A strong, fast plasma flow originates from the outer layer of the solar corona, the solar wind (Fig. 5). The distribution of the solar wind speed has two maxima at 400 km/s and 800 km/s [3]. These types of the solar wind are called slow and fast solar wind or slow and fast solar wind streams. The slow solar wind originated from the normal solar coronal. In X−ray and extreme ultraviolet (EUV) observations, the solar corona has larger regions so-called coronal holes that look dark in these wavelengths (Fig. 6, top right). The fast solar wind is ejected from these coronal holes [1, 2]. The magnetic field lines move together with the solar wind plasma. You can say the magnetic field lines are frozen in the solar wind plasma. The solar wind moves radially outward and the Sun rotates. Very soon, the angular speed of the plasma will be less than the angular speed of the solar rotation. Therefore, a spiral form of the magnetic field is created by these movements. Its name is Parker-spiral. The fast and slow solar wind streams interact with each other and form compressional and rarefaction regions (Fig. 6, bottom). These regions (co−called corotating interaction regions, CIRs) could hit the terrestrial magnetosphere [1]. Their effects and disturbances are not as strong as the effects of a CME however they could cause serious problems for critical infrastructure.

1.2.4 The terrestrial magnetosphere, ionosphere and the aurora

Our planet has a strong magnetic field that is tilted to the Ecliptic (the plane of Earth's orbit around the Sun) and bipole (that means it looks like the magnetic field of a bar magnet). The region where this magnetic field dominates is called the magnetosphere (Fig. 7, top). The solar wind flows faster than the sound speed and the speed of the perpendicular magnetic waves (the Alfvén speed). This flow grabs the magnetic field of the former solar plasma (the magnetic field is frozen into the solar wind plasma). This magnetic field cannot enter the magnetosphere. The information about the obstacle cannot propagate against the supersonic and super–Alfvé nice flow because its maximal propagation speed is the sound and Alfvén–speed. Furthermore, the solar wind cannot hit the magnetosphere without any deceleration. Therefore, I shock, so-called bow shock forms before the magnetosphere (Fig. 7, top). The solar wind passes, slow down, its density and magnetic field magnitude increases, its temperature and entropy increase, becomes more turbulent, and flows around the magnetosphere. Additionally, the solar wind direction changes and flows around the terrestrial magnetosphere. The separation layer between the magnetosheath and the magnetosphere is called magnetopause (Fig. 7, top). The region between the bow shock and the magnetopause is called magnetosheath (Fig. 7, top). The night side of the magnetosphere (that is antisunward) is elongated and extended far beyond the lunar orbit. This region is called the tail (Fig. 7, top). The terrestrial tail situated according to the direction of the solar wind as a windsock [1, 4, 5].

The solar wind enters the terrestrial magnetosphere and creates aurora and the radiation belts (Fig. 7, bottom left). The charger particles of the solar wind always enter the magnetosphere at the north and south magnetic poles of our planet. These regions are called cups (Fig. 7, top). These particles are trapped and rotate around the magnetic field; furthermore, the rotating high-energy particles also move along the magnetic field lines. When these particles approach a magnetic pole they bounce back. Therefore, the charged particles move between the magnetic poles. They also drift perpendicularly to this movement. If you add their location and speed you get a so-called ring current above the magnetic equator. The region of these charged particles is called radiation belts and Van Allen belts [1]. The ring current influences the magnetosphere of the Earth. The charged particles hit and excite the molecules and atoms of the atmosphere. These excited atoms eject visible (green) light (Fig. 7, bottom left). This light is called aurora [1]. The aurora activity is permanent under the aurora oval (Fig. 7, bottom right). The intensity of the aurora is proportional to the bandwidth of the radio communication through the ionosphere (Kjellmar Oksavik, personal communication).

On the boundary of Earth's upper, partially ionized, therefore conductive atmosphere (the ionosphere) and the lower magnetosphere, huge current systems are indicated [6]. These currents and the high-energy particles ejected by solar flares or accelerated CME shocks interact with the ionosphere and might change its transparency and reflectivity (Fig. 8). Therefore, solar activity influences GNSS navigation, satellite, and HF radio telecommunication systems[1]. Both observation and simulation of the variations of the terrestrial magnetic field in this region of our planet are challenging [7]. However, using ground-based magnetometers it is quite easy to record and monitor magnetic disturbances. Based on the measurements of geomagnetic observatories located at high and lower altitudes, you could determine whether a CME or another phenomenon disturbed and caused strong magnetic variations in the magnetosphere [1]. Based on these results the auroral activity could be predicted and currents induced by the rapid variations of the magnetic field could be calculated. These currents are called geomagnetically induced currents (GICs) and their magnitude depends on the conductivity of the surface materials [1]. However, the rapidly variable magnetic field also generates currents in all long conductive objects; such as gas pipelines, electric transmission lines, train overhead wires, submarine internet cables, and transformers [1]. Therefore, solar activity might cause damage to this type of critical infrastructure (Fig. 8).

2 Space Weather effects on critical infrastructure

The space weather phenomena described in Section 1.2 might have serious effects on the critical infrastructure defined in Section 1.1. The sources of the disturbances (Fig. 8, white ellipses) are the radiation outside of the Solar System (so-called cosmic rays), the SEPs (Section 1.2.2), the radiation of solar flares (Section 1.2.2), the solar flare radio bursts (Section 1.2.2), the CMEs (Section 1.2.2), and energetic particles from the radiation belts (Section 1.2.4). These phenomena affect the ionosphere (Section 1.2.4) and induce currents in the objects on Earth's surface (Fig. 8, red rectangles).

2.1 Space Weather effects on ionosphere and long conductors

The ionosphere bounces back the high-frequency (HF) waves. Without this bounding ability, the HF radio broadcast and communications would not be possible on Earth. This capability could be modified and even destroyed by space weather phenomena (Section 1.2.4). However, radio communication is also possible through this layer (Section 1.2.4). Therefore, satellite communication and location determination using the GNSS position system are possible. The transparency of the ionosphere could be decreased by the space weather phenomena. Hence, satellite communication becomes problematic. Aurora is a beautiful tourist attraction and an important indicator of solar activity (Fig. 8, red rectangles). Furthermore, the intensity of the aurora is proportional to the bandwidth of the radio communication through the ionosphere (Section 1.2.4). The observation of the aurora is easy using optical full–sky cameras. The disturbed ionosphere could deviate from the direction of the GNSS signals too. The name of this effect is scintillation which might cause errors in the navigation systems. Finally, the reception of radio waves could be disturbed (Fig. 8, red rectangles).

The rapidly variable terrestrial magnetic field induces geoelectric fields and currents on Earth's surface (Fig. 8, red rectangles). Furthermore, it creates geomagnetically induced currents in power systems, submarine cables, gas pipelines, and train overhead wires (Fig. 8, red rectangles). This is a dangerous effect. This phenomenon could block or destroy communication and energy transfer; furthermore, it is unwelcome for gas transfer. These systems could be protected if we know the magnitude of the effects or switch them off if we could forecast the phenomena.

2.2 Catastrophic Space Weather effects

The Carrington Event was the most intense observed geomagnetic storm. Its maximum peaked from September 1 to 2, 1859. The geomagnetic storm was the result of a CME from the Sun hitting the magnetosphere of our planet [8]. The CME associated with a very bright solar flare on September 1, 1859, traveled 17.6 hours to the Earth [9]. The event caused strong aurora reported globally [10]. The aurora was visible from the poles to low latitude areas such as south-central Mexico, Queensland, Cuba, Hawaii, Japan, and China, and even very close to the equator in Columbia [11–15]. Because of the geomagnetically induced current from the rapidly changing terrestrial magnetic field, telegraph systems in Europe and North America failed, in some cases giving their operators electrocutes [16]. Some telegraph stations sparked and even fired [17]. Some operators could continue to send and receive messages after disconnecting their power supplies [18].

Such strong flares and CME ejection (or solar storms) occur quite rarely on our star. However, we assure you that it will happen again once. Nowadays, its impact will be catastrophic for our critical infrastructure. The gestational and GNSS satellites will be offline or damaged permanently. Therefore, communication and navigation will impossible for a while. The transformer stations will be damaged and all computer systems, all elevators, all air conditioning, and all-electric equipment will be useless. The train, tram, and underground traffic will stop. The electric transfer pipeline will be useless. The gas pipelines must be stopped because of security reasons. Human civilization will step back to the 19th century for months. The effects of such a solar storm (or CME) look similar to a global thermonuclear bombardment using charges with improved microwave radiation capabilities. The researchers at Lloyd's of London and Atmospheric and Environmental Research (AER) in the US estimated the cost of a Carrington event size CME hitting the Earth. The US alone from US$600 billion to $2.6 trillion, which was 3.6 to 15.5 percent of annual GDP in 2013 [19]. Therefore, the authorities must be prepared to recognize such a global catastrophic event using the national resources because the event will be global therefore, you will not be able to ask for help and nobody could help because the situation will be similar all over the world.

2.3 Space Weather prediction centres

Sometimes the space weather effects have catastrofic influence on critical infrastructure. For example, the July 2012 solar storm observed by STEREO, was a CME of comparable magnitude to the one of causing the Carrington Event. However, smaller effects could be also highly disturbing because our civilization is highly sophisticated and the globalisation connected the far sides of the world. Therefore, various nowcast and prediction centres exist on Earth (Table 1). The task of the prediction seems to be clear. However, it is also important to know the recent, current conditions of the terrestrial cosmic environment. This dedicated task uses the same methods and detectors like the forecast systems. Hence, we call this monitoring activity nowcast. The most famous related organization the National Aeronautics and Space Administration (NASA) Goddard Space Flight Center (GSFC) Space Weather Laboratory (https://science.gsfc.nasa.gov/heliophysics/spaceweather/) located in Greenbelt, Maryland, USA. In GSFC staff develops forecsst methods and does general space science research too. The NASA launched and operated the A. . . C. . . E. . . (ACE) and the D. . . (DSCOVR) solar wind monitoring satellites []. In the USA not only the NASA maintaines space weather prediction centre. The Space Weather Prediction Center National Oceanic and Atmospheric Administration (NOAA, https://www.swpc.noaa.gov/) is located in Boulder, Colorado. The C. . . (CIRES) and the University of Colorado also develop tools for space weather forecast. In the United Kingdom the UK MET Office (https://www.metoffice.gov.uk/weather/specialist-forecasts/space-weather) in Exeter, Devon provides space weather forecasts. The UK Met Office (as well as most of other organizations) uses US spacecraft (ACE and DSCOVR) to get solar wind data. One of the most important to maping tool of the heliosphere a model of the magnetized material of the solar wind (so–called magnetohydrodynamic (MHD) simulation), the enlil [], was also developed in the USA. Recenlty a similar model was developed at the KU Leuven, therefore Europe could be independent from the USA in this approach []. China also established its own forecast organisation in Beijing, State Key Laboratory of Space Weather (SKSW, http://english.nssc.cas.cn/l/dss/SKSW/). In Brasil, the Instituto Nacional de Pesquisas Espaciais, Estudo e Monitoramento Brasileiro do Clima Espacial (INPE/EMBRACE; https://www2.inpe.br/climaespacial/portal/en/) provides forecasts. The INPE developes and builds the Galileo Space Solar Telescope (GSST) to burst its solar and space weather activity forecast capabilies. The South African National Space Agency (SANSA, https://spaceweather.sansa.org.za/products-and-services/forecasts-and-predictions) has its space weather monitoring and forecect center in Hermanus, Western Cape. Its budget is quite low (Juha-Pekka Luntama, personal communication), however the rapidly develing space industry of the country need up-to-data predictions. An older nowcast centre is the Auroras Now! (https://aurorasnow.fmi.fi/) developed and maintained by the Finnish Meteorological Institute (FMI) in Helsinki, Finland. Naturaly, the European Space Agency (ESA) has the Space Safety Programme and its Space Weather Service Network (https://swe.ssa.esa.int). The headquoter of the programme located in Darmstadt, Germany but its operation centre situated in Brussels. Various European and other countries founded the European Consortium for Aviation Space weather User Services (PECASUS, https://www.pecasus.eu/). The PECASUS aims to improve the security of aviation.

2.4 Hungarian Space Weather capabilies

Based on the long list above, it seems not only great powers have capability and sources to establish such a service. Therefore, it would be wise to establish the Hungarian National Space Weather Prediction Centre. Hungary has the necessary knowledge (Table 2). In the Wigner Research Centre for Physics at the Department of Space Physics and Space Technology (https://space.wigner.hu) the main research fields are the heliosphere, comets, planetary magnetospheres, dusty plasmas and MHD modelling. In the Centre for Energy Research, at the Space Dosimetry Group (https://www.spacedosimetry.com) the engineers have long experience to build dosimeteres (Pile, []), Langmiur Probes (plasma density and temperature instrument) building and recenly they started developing magnetopmeters. The Institute of Earth Physics and Space Science (https://www.epss.hu) provides ionosonde, GIC and geoelectric field observations; furthermore pocesses a huge database of solar spots observations (the heritage of the former Solar Observatory of Debrecen). They also have experts of the terrestrial bow shock and ground based magnetometers. In the Eötvös Loránd University, the Space Research Group (https://sas2.elte.hu) has experience in building electrostatic wave instruments and cantsats (?) (SMOKE) [] and experts of the plasmasphere and the radiation belts. On the same corridor of the same university in the Department of Astronomy University (https://astro.elte.hu) the latest solar physcist of Hungary works. Finally, in the Technical University of Budapest, Faculty of Electric Engineering, the ... Group developes space probes batteries (https://www.bme.hu). This group build the MASAT, the first Hungarian nano spacecraft. This list of capabilies and experties is not perfect becasuse there is some overlap between groups. It means that some researchers and engineers work in various groups in same time.

Acccording to the list above and Table 2 the Hungarian space scientists possesses the knowledges from Earth's surfsce to the Heliosphere. Some of them have already participated in the work of the ESA's Space Safety Programme (Section 2.3, Table 1). Therefore, founding a national space forecast centre based on political will and funding only.

3 Summary

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Name	Shortcut	URL	Location
NASA Goddard Space Flight Center Space Weather Laboratory	NASA GSFC	https://science.gsfc.nasa.gov/heliophysics/spaceweather/	Greenbelt, MD, USA
Space Weather Prediction Center National Oceanic and Atmospheric Administration	NOAA SWPC	https://www.swpc.noaa.gov/	Boulder, CO, USA
State Key Laboratory of Space Weather	SKSW	http://english.nssc.cas.cn/l/dss/SKSW/	Beijing, China
UK MET Office	na.	https://www.metoffice.gov.uk/weather/specialist-forecasts/space-weather	Exeter, Devon, UK
South African National Space Agency	SANSA	https://spaceweather.sansa.org.za/products-and-services/forecasts-and-predictions	Hermanus, Western Cape, South Africa
Instituto Nacional de Pesquisas Espaciais, Estudo e Monitoramento Brasileiro do Clima Espacial	INPE, EMBRACE	https://www2.inpe.br/climaespacial/portal/en/	
Auroras Now!	FMI	https://aurorasnow.fmi.fi/	Helsinki, Finland
ESA Space Safety Programme Space Weather Service Network	ESA SSA SWE	https://swe.ssa.esa.int	Darmstadt, Germany
European Consortium for Aviation Space weather User Services	PECASUS	https://www.pecasus.eu/	Helsinki, Finland

Table 1 Space weather prediction centres all over the world: from US to China and from South Africa to Finland.

Name	Shortcut	Expecmrties	URL	Location
Wigner Research Centre for Physics, Department of Space Physics and Space Technology	Wigner FK	heliosphere, planetary magnetospheres	https://space.wigner.hu	Budapest
Centre for Energy Research, Space Dosimetry Group	EK	space dosimetry, magnetometers	https://www.spacedosimetry.com	Budapest
Institute of Earth Physics and Space Science	EPSS	ionosphere, bow shock, GIC	https://www.epss.hu	Sopron
Eötvös Loránd University, Faculty of Sciences, Department of Astronomy	ELTE	solar physics	https://astro.elte.hu	Budapest
Eötvös Loránd University, Faculty of Sciences, Space Research Group	ELTE	plasmasphere, radiation belts	https://sas2.elte.hu	Budapest
Technical University of Budapest, Faculty of Electrical Engineering, ... Group	...	instruments, batteries	https://www.bme.hu	Budapest

Table 2 The Space Weather related capabilites and experties of the Hungarian research institutes and universities.

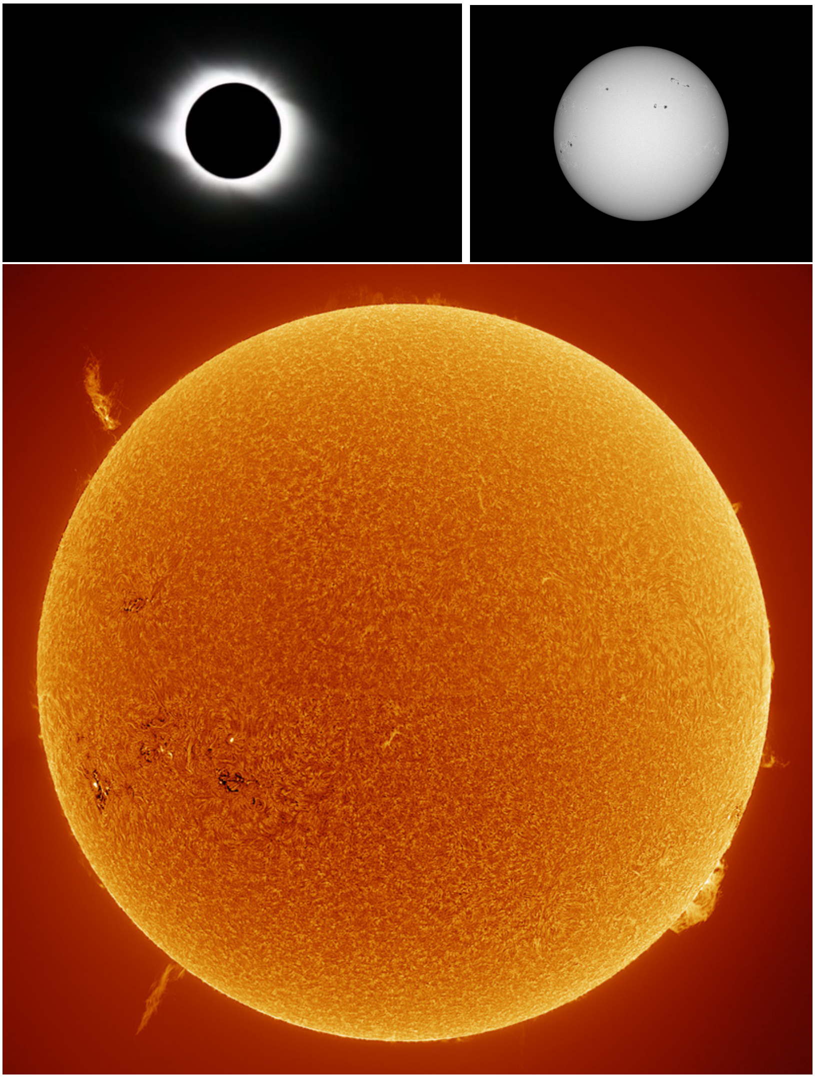

Fig. 1 (Top left) During a total solar eclipse, the hot, relatively faint, extended upper atmosphere of the Sun (the solar corona) becomes visible. (Top right) Even in visible light, you can see structures, and spots on our star. (Bottom) Using H_α filter (656.28 nm) the granulation of our stars becomes visible on the bottom of its transparent atmosphere (the so-called photosphere), and the protuberances, erupt structures around the disc as well. (Credit: https://www.timeanddate.com/, https://c.tadst.com/gfx/600x337/total-solar-eclipse.jpg; https://csillagtura.ro, https://csillagtura.ro/wp-content/uploads/2023/02/20230213_T110800Z_timeisavgof3_s7c_nap_sun_solar_continuum_7p5nm_slc_AS_F500_lapl5_ap635_reg1_ps3.jpg; Peter Borovszky https://tavcso.hu/contents/img/gallery/1002555.jpg.)

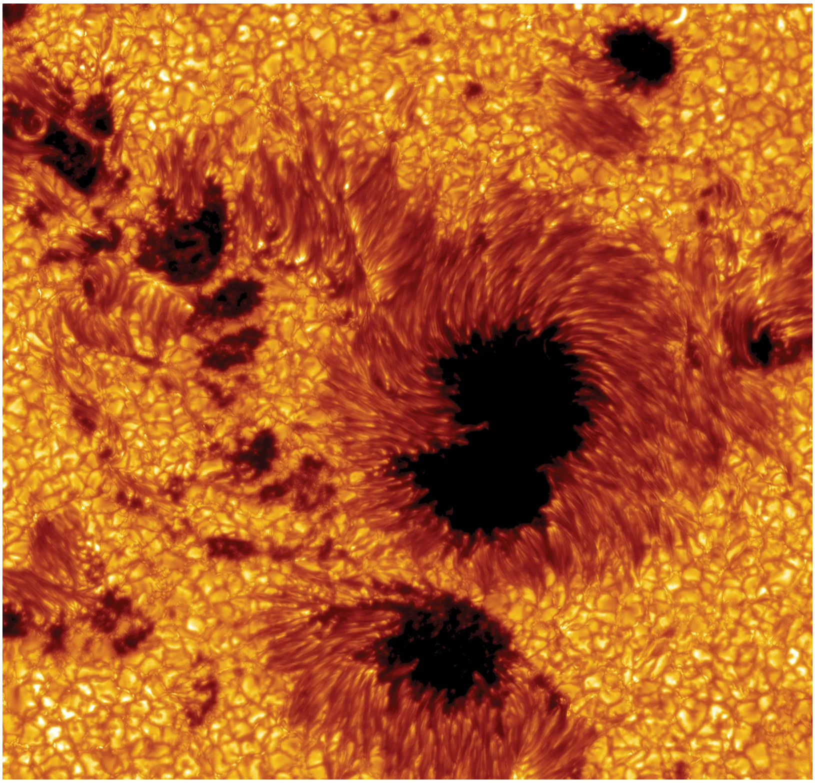

Fig. 2 The sunspots are the prove of the magnetic activity of the Sun. The magnetic field lines intersect the photosphere and cool down a region. The colder regions look darker on the bright disc. (Credit: Encyclopedia Britannica, https://cdn.britannica.com/12/96912-050-D5DB526D/group-region-Sunspot-Swedish-Solar-Telescope-image.jpg)

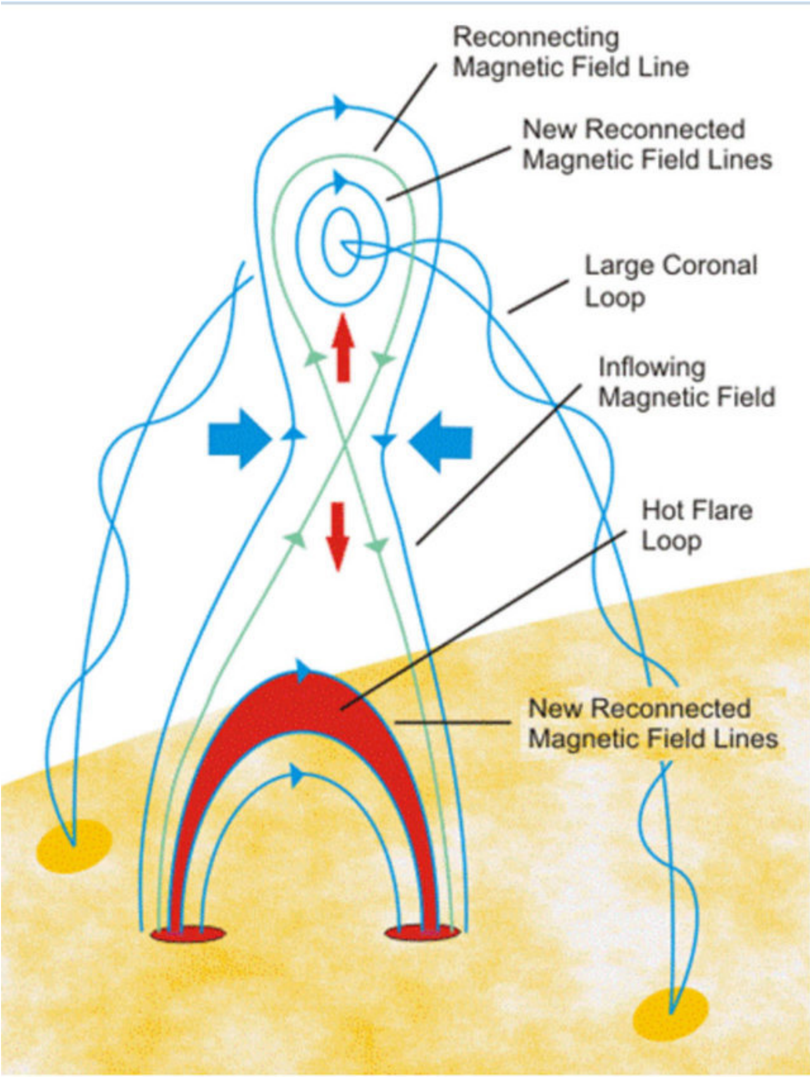

Fig. 3 A draft of magnetic reconnection and a solar flare. (Credit: Gordon Holman and NASA, https://www.researchgate.net/profile/Jose-Campos-Rozo/publication/318404921/figure/fig11/AS:631675696451597@1527614630141/2-An-illustrated-model-of-magnetic-reconnection-and-solar-flare-diagram-Image-Credit_W640.jpg)

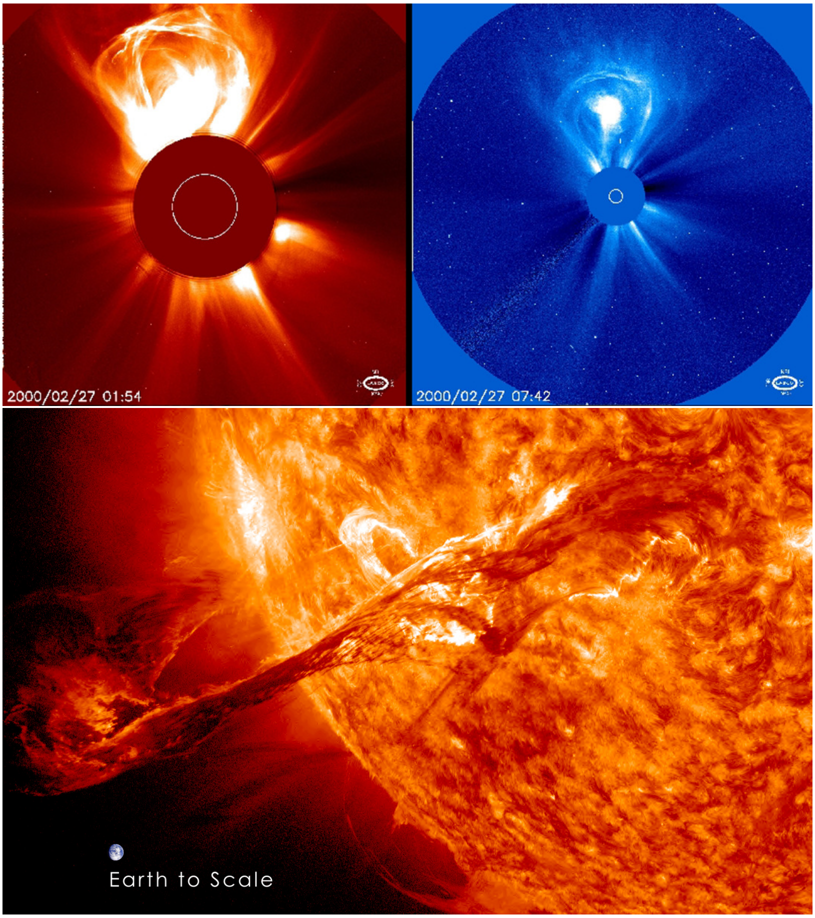

Fig. 4 (Top left and right) A coronal mass ejection on February 27, 2000, taken by SOlar and Heliospheric Observatory (SOHO) Large Angle and Spectrometric Coronagraph Experiment (LASCO) C2 and C3. A CME blasts into space a billion tons of particles traveling millions of miles an hour [20, 21]. (Bottom) Solar Dynamic Observatory (SDO) image of the Earth to scale with the filament eruption on August 31, 2012 [22]. (Credit: SOHO ESA & NASA, https://www.nasa.gov/sites/default/files/thumbnails/image/faq4.jpg; NASA Goddard Space Flight Center, https://svs.gsfc.nasa.gov/vis/a010000/a011000/a011095/earth_scale.jpg)

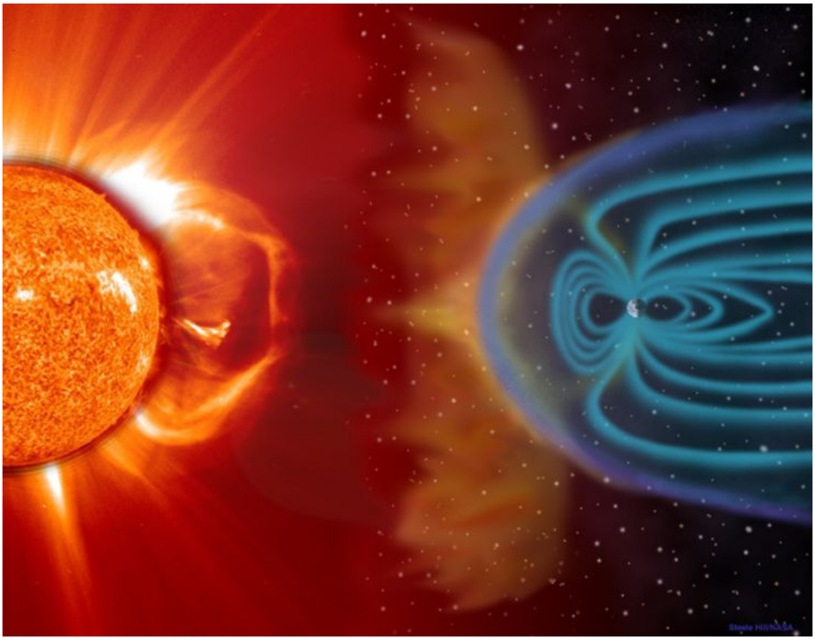

Fig. 5 The CMEs could reach our planet. The Earth's magnetic field, displayed in blue, protects our planet from the harmful radiation of our star. CMEs cause the colorful auroras around the poles as they interact with Earth's magnetic shield and can disrupt GPS and communication satellites. (Credit: NASA Goddard Space Flight Center, https://res.cloudinary.com/dtpgi0zck/image/upload/s--eqSnFkH6--/c_fit,h_580,w_860/v1/EducationHub/photos/solar-wind.jpg)

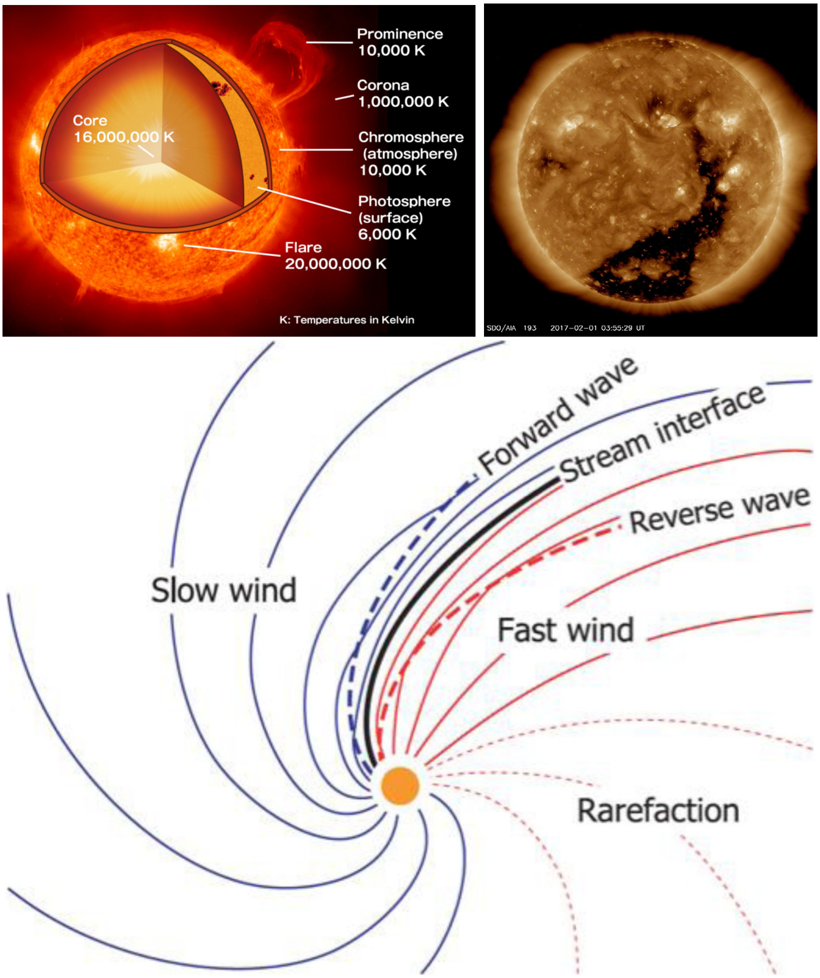

Fig. 6 (Top left) The structure and temperature of the solar atmosphere. The temperature of the solar corona is much higher than the inner layers of the solar atmosphere. With a strong plasma flow, the solar wind originates from the outer layers of the solar corona. (Top right) A coronal hole observation in extreme ultraviolet light of the SDO / Atmospheric Imaging Assembly (AIA) on February 1, 2017 [22, 23]. Coronal holes are areas of the open magnetic field from which solar wind particles stream into space. (Bottom) The solar wind structure in the ecliptic plane shows the fast (slow) solar wind in red (blue). A magnetic field line moves together with (or frozen in) the solar wind plasma. The plasma moves radially outward and the Sun rotates. These movements create a spiral form of the magnetic field, the so-called Parker spiral. The streams interact with each other and forms compressional and rarefaction regions. These regions (so-called corotating interaction regions, CIRs) hits the terrestrial magnetosphere. (Credit: Institute of Space and Astronautical Science (ISAS) / Japan Aerospace Exploration Agency (JAXA), https://hinode.nao.ac.jp/assets_c/2017/02/41406e85f7de7aadb1d61876ea3b7b03aa22a9c6-thumb-720xauto-2671.png; SDO/AIA, NASA, https://sdo.gsfc.nasa.gov/assets/gallery/preview/Coronal_hole_193_Feb.jpg; [24], Fig. 30, https://media.springernature.com/full/springer-static/image/art%3A10.1186%2Fs40645-021-00426-7/MediaObjects/40645_2021_426_Fig30_HTML.png)

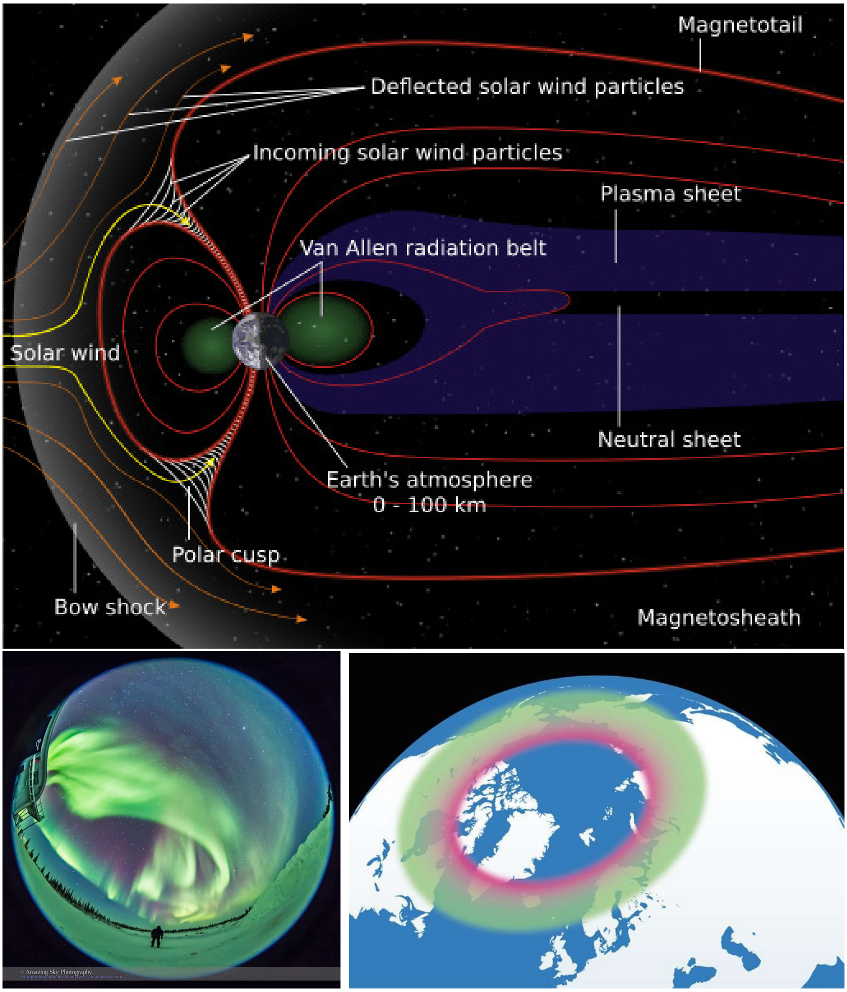

Fig. 7 (Top) The terrestrial magnetosphere and its regions: the bow shock, the magnetosheath, the magnetopause, the radiation belts, the plasmasphere, the cusps, the tail, and the neutral sheets. (Bottom left) The aurora looks beautiful on the night skies of high altitudes. The human eyes can usually observe only the green light. (Bottom right) The solar wind enters the terrestrial magnetosphere and creates aurora. There is aurora in daylight too however you cannot see it. The aurora looks oval on the surface of the Earth around the north and south poles. (Credit: Kiddle, https://kids.kiddle.co/images/thumb/5/50/Structure_of_the_magnetosphere-en.svg/512px-Structure_of_the_magnetosphere-en.svg.png; Amazing Sky Photography, https://amazingsky.files.wordpress.com/2015/02/churchill-aurora-all-sky-2-feb-13-2015.jpg; Discover the World 2023, https://www.discover-the-world.com/app/uploads/2019/06/auroral-zone-northern-hemisphere-discover-the-world-800x0-c-default.jpg)

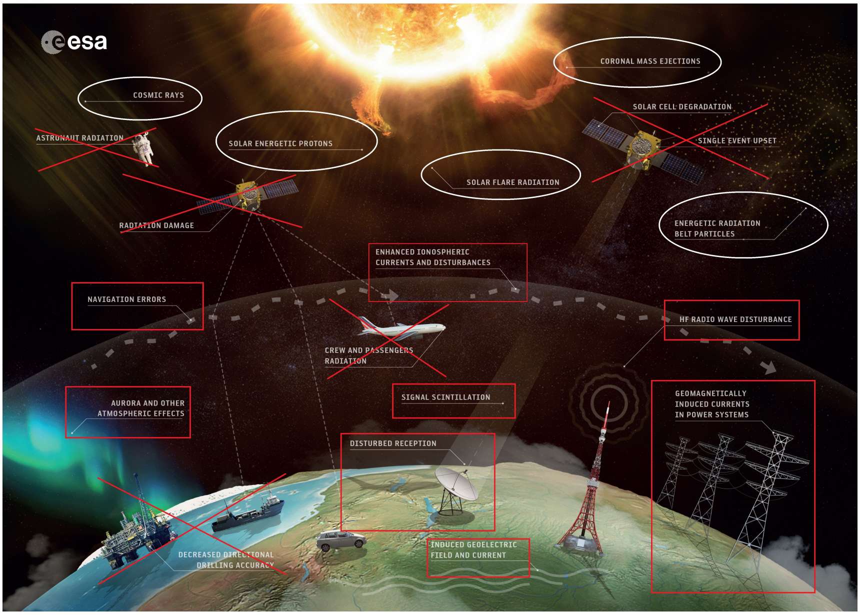

Fig. 8 (White ellipses) Space weather is guided by the radiation from outside the Solar System (cosmic rays), solar energetic particles, solar flare radiation (for example X–rays), radiation from the Earth's radiation belts, and the coronal mass ejections. (Red rectangles) These disturbances cause navigation errors, enhanced ionospheric currents and disturbances, high-frequency radio communication disturbances, GNSS location problems, radio reception disturbances, aurora, and, geomagnetically induced currents in current systems, gas pipelines, and train overhead wires. (Red crosses) Those space weather effects are not considered in this paper. (Credit: ESA, https://www.esa.int/var/esa/storage/images/esa_multimedia/images/2018/01/space_weather_effects/17231521-7-eng-GB/Space_weather_effects_pillars.jpg)