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Sun: Source of Space Weather

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Abstract

The sun is a 4.5 billion-year-old star of our planetary system. It is not only a source of energy and light for humans on Earth, but also one of the biggest subjects of interest for scientists and researchers, to study space weather. Space weather obviously refers to the conditions in space that are of human concern. Space weather is distinct from terrestrial weather. The Sun is directly or indirectly responsible for all the space weather events which affect the space-borne (satellites, rockets) and ground based technological systems (communication, navigation) and in the worst case endangers human health and life (Kumar et al., 2010). Sudden bursts of plasma and magnetic field structures from the sun's atmosphere called coronal mass ejections (CME) together with sudden bursts of radiation, or solar flares, all cause space weather effects here on earth. Thus Solar flares and coronal mass ejections are two transient and most explosive phenomena that occur on the sun releasing enormous amounts of energy. The explosive energy released during these events severely disturbs our space environment and is of great concern to us from space weather point of view. The Carrington Event was the most intense geomagnetic storm in

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recorded history, occurring on 1–2 September 1859 during solar cycle 10. It created strong auroral displays that were reported globally and caused sparking and fire in multiple telegraph systems (NOAA). Like earth, sun also generates a magnetic field that extends out into space known as IMF (Interplanetary magnetic field), but unlike Earth magnetic field, sun' magnetic field is complex due to differential rotation of sun (faster in equator and slow in poles) and change of its polarity over 11 years, known as solar cycle. All eruptive phenomena in the sun are driven by the solar magnetic field. This chapter focuses on the brief introduction about sun and space weather events.

The sun lies at the heart of the solar system and is roughly 109 times the diameter of the Earth; about one million Earths could fit inside the sun. It holds 99.8 percent of the solar system. The Sun is not a solid and typical gas but consists of plasma (collection of charged particles electrons and ions), a fourth state of matter. Thus it is also a source of space plasmas throughout the solar system. The distance between sun and Earth is about 150 million kilometers Due to the presence of very much lighter elements, such as hydrogen (70%) and helium (26%), the average density of the sun is 1.41 g/cc as compared to that of Earth's mean density of 5.52 g/cc. Under its own gravitational attraction, solar material is compressed to such a high central density and temperature, that nuclear reactions take place in the sun. Each second about 5.7×10^{11} kg of hydrogen are converted into helium and about 4.3×10^{3} kg of mass loss each second and it is converted into energy in the form of gamma rays. It releases energy about 3.86×10^{26} J/s. The general structure of the sun can be divided into two parts, solar interior and solar atmosphere. The solar interior is completely opaque and there are no observations. However theoretical models have been suggested. The solar interior of the sun is made up of the Core, Radiative zone and the Convective zone.

The core is a region of solar interior, where nuclear fusion reactions take place at a temperature of order 1.5 degree Kelvin and generate a huge amount of energy. The region above the core is a radiative zone, where energy generated in the core is transferred from the hotter (inner) to the cooler (outer) layers by photons of radiation, each carrying an appropriate quantum of energy. These photons are scattered, absorbed and reemitted over and over again, gradually making their way toward the surface. A photon may take as long as 50 million years to travel all the way through the radiative zone. The region above the radiative zone is convection zone, where hot material from near the radiative zone rises, cools at the Sun's surface, and then plunges back downward to the radiative zone. The regions above the convection zone are visible and belong to the solar atmosphere, from which solar energy is radiated into space. The Sun's atmosphere can also be divided into three regions: the photosphere, the chromosphere, and the corona. The photosphere is the visible surface of the Sun that emits the most of the sunlight. It can be photographed under normal conditions. The temperature of the photosphere is about 6000 degrees Kelvin. The photosphere is characterized by granulation (appearance like rice grains) and facule. It is about 300 miles (500 kilometers) thick. The chromosphere is just above the photosphere and characterized by plages and prominences. Both are active sun features and are present near the sunspot areas. Thickness of the chemosphere is about 2500km.The Corona is the uppermost portion of the solar atmosphere which has a strong temperature gradient over the sun's surface. It is made of structures such as loops and streams of ionized gas. The corona temperature is generally 10^6 K and can even increase, when a solar flare occurs. Heating of corona is an important plasma physics problem. Corona can be seen during a total solar eclipse. Matter from the corona is blown off as the solar wind.

The sun' magnetic field plays an important role in the plasma motion in different regions of the sun, which is much more complicated and variable compared to earth. The strength of the sun's magnetic field is typically only about twice as strong as Earth's field. However, it becomes highly concentrated in small areas reaching up to 3,000 times stronger than usual. It is observed that polarity of the solar magnetic field is reversed after every 11 years which is known as solar cycle. The solar magnetic field plays very crucial roles in creating many phenomena including sunspot, corona heating prominences and solar flares etc.

Space Weather is a term which has become accepted over the past few years to describe the collection of physical processes, occurring in the sun, associated with its intense and disturbed magnetic field and ultimately affecting human activities on Earth and in space. The Sun emits energy, as flares of electromagnetic radiation (radio waves, infra-red, light, ultraviolet, X-rays), and as energetic electrically charged particles through coronal mass ejections (CME) and plasma streams. The particles travel outwards as the solar wind, carrying parts of the Sun's magnetic field with them. The electromagnetic radiation travels at the speed of light and takes about 8 minutes to move from Sun to Earth, whereas the charged particles travel more slowly about 450 to 1200 km/sec, taking from a few hours to several days to move from Sun to the earth. The radiation and particles interact with the Earth's magnetic field and outer atmosphere in complex ways, causing concentrations of energetic particles to collect and electric currents to flow in regions of the outer atmosphere (magnetosphere and ionosphere).These can result in geomagnetic variations, aurora, and can affect a number of technologies as power transmission line, satellites communication. Some of important space weather events are summarized as below:

Sunspots

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The most obvious features of the disturbed magnetic field of the sun are the sunspots. The sunspot was first observed by Galileo around 1600 A.D, but reliable observations have been available since 1870. Sunspots are dark areas on the solar surface; contain strong magnetic fields that are constantly shifting during normal solar rotation. The magnetic field in a sunspot is 1000 or more times stranger than the average magnetic field of the Sun, which inhibits the transport of heat via convective motion in the sun and makes a dark appearance. Sunspots often appear in groups with two sets of spots, in which one set is like the north pole of a magnet and the other is like the south pole of a magnet. The two poles (sunspots) are linked by loops of magnetic field which arch through the sun's corona. A typical spot has a dark central region called umbra (with strongest magnetic field), which is surrounded by brighter but still dark regions with filament-like appearance called penumbra. Over the last 300 years, the average number of sunspots has regularly waxed and waned in an 11-year sunspot cycle (Samuel Heinrich Schwabe in 1843). This sunspot cycle is a useful way to mark the changes in the Sun. Solar Minimum refers to the several Earth years when the number of sunspots is lowest; Solar Maximum occurs in the years when sunspots are most numerous. During Solar Maximum, activity on the Sun and its effects on our terrestrial environment are high.

Solar flares

Solar flares are the most spectacular disturbances seen on the sun, typically lasting several minutes. It can be defined as the sudden brightening and explosive release of energy ($\sim 10^{19} - 10^{25}$ J) from a localized active region of the sun, mainly in the form of electromagnetic radiation, including X-rays, ultraviolet radiation, visible light, and radio waves. A large solar flare generally consists of three phases (Sturrock, 1980; Priest, 1984), namely the pre-flare phase, the impulsive

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phase and the main phase. The first known observations of a solar flare were made on 1 Sep, 1859 by Richard C. Carrington and Richard Hodgson, observing independently in white light. According to the peak flux (watts/square meter) of 100-800 picometer (1-8 , solar flare usually may be categorized into classes X, M, C, or B.(Carrington 1859). X-class flares are intense, M-class flares are moderate .Compared to X- and M-class flares, C-class flares are weak and have ignorable influence on Earth. The flux peak of these class flares X, M, C, or B is of order 10^{-4}, 10^{-5}, 10^{-6}, and 10^{-7} watts m^{-2} respectively, measured by the geostationary operational environmental satellite (GOES) since 1996.

Coronal mass ejections are explosive outbursts of plasma from the Sun's outer atmosphere, the Corona. SOHO/LASCO and EIT images are used to best observe CMEs. CMEs are characterized by their speed, angular width, and central position angle in the sky plane. Their speeds are often fairly constant over the first few solar radii (St Cyr et al. 2000) and range between 300 and 3,000 km s-1 (Bothmer and Zhukov, 2006). The occurrence rate of CMEs vary with solar activity; during low solar activity it is less than one event per day and during high solar activity period it can exceed 10 or more (Bothmer and Zhukov, 2006). A large CME can contain a billion tons of matter that can be accelerated to several million miles per hour in a spectacular explosion. Solar material streams out through the interplanetary medium, impacting any planet or spacecraft in its path. CMEs heading towards Earth have the potential to cause geomagnetic storms. The solar wind of a magnetic storm can interfere with the Earth's magnetosphere, disrupting radio and GPS signals. A geomagnetic storm can also damage power grids; in 1989, in Quebec, a solar storm was to blame for a massive power outage there. Thus solar flares and CMEs are two most important energetic explosions in the solar atmosphere.

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Coronal holes

A coronal hole is a large region in the corona which is less dense and is cooler than its surroundings. Coronal holes are variable solar features that can last for weeks to months and may appear at any time of the solar cycle but they are most common during the declining phase of the cycle. These holes are rooted in large cells of unipolar magnetic fields on the Sun’s surface; their field lines extend far out into the solar system. These open field lines allow a continuous outflow of high-speed solar wind.

Geomagnetic storm

A geomagnetic storm is a temporary disturbance of the Earth's magnetosphere, caused by sudden strong variations in the speed, density and magnetic properties of the solar wind. It occurs when very efficient energy is transferred into the earth magnetosphere from solar wind via magnetic reconnection (Dungey, 1961; Fairfield et al., 1971; Gonzalez and Tsurutani, 1987). It is the most important space weather phenomenon in sun-Earth connection, which can affect global magnetosphere-ionosphere-thermosphere system (Blanch et al., 2005) and generally associated with either Coronal Mass Ejections (CMEs) or Co-rotating Interaction Regions (CIRs).

Solar prominences:

Solar Prominences are originated as clouds of solar material held above the sun’s surface by fields of magnetic force .The clouds remain suspended, relatively quiescent until they erupt, releasing large amounts of solar matter into space.

Auroras: Auroras or northern lights are atmospheric phenomena. These are beautiful dances of lights seen in the night sky. It begins between 70 and 80 degrees latitude. As a storm intensifies, the aurora spreads towards the equator. They are driven by the energy coming from the Sun. When the Sun is active, it often produces mass ejections of charged particles that get trapped by the earth's magnetic field. Guided by the magnetic field, the high energetic particles flow towards the earth's poles and due to high energy it enters into the earth's ionosphere, where they collide with nitrogen and oxygen molecules, atoms and ions. As a result of this interaction, green, blue and red light is emitted. Green and red light emitted due to oxygen and violet-blue light due to nitrogen. It is called the aurora borealis in the northern hemisphere and aurora Australis in the southern hemisphere. It is observed that three kinds of space weather events (solar flares, CMEs and coronal holes) have the potential to affect the near Earth environment. The effects of space weather can range from damage to satellites to disruption of power grids on Earth. For example, in 2012, scientists publishing in the journal *Space Weather* suggested that a 2001 power failure in New Zealand was caused by a solar storm.

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