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# The Sun and Earth's Space Environment

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*Abstract*— **Earth's space environment is closely controlled by solar variability over various time scales. Solar variability is characterized by its output in the form of mass and electromagnetic output. Solar mass emission also interacts with mass entering into the heliosphere in the form of cosmic rays and neutral material. This paper provides an overview of how the solar variability affects Earth's space environment.**

**Keywords-*space weather; coronal mass ejections; solar energetic particles; geomagnetic storms; climate***

## I. INTRODUCTION

The Sun is ultimately responsible for the survival of living beings on Earth. Most of the energy that the humankind uses today is the direct result of the heat and light from the Sun on Earth, except possibly the nuclear and geothermal energy. Thus the Sun forms the basis for life on Earth via the black body radiation it emits. In addition to the electromagnetic emission, the Sun also emits mass in the form of solar wind and coronal mass ejections (CMEs). Solar energetic particles (SEPs) can also be considered as mass emission, but they are emitted during solar flares and CMEs. Both the mass and electromagnetic energy output of the Sun vary over a wide range of time scales, thus introducing disturbances on the space environment that extends from the Sun through the entire heliosphere including the magnetospheres and ionospheres of planets and moons of the solar system. In addition to the variability of the Sun, the space environment is also affected by material entry into the heliosphere in the form of neutral matter and galactic cosmic rays that interact with the mass emission from the Sun producing additional variability in the space environment.

Although our habitat is located in the neutral atmosphere of Earth, we are intimately connected to the non-neutral space environment starting from the ionosphere to the magnetosphere and to the vast interplanetary space. The variability of the solar mass emissions results in the interaction between the solar wind plasma and the magnetospheric plasma leading to huge disturbances in the geospace. The Sun ionizes our atmosphere and creates the ionosphere. The ionosphere can be severely disturbed by the transient energy input from solar flares and the solar wind during geomagnetic storms. The magnetosphere protects us from the dangerous cosmic rays, but it creates its own energetic particles that can harm humans and their technological systems flown into the magnetosphere. Similarly CMEs that deflect galactic cosmic rays approaching Earth, can also produce their own energetic particles. The complex interplay between Earth's magnetic field and the solar magnetic field carried by the solar wind presents varying conditions that are both beneficial and hazardous to life on Earth. This paper presents some of the key aspects of this Sun-Earth connection.

## II. SOLAR VARIABILITY

The space environment changes over time scales ranging from seconds to millennium. The short time scale fluctuations are termed as space weather and the long term averages and extremes belong to the realm of climate. Solar activity is one of the important manifestations of the solar variability. Compact magnetic regions emerge from under the solar surface and live for days to weeks. These are known as active regions. At the photospheric layer, the active regions consist of sunspots, which are regions of very high magnetic field (up to several thousand G). Active regions are typically bipolar or multipolar, which means hot magnetic loops connect the opposite polarity patches. These loops are hot (emit in soft X-rays and in extreme ultraviolet wavelengths) and constitute the active region corona. The number of active regions present on the Sun reaches its maximum value approximately every eleven years during a period known as the solar activity maximum. Powerful CMEs and flares originate from active regions. Thus the presence of active regions on the Sun directly facing Earth represents a potentially dangerous situation because CMEs released from such active regions are highly likely to reach Earth and disturb the space environment. During the beginning of a solar cycle, sunspots appear at latitudes near 40° and then progressively at lower latitudes before the activity declines to a minimum level. The solar activity thus has a periodicity of 11 years (see Figure 1).

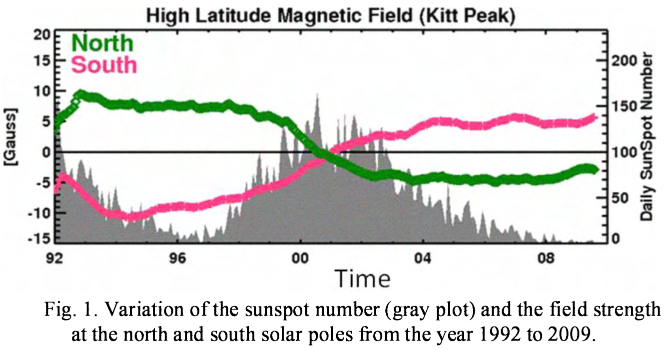


Fig. 1. Variation of the sunspot number (gray plot) and the field strength at the north and south solar poles from the year 1992 to 2009.

When a new cycle begins, the leading polarity (the western part of the active region) has a sign opposite to that of the previous cycle. Thus active regions return to the same sign every 22 years. Active regions originate at any longitude, but they can face Earth due to solar rotation. The 22-year magnetic cycle can also be observed in the sign of the magnetic field at the solar poles. The average polar magnetic field reaches a minimum value and changes the sign near the solar activity maximum. The sunspot fields and the polar fields are considered to be related to each other via the solar dynamo that sustains solar magnetism. Variability in the solar magnetism is considered to be important for both space weather and Earth's climate.

*A. CMEs*

CMEs are large-scale plasma structures that erupt from closed magnetic field regions on the Sun, such as active regions and filament regions. Although the exact mechanism of CME eruption is not understood, it is believed that photospheric motions and/or newly emerging flux stress the magnetic field configuration, thereby storing free magnetic energy in the source regions. The stored energy is then released in the form of CMEs and flares. The released energy is portioned into mass motion (CMEs) and plasma heating (flares).

Fig. 2 shows a large-scale CME in images obtained by the Solar and Heliospheric Observatory (SOHO) mission's Large Angle and Spectrometric Coronagraph (LASCO). The image before the CME eruption shows the solar corona in white light with many bright streamers and the solar disk in EUV observed by SOHO's Extreme-ultraviolet Imaging Telescope (EIT). The two frames were obtained less than an hour apart. The CME can be seen as a large bubble-shaped structure filling the southwest quadrant of the image, overlying the bright flare on the solar disk (pointed by arrow F). There is also a disturbance surrounding the bubble as can be seen from the deflection of the streamer structure marked S. The disturbance is associated with the bow shock driven by the CME that moved out with a speed of 2400 km/s.

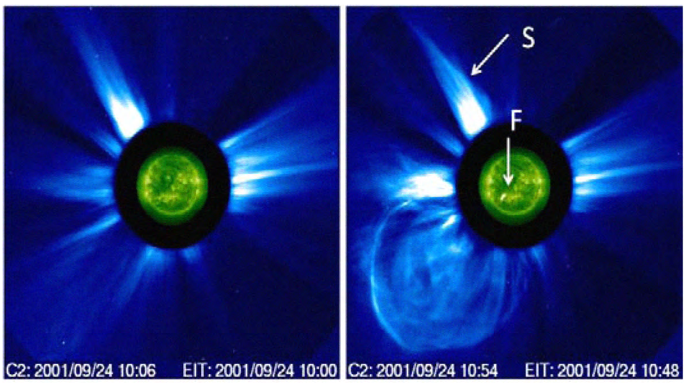


Fig. 2. Two composite frames of coronal images from SOHO/LASCO (outer) and EIT (inner) showing the dramatic expulsion of a CME from the Sun. The flare site (bright patch on the solar disk) is pointed by the arrow F. The CME is surrounded by a shock disturbance, whose signature can be found as the deflection of a streamer (pointed by arrow S). The dark disk is the occulter in the coronagraph.

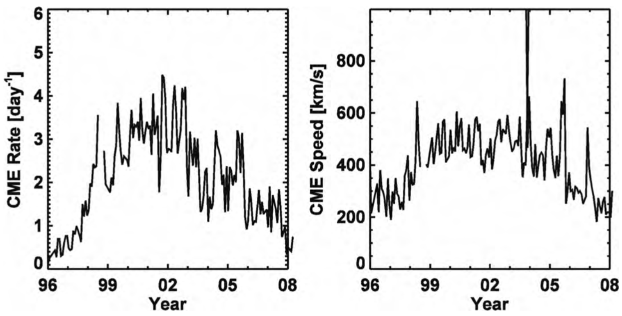


Fig. 3 CME daily rate (left) and average speed (right) averaged over Carrington Rotation period (27 days). The spikes are due to some persistent super active regions.

This is one of the exceptionally fast CMEs, whereas the average CMEs have a speed typically less than 500 km/s. More than 10000 CMEs have been recorded by LASCO over the past 13 years of operation. Details of CME properties can be found, e.g., in [1-3]. Here we summarize the statistical properties of CMEs detected by LASCO.

(1) The CME speed (projected on the sky plane) ranges from ~20 km/s to more than 3000 km/s, with an average value of 466 km/s. (2) The apparent angular width ranges from $<5^o$ to $360^o$ with an average value of $\sim 41^o$ ($60^o$ when CMEs wider than $30^o$ are considered). (3) CMEs faster than solar wind decelerate, while the slower ones accelerate. CMEs with speeds close to the solar wind speed do not have observable acceleration. (4) CME mass ranges from $\sim 10^{12}$ to $> 10^{16}$ g with an average value of $\sim 10^{14}$ g. (5) From the observed mass and speed, one can see that the kinetic energy ranges from $\sim 10^{27}$ to $>10^{33}$ erg, with an average value of $5.4 \times 10^{29}$ erg. (5) The daily CME rate averaged over Carrington rotation periods (~27 days) ranges from <0.5 (solar minimum) to >6 (solar maximum). The average speed increases from ~250 km/s during solar minimum to >550 km/s during solar maximum (see Fig. 3). (6) CMEs moving faster than the coronal magnetosonic speed drive shocks, which accelerate solar energetic particles (SEPs) to GeV energies. The shocks also accelerate electrons, which produce nonthermal radio emission (type II radio bursts) throughout the inner heliosphere. CMEs are often associated with EUV waves, which may be fast mode shocks when the CME is fast enough [4]. (7) CMEs are multithermal plasmas containing coronal material at a temperature of ~ a few $\times 10^6$ K and prominence material at ~8000 K in the interior of CMEs. (8) Some energetic CMEs move as coherent structures in the heliosphere all the way to the edge of the solar system. (9) Theory and interplanetary observations suggest that most CMEs contain a flux rope structure.

*B. Flares*

A solar flare can be defined as a sudden and rapid release of energy from a localized region on the Sun mainly in the form of electromagnetic radiation over the entire spectrum. The radiation is from plasma heated to tens of millions K. Particles accelerated during the flare energy release produce nonthermal emission in radio and X-ray wavelengths. The heated plasma resides in the closed loops created during the eruption process. Fig. 4 shows two soft X-ray flares with their energies differing by more than four orders of magnitude. CMEs are accompanied by solar flares whose intensity in soft X-rays is correlated with the CME kinetic energy [5]. However, more than half of the flares are not associated with CMEs. Such flares, known as confined flares, are generally compact and originate from deeper layers of active regions.

### *C. Coronal Holes*

The solar polar fields are high during solar minima and large coronal holes are present at the solar poles. Coronal holes are sources of high-speed solar wind (speeds up to ~800 km/s). As the solar cycle progresses, the polar holes shrink and low-latitude coronal holes develop either as isolated patches or as low-latitude extensions of polar holes. In the declining phase, the equatorial coronal holes dominate. Coronal holes have distinct magnetic properties in that the photospheric field is unipolar and enhanced with respect to the surrounding quiet Sun. The enhanced magnetic field somehow contributes to the increased flow speed. The speed variability due to the coronal holes leads to an interesting phenomenon known as the corotating interaction regions (CIRs). Fast wind from coronal holes catches up with the slow wind originating from the surrounding areas, compressing it and forming CIRs. CIRs can impact Earth's magnetosphere causing effects similar to those following the CME impact.

## III. SPACE WEATHER

Space weather affects our day-to-day activities because the human society is more and more dependent on space technology from agriculture to oil prospecting, from telecommunication to XM radio, from airplane travel to living on the International Space Station, and so on. The dominant subset of space weather that is relevant for space technology is the particle radiation or energetic particle environment, including electrons, protons, neutrons, and charged ions with energies from keV to GeV [6]. Radiation exposure increases the risk to long-term astronaut health as well as some risk of acute effects. A radiation event can damage/disrupt critical electronics on the satellite or interfere with communications for both human space flight and robotic missions. In the case of human space flights, response to radiation event can temporarily suspend mission operations. Radiation exposure limits the life of some electronics and components. Single-event upsets are a risk to avionics and can lead to loss of launch vehicles. Response to a radiation event can delay launch. Thus understanding and predicting the sources of particle radiation is of primary importance for a wide variety of technological applications. All the three categories of solar variability discussed in the previous section result in the production of particle radiation. CMEs and flares produce SEPs. When CMEs and CIRs impact Earth, they produce geomagnetic storms that result in energization of electrons inside the magnetosphere. Flare radiation causes excess ionization in the ionosphere, which can potentially affect radio communication and navigation. Currents in the ionosphere can induce surges in electrical power grids, occasionally disrupting them. Currents can also be induced in the ground that ultimately leads to the corrosion of oil and natural gas pipelines.

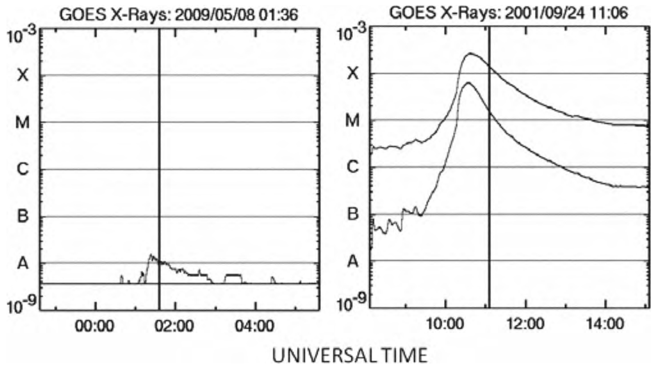


Fig. 4. Examples of soft X-ray flares differing by four orders of magnitude. The flares were observed by the GOES satellite.

## IV. CMES AND SPACE WEATHER

CMEs are responsible for the two major sources of space weather: SEPs and magnetic storms (see Fig. 5 for a summary). The CMEs that produce these two effects differ in terms of their solar source locations and the internal magnetic structure. The spatial domains where the space weather effects are generated are also different. SEP production typically starts when the CME-driven shock is within a few solar radii from the Sun and continues in the interplanetary medium so long as the shock is strong enough to accelerate particles [7]. When the shock arrives at the observing spacecraft, a sudden increase in SEP intensity is observed. The increase is due to the locally accelerated particle in the shock, which is traditionally known as the energetic storm particle event. Geomagnetic storms occur when interplanetary CMEs (ICMEs) and/or the shock sheaths reach Earth's magnetosphere. The shock compresses the magnetosphere producing the sudden commencement of highly disturbed signal in the ground based magnetometers. The intensity and duration of the southward component of the magnetic field in the sheath and ICME determine the strength of the resulting magnetic storm. Thus the magnetic structure of the ICME is important for geomagnetic storms, but not for SEPs. During magnetic storms, particle acceleration also takes place inside the magnetosphere, thus CMEs are indirectly responsible for this second source of energetic particles.

### *A. Geomagnetic Storms*

Geomagnetic storms occur when an interplanetary structure arrives at Earth's magnetosphere with an out-of-the-ecliptic field component that points southward. Any interplanetary structure that can produce a geomagnetic storm is said to be geoeffective. The south-pointing field reconnects with the north-pointing field at the magnetopause, leading to the buildup of the magnetospheric ring current and the aurora. Ground based magnetometers record the storm as the reduction in Earth's horizontal magnetic field. The storm strength is measured by an index such as the disturbance storm time (Dst) index, which is an average of the horizontal magnetic field variation measured at several stations near the equator.

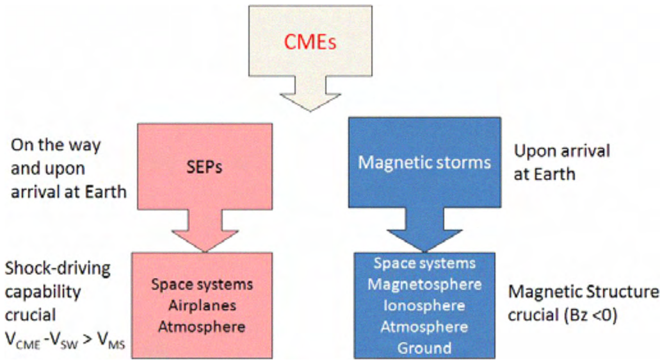


Fig. 5. Illustration of the two space weather effects of CMEs: SEPs and geomagnetic storms. For SEPs, the CME speed ($V_{CME}$) relative to the solar wind speed ($V_{SW}$) must exceed the ambient magnetosonic speed ($V_{MS}$). For magnetic storms, the CME must contain an out-of-the-ecliptic component (Bz <0).

The interplanetary magnetic field typically has no out-of-the-ecliptic magnetic field component. The flux rope structure of ICMEs adds such a component to the interplanetary field. If the axis of the flux rope is in the ecliptic plane, either the front or the back of the flux rope has the south-pointing field. When the flux rope axes are perpendicular to the ecliptic plane, the existence of the southward field depends on the direction of the axial magnetic field. For example, flux ropes with north-pointing axial field have no southward component at all. Thus high-inclination flux ropes with north-pointing axes do not produce geomagnetic storms. On the other hand, flux ropes with south-pointing axes have southward throughout the flux rope and hence highly geoeffective.

Shock-driving ICMEs contain the following structures: shock, sheath, and the flux rope at 1 AU. The shock and the front boundary of the flux rope delineate the sheath region. The sheath contains the compressed heliospheric field that can contain south-pointing field and hence can be geoeffective. Depending on the magnetic structure in the sheath and cloud portions, the following situations are encountered: (1) sheath and MC are geoeffective, (2) sheath alone is geoeffective, (3) MCs alone are geoeffective, and (4) none are geoeffective. The last situation arises when neither the sheath nor the MC contains south-pointing magnetic field component. When both sheath and MC are geoeffective, the Dst time profile can be complex depending on the location of the south-pointing field in the sheath and cloud portions.

While the occurrence of a geomagnetic storm requires the existence of the southward component of the magnetic field in an interplanetary structure, the storm intensity depends also on the speed of the magnetic structure. Fig. 6 shows a plot of the Dst index as a function of the product of the speed (V) and southward field magnitude (Bz) for a set of 50 flux ropes. The correlation between VBz and Dst is very high, with a correlation coefficient (r) of 0.90. Similar high correlation has also been found for the storms caused by the Bz in the sheath portion of flux ropes [8].

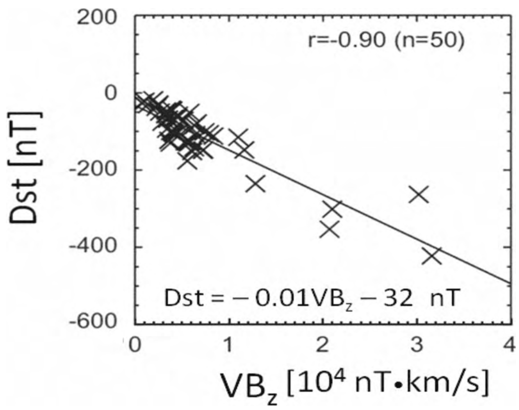


Fig. 6. Dependence of the strength of the geomagnetic storm on the speed of the interplanetary structure (V) and the magnitude of the southward field it contains (Bz).

## B. SEP Events

Physical processes in the solar atmosphere are capable of accelerating some of the particles that constitute the atmosphere to GeV energies. During solar flares, the magnetic reconnection process is thought to accelerate particles and inject them toward and away from the Sun. The particles injected toward the Sun interact with the solar chromosphere and photosphere and produce the flare emission. Particles injected away from the Sun travel along interplanetary magnetic field lines and are detected as SEP events. CME-driven shocks also accelerate particles as they travel from very close to the Sun into the interplanetary medium. During major SEP events, both large flares and energetic CMEs are observed, so it is not easy to separate the contributions made by the two processes until late in the event when the flare has subsided but the CME-driven shock continues to produce SEPs. Since SEPs propagate along interplanetary magnetic field lines, Earth has to be magnetically connected to the acceleration site to detect them.

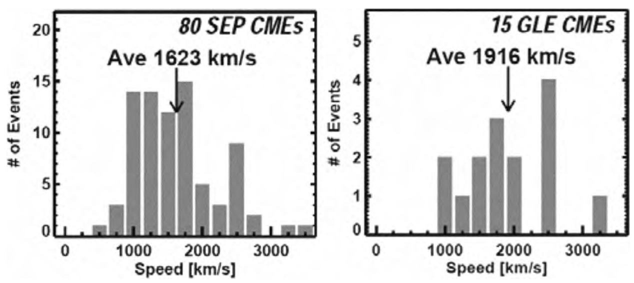


Fig. 7. CME speed distribution for CMEs associated with SEP events (left) and GLE events (right). The average speeds of the distributions are marked on the plot.

SEP events are invariably associated with fast and wide CMEs: The average sky-plane speed of SEP-associated CMEs is ~1623 km/s, which is 3-4 times larger than the speed of average CMEs (see Fig. 7). SEP events can also reach the neutral atmosphere and produce secondary particles such as neutrons and muons that can be detected by ground-based instruments. Such events are known as the ground level enhancement (GLE) events. CMEs associated with GLEs have the highest average speed (~2000 km/s). Large SEP events with particle energies exceeding 100 MeV can interact with the atmospheric molecules producing radicals that ultimately lead to ozone depletion.

### *C. Solar Sources of SEP and Storm Producing CMEs*

Fig. 8 shows the solar sources of CMEs that produced particle and magnetic storms during solar cycle 23 (1996 – 2007). Only intense magnetic storms are considered (Dst <-100 nT). The storms are also grouped into three intensity ranges. CMEs originating from close to the disk center cause the biggest magnetic storms because these CMEs impact head-on on Earth's magnetosphere. The less intense storms have a slightly wider distribution in longitude. Occasionally, storms are caused by exceptionally fast CMEs from the solar limb, by virtue of their shock sheaths. There is also slight western hemispheric bias of the magnetic storm sources probably because CMEs are deflected eastward due to solar rotation.

The particle storms in Fig. 8 were detected by the GOES satellites and the associated CMEs identified from SOHO data. The SEP sources have a distinct western bias because of the spiral structure of the interplanetary magnetic field along which the SEPs propagate. Only those SEPs propagating along the field lines connected to the GOES satellite are detected. CMEs from the eastern hemisphere also produce SEP events, but they are unlikely to arrive at a satellite along the Sun-Earth lines. Fig. 8 shows a few weak SEP events caused by CMEs from near the east limb. These CMEs are extremely energetic and the shocks are very large-scale so that their western flanks cross the field lines that connect to the Earth observer. For the connectivity reason, CMEs originating from behind the west limb produce an SEP events at Earth, while those behind the east limb almost never do [9]. Fig. 2 further illustrates that it is important to image CMEs when they occur on the Earth-facing side of the Sun and estimate its properties when they are close to the Sun in order to develop the capability to predict particle and magnetic storms.

### *D. Geomagnetic Storms due to CIRs*

The primary requirement for geomagnetic storms is the existence of southward component of the interplanetary magnetic field. In the solar wind, one often observes Alfven waves, which are likely to have out-of the-ecliptic excursions of the magnetic field. When a coronal hole crosses the central meridian of the Sun, Earth can encounter a CIR. The Alfvenic fluctuations get amplified in the CIR resulting in large southward magnetic field component. The magnitude of Bz and the solar wind speed in the interaction regions are often comparable to those in ICME structures [10]. The storms caused by CIRs are generally of low intensity; intense storms occur only occasionally. However, the CIRs storms can be more frequent than the CME storms, especially during the declining phase of the solar cycle when low-latitude coronal holes occur in great abundance. Another distinguishing characteristic of the CIR storms is that they are associated with high energy electrons in the magnetosphere and an enhanced precipitation of such electrons in the polar regions [11].

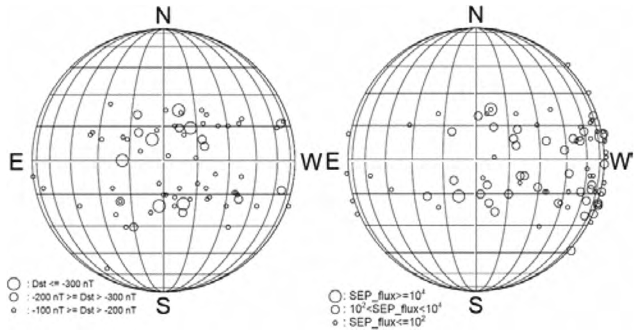


Fig. 8. Solar sources CMEs that produce magnetic storms (left) and SEP events (right). Storm and SEP events are distinguished by three intensity levels.

## V. SOLAR ACTIVITY AND EARTH CLIMATE

Space weather is not the only consequence of the varying solar activity represented by the sunspot number. The amount of radiation received by Earth (total solar irradiance or TSI) is also affected by the solar activity. Spacecraft observations have shown that the TSI varies by ~0.1% during a solar activity cycle and is in phase with the sunspot number. This is somewhat surprising because increase in the number of sunspots should actually decrease the amount of radiation received by Earth because sunspots are dark, so less radiation is emitted. The paradox can be resolved when one pays attention to the fact that sunspots appear on the solar surface along with extended bright regions (faculae) of high magnetic field, which are bright. This is illustrated in Fig. 9 using an intensity image and a magnetogram obtained by SOHO during the maximum phase of solar cycle 23. The net result is that the irradiance is the highest during the solar maximum [12]. During some cycles the sunspot number is extremely low, which means Earth does not receive enough energy, which can lead to global cooling. The 11 year cycle seems to be modulated by low sunspot activity with a period of ~80 years.

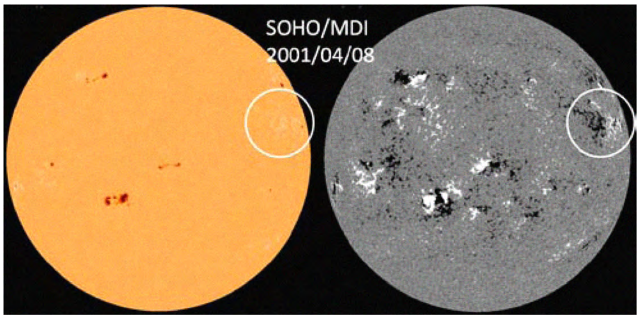


Fig. 9 Intensity (left) and magnetogram (right) obtained by SOHO on 2001 April 8. Note the bright region (enclosed by the white circle) near the sunspot associated with enhanced magnetic field. Many other sunspots and bright regions (faculae) can be found on the solar disk.

Table I shows a list of recent minima with their durations. There are excellent historical records to show that there was global cooling in the medieval period when the Maunder minimum was in progress [13]. Some researchers believe that we may be entering into another global minimum based on the low solar activity in solar cycle 24, which started in the beginning of 2008, but remains low-key. The low solar activity is also indicated by the subdued polar field strength during cycle 23, which is thought to be converted into the sunspot fields during cycle 24 (see Fig. 1). The low solar activity has a number of consequences: The plasma density and magnetic field in the heliosphere is significantly reduced (by ~30%), which is likely to decrease the Alfven speed by about 15%. Such reduction will make it easier for CMEs to drive shocks in the interplanetary medium.

The current value of the average interplanetary magnetic field (IMF) has declined below 4 nT [15]. Accordingly, the cosmic ray intensity has reached record levels, nearly 20% above the highest level recorded in the space age. Even though such high level of cosmic ray intensity is unprecedented in the space age, there have been several intervals that had even smaller values of the IMF as has been inferred from the abundance of berilium-10 ($^{10}$Be) isotope found in ice cores covering the past 600 years [16]. $^{10}$Be isotope is produced by the interaction of cosmic rays protons with the atoms in Earth's atmosphere. Thus high abundance of $^{10}$Be indicates high level of cosmic rays and hence low values of IMF. In fact the ice core data indicate that the IMF had values as low as 1 nT and as high as 8 nT [17] compared to the recent 5 nT.

TABLE I. LIST OF RECENT GRAND MINIMA

| Grand minima [14] | | |
|---|---|---|
| ***Name*** | ***Start*** | ***End*** |
| Oort | 1040 | 1080 |
| Wolf | 1280 | 1350 |
| Spörer | 1460 | 1550 |
| Maunder | 1645 | 1715 |
| Dalton | 1790 | 1820 |

Increased level of cosmic ray intensity has its own effect on climate due to a different process. The increased ionization produced by the cosmic rays means increased number of ions in the atmosphere that can help the formation of low clouds. The increase in low cloud cover can reduce the amount of solar energy received by the solar atmosphere, thus contributing to additional global cooling, compounding the effect of low solar activity. The net result of course will depend on the extent of warming caused by the increased greenhouse gas emission that has been increasing since the industrial revolution and seems to have become the dominant factor at present. One has to include other factors such as the volcanic eruptions, El Niño, ocean-atmosphere interaction and so on in sophisticated computer models to understand the climate variation. Earth's climate seems to be related to processes on Earth's surface, in the interplanetary medium, on the Sun and in our galaxy [18, 19].

Processes of even longer time-scales affect Earth. Movement of the solar system within the galaxy may lead to different cosmic ray environments. Stellar evolution is expected to take the Sun to the red-giant phase (when the solar disk will extend beyond Earth's orbit) before the final white-dwarf phase.


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