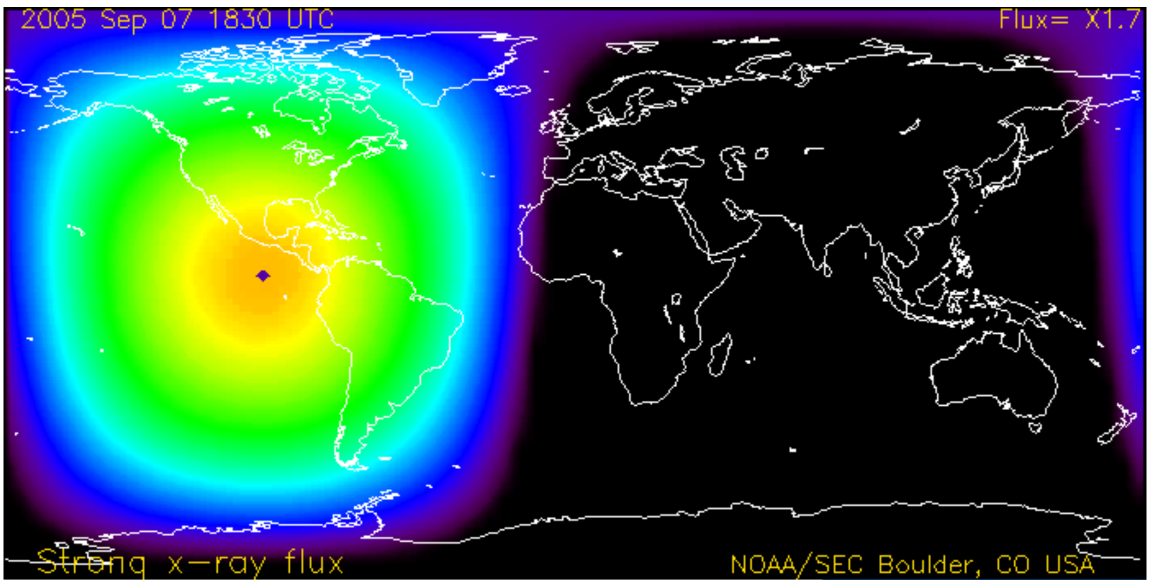
Chapter 14

Ionospheric Storms



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14 Ionospheric Storms

A sudden change in ionospheric conditions, caused by events occurring on the Sun, mark the onset of an ionospheric storm. The storm can last a few hours to several days or more.

During an ionospheric storm one of two things, or both, can occur.

- Absorption of 160 thru 20 meter radio signals dramatically increases with the longer wavelength signals being affected the most.

- Critical frequencies suddenly drop adversely affecting 20 through 10 meters with the shorter wavelength signals being affected the most.

Ionospheric storms are much different than geomagnetic storms. Geomagnetic storms cause significant dips and fluctuations in Earth's magnetic field. A fluctuating magnetic field induces high electrical currents in electrical power distribution systems causing devastating damage and long power outages. Induced electrical currents also weaken long pipe lines and seriously damage other infrastructure potentially causing hundreds of billions of dollars in damage. This threat is the reason fleets of spacecraft are orbiting the Earth and Sun monitoring and studying solar events that could produce catastrophic geomagnetic storms. Ionospheric storms cause perturbations in the ionosphere adversely affecting HF radio communications.

While they are different, events occurring on the Sun often cause both ionospheric and geomagnetic storms to occur. The occurrence of one type of storm may indicated that the other type of storm is about to commence. While this is not always true, it happens enough to be vigilant should either type of storm occur.

14.1 The Sun's Atmosphere

Ionospheric and geomagnetic storms originate in what we regard as the Sun's atmosphere, illustrated in Figure 1.

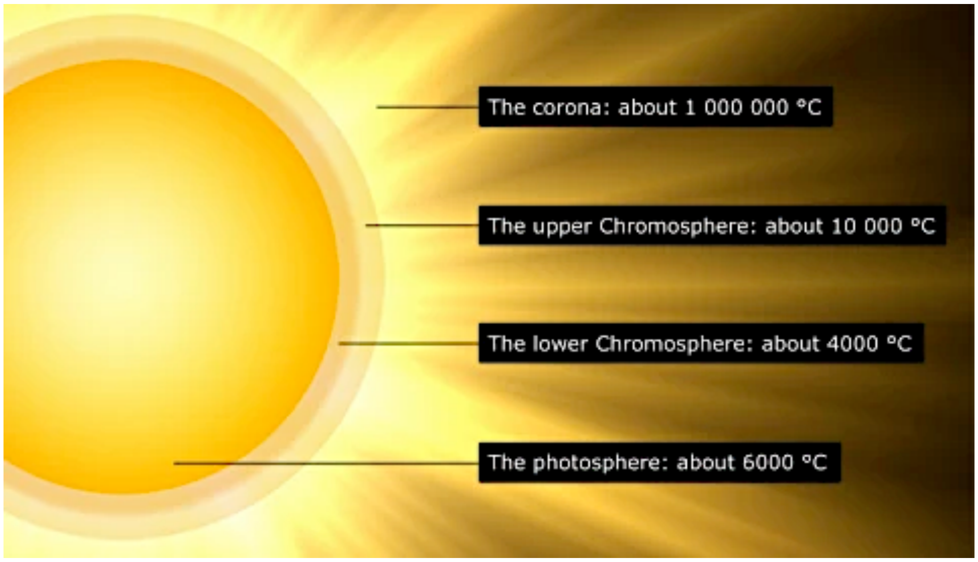


Figure 1 The Sun's atmosphere (source: Socratic)

14.1.1 Photosphere

The photosphere shown in Figure 2 is the visible surface of the Sun, the part of the Sun that radiates the light that we see. The photosphere emits 99% of the Sun's light and heat. The intensity of this radiation decreases rapidly from the base to the top of the photosphere, a distance of only 500 km. The rapid change in intensity over a such a short distance gives the Sun a sharp well defined outer edge, instead of a fuzzy edge that one might expect from a large ball of gas. The fact that the photosphere is the furthest that we can see into the Sun, coupled with the Sun's sharp edge, gives the impression that the photosphere is the Sun's surface.

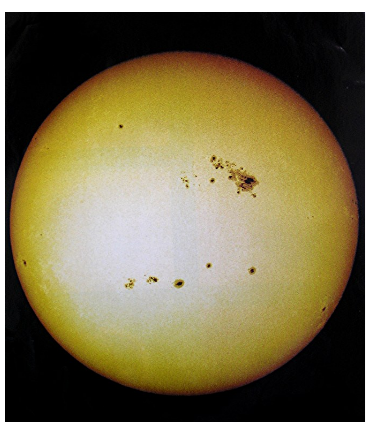


Figure 2 Photosphere (source: NASA Goddard Space Flight Center)

We assume that the photosphere is a very dense, almost "hard", layer of gas since we perceive it to be the Sun's surface. However, that is not the case at all. The photosphere's density is 10,000 times less than Earth's sea level atmosphere. The photosphere is hot, twenty times hotter than the surface of the Earth (6,500 $°K$ verses 300 $°K$ for the Earth), and the chromosphere and corona are much hotter yet.

Almost all of the hydrogen and helium gas in the photosphere is in atomic form. Only about 3% of the atoms in the photosphere are ionized. Despite this low level of ionization, the electron density in the photosphere is still a million times greater than in the Earth's ionosphere

The spectrum of light emitted by the photosphere is shown in Figure 3. This spectrum is determined primarily by the photosphere's 6,500 $°K$ temperature. Notice that 44% of the spectrum is visible light while only 0.001% of the spectrum is the extreme ultra-violate (EUV) light responsible for Earth's ionosphere and HF radio communication.

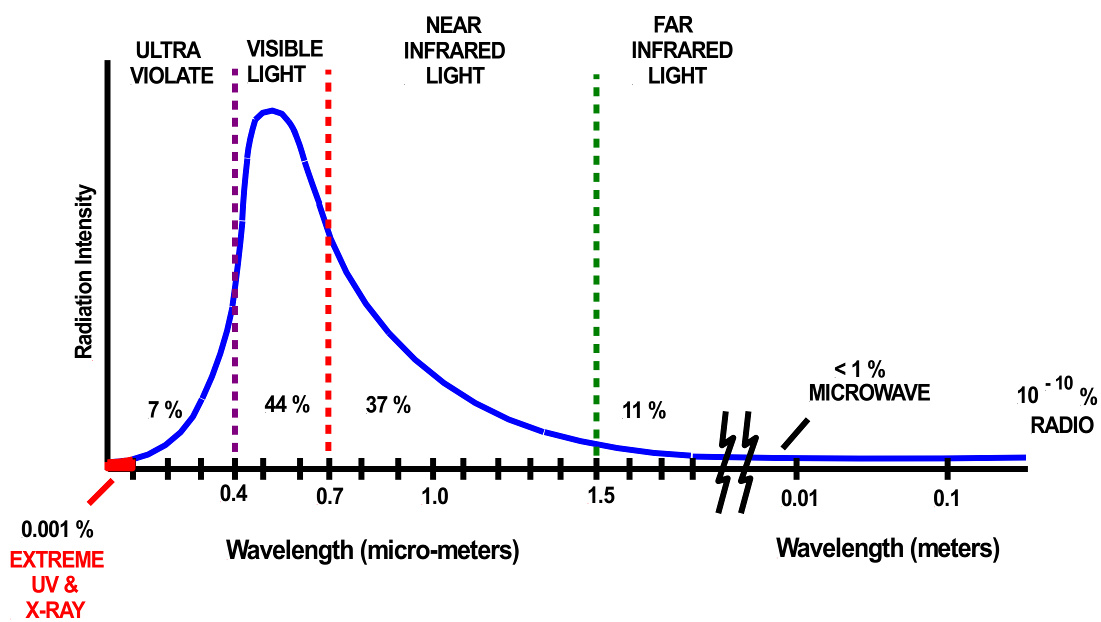


Figure 3 Solar spectrum (source: author)

14.1.2 Chromosphere

The chromosphere stretches outward from the top of the photosphere to an altitude of around 2,300 km. Normally the chromosphere is not visible because the photosphere is so bright. In fact, the photosphere is 10,000 times brighter than the chromosphere. However, the chromosphere can be seen as a rosy red ring along the outer edge of the Sun during a full solar eclipse. During a full eclipse the Earth's moon blocks out the bright photosphere allowing the chromosphere to be seen. A full eclipse is shown in Figure 4

Figure 4 View of chromosphere during a solar eclipse (source: Wikipedia)

The name chromosphere means sphere of color. The chromosphere's reddish appearance, shown in Figure 5, is the result of hydrogen atom electrons dropping from their $n = 3$ to $n = 2$ energy levels, emitting photons in the process. The wavelength of these photons is 656.3 nm which is in the red part of the spectrum. The chromosphere can be observed in great detail by viewing the Sun with a telescope equipped with a hydrogen-alpha (H_α) filter.

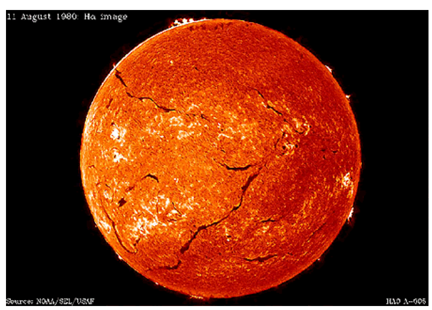


Figure 5 Chromosphere seen in H-alpha light (source: universitytoday.com)

The density of the chromosphere is ten thousand times less than the photosphere.

The chromosphere temperature rises from 4,400 $°K$ at 500 km to around 20,000 $°K$ at an altitude of 2,300 km as illustrated in Figure 6. A temperature plateau occurs from 1,000 to 2,000 km. Over this distance the chromosphere's temperature slowly rises from 6,000 to 7,000 $°K$. The plateau is caused by the ionization of hydrogen which occurs at temperatures > 5,000 $°K$. The chromosphere temperature rises quickly after the hydrogen becomes fully ionized. This occurs at an altitude of about 2,100 km and temperature of 8,000 $°K$. A second plateau occurs at approximately 2,300 km. This plateau is defined as the transition zone between the upper chromosphere and the bottom of the corona. The transition zone is about 300 km wide extending from an altitude of 2,300 to 2,600 km.

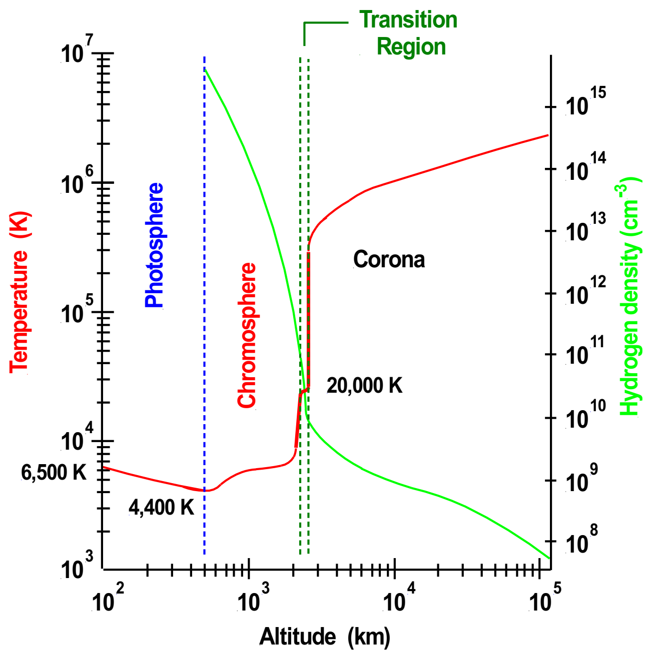


Figure 6 Chromosphere temperature - density profile (source: adapted from A. Gabriel 1976)

14.1.3 Corona

The corona begins at the top of the transition zone, just above the chromosphere. It extends outward for more than 2 million km. There is no actual upper boundary for the corona. It continuously thins as it stretches outward from the Sun and eventually disappears into interplanetary space.

Like the chromosphere, the corona is normally not visible because the photosphere is so bright. In perspective, the photosphere is 10,000 times brighter than the chromosphere and a million times brighter than the corona. During a full eclipse the white coronal light is visible surrounding the Sun as shown in Figure 7.

The corona is extremely hot ranging from around 1 million degrees just above the transition zone to well over 2 million degrees in the outer part of the corona.

The corona's white light, at altitudes out to $1.5 \; x \; 10^6$ km, is produced by highly energetic free electrons scattering light radiated by the photosphere. Further out grains of interplanetary dust are responsible for the scattering.

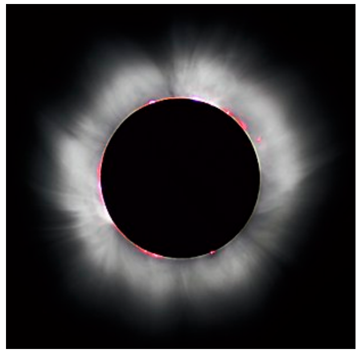


Figure 7 White corona during a solar eclipse (source: Wikipedia)

14.2 Variations In Ionospheric Storms With The Solar Cycle

The number and severity of ionospheric storms vary with the 11 year solar cycle.

The Sun's magnetic field is created in its convection zone (Figure 8) very near to its surface. This combined with the Sun's differential rotation (the Sun's equator rotates faster than its poles) causes the 11 year solar cycle to occur.

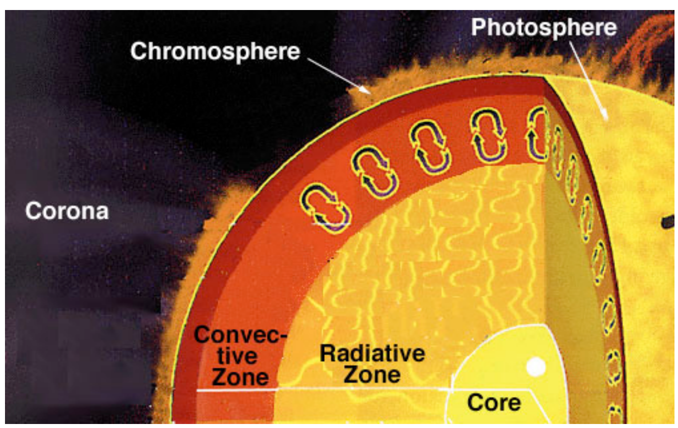


Figure 8 Structure of the Sun (source: eng.libretexts.org)

At the beginning of a solar cycle the Sun's magnetic field is a uniform north – south field with a strength of around 1 gauss as illustrated in Figure 9a. This is known as solar minimum with very few if any sunspots visible on the Sun. Differential rotation stretches out the north – south magnetic field lines along the equator, illustrated in Figure 9b. Over time the magnetic field becomes wrapped around the Sun many times (Figure 9c). Winding the magnetic field around the Sun in tighter ever increasing number of turns is not a sustainable process. Something has to break, and it does! Continued winding, twisting, and knotting creates tremendous stress in the magnetic field driving field intensities to well over 3,000 gauss. The enormous stress eventually causes the field to rupture in many places. As it does so high arching prominences, coronal loops, sunspots, and solar flares erupt from the Sun. The Sun reaches solar maximum during this very turbulent phase of the solar cycle with large numbers of sunspots visible on the solar surface. As the magnetic field disintegrates, sunspots gradually disappear and the Sun again approaches solar minimum with a quiet north-south magnetic field.

Phases of the solar cycle are illustrated in Figure 10. Few ionospheric storms occur during solar minimum when there are few if any sunspots visible on the Sun's surface (yellow part of the trace in Figure 10). The number of storms gradually increases during the ascending phase of the solar cycle (orange) as sunspots begin to appear. The greatest number of ionospheric storms occur during solar maximum (red). As indicated above, this is the most active part of the solar cycle with large numbers of sunspots visible along with stressed magnetic fields violently erupting from the Sun's surface creating huge coronal loops, solar flares, and coronal mass ejections. A surprising number of storms occur during the descending phase (brown). These storms are formed primarily by coronal holes which occur most frequently during the solar cycle descending phase.

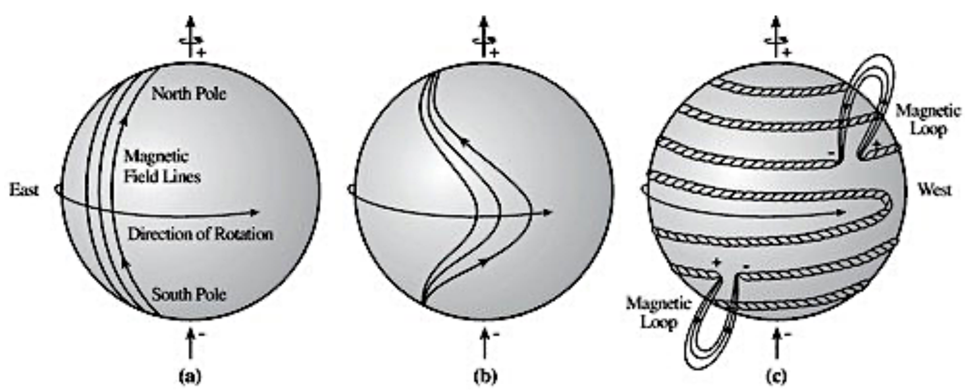


Figure 9 Evolution of a solar cycle (source: NASA's Cosmos – ase.tufts.edu)

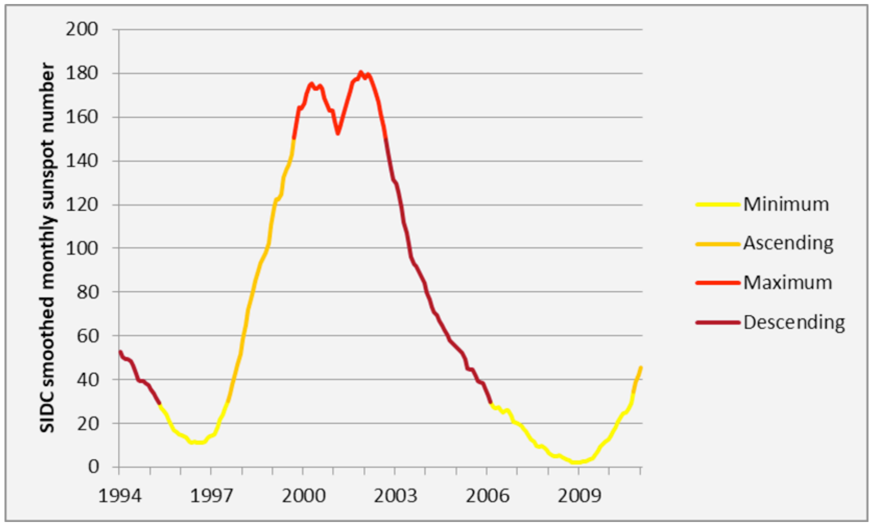


Figure 10 The solar cycle (source: STCE)

The current solar cycle phase and number of visible sunspots is available by clicking on "Solar Cycle Progression" under the "Current Conditions" tab at www.skywave-radio.org. Figure 11 shows the progression of Solar Cycle 25 in October 2022. At that time the solar cycle was in the ascending phase and developing faster than predicted. The red trace is the predicted progression of the solar cycle.

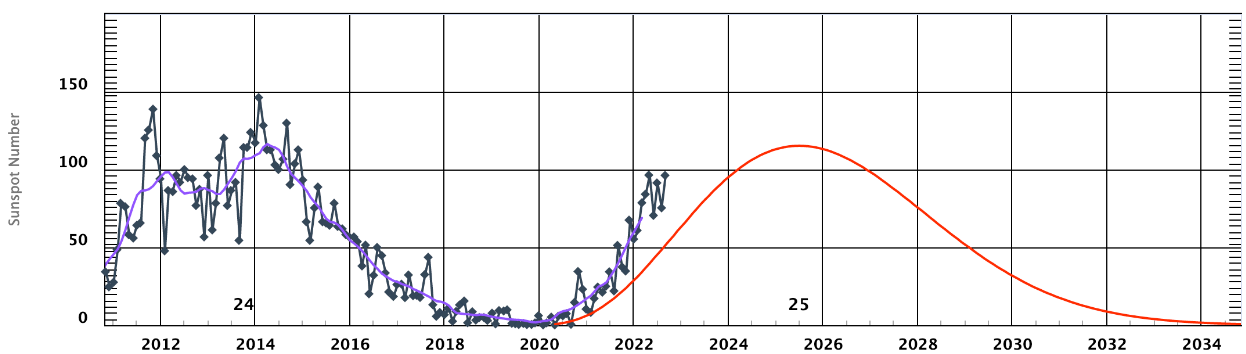


Figure 11 www.skywave-radio.org > Current Conditions > Solar Cycle Progression

14.3 Solar Events Impacting Earth's Ionosphere

Events occurring on the Sun are not only responsible for creating Earth's ionosphere, but for the storms disrupting the ionosphere as well. These events include:

- Sunspots,
- Plages,
- Prominences,
- Coronal Loops,
- Coronal Holes,
- Coronal Mass Ejections (CME),
- Solar Flares, and
- Solar Winds

14.3.1 Sunspots

A sunspot develops at a point where the Sun's magnetic field erupts through the photosphere as shown in Figure 12. A second sunspot occurs at the location were the magnetic field plunges back into the photosphere. Sunspots have magnetic polarities created by the magnetic field's direction of flow. The field flows out of a magnetically north (N) sunspot and into a magnetically south (S) sunspot.

The peak intensity of the field emanating from a sunspot is in the neighborhood of 3,000 to 4,000 gauss. This field is so intense that it suppresses the upward flow of hot plasma from the Sun's interior. This causes the sunspot site to be over 2,000 degrees cooler than the surrounding photosphere. The sunspot's lower temperature is why it appears black in color.

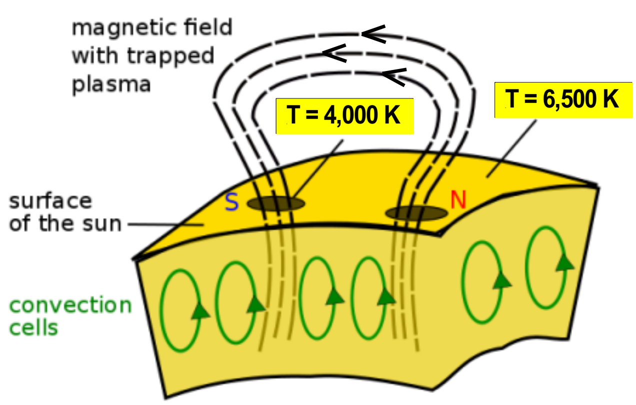


Figure 12 Formation of sunspots (source: Sky Maps with Pierre Auger Data)

The center of a sunspot is the umbra while the outer lighter colored region is the penumbra shown in Figure 13. The umbra is the lowest temperature (blackest) part of a sunspot. The temperature of the umbra usually ranges from about 3,800 to 4,100 degrees kelvin compared to 6,500 K of the surrounding photosphere (the yellow grainy region shown in Figure 13). The penumbra around the outer edge of the sunspot is warmer and lighter in color. It is characterized by large numbers of elongated dark and bright filaments that extend outward from the umbra. Out flows of material occur in the penumbra, beginning at the umbra, reaching a maximum speed of 2 – 6 km/s, and then dissipating outside the penumbra.

Sunspots can be huge. Large sunspots (including both the umbra and penumbra) can be 50,000 km or more in diameter. More typically, the umbra is around 10,000 km in diameter, about the same size as the Earth. The Earth's diameter is 12,756 km. Sunspots appear, last several days, and then disappear. Some sunspots may last for several weeks.

Sunspots are part of the Sun's photosphere and thus rotate with the Sun. In Figure 14 sunspots move from left to right as the Sun rotates. Sunspots that disappear around the Sun's right limb may reappear about 13 days later on the left side of the Sun.

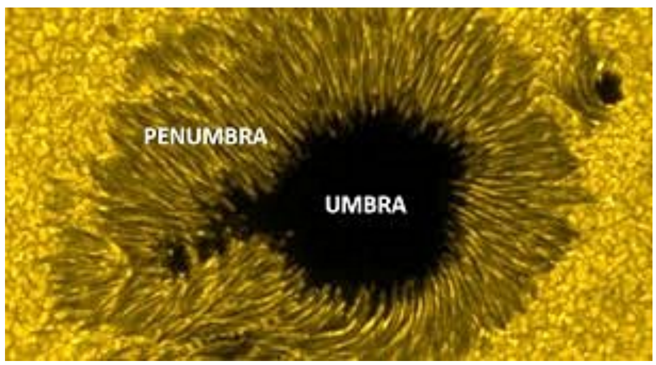


Figure 13 A closer look at sunspots (source: spaceweatherlive.com)

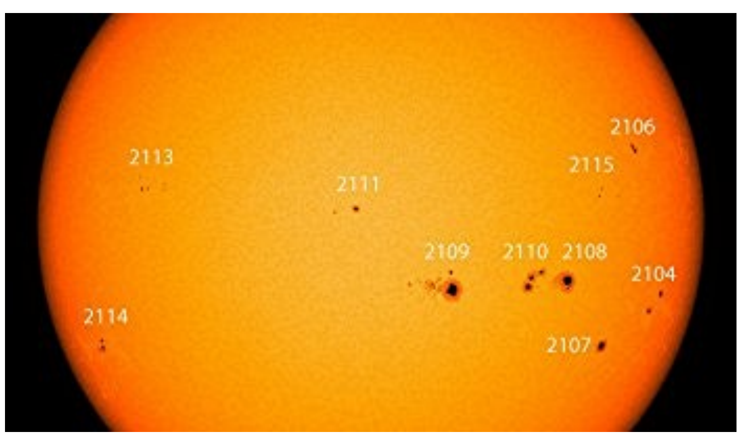


Figure 14 Sunspots on the face of the Sun (source: NOAA Space Weather Prediction Center)

While isolated individual sunspots do form, most sunspots occur in pairs, or more commonly in sunspot groups aligned with the Sun's direction of rotation. A typical sunspot group is shown in Figure 15. The group rotates with the Sun so the large sunspots on the right are the leading spots while those on the left are the trailing or following sunspots.

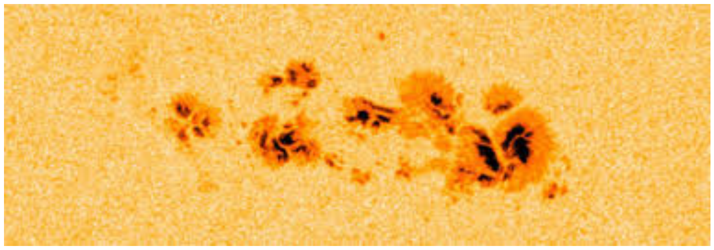


Figure 15 Sunspot Group (source: SpaceWeatherLive.com)

Sunspots begin forming at high solar latitudes during the ascending phase of the solar cycle as illustrated in the Figure 16 sunspot "butterfly" diagram. Around 1988 in Figure 16 sunspots were beginning to form around 30º latitude with few sunspots below that latitude. By 1994, near solar maximum, sunspots were appearing at latitudes below 20º while no sunspots were visible at 30º. As the next solar minimum approached in 1998 only a few spots were present near the equator. Notice that very few sunspots occur along the equator itself. The reason for this is that the magnetic polarity of sunspots in the northern hemisphere is opposite that of sunspots in the southern hemisphere. As sunspots approach the equator, the northern and southern hemisphere sunspots cancel each other out.

Sunspots themselves do not do much for us. Their temperatures are too low to produce the Extreme Ultra Violate (EUV) radiation need to ionize Earth's atmosphere. Their temperatures are also too low to produce ionospheric storms. However, sunspots are easy to see and act as markers for solar activity that does impact us.

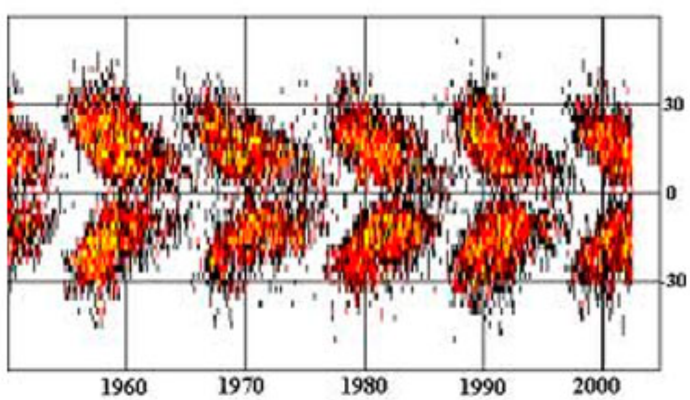


Figure 16 Sunspot butterfly diagram (source: sunlive.co,nz)

14.3.1.1 Smoothed Sunspot Number

The daily number of sunspots visible on the Sun for 2008 through 2019 is shown as the yellow data in Figure 17. The Smoothed Sunspot Number SSN (red trace in Figure 17) is the average of the monthly mean sunspot numbers (black trace) over 13 months from 6 months before to 6 months after the month of interest. For SSN calculations, months have the same weighting except for the first and last months in the series each of which is given a weighting of one half (0.5).

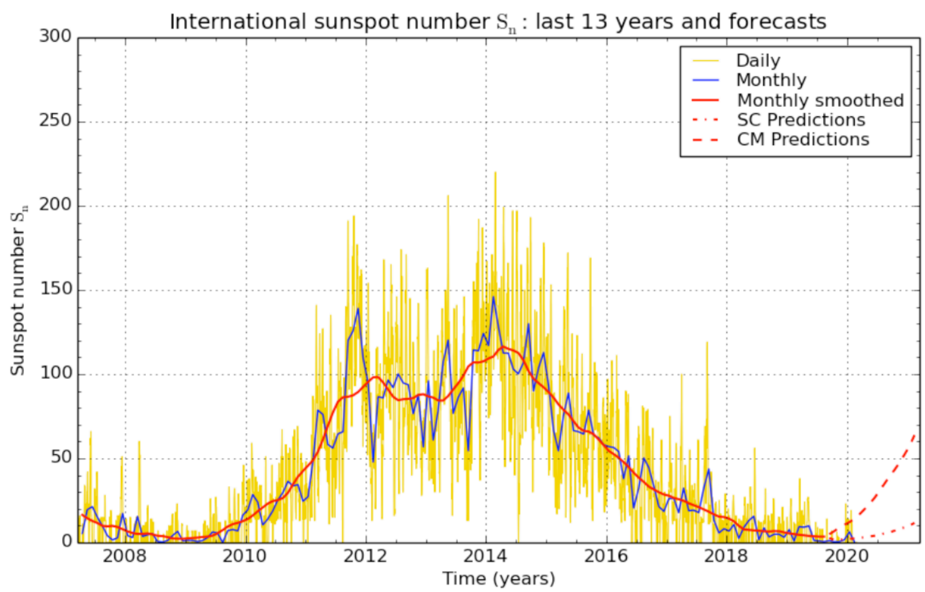


Figure 17 Smoothed Sunspot Number (source: SILSO Graphics)

Sunspot numbers and smoothed sunspot numbers are typically shown on websites displaying current space weather conditions. Generally, only one number is shown, either SN or SSN. It is important to realize that SN and SSN are not the same thing. As indicated above, SN is the current daily sunspot number while SSN is a long term average of sunspot numbers. SSN is one of the most widely used indices for ionospheric work. For example, most HF propagation prediction software uses SSN in combination with the International Reference Ionosphere mathematical model.

14.3.1.2 Solar Flux Index

Sunspot numbers are a visual indication of solar activity. The 10.7 cm (2.8 GHz) radio frequency solar flux index (SFI) is an electromagnetic indicator of solar activity. SFI varies between 65 at solar minimum to around 225 at solar maximum. As shown in Figure 18 both measures track very closely.

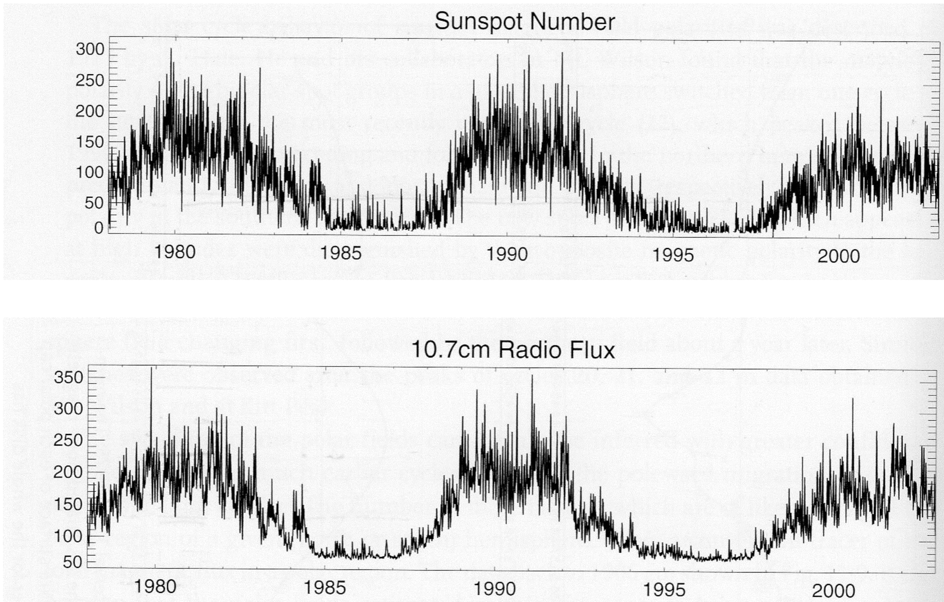


Figure 18 Sunspot numbers and SFI (source: G. deToma)

Figure 19 shows a portion of the VE3EN space weather website for October 28, 2022. Notice that this website shows SFI and SSN values for that day. The compete VE3EN website can be accessed by clicking on “Solar Parameters” under the “Current Conditions” tab at www.skywave-radio.org.

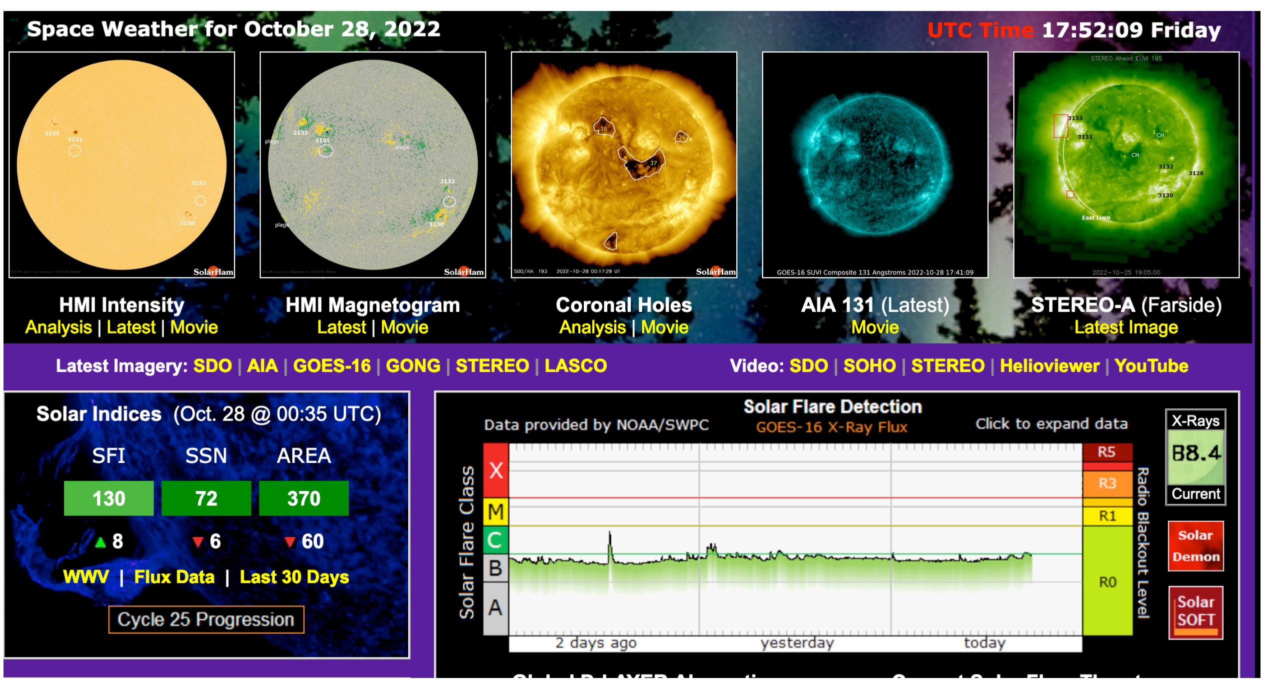


Figure 19 Portion of the VE3EN space weather website

14.3.2 Plages

Plages are hot white irregularly shaped areas visible in the image of the chromosphere shown in Figure 20. Plages are formed in the chromosphere by intense magnetic fields radiating out from the underlying photosphere. Plages occur in active sunspot regions of the Sun and usually form several days prior to sunspots in the area. Plages typically last long periods of time, longer than their associated sunspots, and emit copious amounts of EUV radiation responsible for ionizing Earth's upper atmosphere.

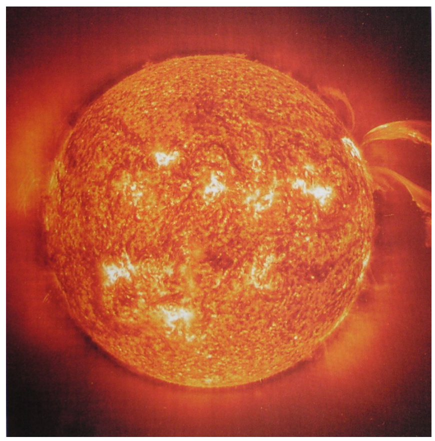


Figure 20 Sun's chromosphere shown in H alpha (H_α) light (source: universitytoday.com)

Plages are difficult to see without the aid of specially equipped telescopes. However, sunspots are easy to see and thus act as markers indicating the locations and number of plages present.

14.3.3 Prominences and Filaments

Prominences are large bright loops and curtains of relatively cool plasma suspended above the photosphere by strong arching magnetic fields. A prominence occurring on the edge of the Sun is shown in Figure 21. Figure 22 is a curtain prominence.

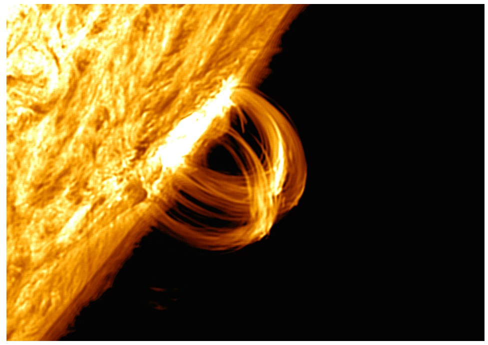


Figure 21 Arching Prominence (source: Astronomy Magazine)

Figure 22 Quiescent hedgerow curtain prominence (source: Sky & Telescope)

A prominence is caused by the Sun's stressed magnetic field erupting through the photosphere carrying with it electrically charged plasma. The charged plasma, often traveling at speeds of 40 km/sec, follows the contours of the magnetic field giving a prominence its bright arching shape. The strength of the magnetic field within a prominence typically ranges from 10 to 800 gauss, compared to the Sun's quiet bipolar field of around 1 gauss and intensities of over 3,000 gauss in twisted knotted magnetic field lines during solar maximum. A prominence extends into the corona often 50,000 km or move above the photosphere and usually lasts for several hours. In some cases a prominence can remain in place for 2 - 3 solar rotations (a couple of months). The temperature within a prominence is on the order of 7,000 degrees kelvin, much cooler and more dense than the surrounding corona. The stability of a prominence is due to the equilibrium between its opposing magnetic and gravitational forces. Disruption of this equilibrium causes prominences to collapse, sometimes catastrophically producing small solar flares and coronal mass ejections.

Filaments and prominences are the same thing seen from different perspectives. A prominence appears as a bright arching formation when viewed on the edge of the Sun against the black background of interplanetary space. When viewed on the face of the Sun, it appears as a dark erratic scare or filament, as illustrated in Figure 23. A filament is dark in appearance because it is relatively cool compared to the chromosphere below it.

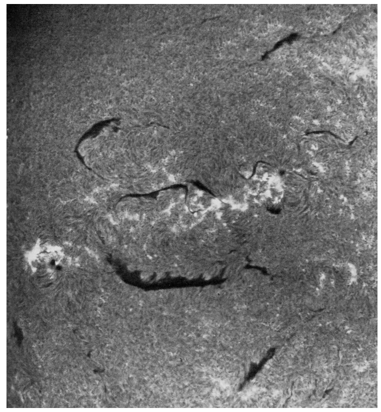


Figure 23 Filaments on the solar disk (source: Big Bear Solar Observatory)

14.3.4 Coronal Loops

Coronal loops are markedly different from prominences. Coronal loops are created by upwelling magnetic fields generated inside the Sun with their foot points anchored in the photosphere, similar to prominences. But unlike prominences, coronal loops are much larger extending far out into the corona, as illustrated in Figures 24. The size of the Earth relative to a coronal loop is illustrated in Figure 24. Coronal loops often form above sunspot groups in the active regions of the Sun magnetically connecting one region on the solar surface to another.

Figure 24 Coronal loop (source: NASA's Cosmos)

The plasma filling a coronal loop is much hotter than in a prominence. Because of its high temperature, a coronal loop can not emit light from neutral hydrogen atoms. At coronal loop temperatures all hydrogen atoms are fully ionized. That is, each atom has lost its one and only electron. The remaining hydrogen ion (a positively charged proton) can not radiate light since it no longer has an electron capable of jumping between energy states. Instead, due to its extreme heat, a coronal loop emits copious amounts of extreme ultraviolet and x-ray radiation in addition to thermal emissions from its 100,000 ^oK plasma. Coronal loop plasma also contains some heavy ions such as iron. These ions still have a complement of electrons left after ionization that can emit light at discrete wavelengths. These emission lines are frequently used to determine the temperature and density of coronal loop plasma.

The foot points of a coronal loop, anchoring it to the photosphere (Figure 24), typically move independent of each other. This is due to plasma flows in the Sun's underlying convection zone in addition to the Sun's differential rotation. As the foot points move, loop field lines become twisted and tangled until the loop eventually collapses. In some cases the energy built up in the tangled twisted field lines becomes so great that the field lines violently rupture creating a massive solar flare.

14.3.5 Coronal Holes

Coronal holes are dark areas seen in the solar corona when viewed in EUV and soft X-ray light. They appear dark, like those shown in Figures 25, because they are cooler and less dense than the surrounding corona plasma.

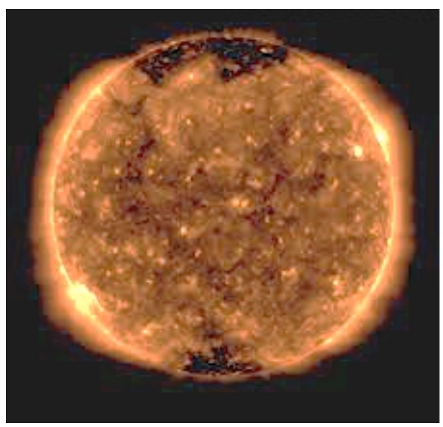


Figure 25 Large dark regions are coronal holes (source: NOAA www.swpc.noaa.gov/phenomena)

Coronal holes can develop at any time and any location on the Sun. However, they occur most often at the solar north and south poles. Some of these grow and expand into lower solar latitudes, while others spin off individual holes. Coronal holes can also develop at regions other than the solar poles. Coronal holes occur most often and last longer during the declining phase of a solar cycle. In some cases coronal holes can last for several solar rotations (for several months).

Magnetic fields flowing out of coronal holes are open, expanding into interplanetary space without returning to the Sun. These unipolar magnetic fields allow streams of relatively fast solar winds, known as high speed streams (HSS), to escape into space. In fact, long-lasting coronal holes are a major source of high speed streams that can buffet Earth for many days and then reoccur every 27 days as the Sun rotates. Like the coronal holes from which they flow, high speed streams occur most frequently during the declining phase of the solar cycle.

14.3.6 Coronal Mass Ejections

A corona mass ejection (CME) is a huge eruption of coronal plasma, with its associated frozen-in magnetic field, that moves outward from the Sun into interplanetary space. CMEs vary widely in size, shape, and speed. Some look like loops, other like bubbles, and some are irregular in shape. Figure 26 is an example of a CME. To produce Figure 26 a disk was installed on the camera and positioned over the main part of the Sun, blocking the intense light from the photosphere, so that the corona mass ejection could be seen.

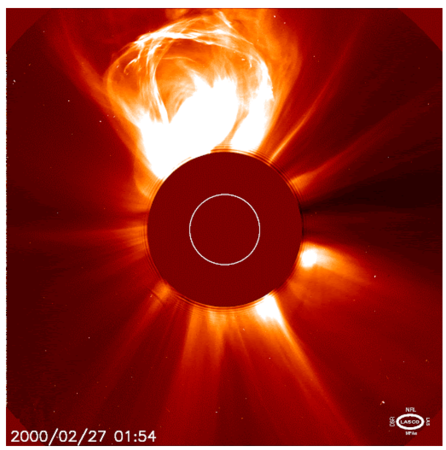


Figure 26 Coronal Mass Ejection (source: www.astronet.ru)

CMEs are often caused by the collapse of coronal loops and prominences as magnetic fields re-align and reconnect into lower energy states. Catastrophic collapse of coronal loops and prominences can trigger solar flares which also produce CMEs.

A CME can eject billions of tons of coronal material outward from the Sun at speeds typically ranging from 200 to 500 km/s. Some energetic CMEs can reach speeds of 3,000 km/s or more. A shock wave is created when the CME travels faster than the background solar wind. The shock wave often accelerates charged particles ahead of it which can create intense particle (proton) storms as the CME impacts Earth. During solar maximum several CMEs of various sizes and shapes occur per day. At solar minimum one CME is typically observed every 5 days or so.

Most CMEs are ejected outward from the Sun into the solar system away from the Earth. However, a CME launched in Earth's direction can arrive in as little as 15-18 hours. Slower CMEs may take several days to arrive. A CME expands as it travels away from the Sun. A large CME can encompass nearly a quarter of the distance between the Sun and Earth by the time it reaches Earth.

14.3.7 Solar Flares

Solar flares are the most common cause of intense ionospheric storms.

A solar flare is a massive, sudden, explosive release of stored solar energy. Solar flares are huge. The solar flare shown in Figure 27 is larger than the Earth.

Figure 27 A solar flare (source: NASA)

A flare is often caused by the collapse of a coronal loop, like the one shown in Figure 28. Notice the size of the coronal loop in Figure 28 compared to the size of the Earth. Coronal loops are huge.

Figure 28 Coronal loop (source: NASA's Cosmos)

As described above, coronal loops are formed by magnetic fields erupting out of the Sun's photosphere. The problem is that foot points anchoring a coronal loop to the photosphere move. If the foot points moved together, a coronal loop would rotated back and forth in a beautiful twirling dance. However, the foot points do not move together. They move randomly in different directions causing the coronal loop's magnetic field lines to become stretched out, twisted, and tangled into an hour-glass shape as illustrated in Figure 29.

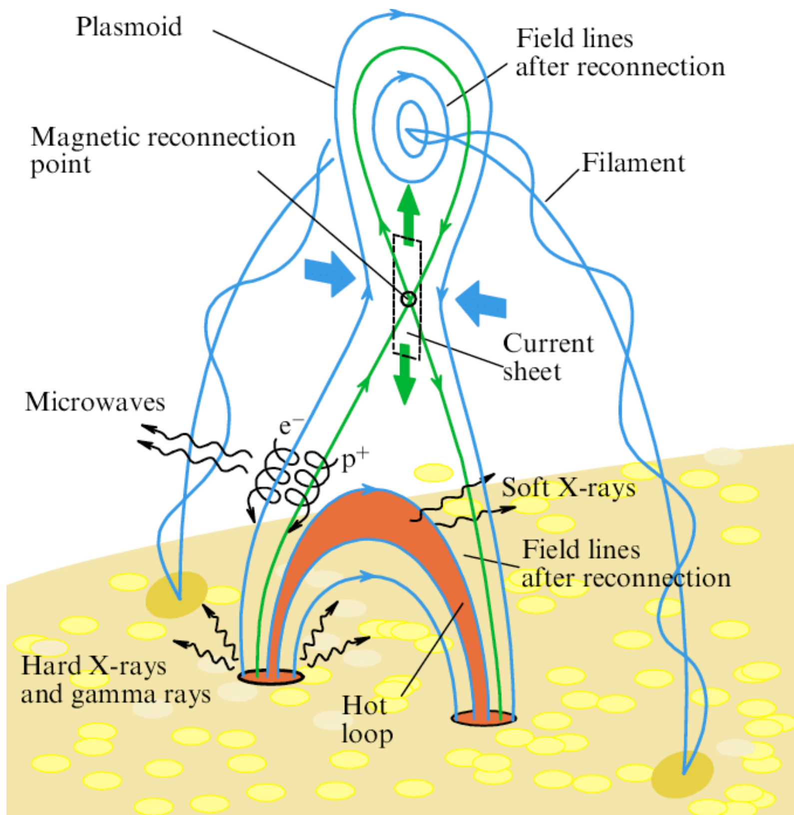


Figure 29 Formation of a solar flare (source: ResearchGate)

Outbound and returning magnetic field lines (the green lines in Figure 29) are squeezed closer and closer together forming the hour glass neck. Energy builds up rapidly in the neck region eventually becoming so great that outbound and returning magnetic field lines "short circuit" rupturing the coronal loop and initiating a solar flare.

Below the rupture, outbound and returning field lines reconnect into a much smaller hot magnetic loop anchored in the photosphere. Hot plasma consisting of energetic electrons plus hydrogen and helium nuclei stream down the reconnected field lines. These energetic particles are traveling at nearly the speed of light. Nuclear reactions are triggered as these particles crash into the upper chromosphere. The nuclear reactions release a massive amount of energy in the form of gamma rays, x-rays, extreme ultra violate light, visible light, and radio waves. The amount of energy typically released by a large flare is equivalent to millions of 100 – megaton hydrogen bombs exploding all at once.

Above the rupture, magnetic field lines also reconnect forming a plasmoid of hot electrons plus hydrogen and helium nuclei. These particles are accelerated to very high energy levels producing solar energetic particles (SEPs) and high speed solar winds. The plasmoid rapidly expands into interplanetary space as a coronal mass ejection (CME).

14.3.8 Solar Winds

Solar winds are the second most common cause of ionospheric storms.

Solar winds consist of hot plasma (electrons and positively charged ions) that continuously flow outward at various speeds from coronal holes, CMEs, solar flares, and other disturbances on the Sun.

Solar winds deform Earth's magnetic field into a comet shaped magnetosphere illustrated in Figure 30. The bow shock always faces toward the Sun while the magnetosphere tail faces away from the Sun, the same as comets. The Earth rotates within the stationary magnetosphere.

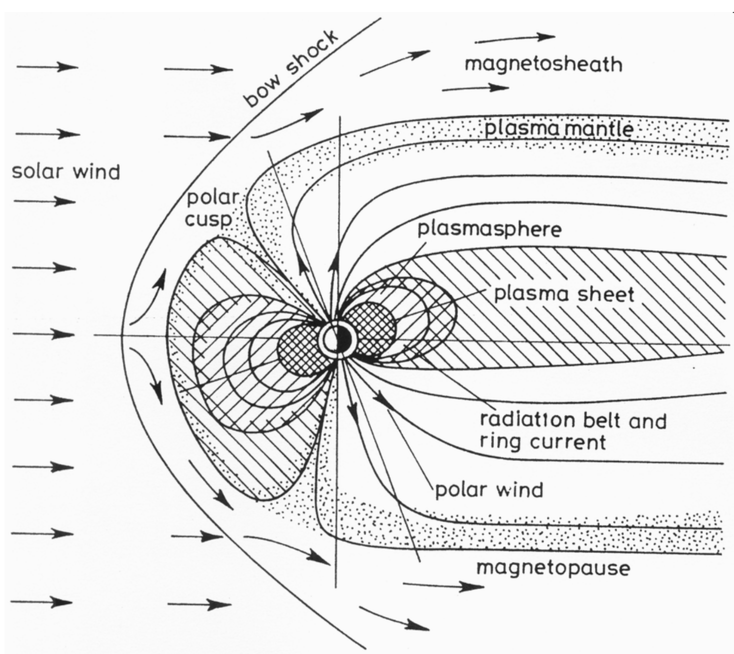


Figure 30 Earth's magnetosphere (source: Davies)

Slow speed background solar wind emanates from the Sun all the time. Higher speed winds are produced by coronal holes, CMEs, and solar flares. The solar wind is very tenuous with a density around 5 particles per cm^3. Wind speeds range from about 250 to 750 km/s near Earth. Note that 447 km/s is equal to 1 million per hour. Solar wind temperature near Earth is 100,000 to 150,000 ^oK.

An extremely important characteristic of the solar wind is that it contains an embedded magnetic field. The magnetic field is known as the Interplanetary Magnetic Field (IMF). The magnetic field originates internal to the Sun. However, in the corona a small portion of the Sun's magnetic field becomes "frozen in" the solar wind plasma due to the plasma's very high electrical conductivity. The IMF propagates throughout the solar system, carried along by the solar wind, hence its name "interplanetary magnetic field". The strength of the IMF field averages only about 5.6 nT. The direction of the IMF relative to Earth's magnetic field is constantly changing. A southward directed IMF points in the opposite direction of Earth's magnetic field. A southward IMF impacting Earth can create severe ionospheric storms. Very few storms occur when the IMF is pointed northward.

Current solar wind conditions can be obtained by clicking on "Solar Wind" under the "Current Conditions" tab of the www.skywave-radio.org website. Figure 31 shows the solar wind conditions on September 16, 2022. On that day the magnetic field was pointed slightly north (red B_z trace slightly positive). The solar wind density (orange trace) was below normal. The dashed line represents the normal solar wind density. The wind speed (yellow trace) at around 350 km/s was relatively slow. Finally, the solar wind temperature was about normal. The solar wind on this particular day was rather subdued.

For more information refer to the chapter on Solar Winds.

14.4 Formation of Earth's Ionosphere

As we know, Earth's ionosphere is formed by Extreme Ultra Violate (EUV) radiation from the Sun ionizing Earth's upper atmosphere. The source of solar EUV radiation is primarily:

- Plages and
- Coronal Loops

Plages and coronal loops increase in number as the solar cycle approaches solar maximum, and decline after that. Consequently, the level of ionospheric ionization varies with the 11 year solar cycle, ionization being greatest during solar cycle maximum and least at solar cycle minimum.

EUV radiation is VERY deadly. The ionosphere shields us from EUV radiation making life as we know it possible on Earth.

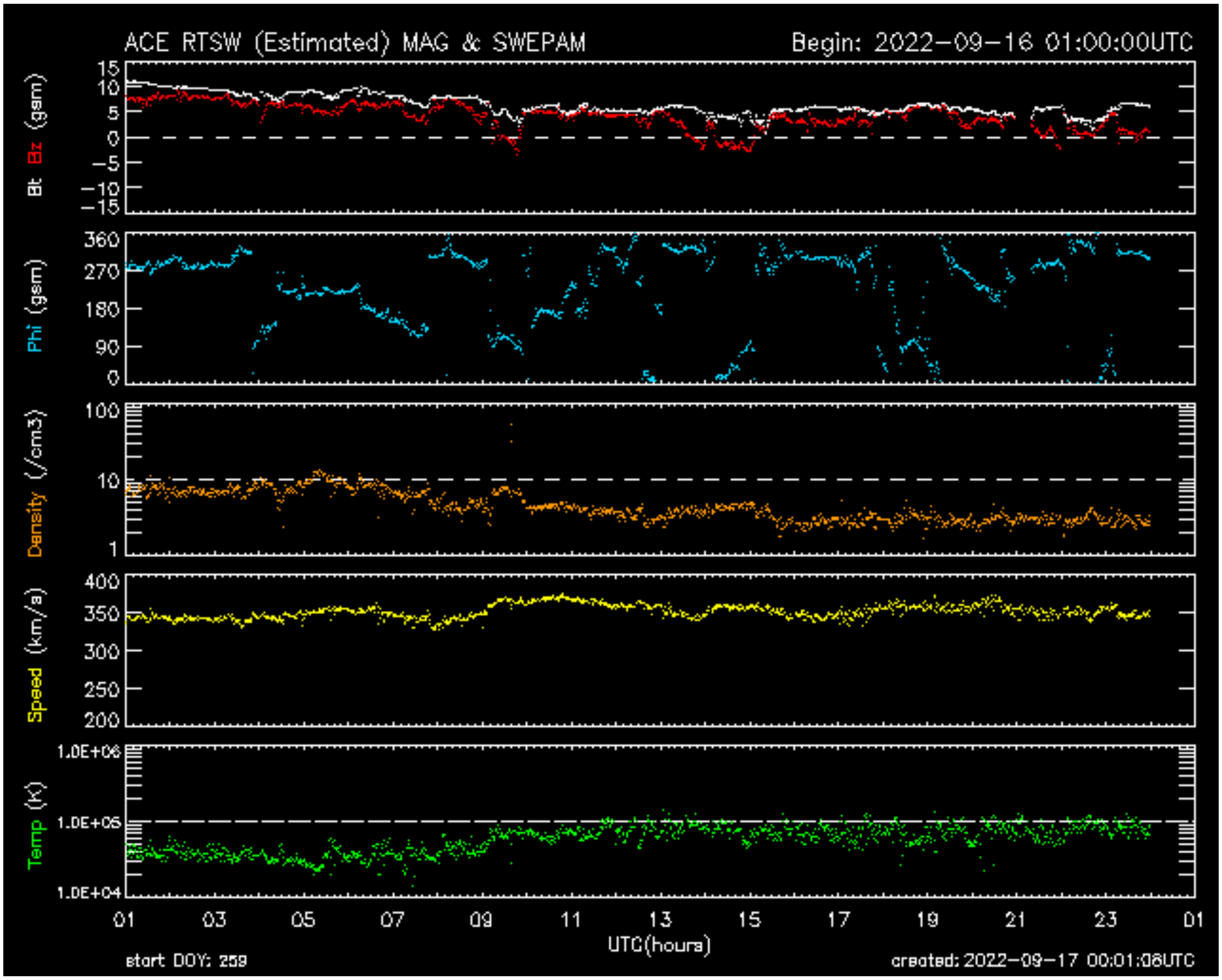


Figure 31 Solar wind characteristics (source: Space Weather Prediction Center)

Solar EUV radiation is intense as it encounters Earth's upper atmosphere. But, at high altitudes Earth's atmosphere is so thin that there are few atoms to ionize, as illustrated in Figure 32. As the radiation penetrates deeper into the atmosphere, the density of the atmosphere increases (more atoms and molecules) resulting in higher levels of ionization. The ionization process continuously weakens EUV radiation. Consequently, at some point the number of atoms and molecules ionized begins decreasing as the radiation penetrates further down into the atmosphere, even though the density of the atmospheric continues to increases. Eventually the ionization disappears, establishing the ionosphere's lower boundary. As illustrated in Figure 32, the ionization process results in maximum ionization occurring toward the middle of the ionosphere, with no ionization at the ionosphere's upper and lower boundaries.

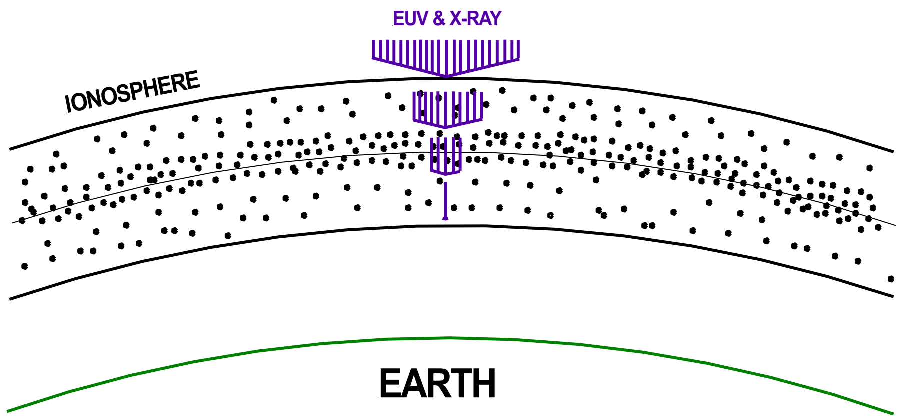


Figure 32 Formation of the ionosphere (source: author)

The level of ionospheric ionization is typically measured in terms of critical frequency. Critical frequency is the highest frequency radio signal that can be transmitted straight up and reflect from the ionosphere as illustrated in Figure 33. A higher frequency radio signal transmitted straight up will pass through the ionosphere into outer space.

Figure 34 shows the global critical frequency map for November 3, 2022 at 15:30 UT. The critical frequency color code for the map is shown on the right. The highest levels of atmospheric ionization occur in the regions with the highest critical frequencies. For example, ionization is greatest during daylight hours on either side of the equator where critical frequencies were 13 to 14 MHz at 15:30 UT on November 3rd. Notice that the critical frequencies are one to two MHz lower along the equator itself, consistent with the Appleton equatorial anomaly. The lowest levels of ionization, and thus lowest critical frequencies, occur at night, particular in the polar regions. At 15:30 UT the critical frequency above Alaska was only 2 MHz.

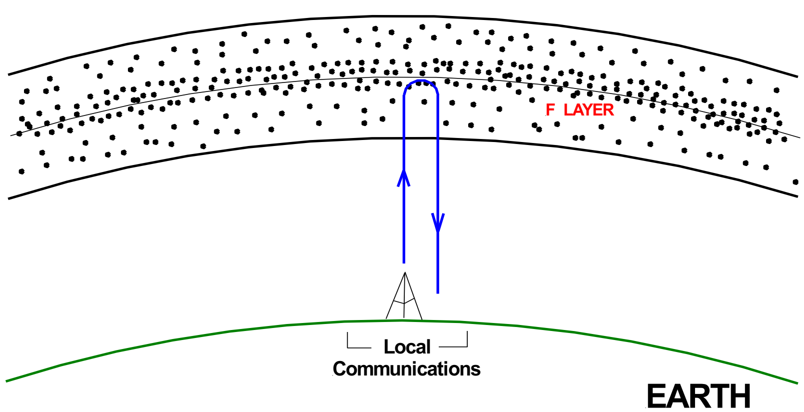
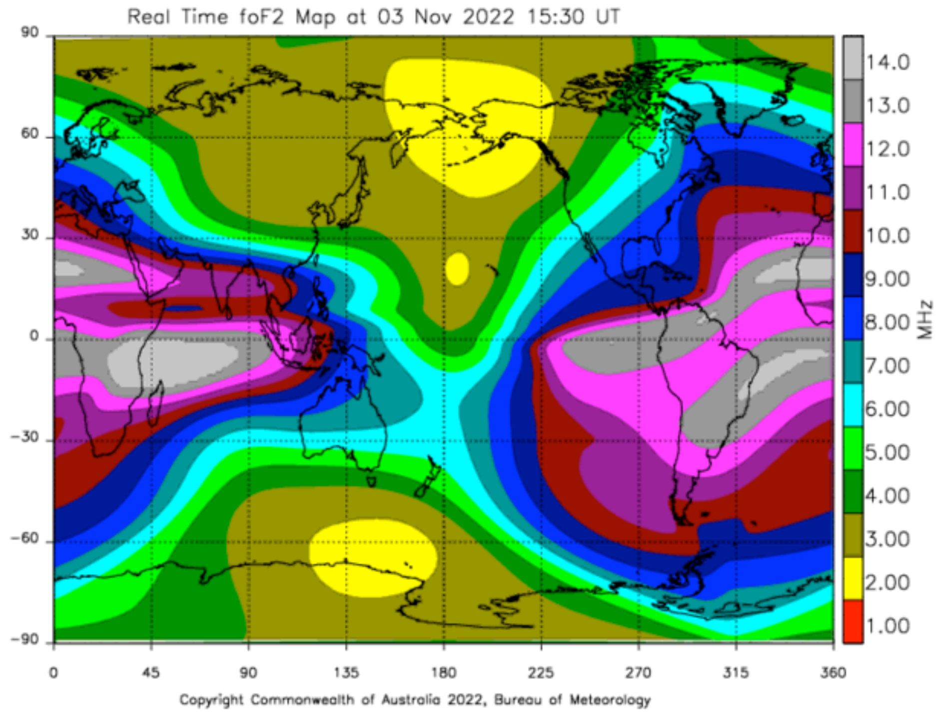


Figure 33 Critical frequency (source: author)



www.skywave-radio.org > Current Conditions > Critical Frequency

Figure 34 Global Critical frequency map (source: Commonwealth of Australia)

Current ionization levels, measured in terms of critical frequencies, are always available by clicking on "Critical Frequency" under the "Current Conditions" tab of the www.skywave-radio.org website.

14.5 Ionospheric Storms

A sudden change in ionospheric conditions marks the onset of an ionospheric storm. These storms are caused by events occurring on the Sun and can last a few minutes to several days or more.

During an ionospheric storm one of two things, or both, occur.

- Absorption of 160 thru 20 meter radio signals dramatically increases with the longer wavelength signals being affected the most.
- Critical frequencies suddenly drop adversely affecting 20 through 10 meters with the shorter wavelength signals being affected the most.

Ionospheric storms are much different than geomagnetic storms. Geomagnetic storms cause fluctuations in Earth's magnetic field potentially causing serious trillion dollar damage to our technological infrastructure. Ionospheric storms cause perturbations in Earth's ionosphere disrupting HF radio communications.

While ionospheric and geomagnetic storms are quite different, they are caused by the same violent solar events. In addition, the occurrence of one type of storm may indicated that the other type of storm is about to commence. While this is not always true, it happens enough to be vigilant should either type of storm occur.

There are three types of ionospheric storms:

- X-ray radiation storms,
- High energy particle storms, and
- Solar wind storms.

Earth's polar cap region and auroral zones are the breeding grounds for high energy particle storms and solar wind storms. X-ray radiation storms immediately impact all daylight regions of the Earth, particularly those areas where the Sun is directly overhead. All three types of storms are triggered by violent activity on the Sun including solar flares, coronal mass ejections (CMEs), coronal holes, etc.

14.5.1 X-ray Radiation Storms

X-ray radiation storms are caused by sudden large increases in x-ray radiation from the Sun, generally caused by solar flares. An x-ray radiation storm dramatically increases D layer absorption in daylight regions of the Earth, usually blacking out HF radio communications in the area. An x-ray storm is large impacting all latitudes from equatorial through high latitudes, with the greatest impact at local noon in regions where the Sun is directly overhead.

The x-ray radiation emitted by a solar flare reaches Earth in a little over 8 minutes. Figure 35 shows the dramatic increase in x-ray radiation following a large solar flare on September 7, 2005. The x-ray radiation from this flare was measured by a GOES satellites (Figure 36) in synchronous orbit around the Earth. Note that x-ray radiation can not be detected by ground level sensors since solar x-ray radiation is completely absorbed in the ionosphere. If this were not the case, large populations of people would experience radiation sickness every time a large solar flare occurred.

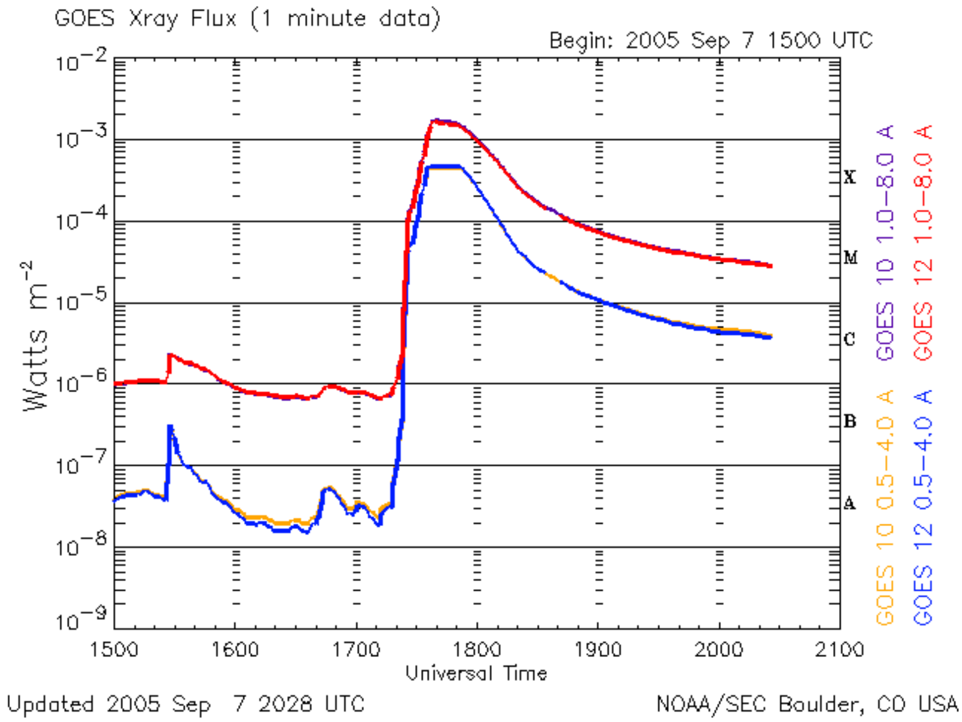


Figure 35 September 7, 2005 solar flare (source NOAA)

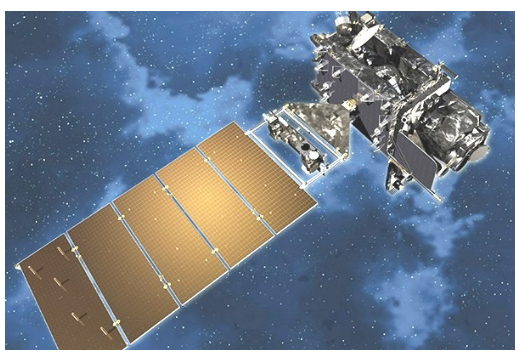


Figure 36 GOES 16 Spacecraft (Source: NOAA)

In Figure 35, the vertical axis indicates the strength of the x-ray radiation. The axis is similar to the earthquake Richter scale. Each band (A, B, C, etc.) represents a times 10 increase in x-ray radiation strength. The solar flare shown in Figure 35 produced a thousand times increase in the level of x-ray radiation impacting Earth.

The x-ray radiation from this particular flare heavily ionized the D layer causing extensive absorption of HF radio signals throughout North and South America as illustrated in Figure 37. Note in this figure that all zones of the ionosphere (equatorial, mid-latitude, and high-latitude) were affected by this flare. The black diamond in Figure 37 represents the Sun's position at local noon. In this figure the Sun was located above the Pacific Ocean south of Central America. The colored bands indicate the highest radio frequencies affected by the flare. In this case, all frequencies below 25 MHz were affected throughout North and South America, pretty much blacking out all HF radio communications in the region. The bar graph on right side of the figure shows signal attenuation by frequency, with lowest frequency signals attenuated the most.

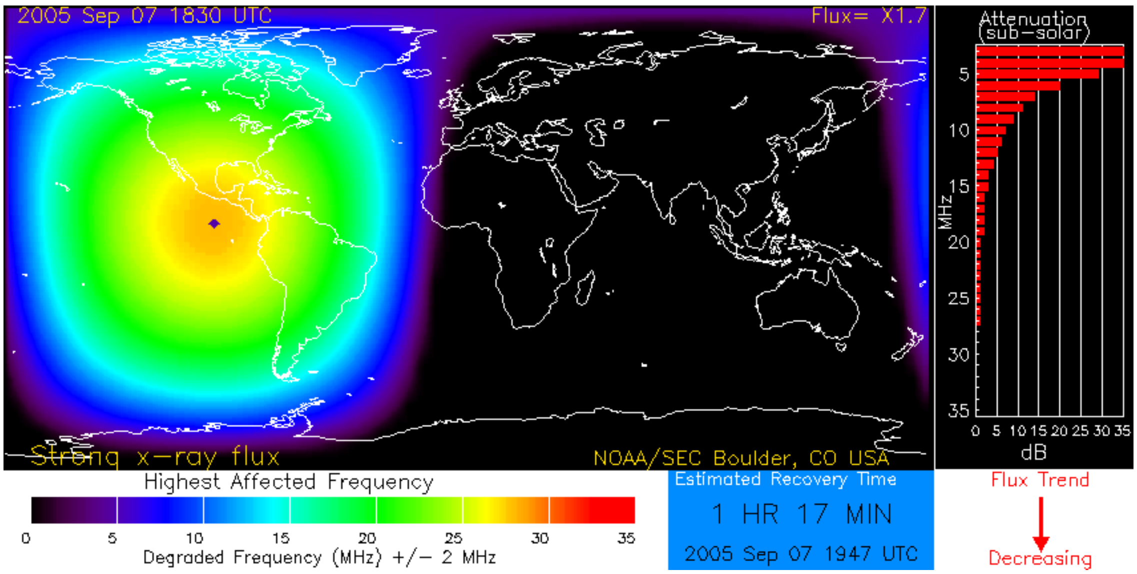


Figure 37 Solar flare D-Layer ionization (source: NOAA)

At the time this flare occurred several amateur radio operators, including the author, had just concluded participation in a weekly 40 meter California emergency communications net. Prior to the net we checked propagation conditions by monitoring the National Institute of Standards and Technology (NIST) WWV radio station transmitting on 5, 10, 15, and 20 MHz. Strong signals were received on all 4 frequencies. The emergency net went well with stations throughout California being easily received. Following the net we check WWV again. To our surprise, 5 MHz was completely dead. 10 MHz was shaky with rapid fading in and out. 15 and 20 MHz were both solid. We tuned back down the bands. 15, 10, and 5 MHz were now completely dead. We tuned back up to 20 MHz and found that it was dead also. This sequence of events is typical for the onset of a major x-ray radiation storm. The lowest frequency signals are lost first with progressively higher frequency signals lost in order.

An x-ray storm can last from a few minutes to several hours. This particular x-ray storm lasted a considerable part of the day. The region of the Earth affected by an x-ray radiation storm moves westward as the Earth rotates to the east. This x-ray storm impacted the far east (Korea, Japan, China, etc.) later in the day.

If an x-ray storm occurs in the morning local time, as it did in Figure 37 for Japan, the best long distance radio communications is with stations to the west, away from the approaching storm. If it occurs in the afternoon local time, as it did for Europe, the best communications is to the east, again away from the storm. If the storm hits around noon there is nothing you can do about it. Go have a good lunch. However, later in the afternoon look to the east for radio signal recovery as the storm moves westward.

14.5.2 High Energy Particle Storms

Solar Energetic Particles (SEPs) from coronal mass ejections (CMEs) and solar flares reach Earth in 20 minutes to an hour or so. SEPs are primarily hydrogen protons stripped of their electrons and accelerated to nearly the speed of light by CMEs and solar flares. Upon reaching Earth, the particles are constrained to move along Earth's magnetic field lines, spiraling down into the polar cap regions as the magnetic field lines become vertical (Figure 38). The SEPs highly ionize the D layer polar cap ionosphere causing HF radio signals passing through the area to be heavily absorbed, creating a Polar Cap Absorption event (PCA). Lower frequency signals are more heavily absorbed than higher frequencies, as is the case in all D-layer absorption phenomena. In extreme cases, a complete radio blackout can occur over the poles lasting for several days.

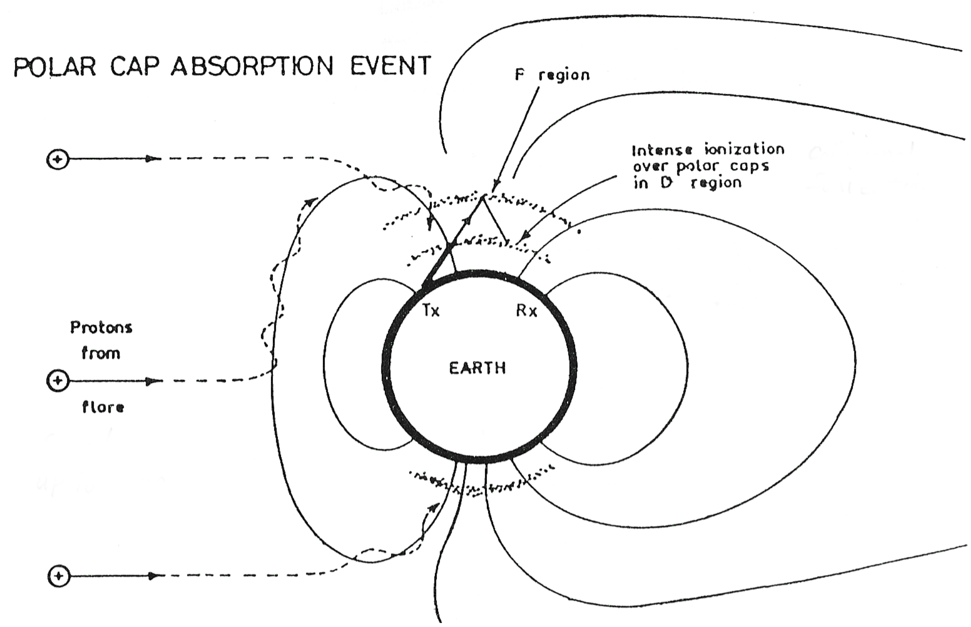


Figure 38 Polar Cap Absorption event (source: McNamara)

PCAs occur more often during solar maximum when solar flares and CMEs are prevalent. It is not unusual for PCAs to occur in groups with two or more PCAs occurring within a few days of each other. PCAs also tend to occur more during daylight hours than at night. A PCA typically appears at very high latitudes and then expands toward the equatorial edge of the polar cap.

GOES satellites continuously monitor the proton flux arriving from the Sun. The GOES proton flux data for a 3 day period in early June 2022 is shown in Figure 39. Proton flux is at minimal levels in this figure. The NOAA Space Weather Prediction Center issues a warning if the proton flux energy level exceeds 10 MeV. Proton flux above this level can cause serious problems, including damaging spacecraft and causing biological DNA damage to passengers and crew in aircraft flying over the poles. An electron volt (eV) is the energy acquired by an electron falling through a potential of 1 volt. Current proton flux data is available by clicking on "Proton Flux" under the "Current Conditions" tab of the www.skywave-radio.org website.

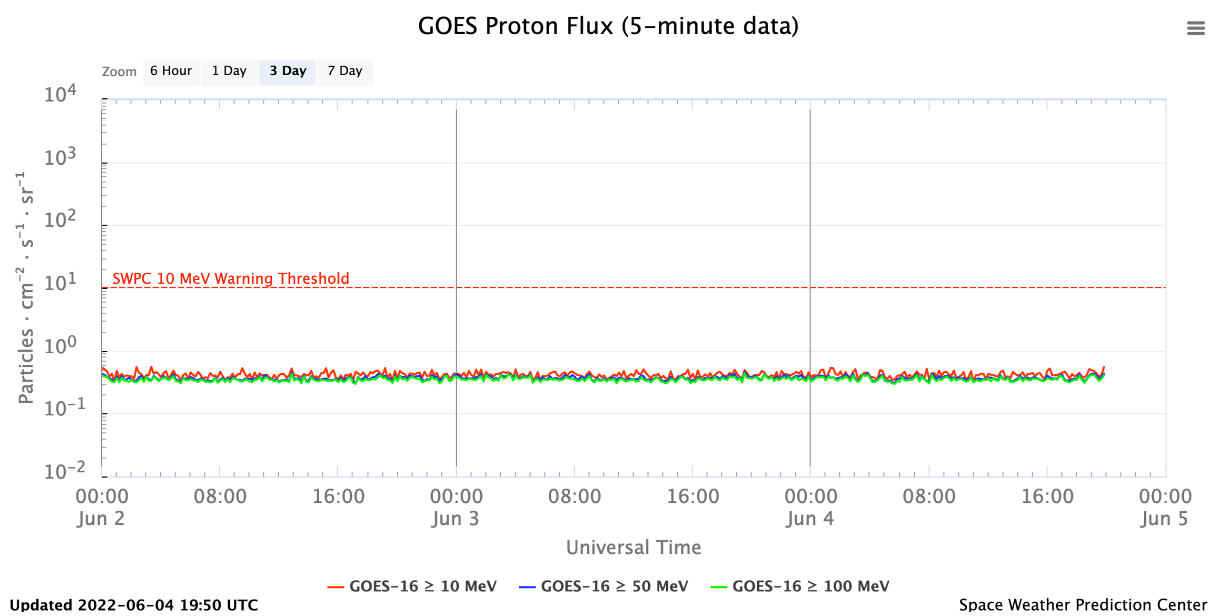


Figure 39 GOES Proton Flux (source: Space Weather Prediction Center)

Only the largest solar flares and CMEs emit charged particles with high enough energy to ionize the D layer. Consequently, polar cap absorption events occur infrequently, typically around 10 per year during solar maximum and only one or two per year during solar minimum.

Neutral atoms in the upper atmosphere are ionized when struck by a charged particle with sufficient energy to knock an electron out of the atom. Molecules are ionized in the same way. In order to ionize the D layer, SEPs must have enough energy to penetrate through the F and E layers and still have sufficient energy left to ionize D-layer molecules. Solar energetic particles must have energy levels greater than 20 MeV to do this.

Figures 40 shows the D layer absorption chart during a PCA occurring on April 23, 2023. Notice that the high latitude region is red indicating a very high absorption level throughout the region. Figure 41 is the corresponding proton flux chart for the same time and date. Notice that the proton flux spikes above the 10 MeV warning threshold to about 20 MeV, sufficient to generate a PCA. This particular PCA was caused by a CME passing Earth.

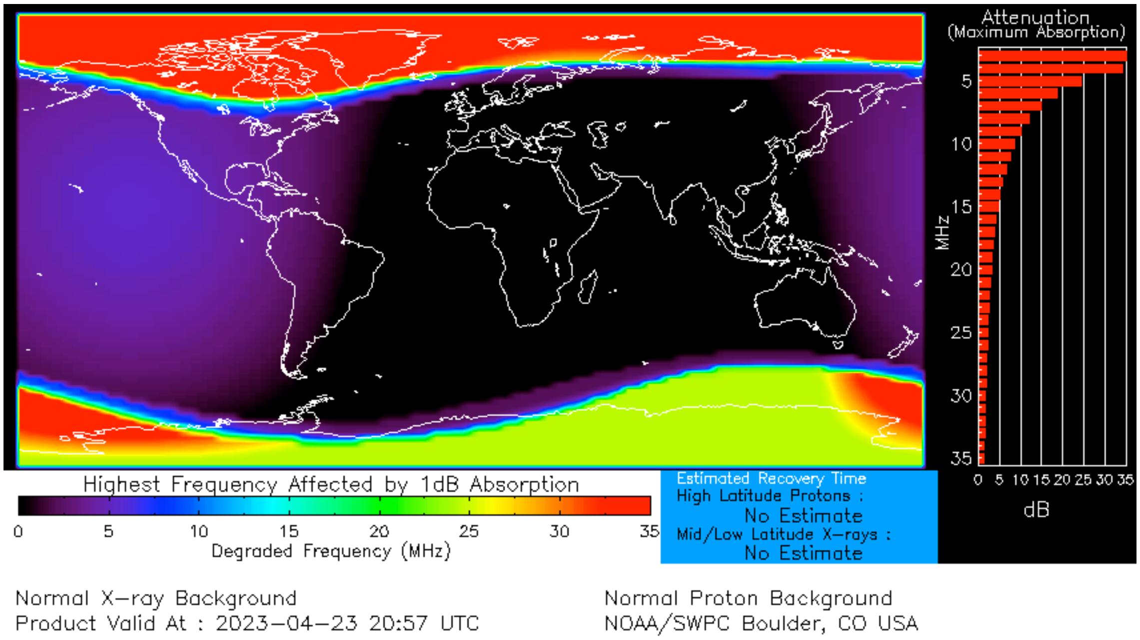


Figure 40 PCA occurring on 4/23/2023 (source: NOAA/SWPC)

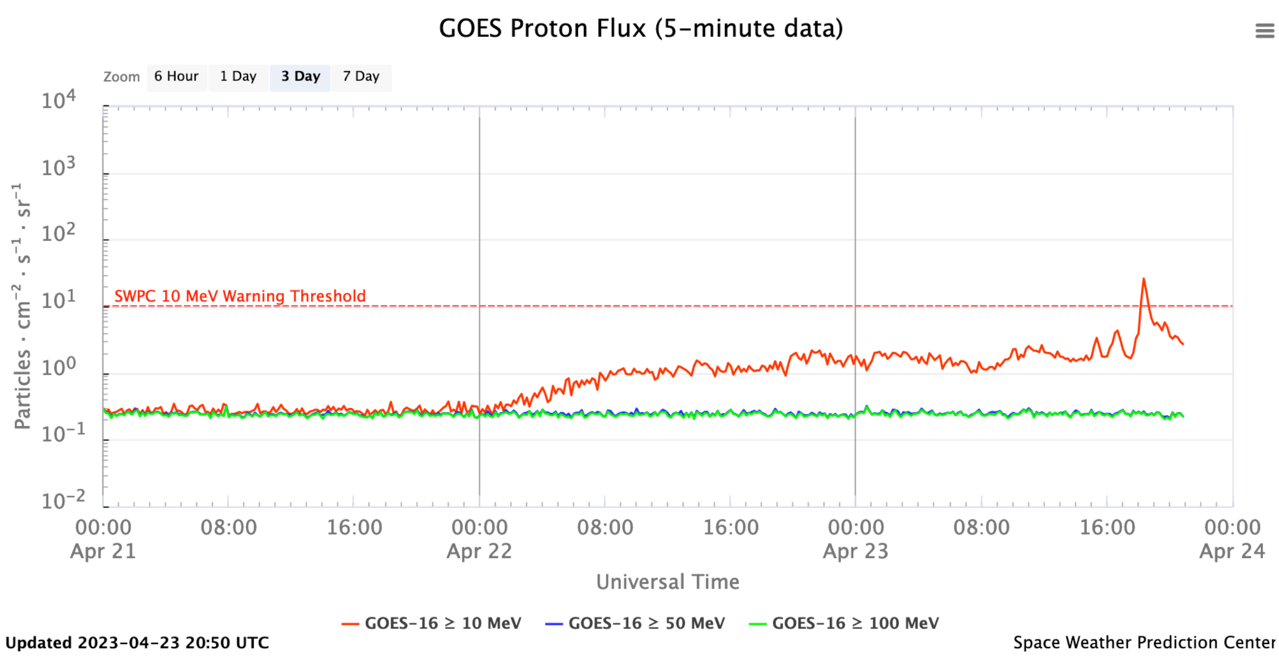


Figure 41 Corresponding proton flux for 4/23/2023

Charge particles from solar flares and CMEs also ionize polar cap atoms and molecules in the F and E regions. This ionization increases F and E region electron densities which is conducive to HF radio wave propagation. But this beneficial ionization is masked by D layer absorption.

14.5.3 Ionospheric Solar Wind Storms

Ionospheric solar wind storms and the better known geomagnetic storms are quite different, even though they both originate from the same solar wind phenomena. Both types of storms are caused by strong solar winds with southward directed interplanetary magnetic fields (IMF) impacting Earth's magnetosphere. Geomagnetic storms cause significant dips and fluctuations in Earth's magnetic field. In contrast, ionospheric storms are characterized by large drops in F2 critical frequencies. Ionospheric solar wind storms typically originate in the auroral ionosphere and drift into the mid-latitudes, carried along by thermospheric winds.

14.5.3.1 Solar Wind High Speed Stream (HSS)

CMEs, coronal loops, solar flares, and coronal holes eject billions of tons of coronal material, along with its weak embedded IMF magnetic field, into interplanetary space. The ejected material produces solar wind high speed streams (HSS) flowing in a spiral outward from the Sun (Figure 42). The solar wind actually flows out radially from the Sun. However, the Sun's rotation causes the high speed stream to take on its spiral shape when viewed from above. X-ray radiation and high energy protons also follow spiral paths to Earth, but their transit time is so short relative to the Sun's rotation that the spiral shape is not apparent.

The HSS wind and its associated IMF field reach Earth in about two to four days. When the wind arrives one of two things can happen. If the continuously changing IMF happens to be directed northward, very little if anything happens. However, if the IMF is pointed southward, it connects to Earth's northward magnetic field. The interconnected magnetic fields are dragged across the polar region by the solar wind. In the process, the polar region magnetic field lines are pealed open in the vicinity of the polar cusp (Figure 43), allowing charged solar wind particles to stream down into the magnetosphere.

Some of the particles become trapped in Earth's Van Allen radiation belts (Figure 44) and bounce back and forth along magnetic field lines between Earth's north and south polar regions (Figure 45). The position of the radiation belts within the magnetosphere is shown in Figure 43.

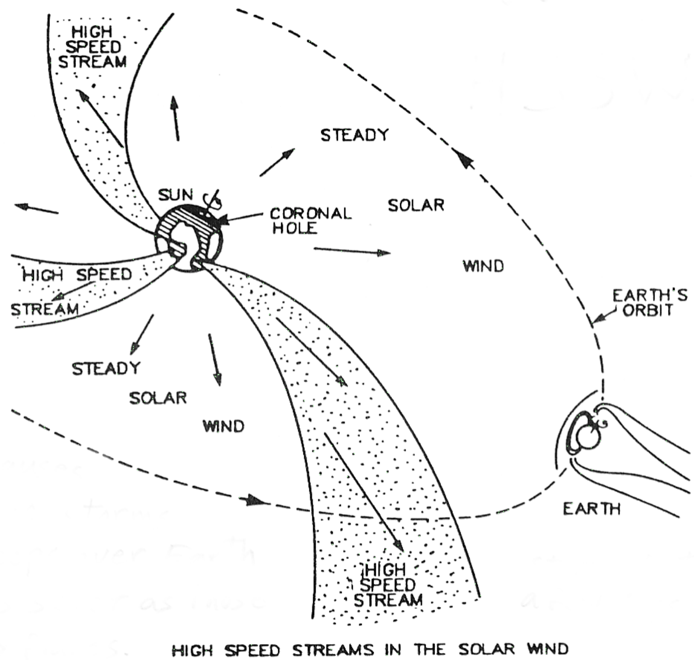


Figure 42 Solar Wind High Speed Streams (source: McNamara)

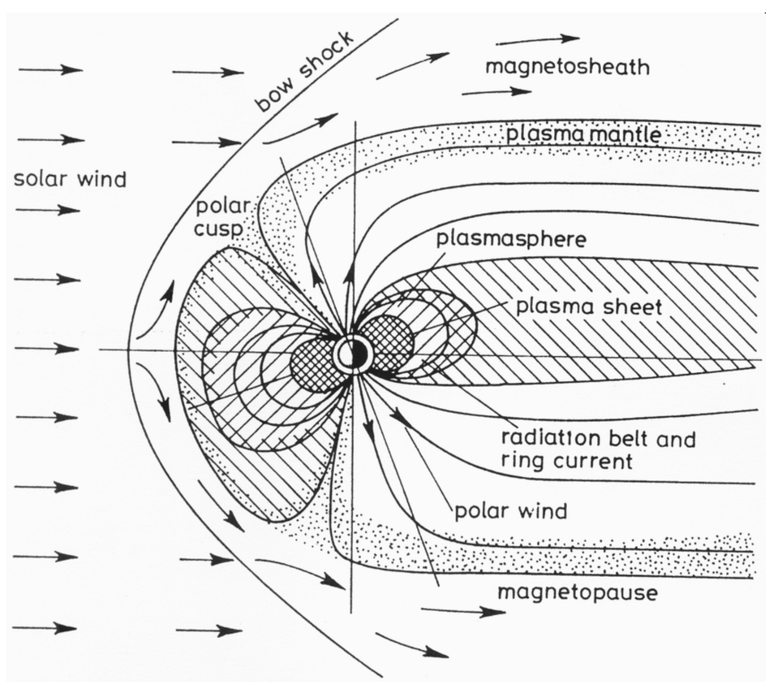


Figure 43 Earth's Magnetosphere (source: Davies)

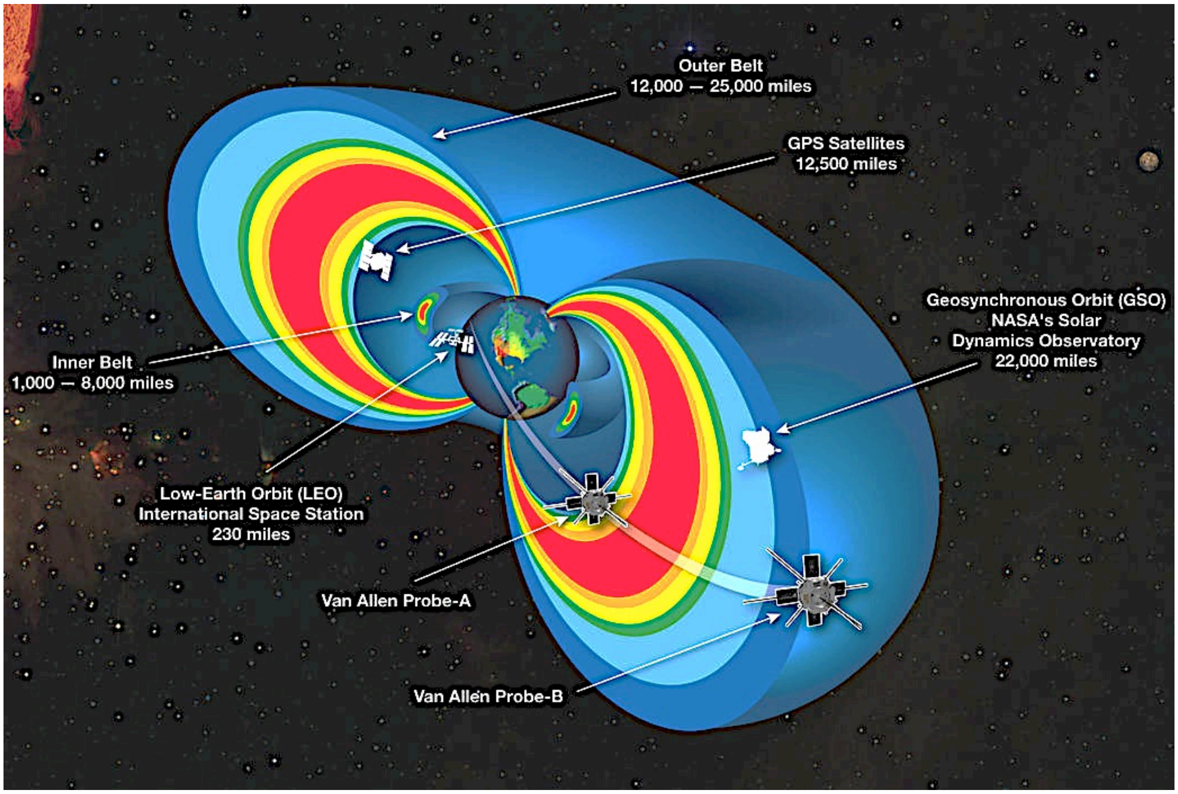


Figure 44 Cutaway model of the radiation belts (source: NASA)

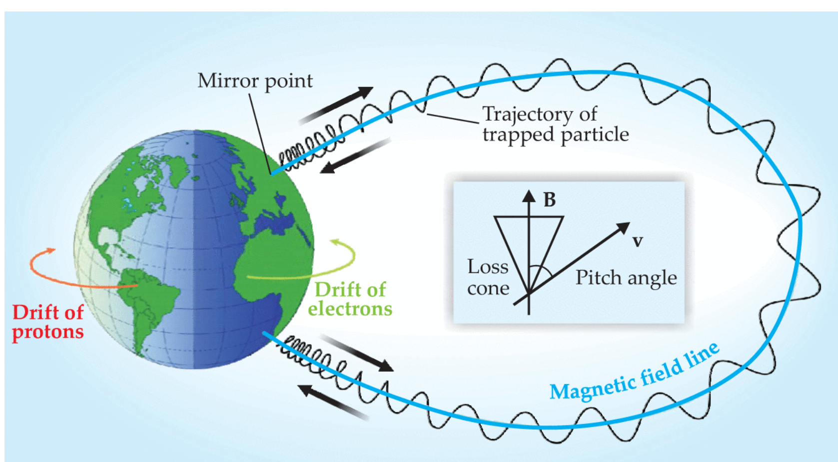


Figure 45 Trapped Charged Particles (source: Physics Today – Scitation)

14.5.3.2 Equatorial Ring Current

At an altitude of approximately 10,000 miles (16,000 km) above the equator gradients in Earth's magnetic field cause the trapped positively charged particles to drift westward while the trapped electrons drift to the east, creating a westward equatorial ring current (Figure 45). The current is positioned between the inner and outer radiation belts.

The equatorial ring current is the primary cause of geomagnetic storms. Normally the ring current is in a quiescent state. However, the strength of the ring current dramatically increases when a HSS wind (Figure 46) sweeps past Earth injecting huge quantities of solar wind particles into the radiation belts.

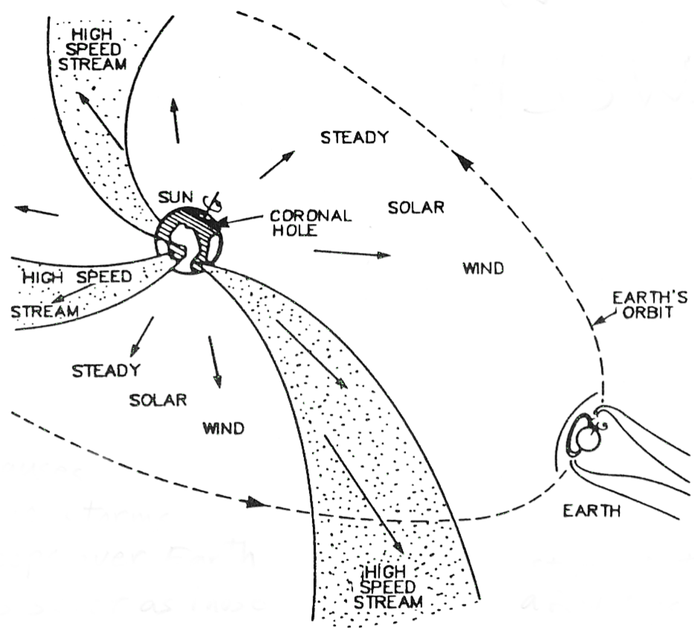


Figure 46 Solar Wind High Speed Streams (source: McNamara)

The ring current produces its own magnetic field. This magnetic field opposes Earth's core magnetic field creating a dip in Earth's magnetic field strength during a magnetic storm. The strength of the core field in the equatorial region is around 40,000 nT. In comparison, the strength of the ring current magnetic field is on the order of 200 nT during a strong geomagnetic storm. While the strength of the ring current field is only 1/2 % of the core field, the fluctuations that it causes in the core field induces high electrical currents in electrical power distribution systems and long pipelines. The induced electrical currents can potentially cause trillions of dollars in damage and power outages lasting weeks if not months. The ring current and the geomagnetic storms that it creates are of paramount importance with the potential to significantly and adversely impact our high-tech society. For this reason, fleets of spacecraft orbit the Earth and Sun monitoring and studying solar events that produce geomagnetic storms.

14.5.3.3 Development of Ionospheric Solar Wind Storms

Development of an ionospheric solar wind storm is much different.

Not all of the solar wind particles streaming down into the magnetosphere are captured in the radiation belts. Some continue down through the radiation belts and associated equatorial ring current into Earth's auroral zone atmosphere as illustrated in Figure 47.

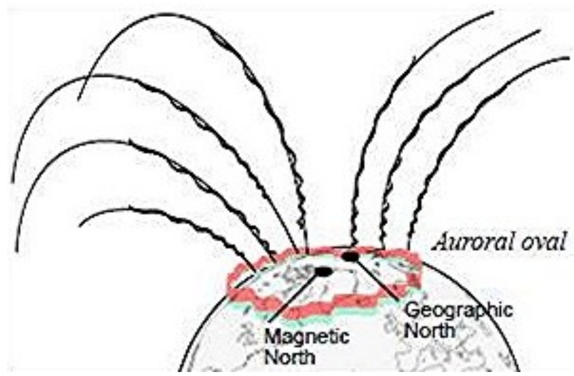


Figure 47 Particles flowing into Auroral Oval (source: NOAA Space Environment Center)

Collisions of these particles with neutral atoms and molecules change the chemical composition of the auroral ionosphere, heat the atmosphere, and change the circulation patterns of thermospheric wind. Heating plus changes in chemical composition accelerates the recombination of electrons with ions, decreasing electron densities in the auroral ionosphere, particularly in the F region.

Convection currents carry the electron depleted auroral plasma down into mid latitudes causing F2 layer critical frequencies to drop by a factor of 2 or more. The drop in critical frequency impacts the higher HF bands more than lower frequencies. Radio frequencies from 20 through 10 meters are affected the most. These bands often disappear for a week or more.

Figure 48 shows a typical critical frequency map in the absence of a solar wind storm. Notice in Figure 48 that critical frequencies over the United States range from 7 MHz in the northern states to 10 MHz over Miami, Florida. Figure 49 shows the critical frequencies at the same time of day nine days earlier during a solar wind storm. The critical frequencies during the storm are 3 MHz less, nearly 1/2 the critical frequencies for non-storm conditions.

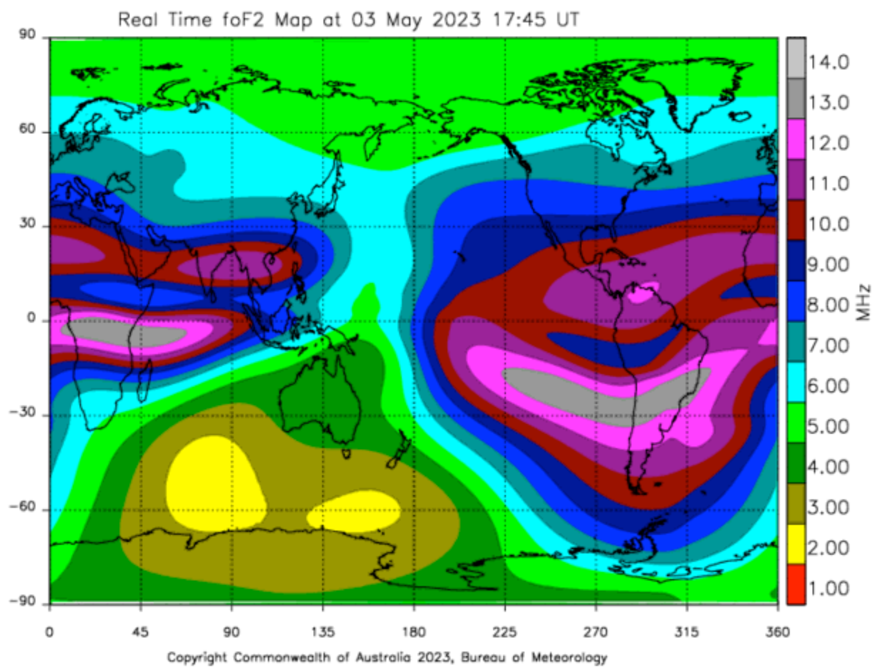


Figure 48 Critical frequency map in the absence of a solar wind storm

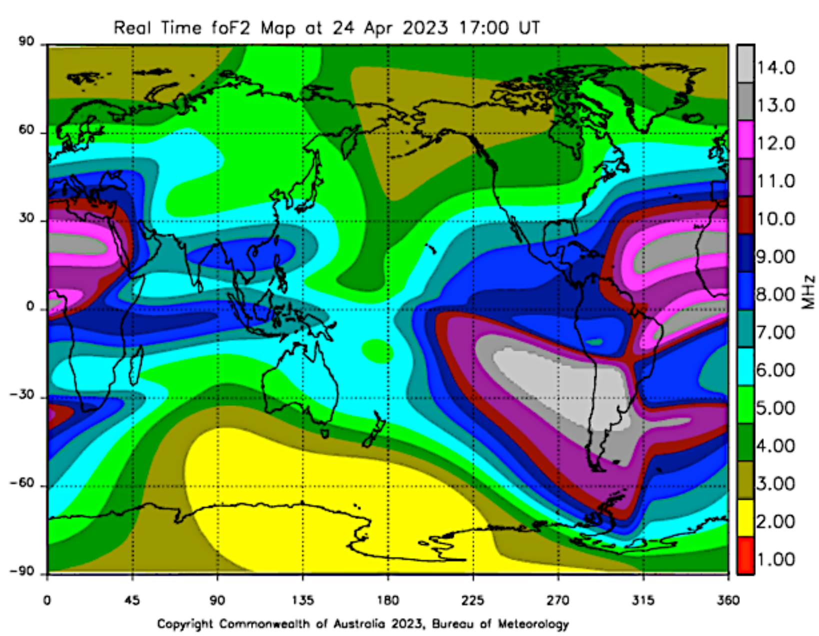


Figure 49 Critical frequency map during a solar wind storm

14.5.3.4 Highest Occurrence of Solar Wind Storms

Surprisingly, the highest occurrence of solar wind storms occurs during the declining phase of the solar cycle, one to two years following solar maximum as illustrated in Figure 50. These storms are produced primarily by coronal holes. In Figure 50, the number of sunspots is shown by the red trace while the number of disturbed days caused by ionospheric solar wind and geomagnetic storms is shown by the blue trace.

Unlike solar flares, coronal hole induced solar wind storms are not preceded by x-ray and proton storms. Coronal hole solar wind storms are most likely to occur in the spring and fall during the declining phase of a solar cycle. In the spring and fall Earth's magnetic field is favorably aligned with the IMF increasing the chance of intense geomagnetic and ionospheric storms. Coronal hole induced storms also occur during the active phase of the solar cycle but are less in number than solar flare and CME induced storms.

Coronal holes can last for a long time. Consequently, the high speed solar wind flowing out of a particular coronal hole can sweep past Earth (Figure 51) with each solar rotation causing ionospheric solar wind storms that reoccur every 27 days.

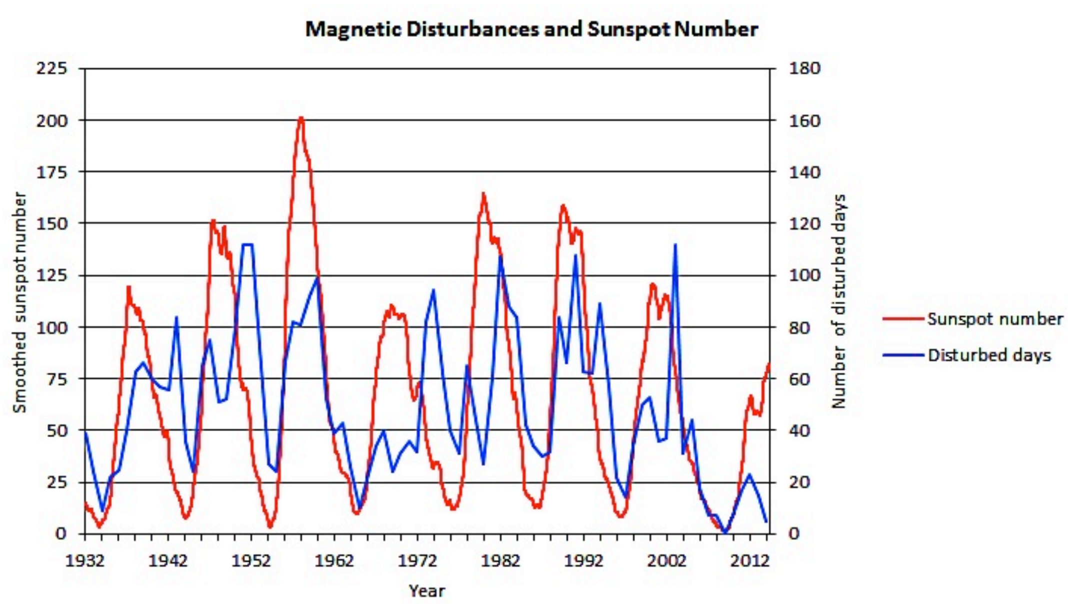


Figure 50 Occurrence of solar wind storms (source: Space Weather Services)

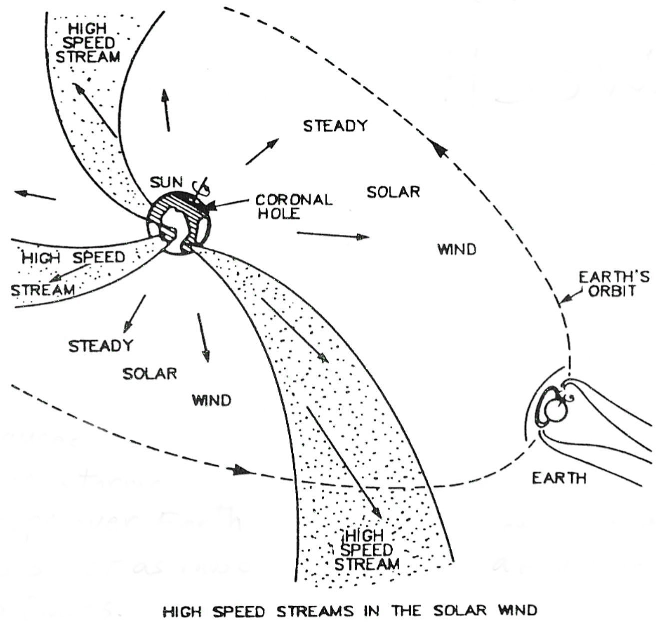


Figure 51 Solar Wind High Speed Stream (source: McNamara)

14.5.3.5 Planetary K Index

The planetary K – index, illustrated in Figure 52, is a measure of geomagnetic activity. A low K_p value ($K_p < 4$) indicates that Earth's magnetic field is quiet, solar winds are subdued, and the equatorial ring current is in a quiescent state. A K_p value around 4 indicates that the magnetic field is moderately disturbed as the result of a modest solar wind and some enhancement of the equatorial ring current. A high K_p value, greater than 4, signifies that a strong solar wind with a southward directed IMF is impacting Earth's magnetosphere, greatly enhancing the ring current and producing an intense geomagnetic storm. The characteristics of the storm include rapid fluctuations in Earth's magnetic field along with field strengths below their nominal level. In extreme cases, the storm can cause significant damage to our technological infrastructure.

The K_p value is obtained by averaging together the amplitude and phase of the magnetic field measured over a 3 hour period. The measurements are performed at 12 magnetic field observatories around the world. The observations from the various observatories are combined together to provide the planetary K_p value. The value of K_p for each 3 hour period ranges from 0 (very quiet) to 9 (very disturbed) on a quasi-logarithmic scale. Values of K_p for September 27 through 30, 2020 are shown in Figure 52. Notice in Figure 52 that green bars ($K_p < 4$) indicate quiet geomagnetic conditions. Yellow bars ($K_p = 4$) signify minor storms and red bars ($K_p > 4$) indicate major to severe storms.

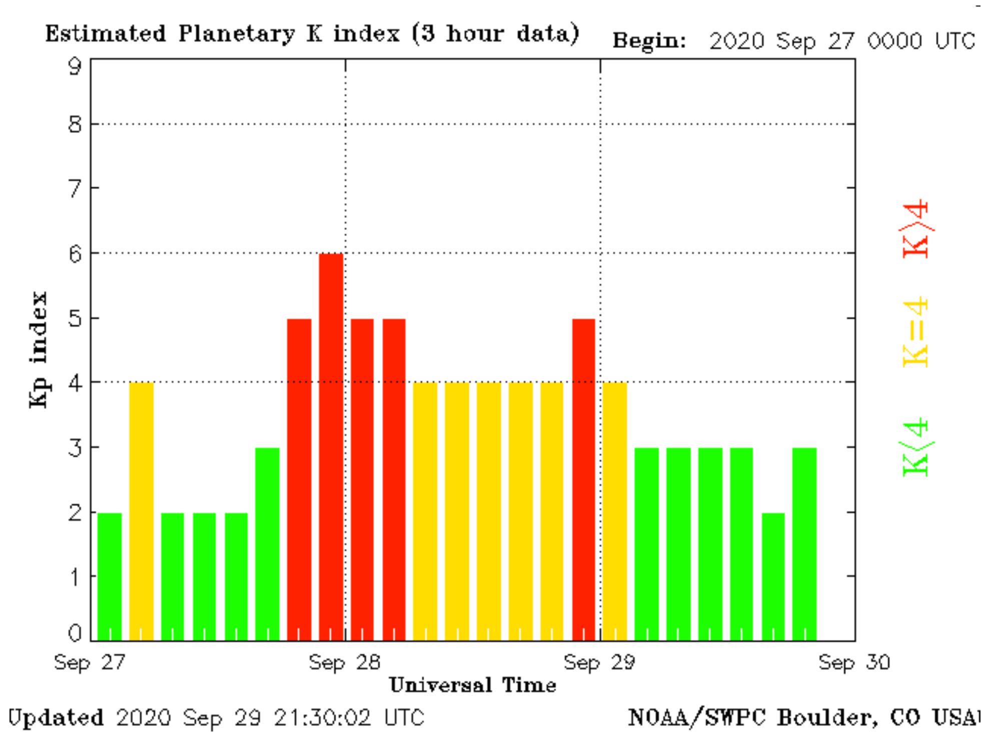


Figure 52 K_p Values for September 27 – 30, 2020

While the K_p value is a measure of magnetic field activity, it also provides a reasonably good indication of ionospheric solar wind storms since geomagnetic and ionospheric storms are produced by the same solar wind phenomena. A high K_p value indicates that an ionospheric solar wind storm is probably occurring at polar and mid-latitudes, suppressing F2 critical frequencies, and adversely affecting radio operations on 20 through 10 meters.

The current K_p index value can be obtained by clicking on "K_p Index" under the "Current Conditions" tab at www.skywave-radio.org.

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