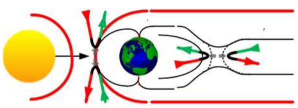
Summary of Geomagnetic Effects Observed During a Solar Cycle

Whitham D. Reeve

1. Introduction



A recent article showed the types and characteristics of solar radio emissions that might be detected throughout a solar cycle {Reeve21}. In addition to the radio phenomena received at Earth, geomagnetic effects and disturbances may be observed. These result from the interaction of Earth's magnetic field with the interplanetary magnetic field (IMF) and solar wind, both of which are controlled by the Sun. An indicator of solar activity is the number of sunspots. Sunspots follow a cyclic pattern lasting about 11 years from minimum at the beginning through maximum to minimum at the end when the Sun's magnetic field polarity reverses and the next cycle starts. Solar cycle 25 started December 2019. For a regularly updated plot that shows the progress of the solar cycle, see {NOAA25}.

Geomagnetic disturbances are initiated by solar phenomena. The major causes are flares, coronal mass ejections (CME), coronal hole high-speed streams (CHHSS), corotating interaction regions (CIR), and solar sector boundary crossings (SSBC). Because of relatively long travel times, magnetic observations on Earth may be delayed from hours to days or weeks with respect to a particular event at the Sun; however, strong solar flares can have an almost immediate effect on the geomagnetic field because flare x-ray radiation, which induces the disturbance, propagates at light-speed.

Solar activities, such as sunspots and coronal holes, that persist for more than one solar rotation cause recurring geomagnetic effects at about 27-day intervals. Some geomagnetic activity has no obvious source but is interesting nonetheless. Even time periods when Earth's magnetic field is very quiet are interesting, especially at higher latitudes because they are so rare (figure 1). Very quiet days, when the K-index was zero for a full 24 hours, have been recorded only twice at Anchorage in 11 years of observations of solar cycle 24 by the SAM-III magnetometer.

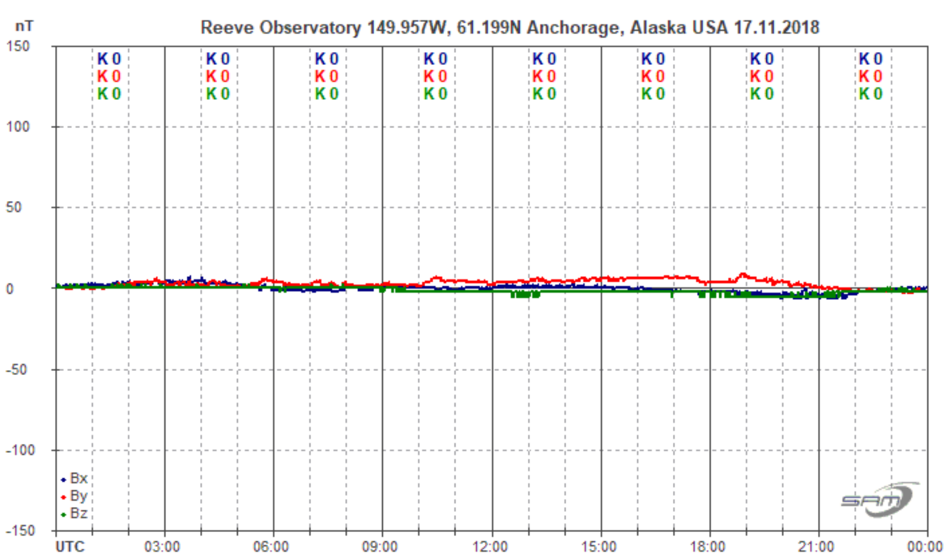


Figure 1 ~ Very rare magnetically quiet day near the end of solar cycle 24 was observed at Anchorage, Alaska on 17 November 2018 with the SAM-III magnetometer. All magnetic components indicate a K-index of zero in each of the eight 3-hour synoptic periods. The system sensors are oriented according to the geographical coordinate system and measure Bx (blue, north-south), By (red, east-west) and Bz (green, vertical).

This article briefly describes each of the phenomena listed above and their geomagnetic effects. All are illustrated through solar images and magnetograms from solar cycle 24, which began December 2008 and ended December 2019. The magnetograms were produced by the SAM-III magnetometer at Anchorage, Alaska, 61.7° north latitude {SAM-III}. All solar images were obtained from NASA. Readers interested in the general topic of geomagnetism may find the tutorial at {Reeve15} useful.

Many government agencies use data from ground magnetometers in *space weather* prediction and research. The Space Weather Prediction Center (SWPC) in the USA provides a lot of free information called *products* and *data* that are useful for correlating with local geomagnetic observations. SWPC regularly produces dozens of reports, observations, models and data summaries related to space weather. Good places to start are the Space Weather Dashboard {DSHBD} and the Products and Data tab on that webpage. Other countries provide similar space weather services, including Australia {SWS} and European Space Agency Space Weather Service Network (ESASWSN). These agencies generally are collaborative with SPWC but tailor their reports and products to their geographic regions.

---

2. Phenomena

Flare: A solar flare is a huge explosive event on the Sun's surface resulting from magnetic instabilities associated with sunspots (figure 2). A flare can last from minutes to hours. The sudden release of magnetic energy causes an intense burst of electromagnetic radiation over an extremely wide frequency range. Particles – electrons, protons, and heavier particles – are accelerated by a flare and, if *geoeffective*, can lead to a number of effects. Geoeffective means the particles are moving in such a way that Earth intercepts them as they travel outward from the Sun. Flares and related phenomena are most common near the peak of a solar cycle when sunspot numbers are high but are unpredictable and may occur any time, even at solar minimum.

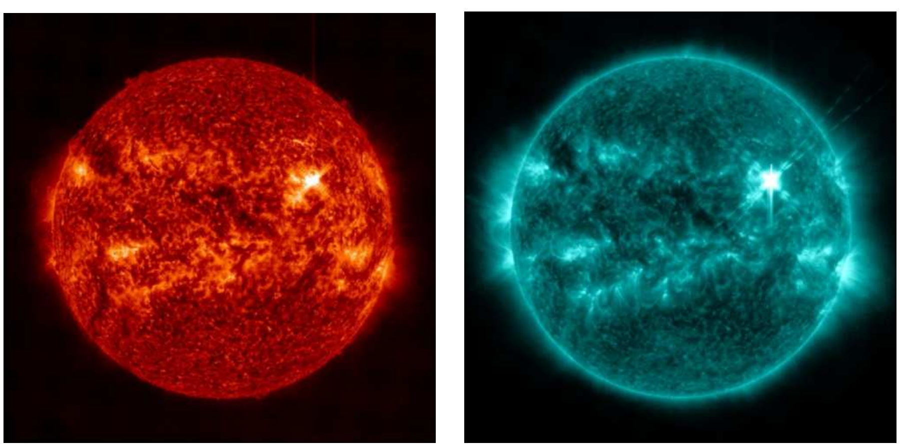


Figure 2 ~ X1.0 solar flare imaged at 30.4 nm (left) and 13.1 nm (right) wavelengths on March 29, 2014. The flare is the bright area on the right above the equator. The 30.4 nm wavelength shows the region between the chromosphere and corona, and 13.1 nm wavelength shows material with a temperature of 10 million kelvin. This flare produced a magnetic crochet described below. Image source: NASA/SDO

The x-ray radiation from a flare propagates at light-speed and reaches Earth after a little more than 8 minutes. When detected, the times of solar events are reported with respect to *Coordinated Universal Time* (UTC). If a part of the flare has a very sudden optical brightness increase (within about 1 minute), it is called an *impulsive flare*. If it also is very strong, the associated x-ray radiation quickly increases the ionization and, thus, the electrical conductivity in the D- and E-regions of Earth's ionosphere. The increased conductivity leads to increased electric currents in the electrojets, which, in turn, produce a sharp change in the magnetic field measured on the ground. As the flare tapers off and the burst of radiation subsides, the ionosphere, electric currents and magnetic field return to their preflare conditions.

When such an event occurs, a real-time trace of the magnetic field measured on the ground has the shape of a crochet hook used for knitting. Thus, the trace on a magnetogram is called a *magnetic crochet*, but its more formal name is *Solar Flare Effect*, or SFE. Magnetic crochets are rare and usually are observed only on Earth's dayside. Locations where the Sun is directly overhead at the time of the flare have the highest likelihood of observing a magnetic crochet when it occurs, but other locations are possible. For example, a weak magnetic crochet produced by the X1.0 flare shown above was observed at Anchorage, Alaska about 4 hours before solar transit (figure 3).

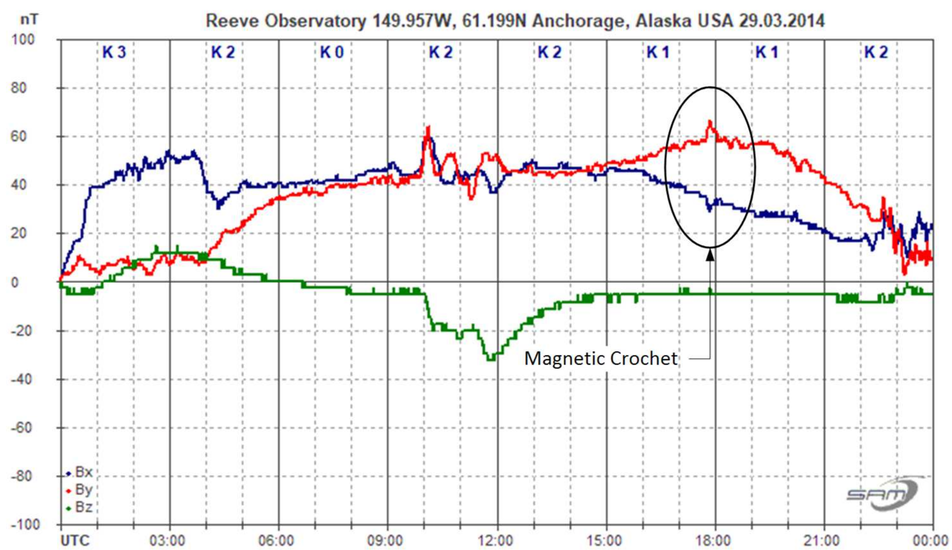


Figure 3 ~ Normalized magnetogram showing measurements at Anchorage, Alaska for the 24 h period on 29 March 2014 near the peak of solar cycle 24. An X1.0 solar flare caused a rare magnetic crochet, which is circled and indicated by the black arrow in Bx and By at 1748 UTC (9:48 am local). This crochet was observed only 2 hours after local sunrise and 4 hours before solar transit. In addition to this crochet, the flare produced numerous radio emissions and an HF radio blackout. The trace colors are as in the previous magnetogram and shown in the lower-left corner. This and subsequent magnetograms have the K-index for each 3-hour synoptic period shown along the top; the vertical scale is magnetic flux density in nT normalized at the beginning of the UTC day.

<u>Coronal mass ejection</u>: The energy released by a strong solar flare can accelerate a huge mass of charged particles, mostly hydrogen and helium ions and electrons, away from the corona above sunspots. The event is appropriately called a *coronal mass ejection*, or CME (figure 4). Not all flares produce a CME and not all CMEs are produced by flares, but most are. A CME can travel at speeds up to 2000 km s^{-1} and, if geoeffective, reach Earth in as little as a day. However, most CMEs have speeds in the 500 to 700 km s^{-1} range and arrive within a week. A fast CME will overtake the slower ambient solar wind and produce a shock front that travels outward.

The CME carries a portion of the Sun's magnetic field into interplanetary space; that is, the field is *frozen-in* to the ejected plasma and moves with it. The vector magnitude of the interplanetary magnetic field, or IMF, at a distance of 1 astronomical unit (AU) from the Sun is on the order of 5 to 8 nT but can increase with solar activity such as a CME. The magnitude of Earth's magnetic field at about 10 Earth radii on the dayside toward the Sun is comparable to the IMF. If the CME is geoeffective, it can disturb the geomagnetosphere as described below.

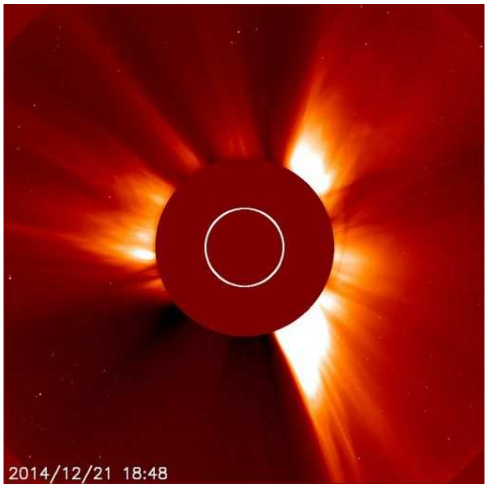


Figure 4 ~ Coronal mass ejection on 21 December 2014 seen as the bright areas. The Sun itself, shown by the white circle, is blocked by an occulting disk in the spacecraft imaging device. This CME intercepted Earth on 23 December only 2 days after leaving the Sun. A CME is a huge 3-dimensional moving mass of charged particles generally with higher density and speed compared to the ambient solar wind. When a geoeffective CME impacts Earth's magnetosphere, the magnetic field is disturbed and oscillates. This generates electric currents in Earth's ionosphere and near-Earth space environment. The electric currents in turn generate additional magnetic field variations and often a geomagnetic storm. Image source: NASA/SOHO/LASCO

Refer to the numbers in figure 5, which shows a conceptual sequence called the *Dungey Cycle* to describe the IMF and magnetosphere interactions when the IMF has a southward component: 1. When the interplanetary magnetic field embedded in the solar wind has a southward component, opposite to Earth's magnetic field, the two fields merge on the dayside of the magnetosphere in a process called *magnetic reconnection*; 2. The formerly closed geomagnetic field lines facing the Sun open as they merge with the IMF. The IMF and magnetosphere are now linked and solar wind plasma can enter the magnetosphere at high latitudes; 3. The open field lines are carried over the Earth's poles by the solar wind. The field lines are stretched out on Earth's nightside in the region called the magnetotail; 4. As they stretch out, the open-field lines move toward the center plane of the tail where they reconnect again, closing the magnetic flux that was opened on the dayside. The time from 1 to 4 is on the order of 1 hour; 5. Part of the flux moves down-tail away from Earth, but, of interest here, part of the magnetic flux returns by internal flows to their origin; 6. This process carries plasma resident in the magnetotail toward Earth; 7. The highly energized electrons in the plasma are trapped by the magnetic field and are further energized when they arrive within a few Earth radii by voltage variations along the magnetic field lines. The cycle may repeat in a quasi-cyclic process called a substorm with a period of roughly 1 to 3 hours. If the IMF is northward, it is deflected around Earth and there is no reconnection.

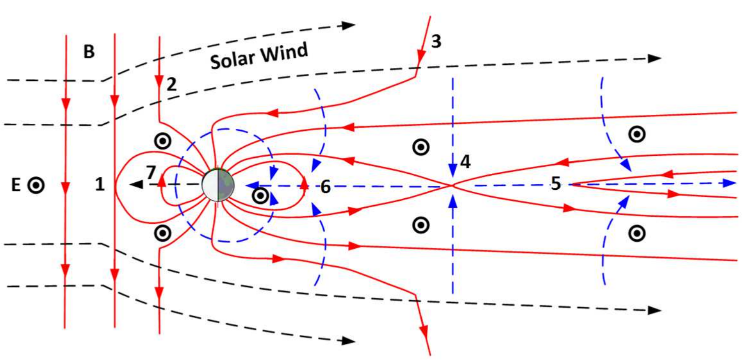


Figure 5 ~ Conceptual drawing of magnetic reconnection. The numbers indicate the sequence described in the text. The Sun is to the left out of view, and the solar wind is shown by the black dashed lines flowing left-to-right. The magnetic field (B) is shown in red; the IMF is southward. Earth is the circle with the sunlit side facing the Sun and has a northward magnetic field. Current flow (E) is into the page shown by the circled dots. Magnetic flux movement is shown by blue arrows. Diagram adapted from: [Seki]

When the charge particles stored in the magnetotail are energized and travel back toward Earth along the stretched out magnetic field lines, they interact with the upper atmosphere at approximately 100 to 300 km altitude to produce aurora. The energy transfer can also produce strong geomagnetic disturbances and a storm (figure 6). It should be noted that simply having a southward component in the IMF does not always lead to a disturbance. Generally, the southward component has to have a large enough magnitude, say > –5 or –6 nT, and be sustained for a period of time so that enough energy transfer can take place.

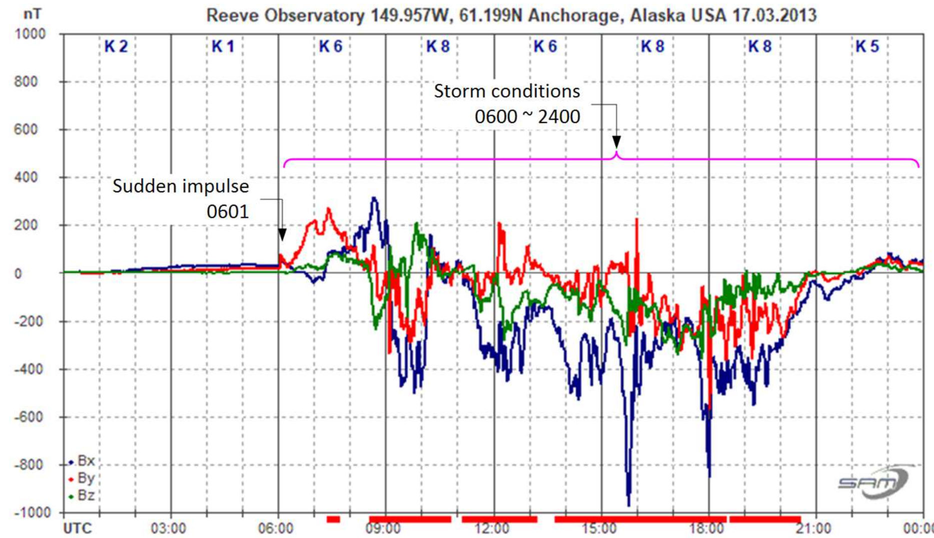


Figure 6 ~ Normalized magnetogram showing a geomagnetic storm observed at Anchorage, Alaska on 17 March 2013 near the peak of solar cycle 24. Although not obvious at this scale, a sudden impulse occurred at 0601 UTC and was followed almost immediately by storm conditions indicated by K-index of 6 during the 0600 to 0900 synoptic period. The storm reached a K-index of 8 for two synoptic periods and lasted the rest of the UTC day. It was caused by a geoeffective CME that occurred 2 days before and traveled with an average speed of almost 900 km s^{-1} to Earth. Note that the magnetic flux density during the storm initially increased but then decreased from normalized levels; the traces show some quasi-periodic structures. These may be due to build-ups and releases of energy in the magnetotail as reconnections took place.

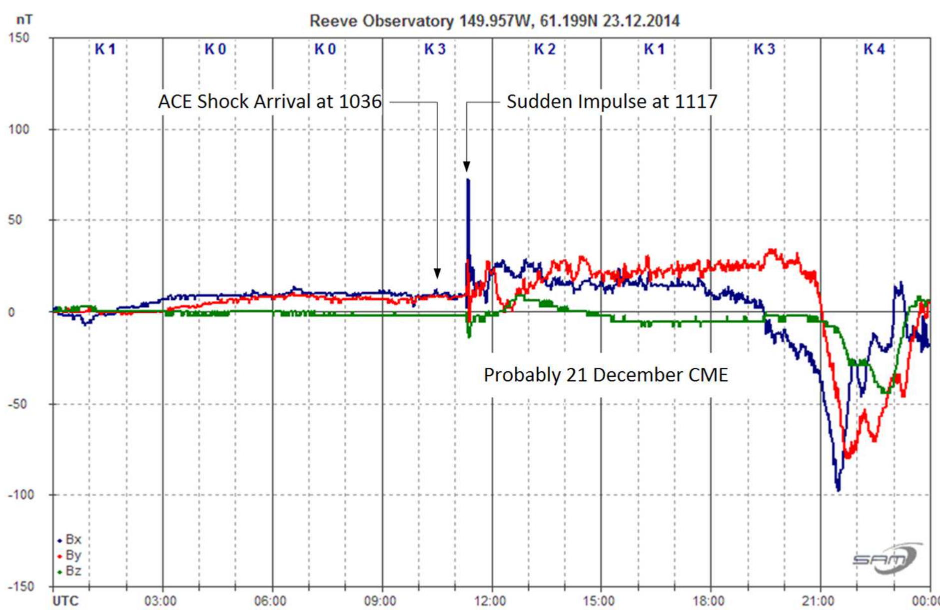


Figure 7 ~ Normalized and annotated magnetogram showing a sudden impulse at 1117 UTC observed at Anchorage, Alaska on 23 December 2014 near the peak of solar cycle 24. Note the vertical scale change compared to the previous magnetogram. The amplitude of this sudden impulse is quite large at about 60 nT. The CME that caused this disturbance is imaged in figure 4. A flare produced the geoeffective CME 2 days before and it arrived at the ACE spacecraft (a sentinel spacecraft $1.5 \cdot 10^6$ km from Earth on the Earth-Sun line) at 1036 UTC and 41 minutes later at Earth. Note the magnetic field disturbances that follow the sudden impulse, especially the bay about 9 hours later, compared to activity before the sudden impulse. The disturbances did not reach actual storm levels until the next day at approximately 1430 UTC.

Disturbances are not limited to situations with a southward IMF. Upon impact, the CME compresses the magnetosphere and suddenly alters the currents flowing in the ionosphere (electrojets), producing a *sudden impulse* (figure 7) or transient measured by ground magnetometers (see {Reeve13} for a more comprehensive discussion of sudden impulses). The sudden impulse may or may not be followed by a storm but often does. *Sudden commencement* is the name often given to a sudden impulse that is followed by a storm.

Coronal hole high-speed stream: Coronal holes are large areas in the solar corona with less dense and colder plasma and where the solar magnetic field lines are able to stretch far into the interplanetary medium (IPM) (figure 8). The wind that originates from a coronal hole is elevated compared to surrounding areas, so it is called a *coronal hole high-speed stream*, or CHHSS. Coronal holes that persist for more than one solar rotation of approximately 27 days are called *recurrent* coronal holes. Coronal holes are the most common source of geomagnetic storms.

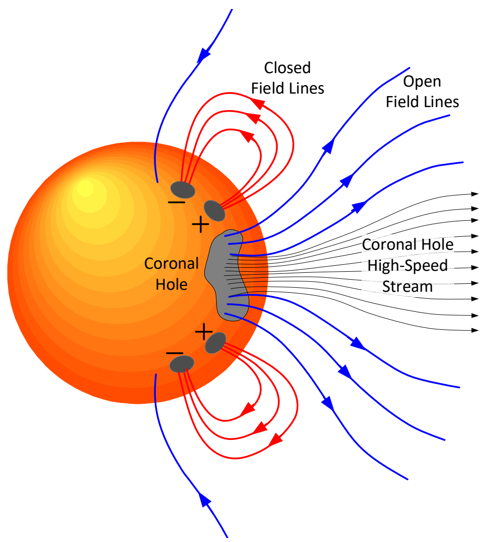


Figure 8 ~ The Sun's magnetic field does not have simple dipole characteristics but is very complex. Closed magnetic field lines shown by the red lines in this conceptual drawing connect the different sunspot polarities and other solar features. Coronal holes have magnetic field lines, indicated by blue lines, that stretch far into the interplanetary medium allowing the solar wind to escape at high speeds. The plasma in the coronal hole regions is less dense and cooler than surrounding areas and the high-speed stream is correspondingly cooler and less dense as well. The Sun's magnetic field lines are frozen-in to the stream and if the stream is geoeffective and has a southward component, that portion of the Sun's field may merge with Earth's magnetic field, leading to a geomagnetic disturbance. The field lines labeled *open* actually are closed but do so at some distance past Earth, so as seen from the perspective of Earth's magnetosphere, they are open.

As the sunspot cycle winds down and goes through the minimum phase, the solar wind is dominated by coronal hole high-speed streams with speeds in the range of 500 to 800 km s^{-1}. The solar wind also has a denser lower speed component of around 300 km s^{-1}. The overall average speed is in the vicinity of 470 km s^{-1}. Larger coronal holes can be a source for high solar wind speeds that buffet Earth's magnetic field for many days. Sometimes a CHHSS becomes geoeffective at about the same time as a CME impacts Earth, leading to a strong geomagnetic storm.

During solar cycle minimum, coronal holes usually are found in the Sun's polar regions (crowns). Because the magnetic fields associated with coronal holes are extremely twisted and complex and heavily influence the wind streams, the solar wind from polar coronal holes often reach the ecliptic plane and affect Earth. As the solar cycle progresses and solar activity increases, the coronal holes occur at all solar latitudes. When a coronal hole is near or on the solar equator, its high-speed wind flow has a high likelihood of becoming geoeffective (figure 9).

A coronal hole does not always cause storms, but it can cause increased geomagnetic activity (figure 10). The wind may simply blow around Earth's magnetosphere and continue on its way; however, if the IMF embedded in the CHHSS has a southward component, the open field lines in the stream can merge with Earth's closed field lines, transferring energy to the magnetotail and manifesting as a geomagnetic disturbance and storm conditions (figure 11) in the same manner as described above for CMEs.

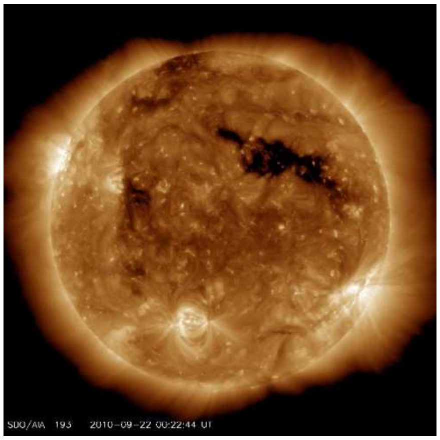


Figure 9 ~ Coronal hole imaged at 0022 UTC on 22 September 2017 during the descending phase of solar cycle 24. Coronal holes are seen as dark areas in images taken at extreme ultraviolet (EUV) and soft x-ray wavelengths. The image shown here was taken at a wavelength of 19.3 nm, which is used to record ultraviolet light coming from gas at a temperature of about 1 million kelvin. The dark areas, such as the elongated black stripe at the upper-right of the solar disk, are cooler and less dense than the surrounding area and have open magnetic field lines that stretch far into the solar system. The open field lines allow the solar wind to easily escape much faster than surrounding areas, the surrounding areas being constrained by closed magnetic field lines. Image source: NASA SDO/AIA

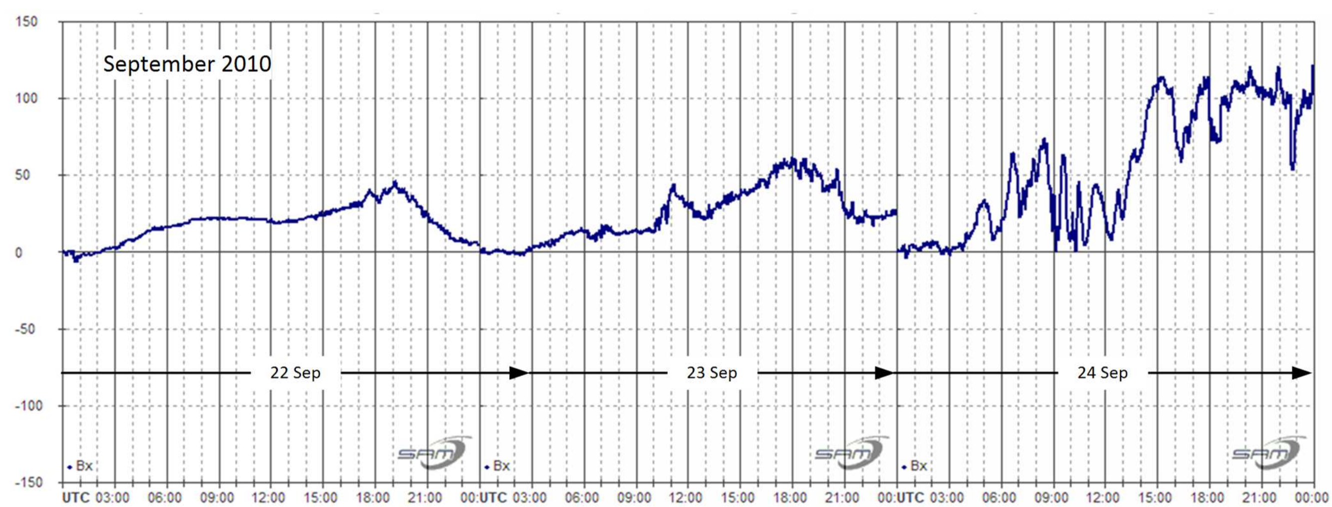


Figure 10 ~ Spliced 24-hour magnetograms at Anchorage, Alaska for the three consecutive days 22, 23 and 24 September 2010 during the ascending phase of solar cycle 24. The trace for 22 September shows a magnetically quiet day before the coronal hole high-speed stream became geoeffective (see previous figure for an image of the coronal hole). The following day, 23 September, also is mostly quiet with some activity starting between 0600 and 1100 as the geoeffective solar wind speed increases and buffets Earth's magnetic field. The CHHSS appears to sweep into full effectiveness (magnetically speaking) starting around 0400 on 24 September. Solar wind velocities increased steadily and reached 600 km s^{-1} on 24 September. The vertical gap at the beginning of 24 September is a plotting artifact due to normalization of the data. These magnetograms were produced by the original SAM magnetometer equipped with a single axis sensor oriented north-south (Bx).

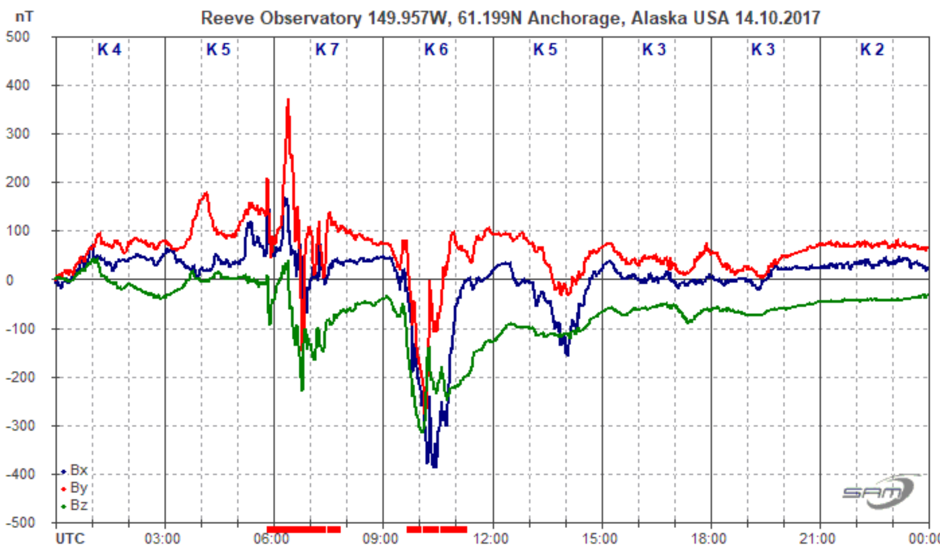


Figure 11 ~ Normalized 24 hour magnetogram at Anchorage, Alaska for 14 October 2017 during the descending phase of solar cycle 24. Storm conditions (K ≥ 5) are indicated during the four synoptic periods from 0300 to 1500, in part caused by the elevated solar wind speeds throughout the 24 h period due to a geoeffective coronal hole in the Sun's polar region. Reconnection was enabled by a southward Bz component in the interplanetary magnetic field, which reached –7 nT.

Corotating interaction region (CIR): The high- and low-speed components of the solar wind form alternating streams in the solar wind flow. They move outward into interplanetary space in a spiral because of the Sun's rotation. As the streams travel away from the Sun, the high-speed flows overtake the low-speed flows, creating a compression region with enhanced plasma density and magnetic flux density. This region is called a *corotating interaction region*, or CIR (figure 12). As viewed by a fixed observer in interplanetary space, the CIR appears to lead the coronal hole high speed stream.

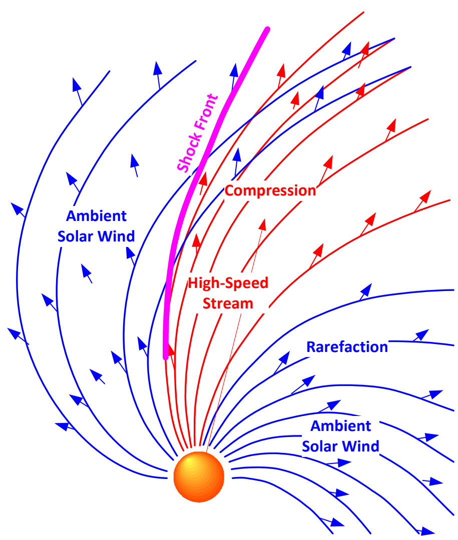


Figure 12 ~ Conceptual illustration of a corotating interaction region looking down on the Sun along its rotation axis. A CIR forms where the low-speed component of the solar wind (blue) is overtaken by the high-speed wind (red) from a coronal hole, forming a shock front (violet) ahead of the compression region. The relatively abrupt changes in the solar wind speed and interplanetary magnetic field at the shock can affect the geomagnetosphere when Earth intercepts it. Because of the spiral structure of the solar wind, Earth intercepts it at about a 45° angle with respect to Earth's orbital direction.

The CIR can result in plasma density enhancement and IMF flux density increase that precedes the onset of the CHHSS lower density and higher wind speed. When Earth intercepts the CHHSS, sentinel spacecraft detect it as an increase in the solar wind speed and temperature and a decrease in plasma density. After passage of the CIR and upon transition into the CHHSS flow, the overall IMF strength near Earth will normally begin to slowly decrease.

Generally, coronal holes located at or near the solar equator are most likely to be geoeffective and result in a CIR passage or higher solar wind speeds, or both, observed at Earth. CIRs and the following CHHSS do not necessarily induce geomagnetic storms but they may have some effect (figures 13, 14 and 15). However, strong CIRs and faster CHHSS can cause periods of increased geomagnetic activity and storming, particularly if the embedded magnetic field has a southward component.

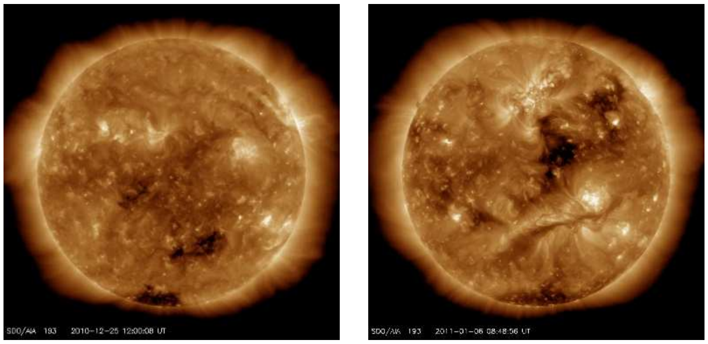


Figure 13 ~ Images at 19.3 nm wavelength of the Sun showing coronal holes in view on the dates of the two magnetograms shown below. Neither coronal hole is particularly large. Left: 25 December 2010; two small coronal holes, one at south pole and one just above the south pole and to the right; Right: 6 January 2011; three coronal holes, south pole, just above the equator near the meridian and one not quite visible in this image at the north pole. Image source: NASA SDO/AIA

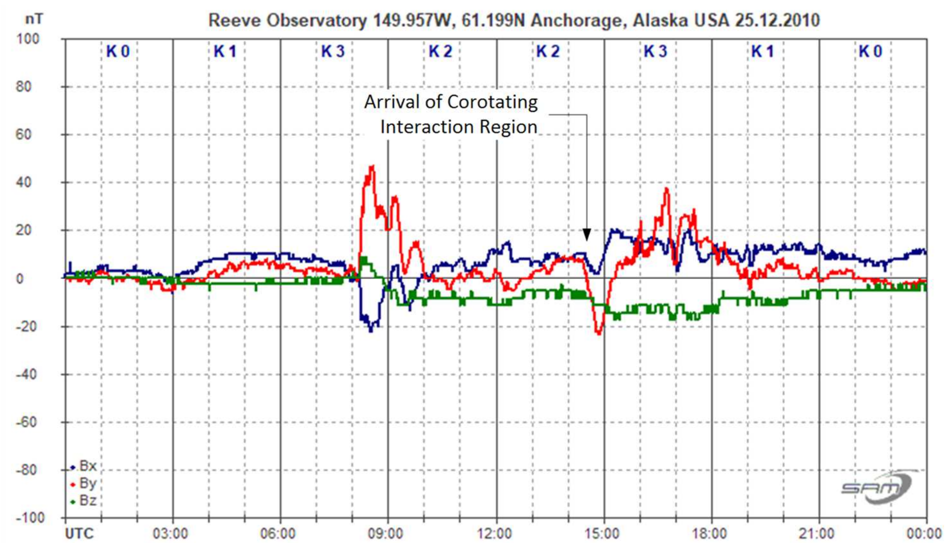


Figure 14 ~ Corotating interaction region on 25 December 2010. Although a coronal hole high-speed stream very likely followed the CIR, it was not reported. Note the dip in both Bx (north-south) and By (east-west) magnetic components immediately after the CIR was intercepted at 1430 UTC. The minor disturbance earlier at 0800 probably was related to the CIR.

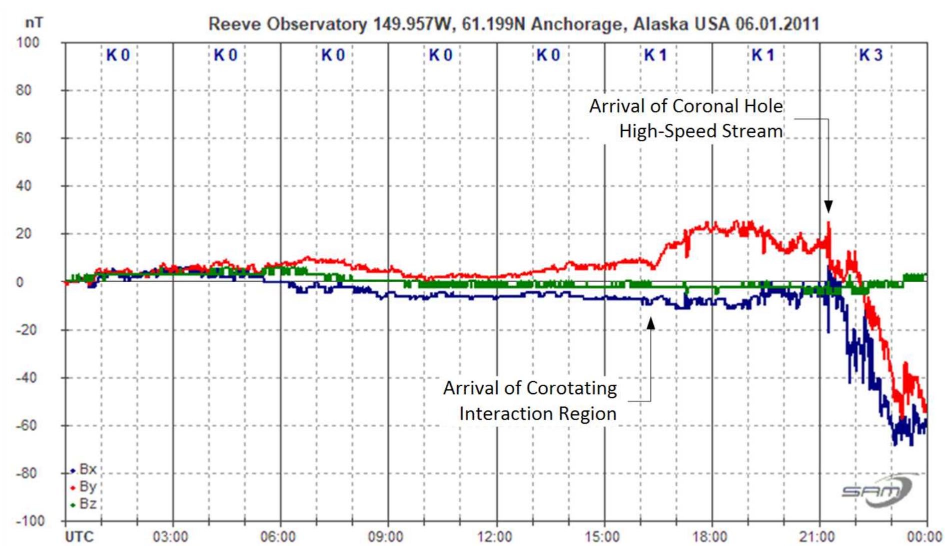


Figure 15 ~ Corotating interaction region followed by a coronal hole high-speed stream on 6 January 2011, about 2 weeks after the previous magnetogram. Note that the CIR had relatively little geomagnetic effect, but the CHHSS that followed about 5 hours later caused a bay, or reduction in measured flux density. Some sharp transients were recorded between the CIR and CHHSS; their source is unknown but they possibly were caused locally (road grader).

Solar Sector Boundary Crossing (SSBC): As previously noted the solar wind carries part of the Sun's magnetic field as it flows away from the Sun, and the solar wind has a spiral shape as it extends out from the Sun due to the Sun's rotation. The Sun's north and south hemispheres have opposite polarity that flip every 11 years, corresponding to the sunspot cycle (22 years for a full magnetic cycle). Along the solar magnetic equator the opposite polarity field lines are parallel, creating a current sheet between them called the *heliospheric current sheet*, or HCS (figure 16, left].

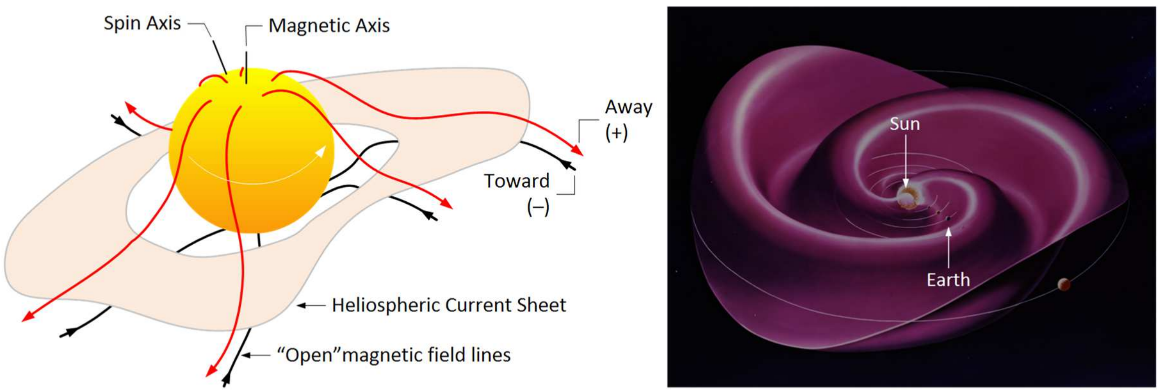


Figure 16 ~ Left: Heliospheric Current Sheet forms between opposite polarity open magnetic field lines from above and below the Sun's magnetic equator (adapted from [Smith78]). Right: The wobbling of the Sun due to misalignment of its rotation and magnetic axes creates folds, or sectors, in the HCS that interact with Earth's magnetic field (adapted from Stanford Solar Center, {STNFRD}). Each passage through a sector is called a solar sector boundary crossing.

The current sheet is warped and develops folds, or sectors, because the Sun's rotational and magnetic axes are not always aligned and it wobbles (figure 16, right). Along the ecliptic plane, the IMF generally has two or four fold-sectors per solar rotation (27 days each). When Earth crosses one of these folds there is a change in the solar wind's magnetic orientation, or polarity, called a *solar sector boundary crossing*. A well-defined sector boundary crossing has a uniform field direction (as measured by sentinel spacecraft) for about 4 days before and after the crossing. The polarity change can simply jostle Earth's magnetic field (figure 17) or, if it includes a southward magnetic field component, merging and disturbance of Earth's magnetic field may result.

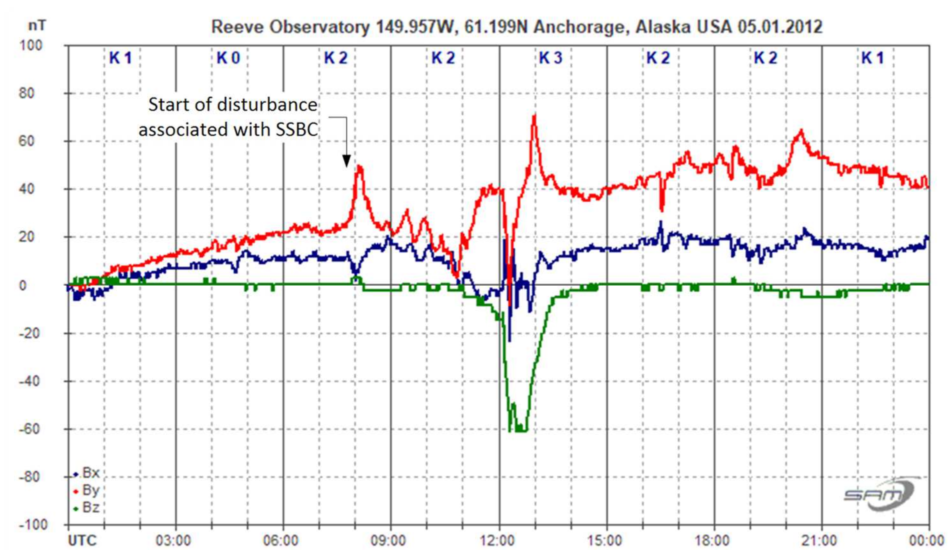


Figure 17 ~ Unsettled conditions possibly caused by SSBC when effects were indicated just before 0800 UTC on 5 January 2012, approximately 4 years into solar cycle 24. This disturbance produced only a K-index of 3 during the 1200 to 1500 synoptic period. According to spacecraft data, the SSBC showed stable magnetic field polarities 7 days before and 4 days after the SSBC, which actually occurred the next day.

Other interesting phenomena: The magnitude of magnetic variations caused by a coronal hole high-speed stream or other solar phenomena may be relatively minor but those variations may include interesting structures, such as *ULF* (ultralow frequency) *waves*, also called *magnetic pulsations* and *micropulsations*. These are periodic variations in Earth's magnetic field with periods from fractions of a second to several minutes. Note that the maximum sample rate of the SAM-III magnetometer is 1 Hz, so fractional second variations cannot be resolved by it.

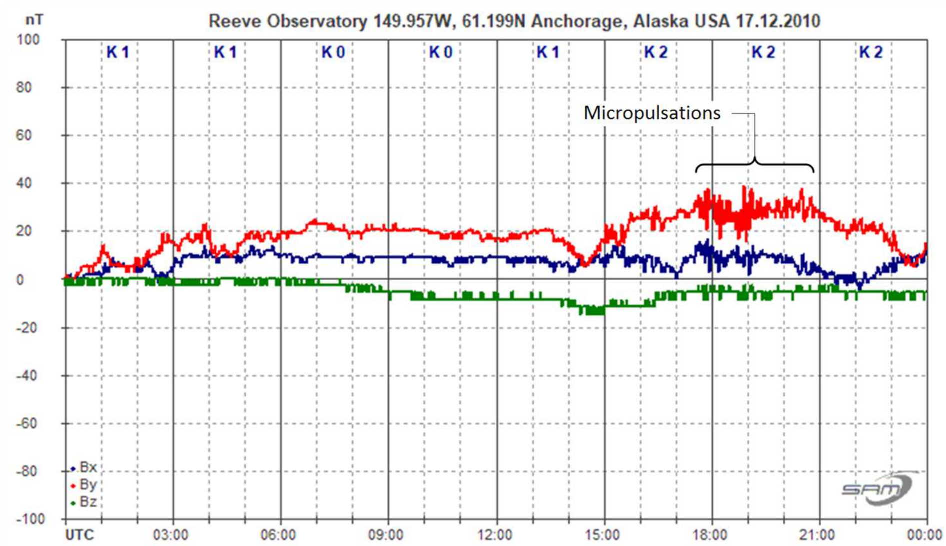


Figure 18 ~ ULF waves possibly instigated by multiple CHHSS on 17 December 2010. The traces throughout the day show some relatively smooth and typical variations. However, at about 1730 UTC, the field experienced short-period pulsations with peak-to-peak amplitudes of about 20 nT. There also is evidence of the waves a few hours before and after this main period. These measurements were made by the SAM-III while set to 0.1 Hz sample rate (10 second sampling period).

There are many causes of ULF waves, all related to wave interactions and resonances in the geomagnetosphere cavity and waveguide where they originate. The solar wind dynamic pressure and external perturbations work in concert with Earth's magnetic field to influence their generation. The pulsations can be irregular (Pi) or continuous (Pc) and their characteristics as measured on the ground depend on many factors including geographic location, particularly latitude, and whether the magnetometer station is on the dayside or nightside of Earth. Historically, pulsations were observed on telegraph wires by rapid changes in the current polarity; early formal observations in the 1850s used a microscope at the end of a very long compass needle.

---

3. Comments

Earth's magnetosphere never responds the same way twice to a given type of phenomena. Generalizations can be made but there are just too any variables involved including solar wind speed and the strength and characteristics of the embedded magnetic field. These may be estimated through modeling but predictions are very difficult. Observations of a given phenomenon with ground magnetometers depend on geographic locations, latitudes and local magnetic environments and whether they are on the dayside or nightside when the event occurs; no two magnetometers will show exactly the same response.

Some observations are not easily explained. Magnetic field measurements may show unexpected variations or none at all from a solar event. A solar event may have occurred days or weeks before making time correlation especially difficult. Multiple flares, CMEs and coronal holes that become geoeffective about the same time have complicated interactions because they unpredictably mix together. Having regular reports from organizations such as SWPC greatly aids identification of an event, particularly at higher latitudes where the magnetic field is naturally more active and subtle changes may be buried in the natural variations.

4. Weblinks & References

{DSHBD} https://www.swpc.noaa.gov/communities/space-weather-enthusiasts

{NOAA25} https://www.swpc.noaa.gov/products/solar-cycle-progression

{Reeve13} Reeve, W., Geomagnetic Sudden Impulses, 2013, available at: http://www.reeve.com/Documents/Articles%20Papers/Observations/Reeve_GeomagSuddenImpulses.pdf

{Reeve15} Reeve, W., Geomagnetism Tutorial, 2015, available at: http://www.reeve.com/Documents/SAM/GeomagnetismTutorial.pdf

{Reeve21} Reeve, W., Summary of Solar Radio Emission Types and Characteristics, 2021, available at: http://www.reeve.com/Documents/Articles%20Papers/Reeve_SolarRadioCycle25.pdf

{SAM-III} http://www.reeve.com/MagnetometerM3.htm

[Seki] Seki, K., et al, A Review of General Physical and Chemical Processes Related to Plasma Sources and Losses for Solar System Magnetospheres, Space Science Reviews, August 2015, DOI 10.1007/s11214-015-0170-y

[Smith78] Smith, E and Tsurutani, B., Observations of the Interplanetary Sector Structure up to Heliographic Latitudes of 16°: Pioneer 11, Journal of Geophysical Research, Vol. 83, No. A2, February 1, 1978

{STNFRD} http://wso.stanford.edu/SB/SB.html

{SWPC} https://www.swpc.noaa.gov/

{SWS} https://www.sws.bom.gov.au/

{ESASWSN} https://swe.ssa.esa.int/current-space-weather

Author: Whitham Reeve obtained B.S. and M.S. degrees in Electrical Engineering at University of Alaska Fairbanks, USA. He worked as a professional engineer and engineering firm owner/operator in the airline and telecommunications industries for more than 40 years and now manufactures electronic equipment used in radio astronomy. He also is a part-time space weather advisor for the High-frequency Active Auroral Research Program (HAARP) and a member of the HAARP Advisory Committee. He has lived in Anchorage, Alaska his entire life. Email contact: whitreeve@gmail.com

Document Information

Author: Whitham D. Reeve

Revisions: 0.0 (Original draft started, 10 Aug 2021)
0.1 (Added NASA images, 11 Aug 2021)
0.2 (Replaced some images for common size, 13 Aug 2021)
0.3 (Reworked magnetograms for common format, 14 Aug 2021)
0.4 (Completed 1st draft, 16 Aug 2021)
0.5 (Added Dungey Cycle, 20 Aug 2021)
0.6 (Readded SSBC, 24 Aug 2021)
0.7 (Completed 1st draft, 30 Aug 2021)
0.8 (Distribution, 08 Oct 2021)

Word count: 4877

File size (bytes): 3734422