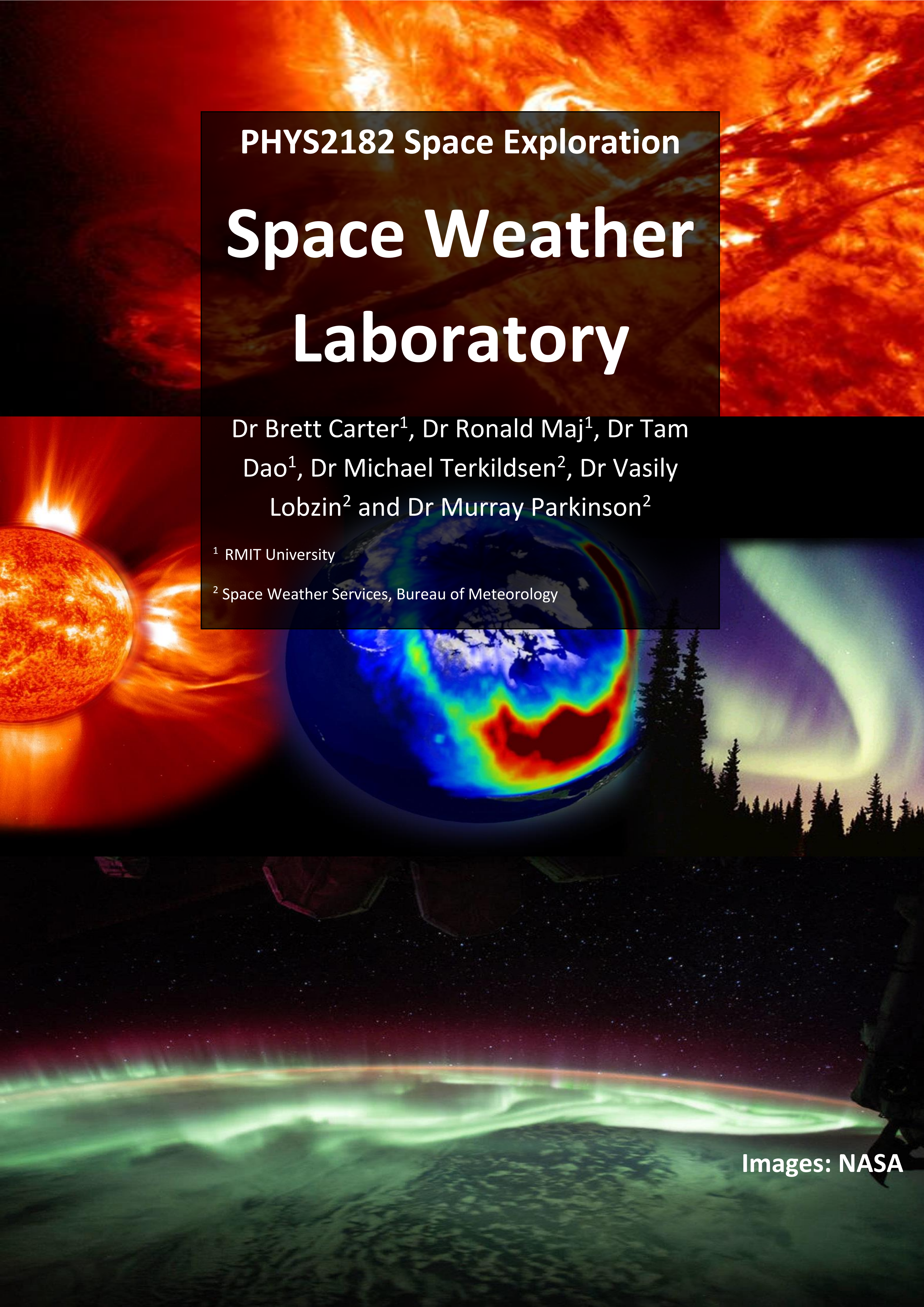

PHYS2182 Space Exploration

Space Weather Laboratory

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Images: NASA

Introduction

"Space weather" is the term given to the state of the near-Earth space environment. The space weather conditions on any given day are generally driven by the Sun, the solar wind, the Earth's magnetic field (magnetosphere) and the Earth's ionosphere (sphere of charged particles at altitudes 90-1000 km).

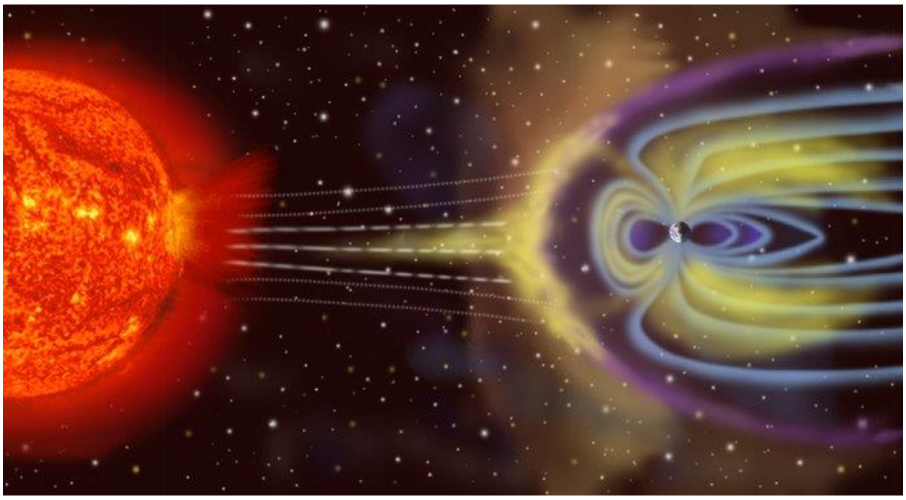

Figure 1. Artist's impression of near-Earth space environment (NASA).

The space weather conditions have various impacts on human technologies, including spacecraft and satellites, aviation, power grids and satellite positioning applications. Therefore, various countries around the world have established space weather forecasting centres, such as the Australian Bureau of Meteorology's Space Weather Services (http://www.sws.bom.gov.au) and the US's NOAA Space Weather Prediction Center (https://www.swpc.noaa.gov/). These organisations are tasked with providing information about current space weather conditions and their predictions for what is to come.

Figure 2. Australian Space Forecast Centre – Bureau of Meteorology (http://www.sws.bom.gov.au)

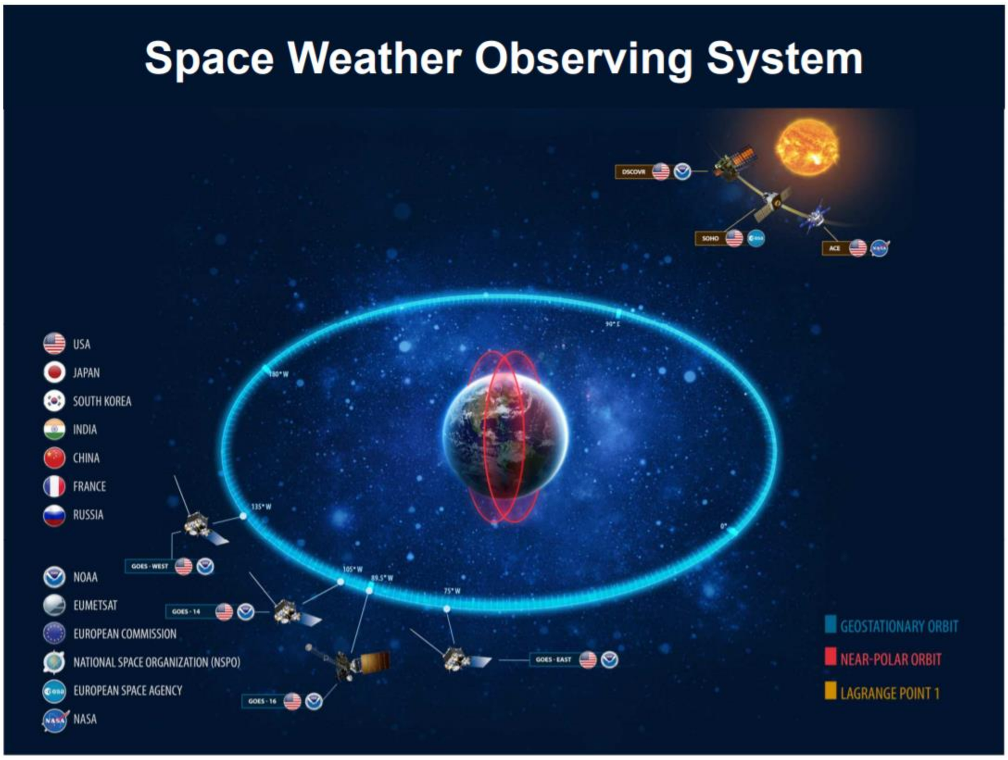

Figure 3. The SOHO, DSCVR, ACE and GOES spacecraft that are tasked with collecting observations to prediction space weather; not to scale **(**https://www.swpc.noaa.gov/).

Space weather forecasters use various space science instruments to determine the state of the near-Earth space environment. For the purposes of this laboratory session, these datasets can be split into three separate categories: (1) Sun, (2) solar wind, and (3) Earth.

(1) **The Sun** observations consist of solar imagery in different wavelengths to reveal various features on the Sun's surface (photosphere) and in the solar atmosphere (chromosphere and corona), taken from spacecraft

(2) **The Solar Wind** observations consist of images of the Sun's corona (called coronographs) and *in-situ* (i.e., "local") observations from spacecraft at the L1 Lagrange point (the gravitationally stable point between the Sun and Earth)

(3) **The Earth** observations consist of particle radiation detections from Earth orbit and magnetic disturbance readings from observatories located around the world

Task

In this laboratory session, it will be your job to forecast the space weather conditions by analysing various space- and ground-based data streams. In the lab, there are three "Desks": (1) the Sun Desk, (2) the Solar Wind Desk, and (3) the Earth Desk. You will be assigned to one of these Desks for the exercise. The group at each Desk will together analyse their respective data streams, develop a forecast and present their findings and predictions to the other Desks. These short informal presentations will facilitate class-wide discussions about what conditions you predict and the impacts (if any). Below you will find the specific manual for your Desk, which will come in handy in recognising noteworthy features that will help shape your forecast.

The Sun Desk

F10.7 Radio Flux

The Sun Desk uses radio observations from the ground to track the solar cycle progression (i.e., the 11-year solar cycle). The F10.7 cm radio flux indicates the brightness of the Sun at the 10.7 cm wavelength, and is a good indicator of the magnetic activity at the Sun.

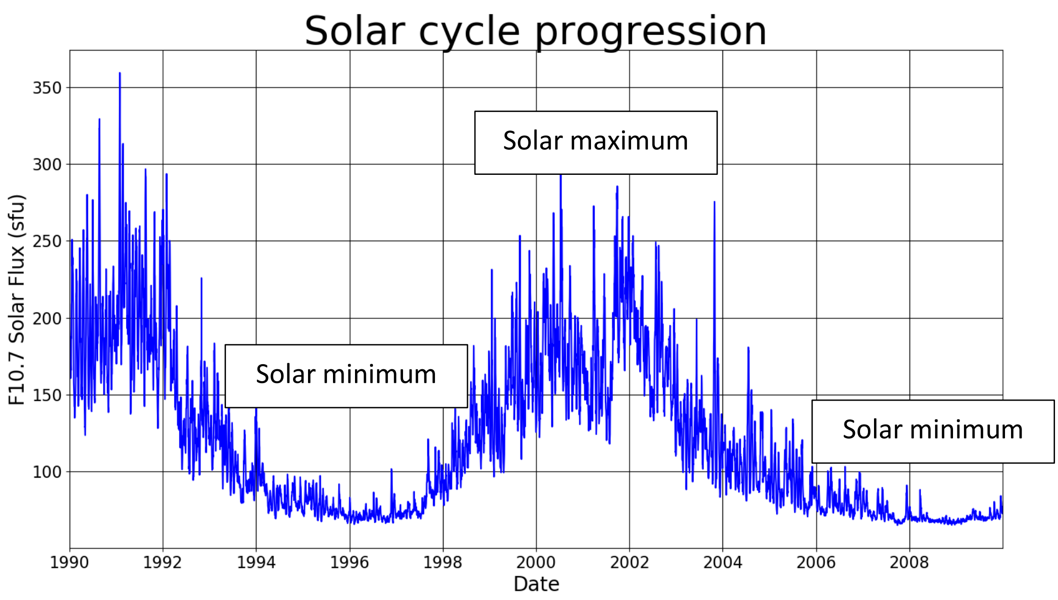

Figure 4. The solar cycle progression, given by the F10.7 cm radio flux (in solar flux units, sfu).

The solar cycle closely resembles a sinusoidal pattern, with solar maxima and minima approximately separated by 5-6 years. Typically, the space environment is more active and variable during solar maximum compared to solar minimum, but that doesn't mean that it's completely quiet (as evidenced by all the spikes in Fig. 4).

Solar imagery

The Sun Desk also uses solar imagery taken from Earth orbit. Below are examples of solar images taken by the Solar Dynamics Observatory (SDO) spacecraft. The Sun rotates from the left to the right as it spins on its axis. As such, the left horizon in these images is referred as the "Eastern limb" and the right is the "Western limb".

HMI Continuum (visible light)

The visible light image clearly indicates the presence of cool regions called "sunspots" on the Sun's surface.

<u>Space weather implications</u>*:* Sunspots are the primary source locations of disturbances that can impact Earth. The complexity of the sunspot region is a good indicator of the potential level of activity. Single or pairs of sunspots are deemed lower risk compared to sunspot clusters containing several sunspots.

Sunspot regions located in the centre of the solar disk are considered to be "Earth-facing" and could eject a Coronal Mass Ejection (CME) towards Earth. However, limb sunspots can also produce CMEs that give Earth a glancing blow.

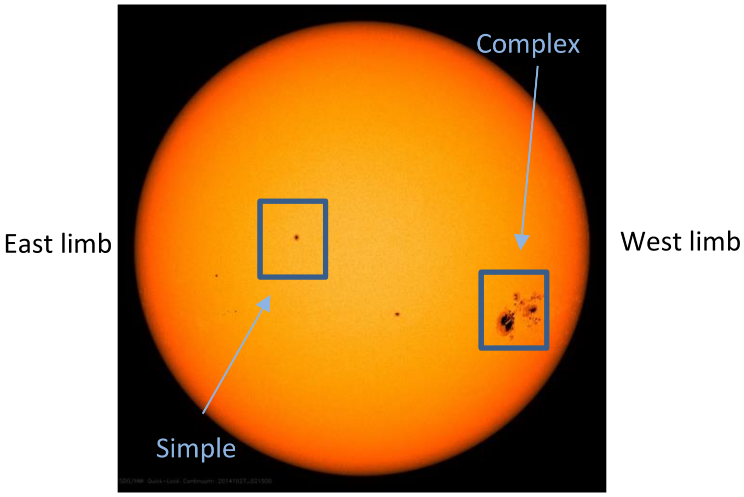

Figure 5. Example HMI Continuum (visible light) image, with simple and complex sunspot regions present.

HMI Magnetogram

The HMI Magnetogram uses spectral line splitting (called the "Zeeman effect") to measure magnetic field orientation on the Sun's surface. In these images, the line-of-sight magnetic field polarity and complexities around sunspots becomes very clear. Black indicates "south" or "inward" magnetic field and white indicates "north" or "outward" magnetic field.

Space weather implications: Sunspot regions with complicated magnetic field structures are likely to produce solar flares and CMEs. By "complicated", we mean magnetic fields with multiple and closely spaced inward and outward magnetic field surfaces; see Figure 6.

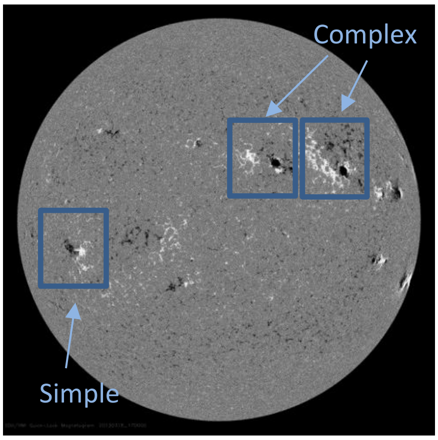

Figure 6. Example HMI Magnetogram image, showing simple and complex magnetic field structures associated with sunspots.

Atmospheric Imaging Assembly (AIA) 193

The AIA 193 images show solar emissions at the wavelength of 193 Angstroms (1Å = 10^{-10}m). At this wavelength, very hot plasma (1 million Kelvin) is visible in the solar corona. Typically, the 193 Å images are brightest near sunspot regions, clearly showing the magnetic field structures around them. Dark regions show locations where plasma is leaving the solar surface.

<u>Space weather implications:</u>

Active regions: Bright regions show the complex nature of the magnetic fields above sunspot regions, called "Active regions". The more complicated structures are more likely to produce solar flares.

Solar flares: Sudden localised intensifications in the AIA 193 imagery are solar flare events. The electromagnetic radiation from solar flares reaches Earth in ~ 8 minutes, impacting the Earth's upper atmosphere and radio communications (including satellite positioning signals). Sometimes, solar flares launch a Coronal Mass Ejection (CME) into space, which can cause geomagnetic storms if they hit Earth. CMEs range in their speeds, but when Earth-directed, typically arrive within 1-3 days of the solar flare taking place.

Coronal Holes: Dark regions in AIA 193 images reveal coronal holes, where plasma streams away from the Sun. When located at the centre of the solar disk, the high-speed stream generally takes 3-4 days to reach Earth, where it can trigger geomagnetic storms (typically less intense than CME-driven storms, but not always).

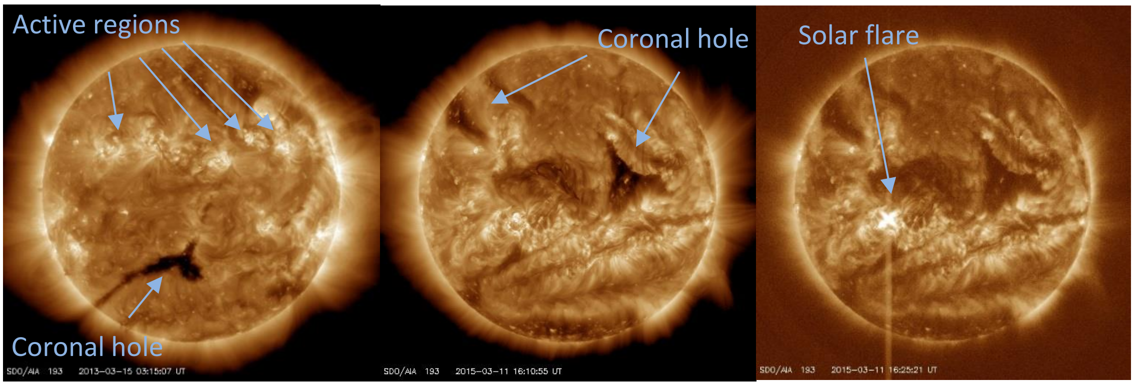

Figure 7. AIA 193 images showing active regions above sunspots, coronal holes and a solar flare.

AIA 304

The AIA 304 images show emissions at 304 Å, which are emitted from the Sun's chromosphere, at temperatures close to 50,000 K. Similar to the AIA 193 images, bright regions generally correspond to sunspot regions. Dark lines/regions are high-altitude plasma structures called "filaments". Sometimes solar material leaves the surface and returns along the magnetic field lines, forming structures called "prominences".

<u>Space weather implications:</u>

Active regions: Similar to AIA 193, bright regions show "Active regions". The more complicated structures are more likely to produce solar flares.

Solar flares: In the same manner as AIA 193 imagery, sudden localised intensifications in the AIA 304 images are solar flare events. Sometimes these are accompanied by CMEs, but not always.

Prominences/filaments: High-altitude plasma structures that are most clear on the solar horizon, where they are referred to as "solar prominences". When viewed on the solar disk, prominences are referred to as "filaments". In most cases, the solar material that forms the prominences/filaments returns to the Sun along the magnetic field in a loop. However, sometimes the magnetic field containing a prominence/filament will escape the Sun and drag the solar material into space, turning it into a CME. When Earth-directed, these can cause geomagnetic storms. Prominences/filaments are not necessarily associated with solar flares.

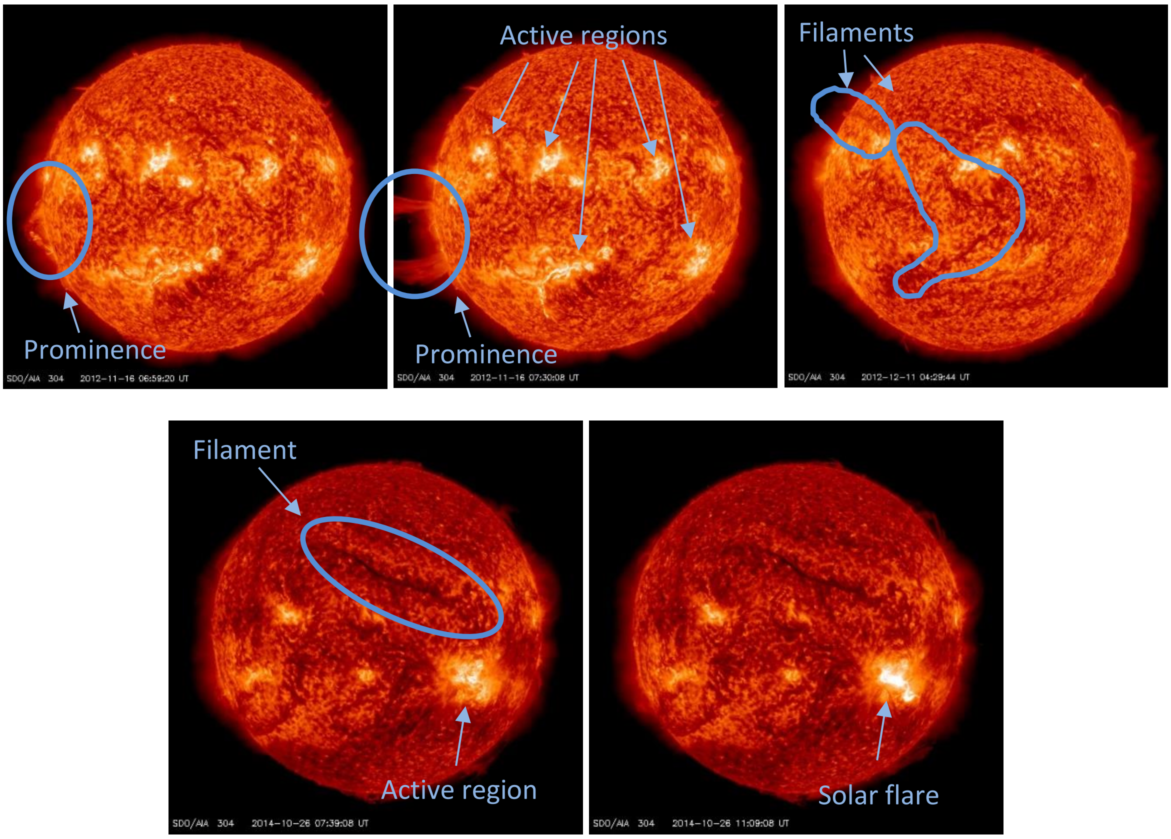

Figure 8. AIA 304 images showing active regions, prominences/filaments and a solar flare.

The Solar Wind Desk

The Solar Wind Desk uses data collected at the Lagrange point L1 by the SOHO, ACE, WIND and DSCVR spacecraft (see Figure 3).

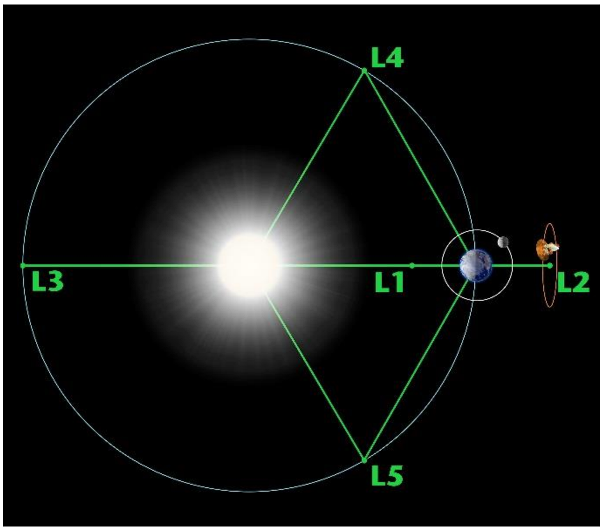

Figure 9. The Lagrange points – regions of gravitational stability in the Sun-Earth system (https://www.solarsystem.nasa.gov).

Solar and Heliospheric Observatory (SOHO)

The SOHO spacecraft has an instrument called "Large Angle and Spectrometric Coronagraph (LASCO)" that collects coronagraph images; images of the solar corona. The LASCO instrument uses a disk to block out the bright Sun, revealing the outer solar atmosphere and the formation of the solar wind. There are two coronagraph images available that provide a small-angle (c2) and wide-angle (c3) view. In these images, CMEs can be observed leaving the Sun, and importantly their approximate travel direction can be determined.

Space weather implications:

Coronal Mass Ejections (CMEs): CMEs cause the largest geomagnetic storms at Earth, so they are very important to spot as early as possible. The c2 and c3 coronagraph images actually give some indication as to whether the CME is Earth-directed or not. If the CME only propagates out from either the Eastern or Western limb, then a direct hit at Earth is unlikely. However, if the CME is Earth-directed, it will form an ellipsoidal pattern, referred to as a "halo" CME. Note: halo CMEs are not always Earth-directed, sometimes they are launched away from us on the other side of the Sun. Unfortunately, one cannot determine if a halo CME is Earth-directed or anti-Earth-directed from coronagraph images alone. Approximate CME speeds can be determined from these images, but they can be quite inaccurate. Typically, Earth-directed CMEs will take between 1 and 3 days to reach Earth.

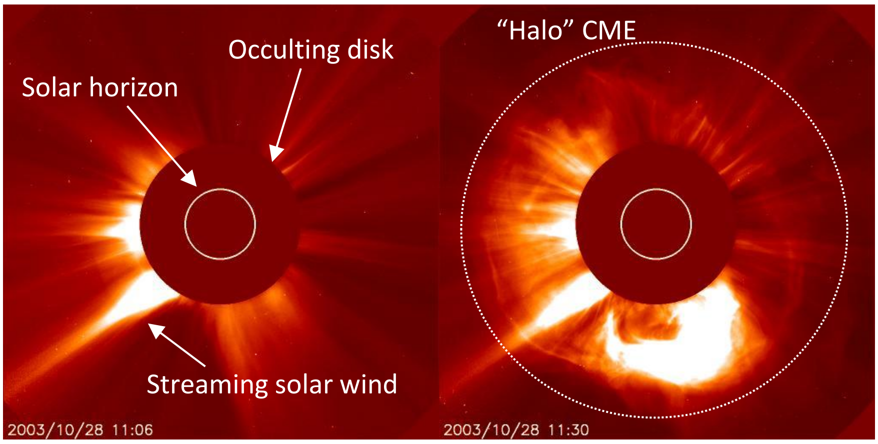

Figure 10. Example c2 coronagraph images, showing the presence of streaming/high-speed solar wind and a "halo" CME.

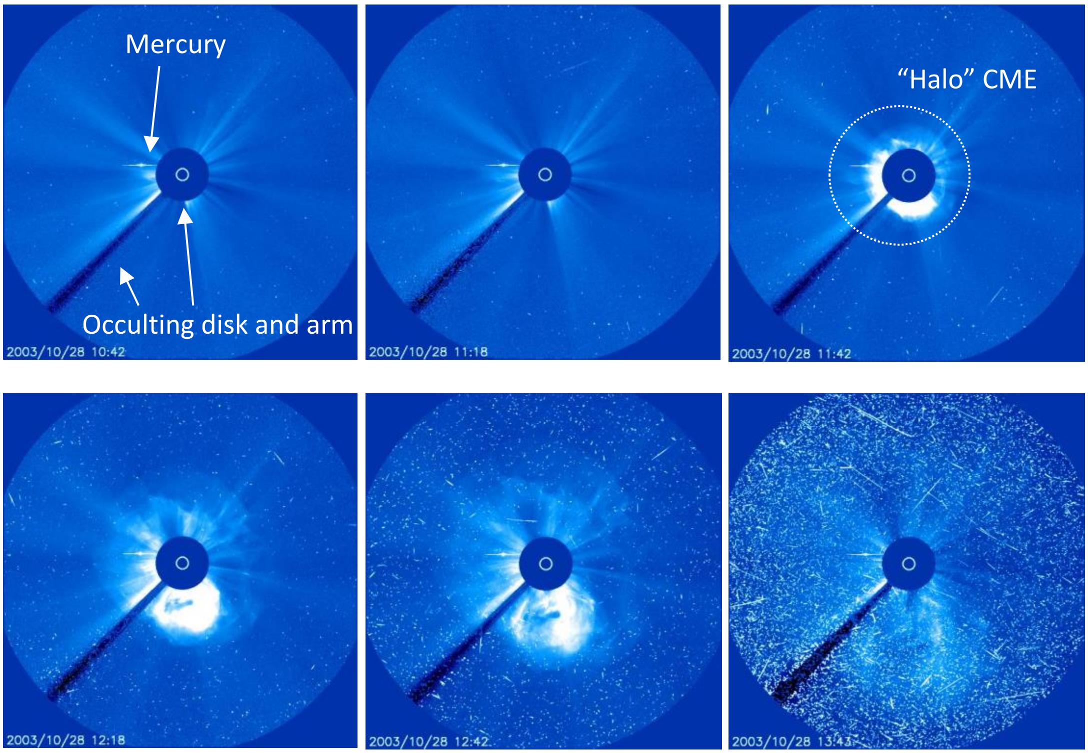

Figure 11. Example c3 coronagraph images showing a "halo" CME. Highly energetic particles that travel close to the speed of light cause streaks all over the image shortly after the CME is launched (a very strong indication that it is Earth-directed).

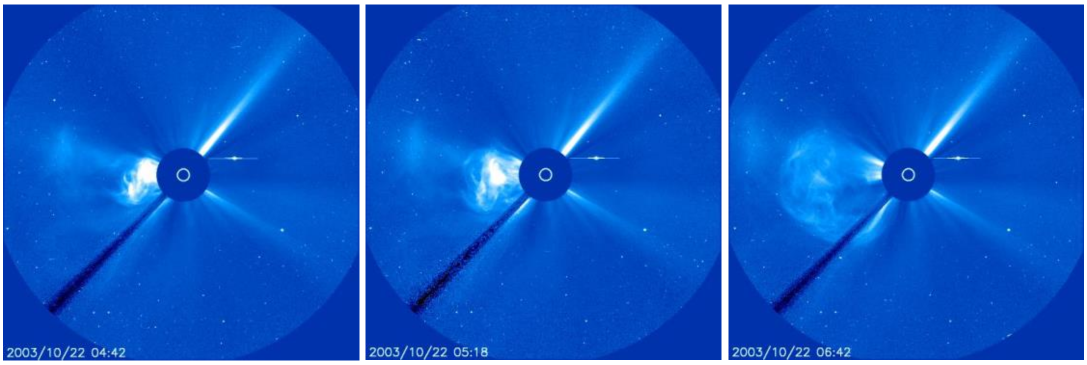

Figure 12. Example c3 coronagraph images showing a CME rising from the Eastern limb. The limited angle range indicates that it is not Earth-directed (although the active region producing this will rotate towards the Earth over the following few days).

ACE/WIND/DSCVR Spacecraft

The ACE, WIND and DSCVR spacecraft all provide complimentary in-situ (i.e., observed "in-place") solar wind data; the spacecraft vary widely in age, so redundancy is quite good for this purpose. While these spacecraft reside at the L1 point, this is still quite close to the Earth, so what is measured at this location is considered to impact the Earth within 0.5-1.5 hours, depending on the solar wind speed. The data collected thus can confirm the presence or absence of "geo-effective" solar wind disturbances – such as CMEs – and provides a short-term but reliable space weather prediction.

Solar Wind Parameters

Magnetic field: The solar wind is a plasma, and therefore carries its own magnetic field. Its magnitude is given as "Bt". Typically, the strength of the solar wind magnetic field is only a few nT (nano-Tesla), but when this gets to larger than 10 nT it could be a sign of pending geomagnetic activity. The "Bz" parameter is the "northward" component of the solar wind magnetic field. If Bz is southward and lower than -5 nT, the impact on the Earth's geomagnetic field will be moderate. If Bz becomes less than -10 nT, then the impact on the Earth's geomagnetic field will be strong. Alternatively, if Bz is small or strongly northward (i.e., showing positive values) then the impact on Earth's geomagnetic field will be more limited. [Earth's magnetic field provides natural shielding against plasma with the same magnetic field polarity.]

Solar wind density: The solar wind density is an important parameter because it can show the presence of shocks that will hit Earth's magnetosphere. Shocks tend to form at the CMEs and other solar wind disturbances. A sudden density increase of an order of magnitude (i.e., x 10) is significant.

Solar wind speed: The solar wind speed also shows the presence of solar wind disturbances, typically in the form of solar wind speed increases. CMEs cause the solar wind speed to suddenly increase, whereas coronal holes (see Figure 7) cause a slower rise. However, both CMEs and coronal holes can cause geomagnetic storms – how severe they will be depends on the magnetic field within them (i.e., Bt and Bz above).

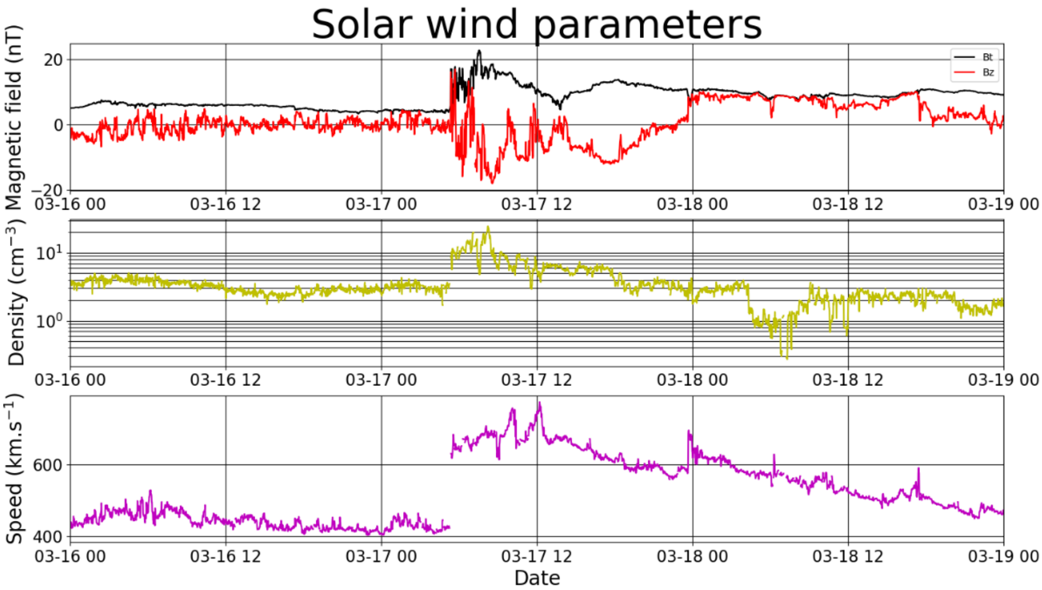

Figure 13. Solar wind data showing the arrival of a CME at approximately 06:00 Universal Time (UT) on March 17th, 2013. Sudden changes in all parameters clearly show the CME's arrival at L1. The strong and prolonged southward Bz indicates that the CME will cause a geomagnetic storm (in this case, it caused a G2 storm; see *NOAA Space Weather Scales* below). The CME speed jumps from 400 km/s to over 600 km/s, and can be used to estimate its arrival time at Earth.

The Earth Desk

The Earth Desk examines data that indicates whether space weather impacts are being felt at that time, and is perhaps the most important Desk. The Earth Desk's data can not only be used as a "verification" tool for any previous forecasts, but it can also be used to issue "nowcast" warnings – e.g., "satellites are likely experiencing surface charging problems" or "power grid operators are likely to be facing difficulties due to the current geomagnetic storm".

The Earth Desk uses solar particle radiation data collected by the GOES satellites (see Figure 3) and magnetic field data collected from observatories around the world.

Earth parameters

GOES Proton Flux: The GOES satellites measure the flux of protons in three categories according to their kinetic energies, measured in "MeV" or Mega electron Volts (1MeV = 1 x 10^6 eV). The three categories are >10 MeV, >30 MeV and >60 MeV. The proton flux levels indicate whether a "Solar Radiation Storm" is occurring or not; see NOAA Space Weather Scales below. Solar Radiation Storms can accompany geomagnetic storms, but due to their high speed, they tend to arrive before the solar wind disturbance that causes the geomagnetic storm; see Figure 15. The flux of high-energy protons in Earth orbit presents a significant hazard to satellites in Earth orbit and to people on flights over the high-latitude regions.

Magnetic Kp and SYM-H indices: Both the Kp index and the SYM-H index indicate the level of magnetic disturbance in the Earth's magnetosphere. The stations used to calculate these indices are shown in the Figure 14. These, and other, magnetic observations serve as the final link in the chain of events that contribute to space weather. The severity of any disturbances in the near-Earth space environment is directly measured here, and the associated impacts are estimated.

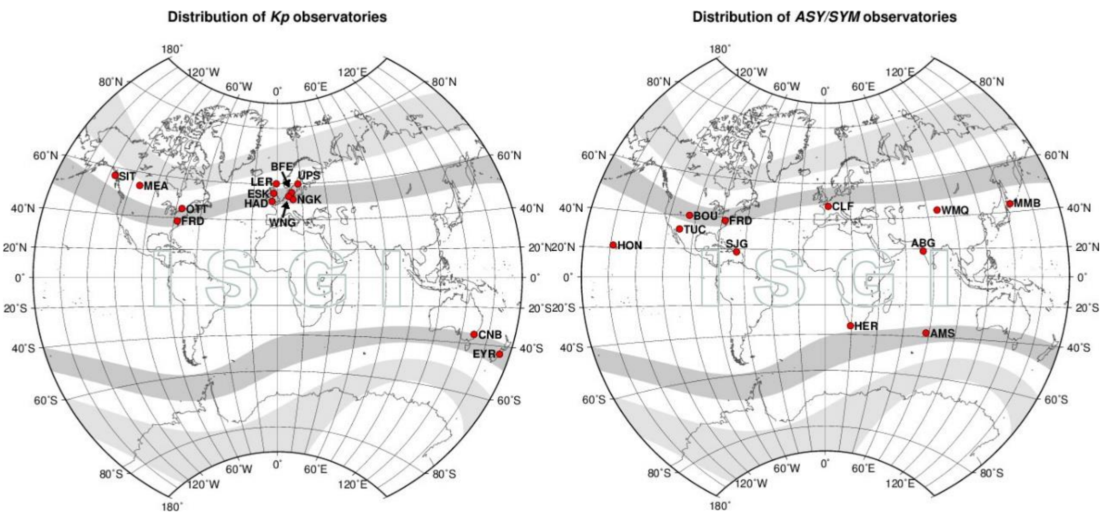

Figure 14. The magnetic field observatories used to measure the Kp (left) and SYM-H (right) indices. (http://isgi.unistra.fr/)

The Kp index is a 3-hourly value that ranges from 0 to 9, with 0-3 indicating “quiet conditions”, 4-6 indicating “moderate” geomagnetic activity and 7-9 indicating “severe” geomagnetic activity. The Kp value indicates, among many other things, the approximate locations of visible aurora in the northern and southern hemispheres.

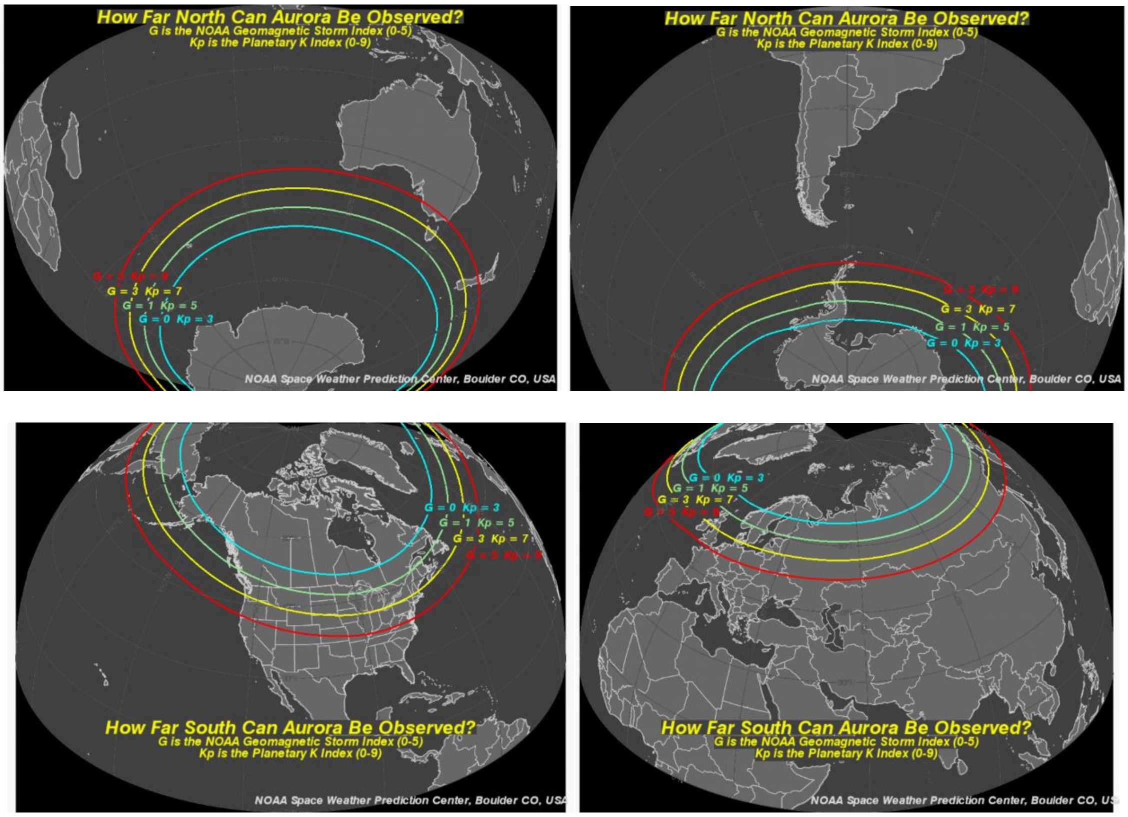

Figure 15. Expected aurora locations based on Kp index (https://www.swpc.noaa.gov/content/tips-viewing-aurora).

The SYM-H index is a direct measure of the electrical current in the magnetosphere. Values close to 0 nT indicate that there is no current, whereas a strong negative value indicates the presence of current and an active geomagnetic storm. By definition, SYM-H > -50 nT indicates “quiet conditions”, -50 nT > SYM-H > -150 nT indicates a “moderate” storm and SYM-H < -150 nT indicates a “severe” geomagnetic storm. In this sense, it provides similar information to the Kp index, but at a much higher time resolution.

Geomagnetic storms can be categorised into three separate phases: (1) the initial phase, in which the SYM-H index sharply rises, (2) the storm main phase, when the SYM-H decreases to a minimum value, and (3) the recovery phase, during which the SYM-H steadily returns back to pre-storm levels (see Figure 16). The initial and main phases are typically quite short in duration (up to 6-12 hours each), but the recovery phase can last anywhere from 24 hours to a week, depending on the storm and the ongoing solar wind conditions.

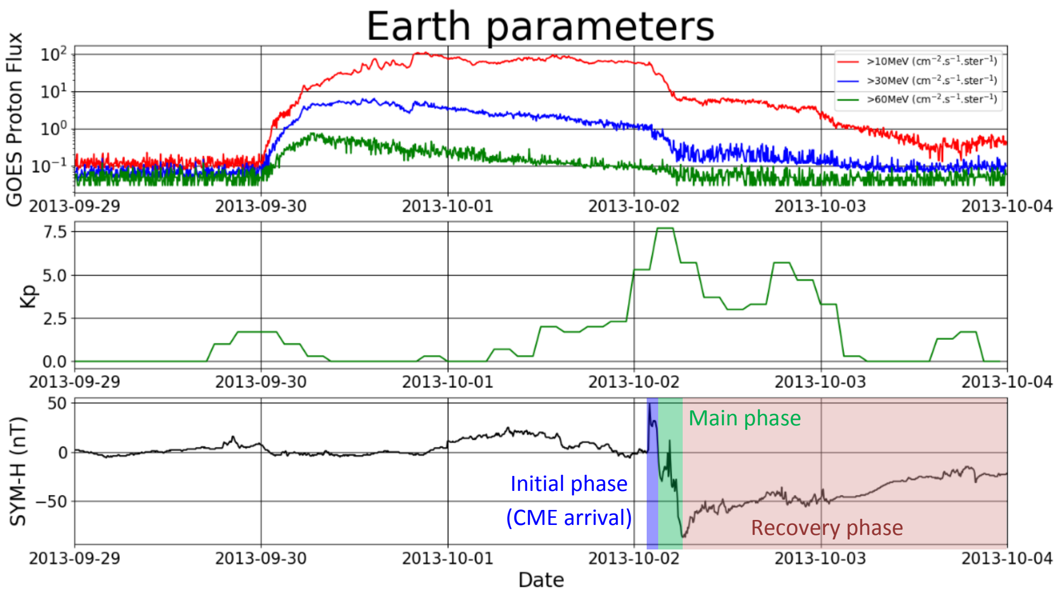

Figure 16. The Earth parameters, showing the arrival of a CME, and the subsequent commencement of a geomagnetic storm in 2013. The Solar Radiation Storm began on Sep 30th, well before the CME arrived on Oct 2nd; high-energy protons travel much faster than the bulk solar wind flow.

Earth impacts

As mentioned above, the Earth Desk parameters can be used to determine what impacts are being experienced, allowing warnings to be issued. The NOAA Space Weather Scales below are commonly used to issue warnings based on current conditions. Note use of the >10 MeV Proton flux to indicate the Solar Radiation Storm level (S1-S5) and the Kp index to determine the Geomagnetic Storm Level (G1-G5), and their associated impacts.

NOAA Space Weather Scales

Category		Effect	Physical measure	Average Frequency (1 cycle = 11 years)
Scale	Descriptor	Duration of event will influence severity of effects		
Geomagnetic Storms			Kp values* determined every 3 hours	Number of storm events when Kp level was met; (number of storm days)
G 5	Extreme	Power systems: widespread voltage control problems and protective system problems can occur, some grid systems may experience complete collapse or blackouts. Transformers may experience damage. Spacecraft operations: may experience extensive surface charging, problems with orientation, uplink/downlink and tracking satellites. Other systems: pipeline currents can reach hundreds of amps, HF (high frequency) radio propagation may be impossible in many areas for one to two days, satellite navigation may be degraded for days, low-frequency radio navigation can be out for hours, and aurora has been seen as low as Florida and southern Texas (typically 40° geomagnetic lat.).**	Kp=9	4 per cycle (4 days per cycle)
G 4	Severe	Power systems: possible widespread voltage control problems and some protective systems will mistakenly trip out key assets from the grid. Spacecraft operations: may experience surface charging and tracking problems, corrections may be needed for orientation problems. Other systems: induced pipeline currents affect preventive measures, HF radio propagation sporadic, satellite navigation degraded for hours, low-frequency radio navigation disrupted, and aurora has been seen as low as Alabama and northern California (typically 45° geomagnetic lat.).**	Kp=8	100 per cycle (60 days per cycle)
G 3	Strong	Power systems: voltage corrections may be required, false alarms triggered on some protection devices. Spacecraft operations: surface charging may occur on satellite components, drag may increase on low-Earth-orbit satellites, and corrections may be needed for orientation problems. Other systems: intermittent satellite navigation and low-frequency radio navigation problems may occur, HF radio may be intermittent, and aurora has been seen as low as Illinois and Oregon (typically 50° geomagnetic lat.).**	Kp=7	200 per cycle (130 days per cycle)
G 2	Moderate	Power systems: high-latitude power systems may experience voltage alarms, long-duration storms may cause transformer damage. Spacecraft operations: corrective actions to orientation may be required by ground control; possible changes in drag affect orbit predictions. Other systems: HF radio propagation can fade at higher latitudes, and aurora has been seen as low as New York and Idaho (typically 55° geomagnetic lat.).**	Kp=6	600 per cycle (360 days per cycle)
G 1	Minor	Power systems: weak power grid fluctuations can occur. Spacecraft operations: minor impact on satellite operations possible. Other systems: migratory animals are affected at this and higher levels; aurora is commonly visible at high latitudes (northern Michigan and Maine).**	Kp=5	1700 per cycle (900 days per cycle)

* Based on this measure, but other physical measures are also considered.
** For specific locations around the globe, use geomagnetic latitude to determine likely sightings (see www.swpc.noaa.gov/Aurora)

Solar Radiation Storms			Flux level of ≥ 10 MeV particles (ions)*	Number of events when flux level was met**
S 5	Extreme	Biological: unavoidable high radiation hazard to astronauts on EVA (extra-vehicular activity); passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk. *** Satellite operations: satellites may be rendered useless, memory impacts can cause loss of control, may cause serious noise in image data, star-trackers may be unable to locate sources; permanent damage to solar panels possible. Other systems: complete blackout of HF (high frequency) communications possible through the polar regions, and position errors make navigation operations extremely difficult.	10^5	Fewer than 1 per cycle
S 4	Severe	Biological: unavoidable radiation hazard to astronauts on EVA; passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk.*** Satellite operations: may experience memory device problems and noise on imaging systems; star-tracker problems may cause orientation problems, and solar panel efficiency can be degraded. Other systems: blackout of HF radio communications through the polar regions and increased navigation errors over several days are likely.	10^4	3 per cycle
S 3	Strong	Biological: radiation hazard avoidance recommended for astronauts on EVA; passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk.*** Satellite operations: single-event upsets, noise in imaging systems, and slight reduction of efficiency in solar panel are likely. Other systems: degraded HF radio propagation through the polar regions and navigation position errors likely.	10^3	10 per cycle
S 2	Moderate	Biological: passengers and crew in high-flying aircraft at high latitudes may be exposed to elevated radiation risk.*** Satellite operations: infrequent single-event upsets possible. Other systems: effects on HF propagation through the polar regions, and navigation at polar cap locations possibly affected.	10^2	25 per cycle
S1	Minor	Biological: none. Satellite operations: none. Other systems: minor impacts on HF radio in the polar regions.	10	50 per cycle

* Flux levels are 5 minute averages. Flux in particles·s^{-1}·$ster^{-1}$·cm^{-2} Based on this measure, but other physical measures are also considered.
** These events can last more than one day.
*** High energy particle (>100 MeV) are a better indicator of radiation risk to passenger and crews. Pregnant women are particularly susceptible.


Image: NASA