SPACE WEATHER

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What is Space Weather?

- According to the dictionary weather refers to the conditions in the air above the Earth, such as wind, rain/snow and temperature.
- Normally we worry about the weather only when there is an extreme weather event, like heavy rainfall, storm or extreme temperature. The weather is due to response of Earth's atmosphere to the solar electromagnetic radiation around visible and infrared wavelengths. While the solar output is essentially constant the variation is due to Earth's rotation and tilt of axis to plane of Earth's orbit.
- Space weather refers to conditions above the Earth's atmosphere, though some effects may be experienced even at the ground level or even below the surface.

- Space weather is also due to the Sun, but is controlled by electromagnetic radiation in radio and X-rays or through flux of charged particles. These are caused by solar activity which varies by several orders of magnitude, which can lead to extreme space weather.

- While extreme terrestrial weather causes heavy casualty in terms of human life, so far there is no report of any casualty from space weather, but it can have high economic costs. So far the economic damage is also much less.

- On November 28, 2025 Airbus grounded about 6000 A320 aircraft for software upgrade after problem caused possibly by cosmic rays which corrupted critical data and one aircraft lost altitude on 30 October.

- While extreme space weather events have been happening since the Earth was formed, the damaging effects were not felt until human beings started using electricity. With more advanced technology the vulnerability is increasing which makes it important during the last several decades.

- The main disruptions include, power grid, communication, satellites, GPS services, radar, air and space travel, etc.

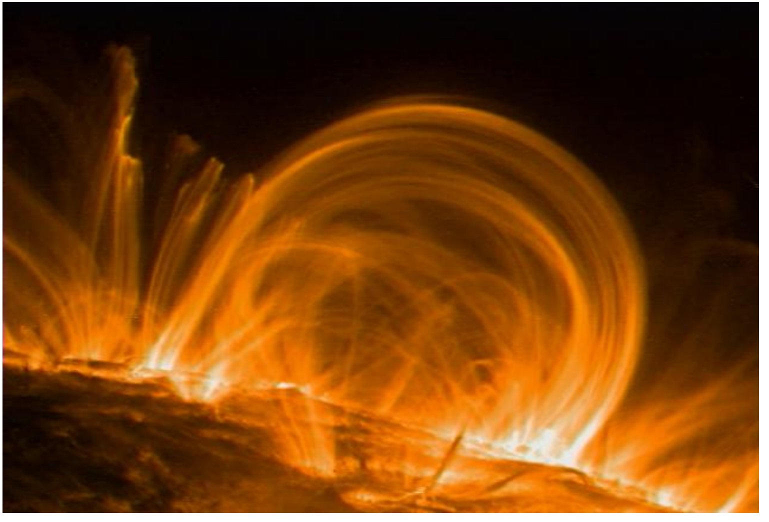
Astronomy Picture of the Day

17 Nov 2025

comet Lemmons

Drivers of Space weather

- The solar activity is due to magnetic field which manifest as sunspots, which are referred to as active regions. The sunspots appear in pairs of opposite polarity connected by magnetic field lines.



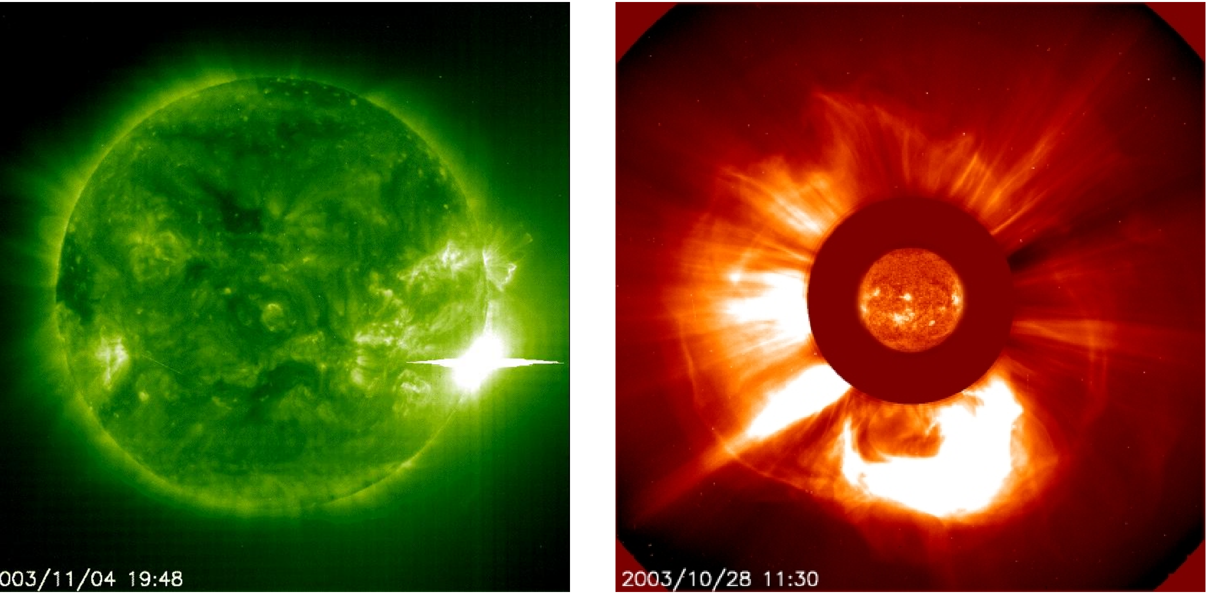
UV image from TRACE mission

- The magnetic energy in an active region can be released through magnetic reconnection when oppositely directed magnetic field lines approach each other driven by turbulence in the photosphere.

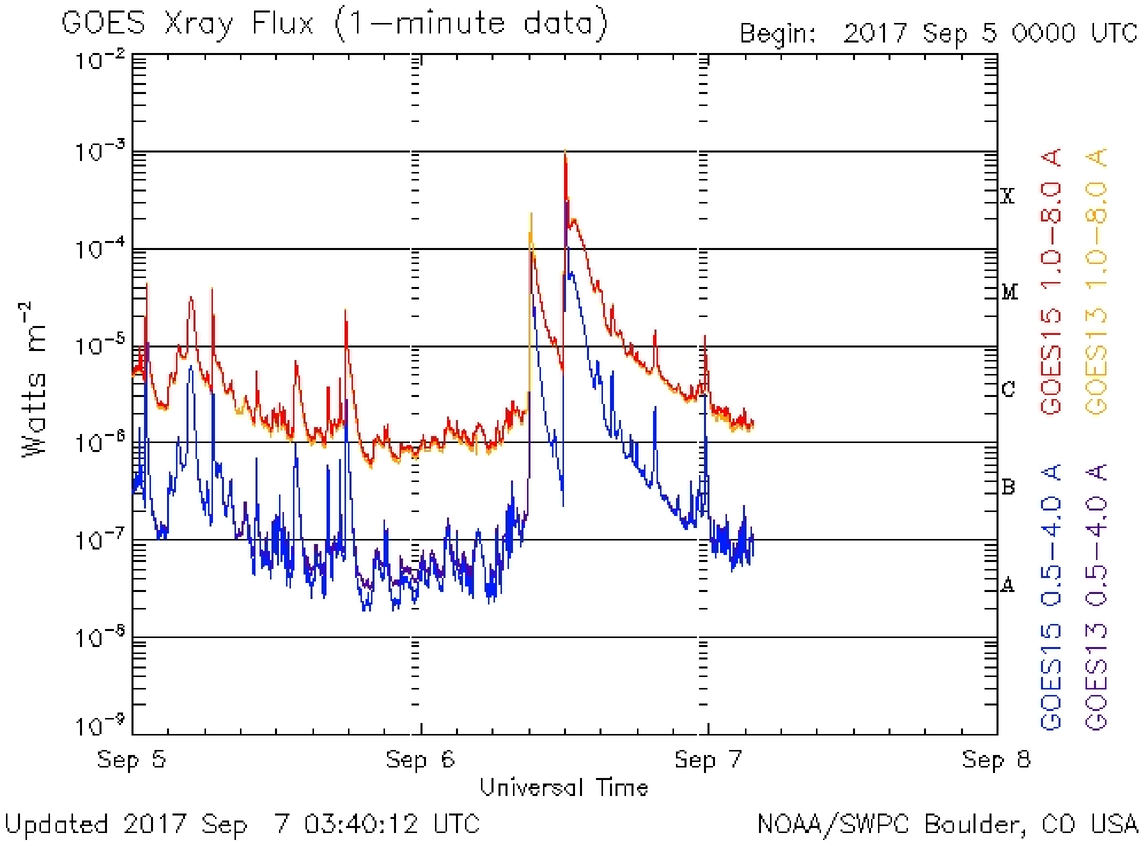
- This process can release 10^{32} erg of energy over a time scale of 100–10000 sec in a very small volume leading to a massive explosion and resulting blast wave can throw out billions of tons of material referred to as a Coronal Mass Ejection (CME) from the Sun with speeds going up to 3000 km/s.

- The energy is released in radio waves, X-rays, high energy protons (up to GeV) referred to as Solar Energetic particles (SEP) accelerated by shock and kinetic energy of CME which is a highly conducting plasma that also carries the magnetic field with it.

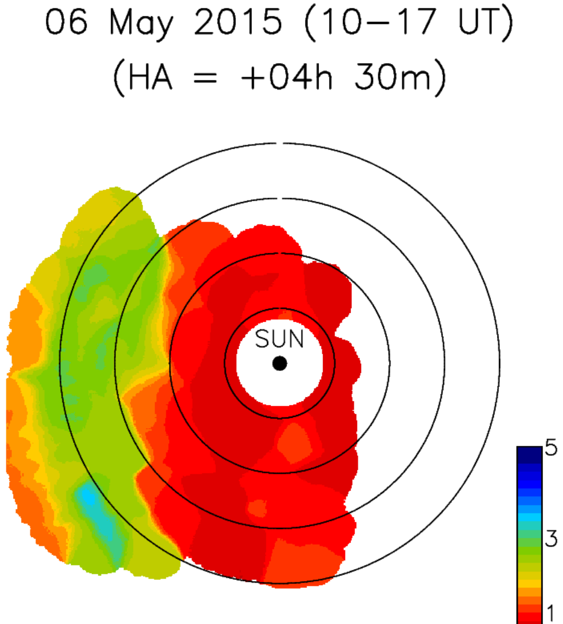
- The strongest space weather storms typically arise from multiple CMEs following each other. The first one clears the interplanetary space for the subsequent ones, which progress more rapidly. Sometime the subsequent CME overtakes the one ahead forming so called cannibal CME.



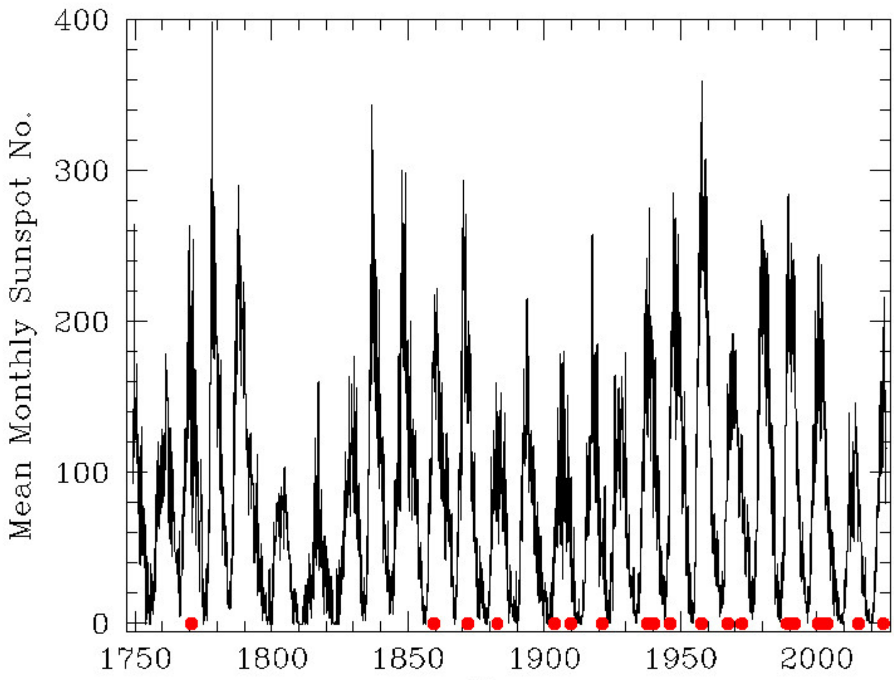
SOHO image of X45 flare on 4 Nov 2003 and CME on 28 Oct 2003


GOES Xray Flux (1-minute data)
Begin: 2017 Sep 5 0000 UTC
Watts m^-2
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
10^-9
X
M
C
B
A
GOES15 1.0–8.0 A
GOES13 1.0–8.0 A
GOES15 0.5–4.0 A
GOES13 0.5–4.0 A
Sep 5
Sep 6
Sep 7
Sep 8
Universal Time
Updated 2017 Sep 7 03:40:12 UTC
NOAA/SWPC Boulder, CO USA

- The CME propagation in interplanetary space can be tracked using InterPlanetary Scintillation (IPS) where scintillation strength in images of distant radio sources is studied to study a CME crossing the line of sight to radio source (Johri & Manoharan 2016).



- The number of sunspots and hence the solar magnetic field has a well known quasiperiodic variation with a period of 11 years. The level of solar activity depends on this number.



Effect on the Earth

- The electromagnetic radiation takes about 500 s to reach the Earth. Thus the X-ray and radio flux will reach the Earth without any warning, while depending on energy, the protons may reach a few min to an hour later. The CME can take 15 hrs to a few days to reach the Earth, thus giving enough warning, though it is difficult to predict the geoeffectiveness of a CME until it reaches close to the Earth.
- The solar radio bursts can jam a radar and also block radio communication at all latitudes during the daytime. It can also disrupt GPS signal.
- The X-ray flux can ionise atoms in the ionosphere adding to ionospheric disturbances from other effects.

- The solar energetic particles (SEP) event can continue for days as the shock in CMEs can also accelerate these. These particles are channeled along the geomagnetic field lines and into the upper atmosphere in polar region. These enhance the ionisation of the lower ionosphere over the polar region giving Polar Cap Absorption (PCA) events, which disrupt radio communication in 1-30 MHz range.

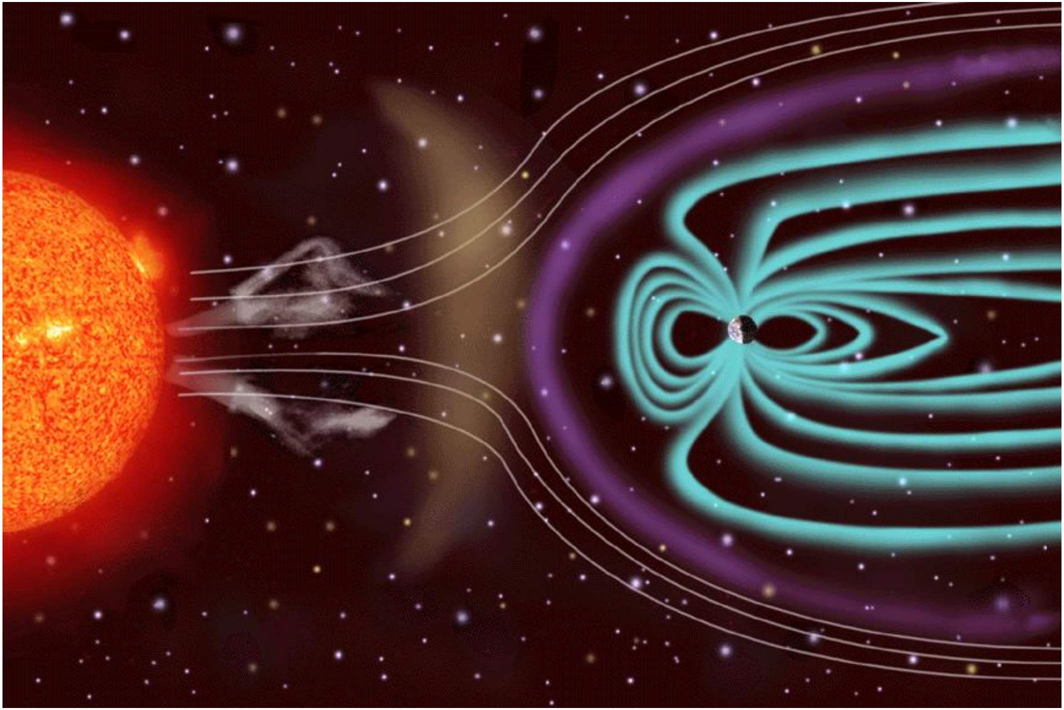
- Aircrafts, ships and facilities in polar region depend on these frequencies. Some airlines operate flights over the poles as that offers a shorter and better path (less head-wind) from e.g., US to China. These flights have to be rerouted to lower latitudes causing some economic loss due to delays and disruptions.

- Federal regulation require the flights to maintain communication with ATC over the entire route. Below a latitude of 82° this communication can be maintained through geostationary satellites (this can also be disrupted by radio bursts). Above this latitude they need to rely on HF communication.

- The PCA events are fairly frequent causing substantial economic losses every year.

- The charged particle flux can also cause increased exposure to radiation for air and space travel, particularly outside the Earth's magnetosphere.

- The solar wind interacts with Earths magnetosphere and distorts it and forms a shock around if.



- CMEs are effective only when they are launched towards the Earth, which means that the flare should happen when the active region is close to the centre of the Sun as viewed from the Earth. When a high speed CME hits the Earth the magnetic field on the sunward side is compressed as a result satellites in geostationary equatorial orbits can fly outside the protection of Earth's magnetic field with much higher radiation field, which can cause damage.

- Further the CME also has a magnetic field and if this is oriented opposite to the Earth's field a magnetic reconnection can happen which will channel the CME plasma into the Earth's upper atmosphere, causing a severe geomagnetic storm. This is the main driver of the space weather.

- The orientation of the CME magnetic field is known only when it passes through the L1 Lagrangian point where there are a few satellites to study the solar wind and interplanetary magnetic field. If the CME magnetic field tilts towards south then reconnection would happen. This can give a warning of about 15–30 mins.

- Influx of charged particles in the ionosphere due to CME will also affect the ionosphere and hence communication and navigation. This introduces a ring current in ionosphere which reduces the strength of geomagnetic field. Ionospheric disturbances can severely affect the over-the-horizon radar which bounces signals off the ionosphere. This also affects radio communication and GPS signal.

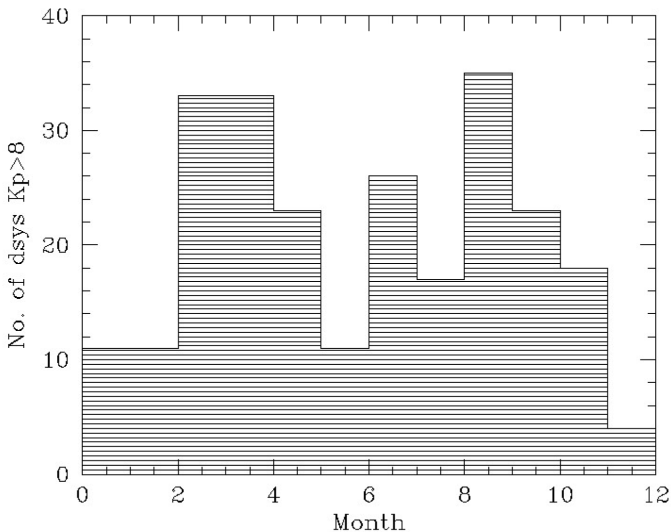
- A geomagnetic storm causes the Earth's magnetic field to change with time which induces current in electrical circuits, causing damages to electrical equipment in satellites and even on ground, referred to as Geomagnetically Induced Currents (GIC).

- Any long conductor, e.g., power line or a pipeline is vulnerable to induced current. Pipelines get eroded faster due to induced currents. East–West alignment of conductor is particularly sensitive. Transformers in power grid are particularly vulnerable as they are designed to handle AC current, while induced current is essentially DC. This causes overheating in some parts and in worst case it can catch fire which completely destroys the transformer.

- The energy deposited in the upper atmosphere heats it up and it expands, thus increasing the density at a given height. This increases drag on low Earth orbit satellites and causes them to shift to lower orbits thus reducing their lifetime. The solar arrays are also degraded due to intense radiation. The 1970 premature destruction of Skylab was due to higher than expected solar activity.

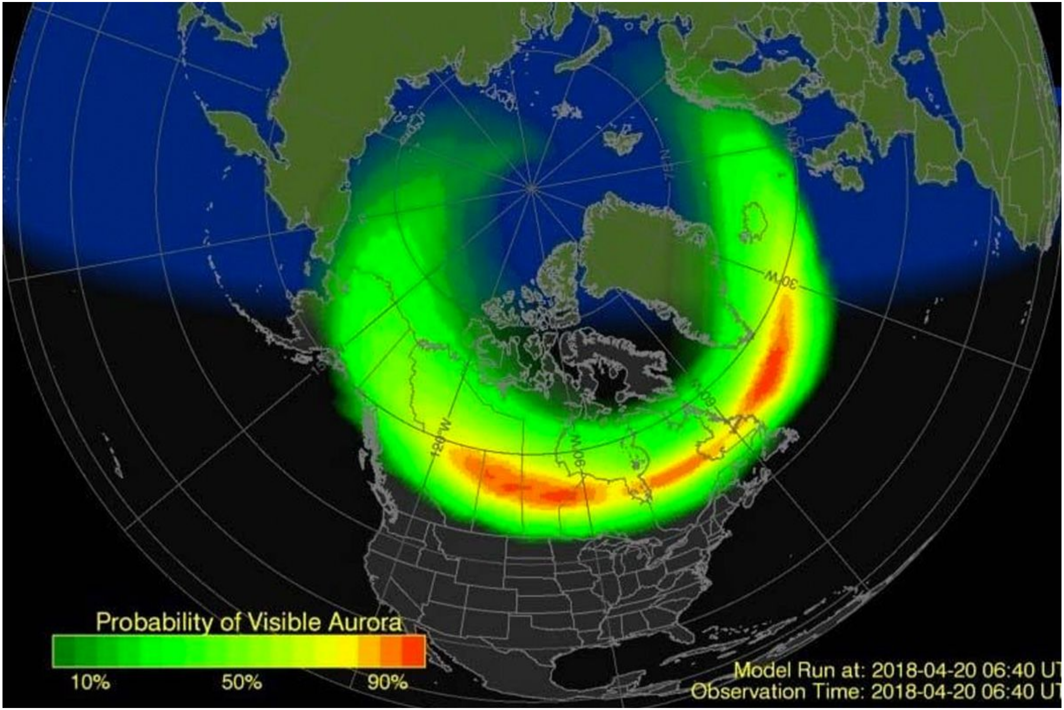
- The charged particles can also lead to spacecraft charging due to accumulation of electrostatic charge on a nonconducting surface by low energy particles. If enough charge is built up, a discharge occurs which can damage the electronics.

- The strength of geomagnetic storm can be measured by the Kp-index which is on a log scale, with maximum value around 9. This is an average over 13 geomagnetic observatories and over 3 hrs in time. The distribution of about 250 days since 1932 with large Kp-index. This shows the Russell–McPherron effect.



- The only manifestation of space weather which can be directly seen by humans is the aurora. These are colourful display caused by charged particles interacting with atoms and molecules in the upper atmosphere at a height of 100–500 km. These displays have been seen at high latitudes long before anything was known about space weather.

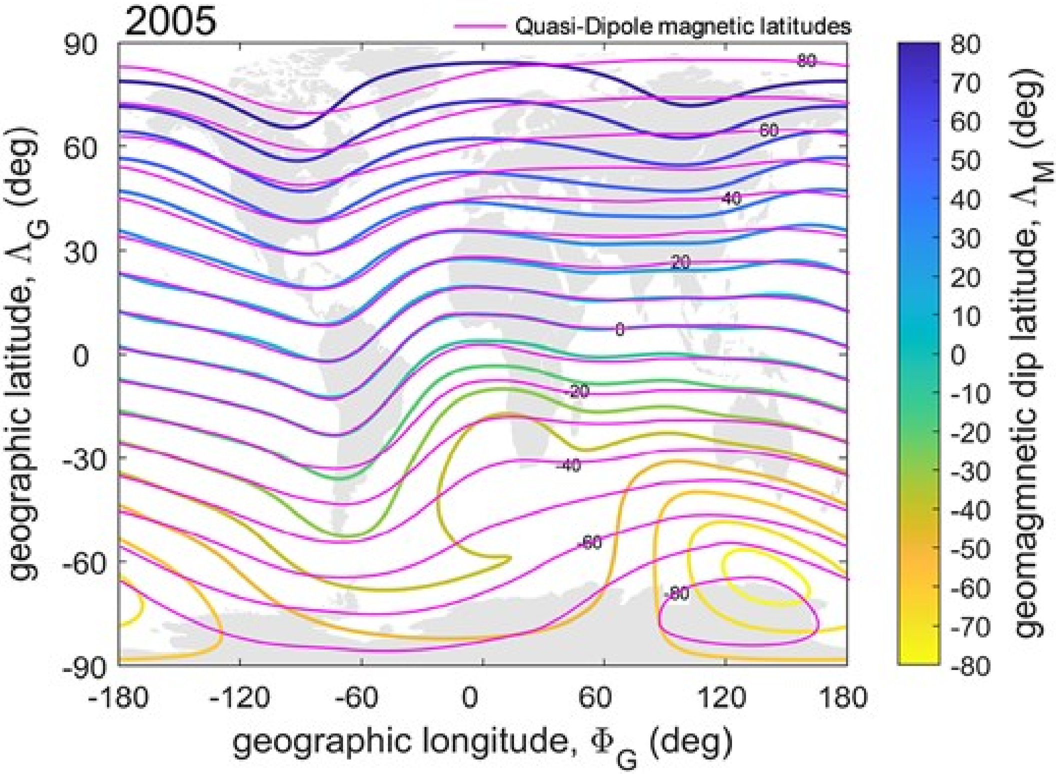
- Auroras are seen primarily at high magnetic latitudes, but during strong geomagnetic storms they can be seen even from tropical regions. Around 70° MLAT there are auroral ovals where auroras are seen almost every night.



Backcountry Journeys

- The colours of aurora depend on the species of atoms or molecules that are excited. Red auroras are formed at high altitudes due to atomic oxygen line at 630 nm. The more frequent collisions at lower altitude suppresses this line. Instead the green line at 557.7 nm also from atomic oxygen dominates. Both these are forbidden lines with life times of 2 min and 0.7 s.

- At even lower altitude blue line at 428 nm due to molecular nitrogen or ionised N_2 dominates. Yellow and pink are a mix of red and green or blue. Different combinations of RGB can produce many different colours.

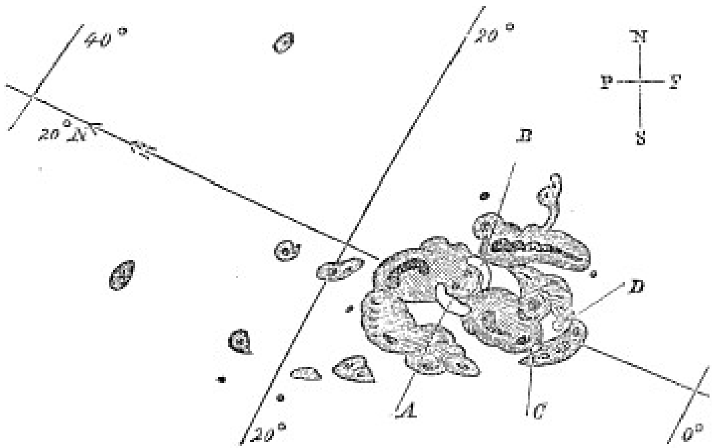


Lockwood et al. 2025

Aurora over Iceland

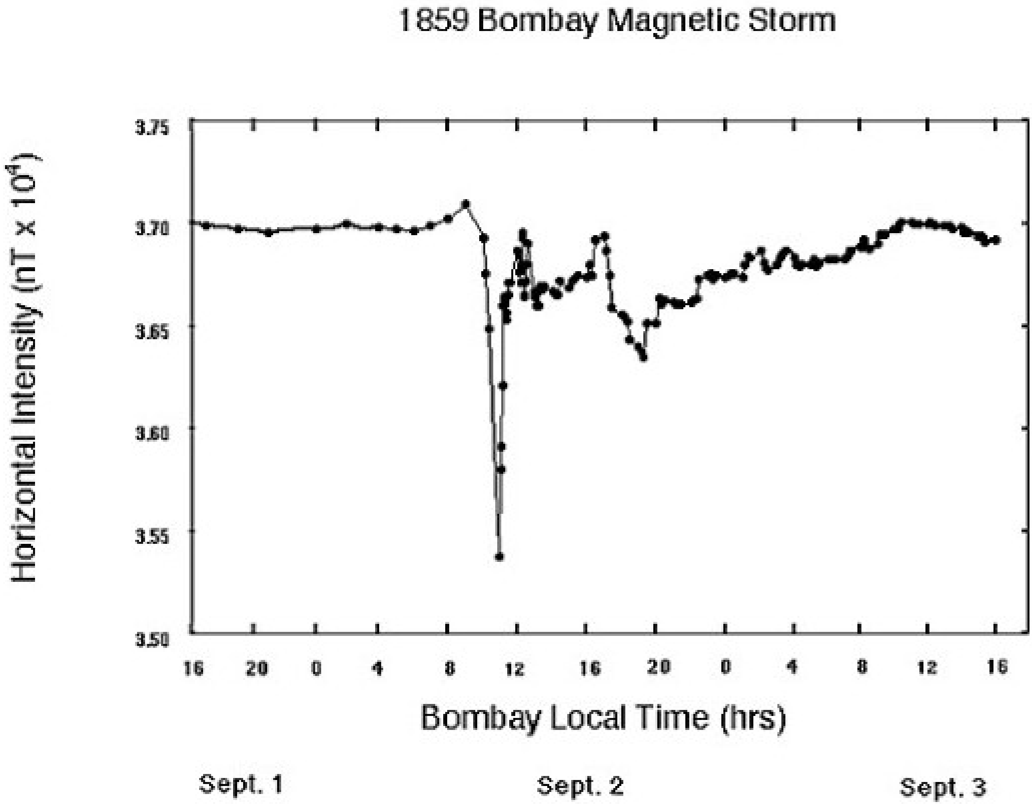
A few Space Weather Events

- The first solar flare was discovered by Carrington on 1 September 1859, who observed a sudden brightening in some active region. The next day there was a severe disruption in telegraph network accompanied by a massive display of Auroras extending to tropical regions in Hawaii, Cuba, Jamaica and San Salvador.



- The first CME was discovered only in 1971, but assuming that a CME was ejected soon after the Carrington flare it took 17 hr 35 min to reach the Earth, giving an average speed of 2300 km/s. This is believed to be the largest flare that is recorded so far. Auroras were visible intermittently from 28 August to 4 September, suggesting multiple flares and CMEs.

- The Colaba observatory in Bombay, recorded the magnetic disturbance measuring a dip of 1600 nT in the horizontal component of magnetic field. That was probably the only magnetic observatory operating in the tropical region and has played a key role in estimating early geomagnetic storms. The observatory was established in 1826 and magnetometer was operational in 1841.



Tsurutani et al. (2003)

- The next major space weather event was on 4 February 1872, which caused disruption in telegraph service all over the world. The Colaba observatory recorded a dip of 830 nT in magnetic field.
- Auroras were reported from as far south as Bombay (9.7° MLAT), Jeypore, Cairo and Khartoum (5.85° MLAT). Auroras were widely reported from India, Bhavnagar, Allahabad, Lucknow, Darjeeling etc.

THE AURORA BOREALIS.

WILL it surprise our readers to learn that the Aurora Borealis was plainly visible in Bombay on Sunday night last? Such was, indeed, the case, and its effects were felt, too. After sunset on Sunday the Aurora was slightly visible, and constantly kept changing colour, becoming deep violet when it was most intense—about three o'clock on Monday morning. It was distinctly visible until sunrise on Monday. The influence of this atmospheric disturbance was unpleasant both for our persons and our correspondence. The cold was unpleasantly keen, and all telegraphic communication was stopped for some hours. Both before and after its height, the Aurora affected the working of both sections of the British-Indian Submarine Cable, one section running east and west, and the other north and south. At 8 o'clock yesterday morning the magnetic disturbance in the telegraph offices was very strong. The extent of this disturbance may be gathered from the fact that all the lines to England in connection with the British-Indian Submarine Cable were affected for hours, and so were the Government lines. At Aden, the Aurora was brilliant in the extreme.

TOI 6 Feb 1872, p2

- Most intense geomagnetic storm of the 20th century occurred during 13–15 May 1921, probably driven by a series of CMEs (Hapgood 2019). Telegraph and telephone services were interrupted due to blown fuses and damaged equipment.
- Many fires were caused through strong earth current during this storm. Telephone exchange at Karlsbad, Sweden was destroyed by a fire. Railroad station at Brewster in New York state was destroyed by fire which started in switch-board. Long distance telephone lines were burned out in New Brunswick, Canada. A control tower about 1 km from New York Grand Central station was destroyed in a fire triggered by a short circuit a few hours after the peak storm. It is not clear if that was due to geomagnetic storm.

- The magnetometer which had been relocated at Alibag went off scale for some time, but this time another tropical observatory at Apia (Samoa) measured a dip of 920 nT. The magnetometer at Hawaii also went off scale. Aurora were observed from Apia (MLAT -15°) and Tonga.

- A solar storm on 23 May 1967 started with the largest recorded solar radio burst in 20th century, causing interference at frequencies of 0.01–9.0 GHz. Intense X-ray flux from an X6 flare caused intense ionisation in ionosphere leading to disruption in HF radio communication on the dayside. Within hours solar energetic particles caused a PCA event disrupting HF radio communication in polar region which lasted for 1 week. There was also a loss of signal between satellite and ground station.

- Radio flux at 1.415 GHz was recorded at 85100 sfu (1 sfu is 10^{-22} W m^{-2} Hz^{-1}). The maximum Kp-index of 9.0 was recorded for 6 hrs on 25–26 May, while the Dst-index was recorded at -374 nT.

- The radar systems operating at 440 MHz at sites in Alaska, Greenland and UK were jammed. The cold war military commanders considered the large scale jamming as an act of war and nuclear armed bombers were ready to take off (Knipp et al. 2016). Just at that time NORAD issued a warning of space weather event and good sense prevailed before the fighters can take off.

- A similar jamming event had occurred during WWII in 1942. A positive fallout from this event was increased priority for study and prediction of space weather by USA.

- On 4 August 1972 there was another strong geomagnetic storm which recorded the fastest CME which took 14.6 hrs to reach the Earth giving an average speed of 2850 km s^{-1}. There were multiple flares with the strongest estimated at X20 also accompanied by a large flux of energetic particles which saturated the detectors, as well as a strong radio burst. However, a subsequent shift of magnetic field northward in CME reduced its geoeffectiveness.
- During this storm a Defense Satellite Communication System mission ended due to power failure. The US Air Forces's Vela satellite to detect nuclear tests on the Earth mistook the disturbance as an explosion, but this was quickly resolved. The ozone layer near north pole was depleted by 46% at 50 km altitude due to charged particle flux, which took more than 50 days to recover.

- The US navy had mined the sea around Vietnam and air force pilots reported seeing about 20 flashes from detonation of these mines. Afterwards it was found that nearly 4000 magnetically sensitive mines were detonated (Knipp et al. 2018).

- This storm occurred between Apollo 16 and 17 missions thus saving the astronauts.

- This storm occurred about 3.5 years after the maximum in solar activity.

- During 13 March 1989 superstorm, caused by 2 CMEs launched by X4.5 and M7.3 flares. The active region caused 11 X class flares during its transit across the Sun. The storm had Dst index of -589 nT.

- The ground induced currents across the Hydro-Quebec power system in Canada caused transformer saturation and subsequent trip out caused generation loss of 9.45 GW of power and the grid collapsed within seconds, causing blackout for about 9 hrs in Quebec affecting 9 million people. During the same storm a large step-up transformer failed at the Salem Nuclear Power plant in New Jersey. These failures prompted extensive review of equipment and procedures and mitigation measures were implemented.

- A number of satellites were temporarily disrupted, including the GOES and space shuttle Discovery.
- Another storm on 16 August 1989 caused a halt of all trading on the Toronto stock exchange when 3 redundant disc drives all failed.

- A major storm peaking on 28–31 October 2003 was caused by 12 X-class flares and CMEs caused by 3 large sunspot groups. This storm occurred when a number of spacecrafts were available for observation. The most geoeffective storm was caused by an X17 flare on 28 October and the resulting CME reached the Earth in 19 hrs. the next day another X10 flare also generated a CME which also reached the Earth in similar time. The largest recorded solar flare estimated at X45 occurred on 4 Nov, when the active region was near the west limb thus sparing the Earth from further storm.

- The Dst index for this storm was -401 nT, which is most likely due to the CME magnetic field turning northwards after some time as measured by ACE.

- The CME was also detected by the Mars Odyssey spacecraft and one of the instrument on board was disabled, Ulysses spacecraft near Jupiter, Cassini spacecraft en route to Saturn and in April 2004 Voyager 2 also detected the CME around 70 AU.

- A Japanese ADEOS-II satellite was permanently disabled. About 50% of the operational satellites, including WMAP, SOHO and ACE were interrupted. One instrument on ACE was permanently degraded due to the storm. Some instruments on ISS were switched off during the storm. 36 of the 70 spacecraft failures in 2003 occurred during the October 2003 storm. USAF which tracks all space debris to warn of possible collision, lost track of about 50% objects in low Earth orbits.

- Polar flights were suspended and there was a communication blackout over Antarctica for over 5 days. The augmented GPS system had to be disabled for about 30 hrs over USA. From 19 October to 5 November, aviation radio communication was disrupted every day for some time. Considering radiation level, Federal Aviation Administration issued first ever advisory that airlines stay below 7500 m while flying above 35° MLAT.

- There was an hour long power failure in Malmo, Sweden and 12 transformers were damaged in South Africa.

- The last major event so far was on 10–11 May 2024, when about 14 X-class flares were seen along with associated CMEs. The most effective were the X4 on 10 May and X5.7 on 11 May. The Dst index recorded was -418 nT. These were accompanied by radio bursts and SEP events, which were not particularly strong.

- Auroras were visible over a wide range of places, including, Hanle, Oman (18° MLAT), Canary Islands and Hawaii. There was no major disruption in any services, except for GPS controlled tractors. About 5000 satellites made emergency maneuvers to maintain their orbits.