Space Climate

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The Sun

The Source of Life
The Source of Troubles

What Is The Sun Made of?

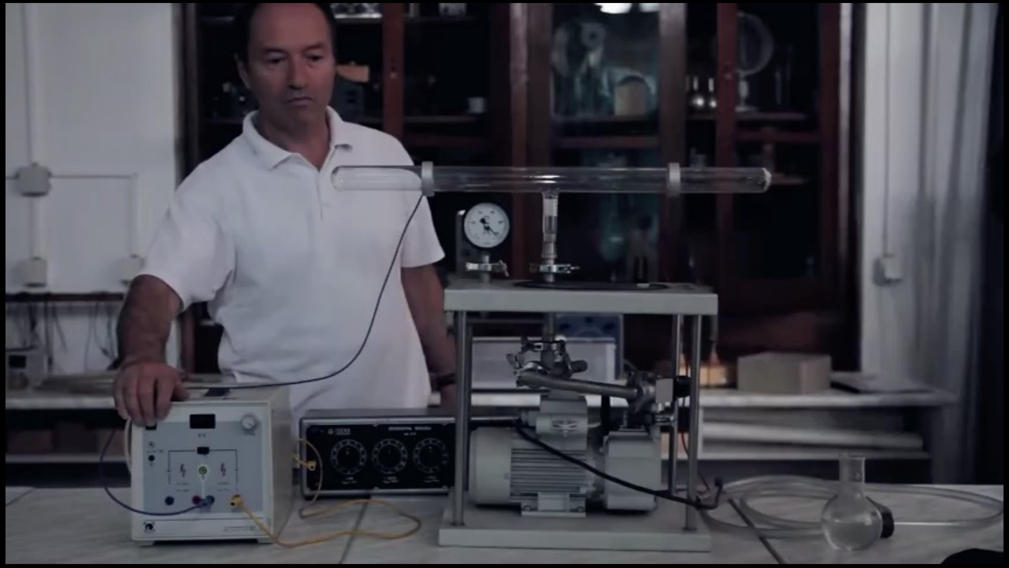
Video Credit: Spitz Creative Media

- Matter in the known Universe is often classified as: solid, liquid, gaseous, and plasma
- The Sun is composed of plasma
- While plasma is rare on Earth, 99.9% of the Universe is made up of plasma
- Plasma: Macroscopically neutral substances containing many interacting free electrons and ionized atoms or molecules
- Plasma behaves like a gas, except that it conducts electricity and is affected by magnetic field

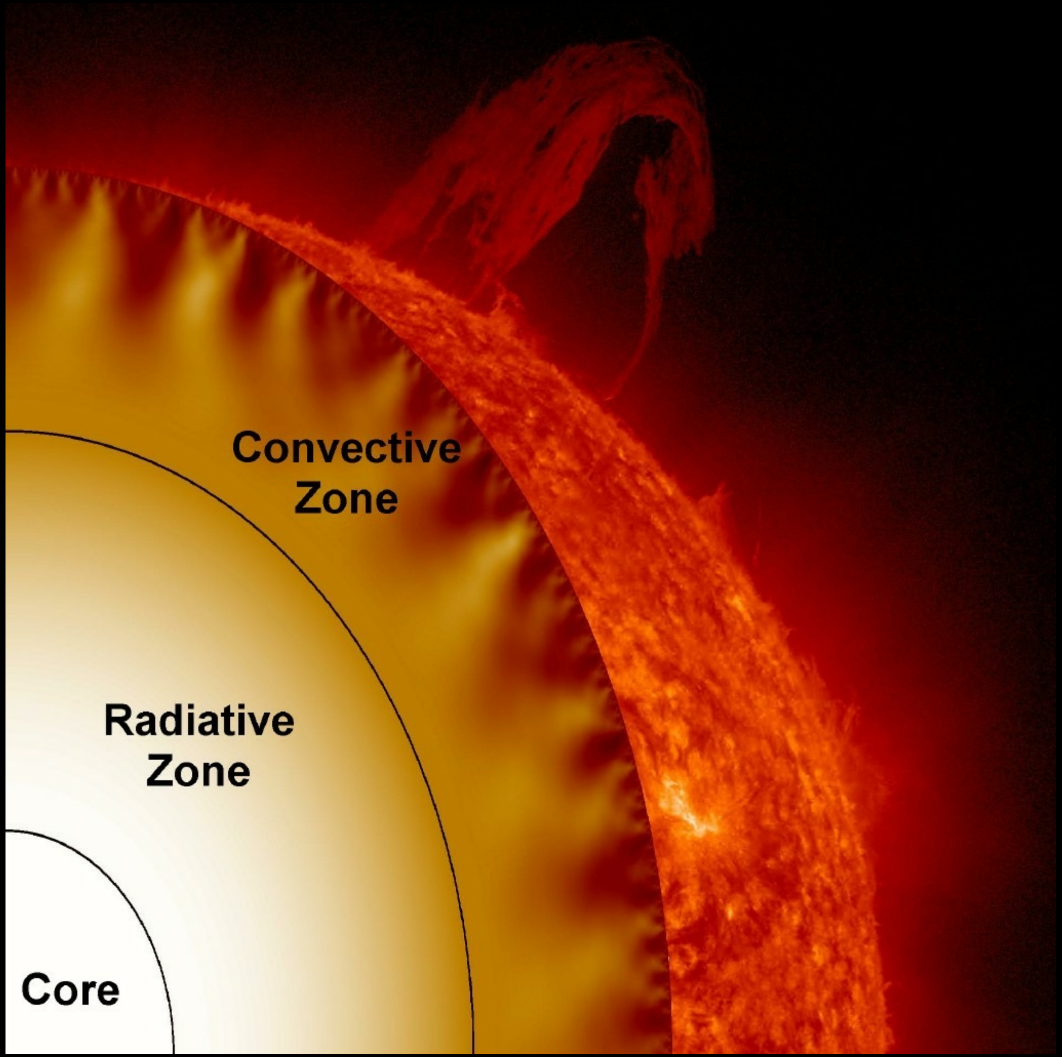
Plasma can be produced by many methods such as :

- Photoionization: ionization occurs by absorption of incident photons whose energy is equal to, or greater than the ionization potential of the absorbing atom
    - **Earth atmosphere is a natural photoionized plasma**
- Gas discharge: an electric field is applied across a gas, which accelerates the free electrons to energies sufficiently high to ionize other atoms by collisions
    - **Glow discharge (a plasma formed by the passage of electric current through a gas)**

Earth's atmosphere, Photo credit: ESA



Glow discharge, Video credit: Oliver Zajkov



Solar interior
Credit: NASA

Core:

- Nuclear fusion process H → He
- Temp: ~15 Million Kelvin, radius: ~ 150,000 km

Radiation Zone:

- Energy moves outward as electromagnetic radiation
- Temp: ~ 7 MK, radius: ~300,000 km

Convection Zone:

- Consist of plasma, generates magnetic field
- Temp: ~ 2 MK radius: ~200,000 km

Photosphere:

- Visible surface, Radius: ~500 km thick, T: 5800 K
- Active regions, sunspots, bright faculae, granules

Chromosphere:

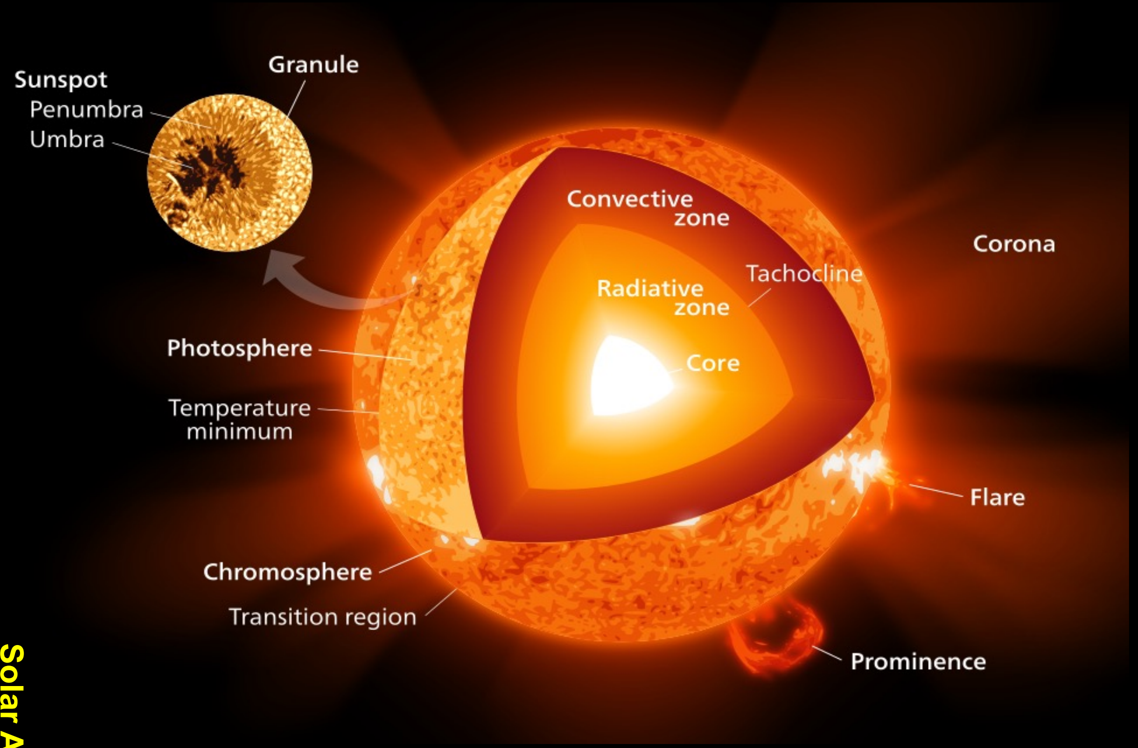
- ~10,000 km thick, T:4000 K at the bottom, 8000 K at the top
- Filaments or prominences

Corona:

- Extremely hot (over 1,000,000 kelvin) but tenuous plasma $<10^9$ cm^{-3}

Solar Atmosphere

$R_\odot$ = 695,700 km



The structure of the Sun
Image credit: Kelvinsong

How do we know that the Solar Corona is hot?

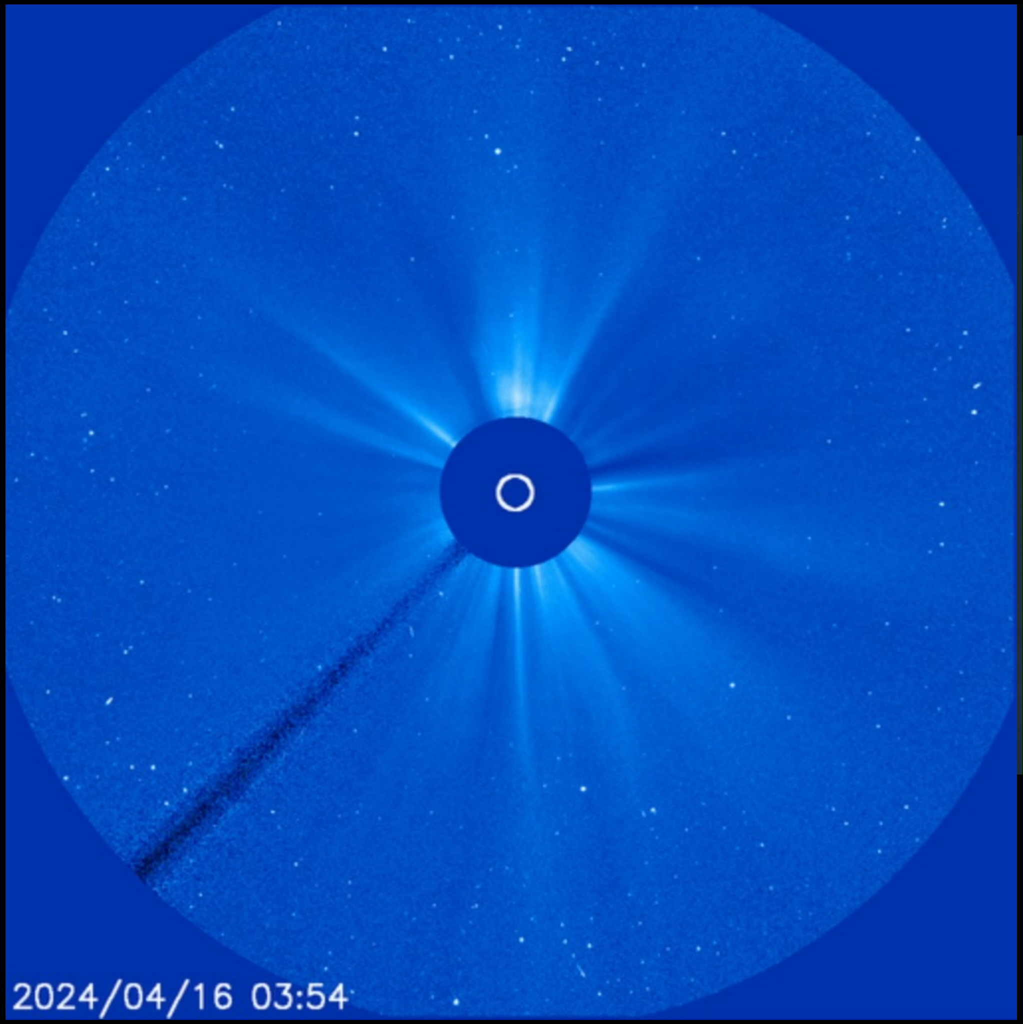
Solar corona

Illustration credit: NASA Goddard Space Flight Center

- Scientists can use spectrometers to analyze light from stars and identify their composition
- Coronal spectral lines were observed since 1869
- But Bengt Edlén – a Swedish astronomer - discovered the elements responsible for these emission lines in 1940
- Highly ionized iron Fe^{+13}
- Such high levels of ionization would require coronal temperatures ~ 1 million Kelvin

Coronal Heating Problem

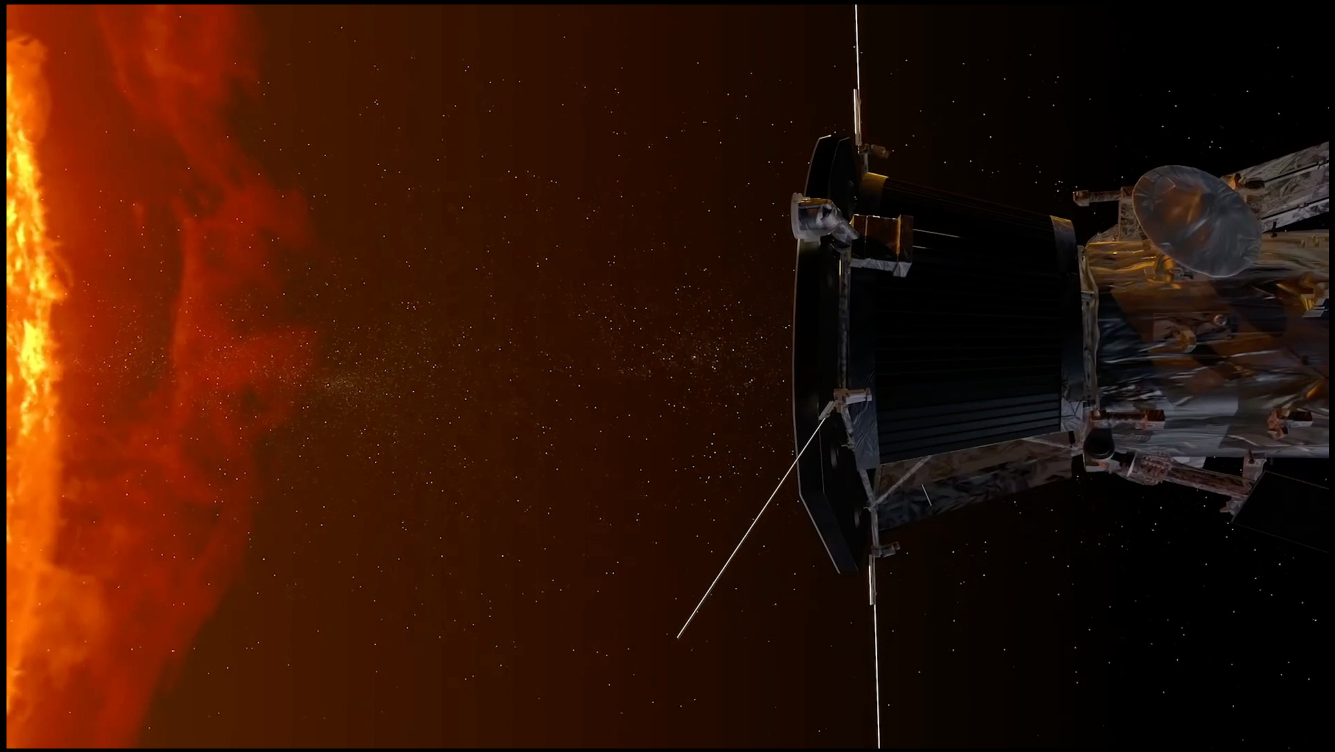
- Corona can be observed during a solar eclipse. The primary coronal emission is in the UV and soft x-ray range
- Corona can also be observed by a Coronagraph
- A coronagraph uses a disk to block the Sun's bright surface, revealing the faint solar corona. In other words, a coronagraph produces an artificial solar eclipse.
- Why solar corona is so hot?
- Coronal Heating problem: A 150-year-old mystery



LASCO coronagraph onboard of SOHO spacecraft
Credit: ESA

NASA's Parker Solar Probe

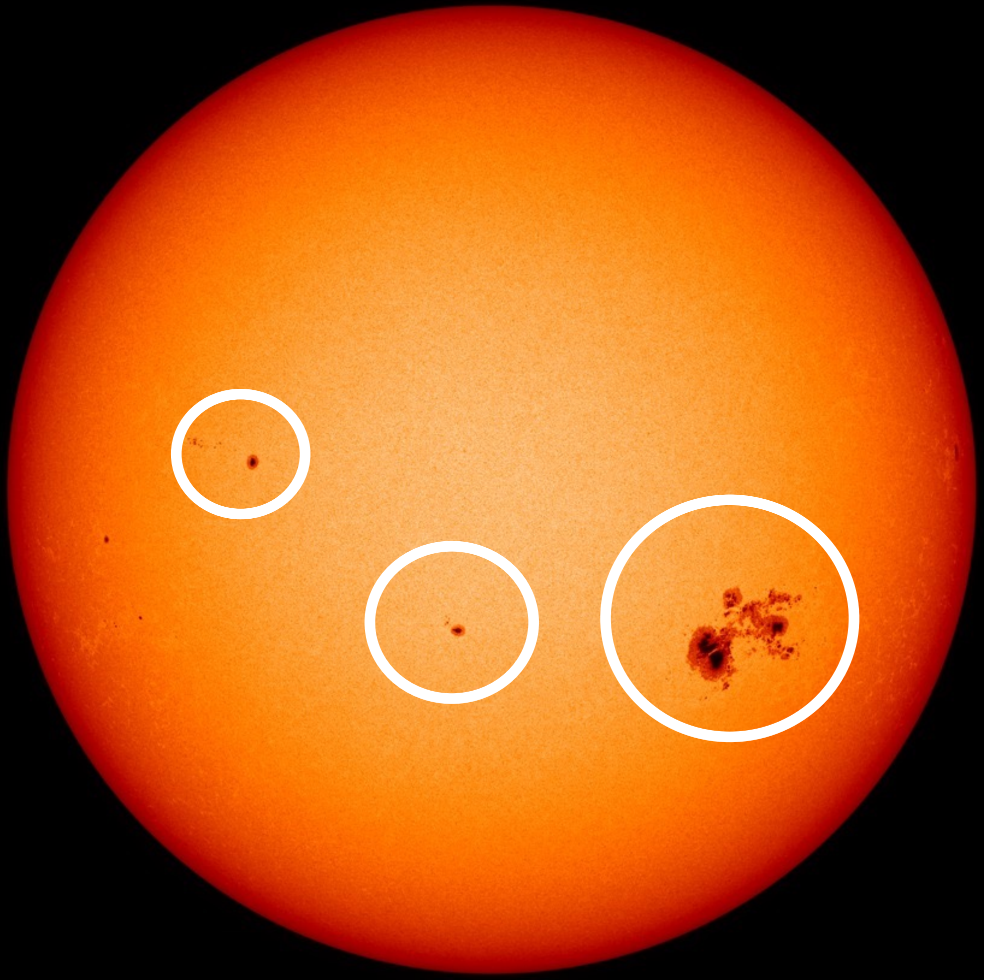
- Launched in August 2018
- One of the primary goals: To Investigate the coronal heating problem
- Closest-ever spacecraft to the Sun
- The space craft will approach ~ 6 million km from the surface of the sun ~2025



Credit: NASA

Sunspots

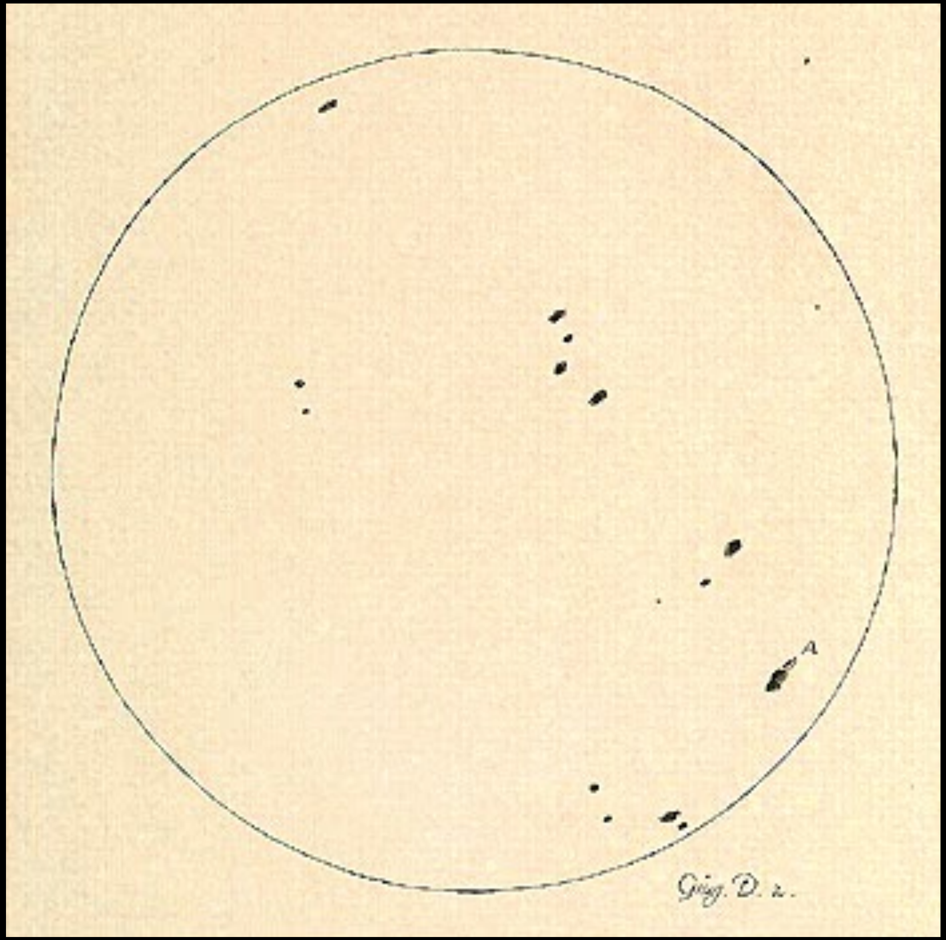
- Sunspots are areas that appear dark on the surface of the solar photosphere
- They appear dark because they are cooler than other parts of the Sun's surface
- Sunspots are only dark in contrast to the bright face of the Sun. If you could cut an average sunspot out of the Sun and place it elsewhere in the night sky, it would be about as bright as the full Moon



Sunspot groups
Credit: SDO/NASA

historical observation of sunspots by Galileo Galilei:

- In 1612 during the summer months, Galileo made a series of sunspot observations
- Because these observations were made at approximately the same time of day, the motion of the spots across the Sun can easily be seen



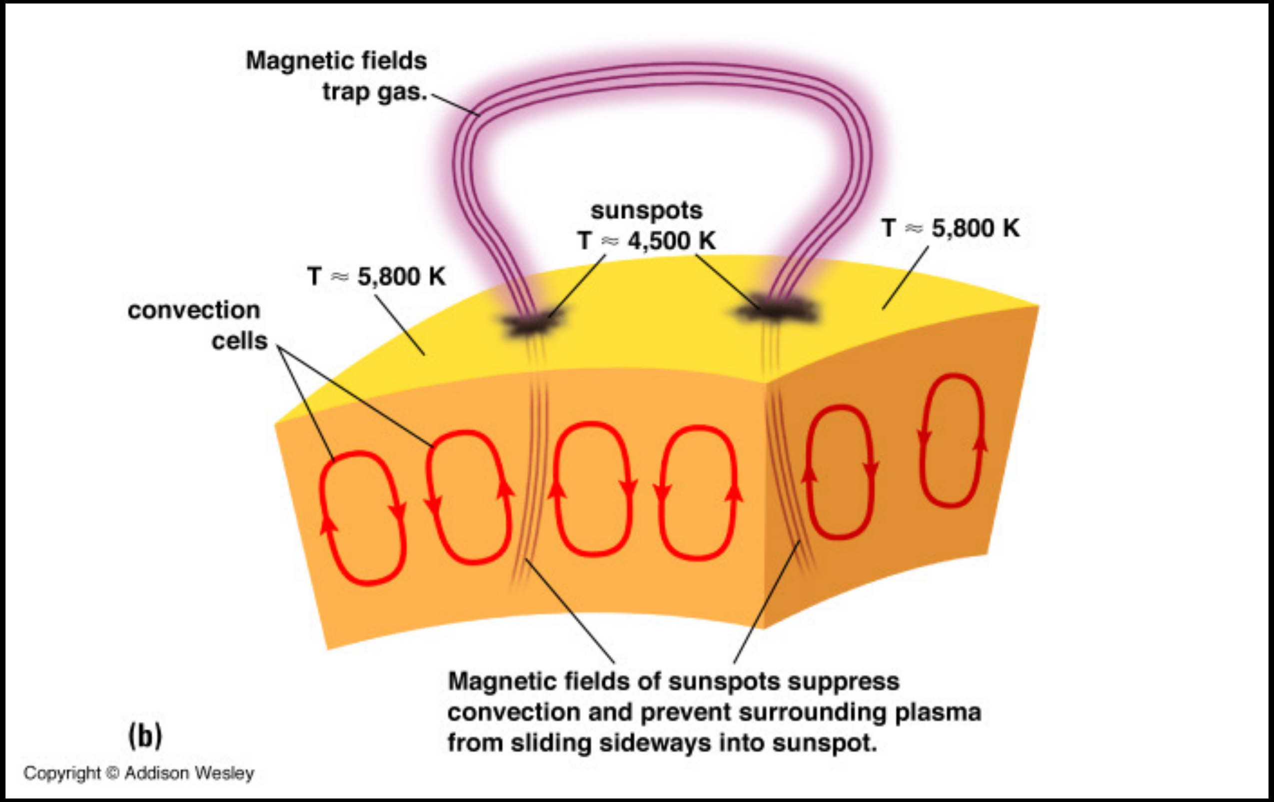
Sunspot Drawing in 1612 by Galileo Galilei

Magnetic field of Sunspots:

- Sunspot first observed on the sun in 1612

- In 1908 (~300 years later) an American astrophysicist George Ellery Hale, showed observationally that sunspots had strong magnetic fields

- In the presence of a sunspot, the magnetic fields gets in the way of energy and heat being transported to the surface, so sunspot appear dark



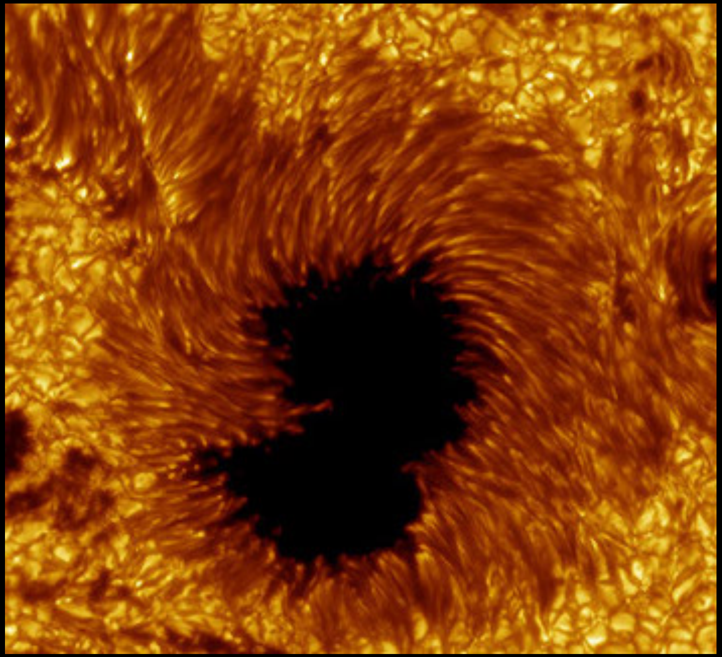
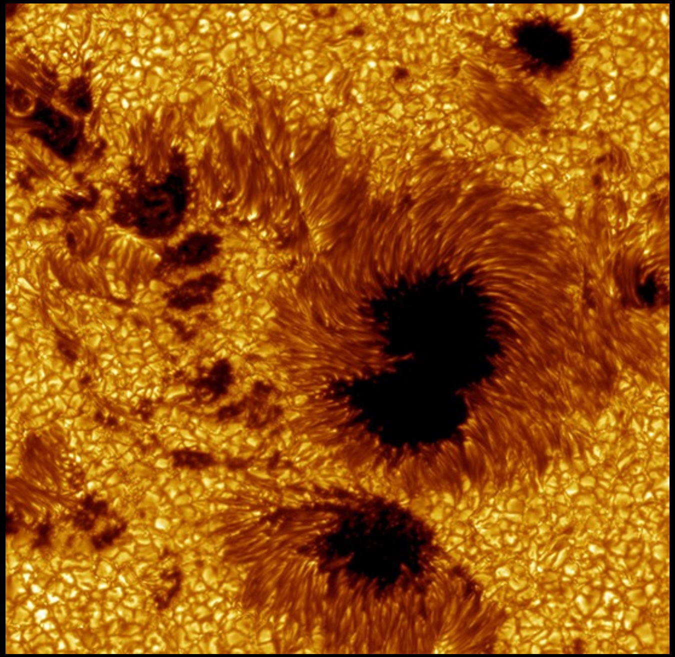


Image credit: Royal Swedish Academy of Sciences / NASA/SDO

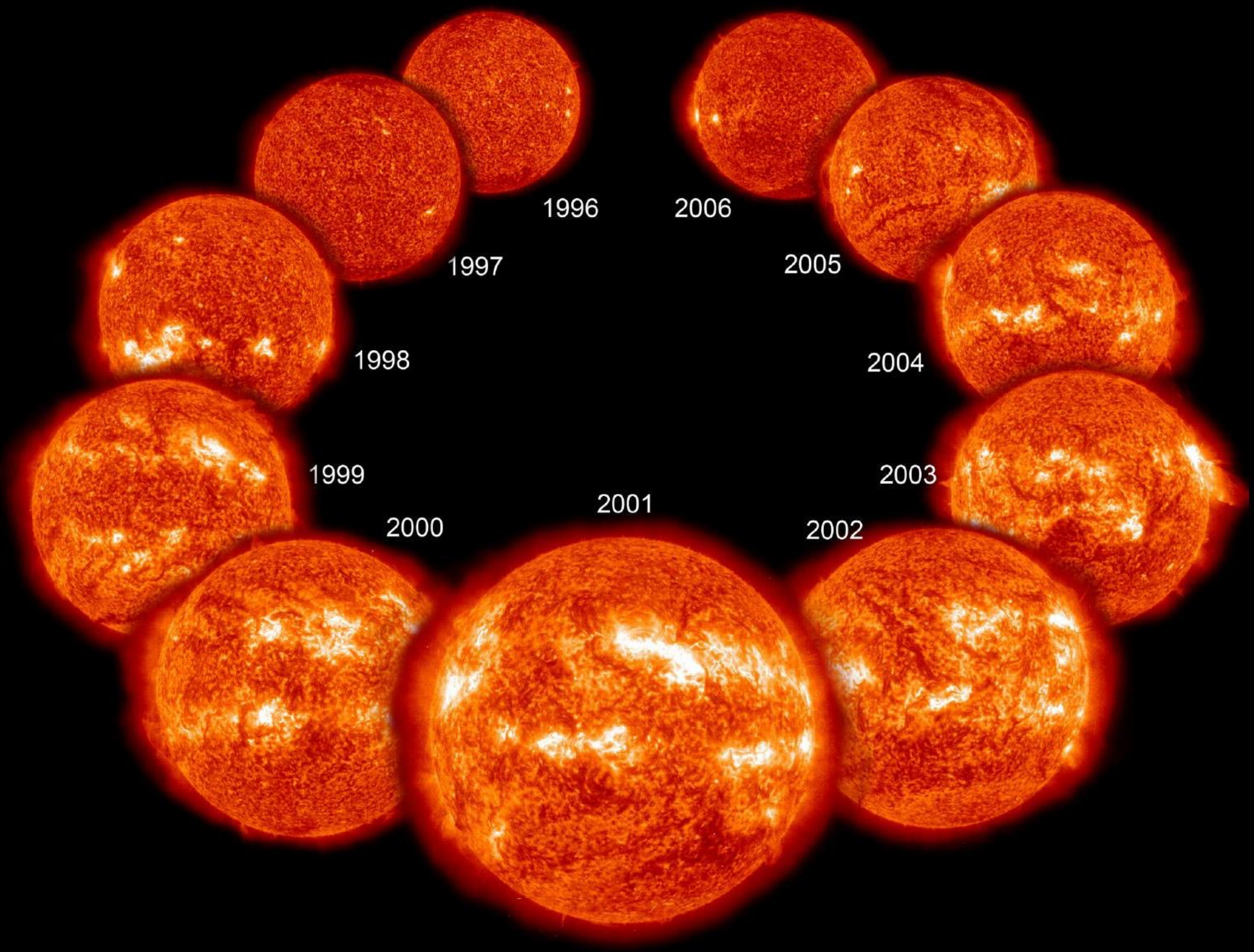


Sunspots:

- Appear dark
- Cooler than the surrounding (Temp: ~ 3000 - 4000 K)
- Magnetic field strength 0.1 to 0.3 Tesla
- Most of flares & CMEs are originated from the Sunspot
- One form of active regions

Solar Active Regions (ARs)

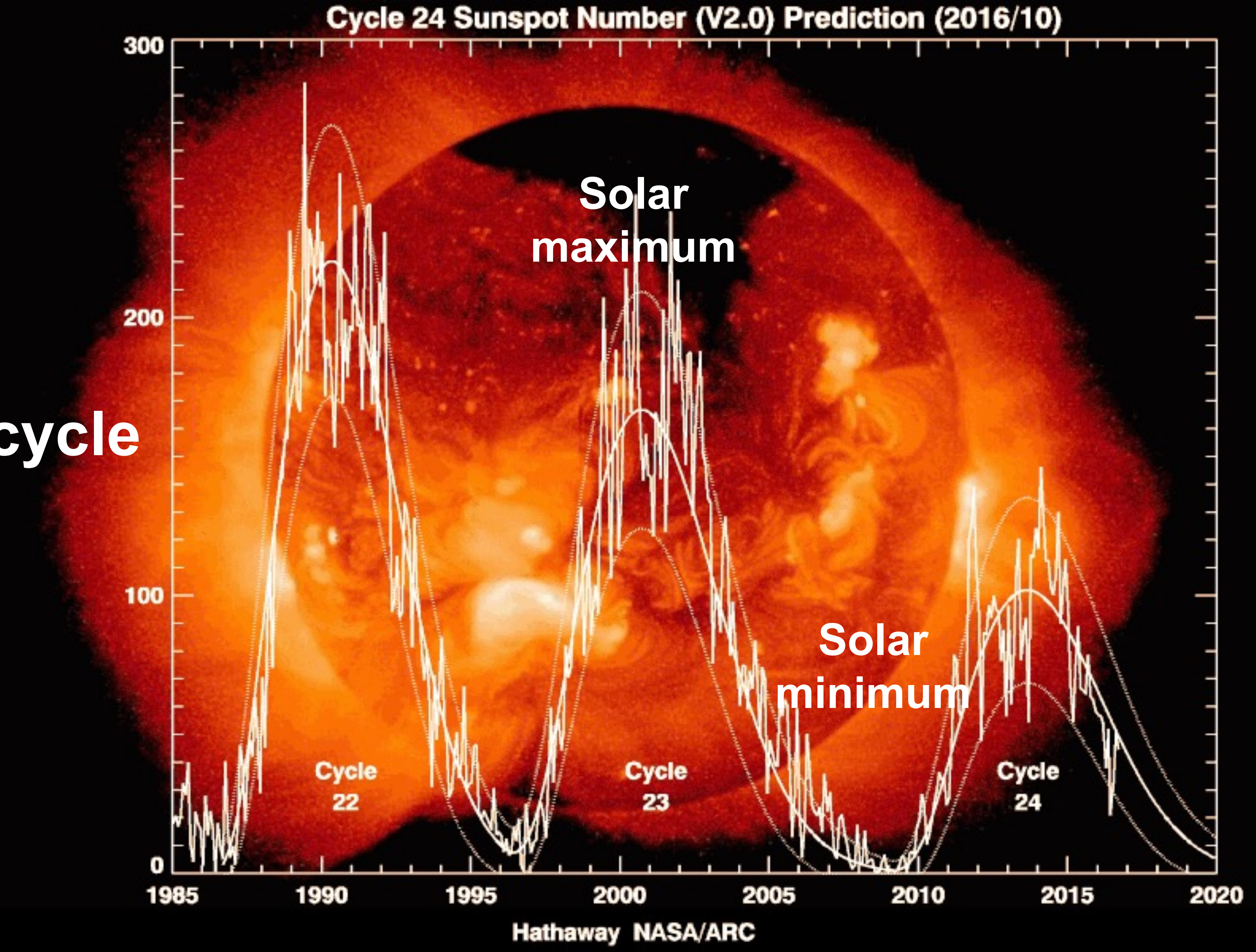
- Area with an especially strong magnetic field
- Not all active regions produce sunspots
- B can be ~1000 or more times stronger than the average magnetic field of the Sun (~0.0001 Tesla)
- Most of flares & CMEs are originated from ARs



Eleven years in the life of the Sun, spanning most of solar cycle 23, as it progressed from solar minimum (upper left) to maximum conditions and back to minimum (upper right) again seen at 28.4 nm (Extreme ultraviolet)

Image Credit: EIT/SOHO, ESA

Solar cycle


Cycle 24 Sunspot Number (V2.0) Prediction (2016/10)
300
200
100
0
1985
1990
1995
2000
2005
2010
2015
2020
Hathaway NASA/ARC
Cycle 22
Cycle 23
Cycle 24
Solar maximum
Solar minimum

Solar Maximum :

The time at which the Sun reaches its highest level of activity, as defined by the 12-month average sunspot number

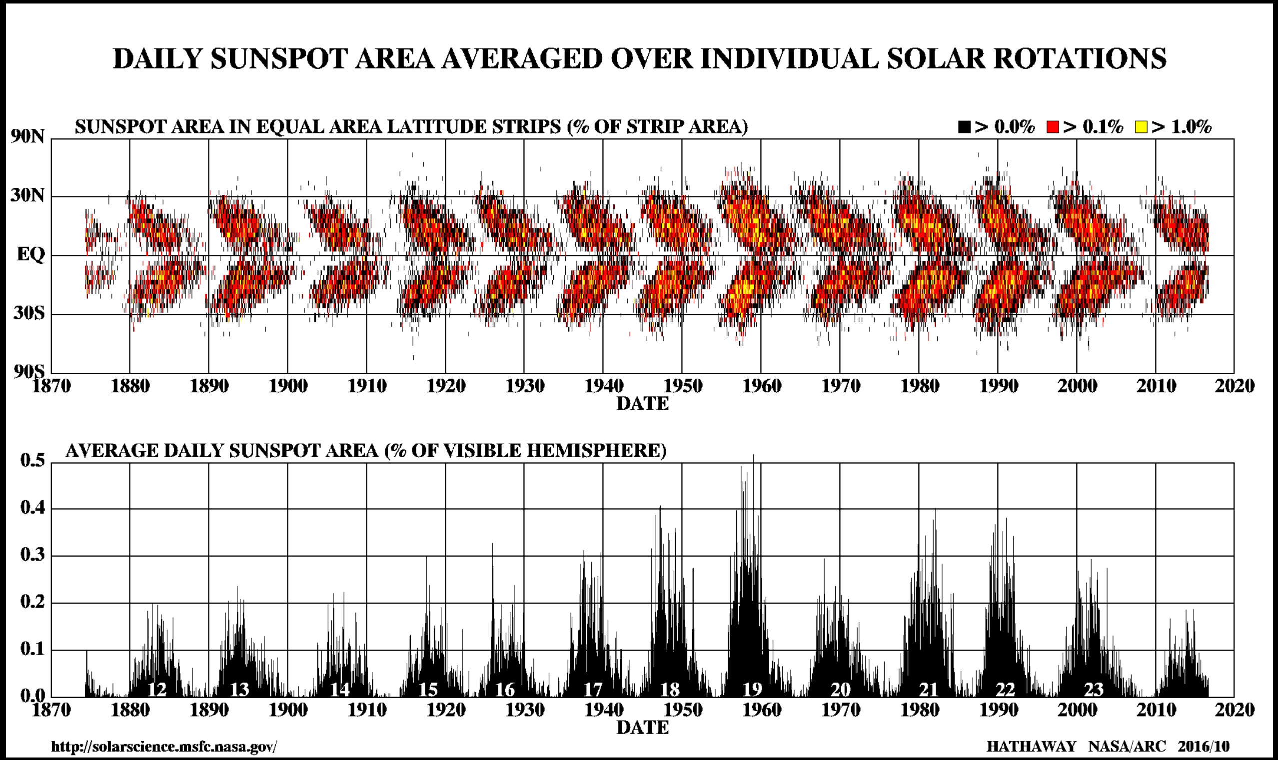
Solar minimum :

The time at which the Sun reaches its lowest level of activity, as defined by the 12-month average sunspot number

Solar minimum and maximum
Credit: NASA

The butterfly diagram

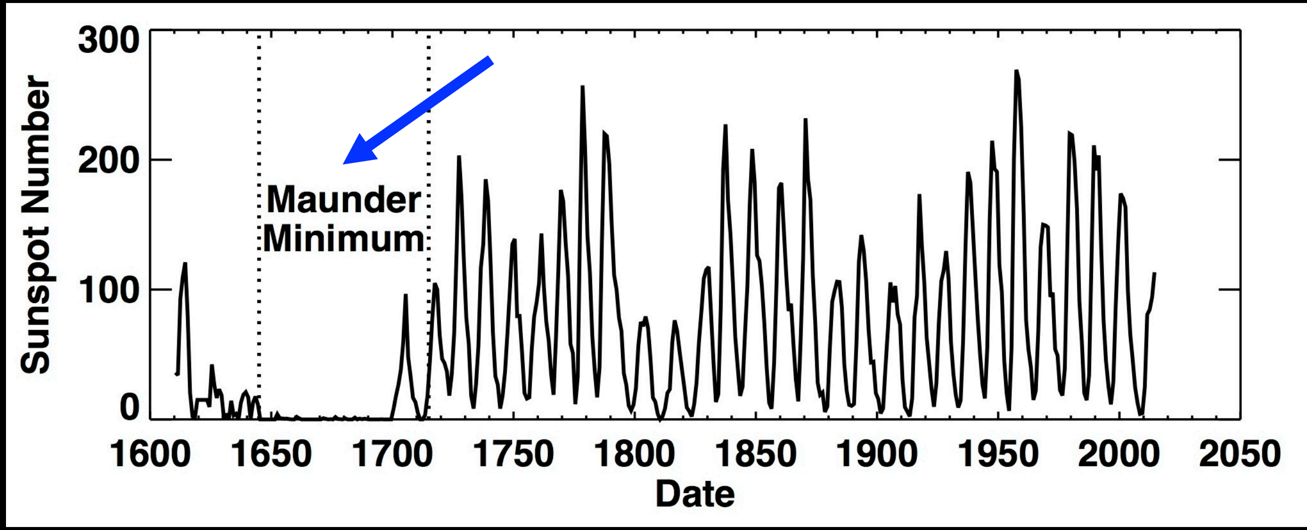
- Detailed observations of sunspots have been obtained by the Royal Greenwich Observatory since 1874
- These observations include information on the sizes and positions of sunspots as well as their numbers
- Sunspots do not appear at random over the surface of the sun but are concentrated in two latitude bands on either side of the equator
- These bands first form at mid-latitudes, widen, and then move toward the equator as each cycle progresses



A butterfly diagram which is showing the positions of the spots for each rotation of the sun since May 1874
Credit: NASA

The Maunder Minimum

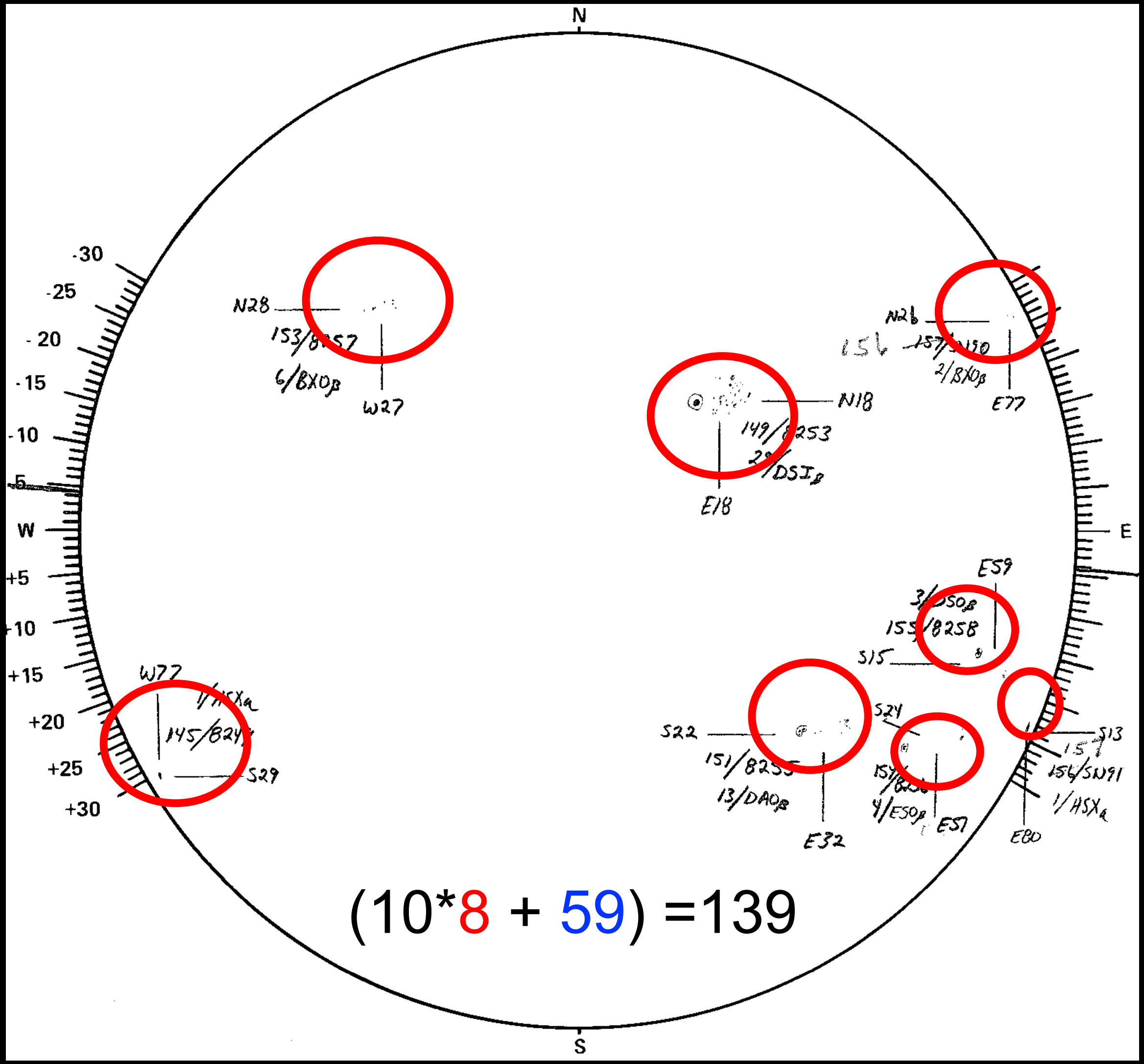
- Early records of sunspots indicate that the Sun went through a period of inactivity in the late 17th century
- Very few sunspots were seen on the Sun from about 1645 to 1715
- This period of solar inactivity also corresponds to a climatic period called the "Little Ice Age" when rivers that are normally ice-free froze and snow fields remained year-round at lower altitudes



Yearly Sunspot Number from 1600 to 2010
Credit: NASA

International Sunspot Number

- Introduced by Rudolf Wolf in 1848
- It is computed using this formula:
- $R = k\,(10 * g + s)$
- g number of sunspot group
- s number of individual spot
- k varies with location & instrumentation, $0 < k \leq 1$

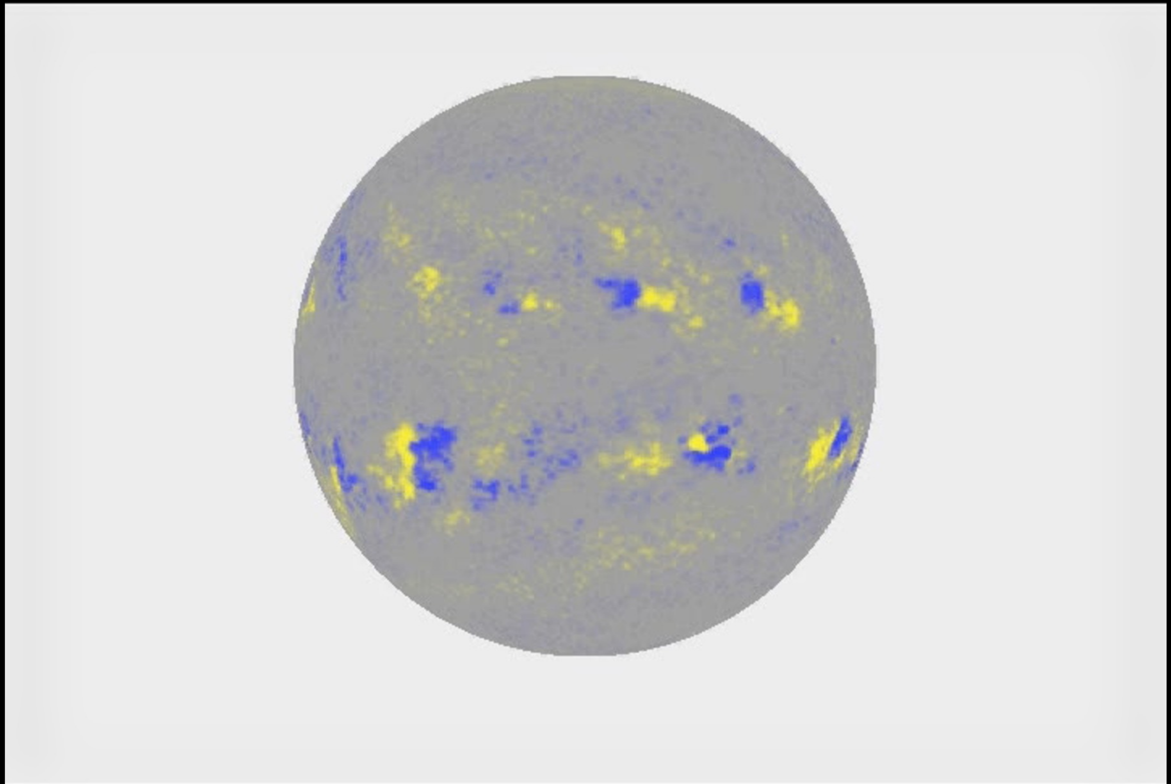


Sunspot drawing credit: NOAA

How are Sunspots produced?

Solar Dynamo

- It is widely believed that the Sun's magnetic field is generated by a magnetic dynamo within the Sun
- Magnetic fields are produced within the Sun by electric currents
- These currents are generated by the flow of plasma
- There is a variety of flows on the Sun's surface and within its interior. Nearly all these flows may contribute in one way or another to the production of the Sun's magnetic field

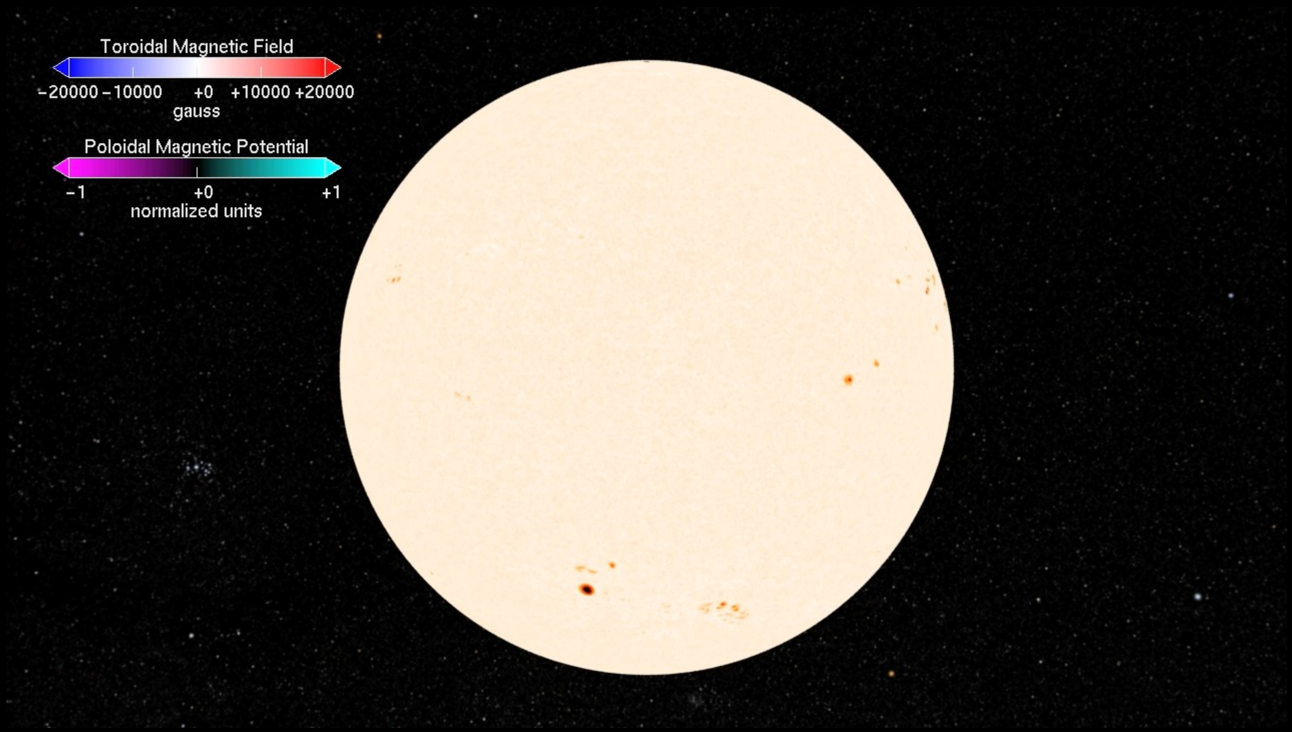


The variation in the Sun's magnetic field from 1980 to 2010

Credit :NASA

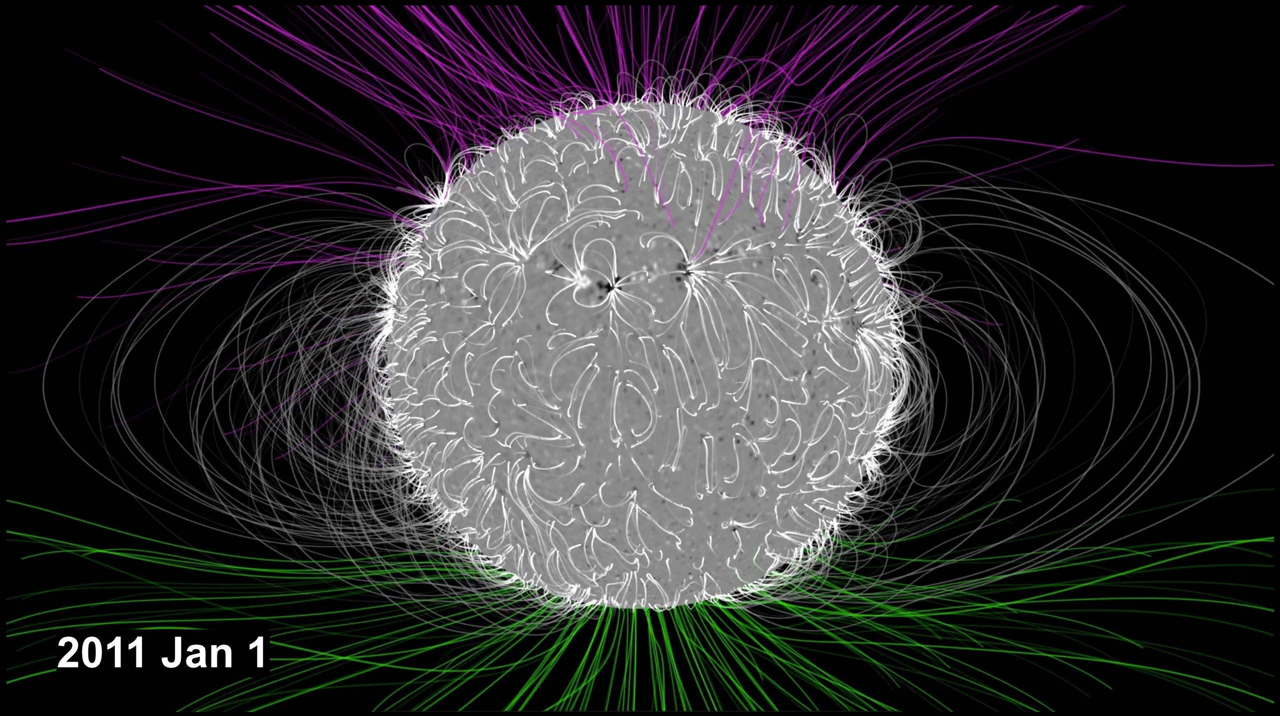
Toroidal and Poloidal Magnetic Fields simulation

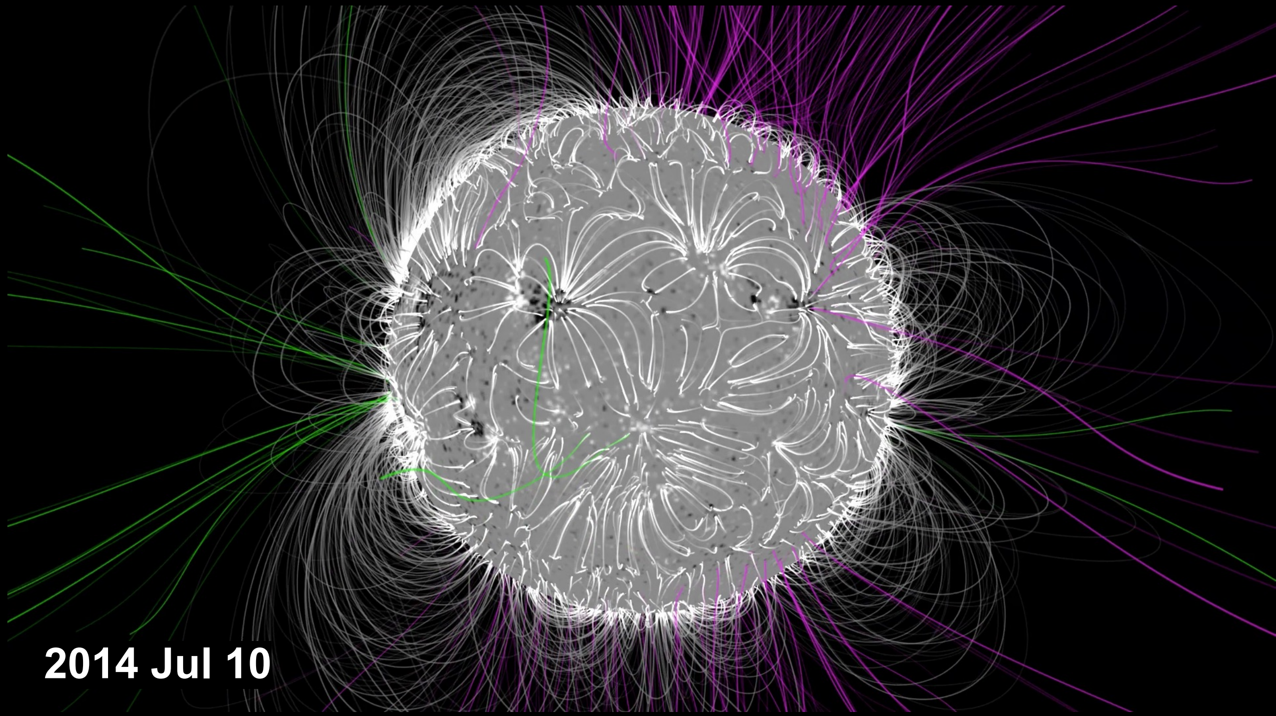
- Near solar minimum, we have relatively simple magnetic line structures
- As the system evolves to sunspot maximum, the field lines in the polar regions become much more twisted
- Intense region of toroidal field exhibit tight bunches of field lines



The evolution of the toroidal magnetic field (represented by colors on the right-hand cross-section), and the poloidal magnetic potential field (represented by colors on the left-hand cross-section)
Simulation credit: NASA

- Solar magnetic field from January 2011 to July 2014
- The magnetic field is much more concentrated near the poles in 2011, three years after solar minimum.
- By 2014, the magnetic field has become more tangled and disorderly, making conditions ripe for solar events like flares and coronal mass ejections.

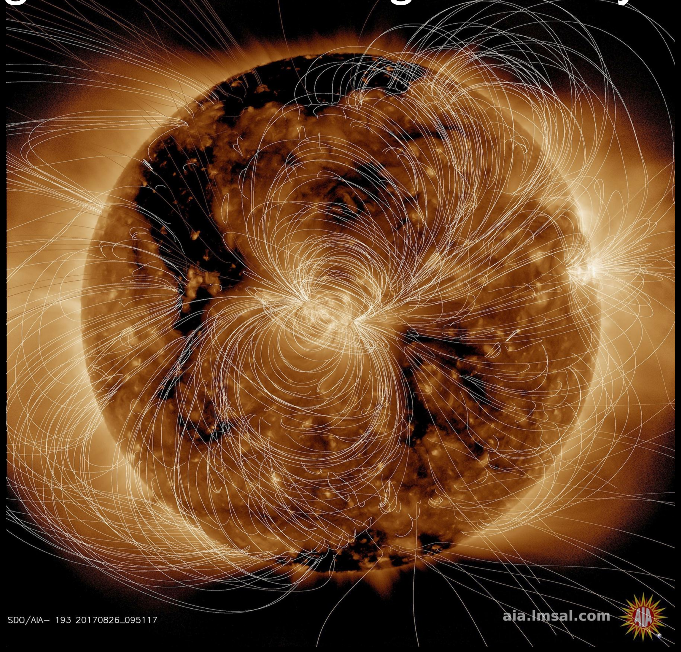




Credits: NASA's Goddard Space Flight Center/Bridgman

How do we know that the magnetic field is continuously generated within the Sun?

- The Sun's magnetic field changes dramatically over the course of just a few years
- The magnetic field changes in a cyclical manner



Computer generated model of the sun’s magnetic field on August 10, 2018, using SDO data

Credit : SDO/NASA

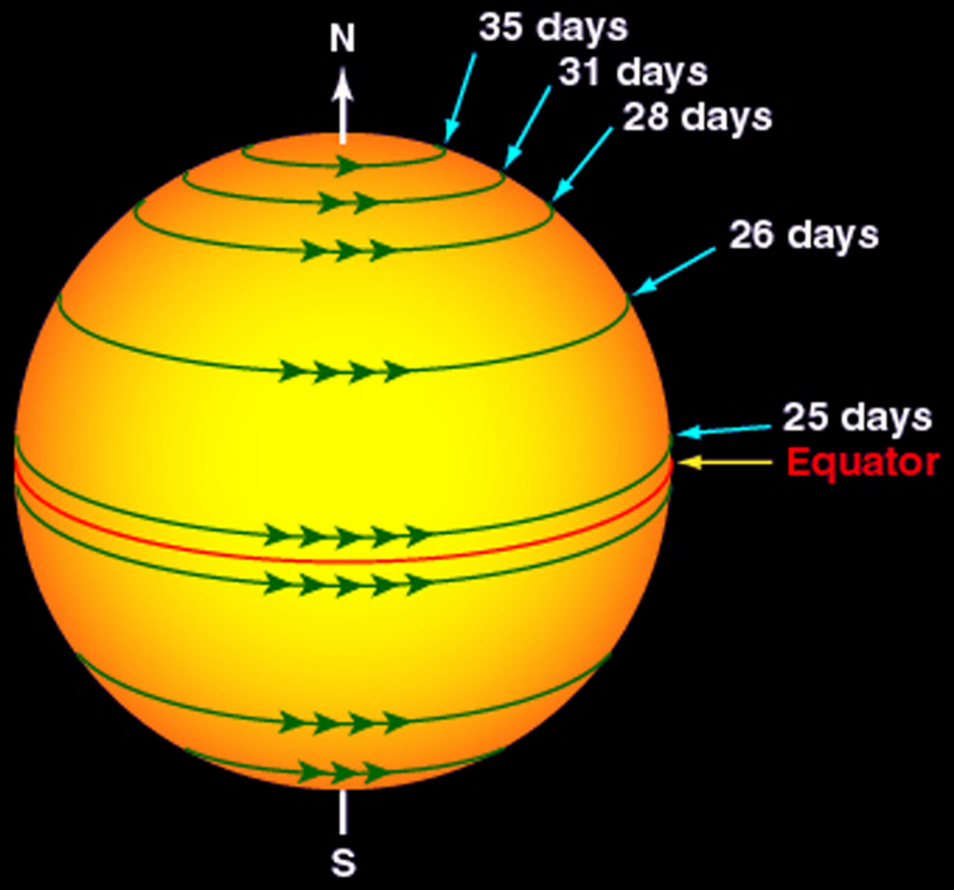
Differential rotation

- This rotation was first detected by observing the motion of sunspots

- The Sun rotates on its axis once in about 27 days

- Solar rotation varies by latitude

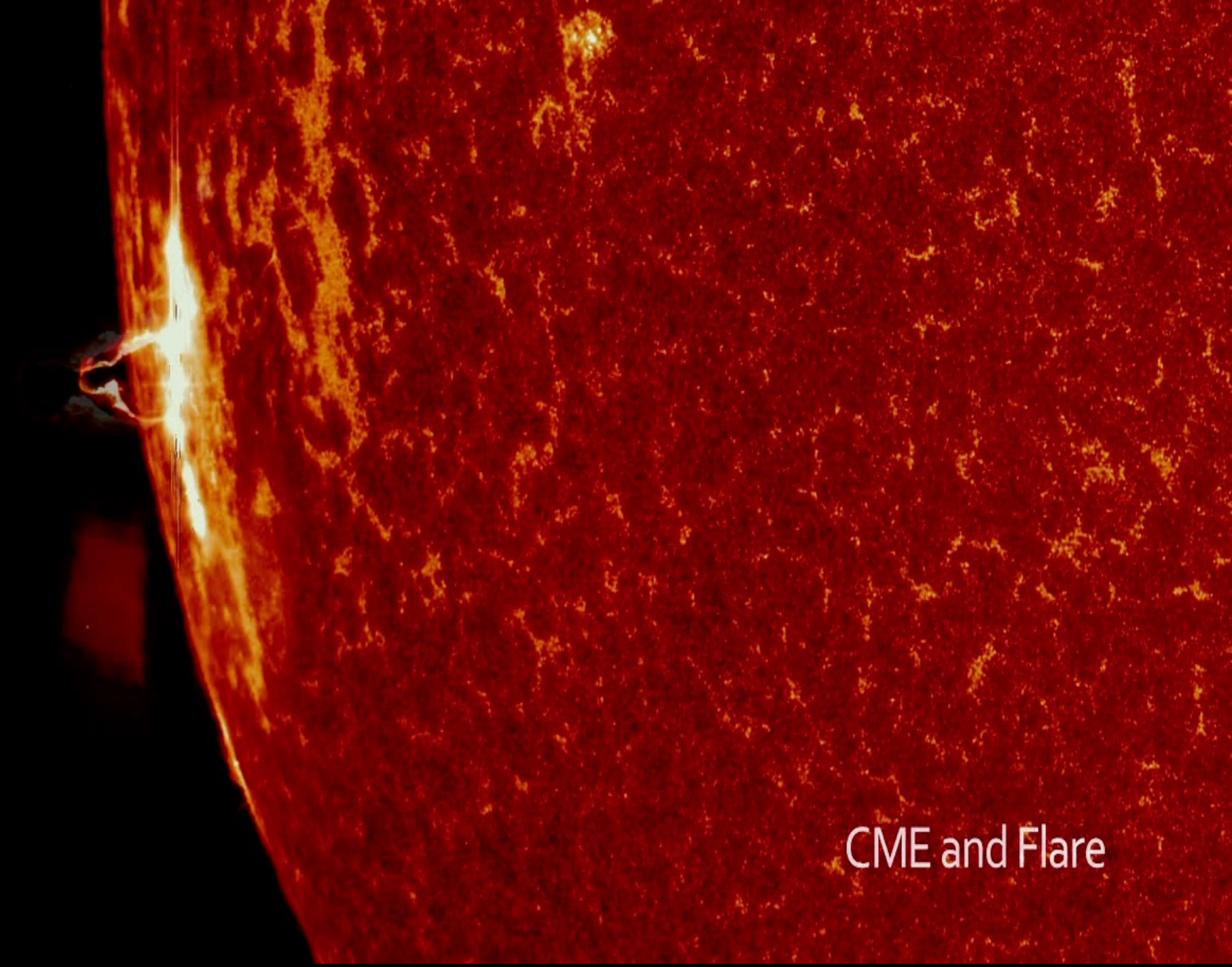
- the Sun's equatorial regions rotate faster (taking only about 24 days) than the polar regions (which rotate once in more than 30 days)



credit: NASA

CME and flare

- Coronal mass ejections (CMEs) and solar flare are explosive phenomena that occur on the Sun
- Often occur together but they are not the same
- Often emerge from solar active regions



Video credit: SDO/NASA

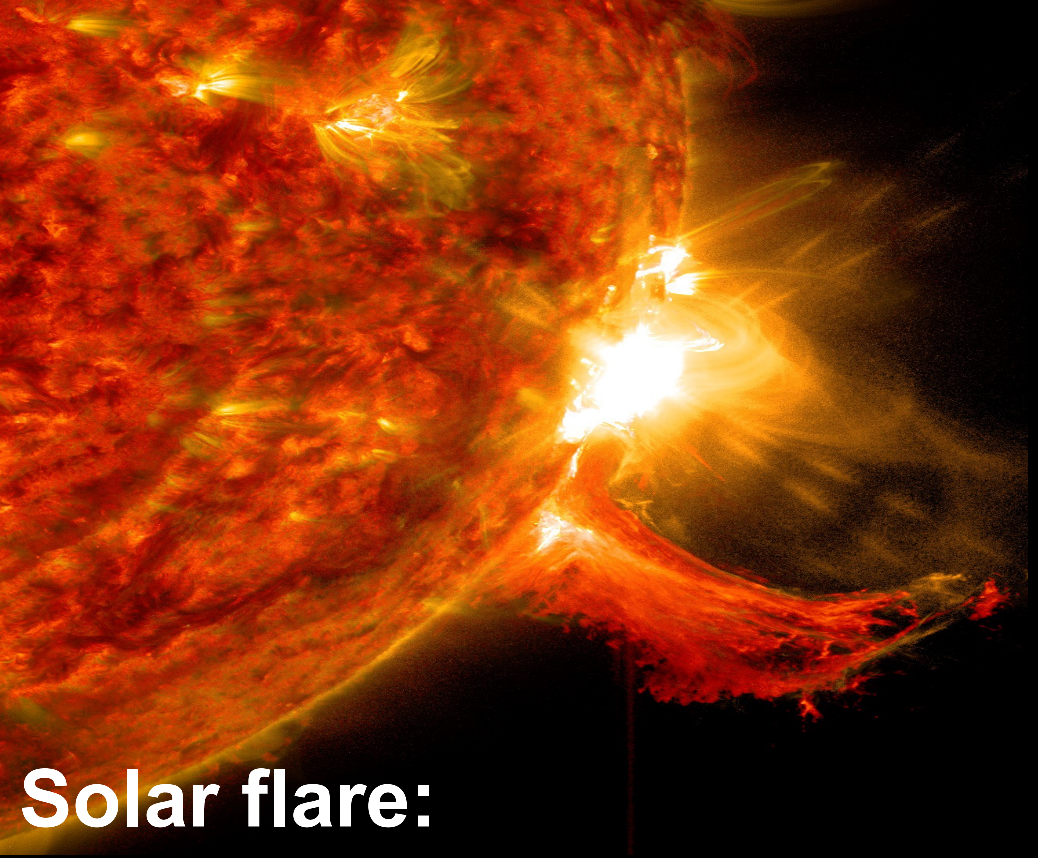
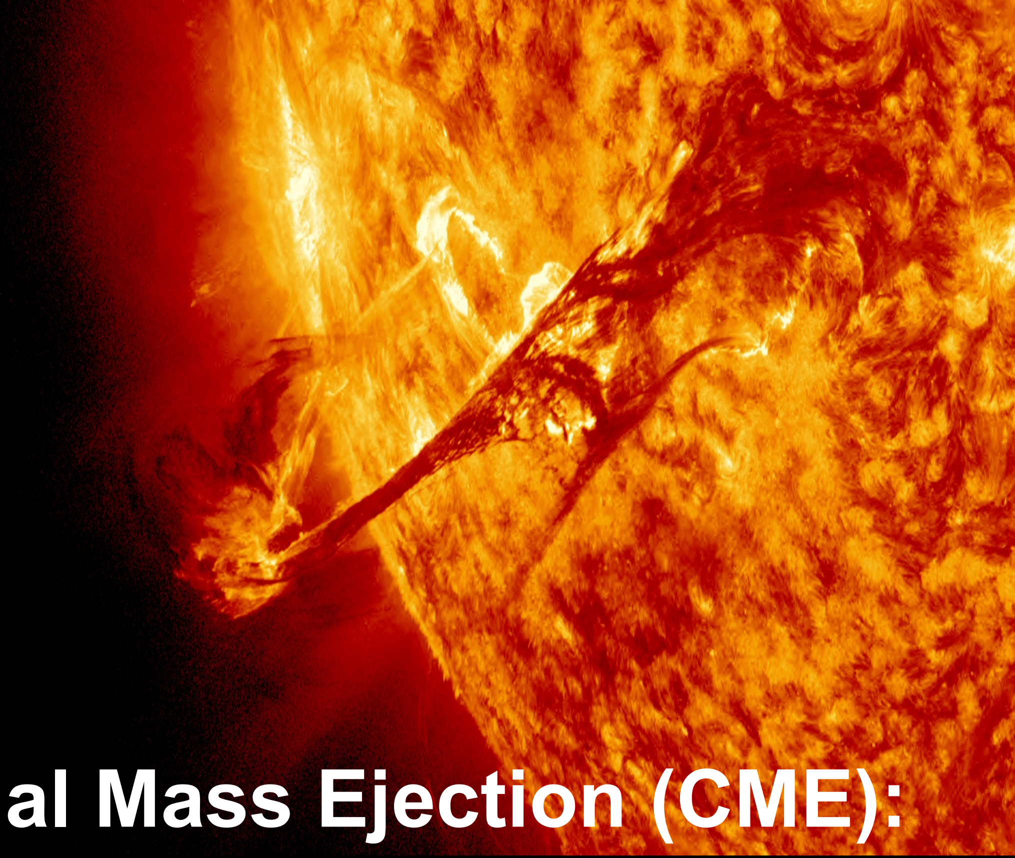


Image credit: NASA



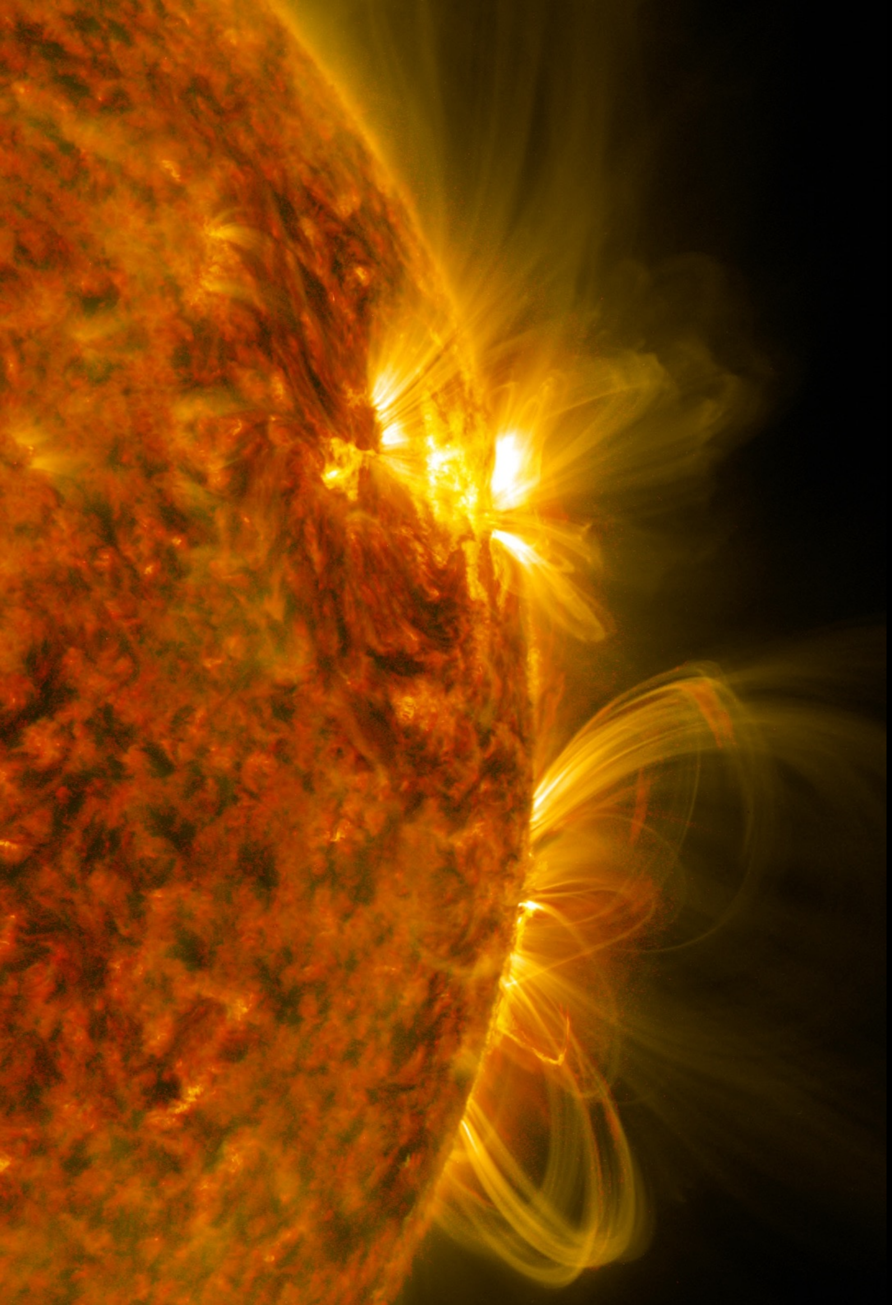
Solar flare:

- Sudden explosion of energy
- Release a lot of radiation reach to the Earth ~500 sec
- Often accompanied by a CME

Coronal Mass Ejection (CME):

- Sudden outflow of plasma
- Might reach to the Earth ~1-2 days
- Often accompanied by a flare

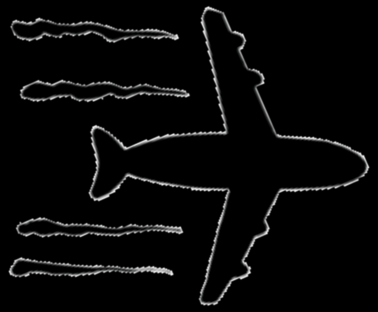
Solar flare classification



Sept. 10, 2017, X8.2-class solar flare observed by SDO. The video shows a blend of light from the 171- and 304-angstrom wavelengths. Image credit: SDO/NASA

- Flares produce electromagnetic radiation across the electromagnetic spectrum at all wavelengths, from radio waves to gamma rays
- Solar flares are classified according to their X-ray brightness, in the wavelength range 1 to 8 Angstroms
- Flares classes have names: A, B, C, M, and X, with A being the smallest and X being the largest
- Each category has nine subdivisions ranging from, e.g., C1 to C9, M1 to M9, and X1 to X9. These are logarithmic scales, much like the seismic Richter scale. So, an M flare is 10 times as strong as a C flare

Solar Wind



Boeing (747) cruise speed is 920 km/h

- Continuous stream of charge particles, mostly electrons and protons
- Average speed 400 (km/s) or 1,440,000 (km/h)
- **Fast solar wind (~750 km/s):** spews from coronal holes
- **Slow solar wind (~350 km/s):** origin is unknown, although in some references the origin of slow solar wind is considered to be ARs

Solar wind arrival time

- Let's consider the speed of the solar wind to be 400 km/s

- How long does it take that this solar wind reaches the Earth?

- The distance between the Sun and Earth is 1 Astronomical Unit (AU) ~ 150 million km

$$t = \frac{x}{V} \rightarrow$$

It takes ~ 104 hours

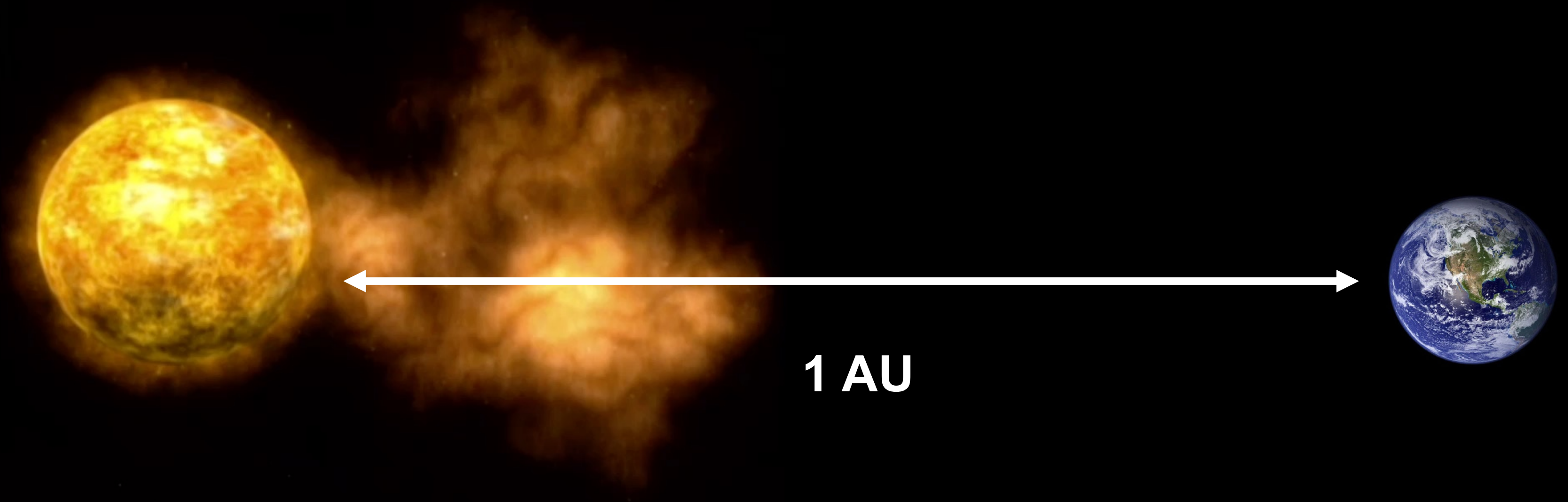
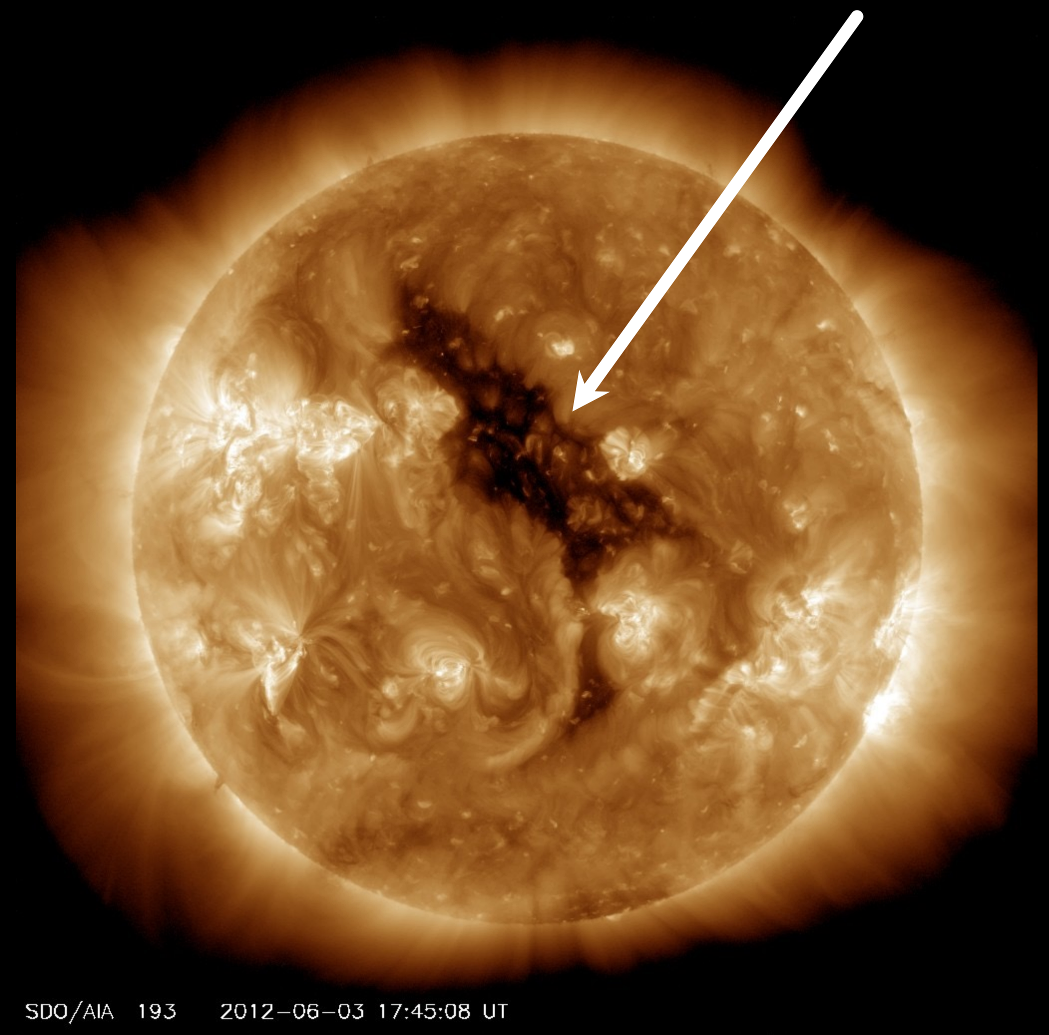


Image and animation credit: NASA/Goddard

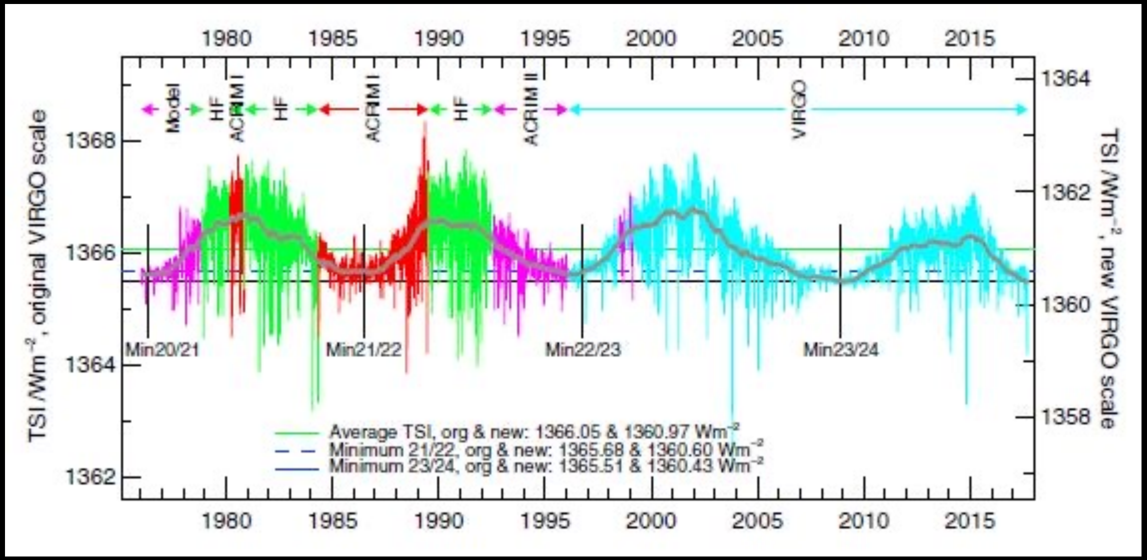
Coronal Holes



- Appear in the Corona
- Observed in the EUV and soft X-ray images
- Cooler and less dense than surrounding plasma
- Associated with open and unipolar magnetic field lines which allows the solar wind to escape more easily to the space
- Produces the fast solar winds, referred to as high-speed streams
- Develop at any time, but more common and persistent during solar minimum

Solar irradiance

- The amount of solar energy that strikes Earth's atmosphere is called total solar irradiance (TSI)
- TSI fluctuates by about 0.1 percent over the course of the sun's 11-year cycle
- Today, scientists are confident that the small variations in TSI associated with the eleven-year solar cycle cannot explain the intensity and speed of warming trends seen on Earth during the last century

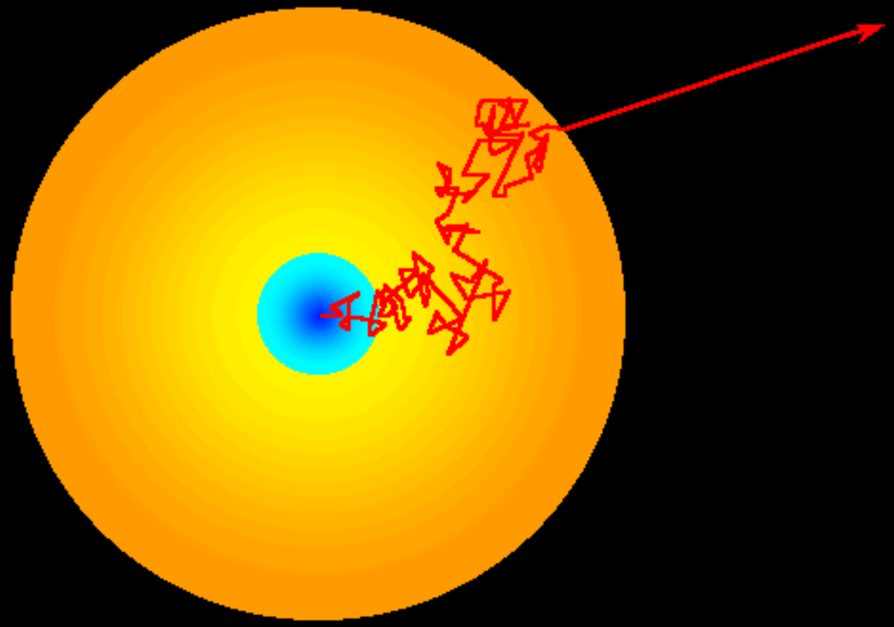


Composite daily values of the Sun's Total Solar Irradiance (TSI) from radiometers on different space platforms since November 1978: HF on Nimbus7, ACRIM 1 on SMM, ERBE on ERBS, ACRIM II on UARS, VIRGO on SOHO, and ACRIM III on ACRIM_Sat. The values of the average and the minima values are also given in the original VIRGO and new absolute VIRGO scales

credit: John Kennewell & Andrew McDonald

How long does it take for photons to travel from the Sun's core to the Earth?

- Photons travel at a speed of 300,000 km/s
- On the way out of the solar core, photons collide with other atoms, which changes their directions all the time, like a ball in a pin ball game
- Hence, it takes about 10,000 to 170,000 years for photons to travel from the core to the surface



Photons escape the sun's core through a series of random steps as they are absorbed and emitted by atoms along the way

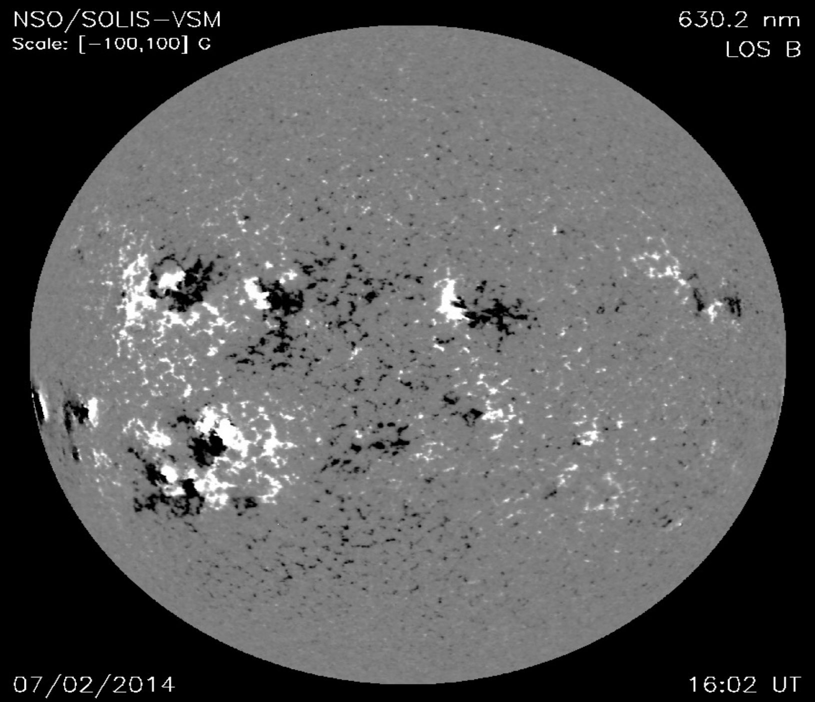
credit: Richard Pogge

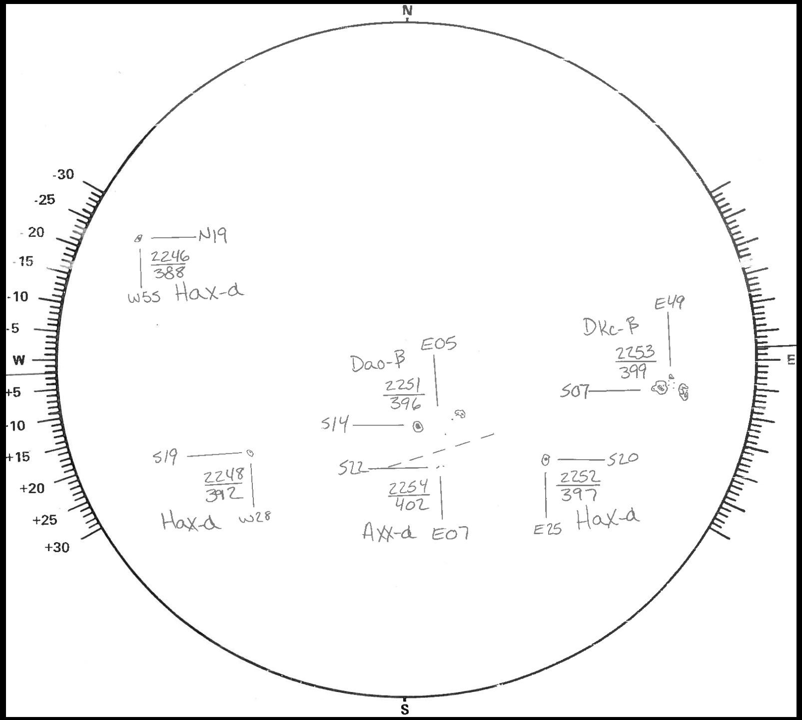
Solar Observation

Ground-based
Space-based

150-Foot Solar Tower
at
Mount Wilson Observatory

Solar Observing Optical Network
at
Holloman Air force base





Magnetogram

07.02.2014

Iron spectral line at 8468 Å

Sunspot Drawing

01.01.2015

Hα spectral line at 6563 Å

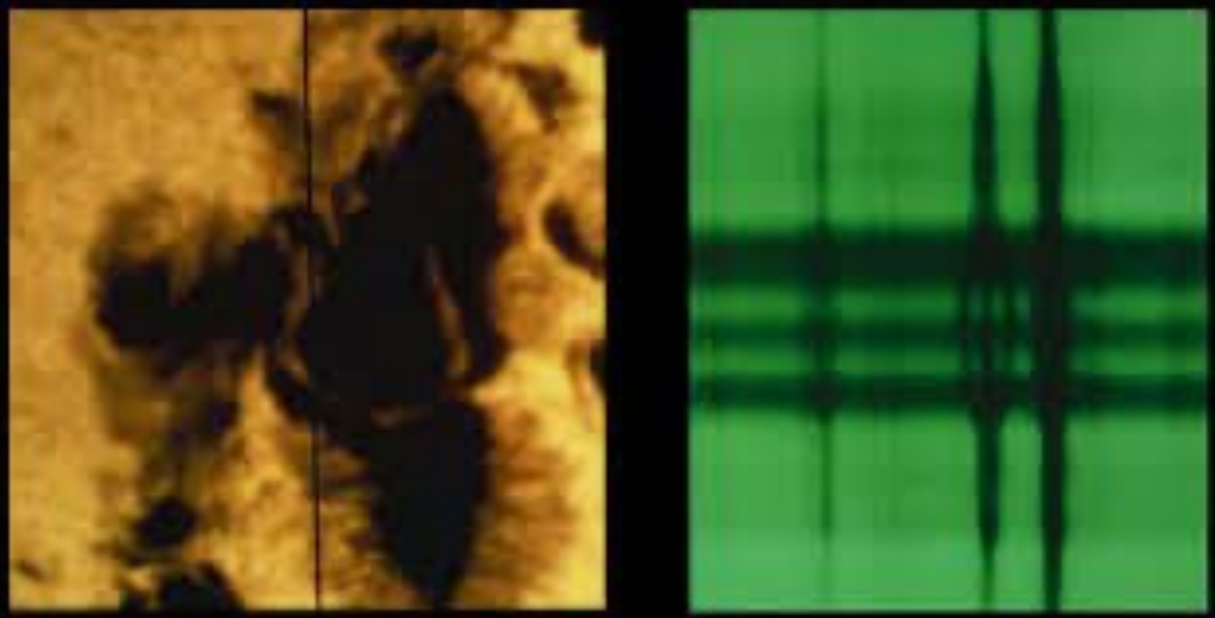
Zeeman effect

- In the presence of a magnetic field, the energy levels of atoms (and ions and molecules) are split into more than one level

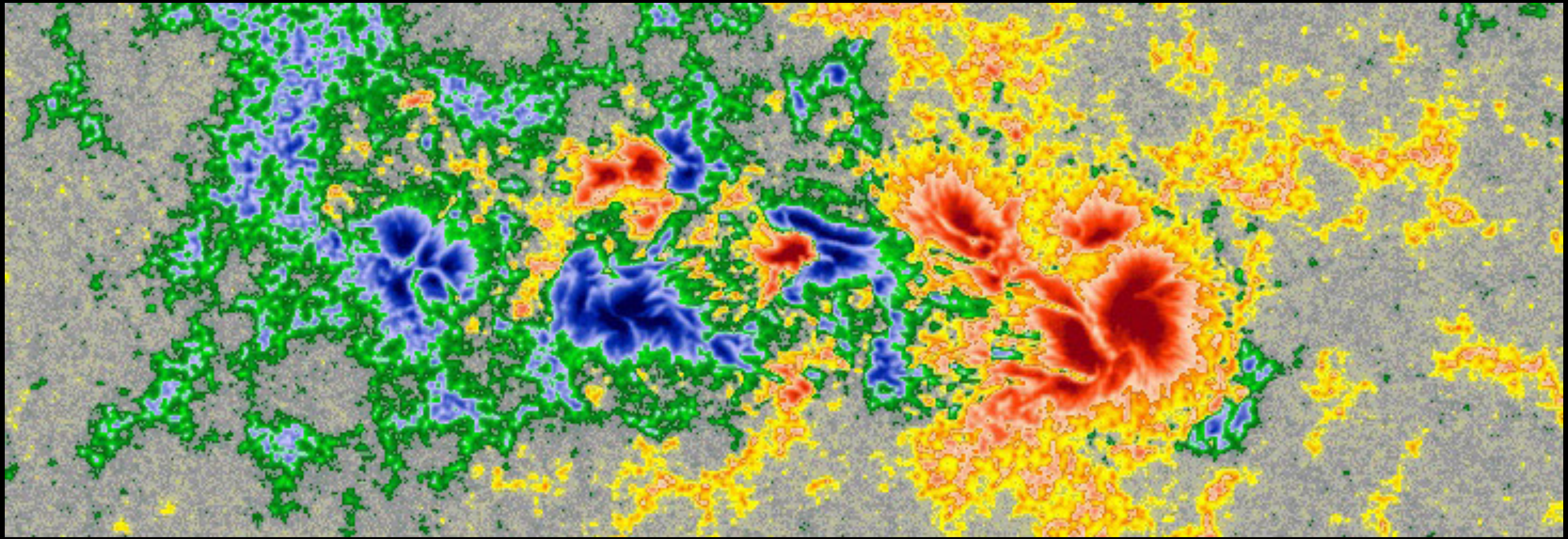
- This causes spectral lines to also be split into more than one line, with the amount of splitting proportional to the strength of the magnetic field

- This effect is called the Zeeman Effect

- A magnetograph is used to measure sunspot's magnetic fields strength and direction

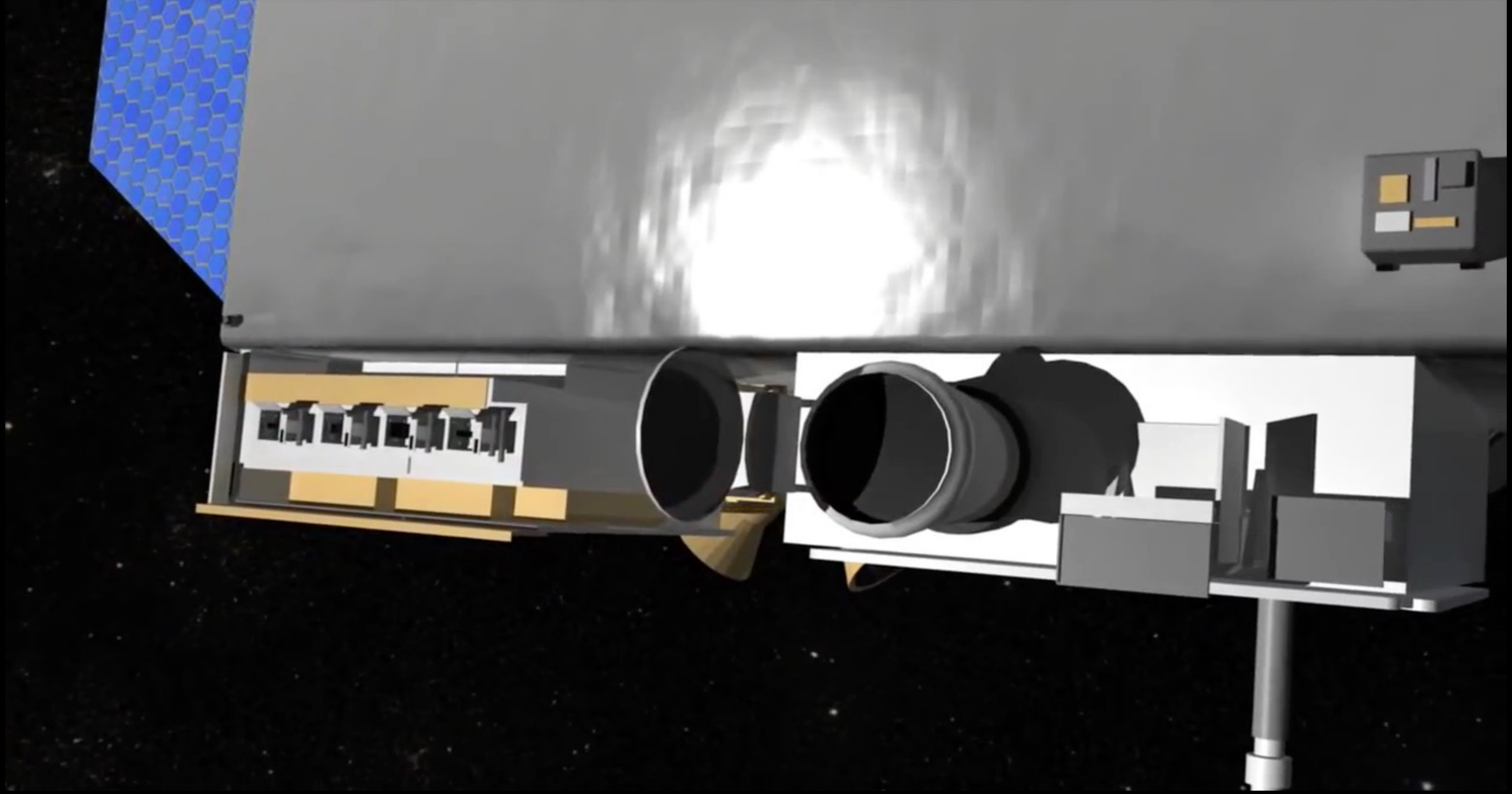


Observation of Zeeman effect in a sunspot



A magnetogram showing an active region. The red color indicates sunspots a negative polarity and the blue color indicates areas with positive polarity sunspots.

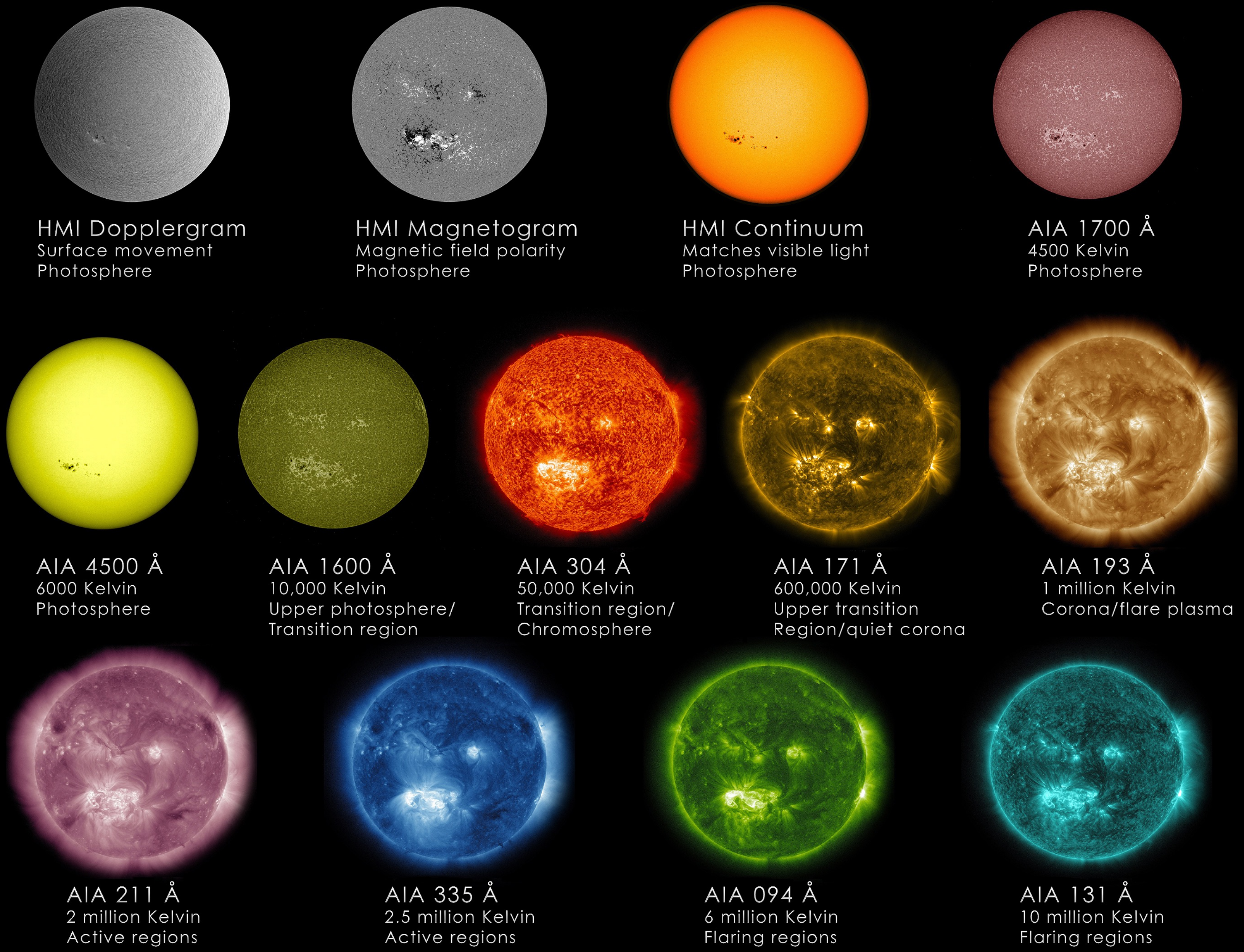
Credit: SDO/NASA



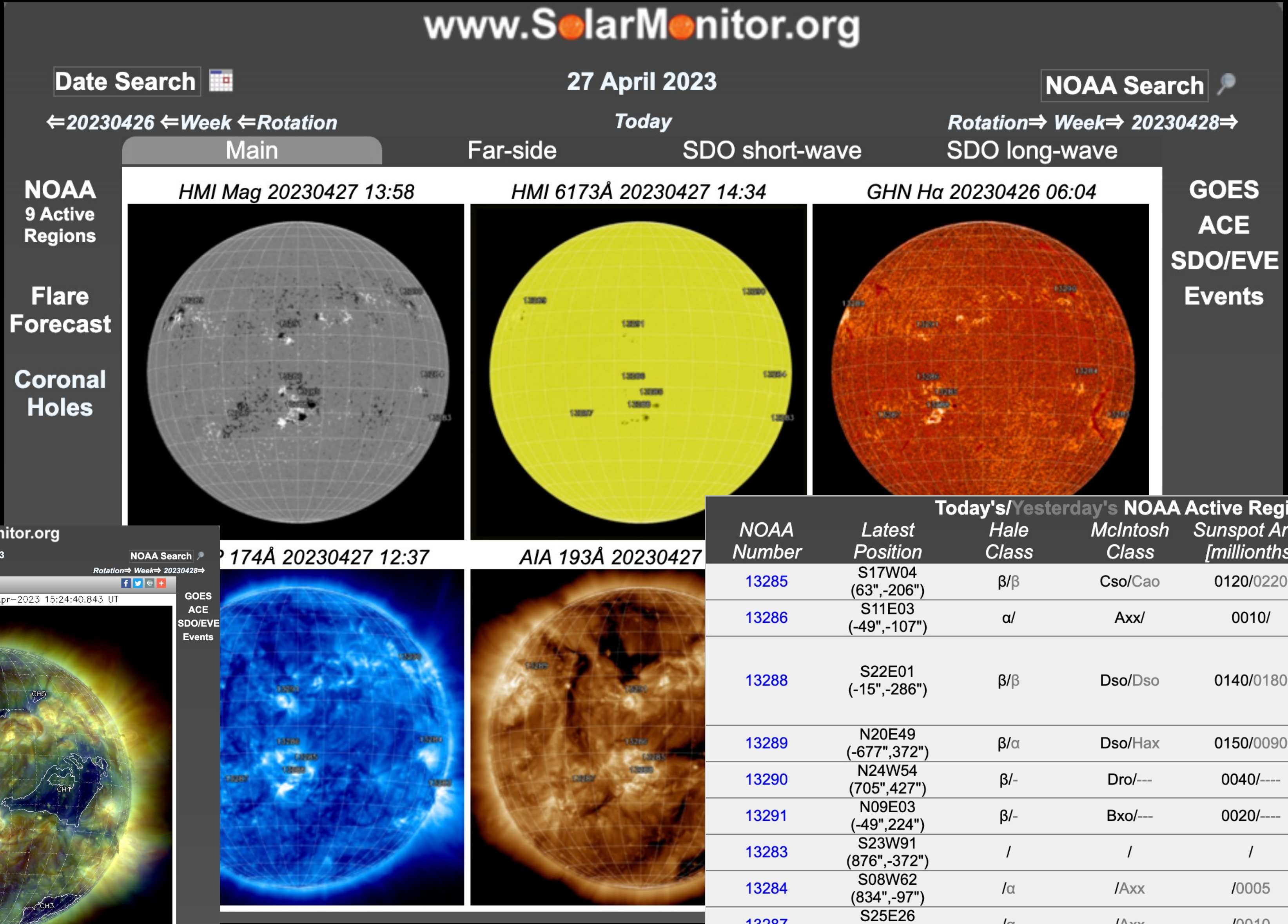
Near-Earth Space Observation

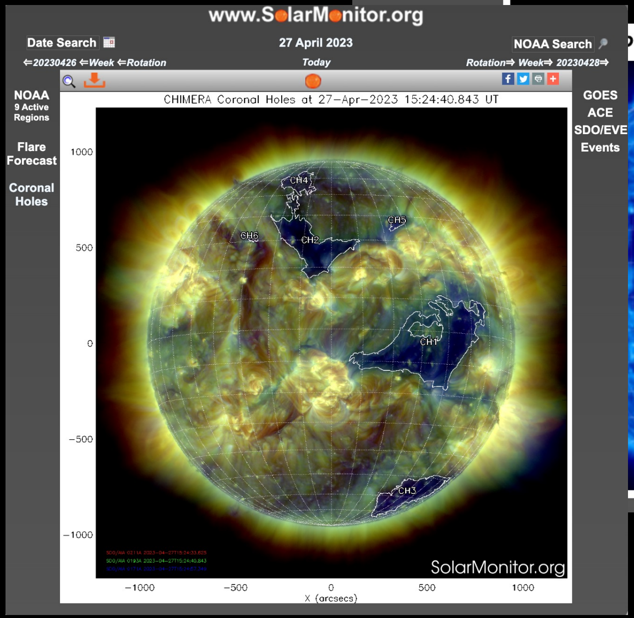
Solar Dynamic Observatory (SDO) Satellite

- Launched in : February 2010 Orbit: ~35,000 km
- HMI: Studies oscillation and magnetic field at photosphere
- AIA: Studies the sun in multiple wavelength (white light, Seven EUV & two UV)
- EVE: Studies solar EUV irradiance



These images show the different ways SDO observes the Sun using the HMI and the AIA instruments onboard the spacecraft
I credit: SDO/NASA





Today's/Yesterday's NOAA Active Regions

NOAA Number	Latest Position	Hale Class	McIntosh Class	Sunspot Area [millionths]	Number of Spots	Recent Flares
13285	S17W04 (63",-206")	β/β	Cso/Cao	0120/0220	04/05	- / C2.7(23:57)
13286	S11E03 (-49",-107")	α/	Axx/	0010/	02/	-
13288	S22E01 (-15",-286")	β/β	Dso/Dso	0140/0180	05/04	M1.8(11:04) C1.4(10:30) C1.2(09:37) C1.0(09:14) C1.2(08:42) / -
13289	N20E49 (-677",372")	β/α	Dso/Hax	0150/0090	03/02	-
13290	N24W54 (705",427")	β/-	Dro/---	0040/----	03/--	-
13291	N09E03 (-49",224")	β/-	Bxo/---	0020/----	04/--	-
13283	S23W91 (876",-372")	/	/	/	/	-
13284	S08W62 (834",-97")	/α	/Axx	/0005	/01	-
13287	S25E26 (-380",-341")	/α	/Axx	/0010	/01	-

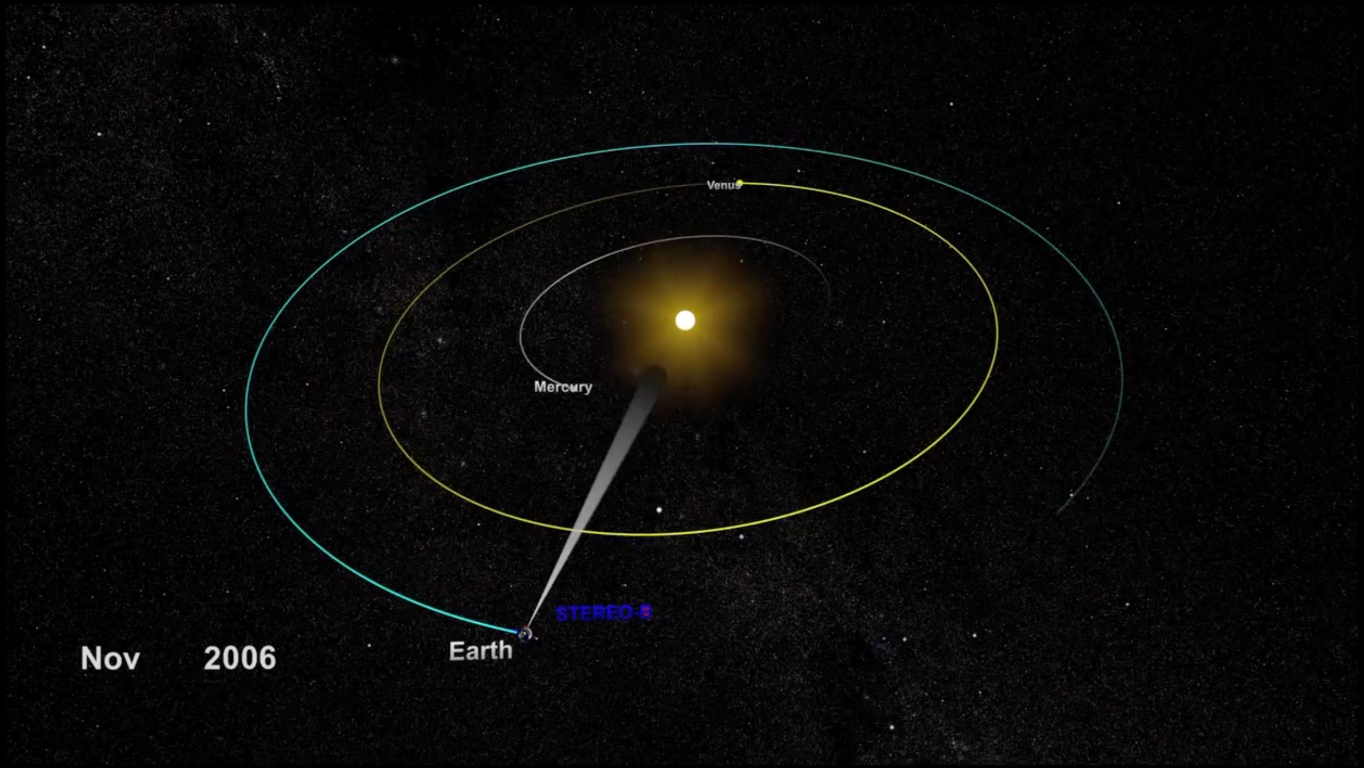
Class (HH:MM) -Today
Class (HH:MM) -Yesterday

https://www.solarmonitor.org/index.php

https://www.swpc.noaa.gov/products/real-time-solar-wind

Twin STEREO A & B

- Two nearly identical spacecraft were launched in 2006
- Studied solar storms
- STEREO A remains active
- STEREO B's mission ended in Oct 2018
- Provided the first-ever 3D view of the Sun's surface
- In 2012, STEREO captured data on an extreme solar storm more powerful than anything seen in the past 150 years



Over the course of its first five years, the orbits of the two STEREO spacecraft have caused them to separate to opposite sides of the sun

credit: NASA

Observations at L1:

- Lagrange points: Zones in space where the gravitational and centrifugal force of two bodies balance out
- Lagrange points can be used by spacecraft to reduce fuel consumption needed to remain in position
- L1 ~1.5 million km
- Spacecraft in L1: SOHO DSCOVR, ACE, Wind

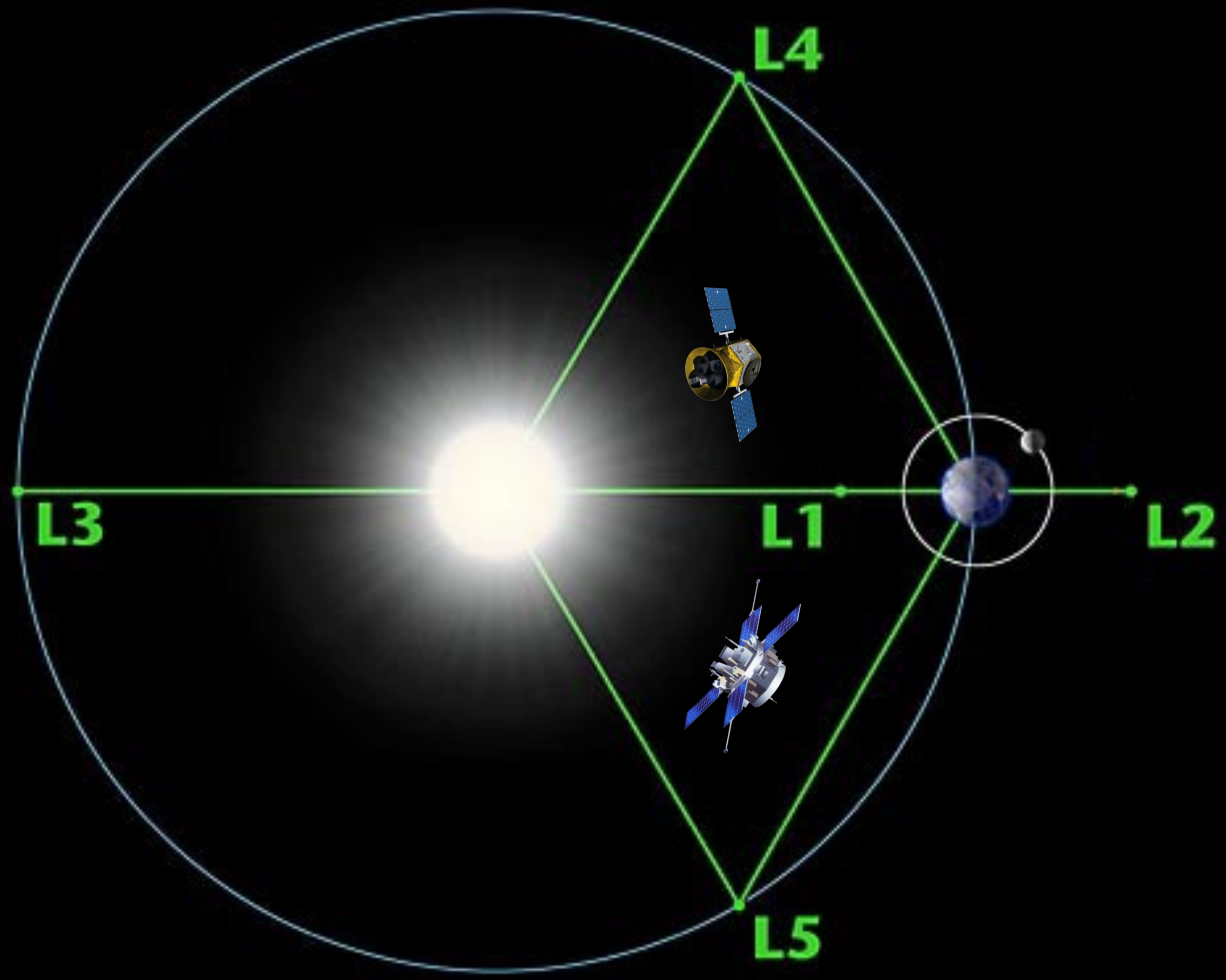
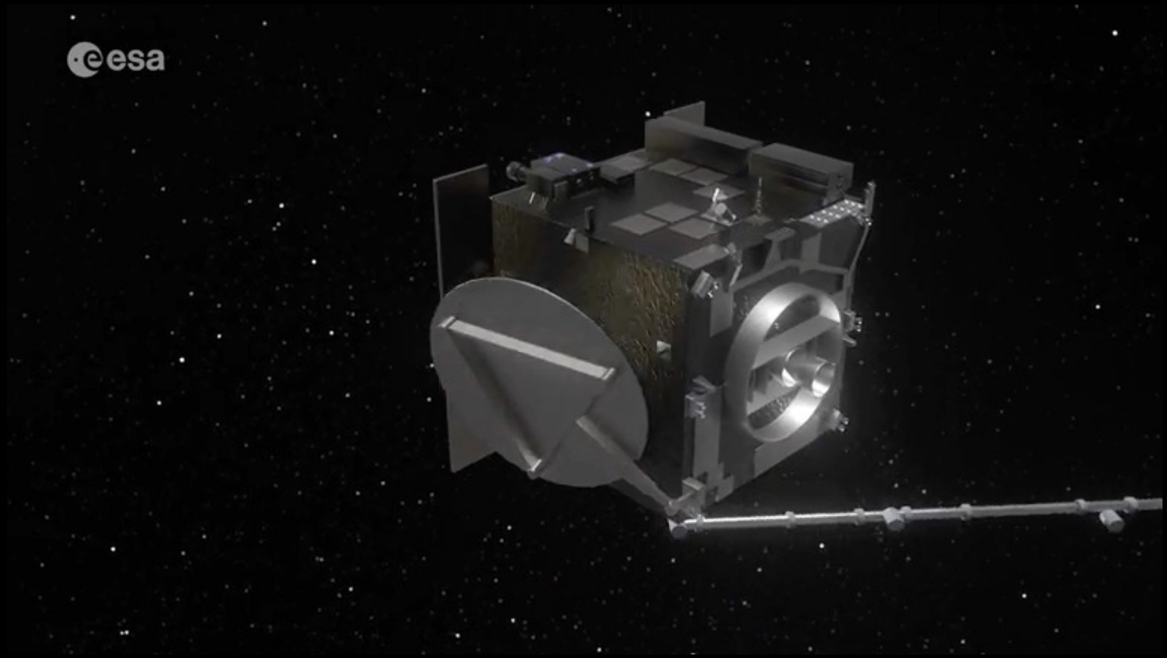


Image credit: NASA/WMAP Science Team

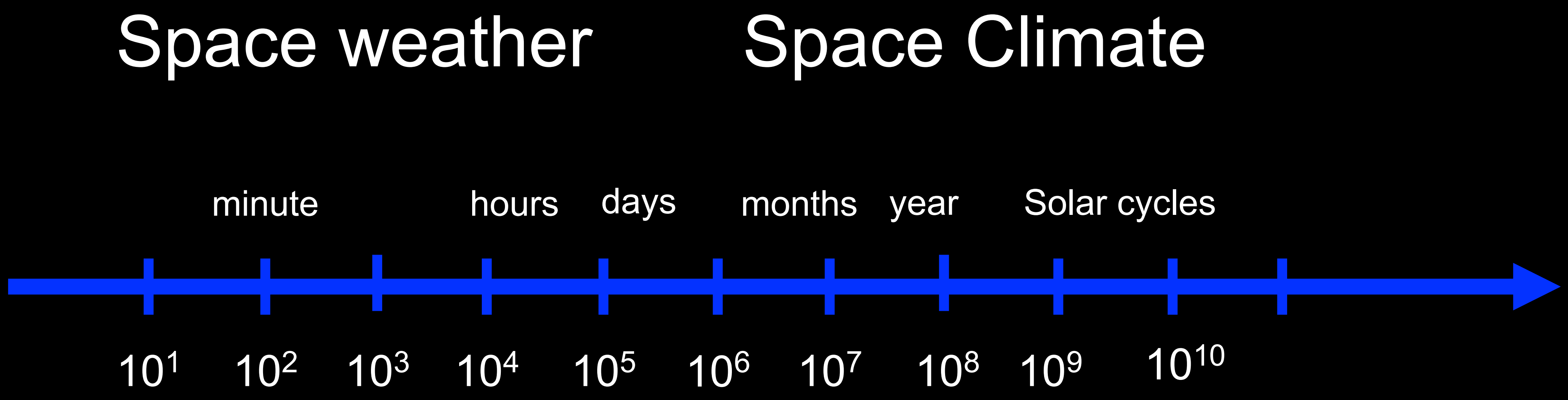
ESA Vigil mission

- Vigil Will be launched in mid 2020s
- Monitoring space weather from L5 (400,000 km from Earth)
- L5 is an ideal location for monitoring for solar events such as CMEs from the side of the Sun
- Vigil will give us time to protect at risk infrastructure on Earth, or life in space



Video credit: ESA

Space Weather
vs
Space climate



Space weather
Space Climate
minute
hours
days
months
year
Solar cycles
10^1
10^2
10^3
10^4
10^5
10^6
10^7
10^8
10^9
10^{10}

Space Climate

Denotes the long-term variations in solar activity, as well as the related long-term changes in the heliosphere, the solar wind and heliospheric magnetic field, and their effects in the near – Earth environment

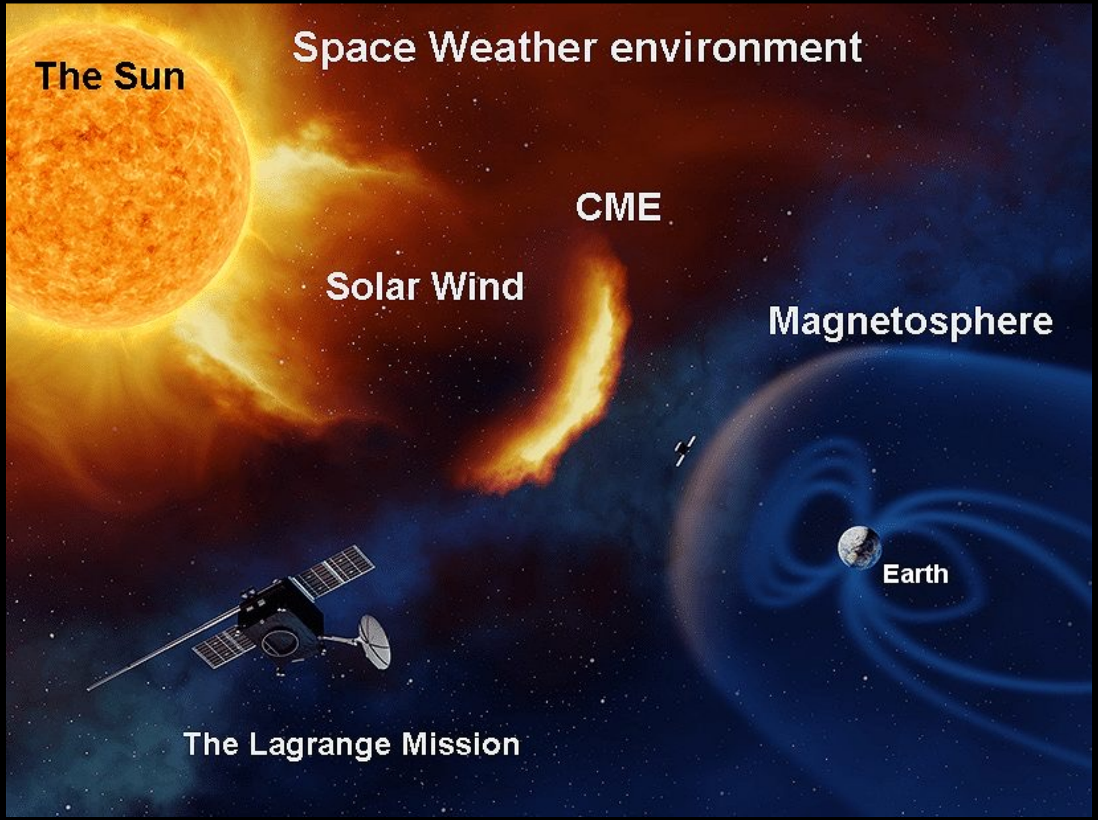


Image credit: ESA

Space Weather

The physical and phenomenological state of natural space environments. The associated disipline aims through observation, monitoring, analysis and modeling, at understandng and predictiong the state of the Sun, the interplanetary and planetary environments, and the solar and non-solar driven perturbations that affect them; and also at forecasting and nowcasting the possible impacts on biological and technological systems

Sun-Earth
Coupling

Interplanetary Magnetic Field (IMF)

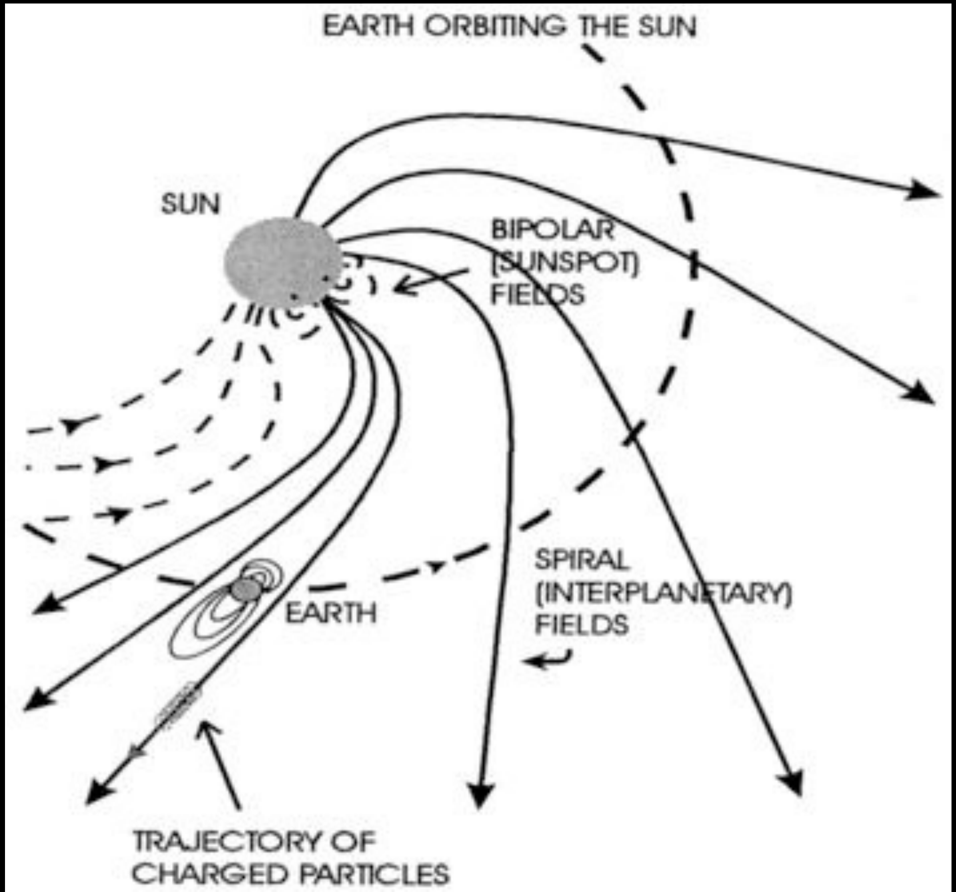
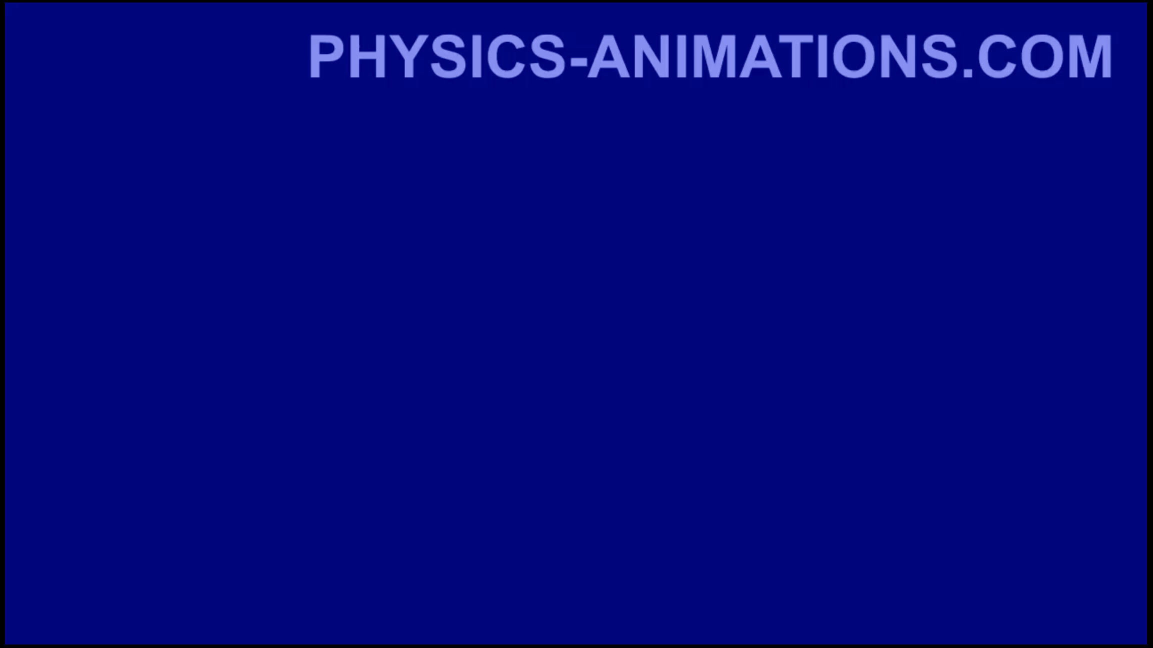


Image credit: NASA/JPL

- IMF: The component of the solar magnetic field that is dragged out from the solar corona by the solar wind into interplanetary space
- Note that the Sun rotates aroundits own axis
- As the Sun rotates, its magnetic field twists into an Archimedean spiral. This phenomenon is often called the Parker spiral

Basics of shock waves



- Let’s imagine an airplane flying with subsonic velocity. So, the wavelength of the sound in front of the airplane will be shorter than the wavelength of the sound behind it

- But if the airplane moves with supersonic velocity, then the sound waves will travel slower than the source, and will superpose with each other behind it, forming a conic surface of high pressure, which is called shock wave

Magnetosphere

- When you look at the Earth from space, it looks like it is floating in a black void
- The Earth's core is surrounded by an ocean of liquid metal. The flow of this material creates electric currents, which in turn creates the magnetic field
- The Earth is surrounded by a complex system formed by the interaction of the solar wind with the Earth's magnetic field
- The solar wind compresses the dayside of the magnetosphere to a distance of ~ 10 $R_\oplus$ and its nightside to possibly 1000 $R_\oplus$
- The magnetosphere is highly dynamic

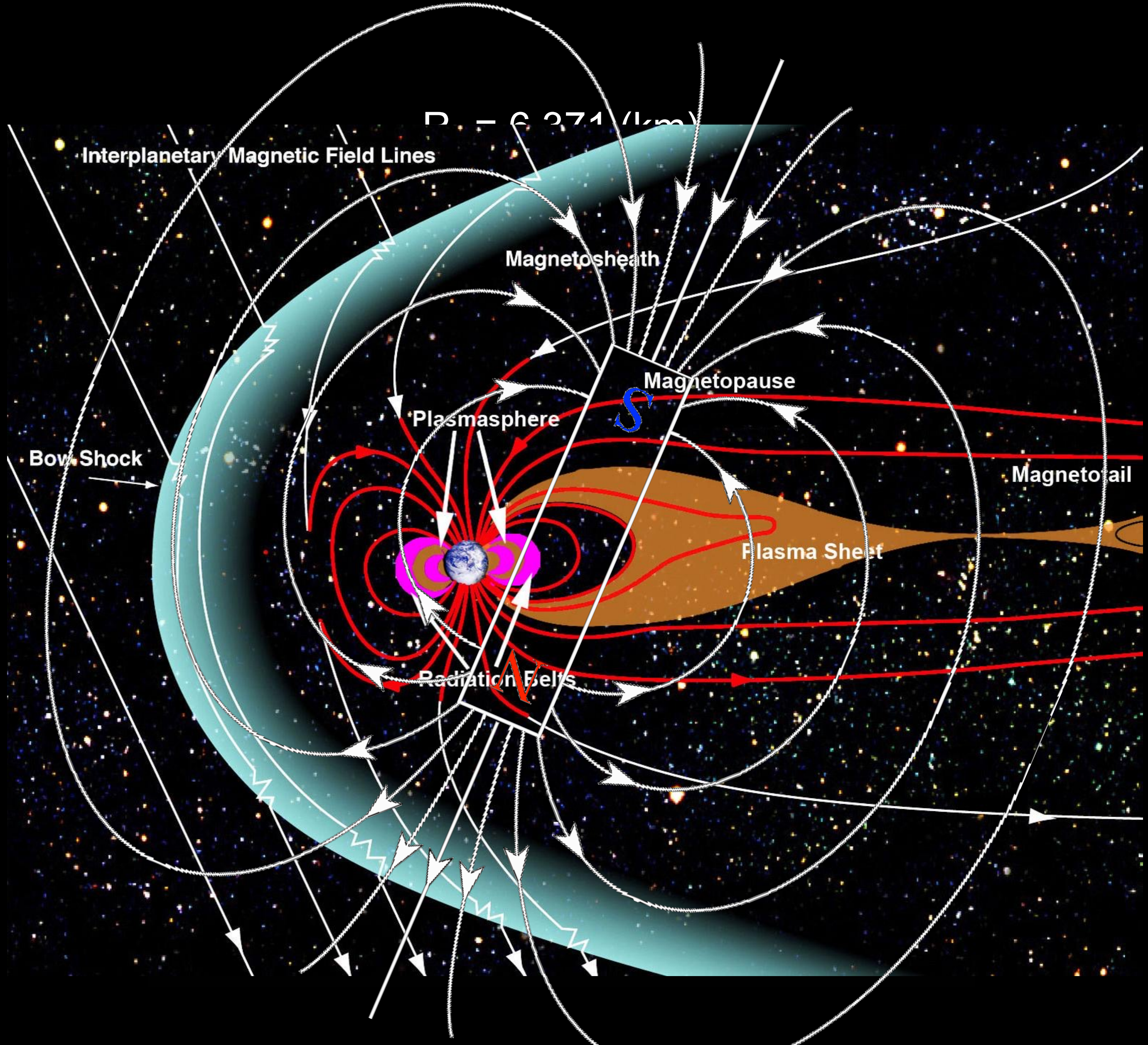


Image credit: NASA

Bow shock

$R_{\oplus}$ = 6,371 (km)

- A shock wave on the dayside of the magnetosphere
- Formed by interaction between supersonic solar wind with the Earth's magnetic field
- Most of the solar wind particles are heated and slowed at the bow shock and detour around the Earth
- It is located ~15 $R_{\oplus}$

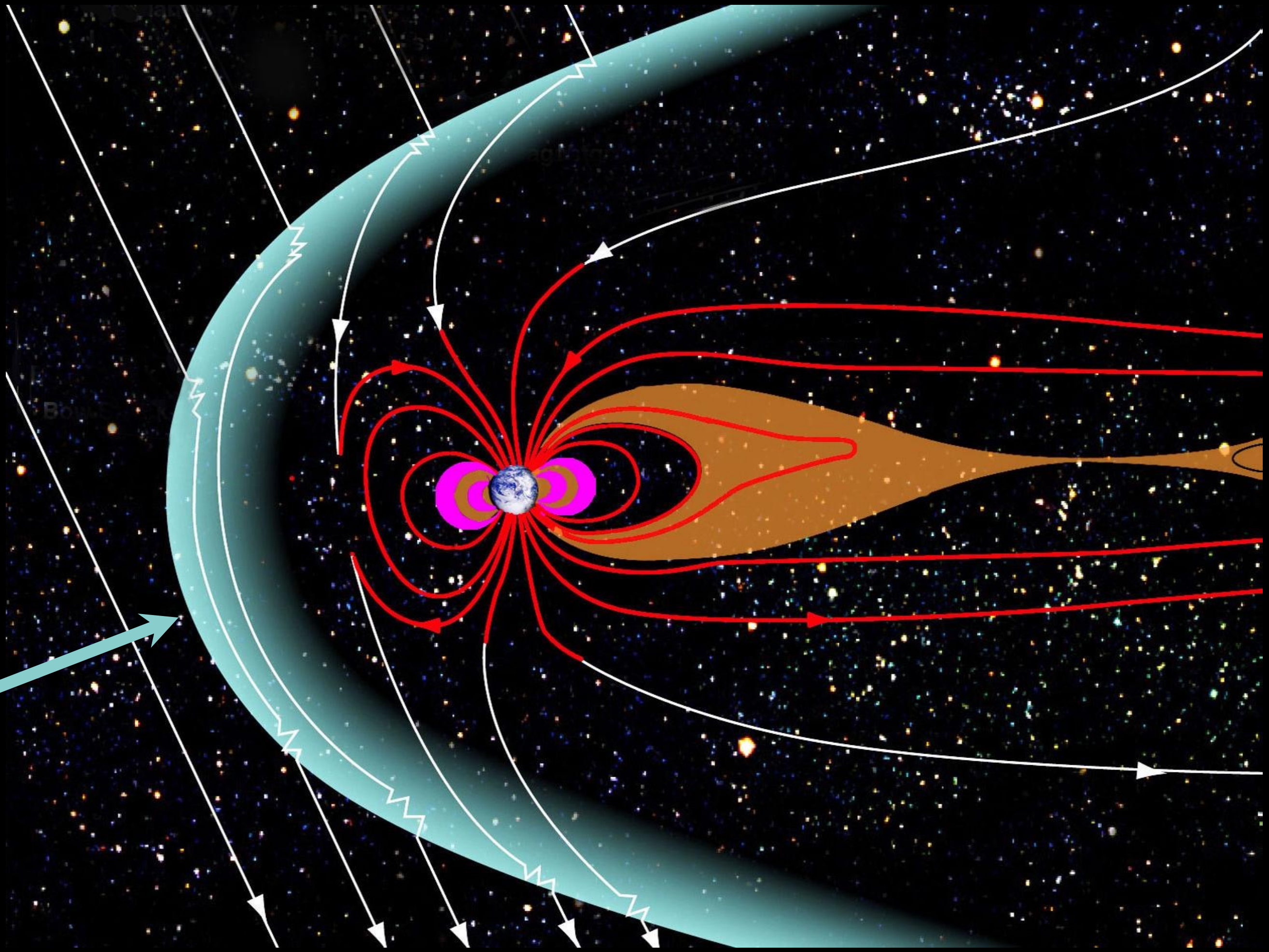


Image credit: NASA/Goddard

Magnetopause

- Magnetopause is the boundary between the magnetosphere and the solar wind determined by the pressure balance between the solar wind one one side and the magnetic pressure of the planetary filed on the other side

- As the solar wind pressure increases and decreases, the magnetopause moves inward and outward in response

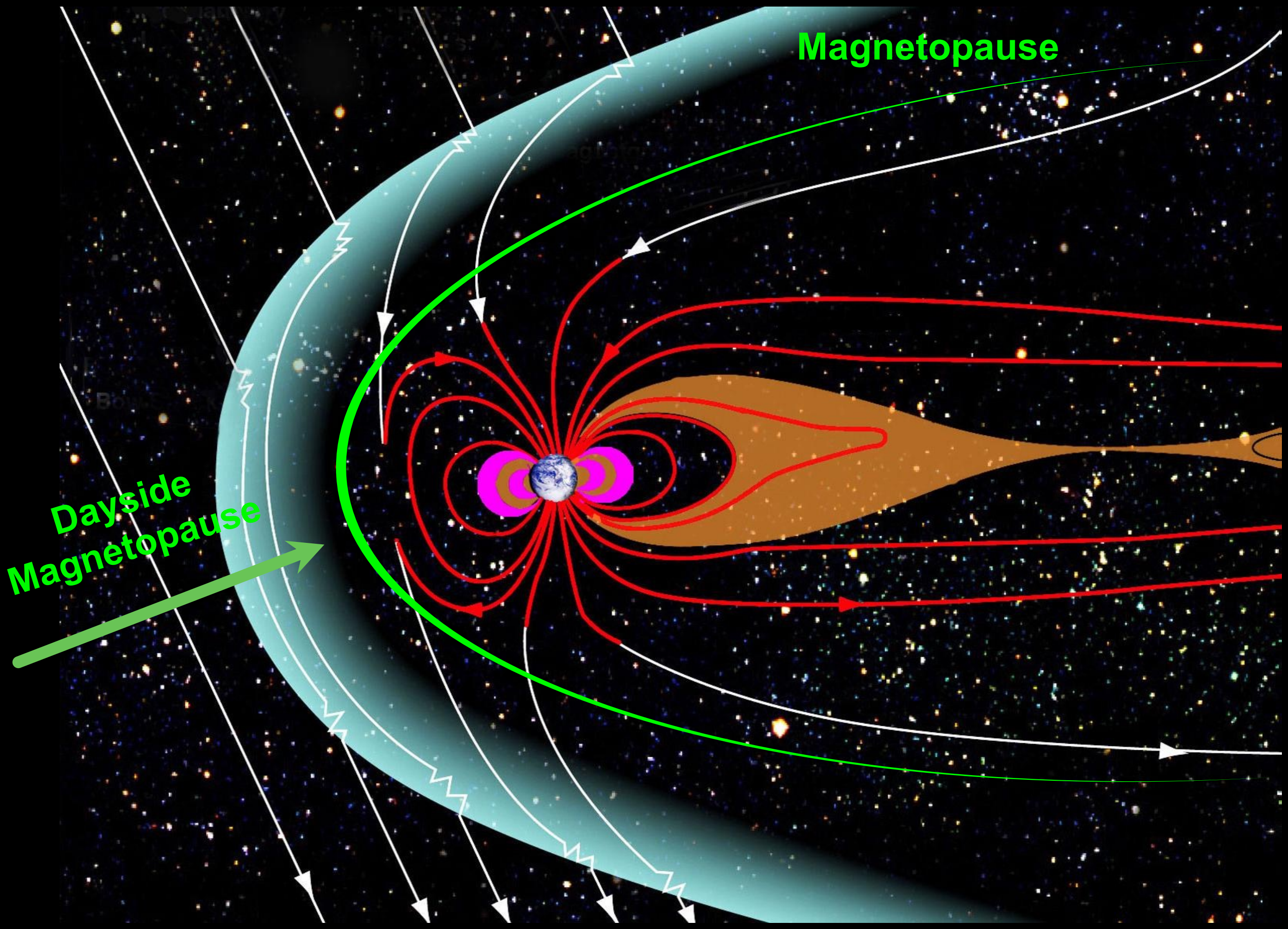


Image credit: NASA/Goddard

Magnetopause

- To understand the behavior of the magnetopause we need consider three types of pressures
- Total pressure = thermal + dynamic + magnetic

$$P = n\,k_B\,T_i \;+\; n\,m_i\,V^2 \;+\; \frac{B^2}{2\mu_0}\;,\quad k_B \sim 10^{-23}$$

Parameters	Solar Wind	Magnetosphere
$k_B T$ [keV]	0.01	5
n [cm^{-3}]	5	0.1
V [km/s]	400	50
B [nT]	5	55
P_{TH} [nPa]	**0.01**	**0.08**
P_{DYN} [nPa]	**1.3**	**0.0004**
P_B [nPa]	**0.01**	**1.2**

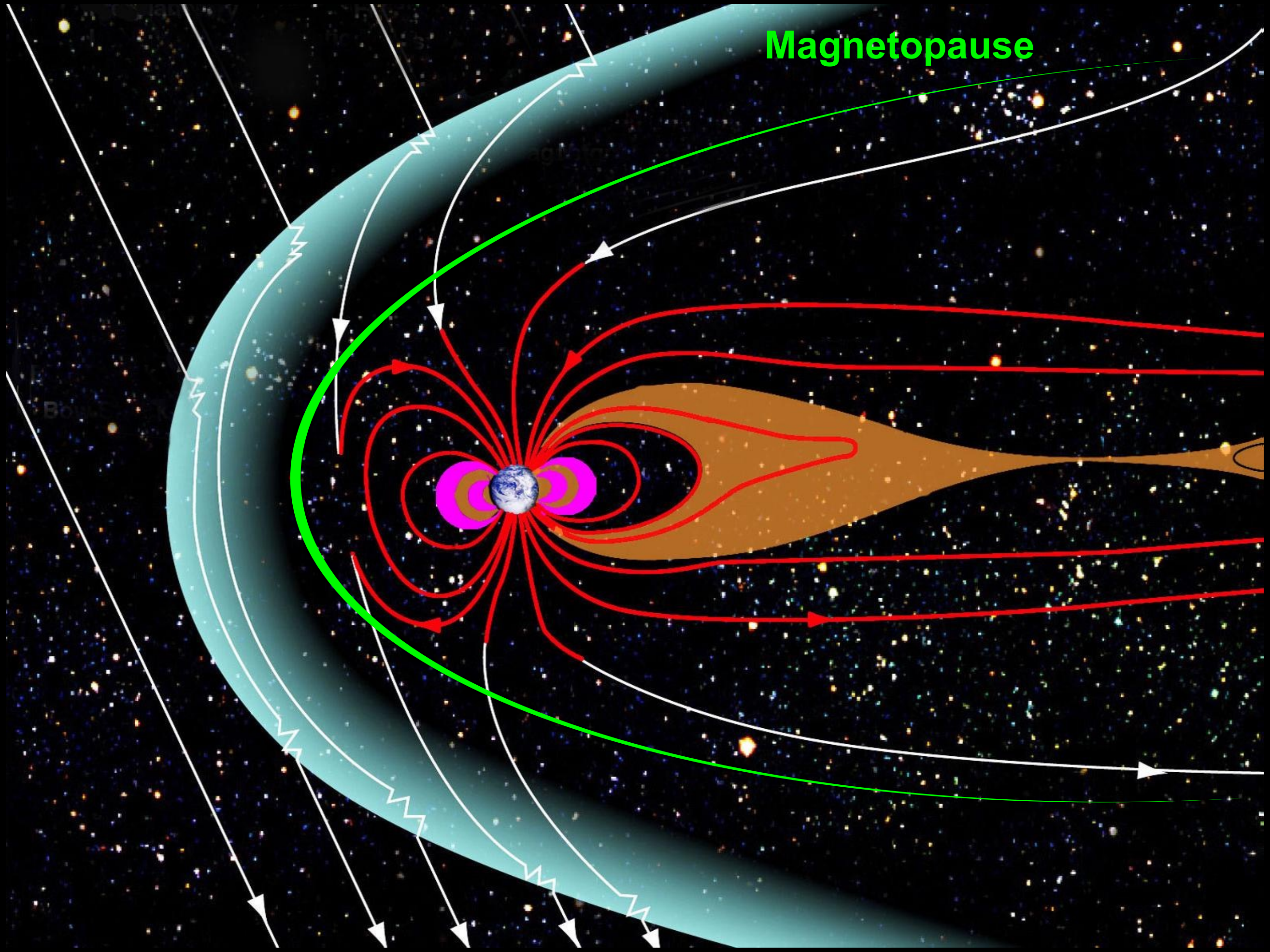
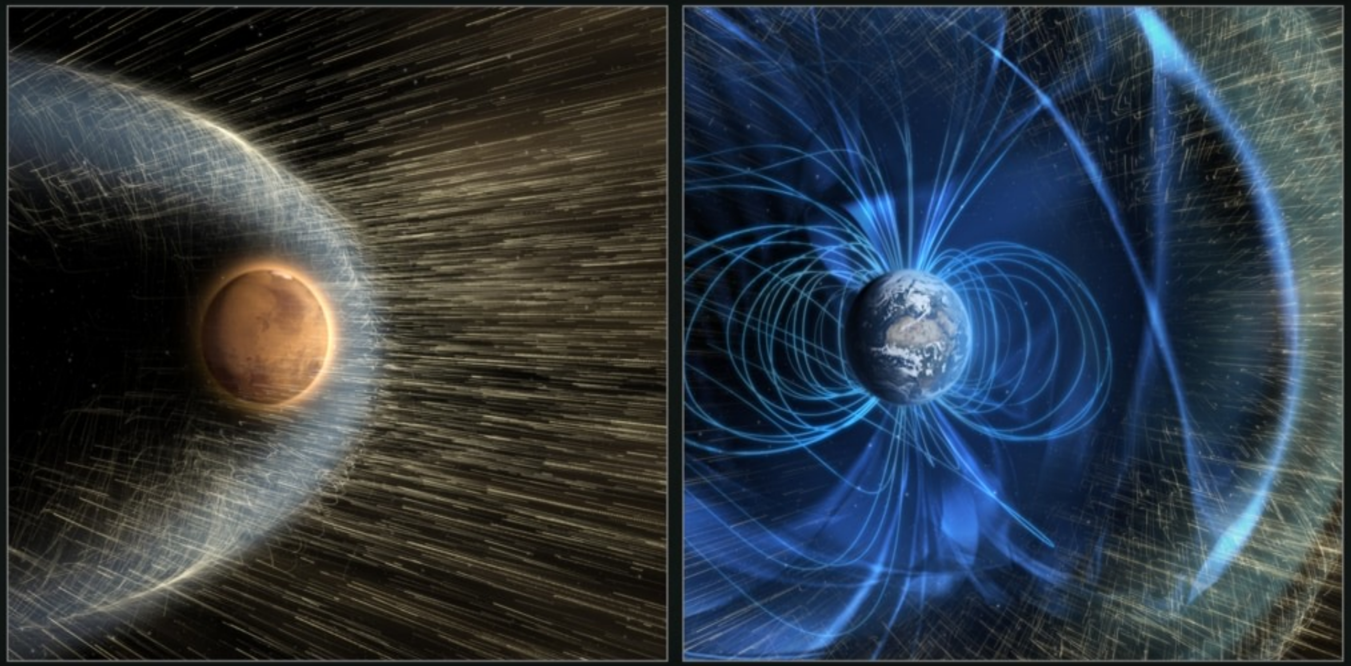


Image credit: NASA/Goddard

Does Mars have a Magnetosphere?

- Mars does not presently have a global magnetic field but had one early in its life, similar to that of Earth
- Solar wind interacts with the Mars upper atmosphere, which leads to formation of the induced magnetosphere from magnetic field tubes of the solar wind
- The absence of a global magnetic field for billions of years has contributed to the erosion of Mars atmosphere by the solar wind and the loss of water



Planet Mars
Credit: NASA/JPL

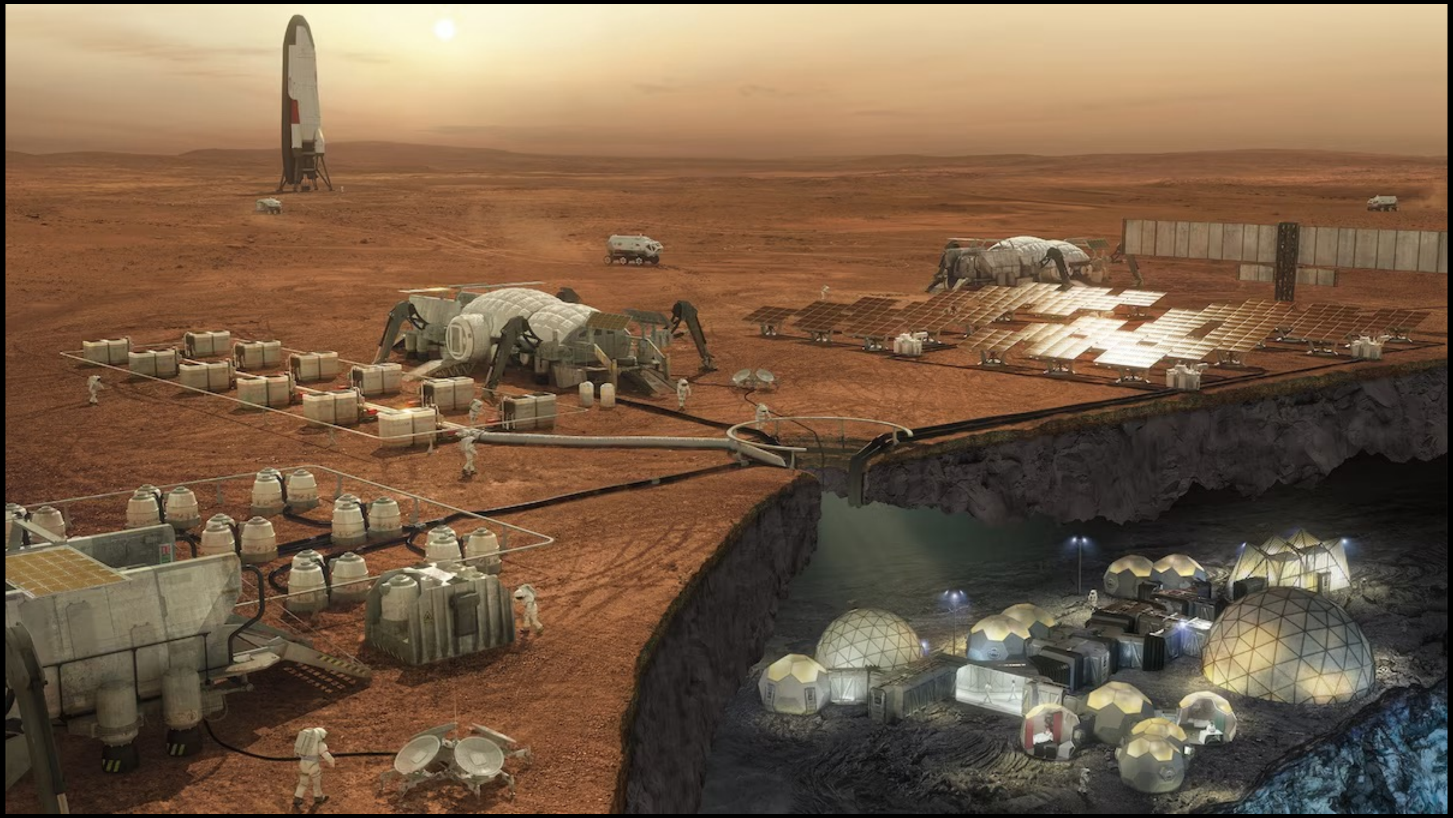
Right: Interaction between Earth's magnetic field and solar wind
Left: Interaction between Mars atmosphere and solar wind
Credit: NASA

Colonization of Mars

- Mars does not have a global magnetic field, and this means on the Martian surface we will not be protected by a magnetosphere

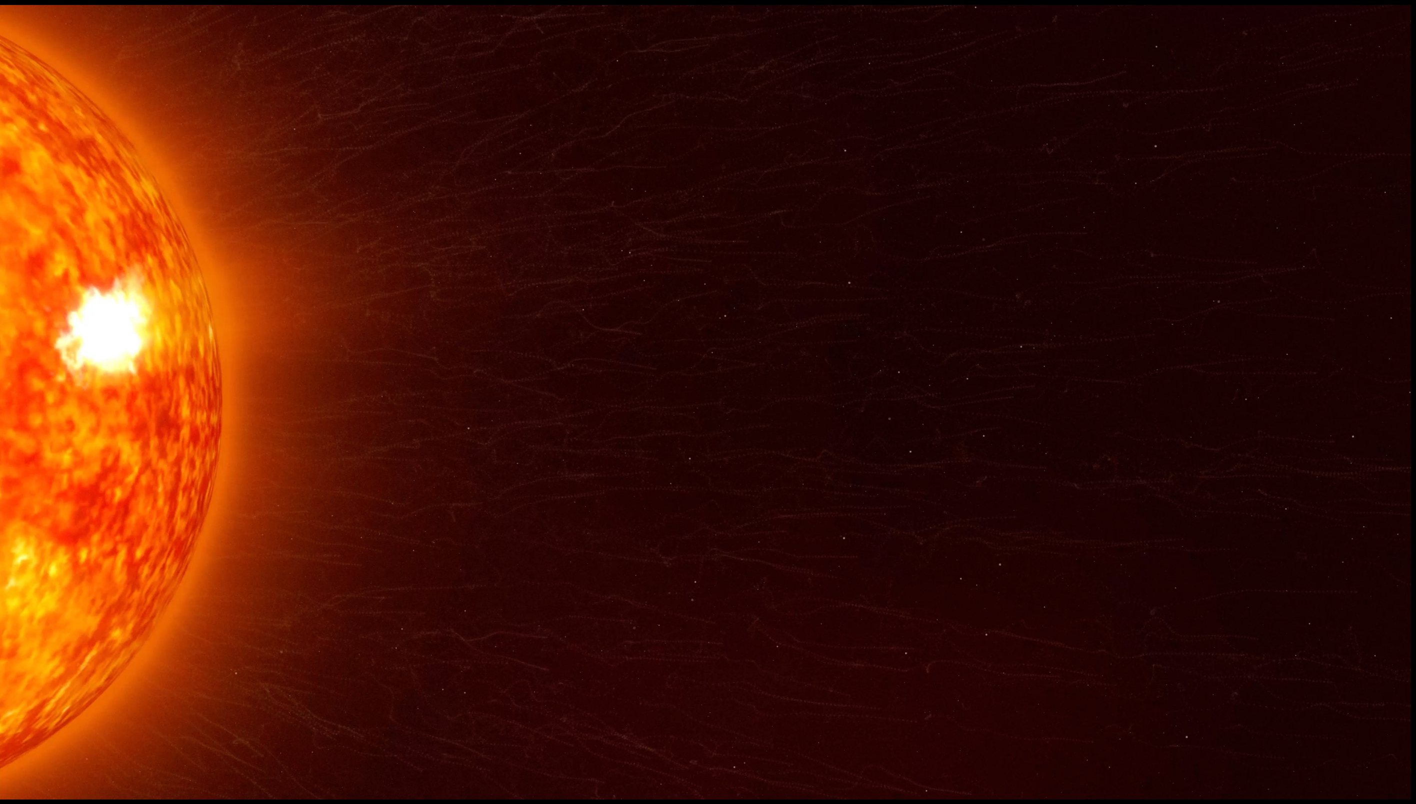
- One of the biggest challenges when it comes to creating settlements on other planets is building a safe space to live

- Martian caves could be turned into well-protected habitats. Their roofs could possibly shield us against the harmful cosmic and solar radiation



Mars colonization
Credit: National Geography

Magnetospheres of Our Solar system



Animation credit: NASA GSFC/CIL/Bailee DesRocher

- Mercury, Earth, Jupiter, Saturn, Uranus, and Neptune each have an intrinsic magnetosphere due to their internal magnetic fields

- Mars and Venus lack a global magnetic field, and they only have induced magnetospheres formed by the solar wind

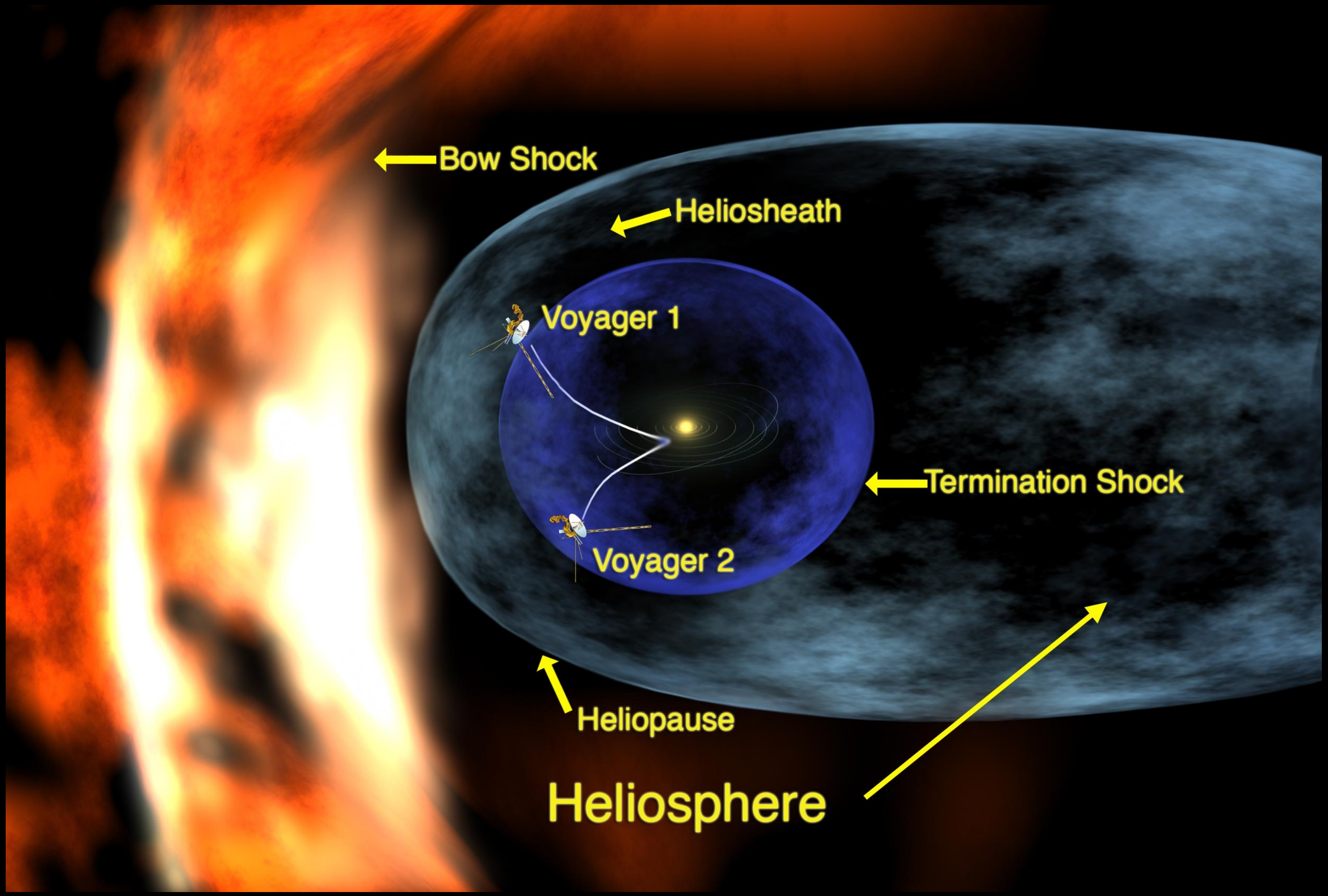


Image credit: NASA/Goddard/Walt Feimer

Heliosphere

- The sun constantly sends out solar wind, which travels past all the planets to some three times the distance to Pluto before being impeded by the interstellar medium
- This forms a giant bubble around the sun and its planets, known as the heliosphere

Radiation belts

- Donut-shaped regions encircling Earth
- High-energy particles, mostly electrons and ions, are trapped by Earth’s magnetic field in these regions
- **Inner belt:** corotates with the Earth about 650 to 9,660 km. proton energy range: 100 keV -100 MeV
- **Outer belt:** Extends on to the magnetopause on the sunward and to about 6 $R_{\oplus}$. Proton energy range: 0.1 to 10 MeV

$R_{\oplus}$= 6,371

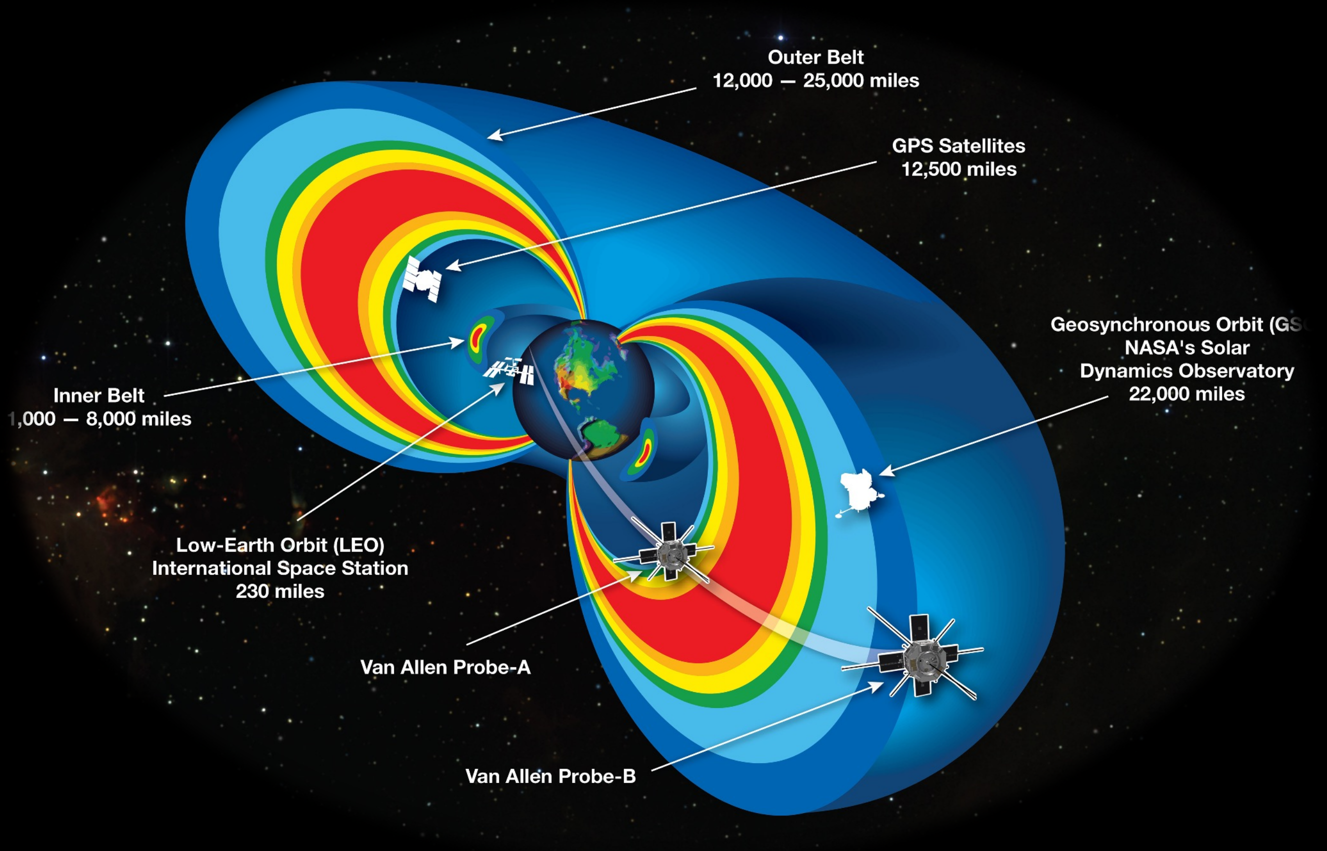


Image credit: NASA


Aurora
Illuminating
Of the Sun-Earth
Connection

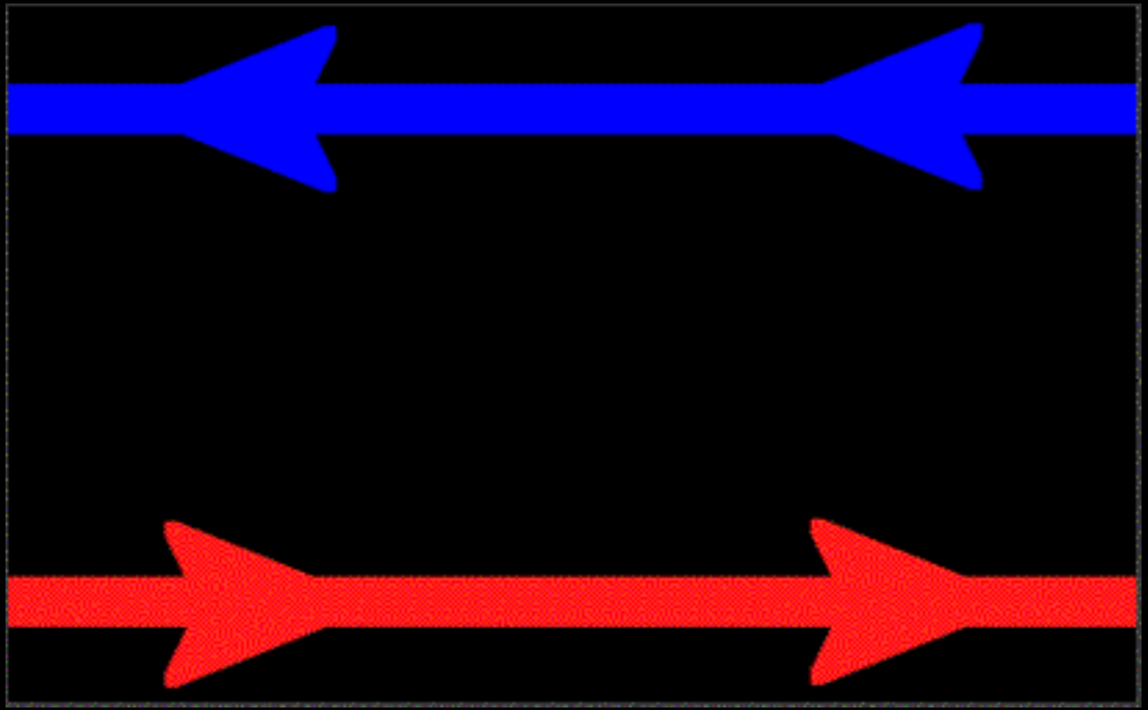
Magnetic Reconnection

- In a plasma, during magnetic reconnection, magnetic field lines of opposite direction break and then reconnect, forming an X-line magnetic topology

- The newly reconnected field lines accelerate the plasma away from the X-line

- Magnetic energy converts to kinetic and thermal energy and accelerates particles

-



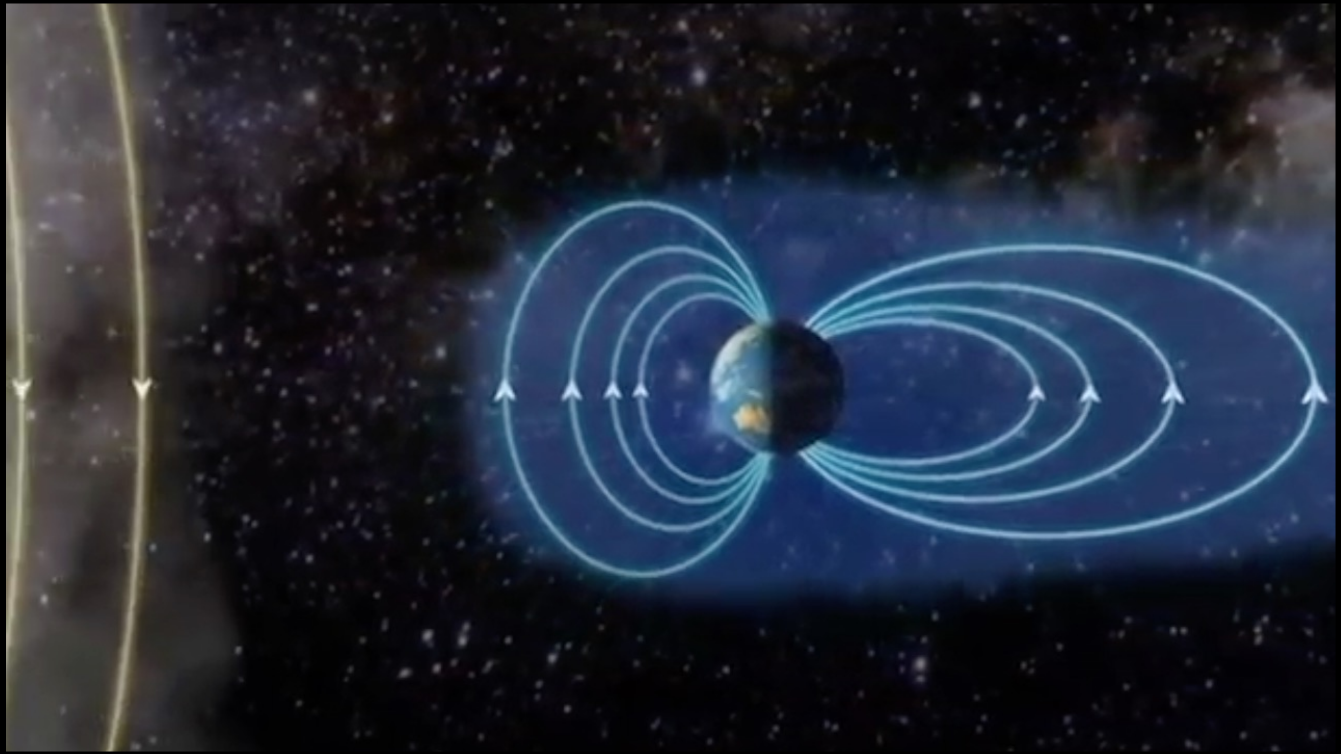
Video credit: NASA/SDO

Magnetic Reconnection

- Breaking and reconnecting of oppositely directed magnetic field lines

- Near earth, mostly happens when IMF is southwards

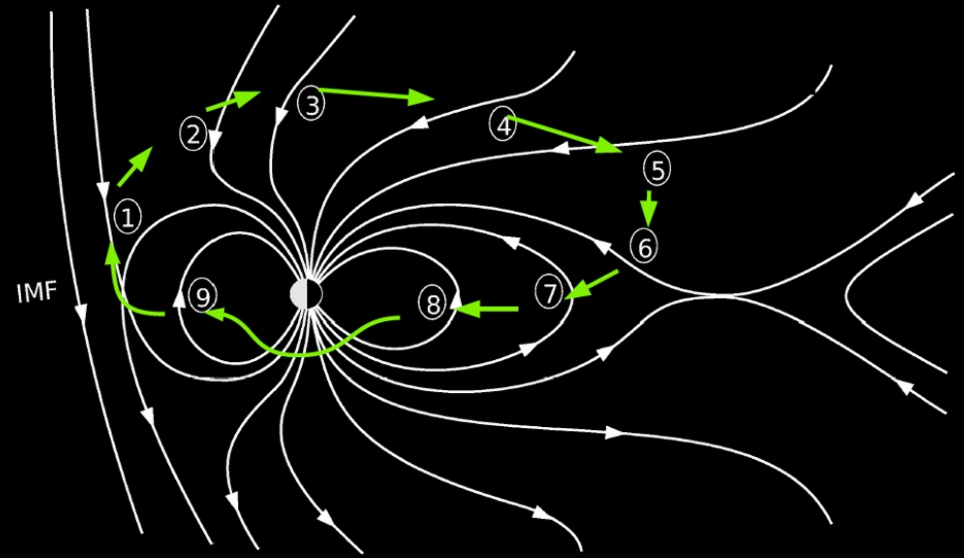
- Magnetic reconnection happens during Solar flares, CMEs and in accretion disks around black holes



Video credit: NASA/SDO

Dungey Cycle

- The Dungey cycle is a phenomenon that explains interactions between a planet's magnetosphere and solar wind
- Magnetic reconnection opens the dayside magnetopause and IMF connects to the Earth magnetic field
- Solar wind flows around the magnetosphere, drives a global convective motion

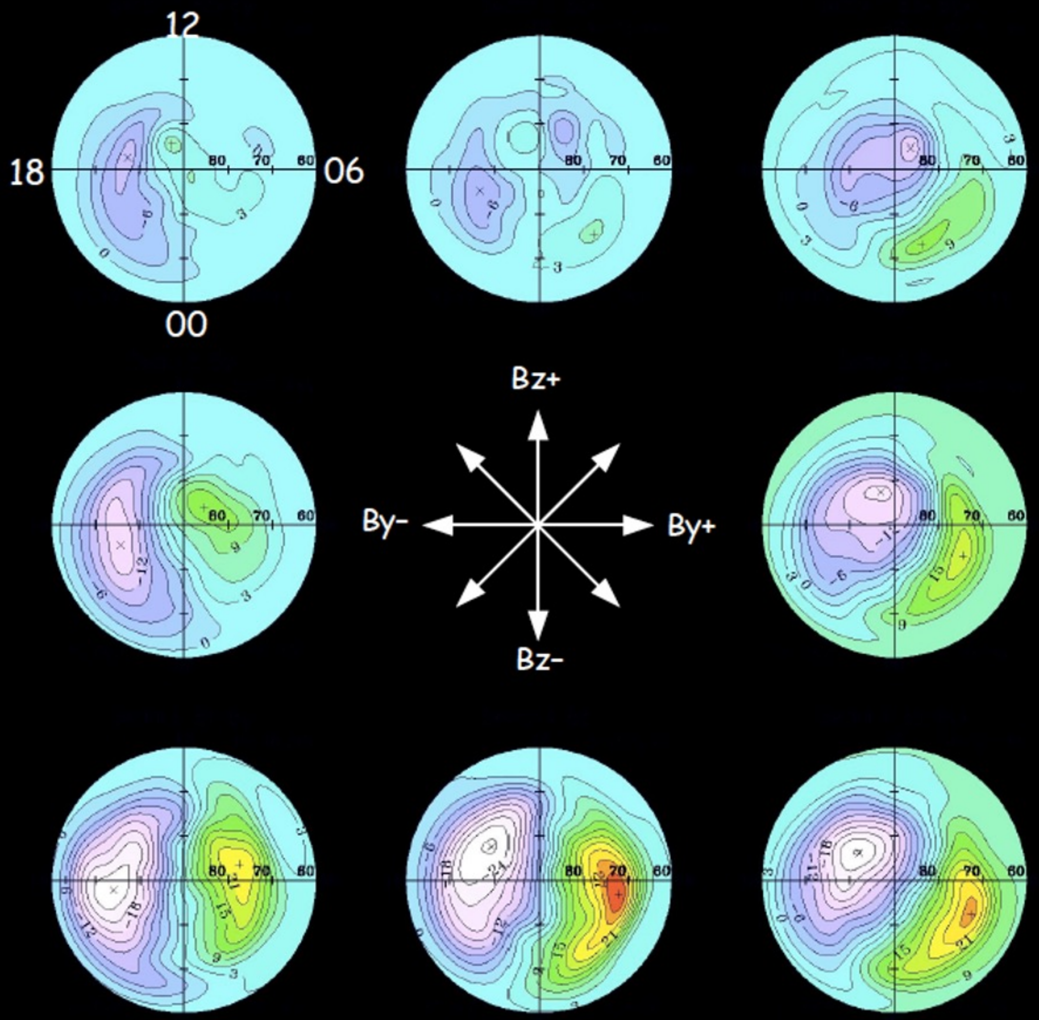


The Dungey cycle. After Dungey, 1961

- When magnetic reconnection opens the dayside magnetopause, plasma starts circulating within the magnetosphere

- Then convection causes circulation of plasma in the magnetically connected ionosphere

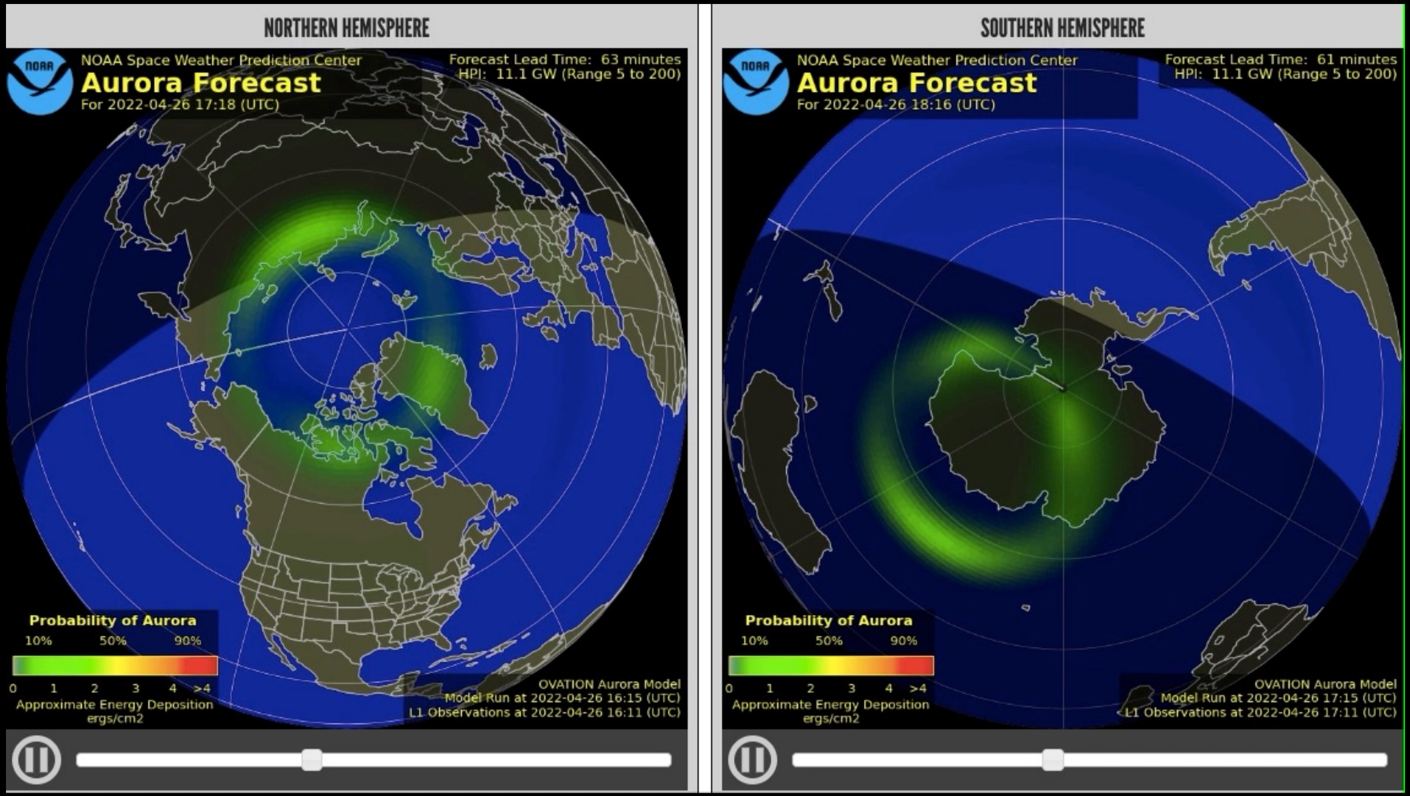
- The magnetic reconnection can happen even when IMF is not southward and then causes convection in ionosphere



North polar cap convection

Auroral ovals

- Regions where the auroras <u>typically occur</u>
- Elliptical region around each geomagnetic pole, from ~56° at midnight ~75° at noon
- Becomes wider during geomagnetic storms and substorms



A short-term forecast of the location and intensity of the aurora
Video credit: NOAA

Geomagnetic storm & Substorm

Geomagnetic storm:

A temporary disturbances of the Earth's magnetosphere which occurs when a solar wind perturbation interacts with the geomagnetic field, auroras can be seen

Substorm:

A localized & brief disturbance in the Earth's magnetosphere, auroras can be seen

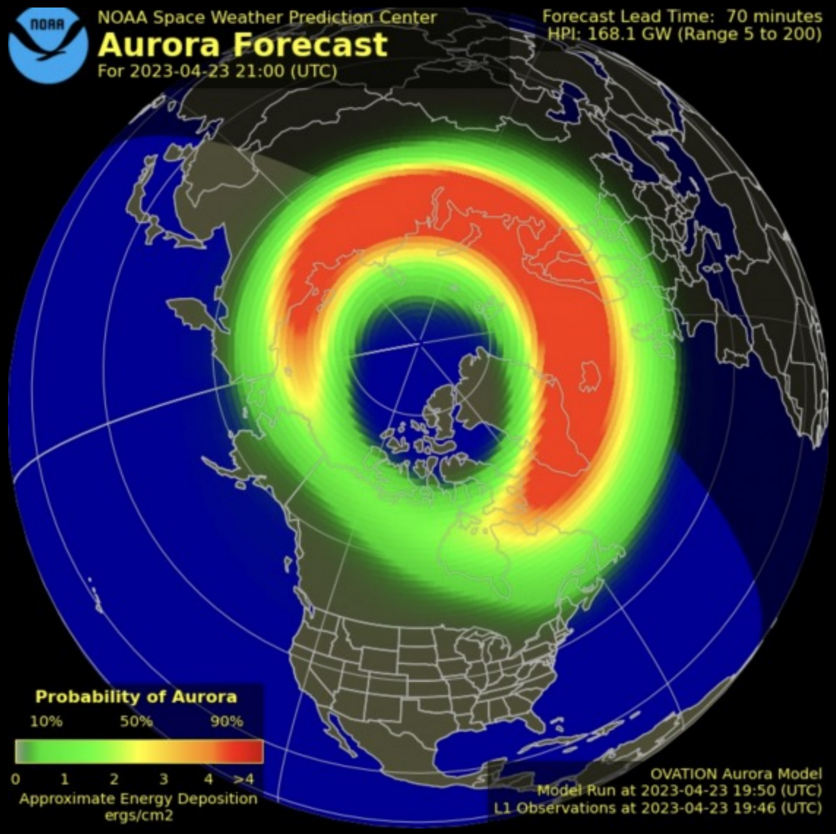


Image credit: NOAA

Geomagnetic storm

- Large scale temporary disturbance of magnetosphere
- Last for several days
- Aurora can be seen from higher to lower latitudes
- Dst index

Image credit: David Cartier Sep. 3, 20112

substorm

- A localized & brief disturbance of magnetosphere
- Last for few hours
- Aurora can be seen in higher latitudes
- AE index

Different Colors of Auroras

- The color of the aurora depends on which atoms is being excited by the incoming particles and on how much energy is being exchanged

- **Oxygen emission**
  - Red color at $\lambda \sim 630.0$ nm
  - Excitation energy ~ 5.6 eV
  - Lifetime ~ 110 s

- **Oxygen emission**
  - Green color at $\lambda \sim 557.7$ nm
  - Excitation energy ~ 10 eV

- **Nitrogen**
  - Blue color at $\lambda \sim 427.8$ nm
  - Excitation energy ~ 100 eV

Video credit: Pål Brekke and Fredrik Broms

Question:

The ionization potential energy for the outermost electron of atomic oxygen is 13.6 eV. Calculate the threshold wavelength that can start the ionization.

Planck constant:
$h = 6.626\times10^{-34}$ [kg.m²/s]

Answer:

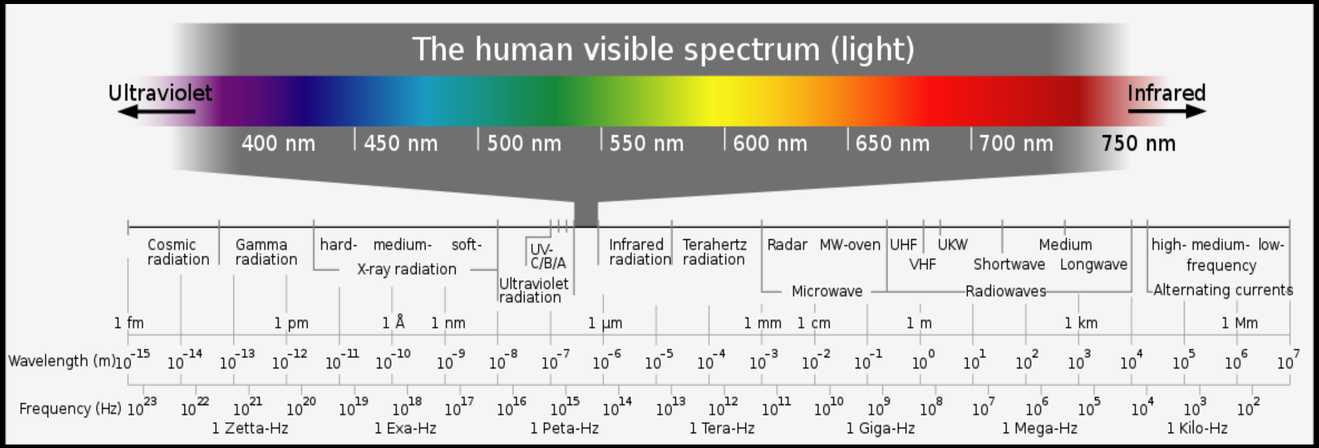
$1\text{eV} = 1.6\times10^{-19}$ [kgm²/s²]

$E = h\nu = \frac{hc}{\lambda}$

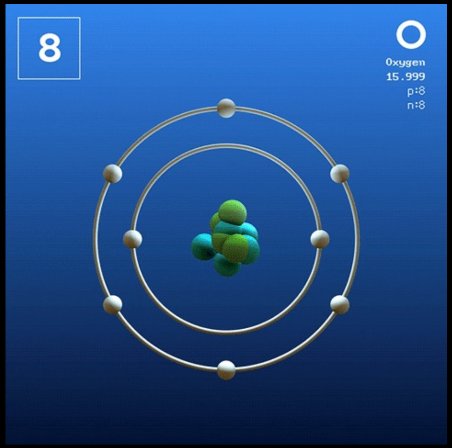
$\rightarrow \lambda = (6.626\times10^{-34})\times(3\times10^{8})/(13.6)\times(1.6\times10^{-19})$

≈ 91 nm

Wavelength smaller than 91 nm can start the ionization
(Far ultraviolet or x-rays and gamma rays)



Electromagnetic Wave Spectrum. Credit: Horst Frank



Can you hear Aurora?

- For many years people have reported clap sounds during auroras. Myth or Fact?
- Auroras occur at altitude between 80 to 500 km
- It is not possible for sound waves to travel there
- Scientist are still working to understand this phenomenon

Video credit: Auroral Acoustic Project

Possible explanation:

- A research has suggested that under the right weather conditions, auroras can be accompanied by a noise!

- The key issue is the formation of a strong temperature inversion layer.

- This occurs only during an excellent “fox weather” conditions meaning; calm, serene sky, temperature drop around 8°C, and at least a moderate geomagnetic activity

- *“Sound producing mechanism in temperature inversion layer and its sensitivity to geomagnetic activity by Unto K. Laine”*

Photo credit: Antti Pietikäinen

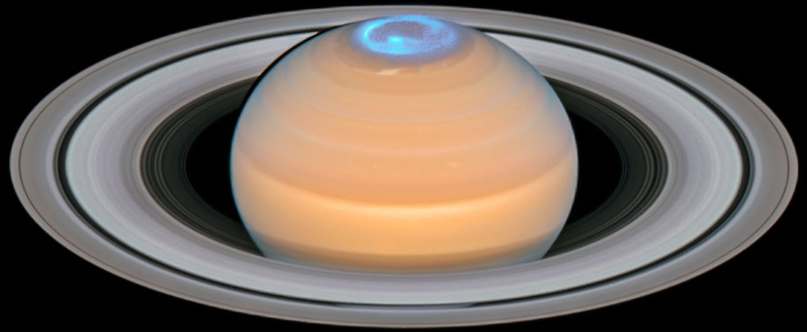
Aurora from space

Video credit: ISS

Aurora on Other Planets

You can find Auroras on Jupiter, Saturn, Uranus and Neptune

Jupiter’s aurora observed by NASA's Hubble Space Telescope



Saturn’s aurora observed by NASA's Hubble Space Telescope

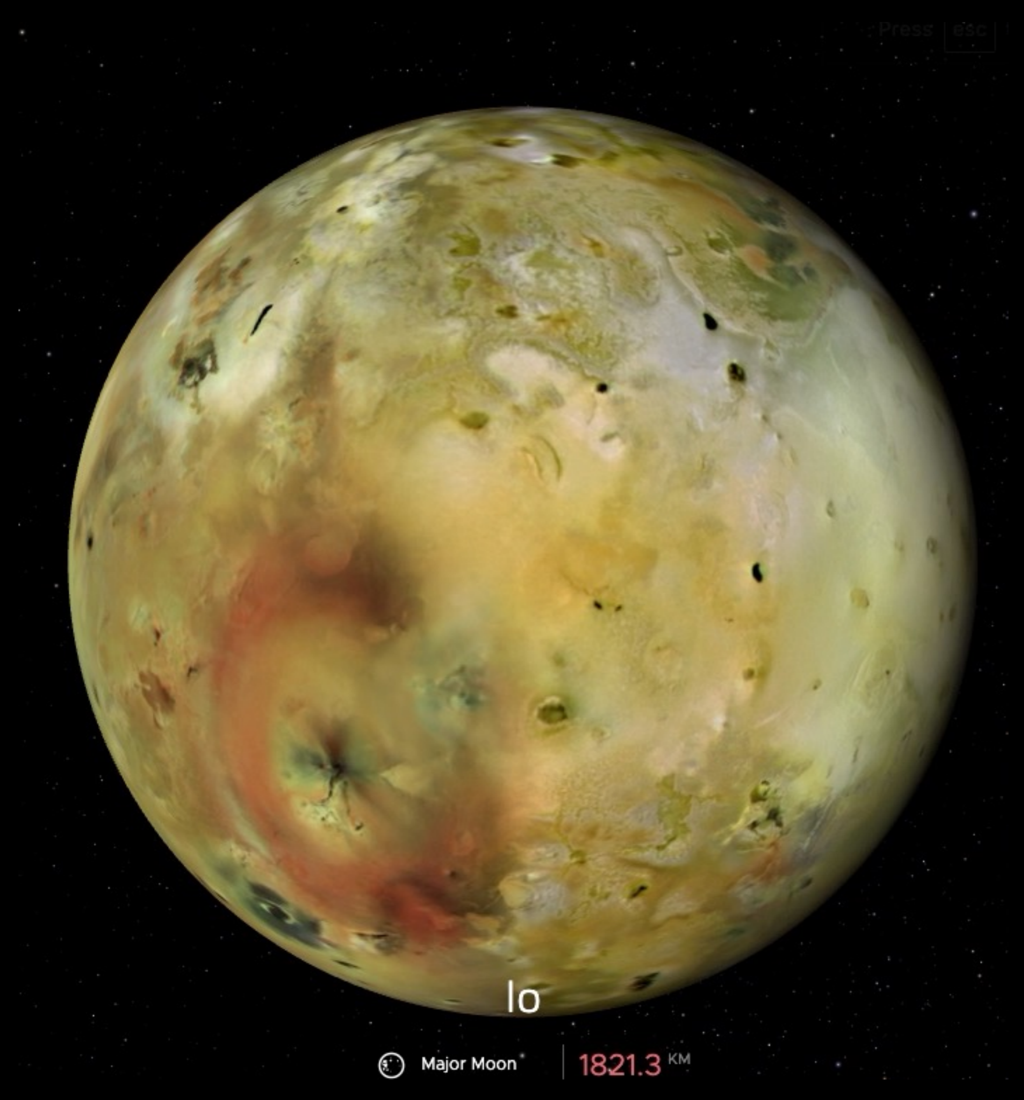
Jupiter's Auroras

- Source of charged particles:
  Solar wind & the Jupiter's moon Io

- Io is the most volcanically active world in the Solar System, with hundreds of volcanoes, some erupting lava fountains dozens of kilometers high

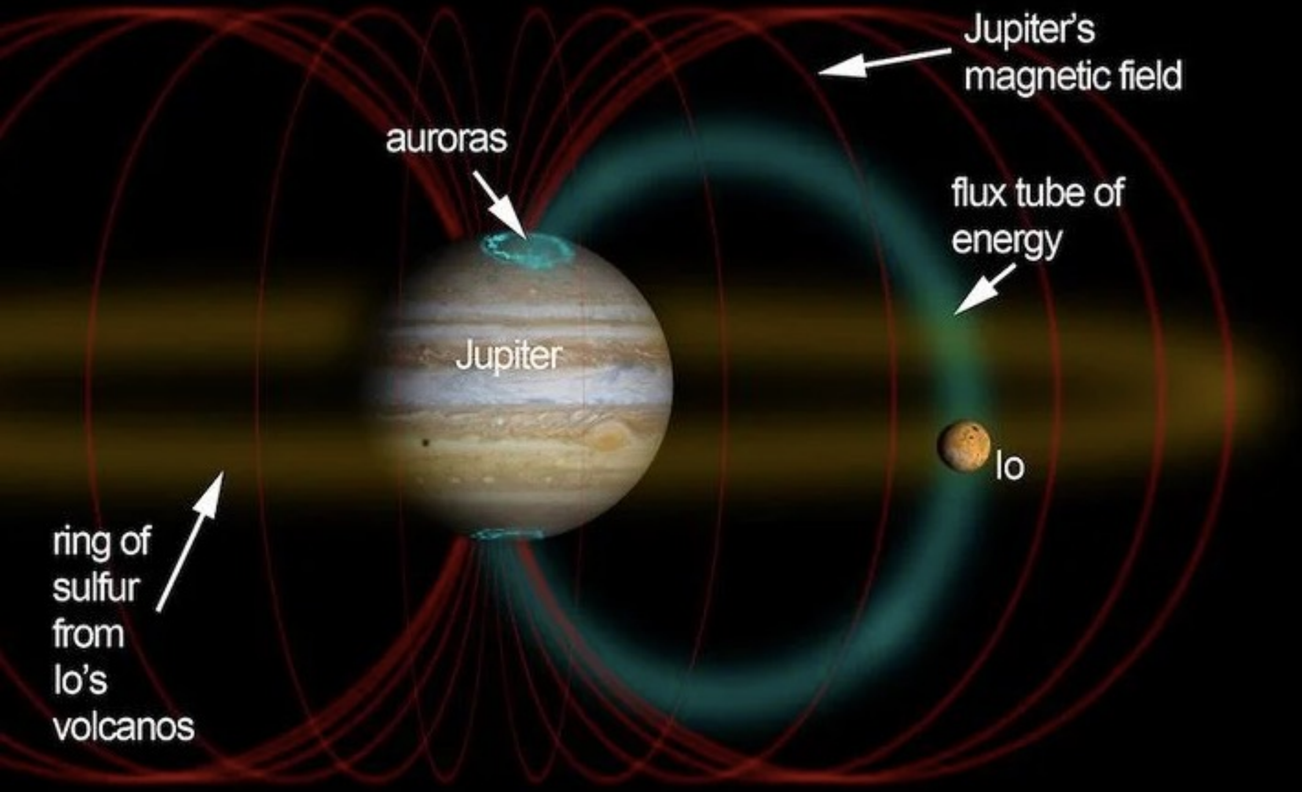
- Jupiter has the most powerful auroras in the solar system

- Auroras on Earth may last for a few hours, but on Jupiter they never end



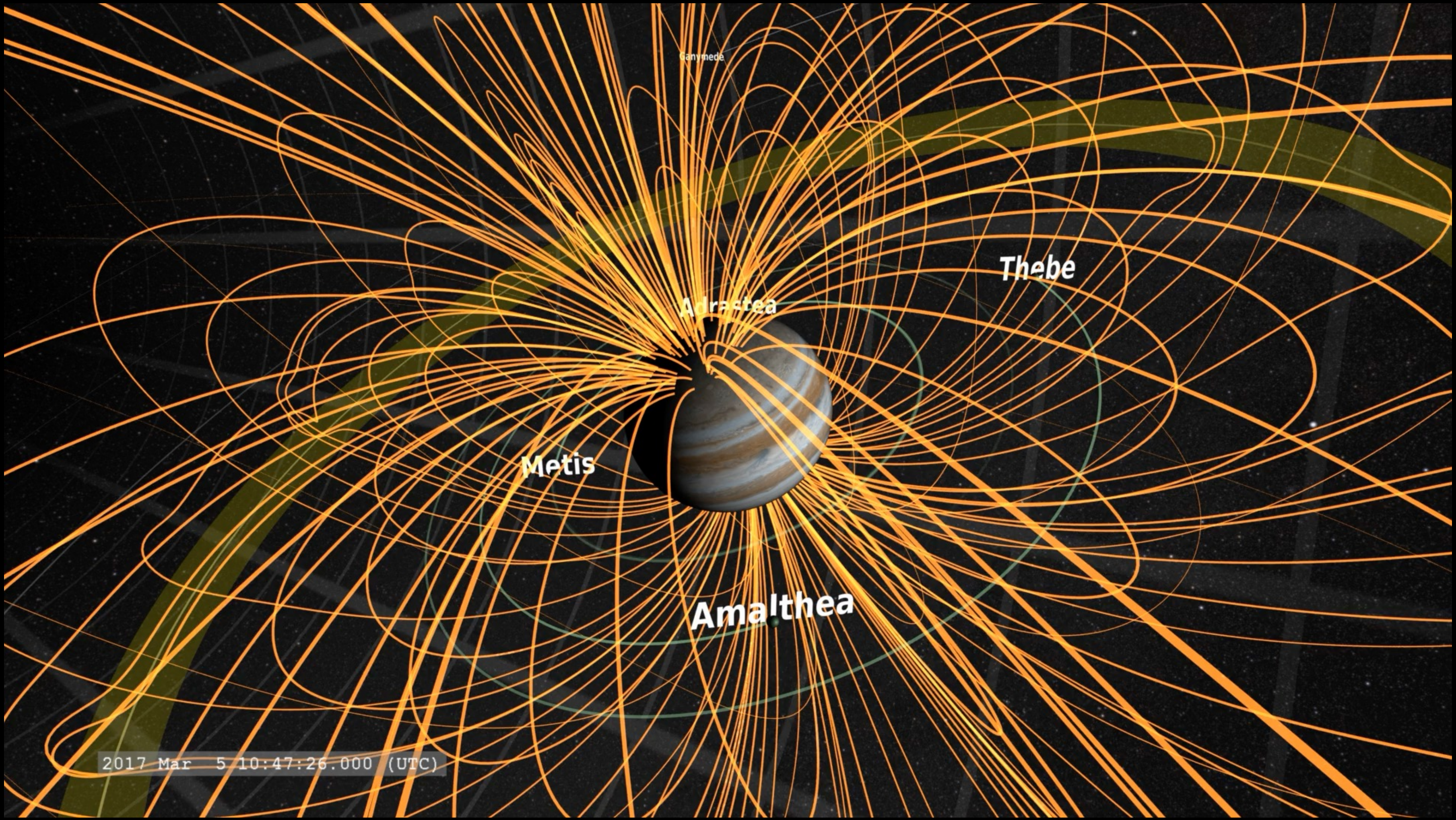
Io: The Jupiter's moon
Video credit: NASA

Jupiter-Io coupling



A schematic showing the Jupiter, Io, Jovian magnetic field lines and Io plasma tours
credit: Ron Miller

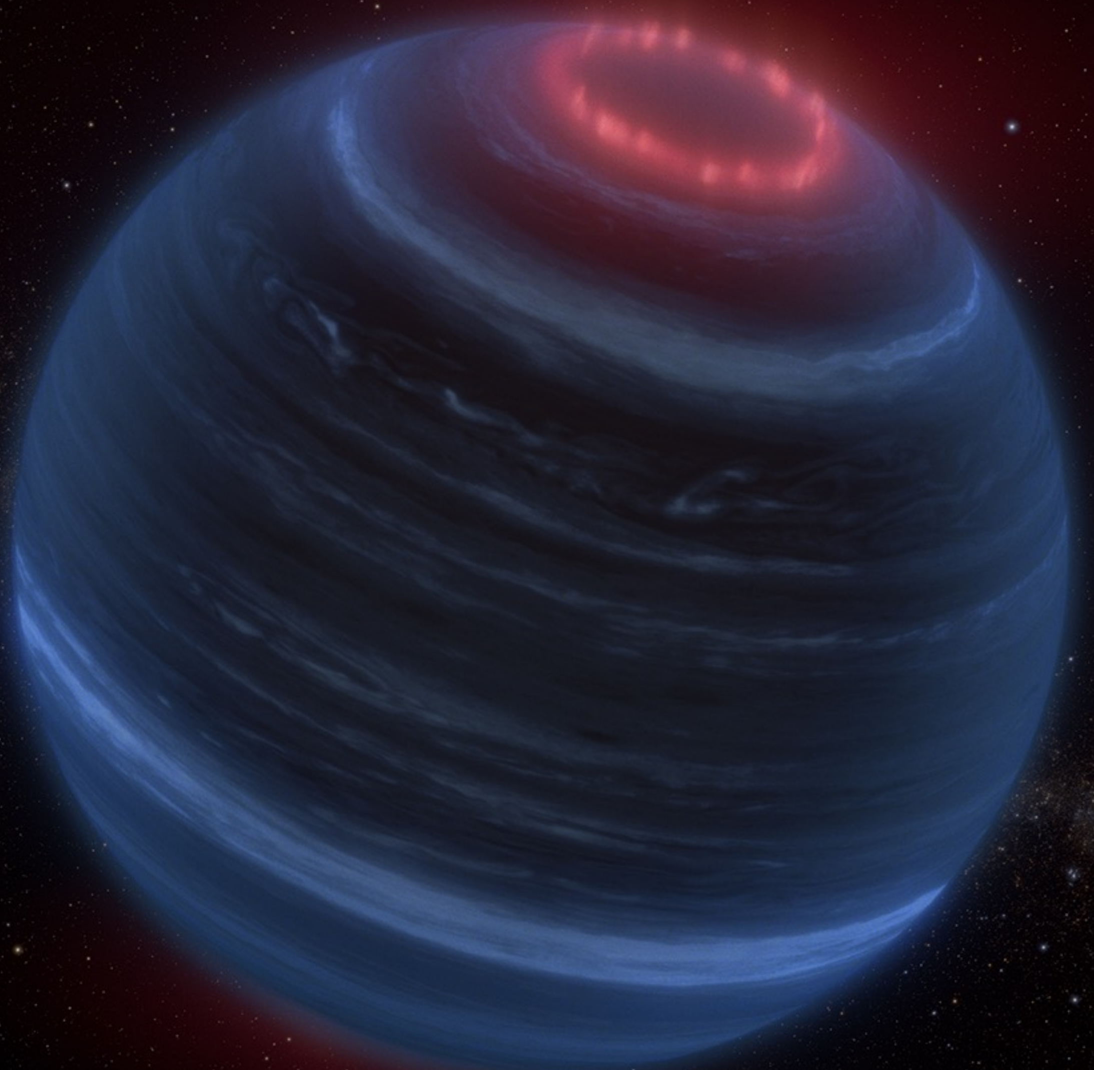
- Io orbits within the Jupiter's intense magnetic field and constantly couples with Jupiter's magnetosphere
- Volcanic eruptions on Io eject large amounts of sulfur dioxide gas into space, forming a large torus around Jupiter
- Io plasma torus is the main source of plasma for the Jovian magnetosphere



A simplified model of Jupiter's massive magnetosphere
Credit: NASA

Signs of Possible Auroras on Isolated Brown Dwarf

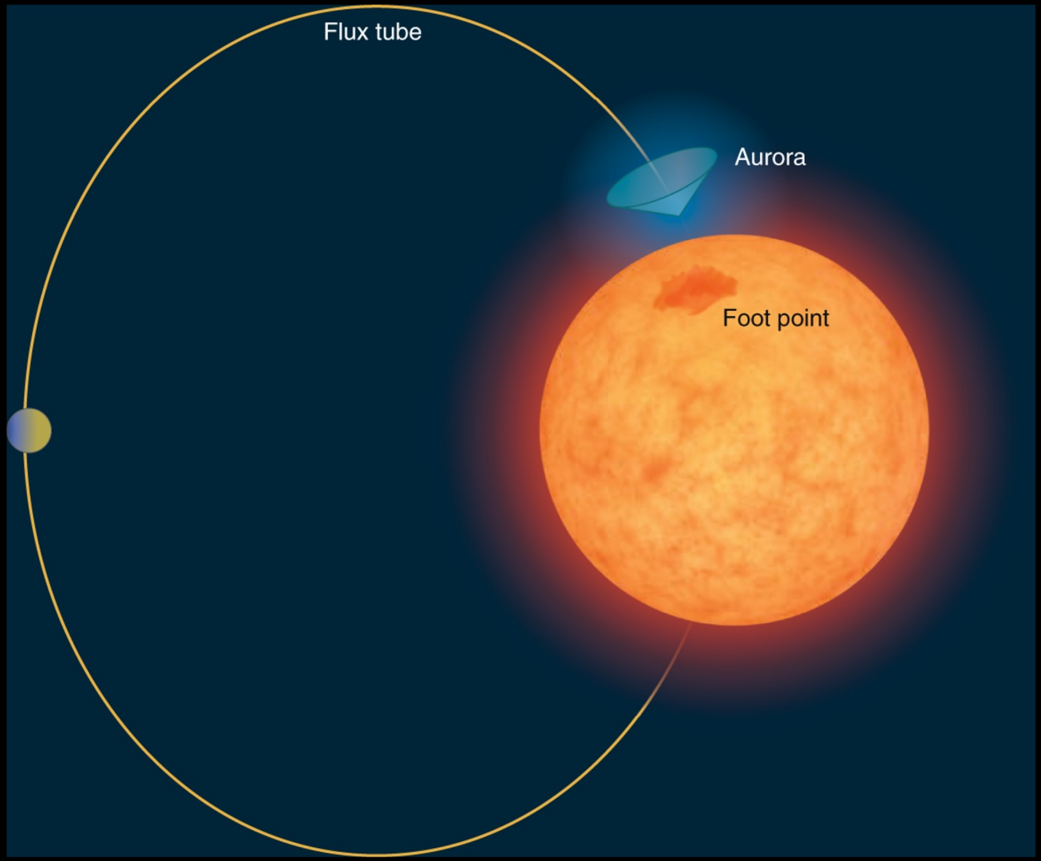
- NASA's James Webb Space Telescope has found a brown dwarf with infrared emission from methane, likely due to processes generating auroras
- This was an unexpected discovery because the brown dwarf is cold and lacks a host star; therefore, there is no obvious source for the upper atmosphere energy
- The absence of a stellar wind to contribute to the auroral process and explain the extra energy in the upper atmosphere required for the methane emission is a mystery



An artist's concept of brilliant auroras on the brown dwarf W1935
Credit: NASA

An Example of A Stellar Aurora

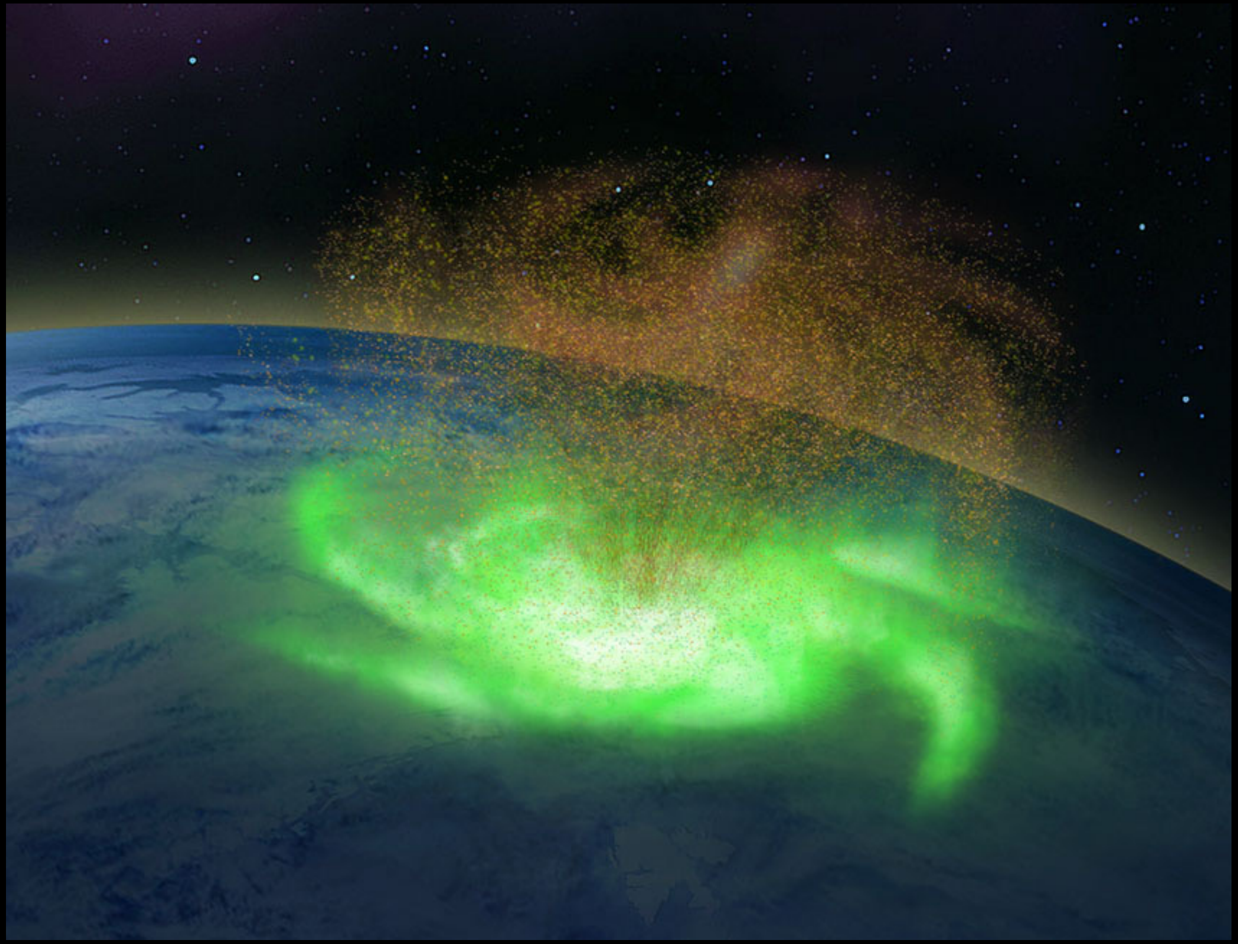
- In 2019, Vedantham et al. found an unusual coincidence between a radio detection and the low-mass/red dwarf star GJ1151
- In 2020, J. Sebastian Pineda concluded that the radio emission from the star could only be induced by the presence of a closely orbiting planet
- The planet candidate around GJ1151 is expected to be linked to its host star through a magnetic flux tube, causing a stellar aurora at its foot



Illuatration credit: J.S, Pineda 2020

Space Hurricane

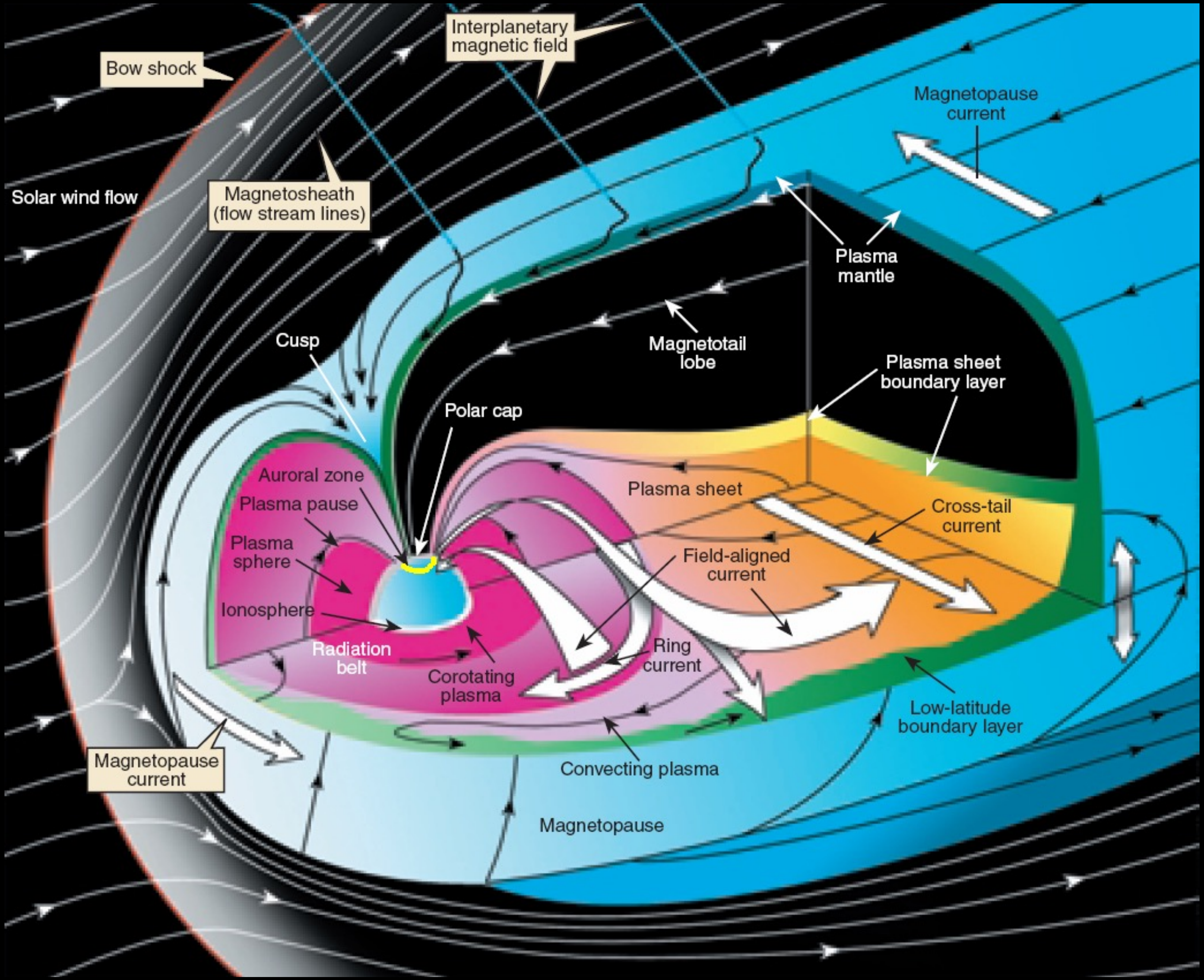
- In 2020, using satellite observations that had been made on 20 August 2014, researchers identified a Space Hurricane in the upper polar atmosphere (altitude ~ 110–860 km)
- The Space Hurricane had a cyclone-like auroral spot around the north magnetic pole
- Its diameter was over 1000 km with multiple arms and anti-clockwise rotation
- The hurricane lasted nearly 8 hours
- The space hurricane happened during very low geomagnetic activity. Therefore, there may be more space hurricanes to be discover



Illuatration credit: space hurricane by Shandong University

Geomagnetic Data

Geomagnetic Indices
Where to Find them
How to Use them



Earth’s magnetosphere. Image credit: NASA

Ring current

$R_\oplus = 6,371$ (km)

- The Ring current is located at ~ 3 to 8 $R_\oplus$, circulates clockwise (when viewed from the north)
- The current produces a B-field in opposition of $B_\oplus$
- Dst index measures the intensity of the ring current
- Deviation of H (north-south) component of the magnetic field
- Dramatic enhancement during geomagnetic storm

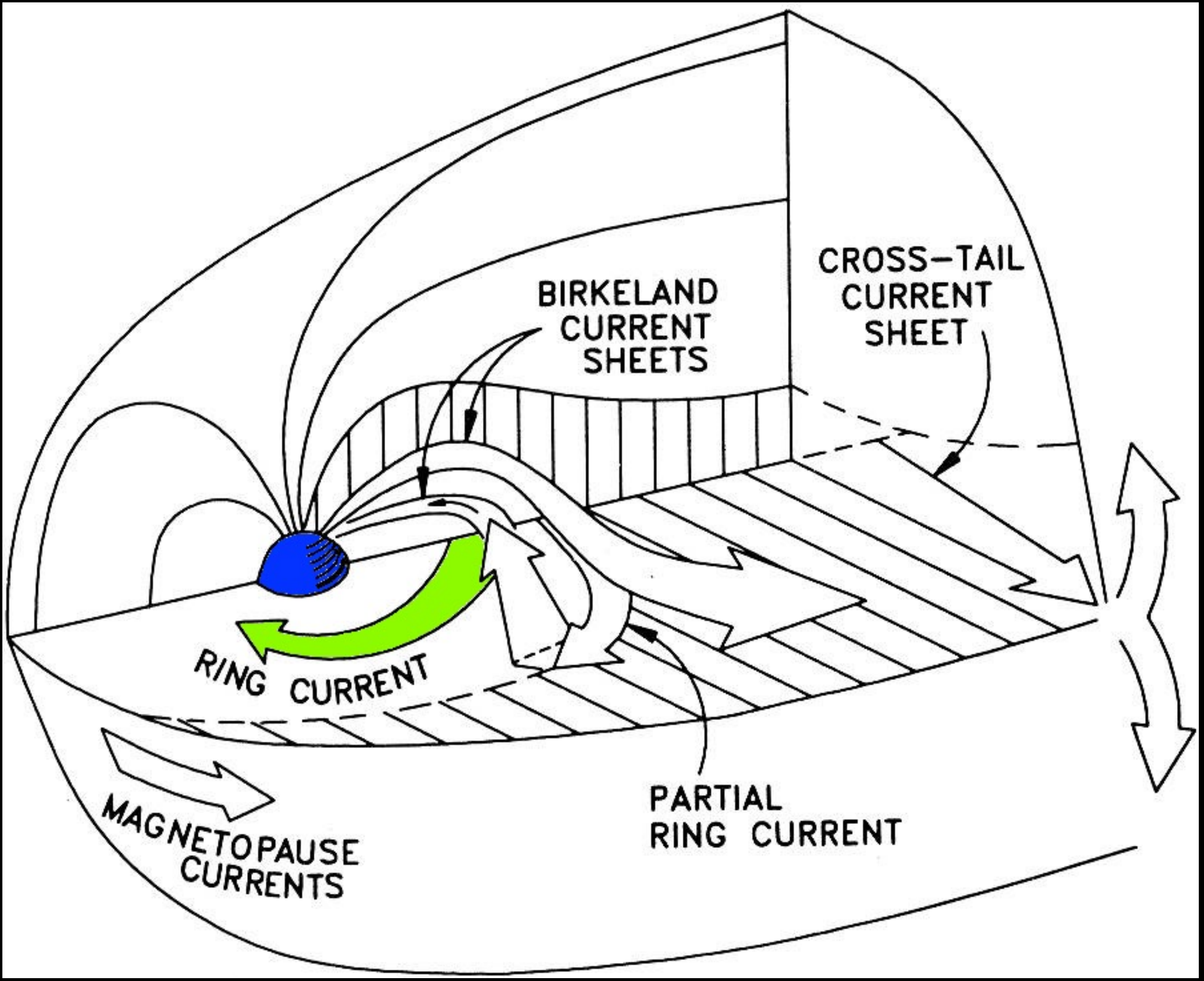
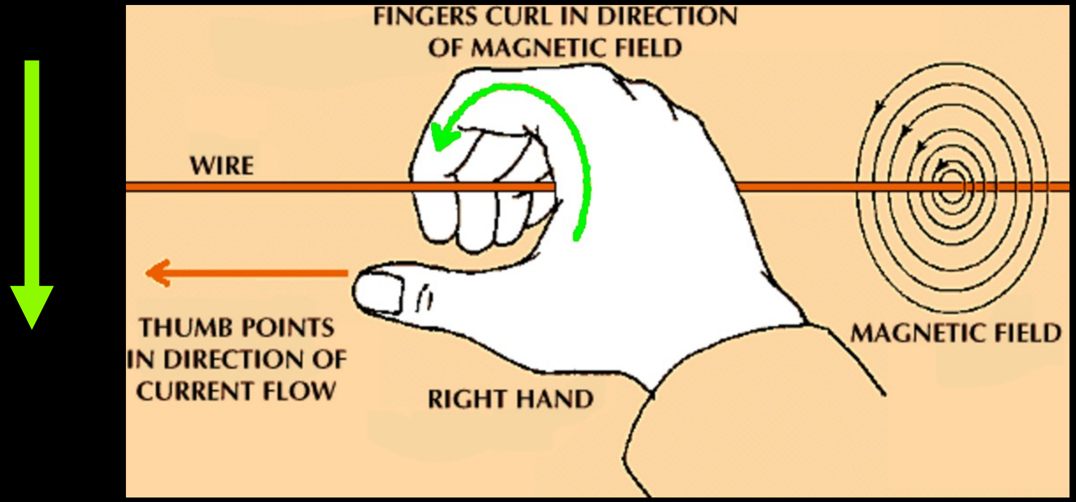


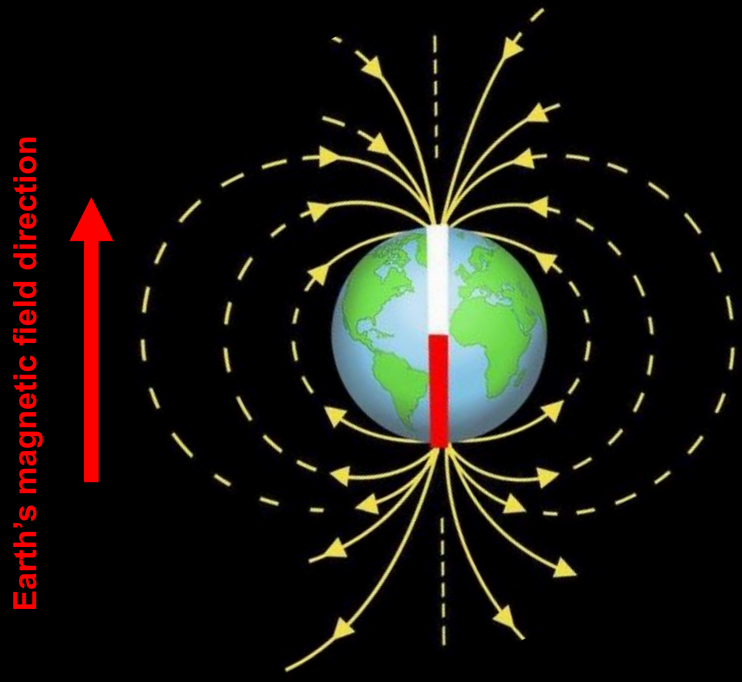
Illustration credit: David P. Stern

How the Ring Current affects the Earth magnetic field

- Moving charge particles create an electric current I=$\frac{q}{t}$ and an electric current induce magnetic field as well

- $\nabla \times \mathbf{B} = \mu_0 \mathbf{J}$





Disturbance storm time (Dst) index

- A measure of the ring current strength
- Four stations near the magnetic equator
  - Magnetic equator: There is no vertical (Z) component to the magnetic field
  - The magnetic equator is not fixed, but slowly changes

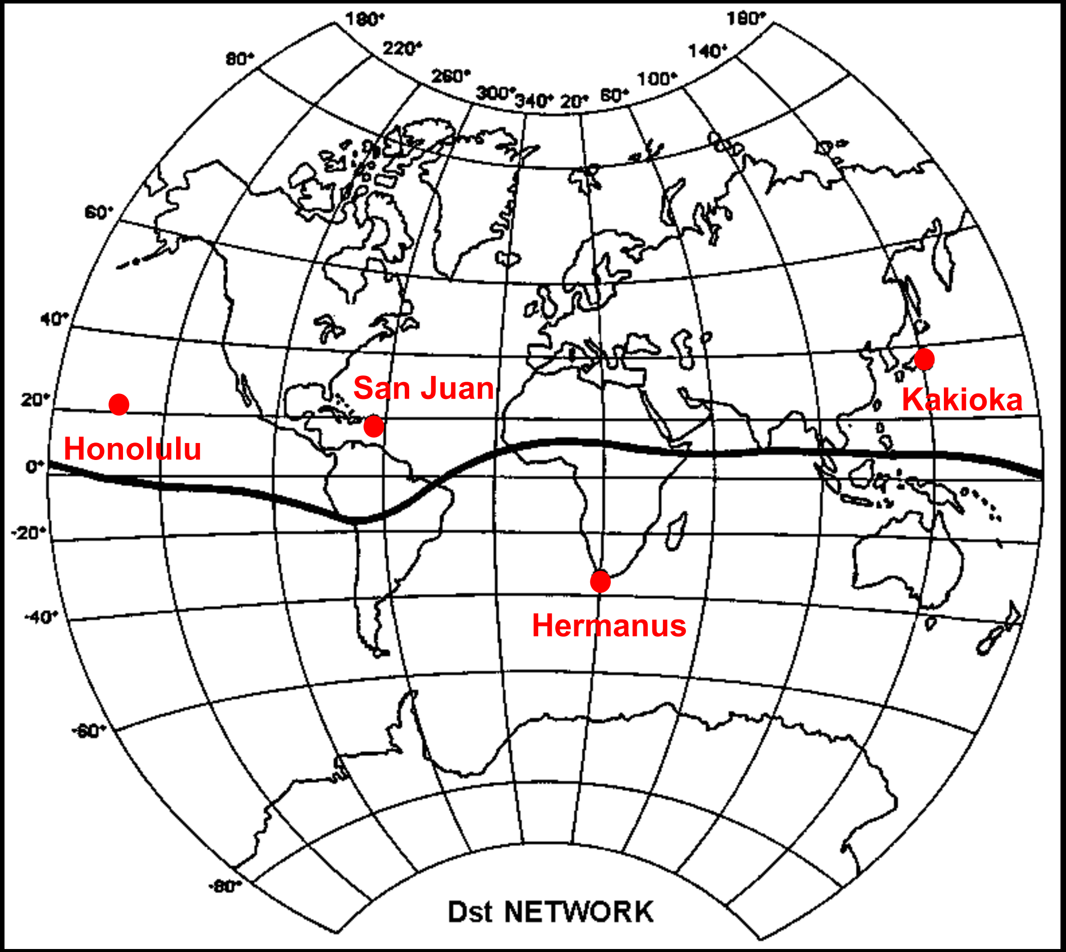
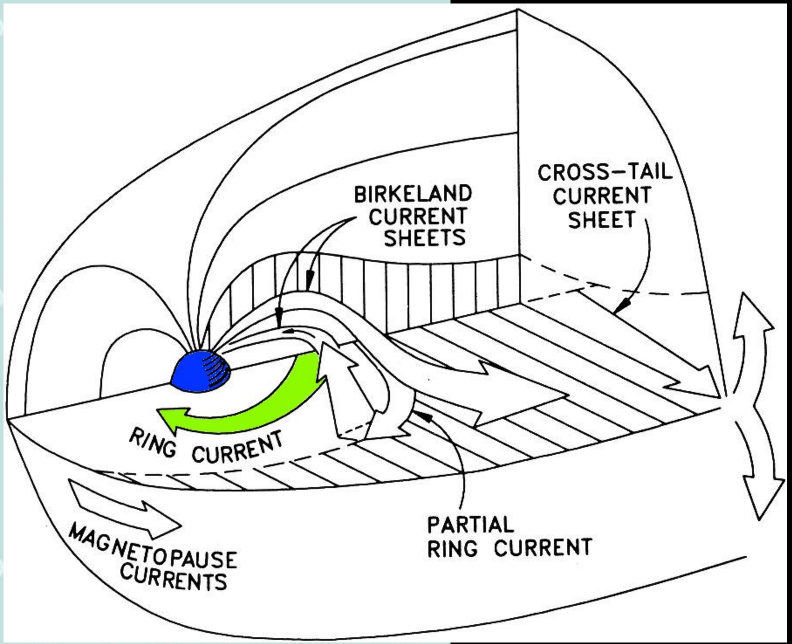


Illustration credit: World Data Center for Geomagnetism

WDC for Geomagnetism, Kyoto
Hourly Equatorial Dst Values (FINAL)
MARCH 2015

unit=nT

DAY	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17							
1	-34	-44	-30	-31	-28	-42	-55	-53	-56	-51	-50	-47	-46	-41	-36	-32	-29							
2	-21	-20	-30	-35	-30	-42	-43	-53	-64	-62	-54	-50	-53	-53	-49	-49	-41							
3	-24	-22	-28	-26	-25	-26	-27	-26	-22	-26	-28	-27	-25	-27	-27	-27	-25							
4	-27	-18	-16	-17	-15	-13	-11	-8	-4	-5	-6	-7	-11	-15	-16	-19	-20							
5	-15	-11	-9	-9	-7	-5	-4	-3	-3	-6	-8	-7	-12	-19	-13	-14	-15							
6	-3	0	2	6	3	-5	-14	-30	-30	-20	-17	-14	-16	-16	-14	-12	-11							
7	-8	-11	-12	-17	-20	-27	-27	-25	-19	-20	-24	-22	-19	-12	-11	-12	-10							
8	-17	-13	-13	-14	-15	-12	-7	-7	-9	-8	-12	-18	-21	-18	-21	-19	-17							
9	-18	-23	-21	-22	-19	-16	-17	-18	-17	-16	-14	-11	-9	-9	-10	-9	-10							
10	-1	-4	-4	-6	-6	-4	-2	-1	1	-3	-7	-3	-5	-6	-6	-7	-7							
11	-6	-6	-6	-6	-5	5	6	8	0	2	1	2	-6	-11	-14	-14	-12							
12	-15	-12	-8	-10	-11	-7	-12	-22	-24	-23	-19	-19	-15	-17	-18	-13	-9							
13	-13	-12	-9	-3	-2	1	1	0	-1	-2	-2	0	-3	-16	-20	-11	-7							
14	-12	-11	-12	-13	-14	-15	-12	-9	-8	-7	-5	-4	-4	-4	1	3	4							
15	-11	-11	-11	-12	-11	-11	-9	-9	-7	-6	-7	-5	-5	-3	1	4	-1							
16	4	10	15	10	7	15	1	-10	-2	5	11	19	17	11	7	12	17	17	15	16	11	9	6	3
17	4	3	3	2	13	45	25	-18	-54	-83	-75	-54	-55	-75	-93	-118	-143	-162	-154	-177	-182	-198	-234	-225
18	-200	-189	-172	-155	-148	-136	-133	-124	-123	-117	-111	-99	-97	-91	-88	-91	-86	-82	-88	-94	-95	-94	-94	-93
19	-99	-94	-86	-81	-86	-84	-81	-73	-71	-70	-73	-76	-77	-83	-84	-80	-73	-72	-71	-70	-71	-69	-65	-70
20	-75	-81	-74	-69	-65	-64	-71	-68	-63	-61	-62	-65	-58	-57	-55	-56	-62	-66	-64	-60	-59	-56	-56	-65



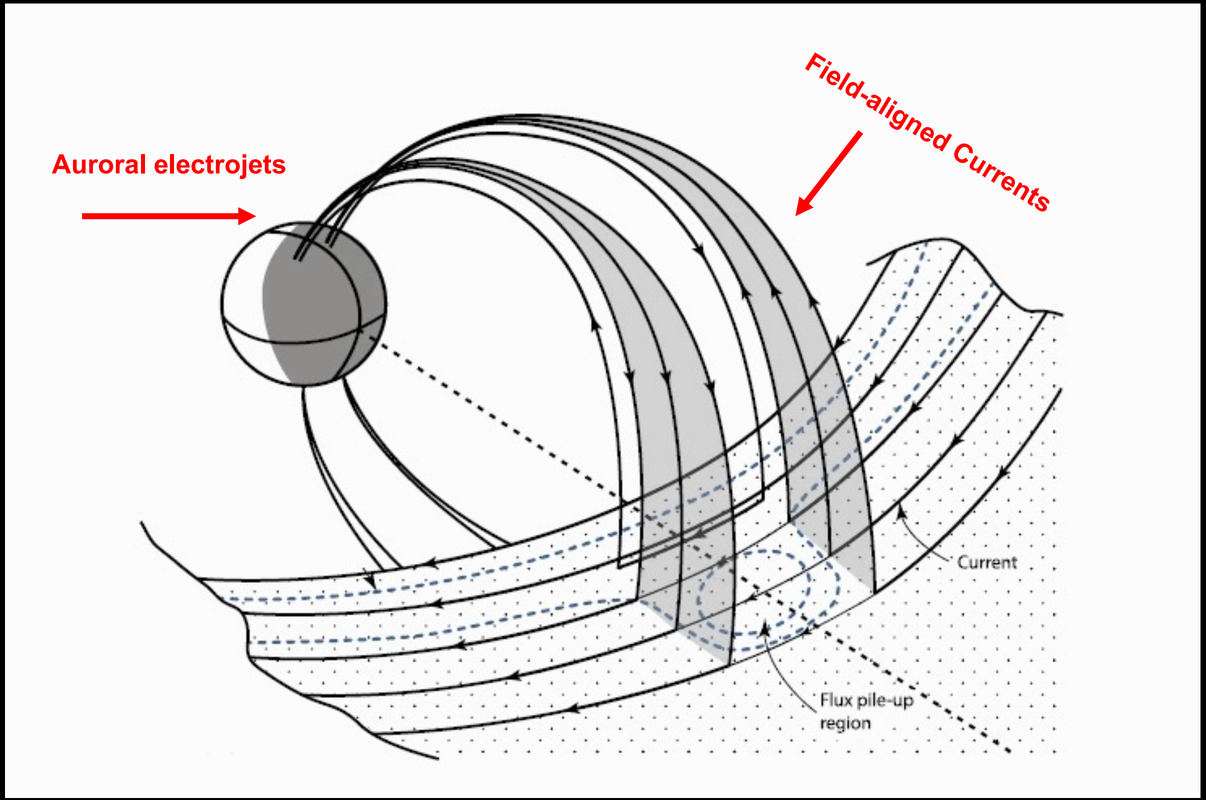
Equatorial and Auroral Electrojets

- An electrojet is an electric current which travel around the Erath's ionosphere
- There are two electrojets: Above the magnetic equator (the equatorial electrojet), and near the Northern and Southern Polar circles (the Auroral electrojets)

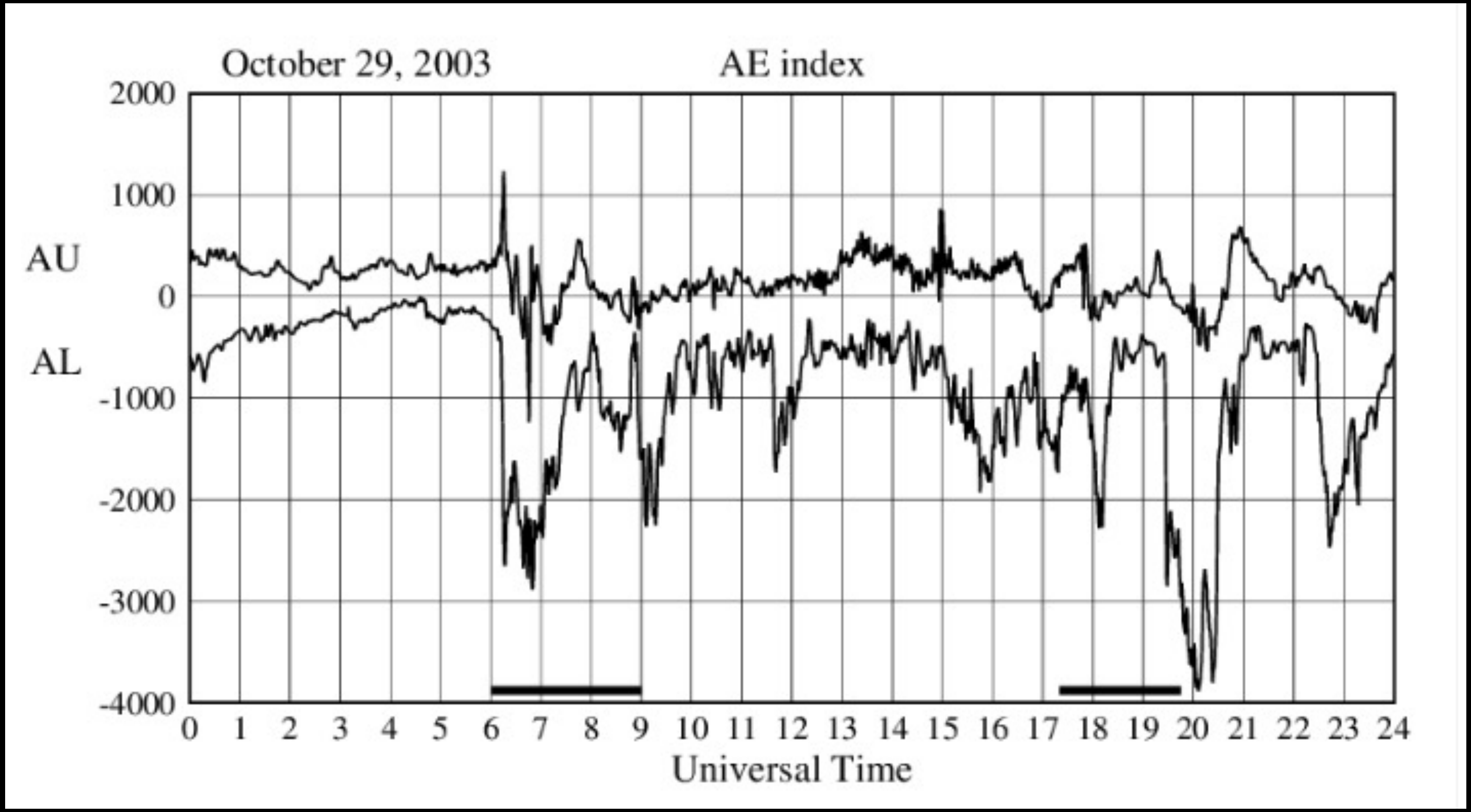
Representation of the East (EEJ) and West (WEJ) auroral electrojet
Image credit: Piccinelli et al. 2014

Auroral Electrojet (AE) index

- AE is designed to provide a global, quantitative measure of auroral zone magnetic activity
- Produced by Auroral Electrojets flowing below and within the auroral oval
- Derived from variations in the horizontal component observed at selected (10-13) observatories near and within auroral oval



Auroral electrojets
credit: L. Kepko. et al



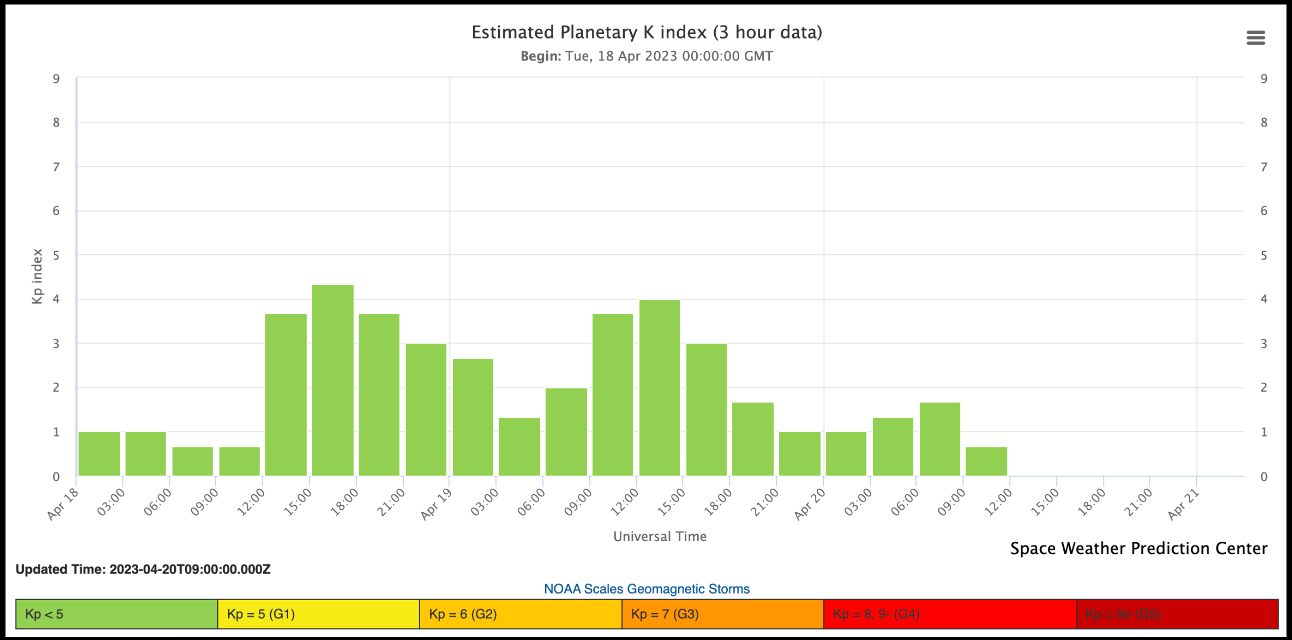
- AU and AL indices are respectively the largest and the smallest values in the horizontal component
- The difference, AU minus AL, defines the AE index

Geomagnetic Kp index

- The K_P is used to characterize the magnitude of geomagnetic storms, or quantifies disturbances in the horizontal component of earth's magnetic field

- 3-hourly range index, 13 geomagnetic observatories (ranging from 44° to 60° northern or southern geomagnetic latitude)

- Scaled from 0 to 9, expressed in thirds of a unit, e.g., 5- is $4\frac{2}{3}$, 5 is 5, 5+ is $\frac{1}{3}$



K_p index
Credit: NOAA

Database for the Geomagnetic indices

- Dst index
- AL/AU or AE index
- Kp index

World Data Center for Geomagnetism

- https://wdc.kugi.kyoto-u.ac.jp/wdc/Sec3.html

- Check Dst index and try to find a Geomagnetic Storm

All sky camera

- Used in meteorology, astronomy and visual observation of auroras
- Capture a photograph of the entire sky
- All-sky cameras that are used for imaging auroras have special optical elements such as fish-eye lenses or spherical mirrors to acquire an image of the whole sky in one shot

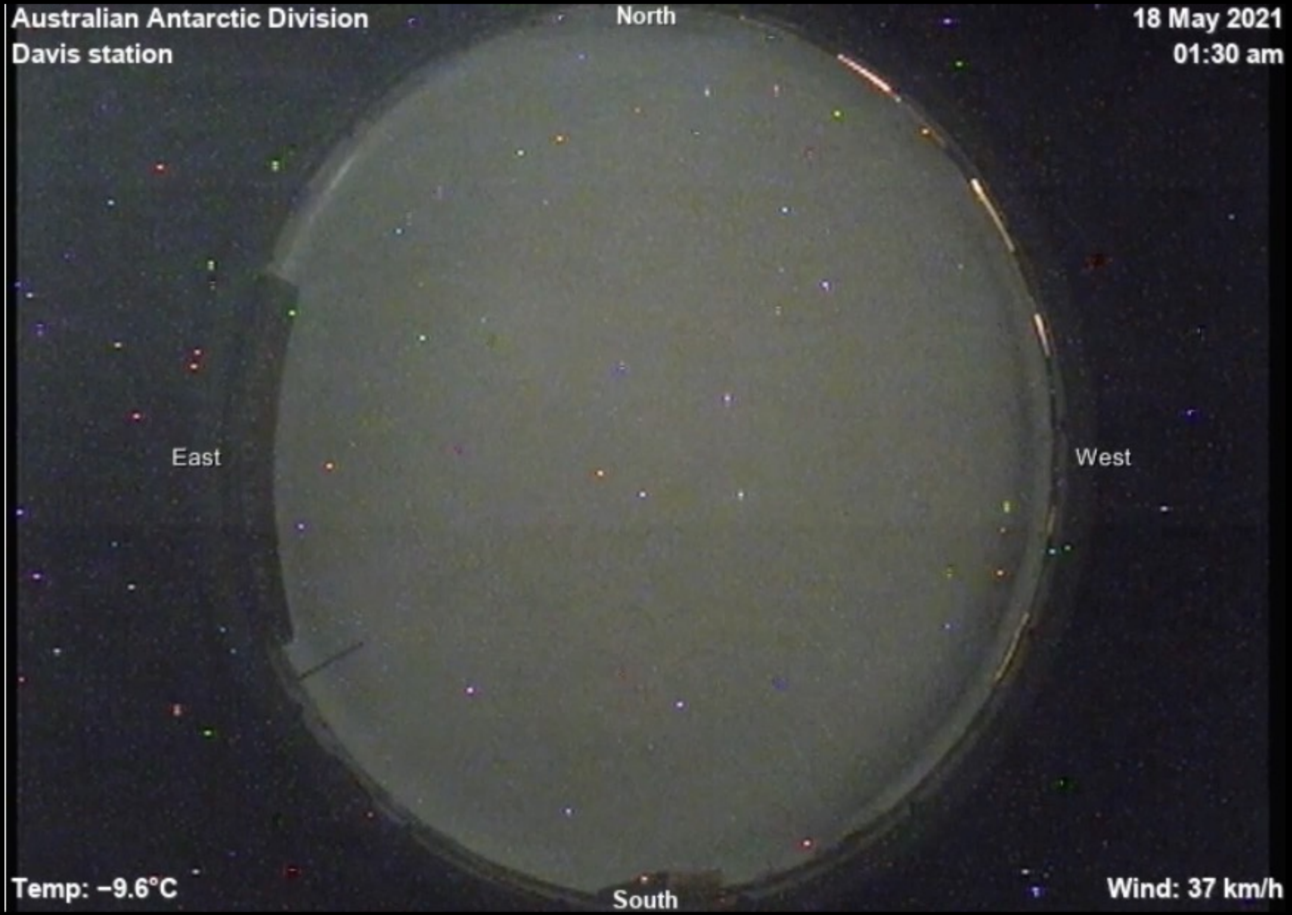
All sky camera data

Tromsø, Norway
Oct. 27, 2010
Photo Credit: Terence Murtagh & Nicholas Holdsworth
Cades Observatory, Kingston, TAS, Australia

- Sodankylä Geophysical Observatory http://www.sgo.fi/Data/RealTime/allsky.php
- Skibotn Observatory, Norway: https://fox.phys.uit.no/ASC/ASC01.html
- Kiruna station, Sweden: https://www2.irf.se/Observatory/?link=All-sky_sp_camera
- Syowa (or Showa) station, South Pole: http://polaris.nipr.ac.jp/~acaurora/aurora/Syowa/ Not working!

Davis Station Sky-cam

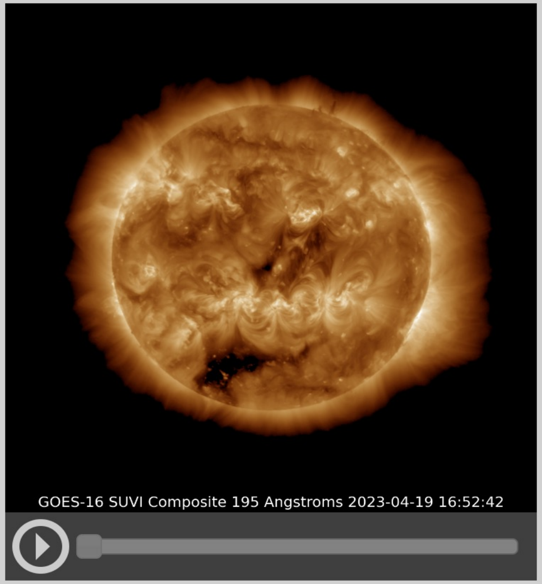
- Davis station is one of the permanent research center in Antarctica
- Operated by Australian Antarctic Division
- Coordinates: 68° 34′ 36″ S, 77° 58′ 3″ E
- Sky-cam produces images of the full sky and provides a view for the study of Antarctic clouds with similar sensitivity to the naked eye
- https://www.antarctica.gov.au/antarctic-operations/webcams/davis/



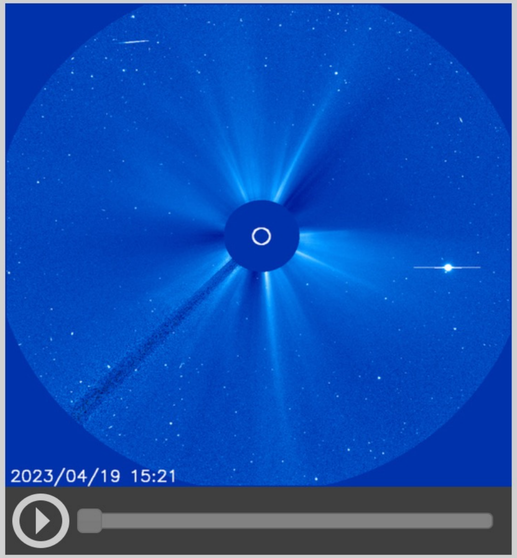
Sky-cam at the Davis station
Video credit: Australian Antarctic Division

NOAA Space Weather Prediction Center

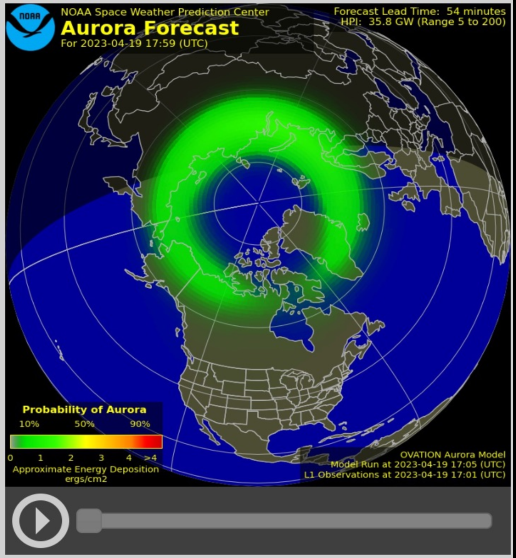
THE SUN (EUV)



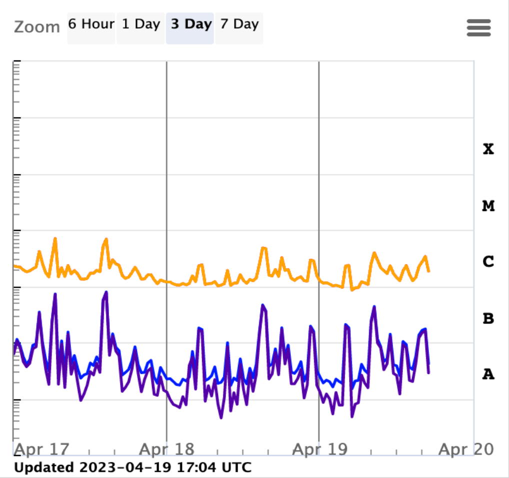
CORONAL MASS EJECTIONS



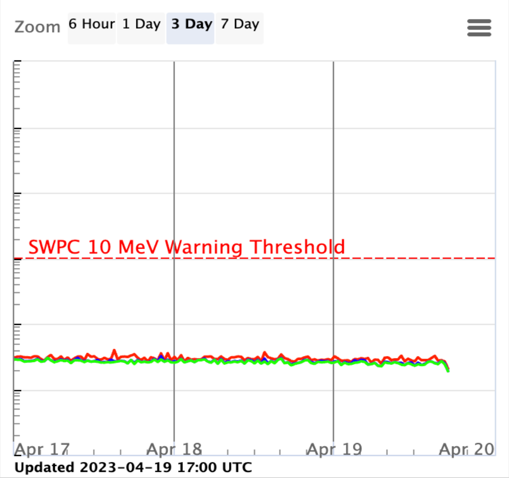
THE AURORA

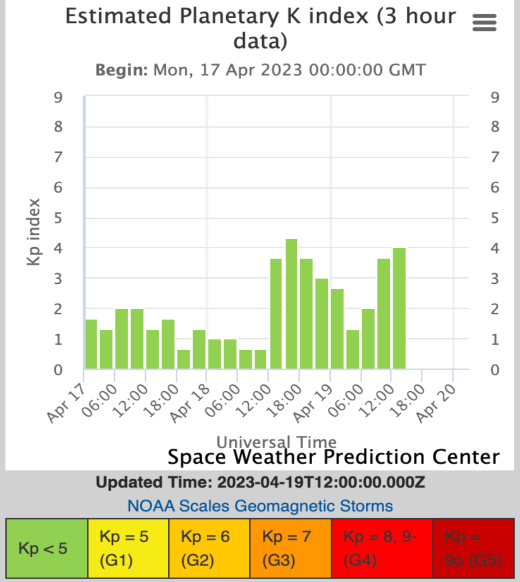


GOES X-RAY FLUX



GOES PROTON FLUX

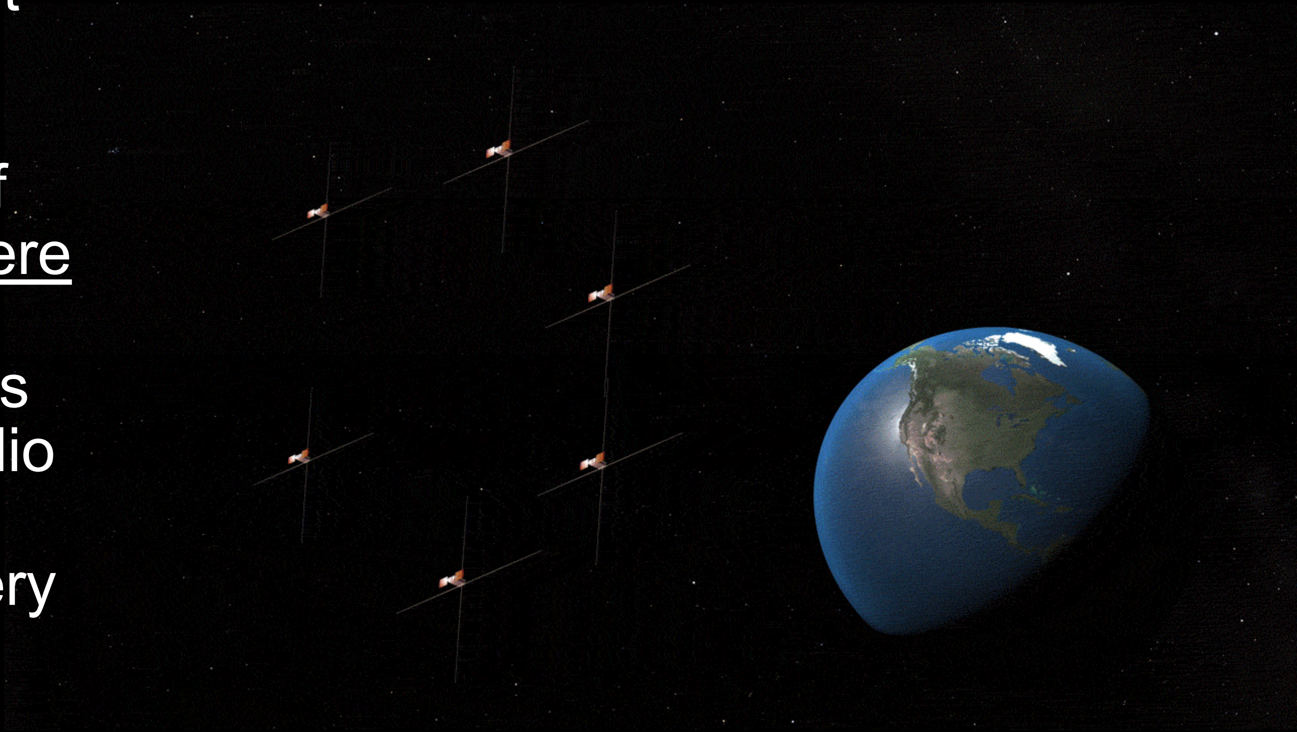




https://www.swpc.noaa.gov/

SunRISE

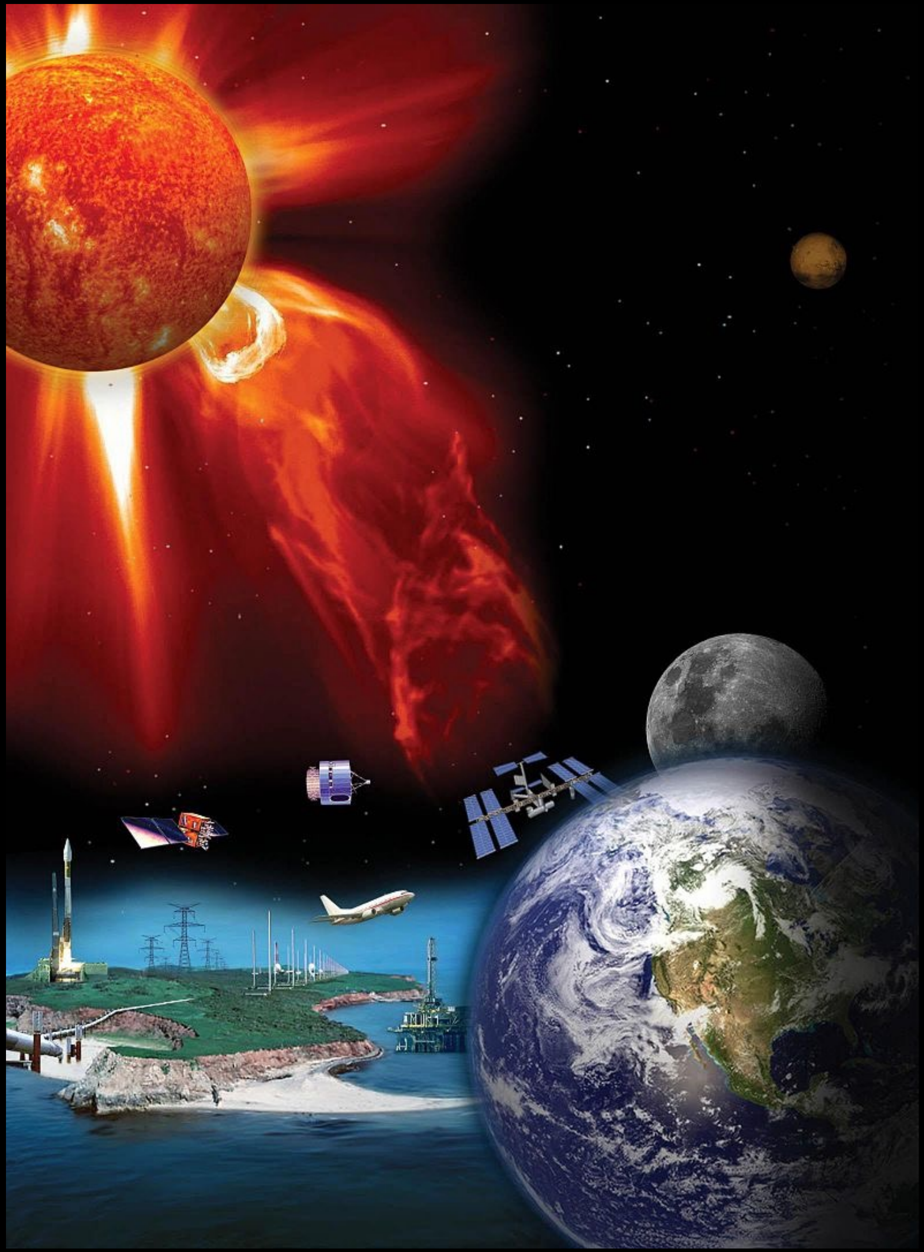
- An array of six CubeSats orbiting Earth at an altitude of 35,000 km
- SunRISE will orbit within 10 kilometers of one another well above Earth's atmosphere
- The constellation of small spacecraft uses interferometry, in which many smaller radio telescopes can be combined to mimic a single, much larger observatory with a very high resolving power
- SunRISE will create detailed 3D maps of where energetic radio emissions occur in the Sun



Animation credit: NASA

Space Weather impacts

Extreme Geomagnetic Storms



credit: NASA

Space Weather Impacts

- GPS systems
  - The charged plasma of the ionosphere bends the path of the GPS radio signal
- Satellite communications
  - Radio signals propagating to and from a satellite in orbit are affected by ionosphere condition
- Satellite Drag
  - Especially for satellite in low Earth orbit (LEO)
  - International Space Station & Hubble telescopes operate in LEO

International Space Station (ISS)

- ISS cruises through low-Earth orbit (~ 400 km), within Earth’s protection, and the station’s hull helps shield crew members from radiation

- Each day, the scientists — who are part of Johnson’s Space Radiation Analysis Group — check the space weather forecast from NOAA's Space Weather Prediction Center

- They might recommend postponing activities that require leaving the safety of the station in case of space storm

March 2022, Astronaut Matthias Maurer of ESA is pictured on the International Space Station's truss structure during a spacewalk to install thermal gear and electronics components on the orbiting lab.

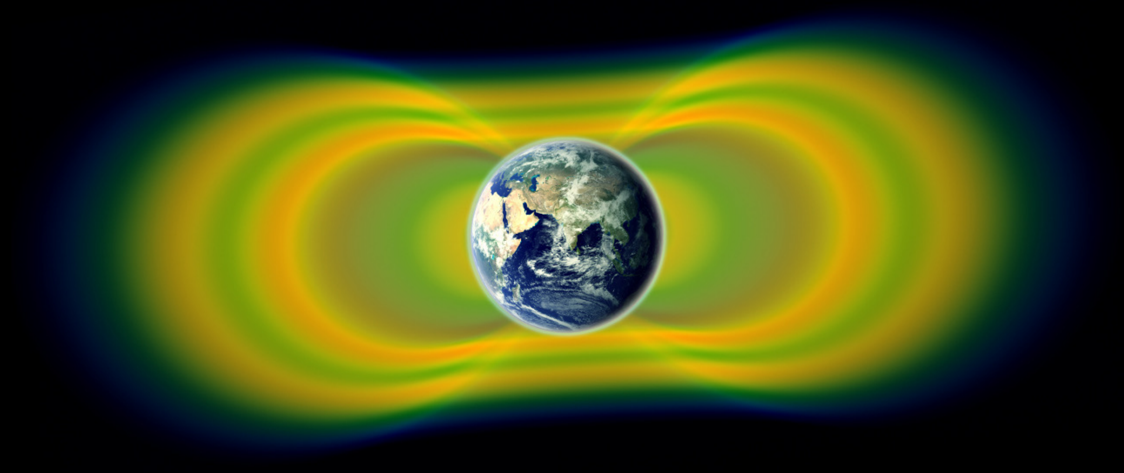
Credit: NASA/ESA

Ahead of Webb Launch, NASA was Watching the Space Weather

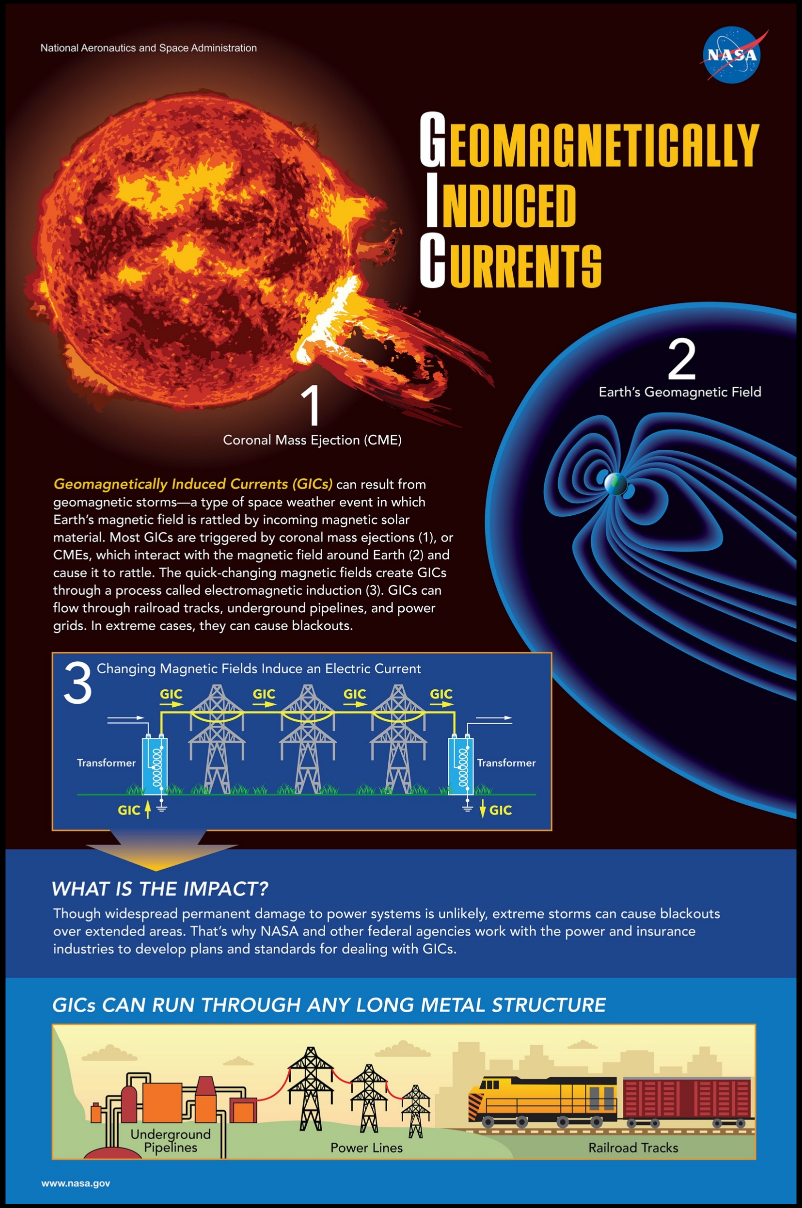
- James Webb Space Telescope (JWST) estimated cost ~ 10 billion USD, launched Dec 2021

- **Kp index:** postpone launching when the Kp index is 4 or higher, to avoid risks of losing communication with the spacecraft in the critical moments after launch

- **Van Allen belts:** One of the biggest threats to spacecraft after launch are the Van Allen radiation belts. So, it is important to monitor the belts, ensuring it stays within acceptable levels for launch



Van Allen radiation belts
credit: NASA



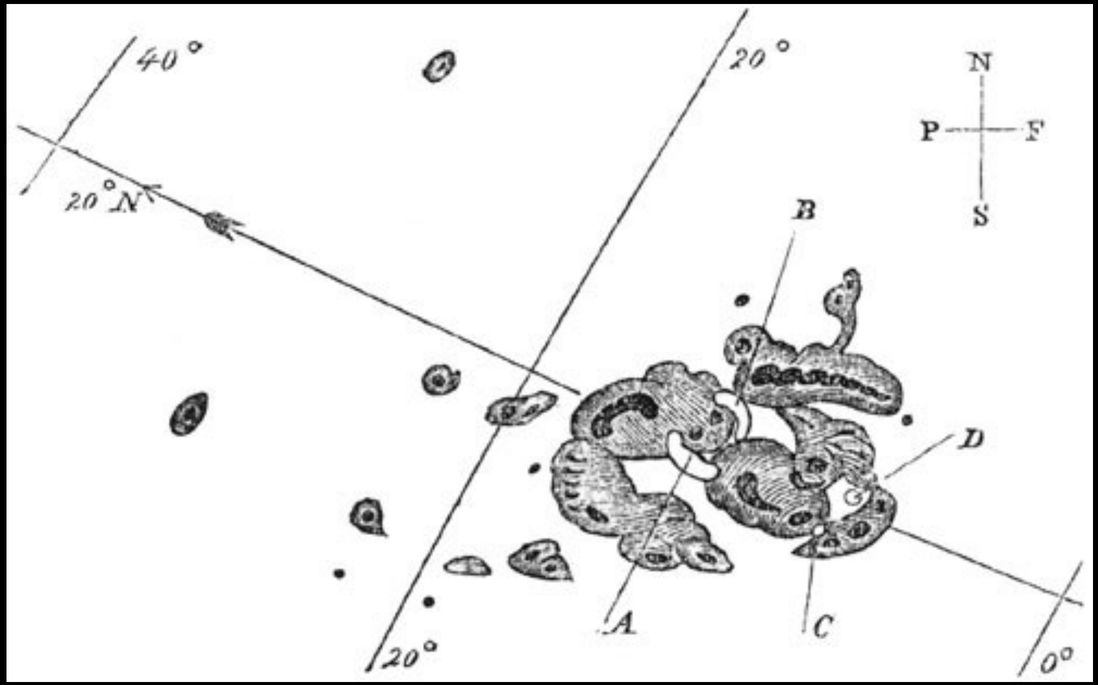
credit: NASA

Geomagnetically Induced Current (GIC)

- Quick changes in the Earth's magnetic field create GICs through electromagnetic induction and cause GIC to flow in power grids, pipelines, and railway systems
- Most GICs are triggered by CMEs
- GIC have become one of the main space weather concerns, and the potential threat in operating high-voltage power transmission systems

Carrington Event

- September 1859, cycle 10
- Major CME arrived in ~18 hours
- Caused Global telegraph lines to spark
- Northern lights were observed as far south as Cuba, Hawaii and Tahiti
- Estimated total economic impact on modern technology : $2 trillion (National Academy of Science)



Sunspot of September 1, 1859, as sketched by Richard Carrington

Solar storm 1967

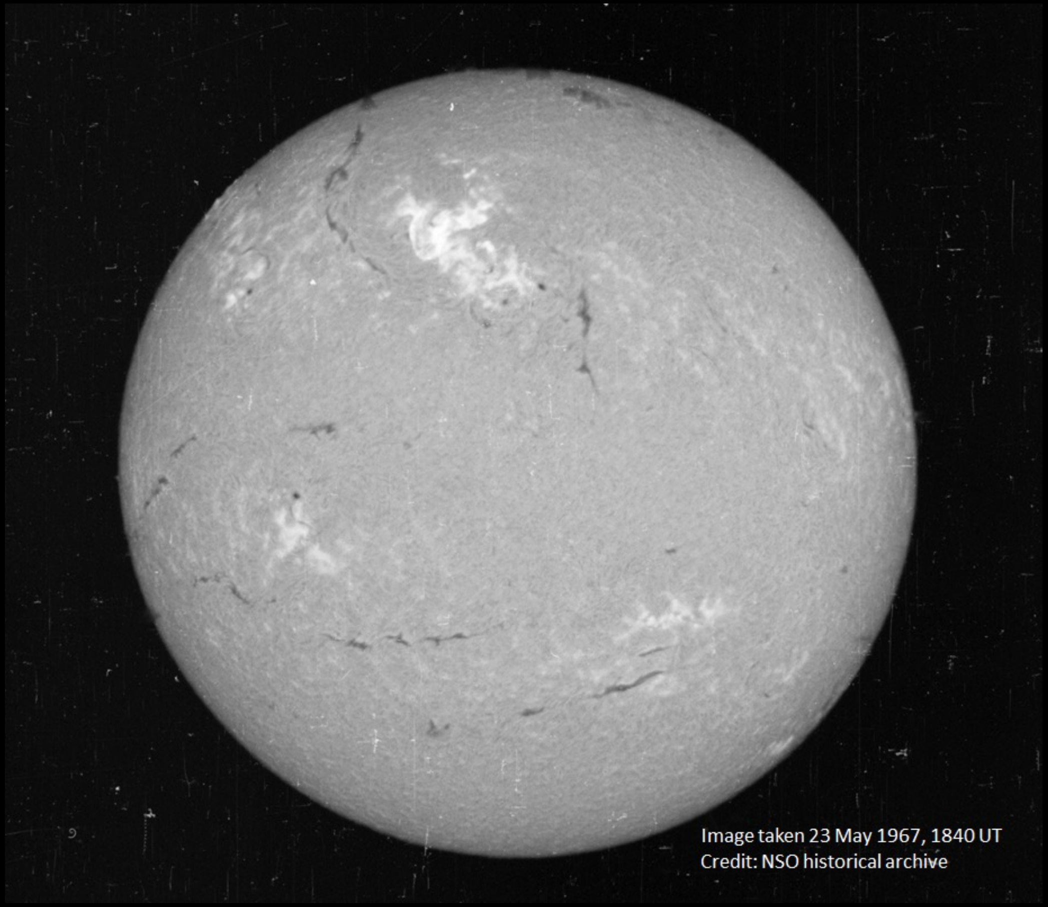
- The U.S. military began monitoring solar activity and space weather in the late 1950s

- On May 18, 1967, an unusually large group of sunspots emerge to the visible disk

- As a solar flare erupted on May 23rd from this sunspot group, radars at all three Ballistic Missile Early Warning System (BMEWS) sites were disrupted. These radars were designed to detect incoming Soviet missiles, appeared to be jammed

- US Air Force prepared aircraft for war but luckily military space weather forecasters conveyed information about the solar flare

- Auroras could be seen in New Mexico, US



A view of the Sun on May 23, 1967, in a narrow visible light (Hydrogen-alpha). The bright region in the top center region of brightness shows the area where the large flare occurred

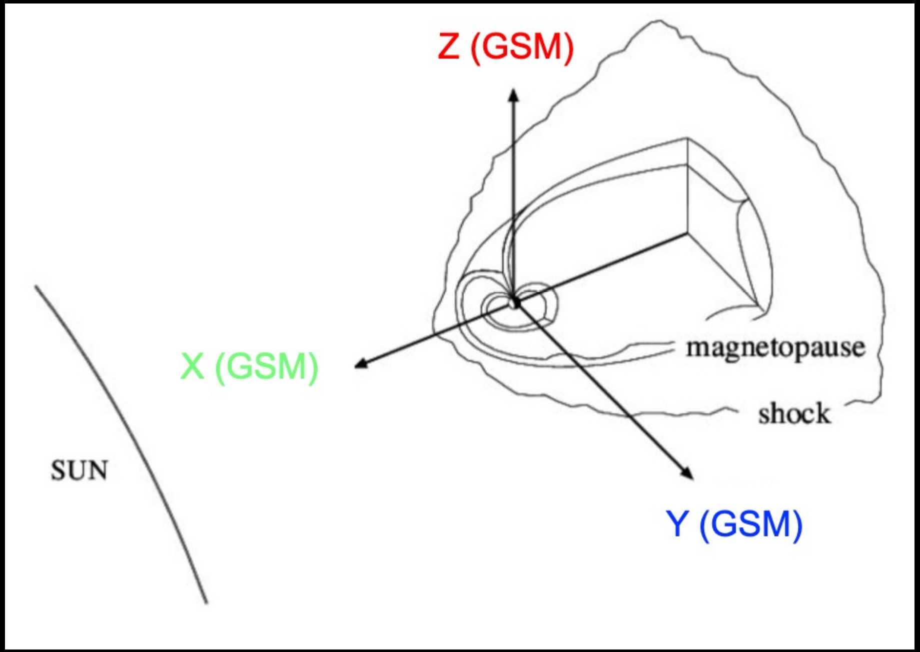
Quebec Blackout

- March 13, 1989
- Caused a 12-hour blackout in Quebec
- Kept the Montreal metro shut and closed the Doral Airport
- Caused a malfunction of the Space shuttle Discovery
- Auroras could be seen as far south as Florida and Cuba

Halloween Geomagnetic Storm

- October 19 to November 7 - 2003
- Cycle 23, 2-3 years after solar maximum
- 17 major flares
- Solar & Heliospheric Observatory (SOHO) satellite failed temporary
- Auroras could be seen in Texas & Florida

- Phi is the angle of the interplanetary magnetic field that is being carried out by the solar wind
- It is measured in the GSM (geocentric solar magnetospheric) coordinate system
- In this system the X-axis points from the Earth to the Sun and the Z-axis is pointing along the direction of the Earth's north magnetic pole. This puts the Y-axis roughly pointing to the left as one looks at the Sun from the Earth
- Phi is the angle made by the field in the XY plane. This means that Phi would be 0° if it were pointing at the Sun and 180° if it were pointing from the Sun to the Earth. Sudden and rapid changes in the Phi angle in conjunction with increased solar wind speeds and B_z fluctuations is common during a CME impact



Credit: Eija Tanskanen