Space Climate

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The Sun

The Source of Life
The Source of Troubles

What Is The Sun Made of?

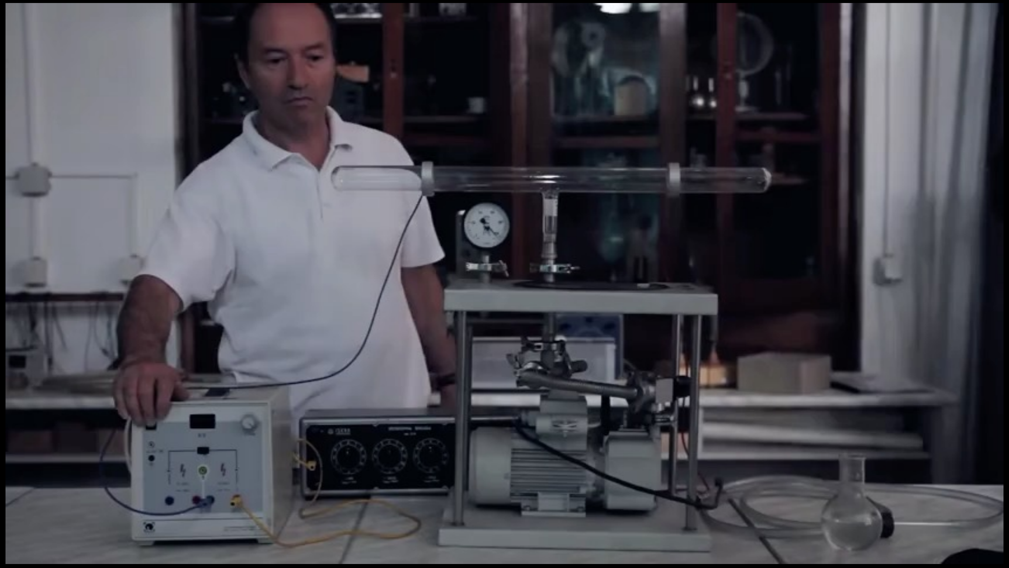
Video Credit: Spitz Creative Media

- Matter in the known Universe is often classified as: solid, liquid, gaseous, and plasma
- The Sun is composed of plasma
- 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 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 the ionized 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

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

Radiation Zone:
- Energy moves outward as electromagnetic radiation
- Temp: ~ 2 MK, radius: ~300,000 km

Convection Zone:
- Consist of plasma, generates magnetic field
- radius: ~200,000 km

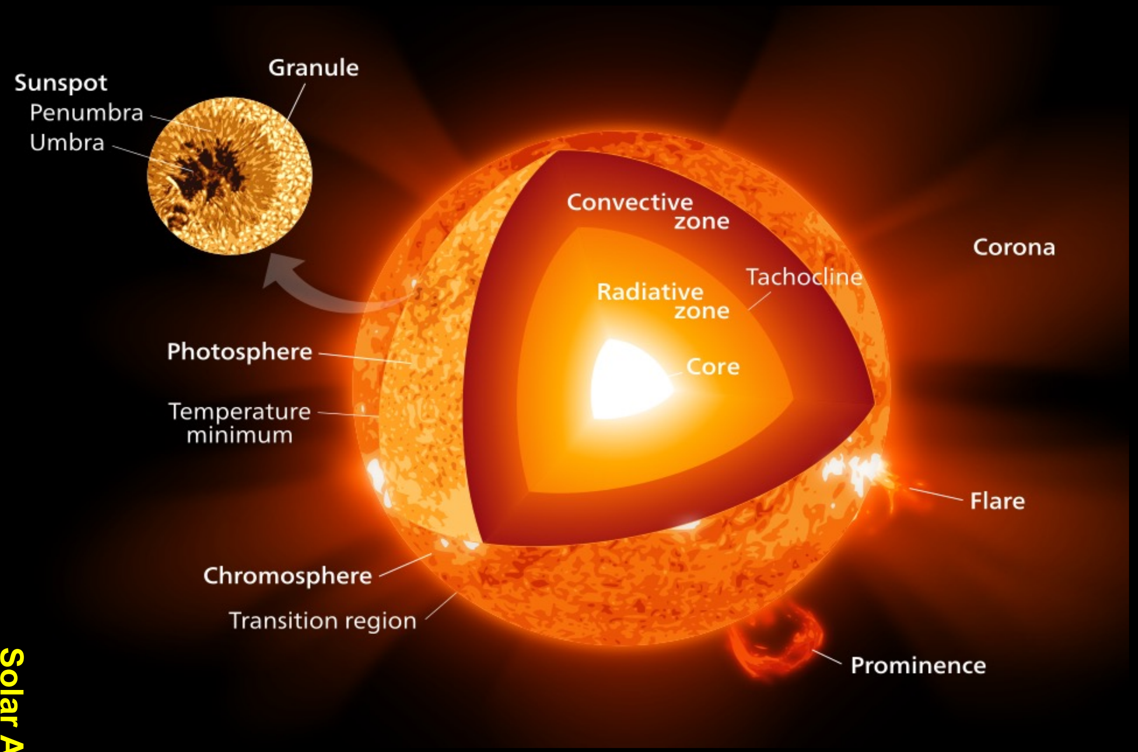
Photosphere:
- Visible surface, Radius: ~500 km thick, T: 5800 K
- Active regions, sunspots, bright faculae, granules

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

Coronal Heating Problem

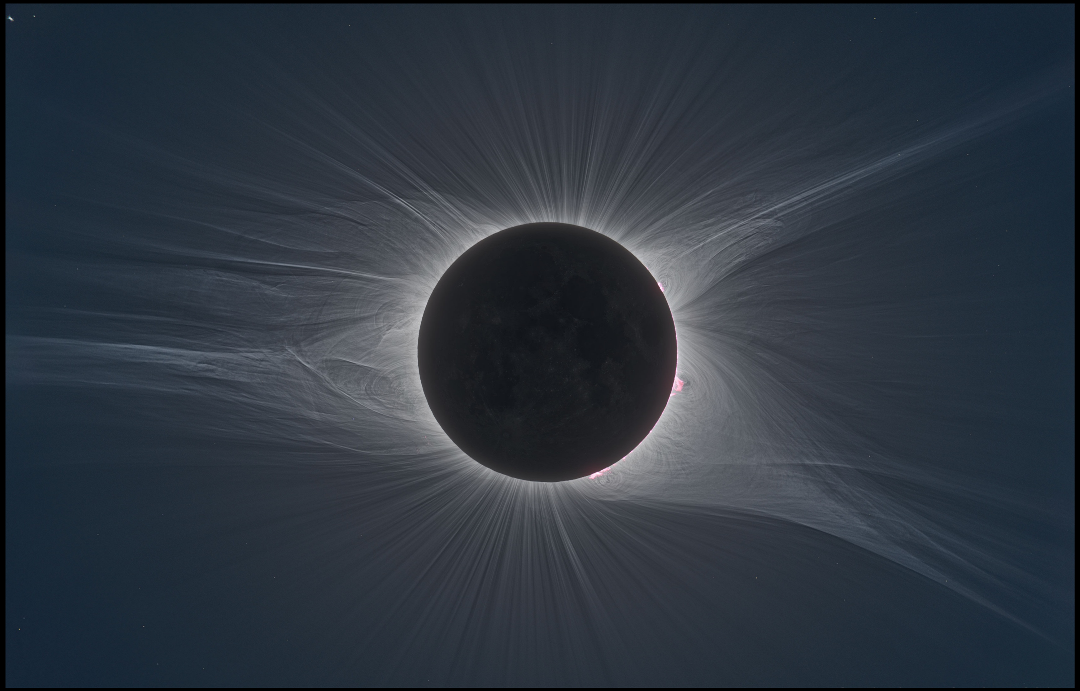
- Corona can be observed during a solar eclipse. The primary coronal emission is in the UV and soft x-ray range

- 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



Solar eclipse of 30 April, 2018

Credit: Nicolas Lefaudeux

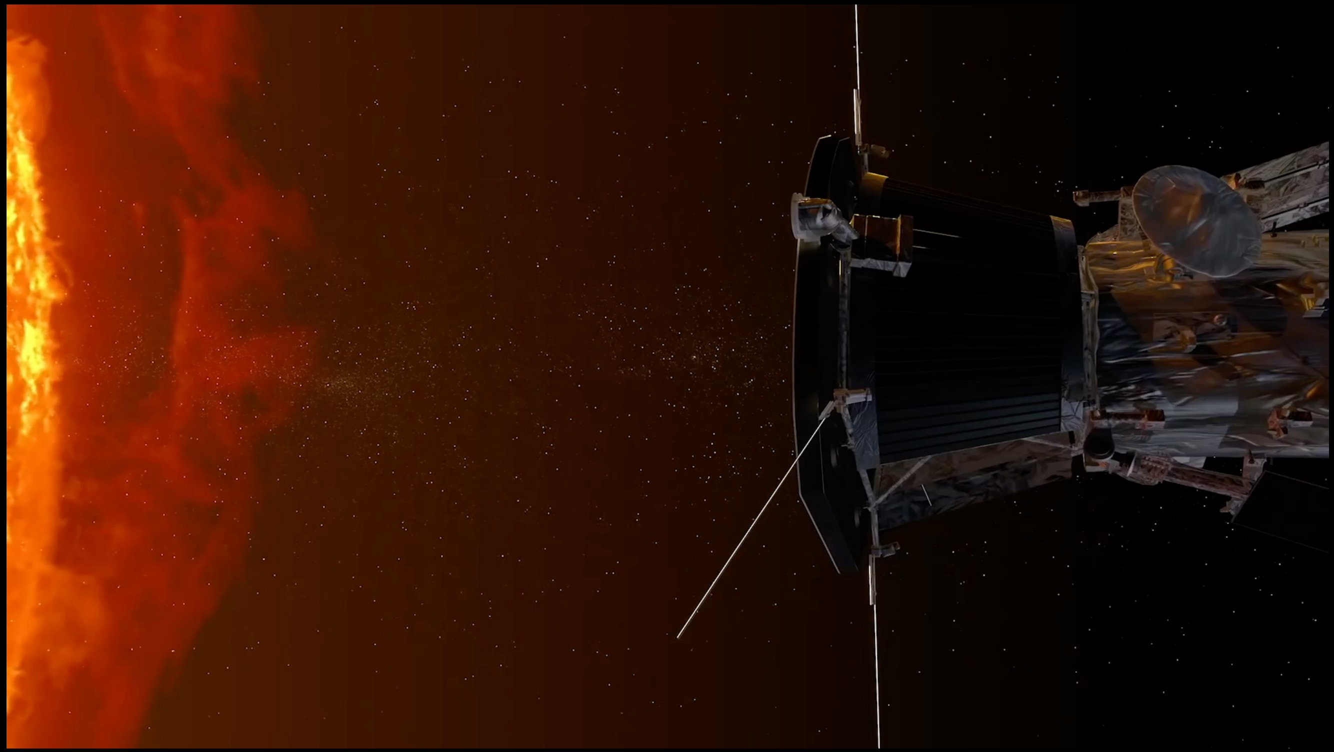
Solar corona

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

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

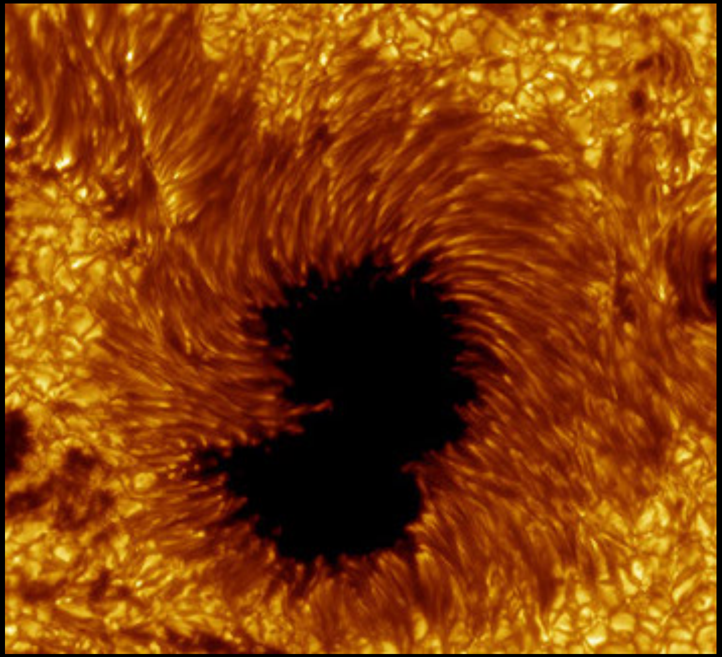
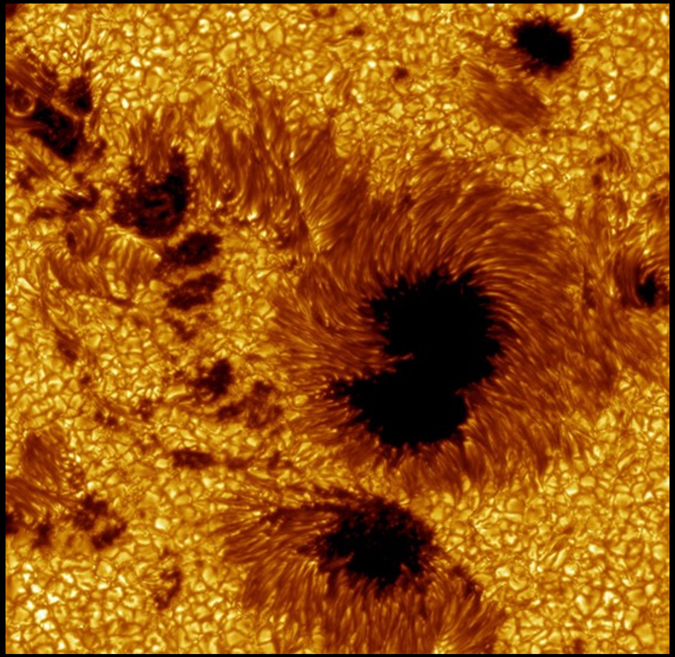


Image credit: Royal Swedish Academy of Sciences / NASA/SDO

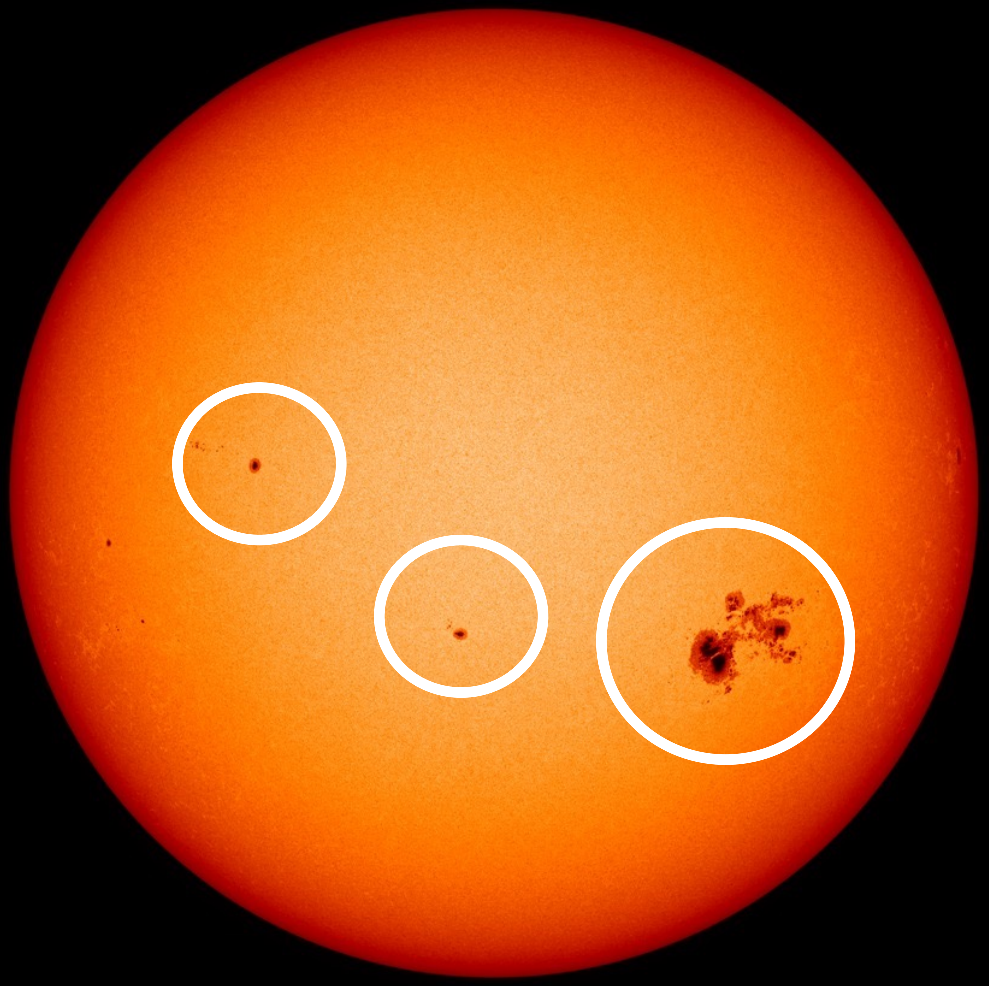


Sunspots:

- Appear dark - the magnetic fields get in the way of energy and heat being transported to the surface
- 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

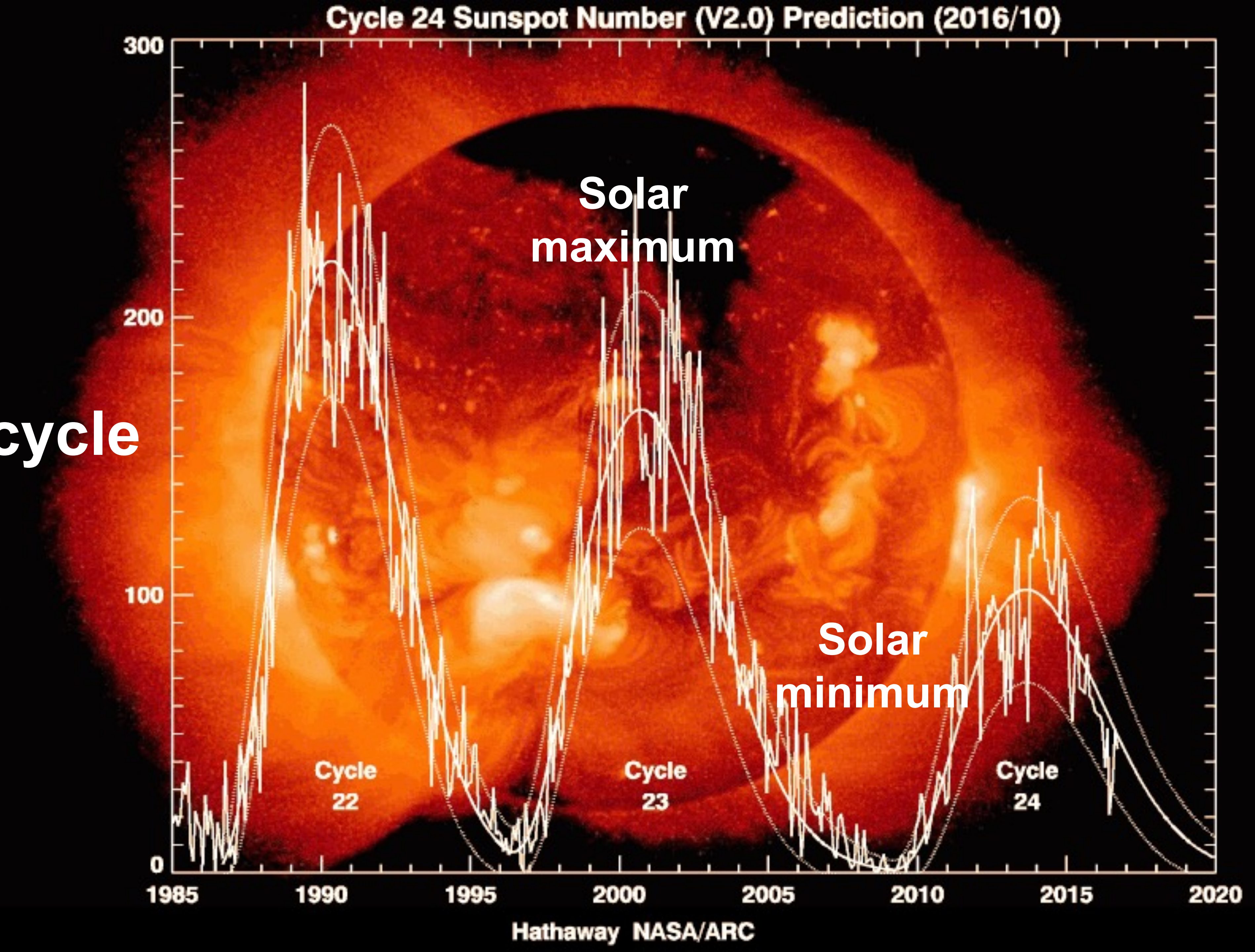
Solar Active Regions (ARs)

- 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



Sunspot groups
Credit: SDO/NASA

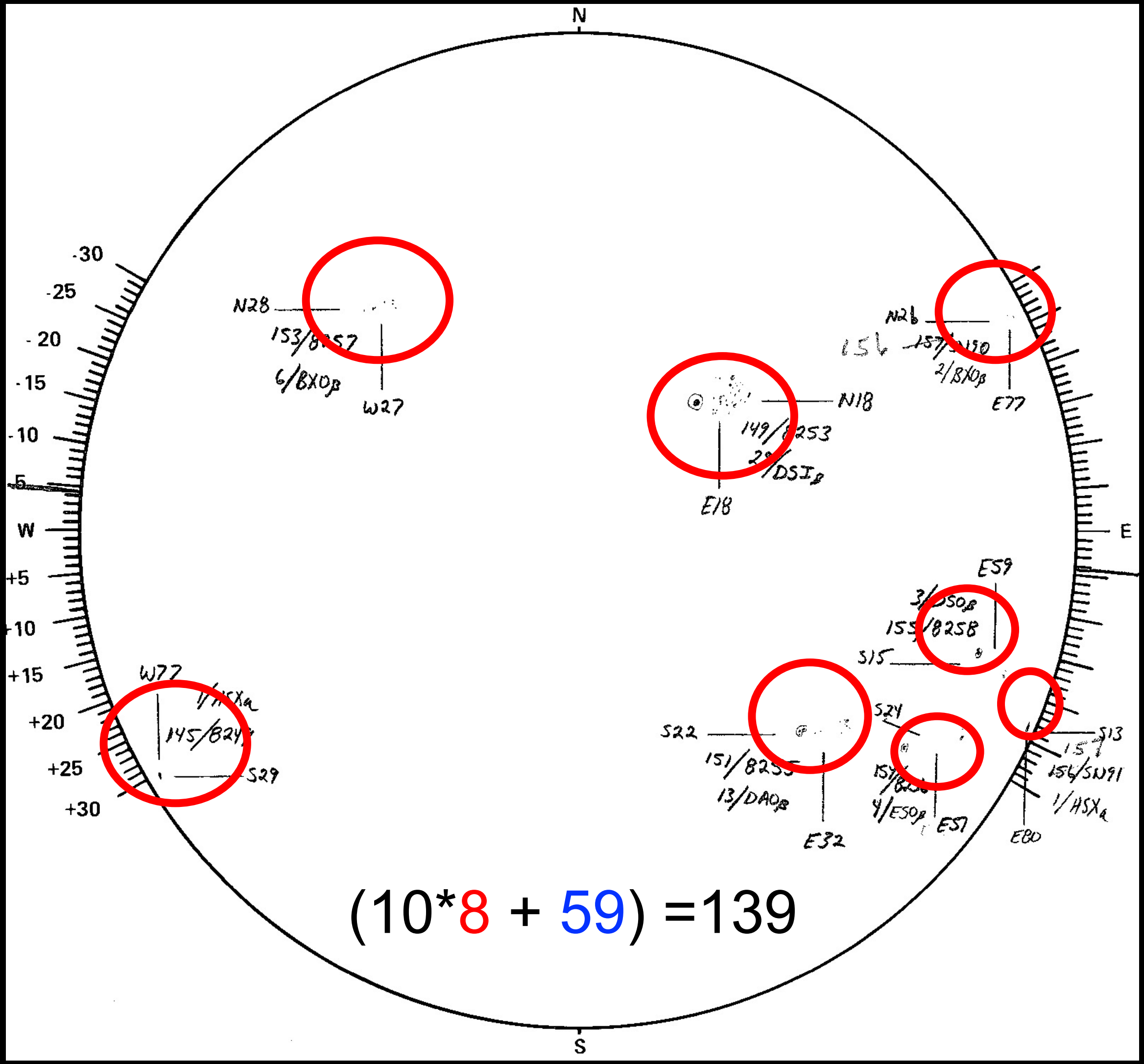
Solar cycle



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

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

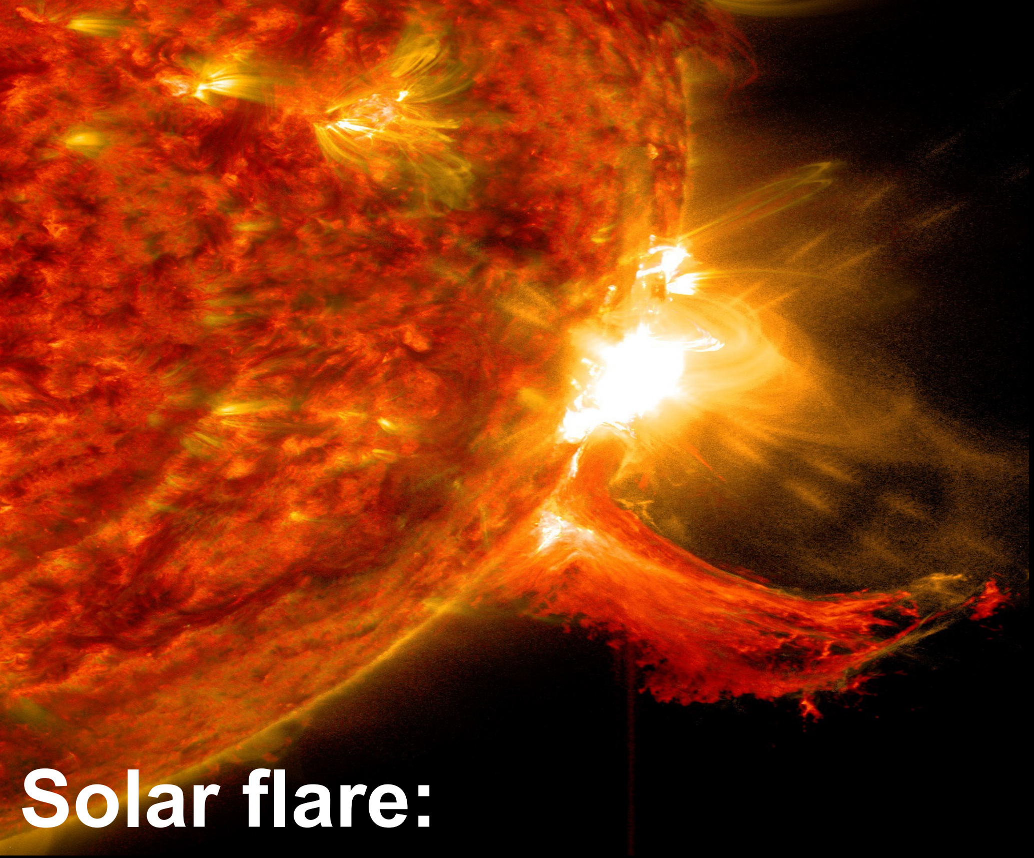
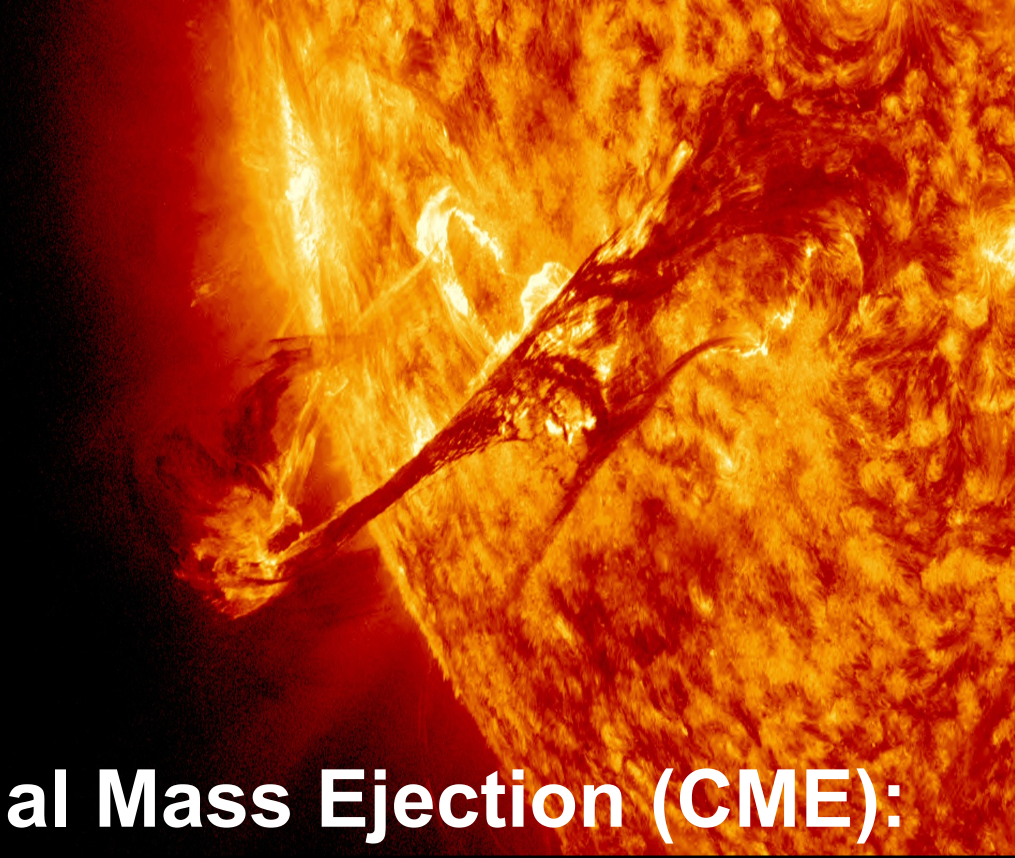


Image credit: NASA



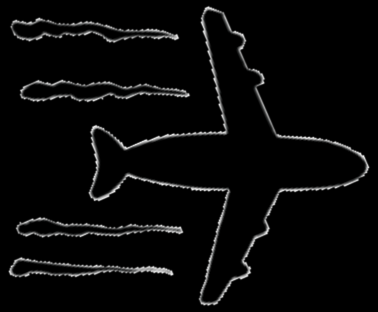
Solar flare:

- 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 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

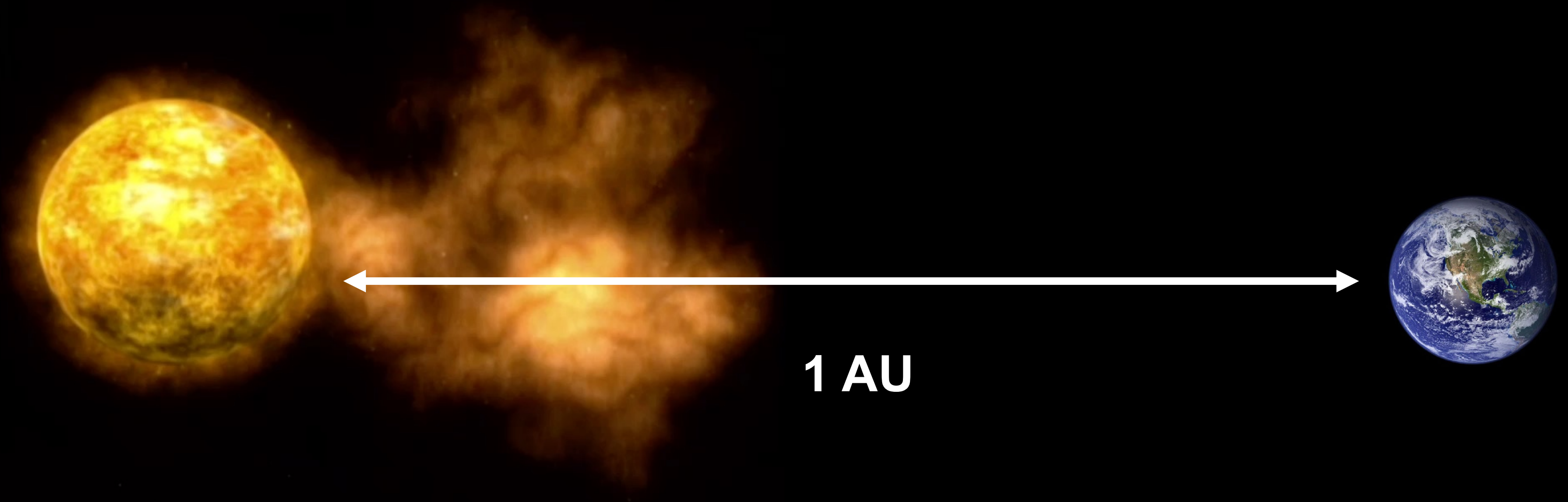
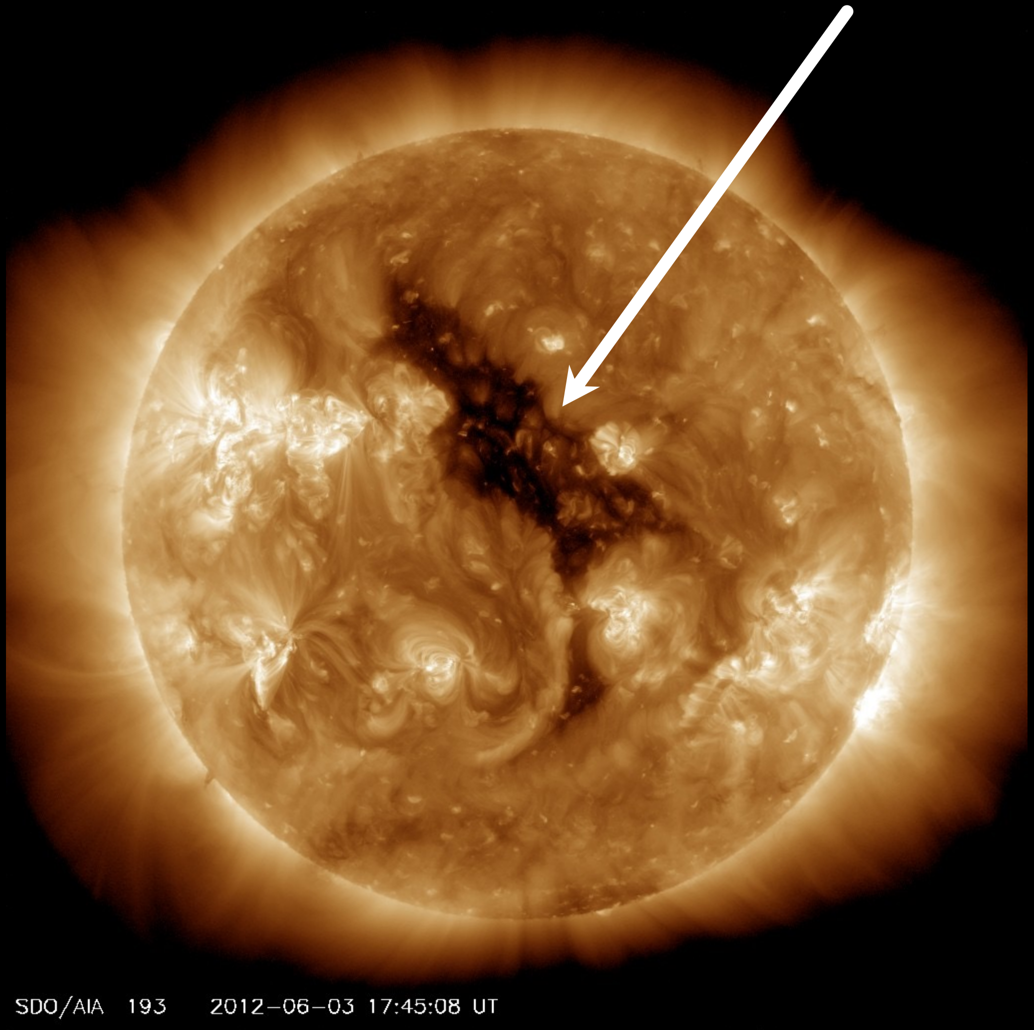


Image and animation credit: NASA/Goddard

Coronal Holes



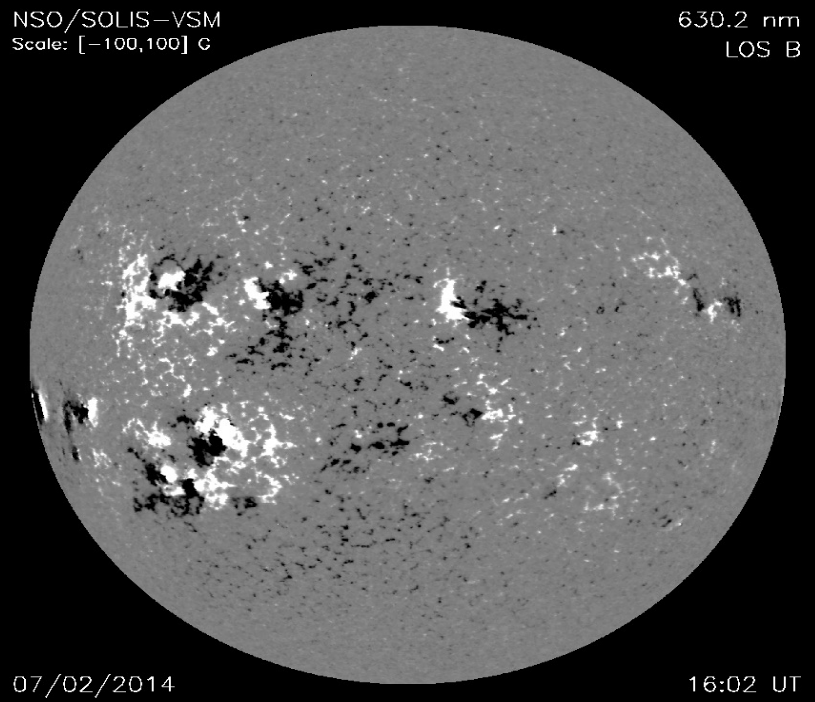
- Appear in the Corona
- Observed in the EUV and soft X-ray images
- Cooler and less dense than surrounding plasma
- Associated with open and unipolar magnetic field lines which allows the solar wind to escape more easily to the space
- Produces the fast solar winds, referred to as high speed streams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

Solar Observation

Ground-based
Space-based

150-Foot Solar Tower
at
Mount Wilson Observatory

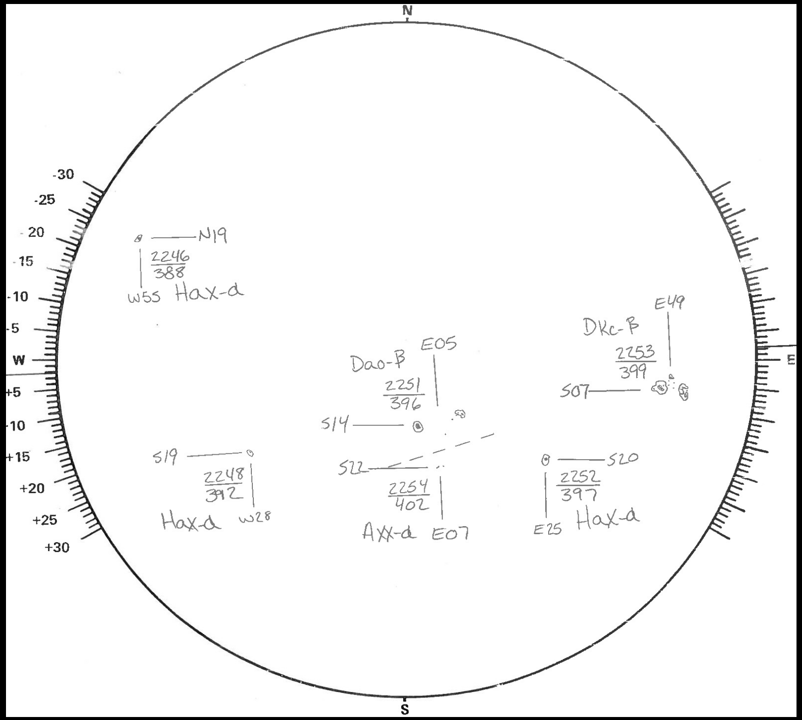
Solar Observing Optical Network
at
Holloman Air force base



Magnetogram

07.02.2014

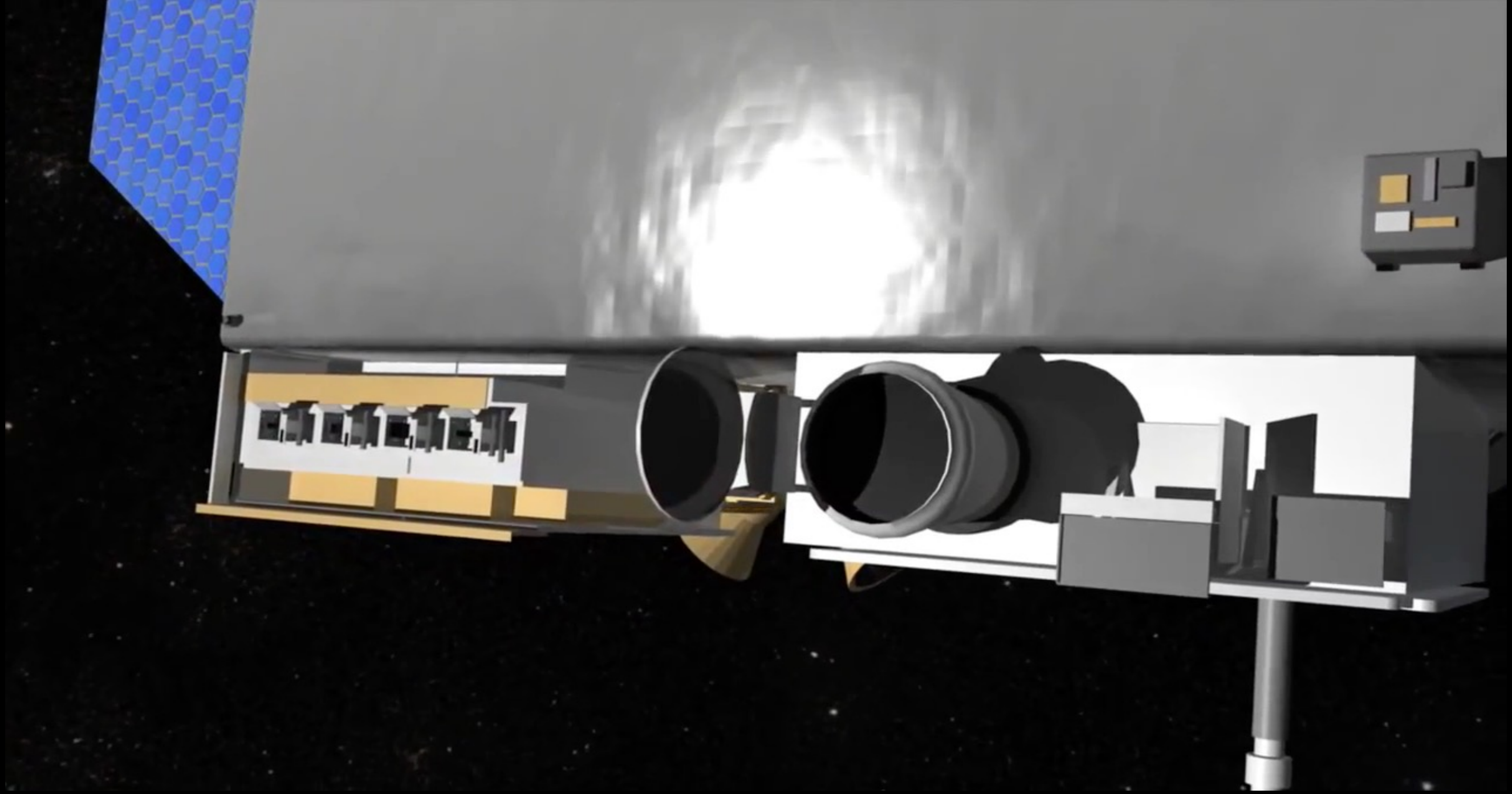
Iron spectral line at 8468 Å



Sunspot Drawing

01.01.2015

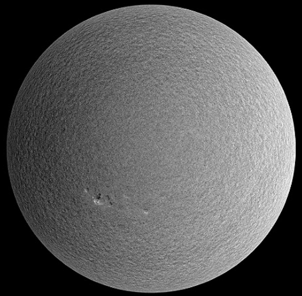
Hα spectral line at 6563 Å



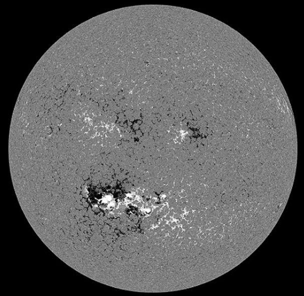
Near-Earth Space Observation

Solar Dynamic Observatory (SDO) Satellite

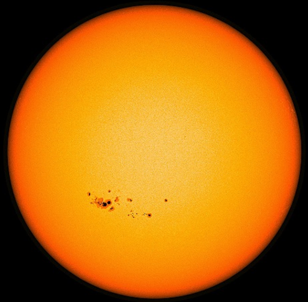
- Launched in : February, 2010 Orbit: ~35,000 km
- HMI: Studies oscillation and magnetic field at photosphere
- AIA: Studies the sun in multiple wavelength (white light, Seven EUV & two UV)
- EVE: Studies solar EUV irradiance



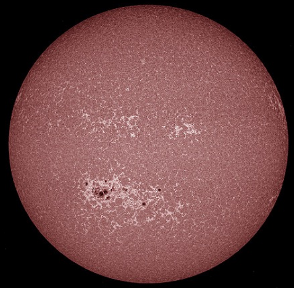
HMI Dopplergram
Surface movement
Photosphere



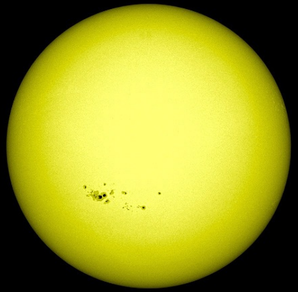
HMI Magnetogram
Magnetic field polarity
Photosphere



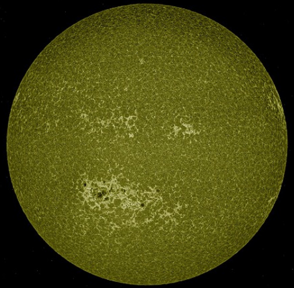
HMI Continuum
Matches visible light
Photosphere



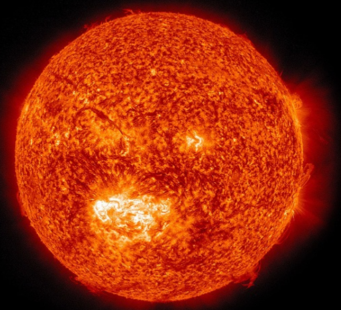
AIA 1700 Å
4500 Kelvin
Photosphere



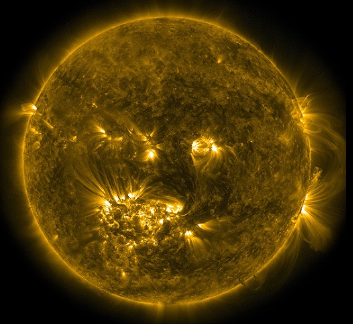
AIA 4500 Å
6000 Kelvin
Photosphere



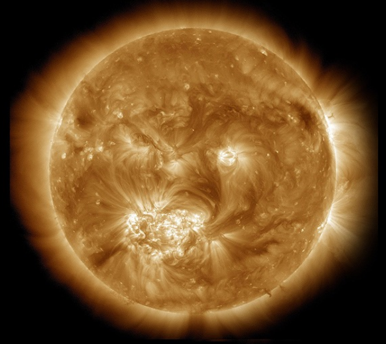
AIA 1600 Å
10,000 Kelvin
Upper photosphere/
Transition region



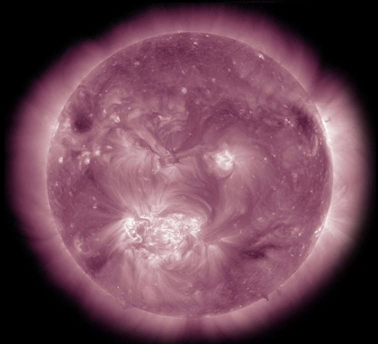
AIA 304 Å
50,000 Kelvin
Transition region/
Chromosphere



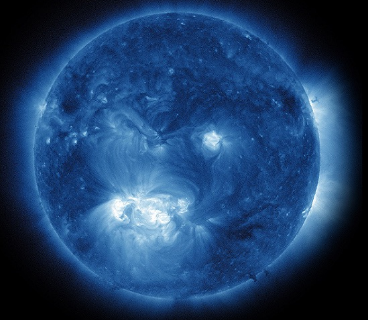
AIA 171 Å
600,000 Kelvin
Upper transition
Region/quiet corona



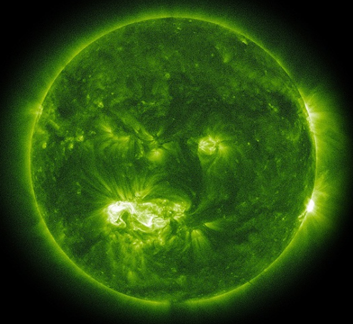
AIA 193 Å
1 million Kelvin
Corona/flare plasma



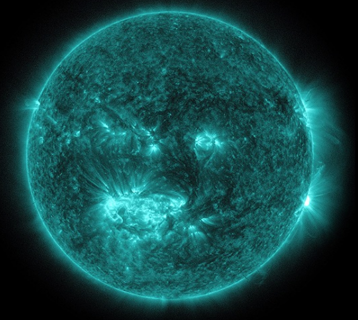
AIA 211 Å
2 million Kelvin
Active regions



AIA 335 Å
2.5 million Kelvin
Active regions



AIA 094 Å
6 million Kelvin
Flaring regions



AIA 131 Å
10 million Kelvin
Flaring regions

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

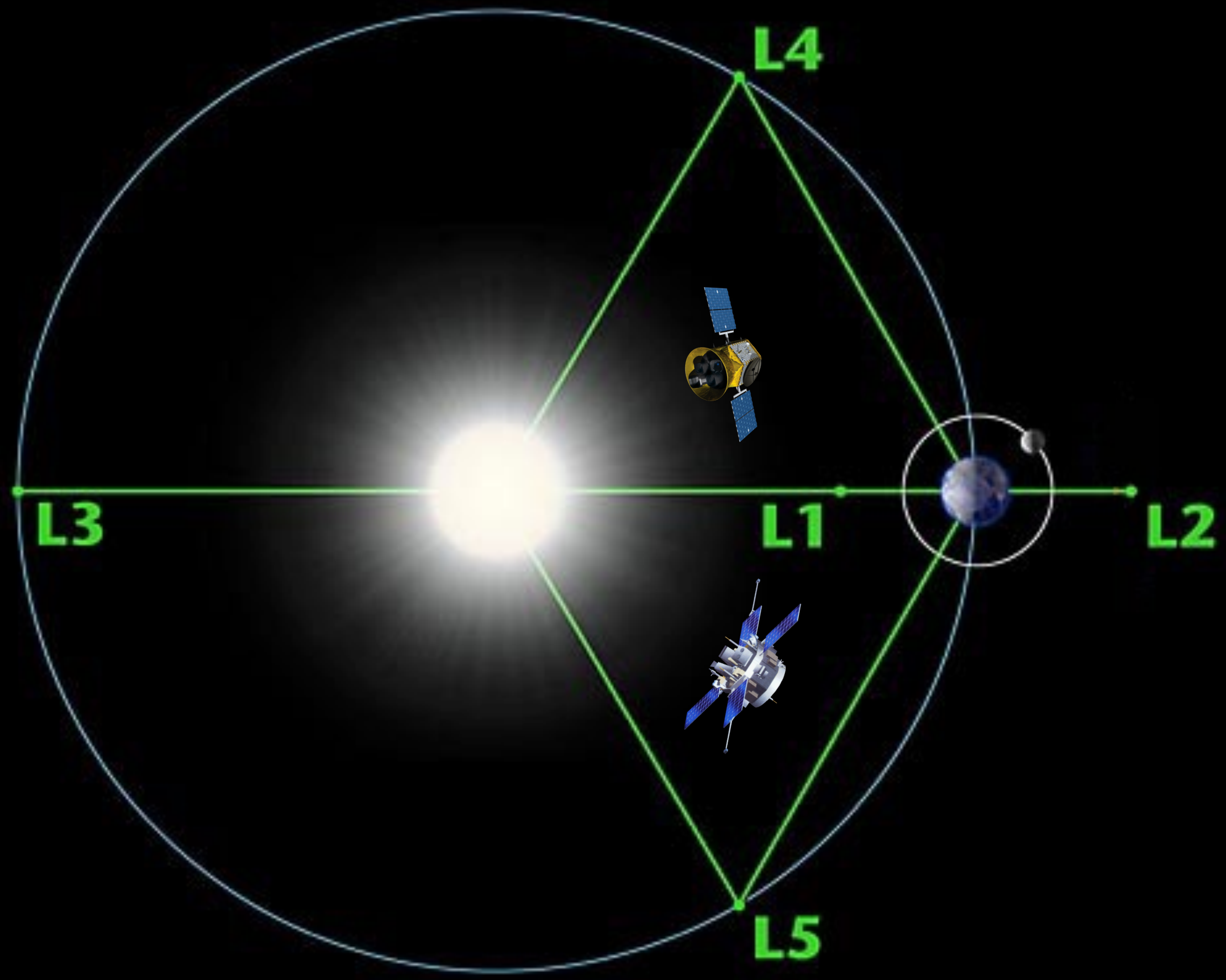
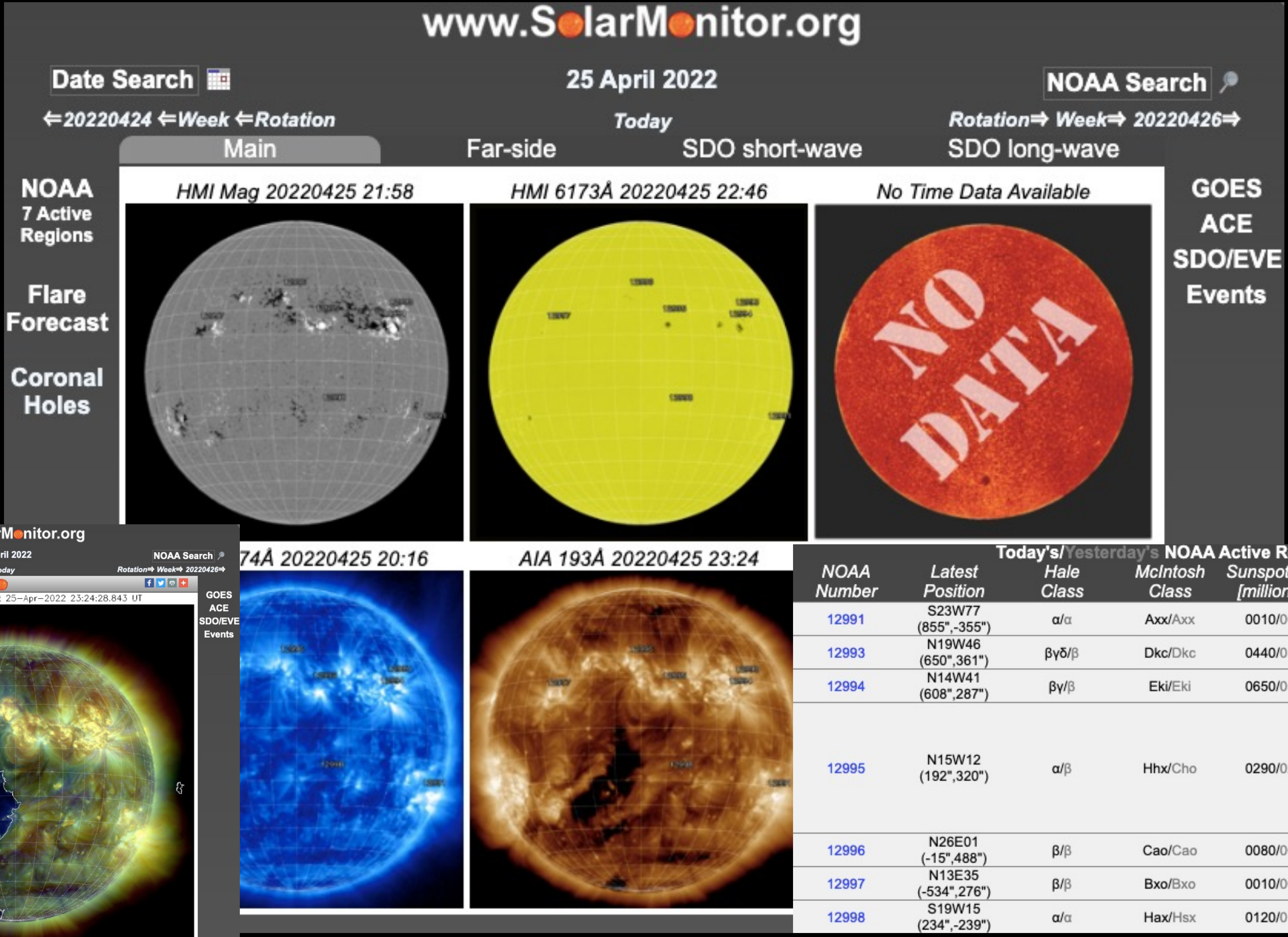
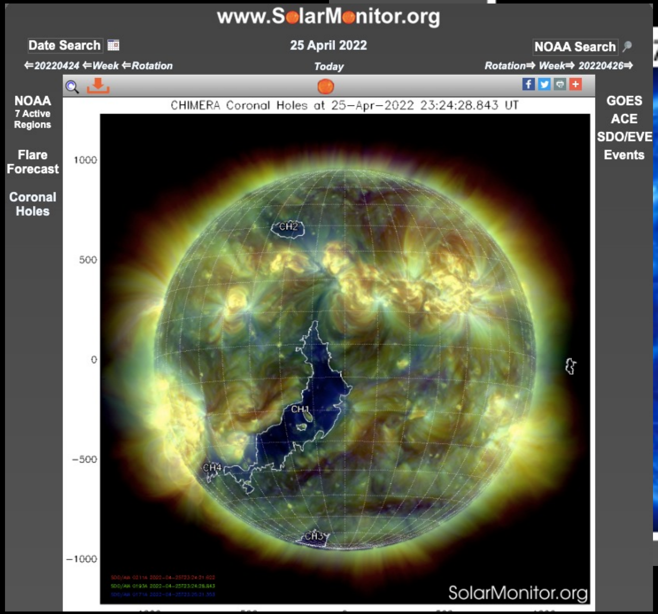


Image credit: NASA/WMAP Science Team





Today's/Yesterday's NOAA Active Regions

NOAA Number	Latest Position	Hale Class	McIntosh Class	Sunspot Area [millionths]	Number of Spots	Recent Flares
12991	S23W77 (855",-355")	α/α	Axx/Axx	0010/0010	01/02	-
12993	N19W46 (650",361")	βγδ/β	Dkc/Dkc	0440/0360	11/10	-
12994	N14W41 (608",287")	βγ/β	Eki/Eki	0650/0580	20/22	- / C2.0(10:39) C1.6(09:12)
12995	N15W12 (192",320")	α/β	Hhx/Cho	0290/0280	03/07	C1.3(12:48) C1.2(12:05) C1.4(10:44) C1.6(08:50) C4.6(05:51) M1.1(03:52) M1.2(01:18) / C2.1(22:58)
12996	N26E01 (-15",488")	β/β	Cao/Cao	0080/0070	02/03	-
12997	N13E35 (-534",276")	β/β	Bxo/Bxo	0010/0010	04/03	-
12998	S19W15 (234",-239")	α/α	Hax/Hsx	0120/0120	01/01	-

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

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

Sun-Earth
Coupling

Interplanetary Magnetic Field (IMF)

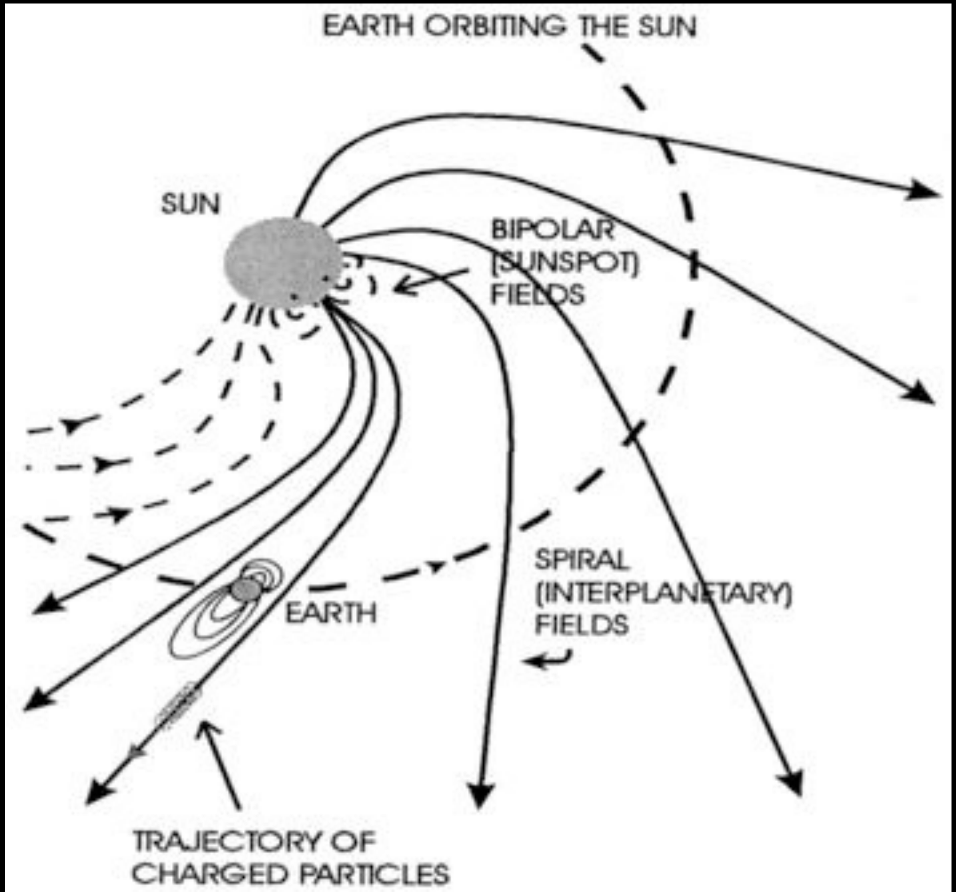


Image credit: NASA/JPL

- 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
- As the Sun rotates, its magnetic field twists into an Archimedean spiral. This phenomenon is often called the Parker spiral

Magnetosphere

- When you look at the Earth from space, it looks like it is floating in a black void
- Th Earth is actually surrounded by a complex system formed by the interaction of the solar wind with the Earth's magnetic field
- The solar wind compresses the sunward side of the magnetosphere to a distance of ~ 10 $R_\oplus$ and its nightside to possibly 1000 $R_\oplus$
- The magnetosphere is highly dynamic

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

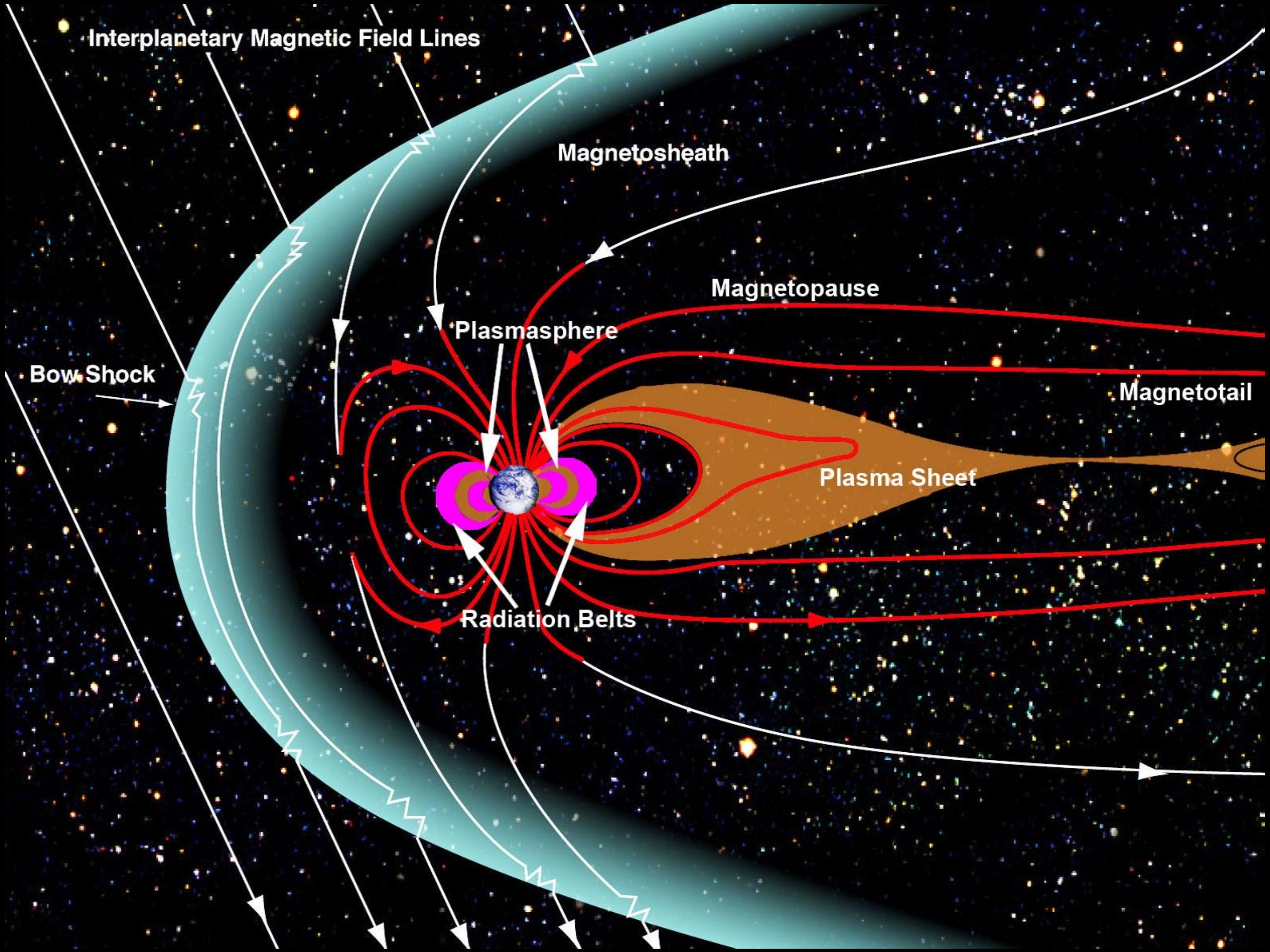
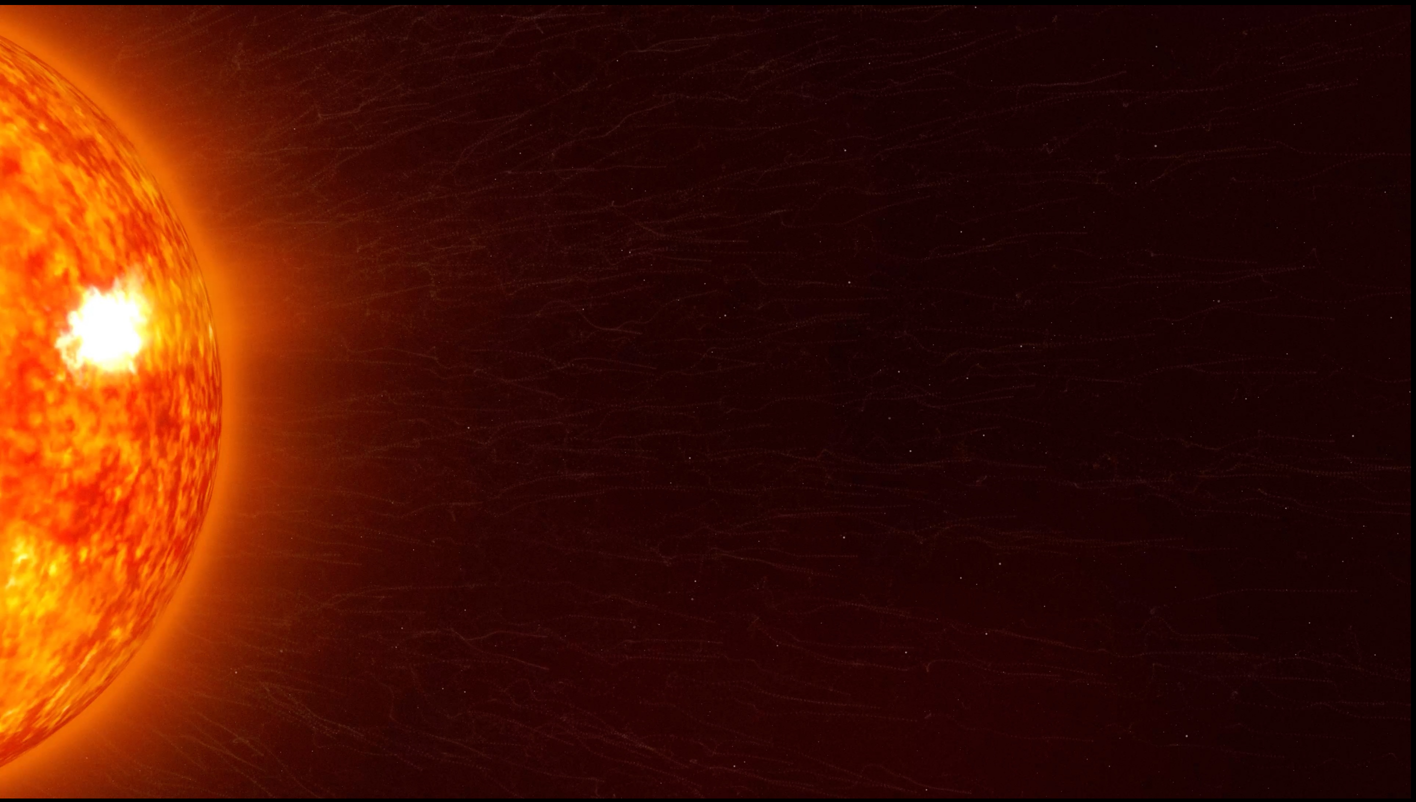


Image credit: NASA



Animation credit: NASA GSFC/CIL/Bailee DesRocher

Magnetospheres of Our Solar system

- 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

Radiation belts

- Donut-shaped regions encircling Earth
- High-energy particles, mostly electrons and ions, are trapped by Earth's magnetic field
- **Inner belt:** part of plasmasphere and 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

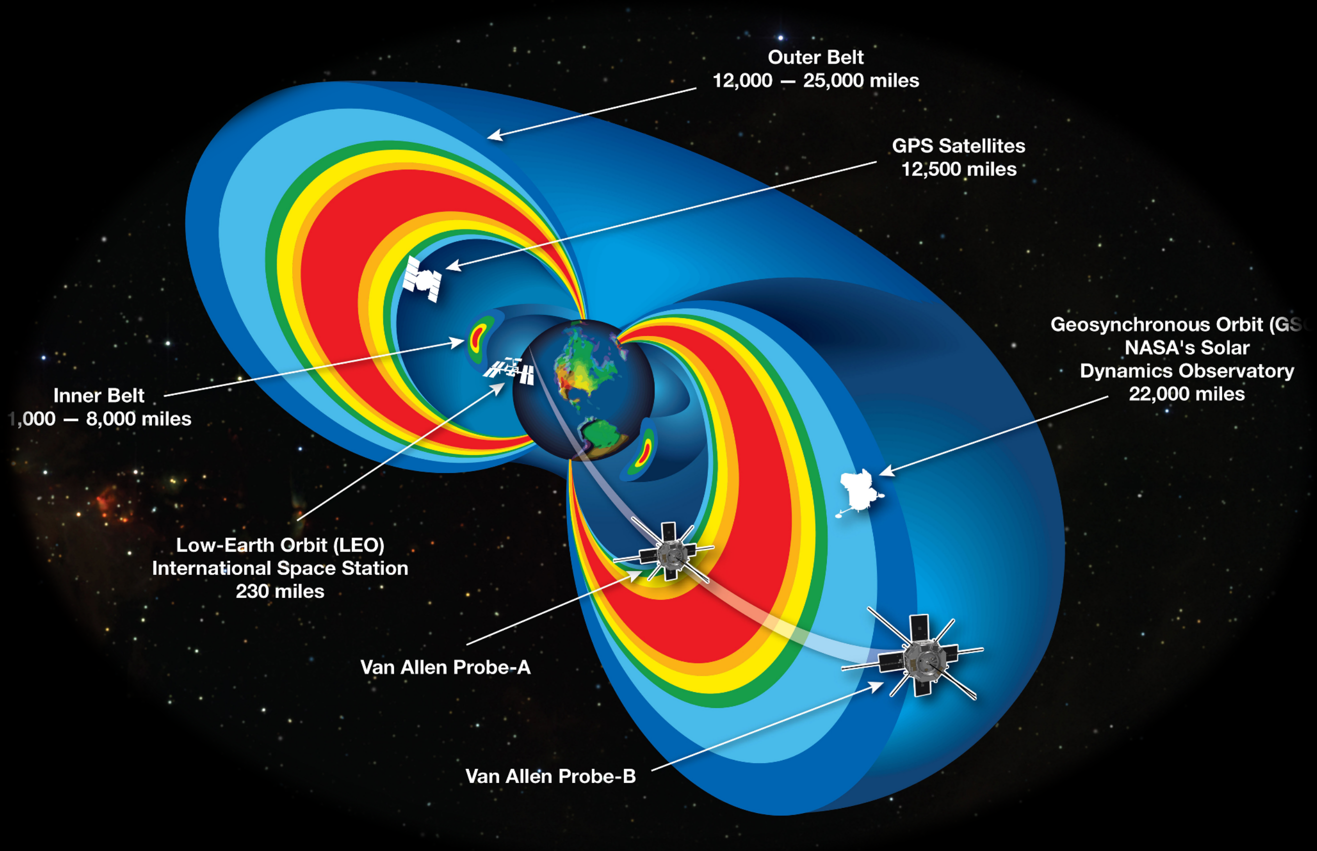
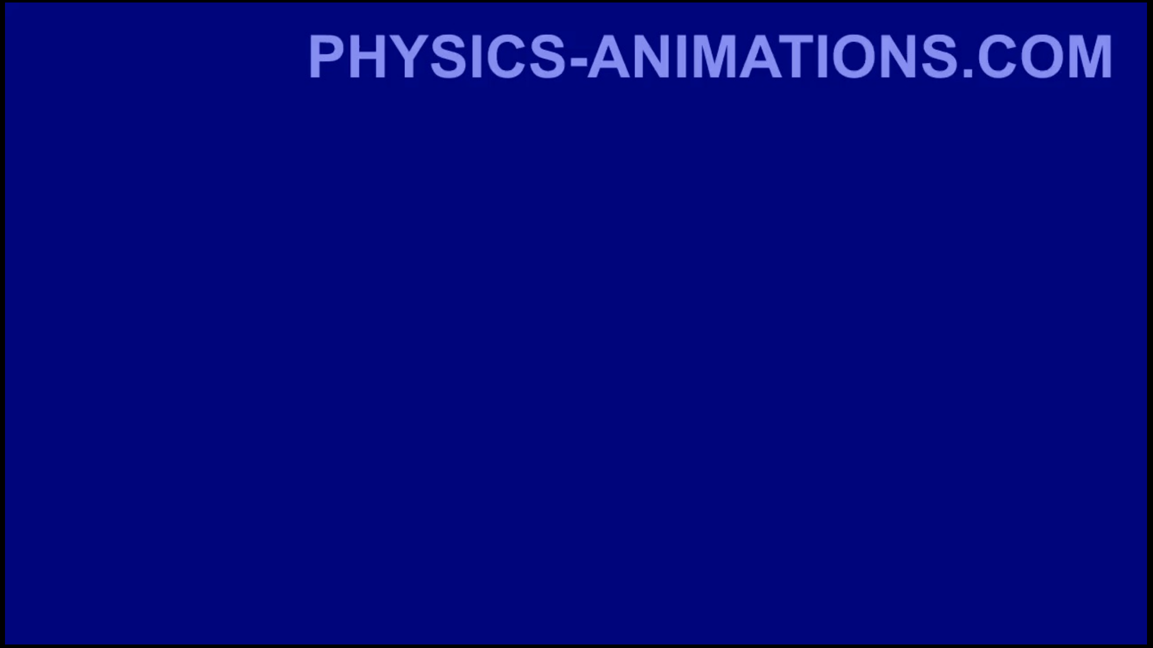


Image credit: NASA

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

Bow shock

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

- A shock wave on the sunward 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 $R_\oplus$

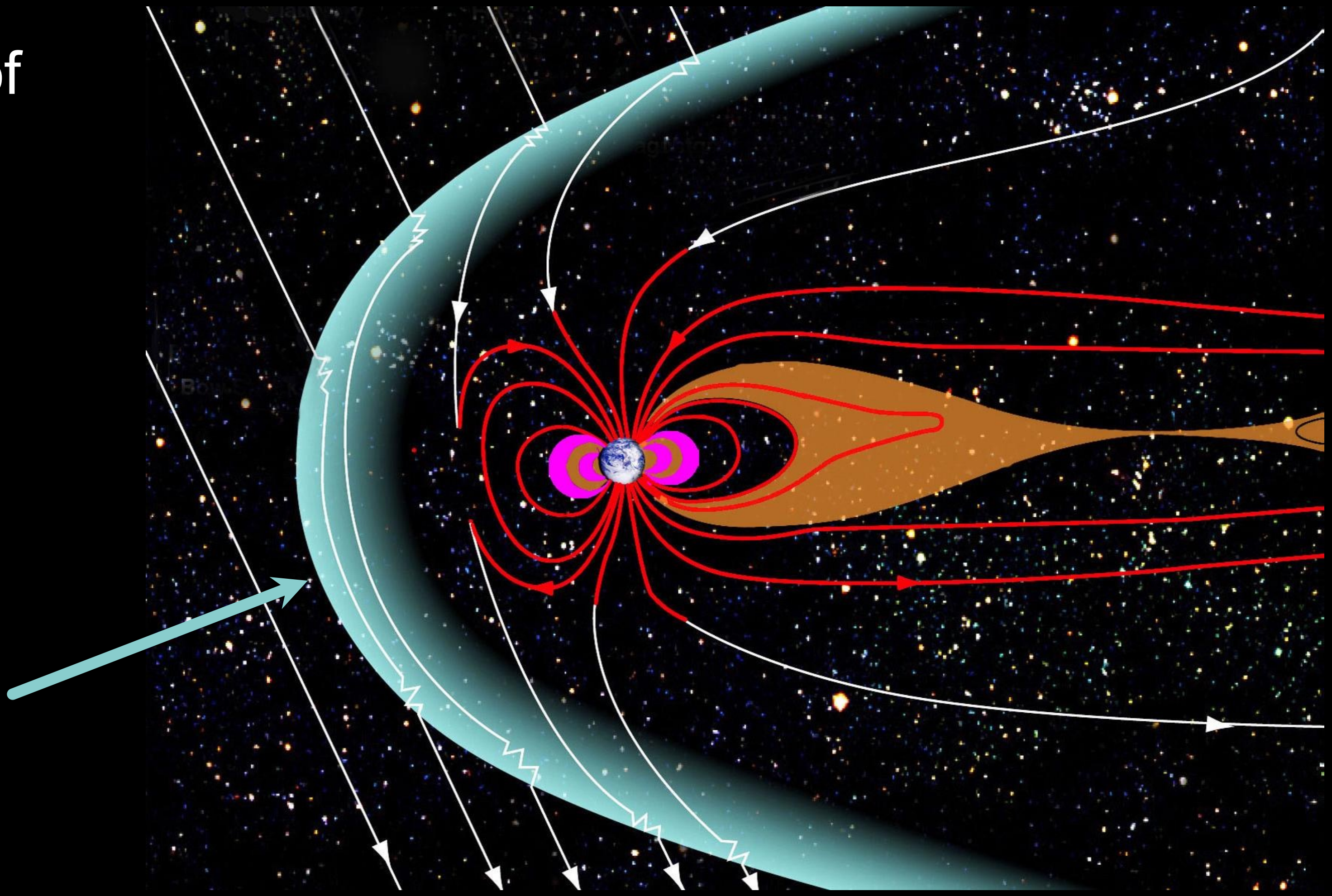


Image credit: NASA/Goddard

Magnetopause

- Boundary between the magnetosphere and solar wind
- Total pressure = thermal + dynamic + magnetic

$$P = n\,k_B\,T_i \;+\; n\,m_i\,V^2 \;+\; \frac{B^2}{2\mu_0}$$

$k_B \sim 10^{-23}$

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**

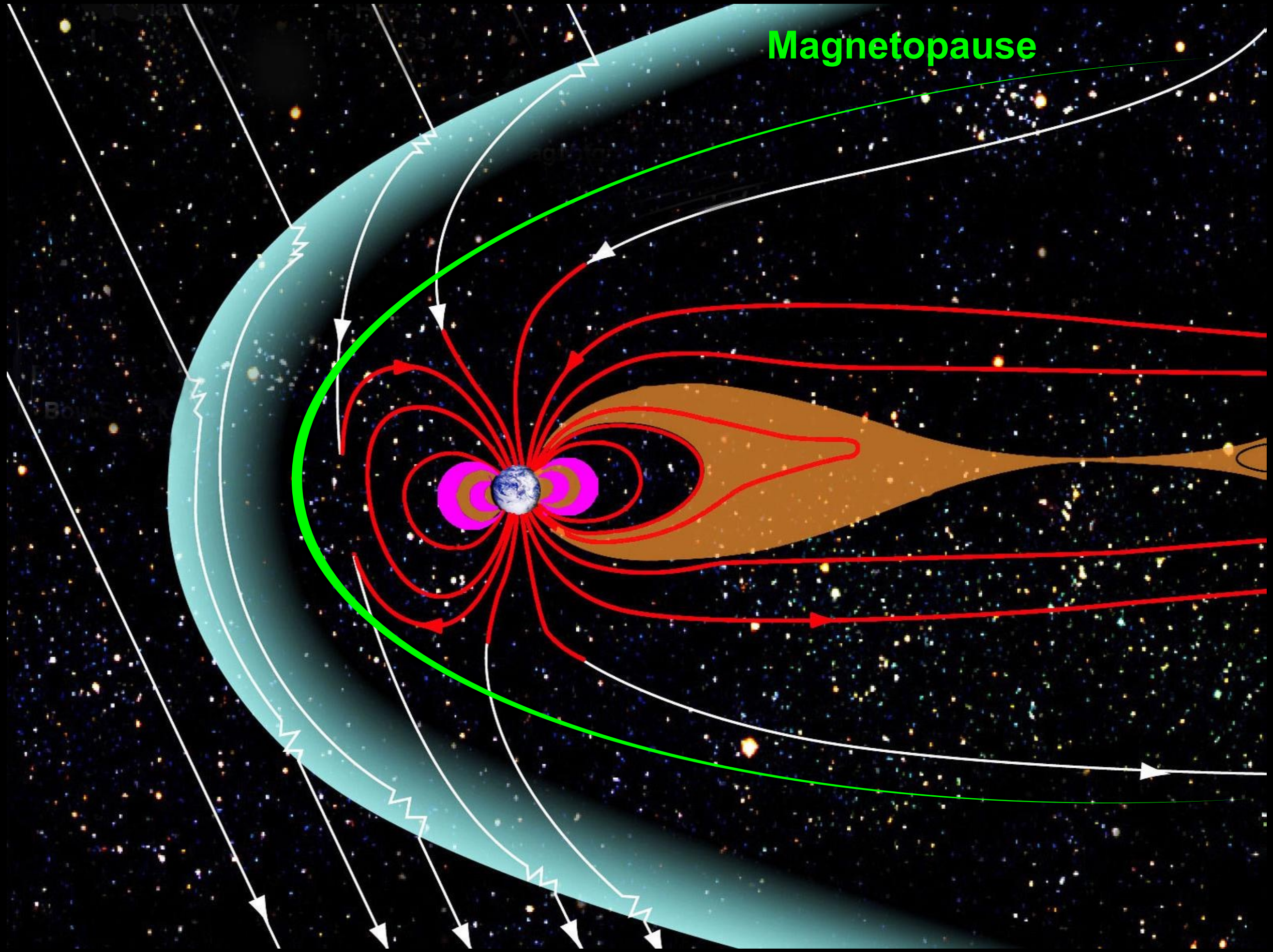


Image credit: NASA/Goddard


Aurora
Illuminating
Of the Sun-Earth
Connection

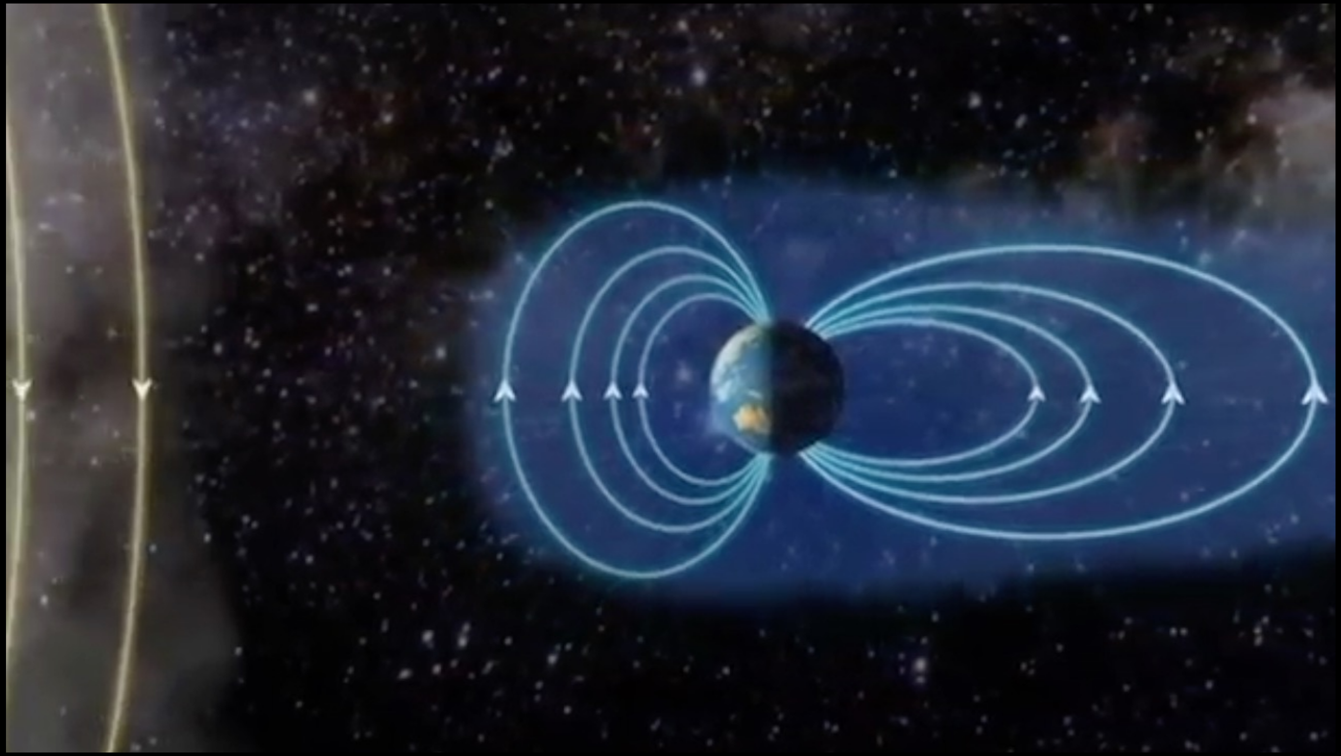
Magnetic Reconnection

- <u>Breaking</u> and <u>reconnecting</u> of <u>oppositely</u> directed magnetic field lines

- Mostly happens when IMF is southwards

- Magnetic energy converts to kinetic and thermal energy and <u>accelerates</u> particles

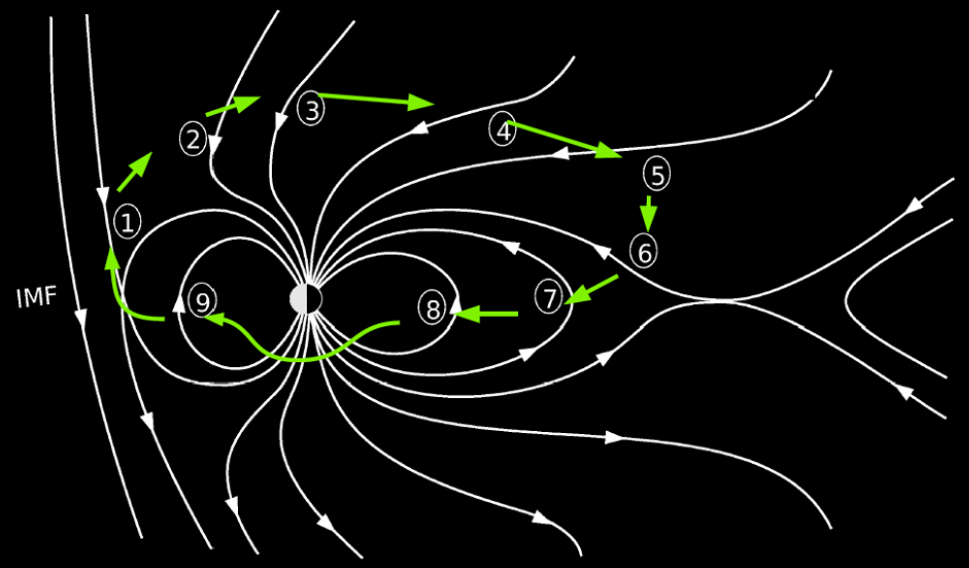
- Magnetic reconnection happens during Solar flares, CMEs and in accretion disks around black holes



Video credit: NASA/SDO

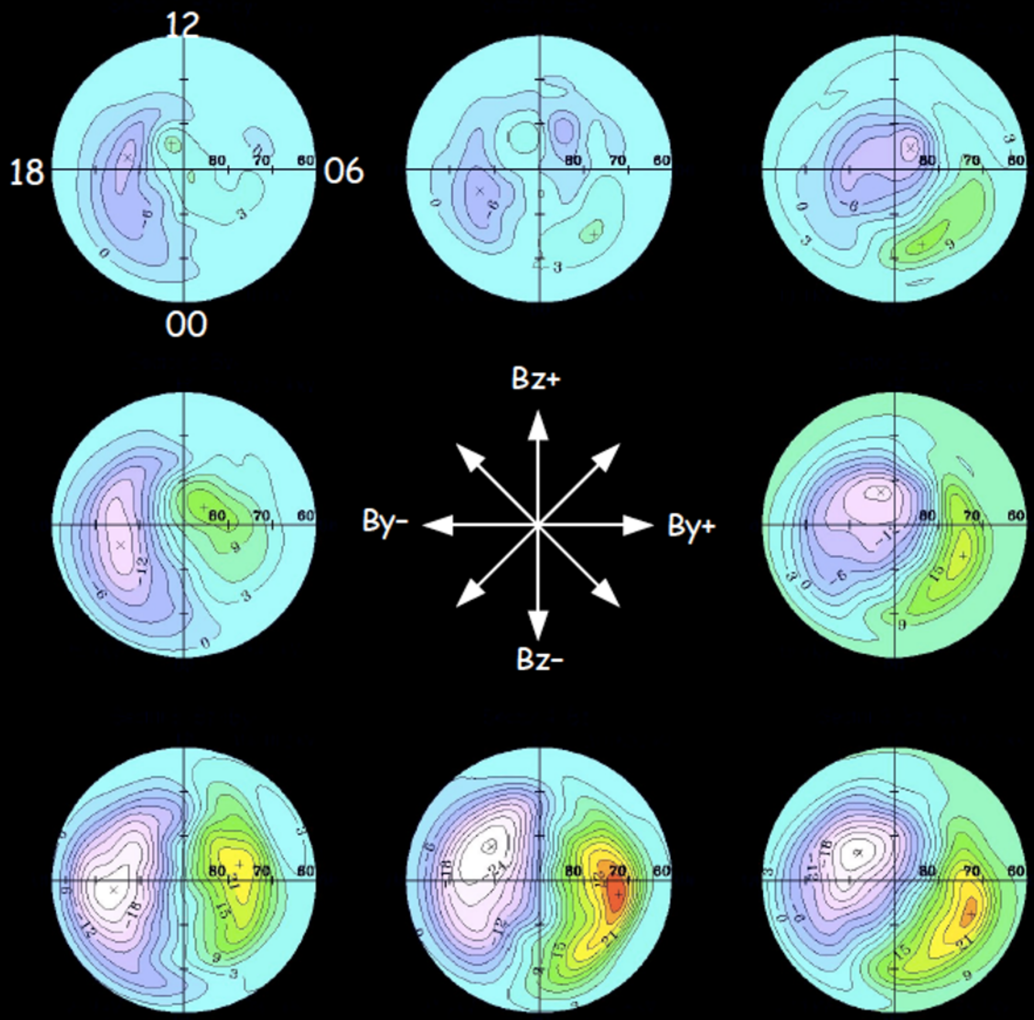
Dungey Cycle

- 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

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

Geomagnetic Storm

- A <u>temporary</u> disturbance of magnetosphere
- Last for several <u>days</u>
- Aurora can be seen from higher to lower latitudes
- Dst index

Image credit: David Cartier Sep. 3, 20112

Substorms

- A <u>localized & brief</u> disturbance of magnetosphere
- Last for few <u>hours</u>
- 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.

$h = 6.626 \times 10^{-34}$ [kg.m²/s]

Answer:

$1eV = 1.6 \times 10^{-19}$ [kgm²/s²]

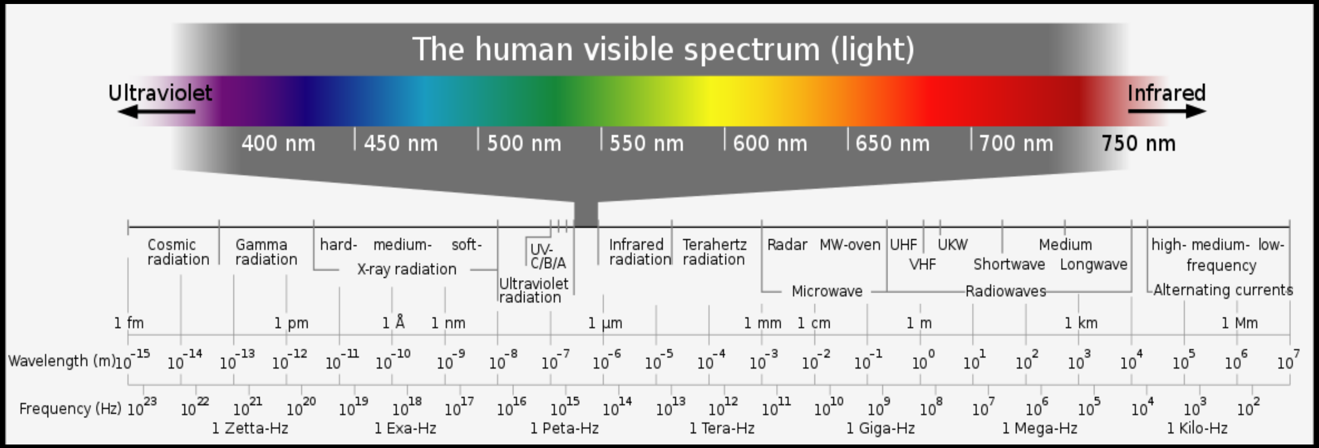
$E = h\nu = \frac{hc}{\lambda}$

$\rightarrow \lambda = (6.626 \times 10^{-34}) \times (3 \times 10^{8}) / (13.6) \times (1.6 \times 10^{-19})$

≈ 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