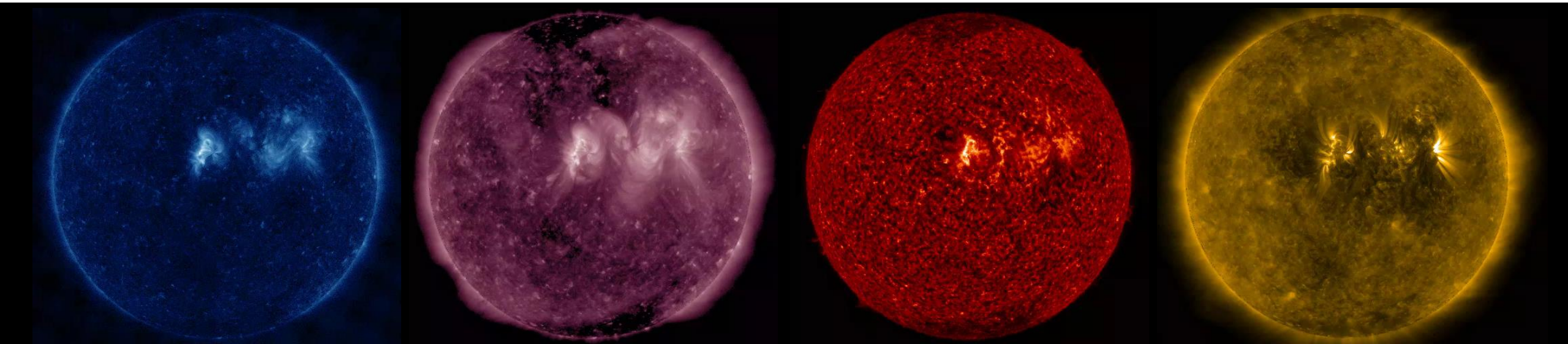
RyanJFrench1 ryan.french.14@ucl.ac.uk

Explosive Energy Release on the Sun and Beyond

1 o'clock Space Lecture

Ryan French

UCL Mullard Space Science Laboratory



Deities of the Sun

Ra

Egyptian god of the Sun

Helios

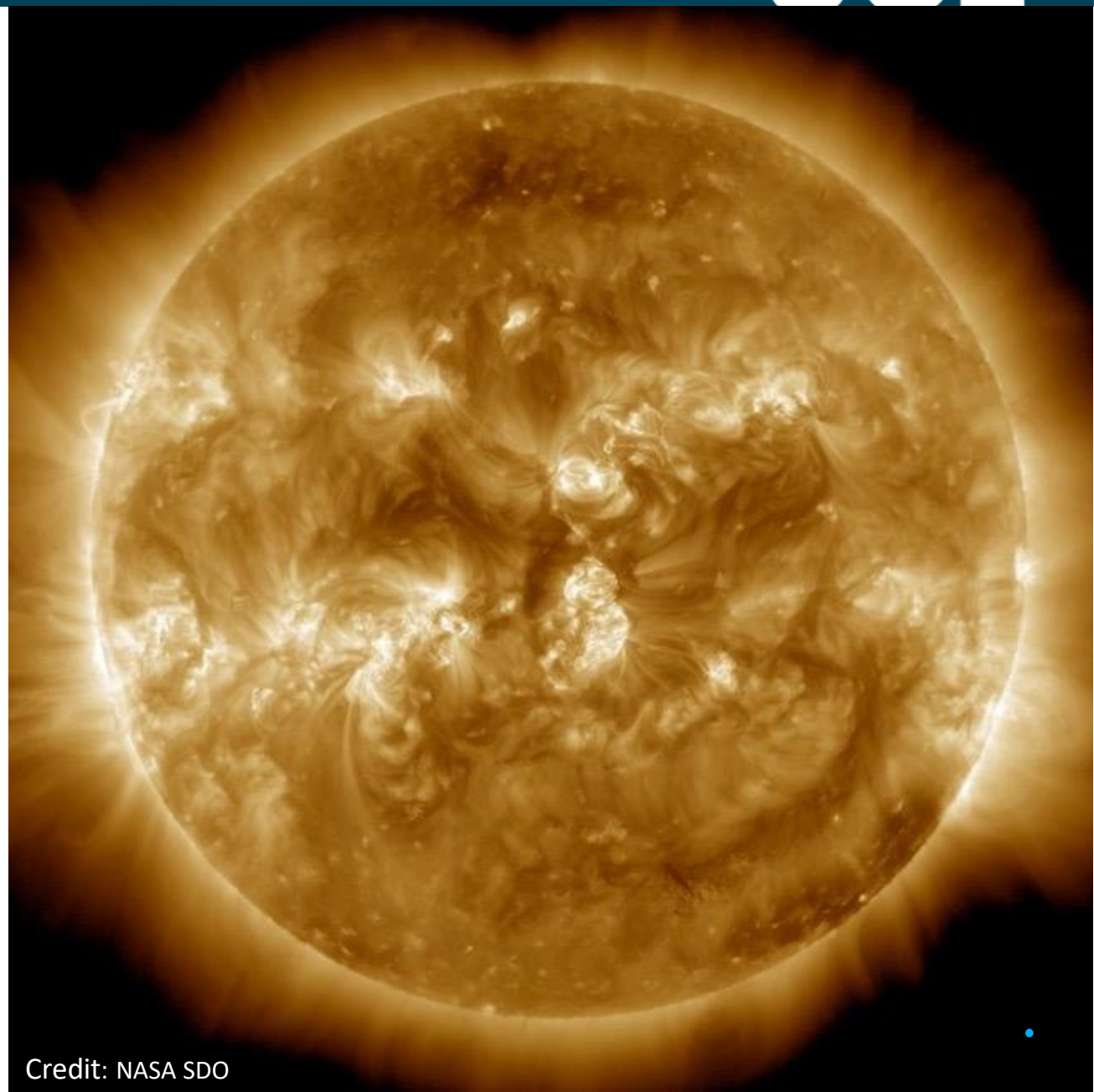
Ancient Greek Titan and Sun God

Huitzilopochtli

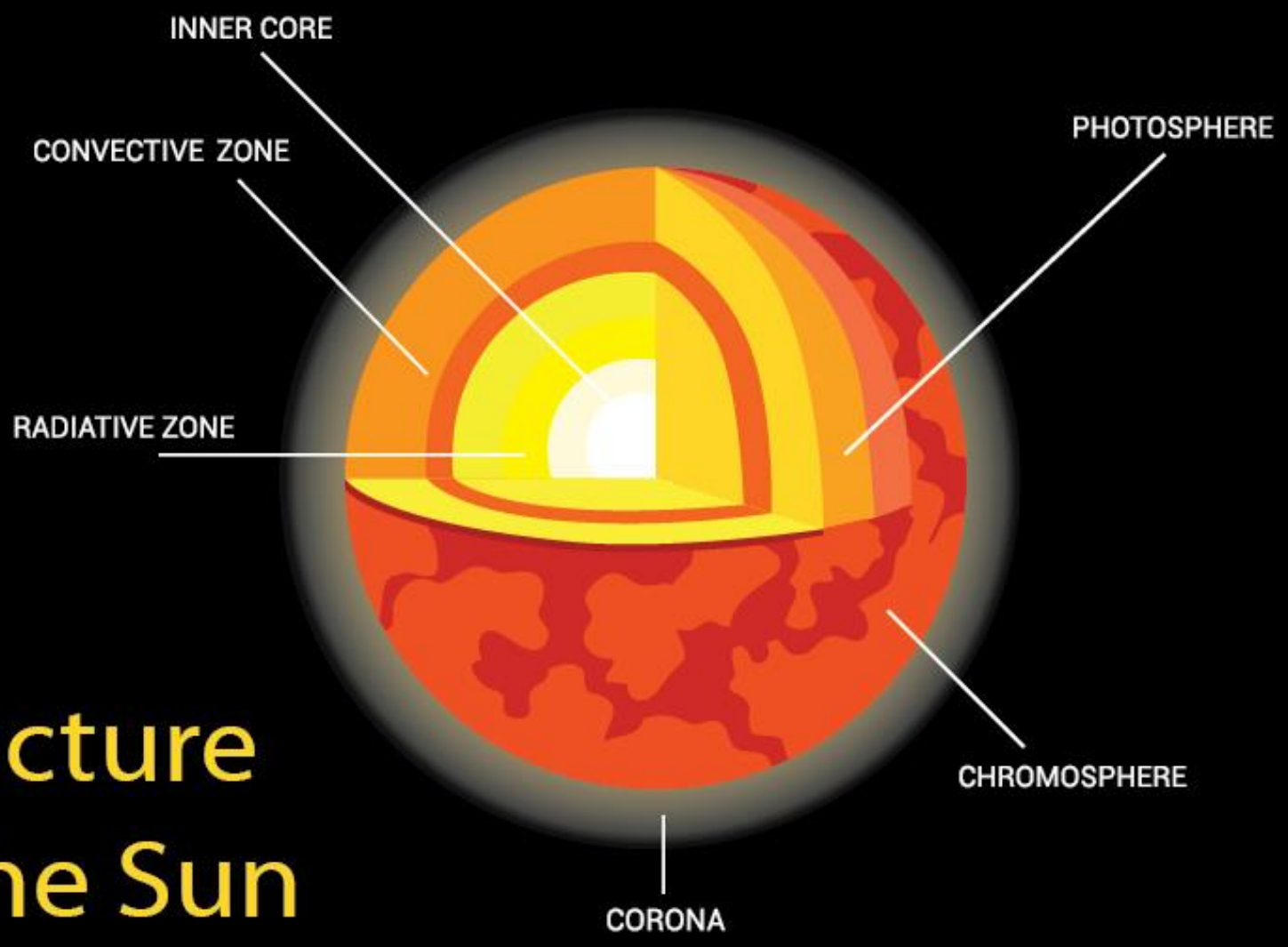
Aztec god of War and the Sun

The Sun

- Age – 4.6 billion years
- Size – 700,000 km radius (100x Earth radius)
- Distance – 150 million km
- Surface temp – 5500˚C
- Core temp – 15 million ˚C
- Energy source – fusion of H → He

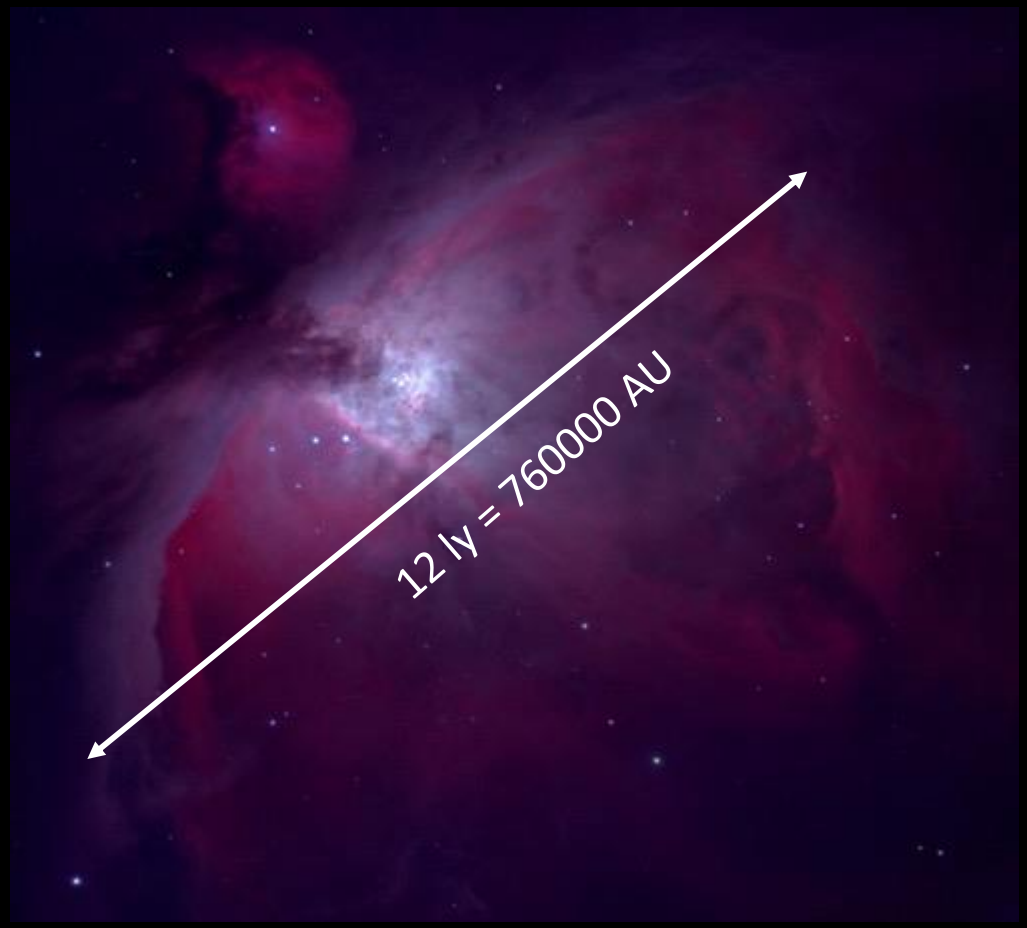


Credit: NASA SDO

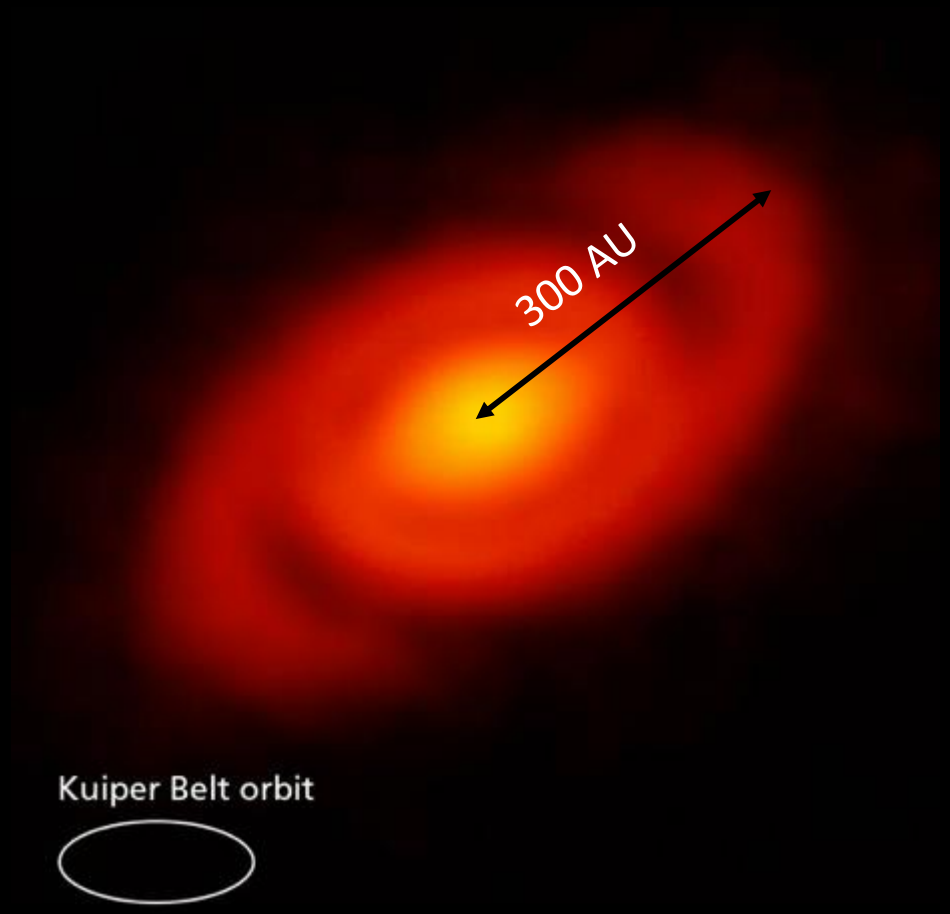


Structure of the Sun

Credit: StudyLadder



Orion Nebula (1344 ly away)



Young Star **Elias 2-27** (450 ly away)
(credit: Max Planck Institute for Astronomy)

Artist's impression
(Credit: How it works)

HL Tau system
(Credit: ALMA, ESO)

Goldilocks Zone

Too hot…

Just right.

Too cold…

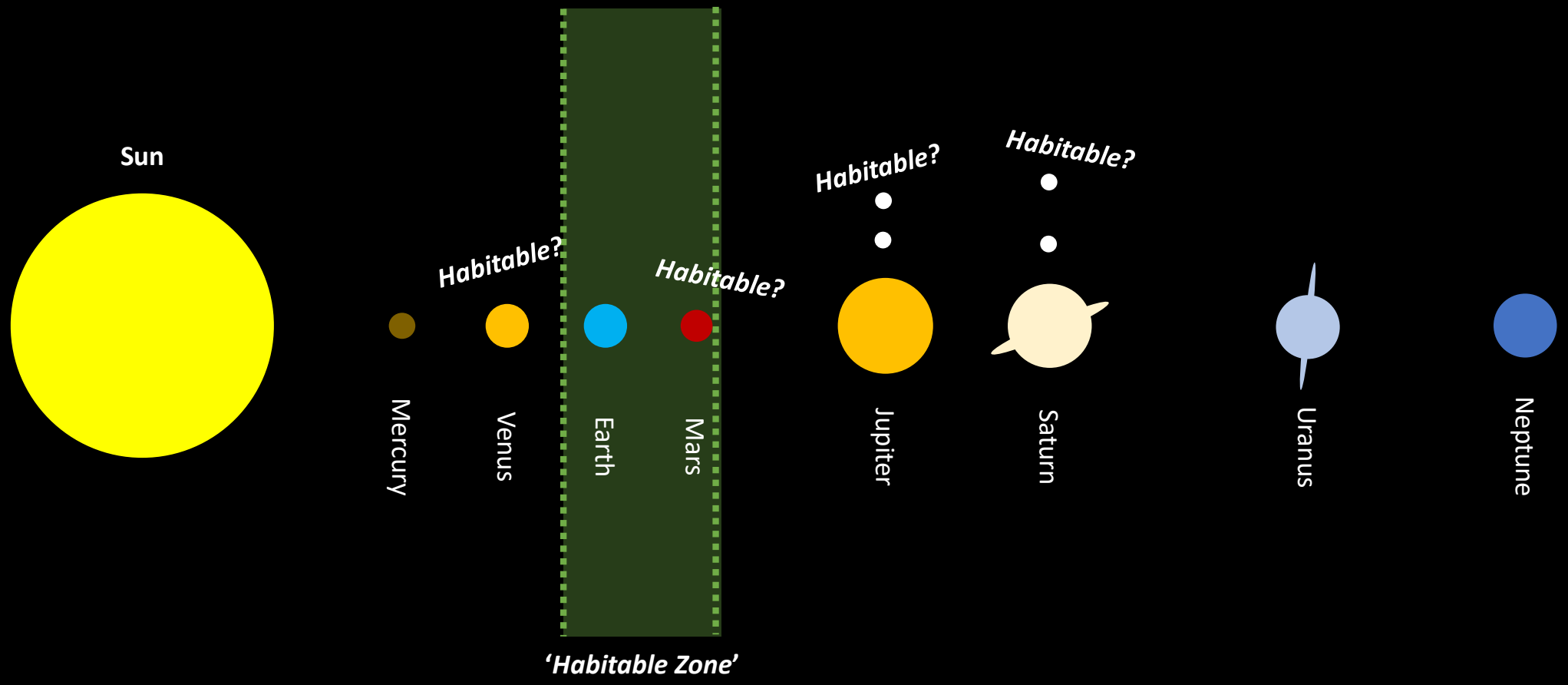
Sun light and heat

Venus
0.72 AU
460 ˚C

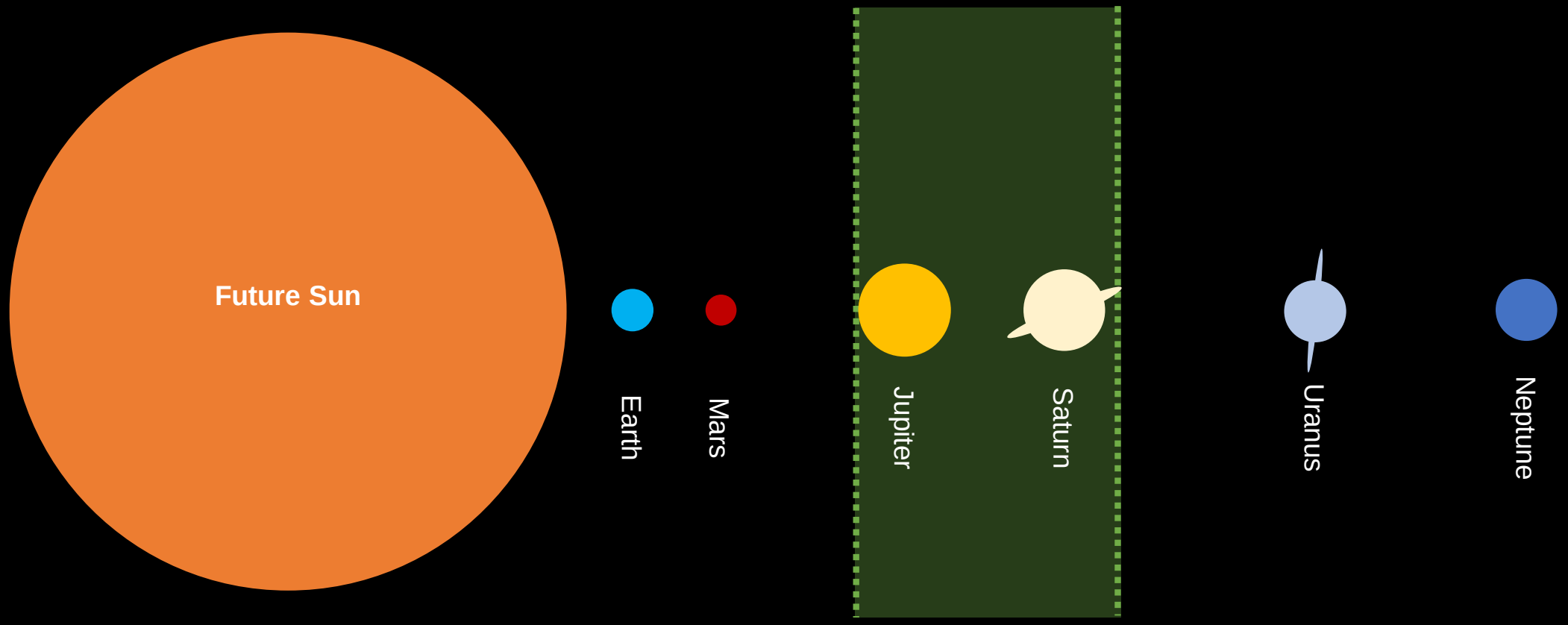
Earth
1 AU
14.6 ˚C

Pluto
39.5 AU
– 238 ˚C

Goldilocks Zone

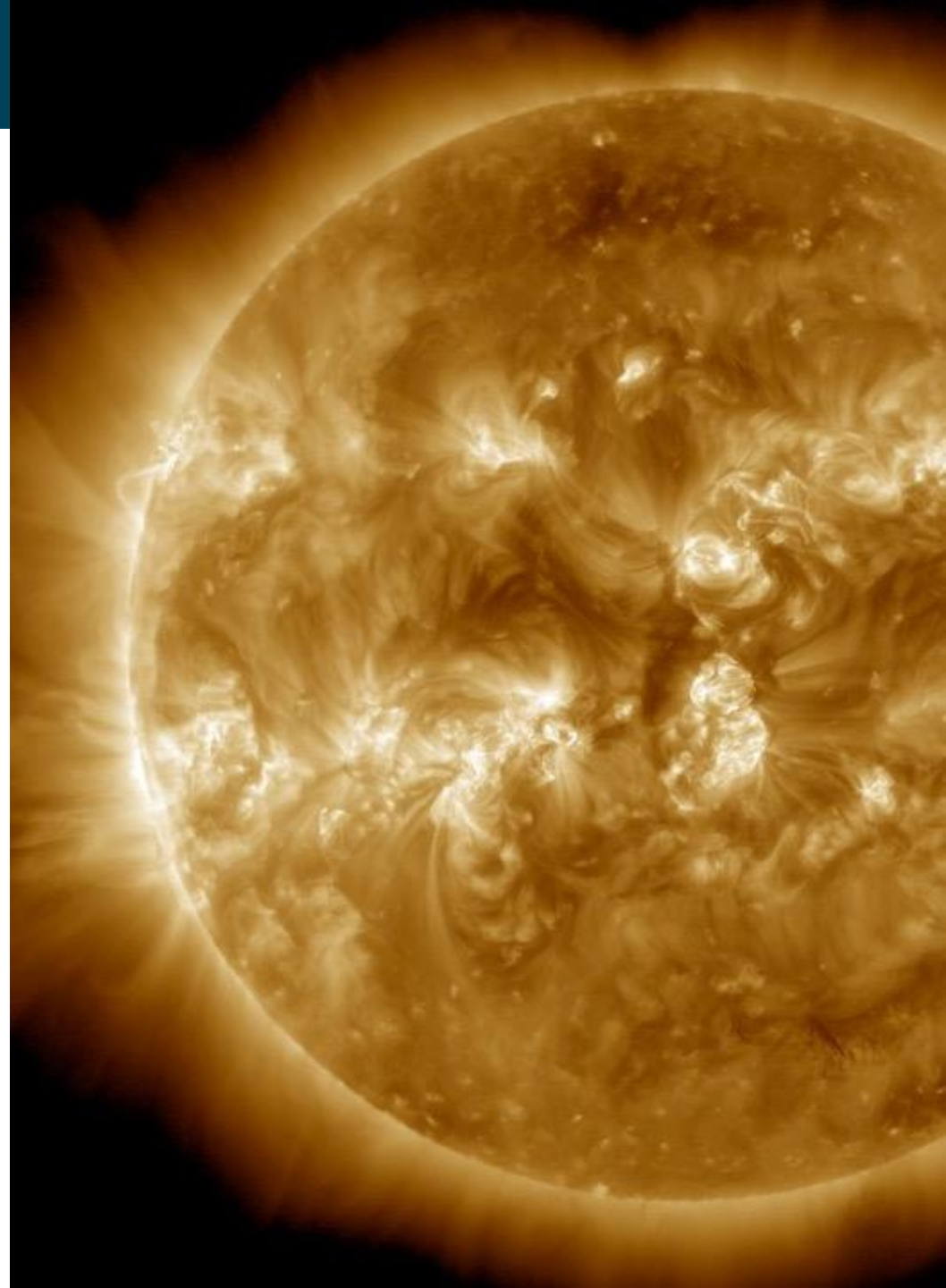


Future Goldilocks Zone



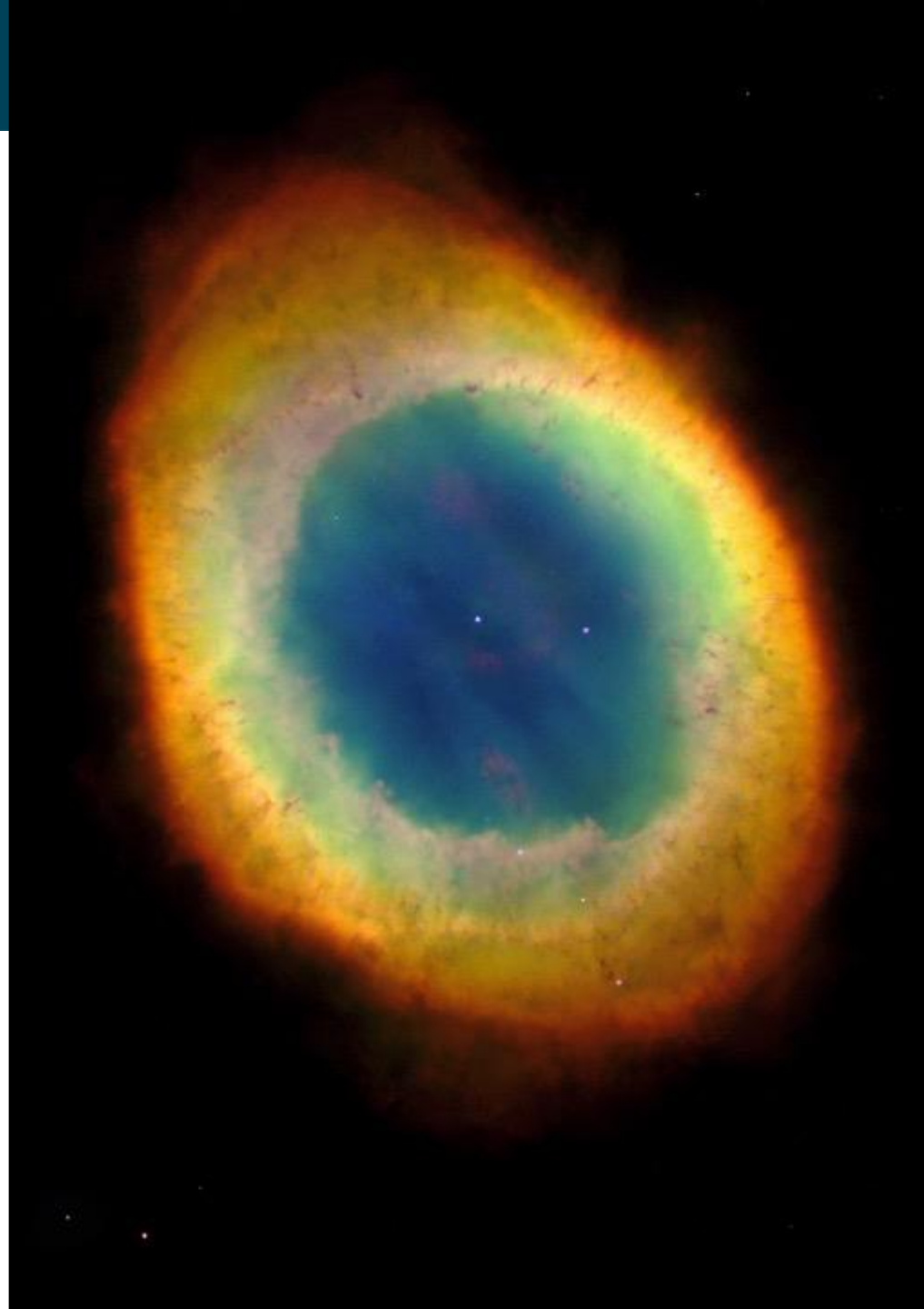
Life of the Sun

- The life of a star is constant battle between gravity, and nuclear fusion in the core.
- The Sun's life as a *main sequence* star is spent fusing H into He.
- In 5 bn years time, H runs out in the Sun's core. It begins to contract, becoming hot enough to fuse He → C. This causes it to expand and become a *red giant*.



Death of the Sun

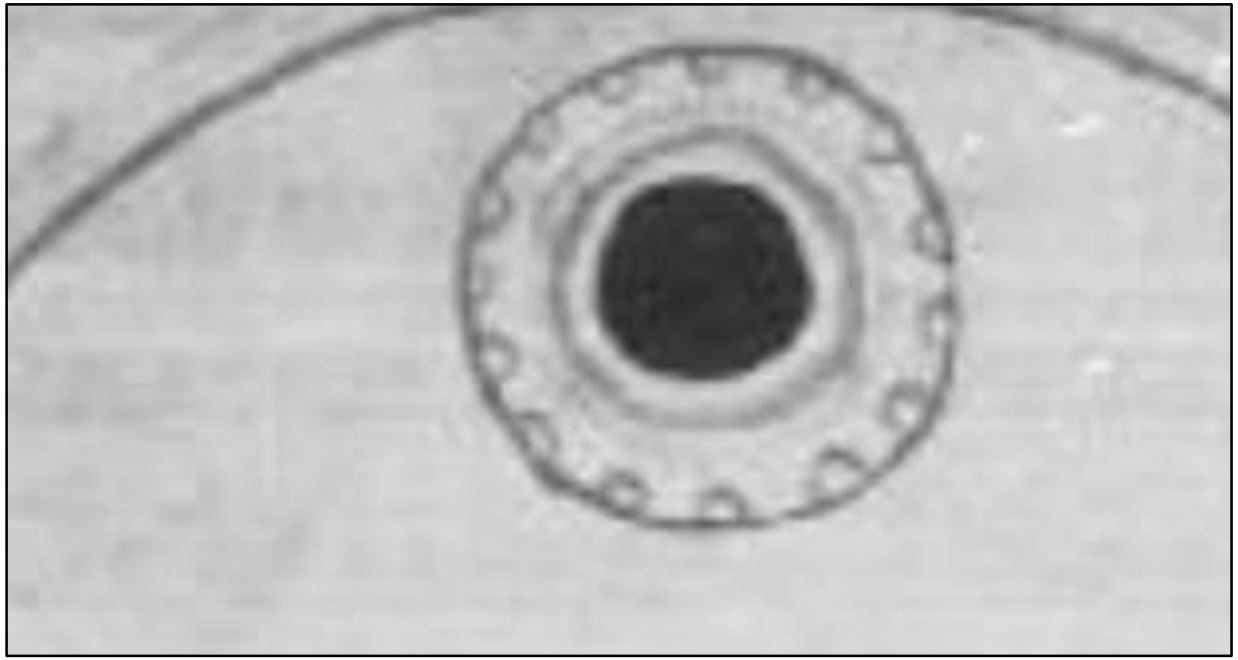
- Eventually, the Sun's core will run out of He fuel. The Sun is not large enough to fuse heavier elements, so fusion stops.
- The Sun contracts, until the compressed atoms in the core resist any further collapse, creating a *white dwarf* star.
- As the core becomes a *white dwarf*, the outer layers of the Sun drift off into space, illuminated by radiation from the old core. This forms a *planetary nebula*.
- *White dwarfs* have no energy source, so slowly cool down over billions of years.



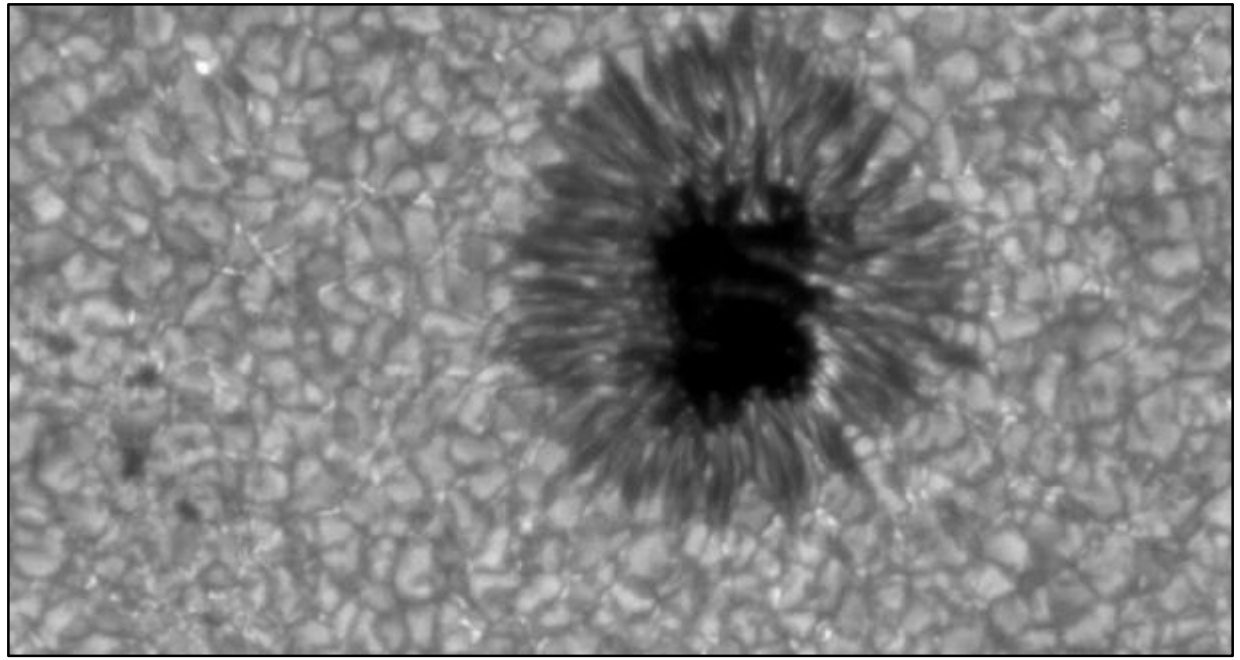
Worcester, England - 1128 AD

Portrait and sunspot diagram from Worcester Chronicles, 1128

Worcester, England - 1128 AD

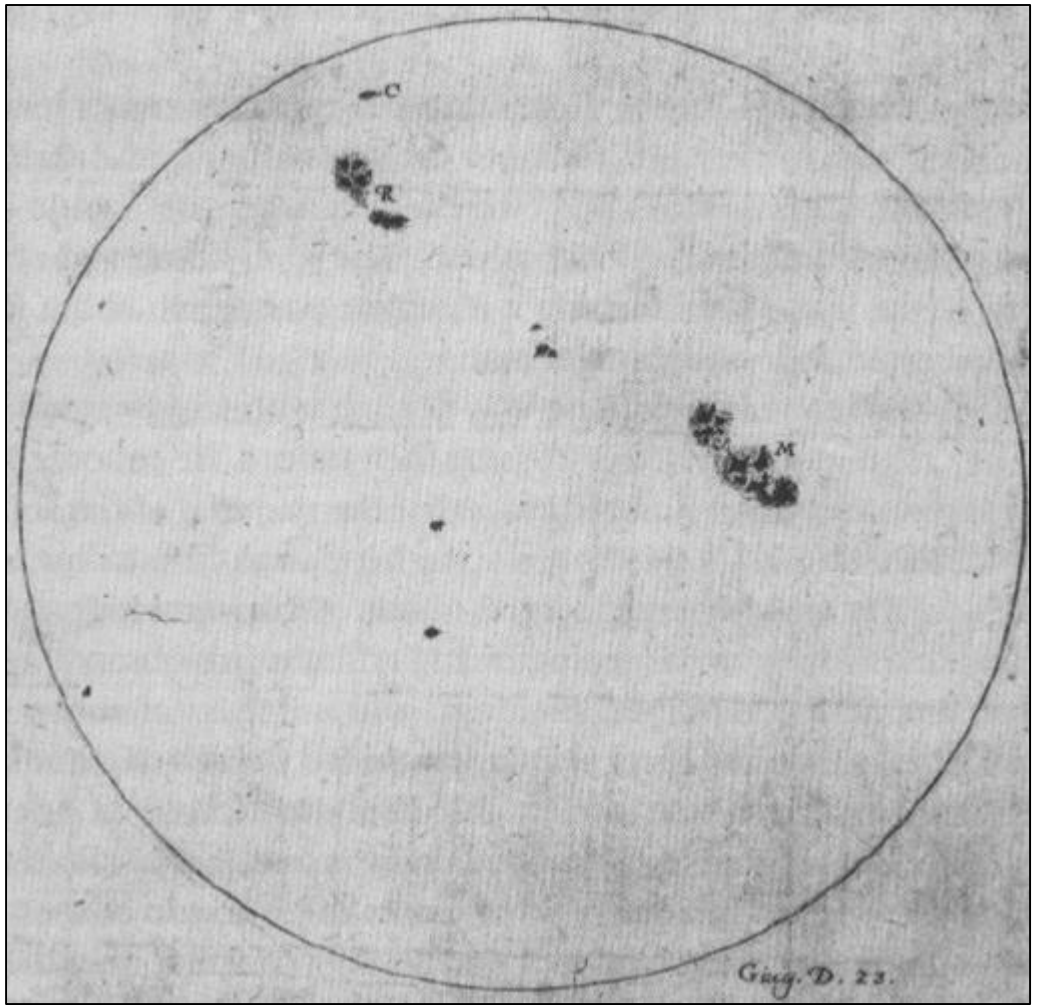


Sunspot diagram from Worcester Chronicles, 1128



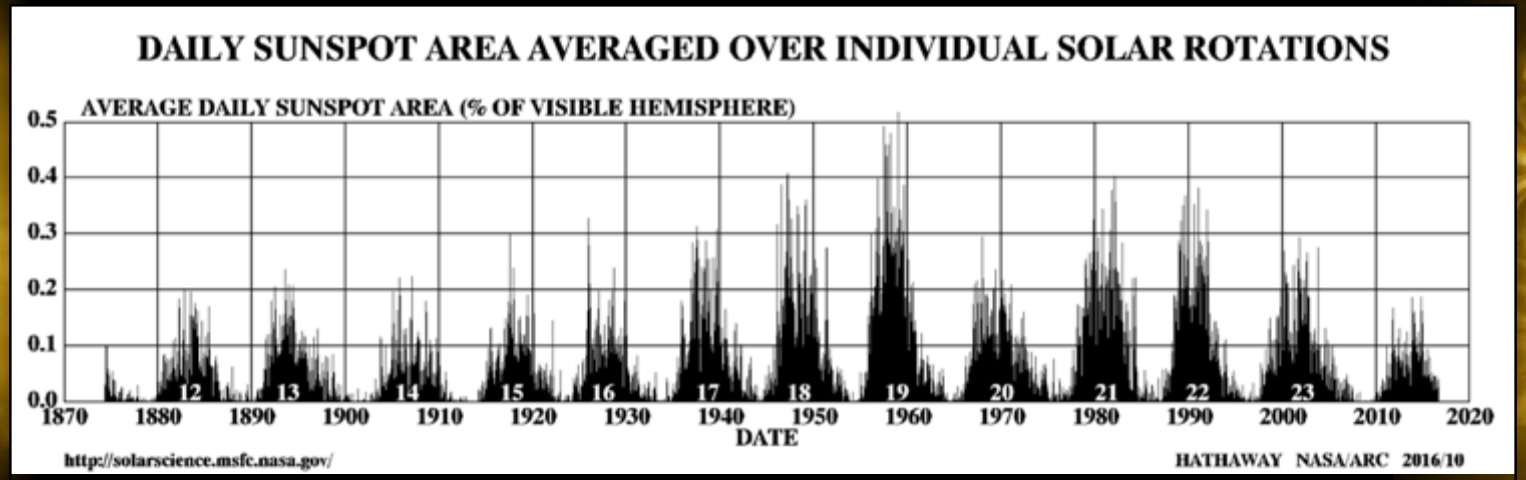
White light sunspot image, 1993

Europe, 1610 - 1801

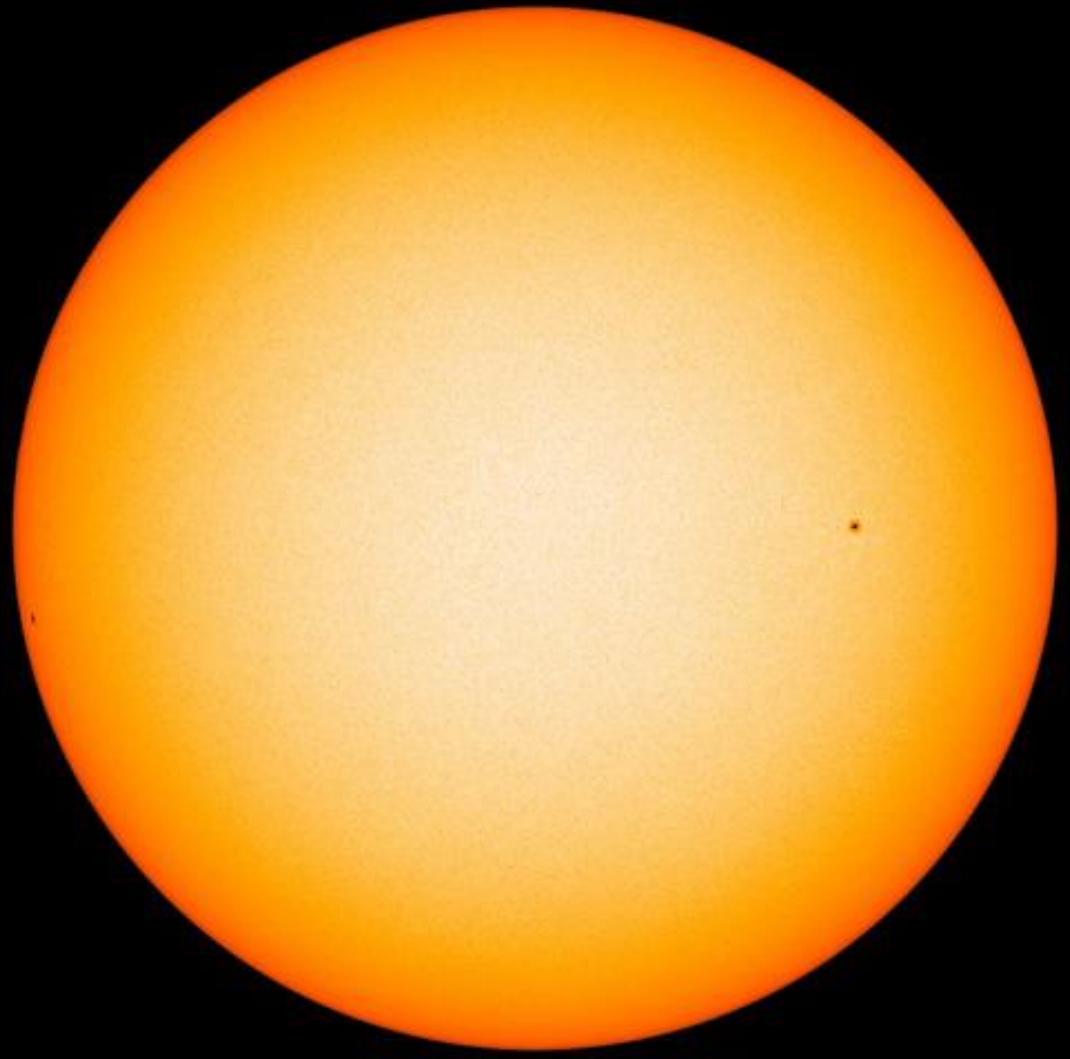


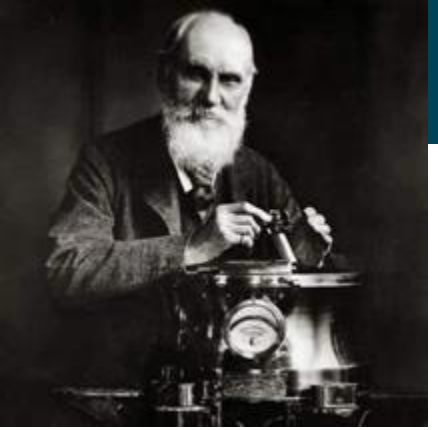
- *'Small planets closely orbiting the Sun'*
  – Scheiner
- *'Perhaps cloud-like structures in the solar atmosphere'*
  – Galileo
- *'Dense objects embedded in the Sun's luminous atmosphere'*
  – Scheiner
- *'Openings in the Sun's luminous atmosphere, allowing a view of the underlying, cooler surface of the Sun'*
  – Herschel

Solar Cycle

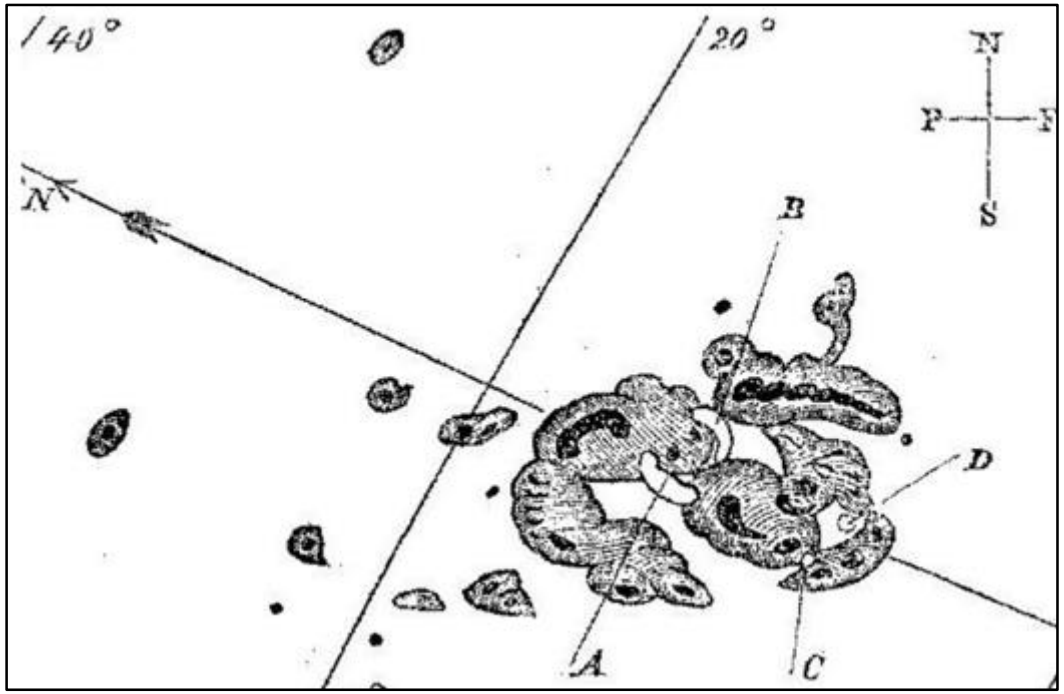

DAILY SUNSPOT AREA AVERAGED OVER INDIVIDUAL SOLAR ROTATIONS
AVERAGE DAILY SUNSPOT AREA (% OF VISIBLE HEMISPHERE)
0.5
0.4
0.3
0.2
0.1
0.0
12
13
14
15
16
17
18
19
20
21
22
23
1870
1880
1890
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
2020
DATE
http://solarscience.msfc.nasa.gov/
HATHAWAY NASA/ARC 2016/10

Sunspots





1859 – Carrington Event



- Richard Carrington – Part time astronomer, part time brewery owner
- September 1st 1859, observed two rapidly brightening areas of light in sunspot centre.
- Intense aurora followed the following night, all the way down to the tropics.
- Strengthen case for link between solar and geomagnetic activity
- First ever solar flare observation? Maybe not.

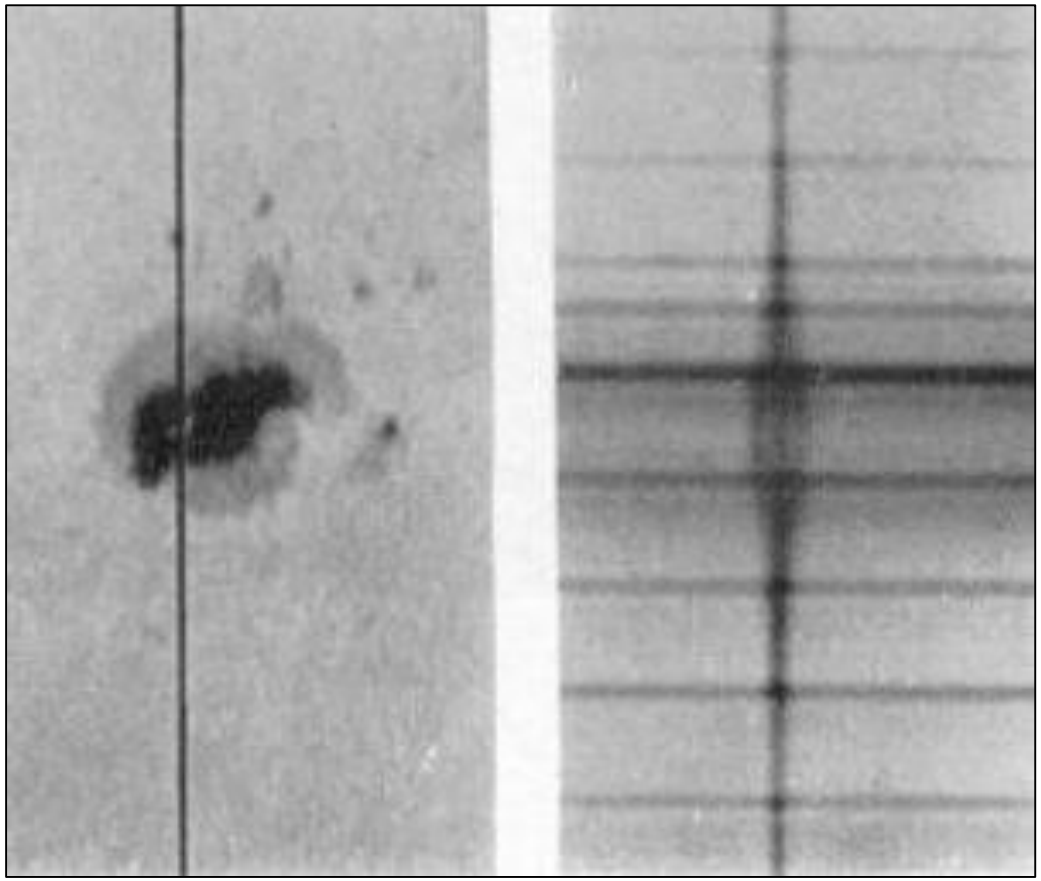
1705 - Stephen Gray noted *'flash of lightning'* in sunspot.

1860 Eclipse – First CME observation

Comparison between G. Tempel's CME sketch from 1860 (left), with modern SOHO satellite's coronagraph imagery of a coronal mass ejection in July 2017

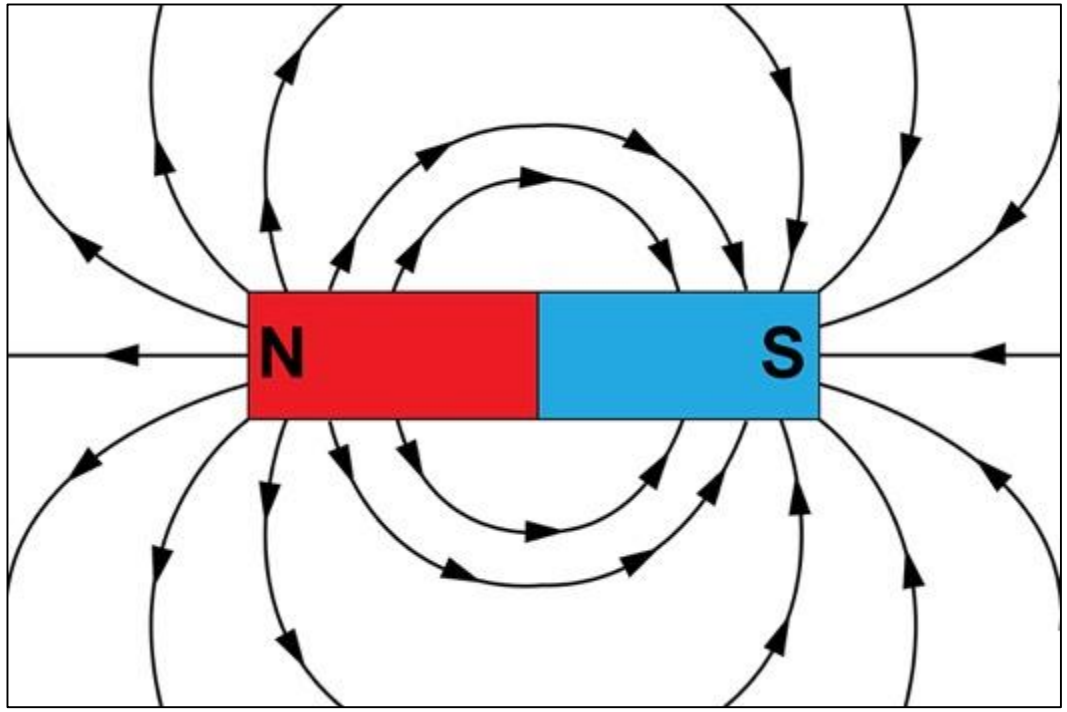
1908 – Sunspots are magnetic in nature

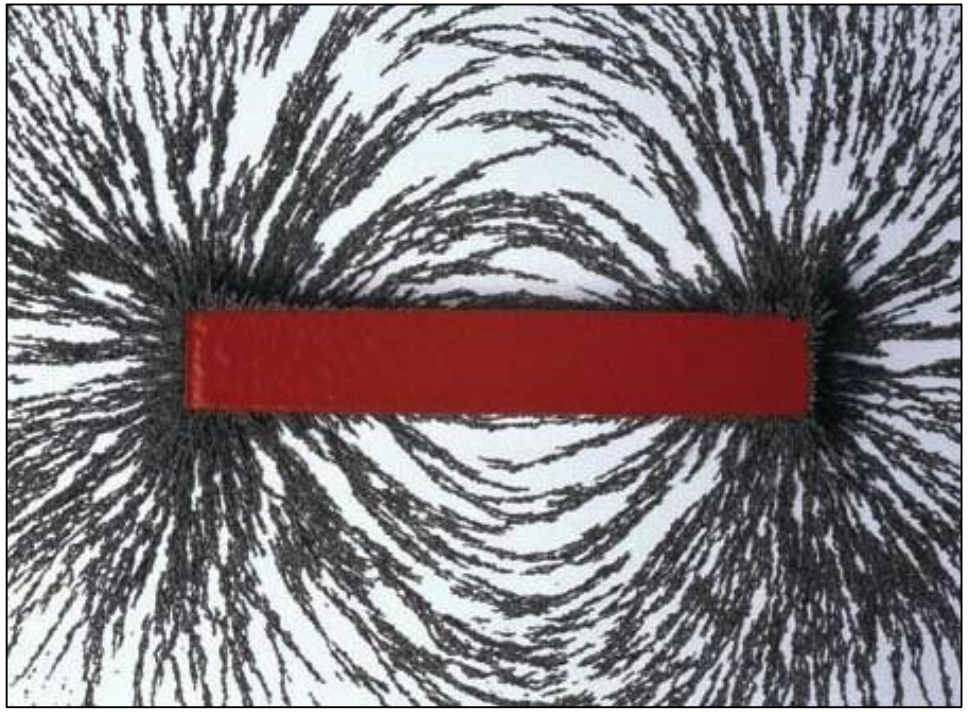
- George Hale observed Zeeman splitting in active regions, proving that sunspots are dominated by complex magnetic fields.
- Sunspot magnetic fields are over 1000 stronger than the Earth's magnetic field.



More Sun historic info - https://www2.hao.ucar.edu/Education/SolarPhysicsHistoricalTimeline

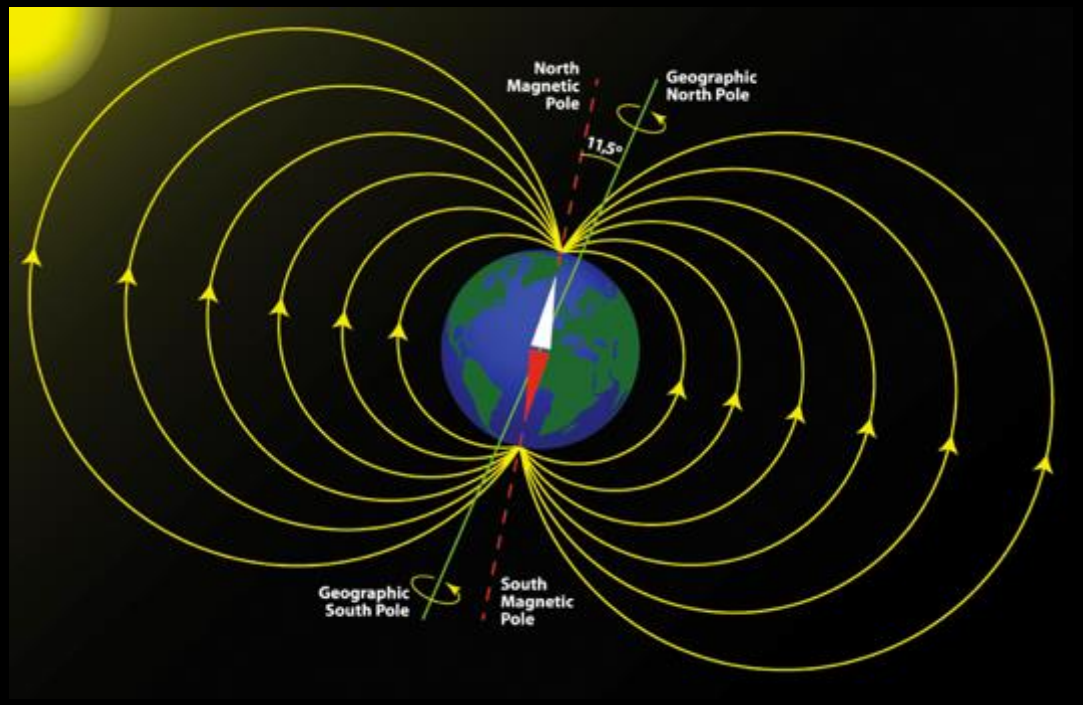
Magnetic fields



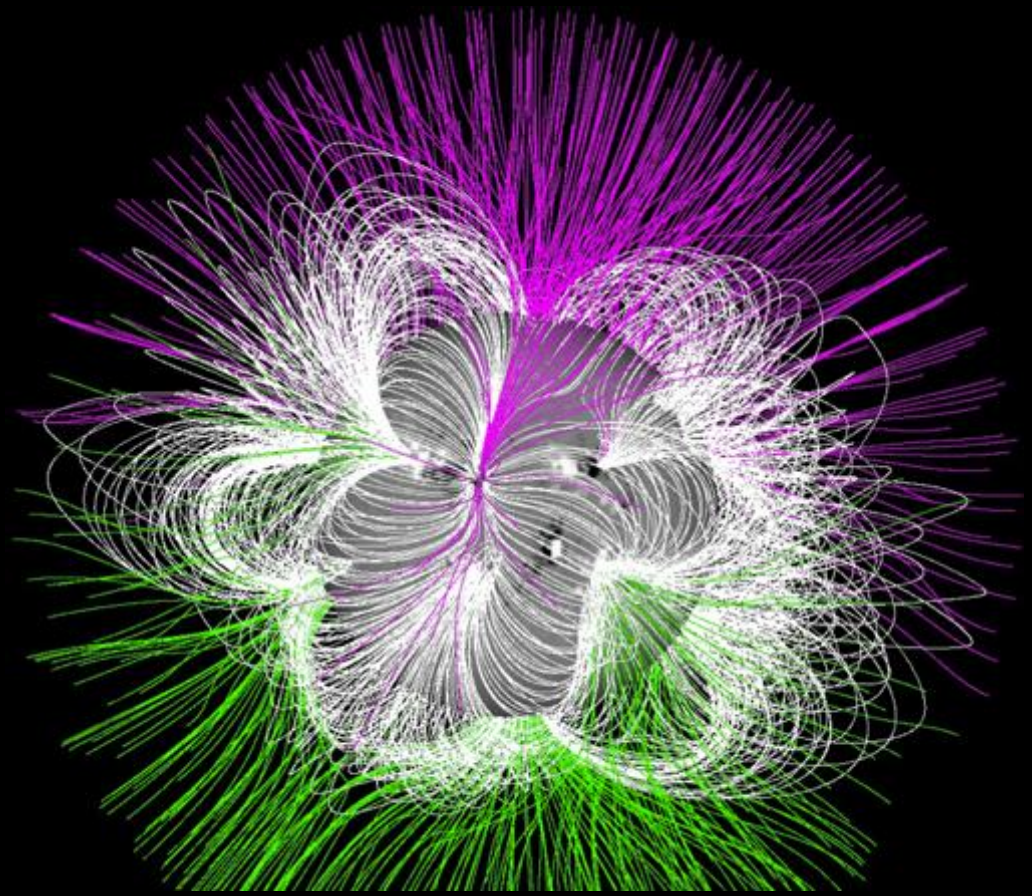


Credit: mammothmemory

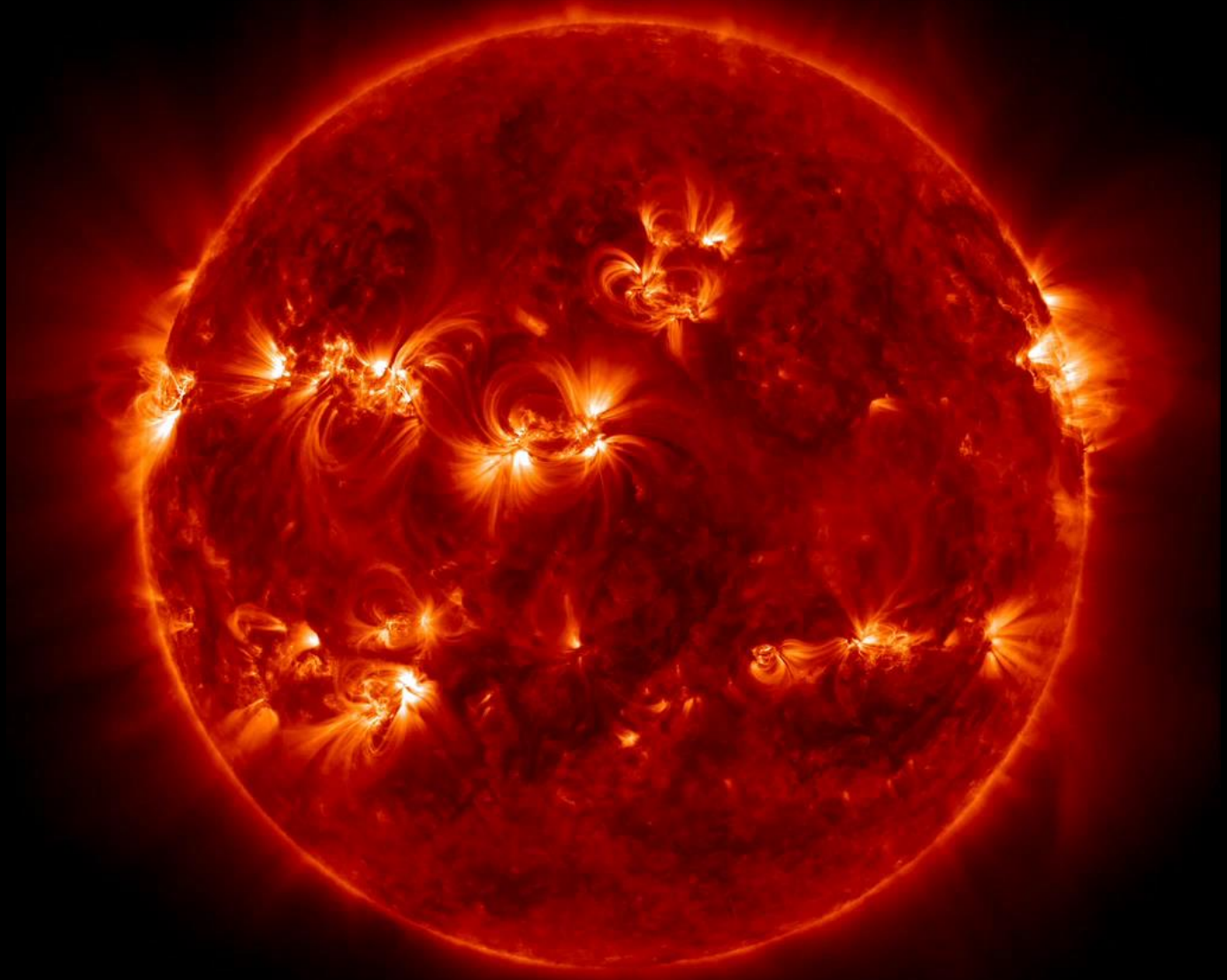
Earth's magnetic field



Sun's magnetic field

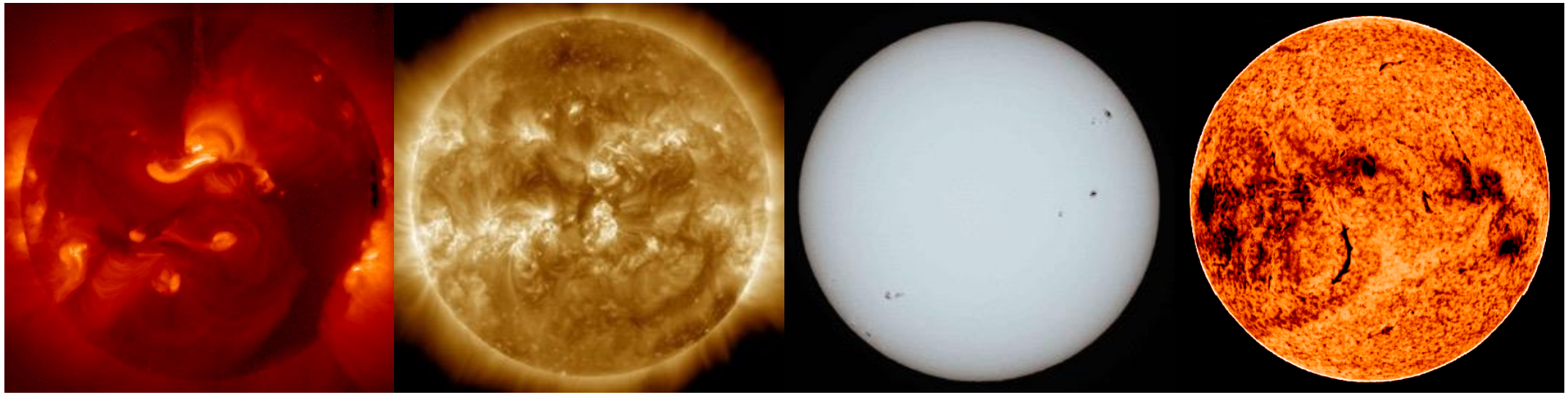


Credit: Live Science



The Sun and the Electromagnetic Spectrum

X-ray **Ultraviolet** **Visible light** **Infrared**



Increasing wavelength

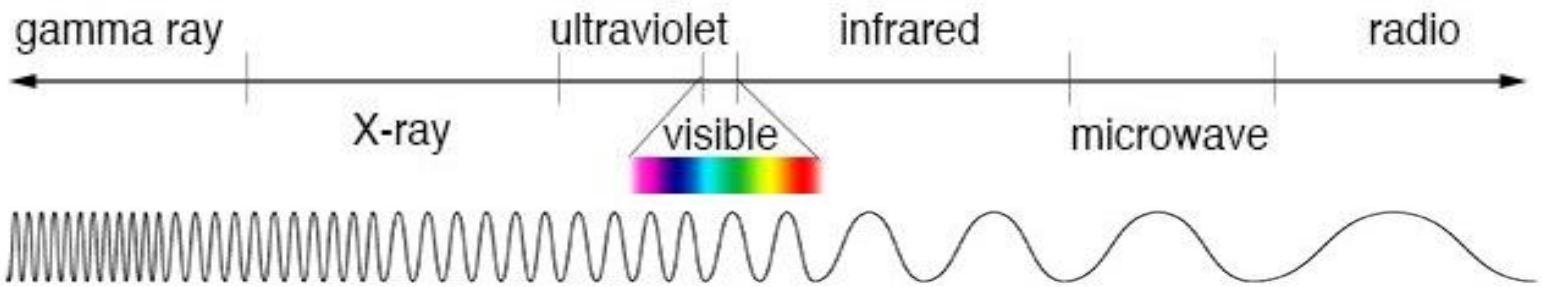
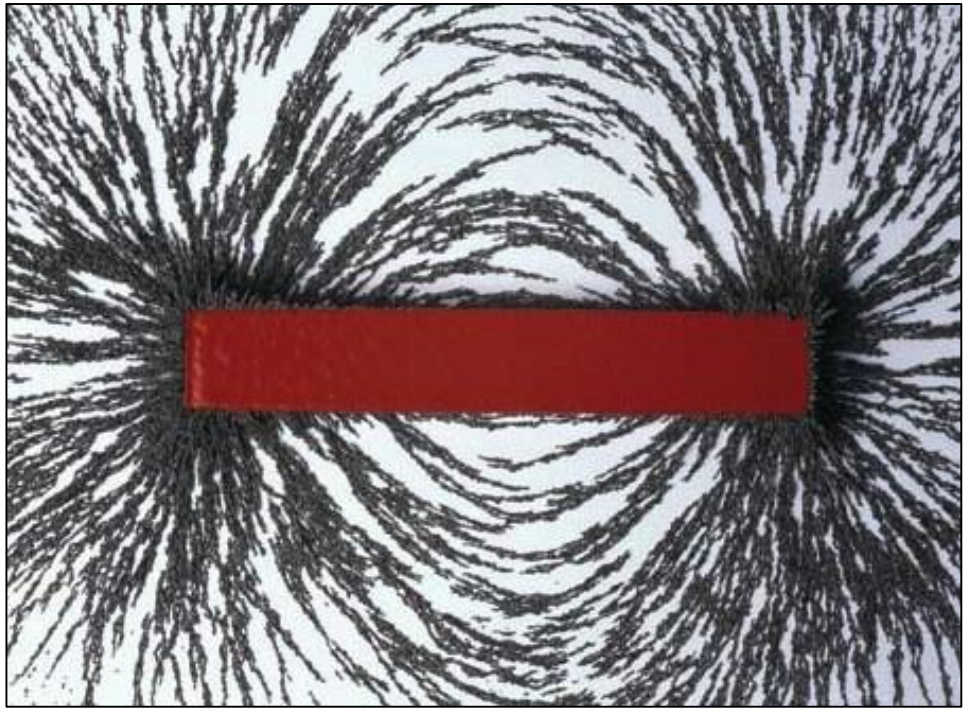
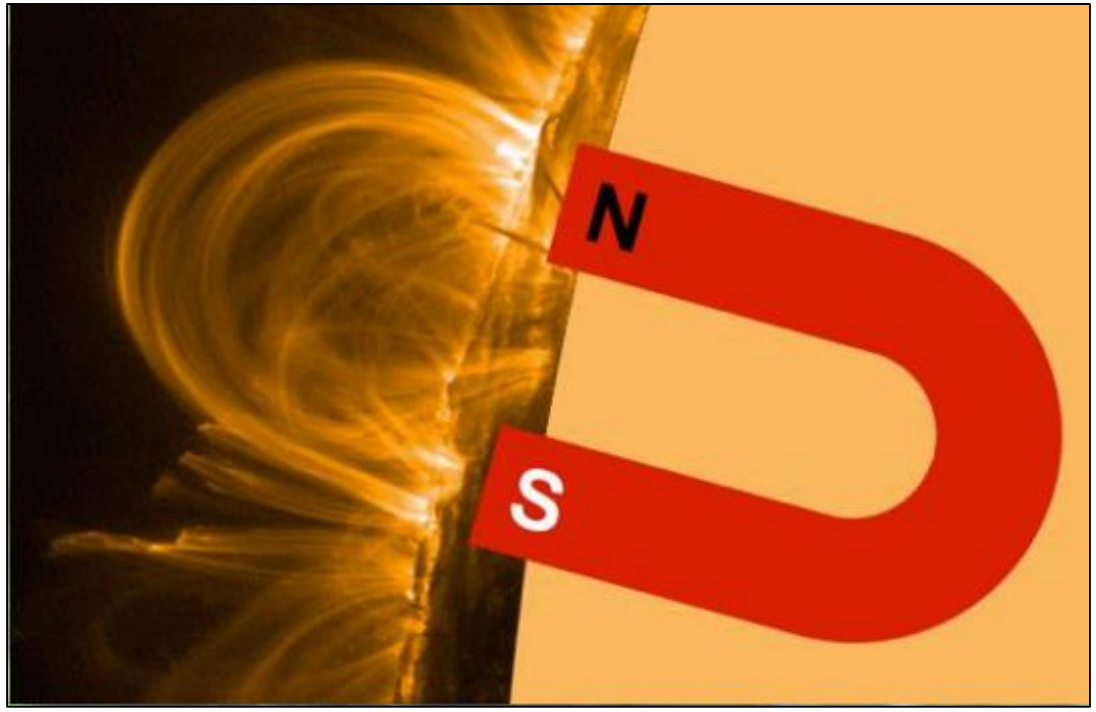


Image credit: NASA

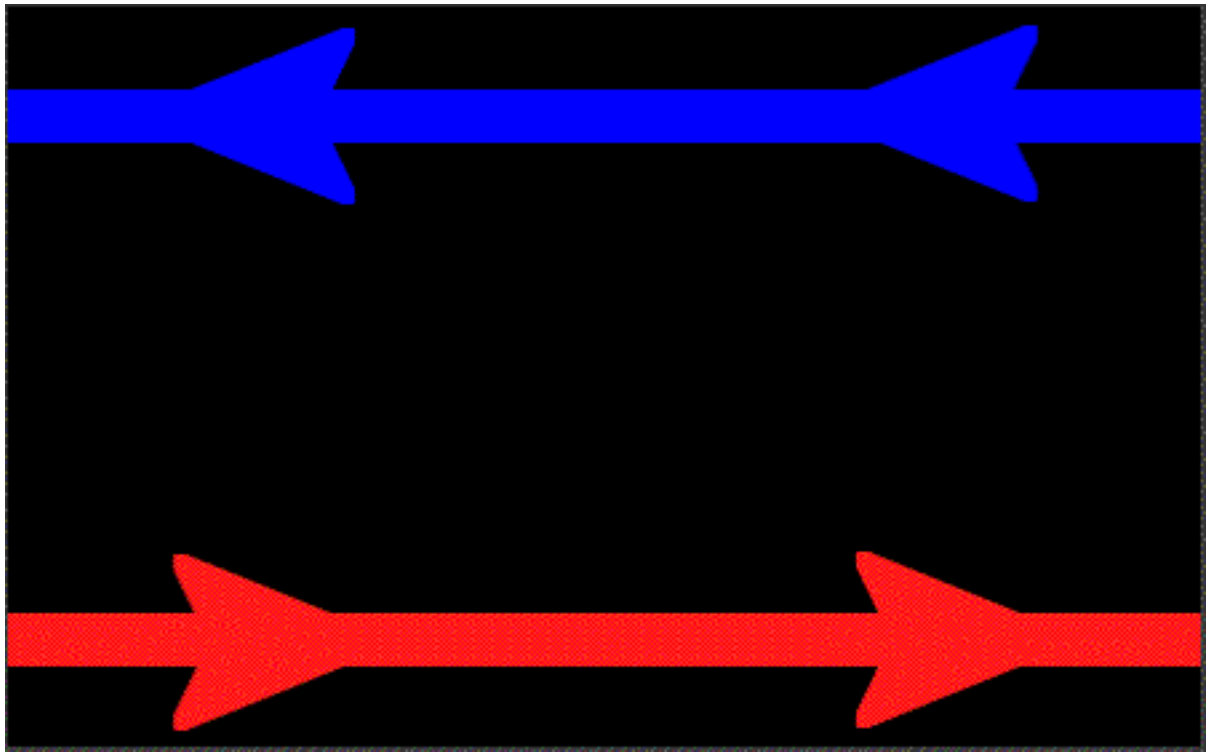
Frozen-in plasma

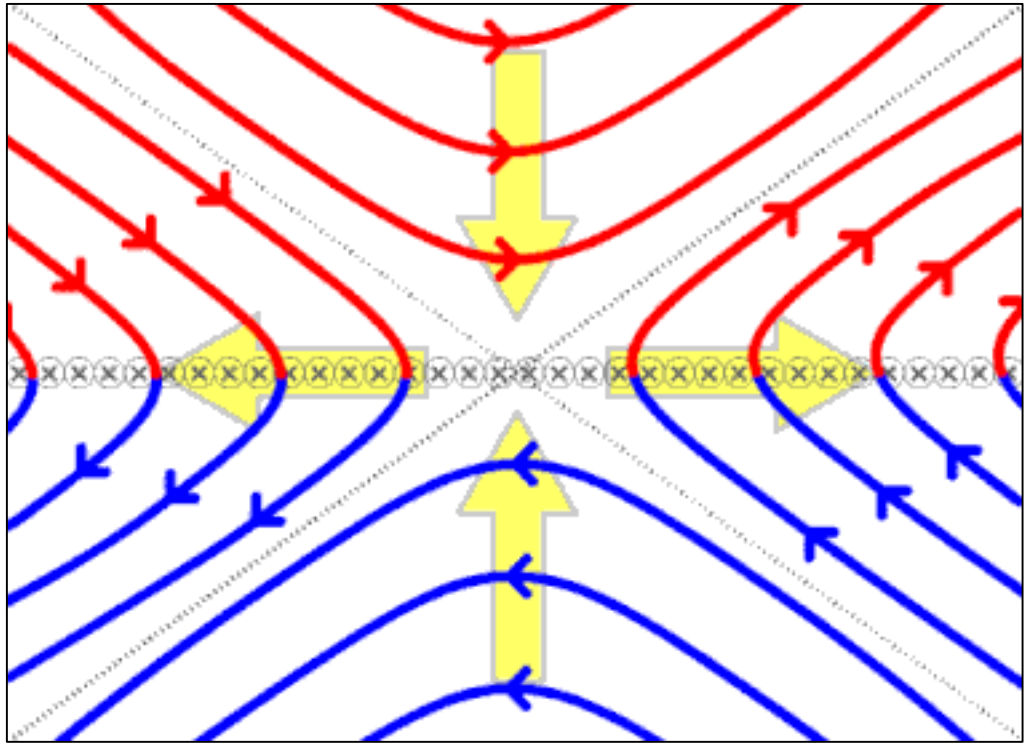




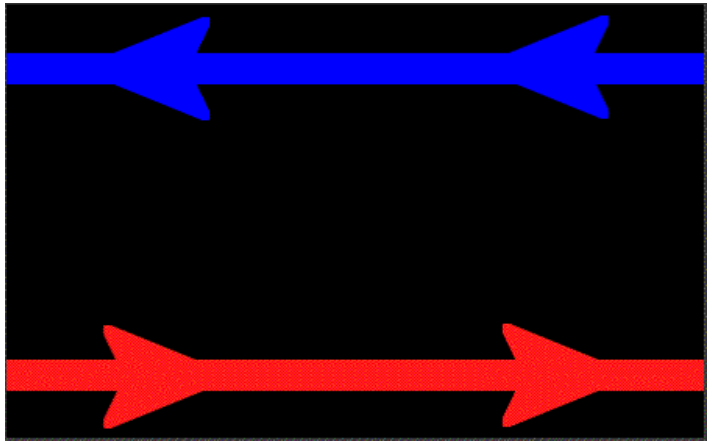
Magnetic Reconnection – the driver of energy release

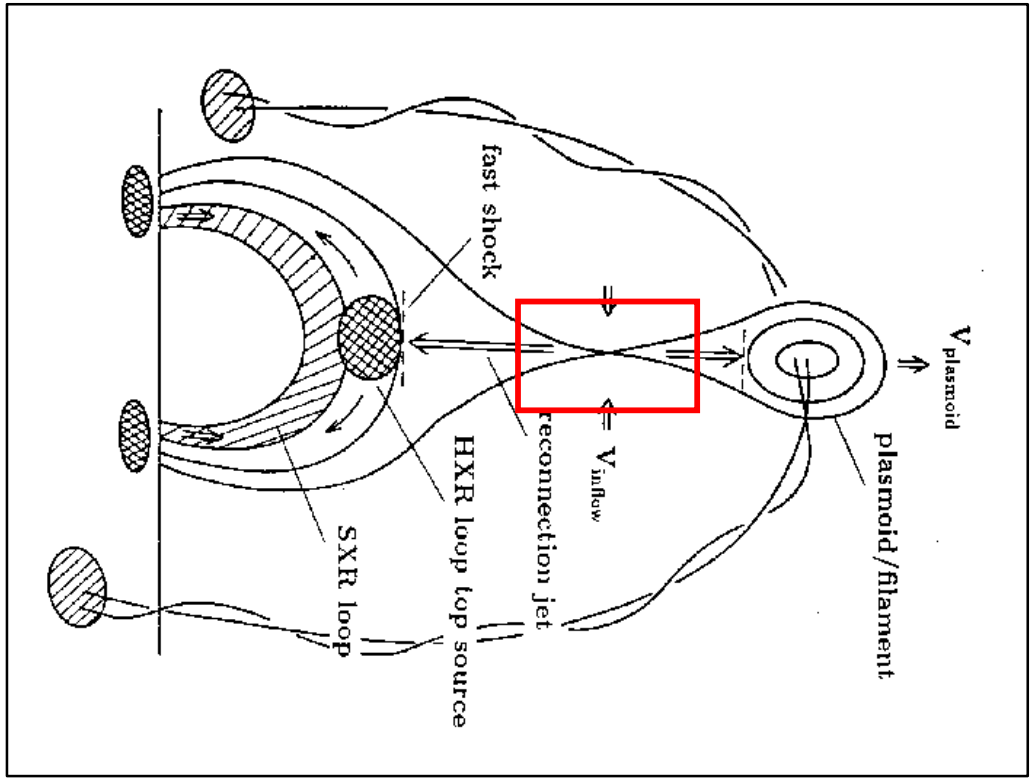
Magnetic potential energy → Heating, particle acceleration and EM radiation

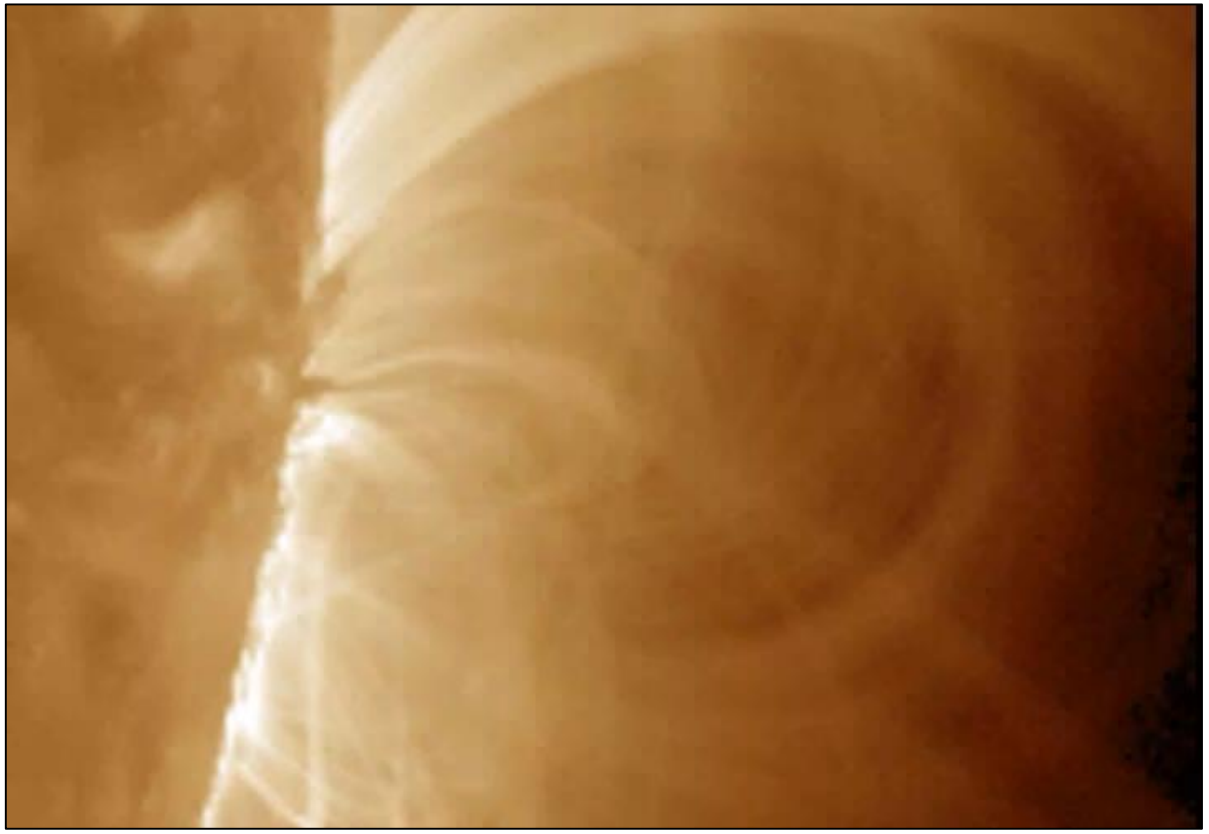




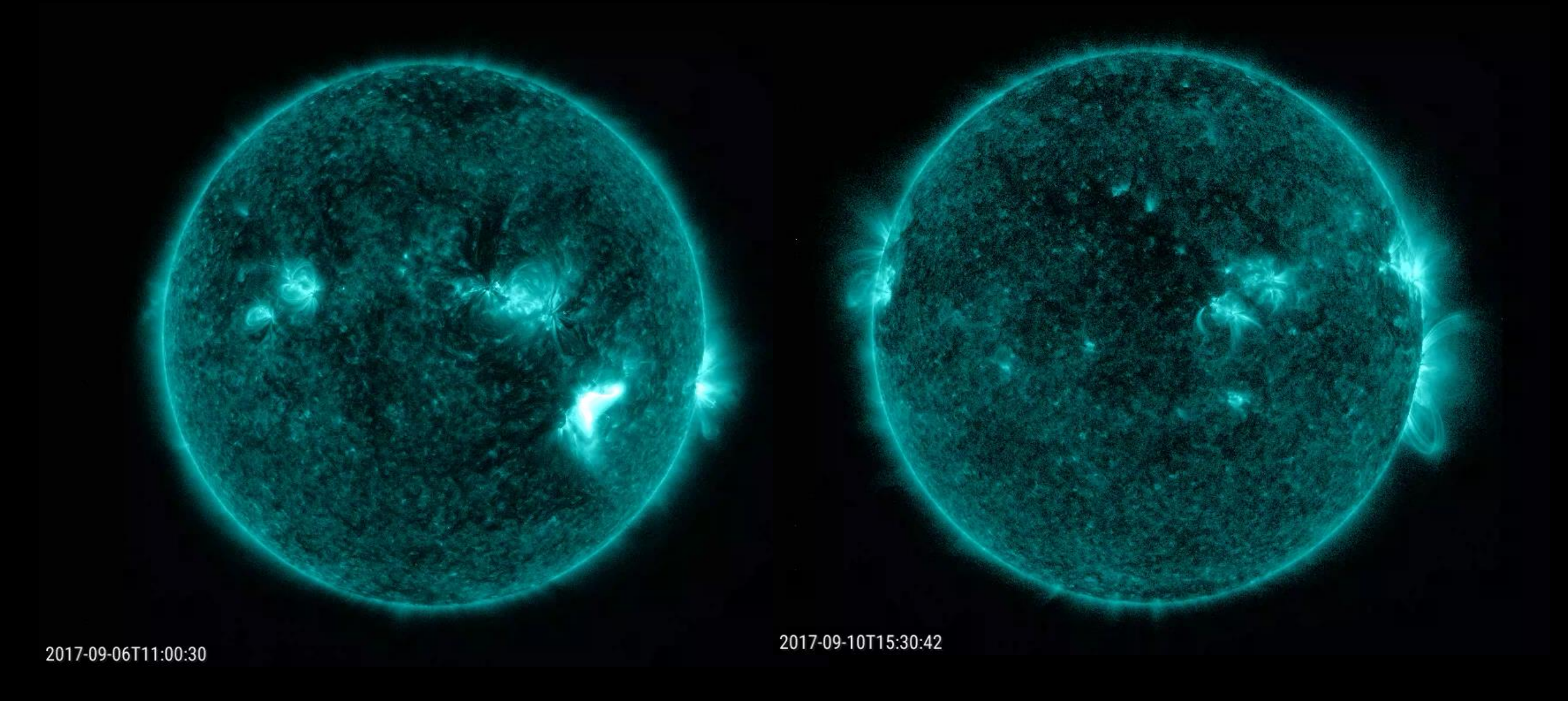
Solar Flares



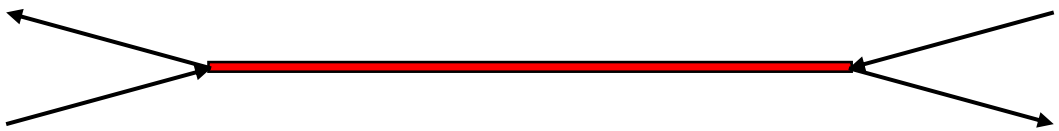




Solar Flares

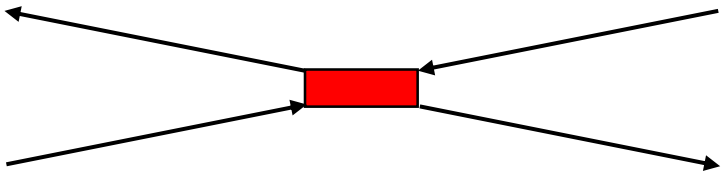


Magnetic reconnection models



Sweet-Parker reconnection (1957)

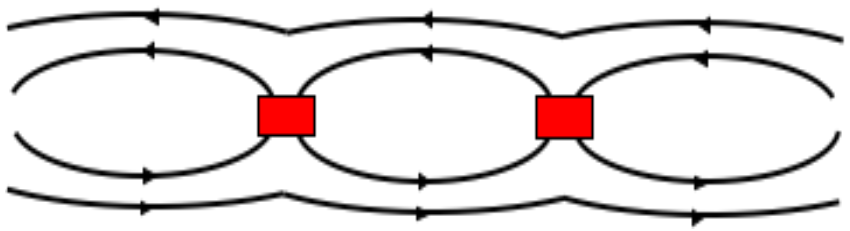
- Magnetic reconnection along an entire current sheet of oppositely orientated field lines.
- Energy release rate is far slower than that observed in flares.



Petschek reconnection (1964)

- Reconnection along a small fraction of the sheet, with a configuration sustained by slow shocks.
- It is unclear whether such a configuration can be sustained during a flare.

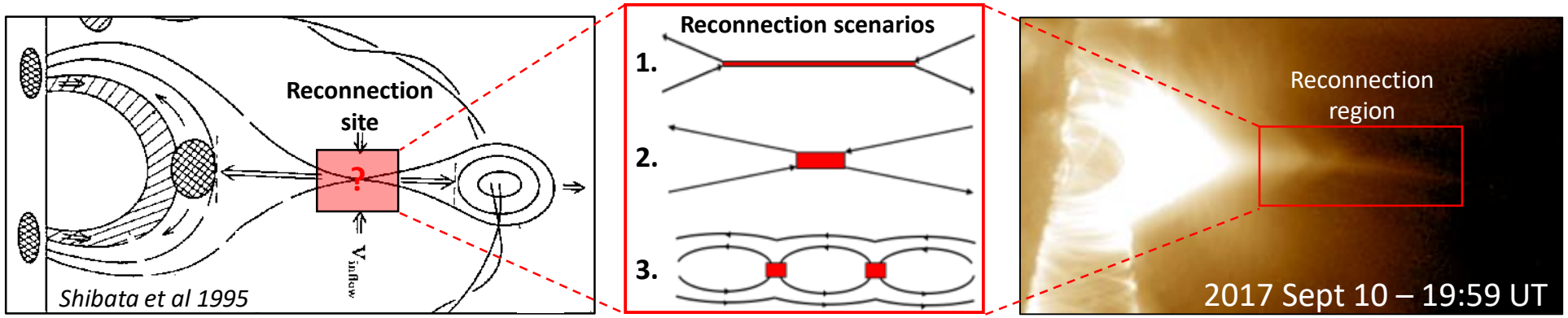
Magnetic reconnection models



Tearing mode / plasmoid instability

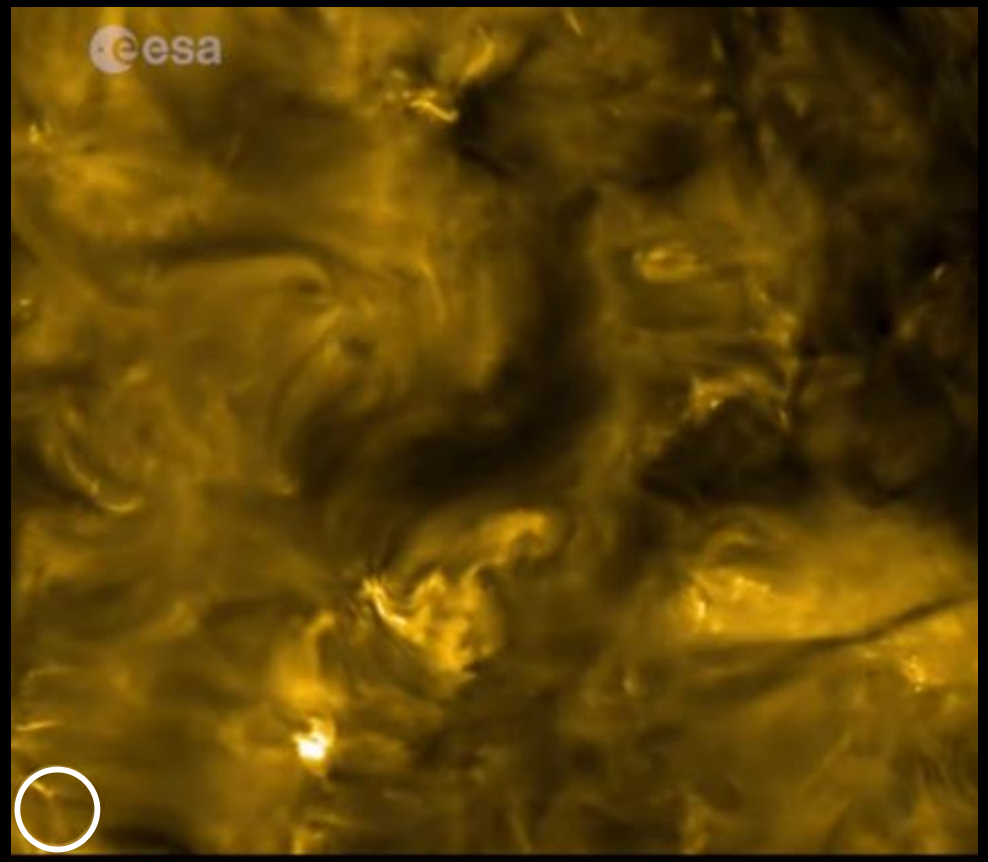
- If the sheet's length greatly exceeds its width, the current sheet collapses/reconnects in certain locations to produce plasmoids or 'magnetic islands'.
- These plasmoids continue to break down to progressively smaller scales in a turbulent cascade.

Which is happening?

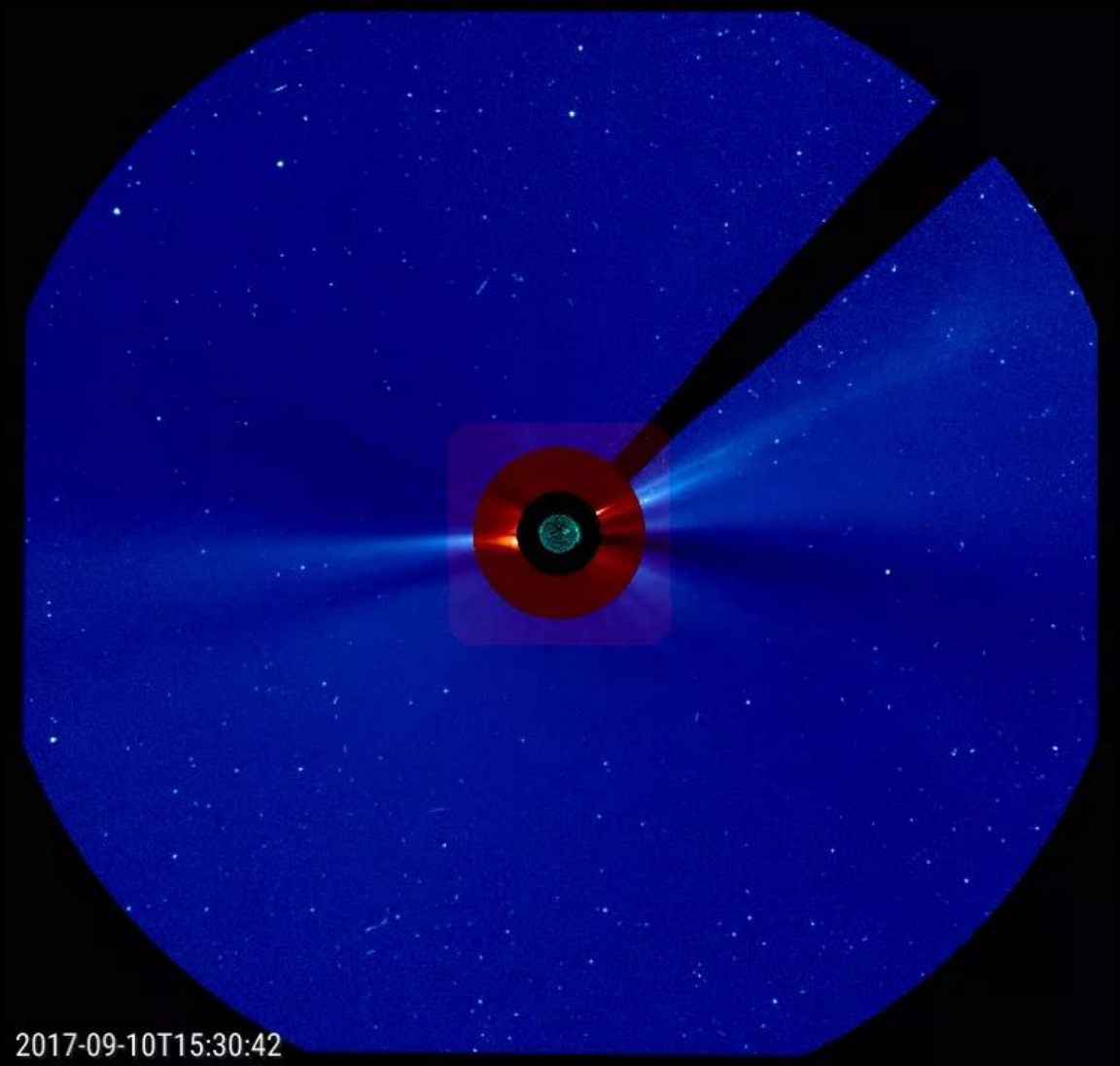


Small-scale Reconnection – Solar Orbiter Campfires

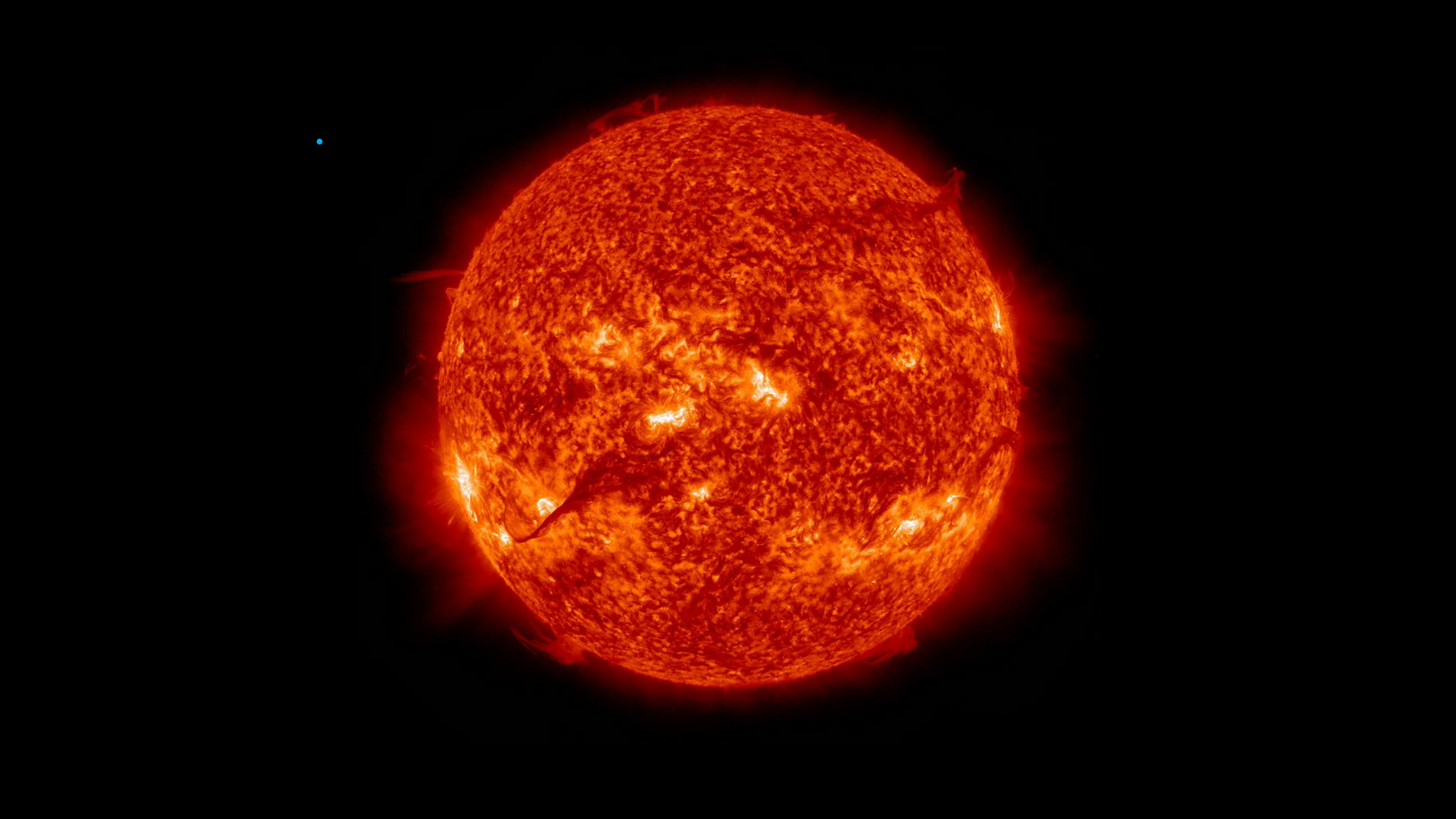
ESA Solar Orbiter EUI – First light images

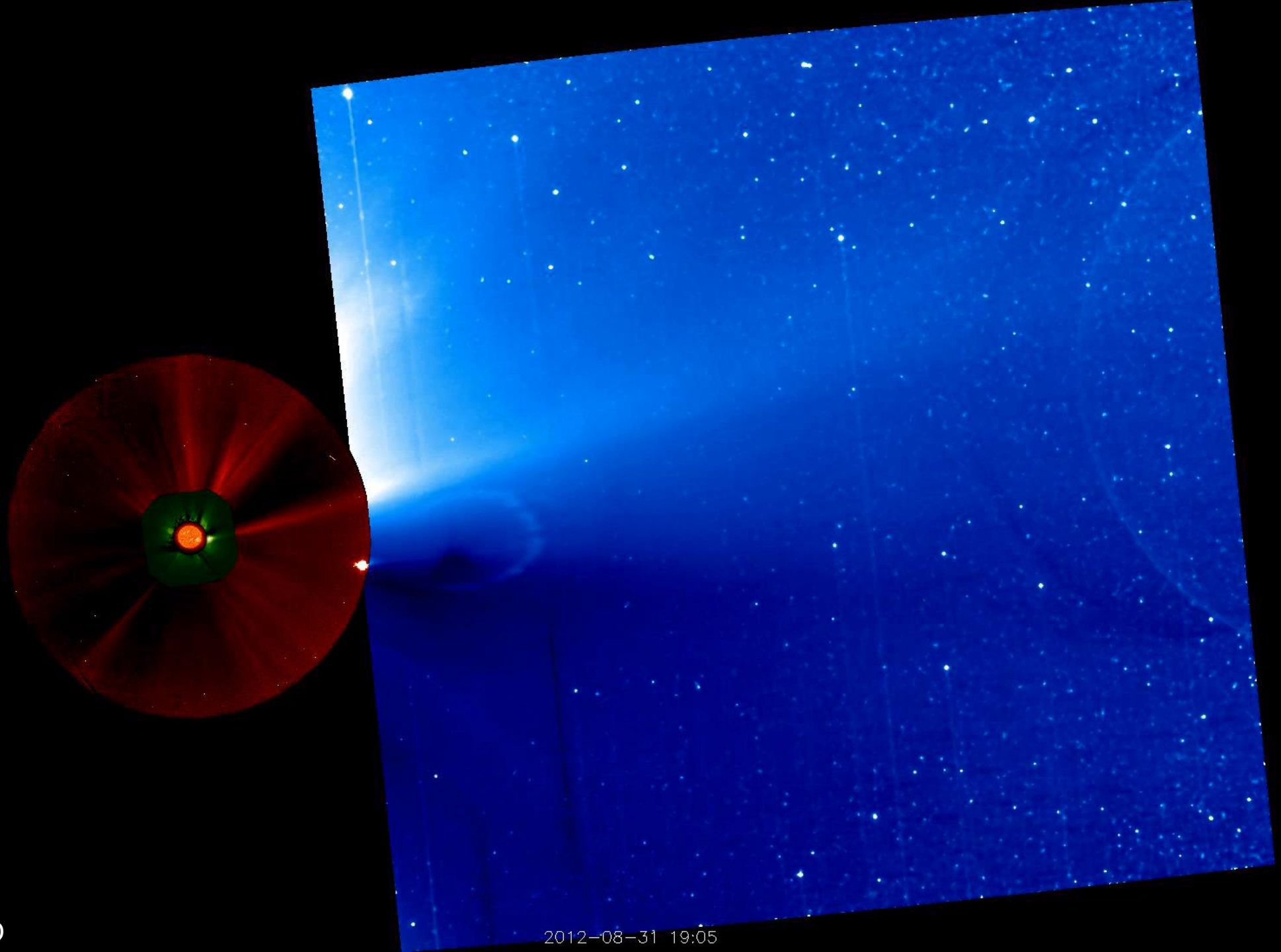


Coronal Mass Ejections (CMEs)



NASA SOHO





NASA STEREO

Arrival at Earth

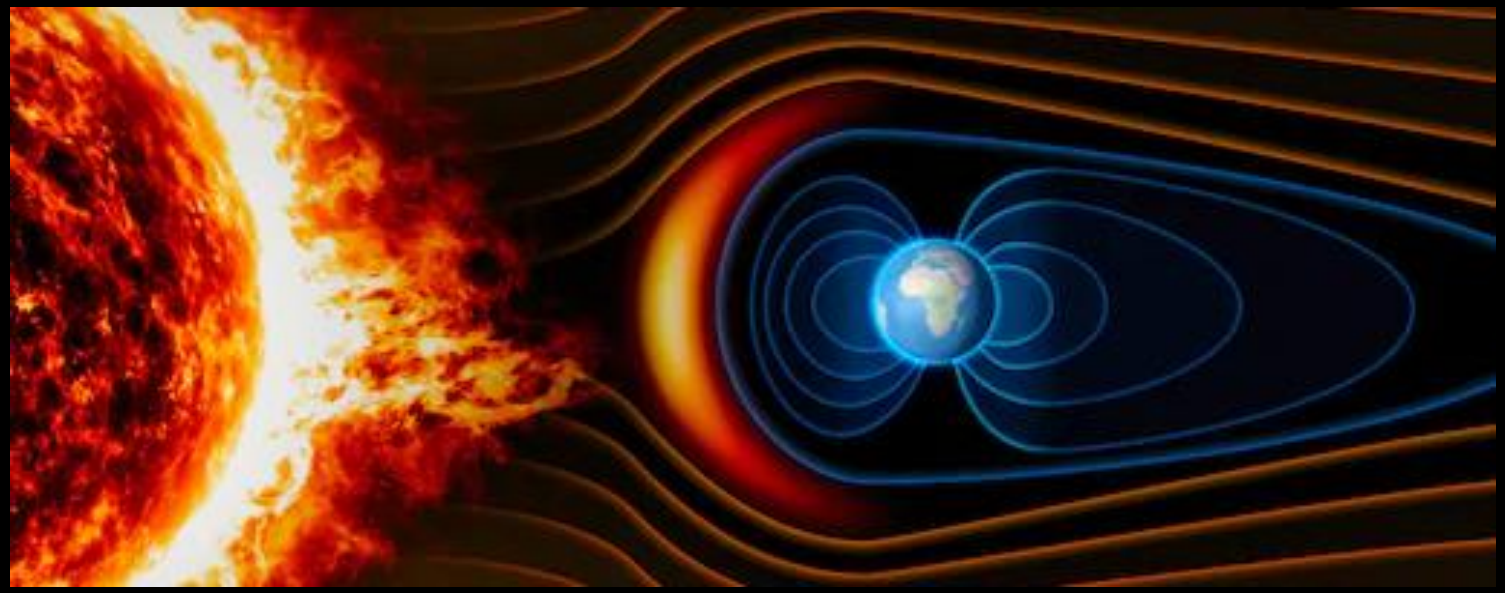
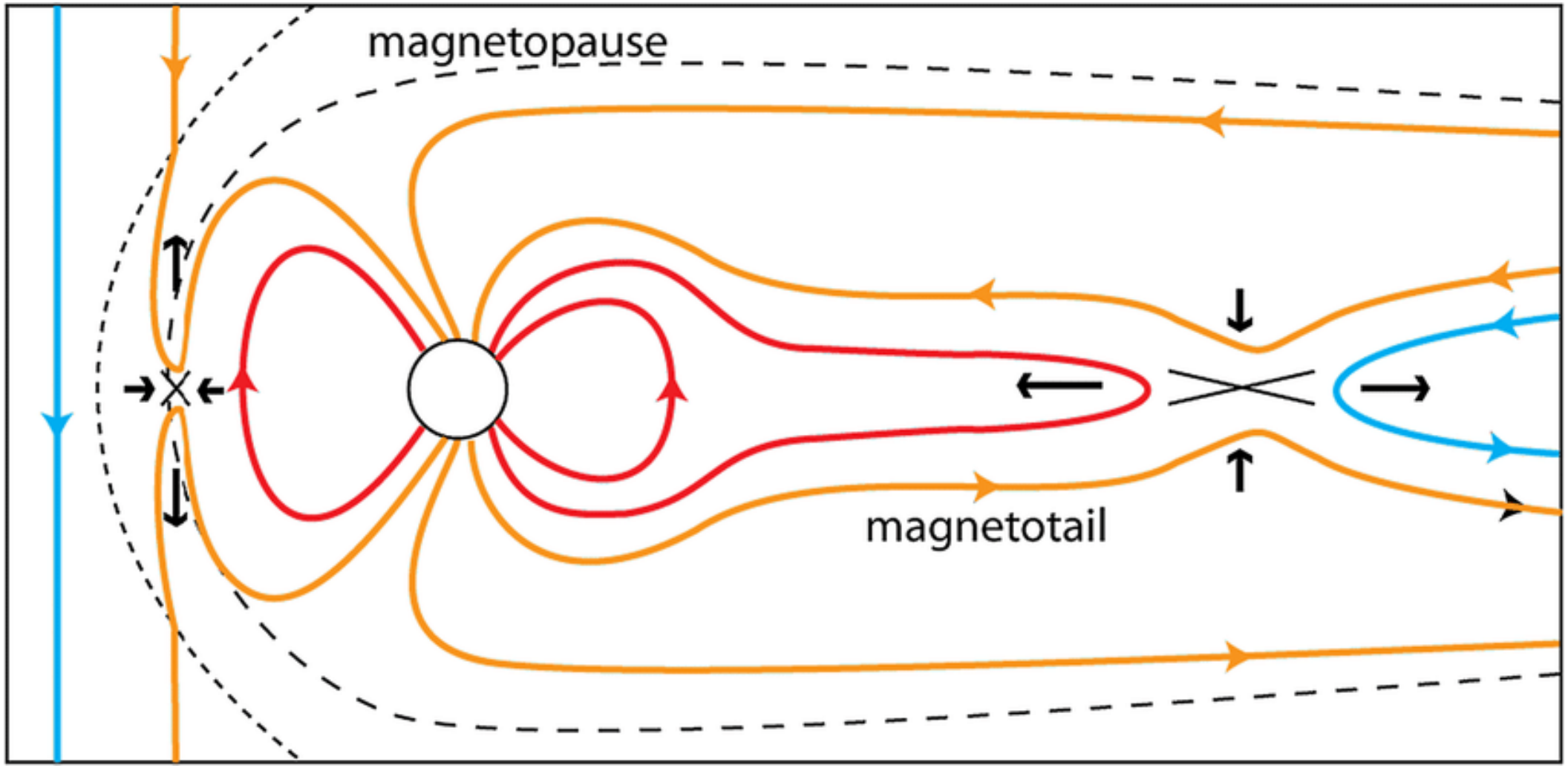


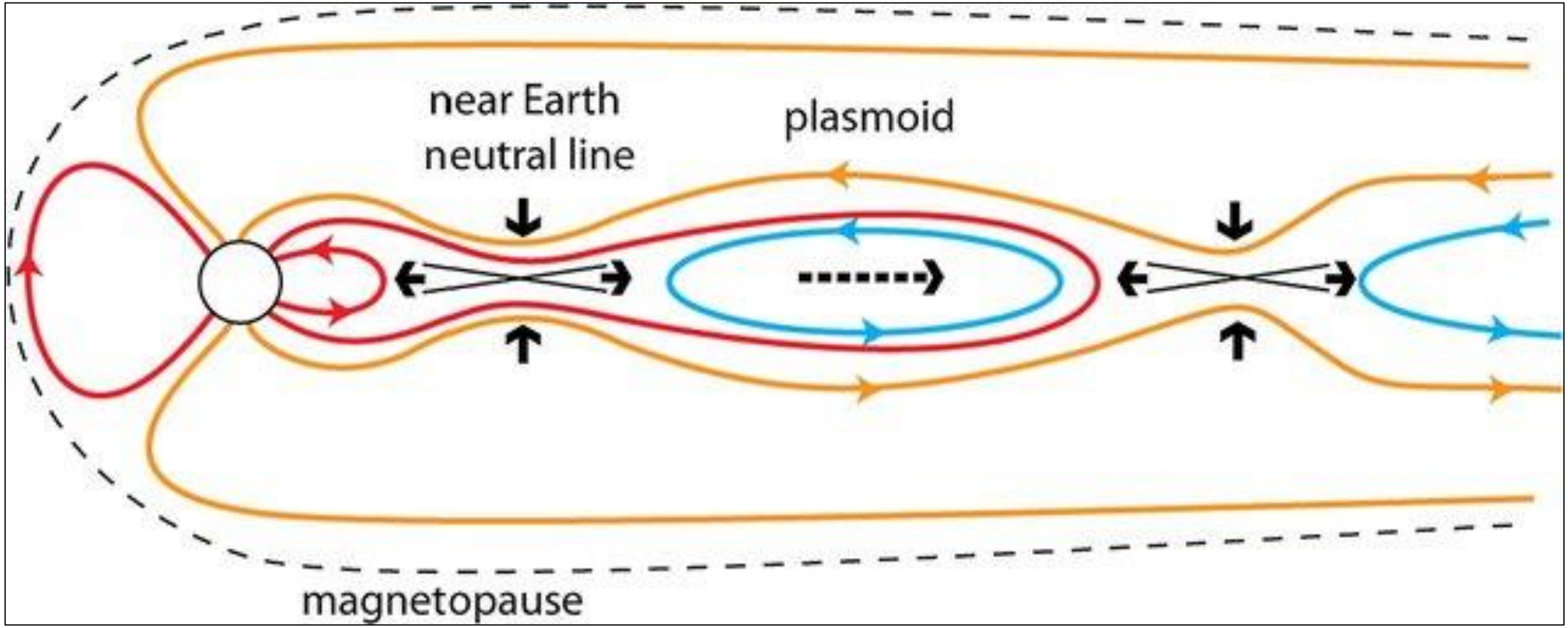
Image credit: NASA

Reconnection at Earth



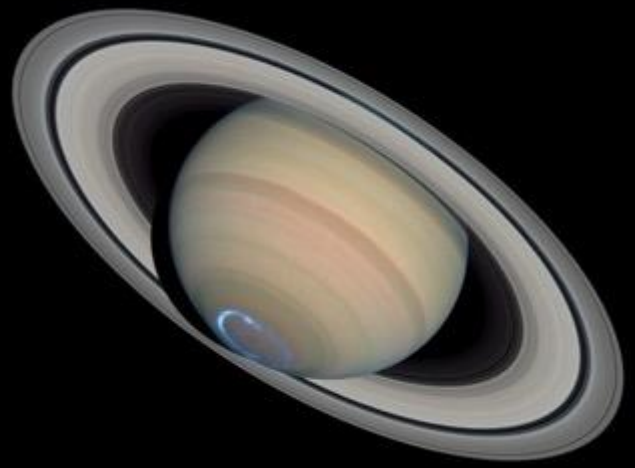
Eastwood et al 2017

Reconnection at Earth

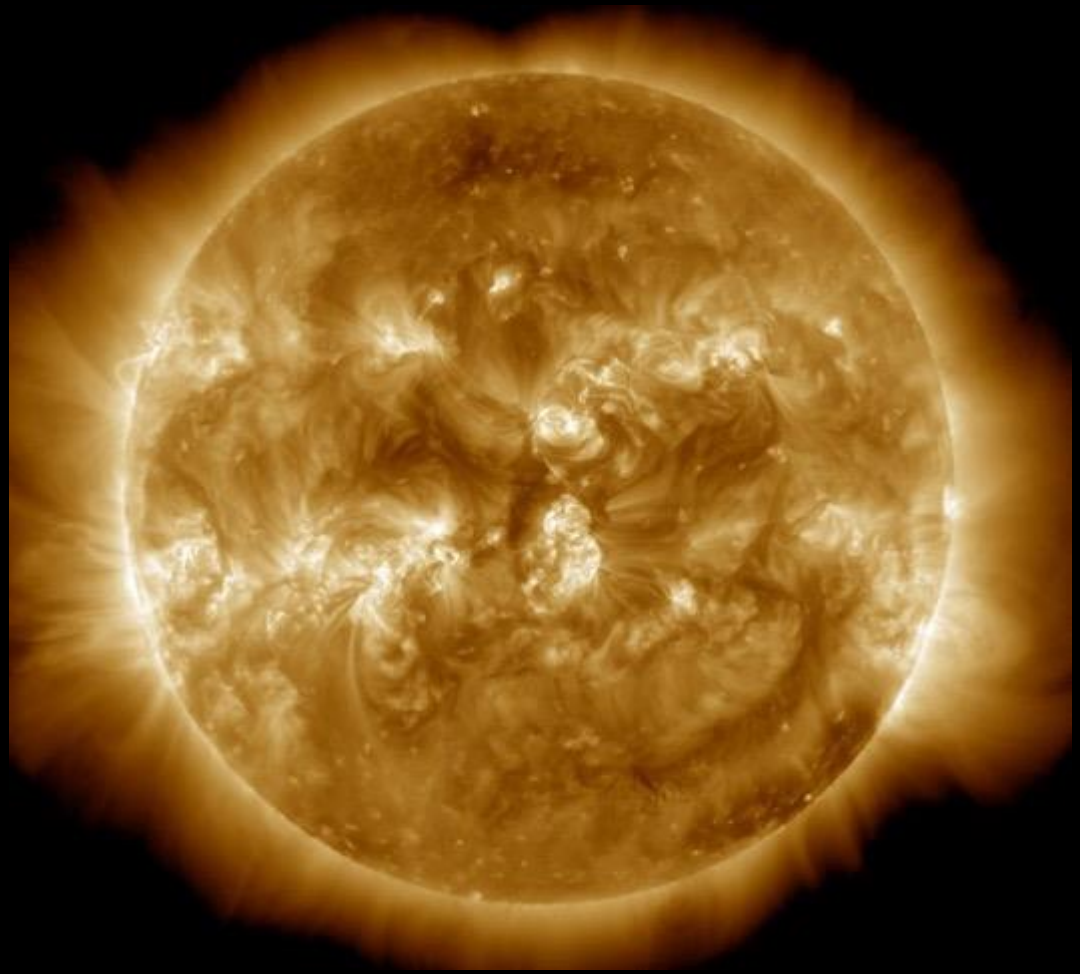


Eastwood et al 2017

Solar System Aurora



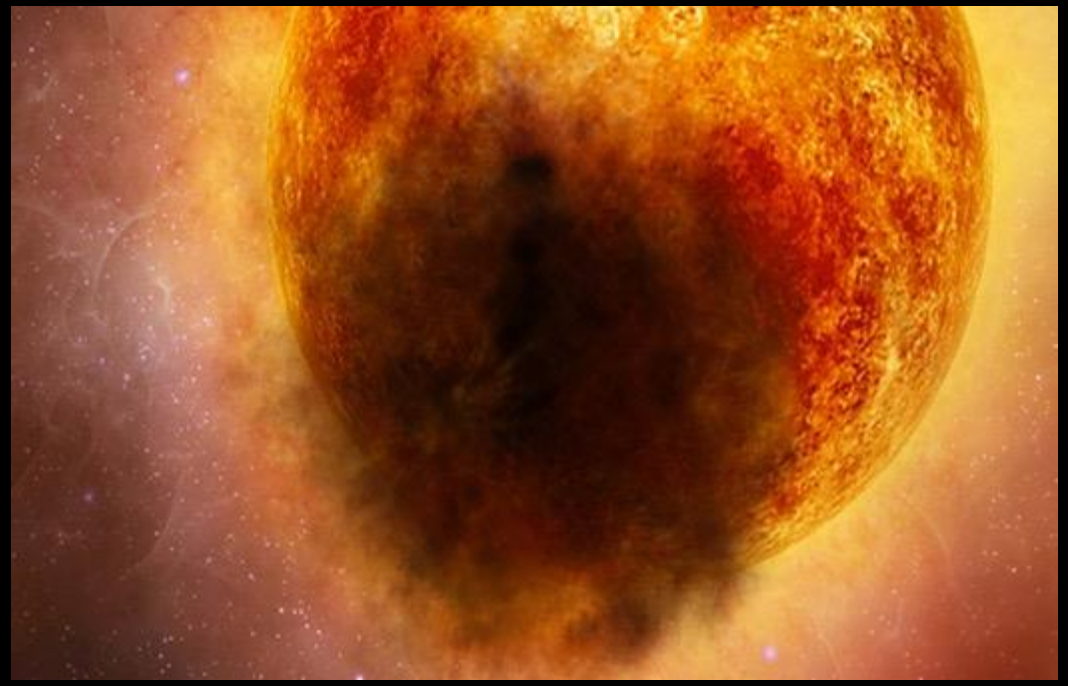
Space Weather



Antares. Credit: ESO

Space Weather on other Stars

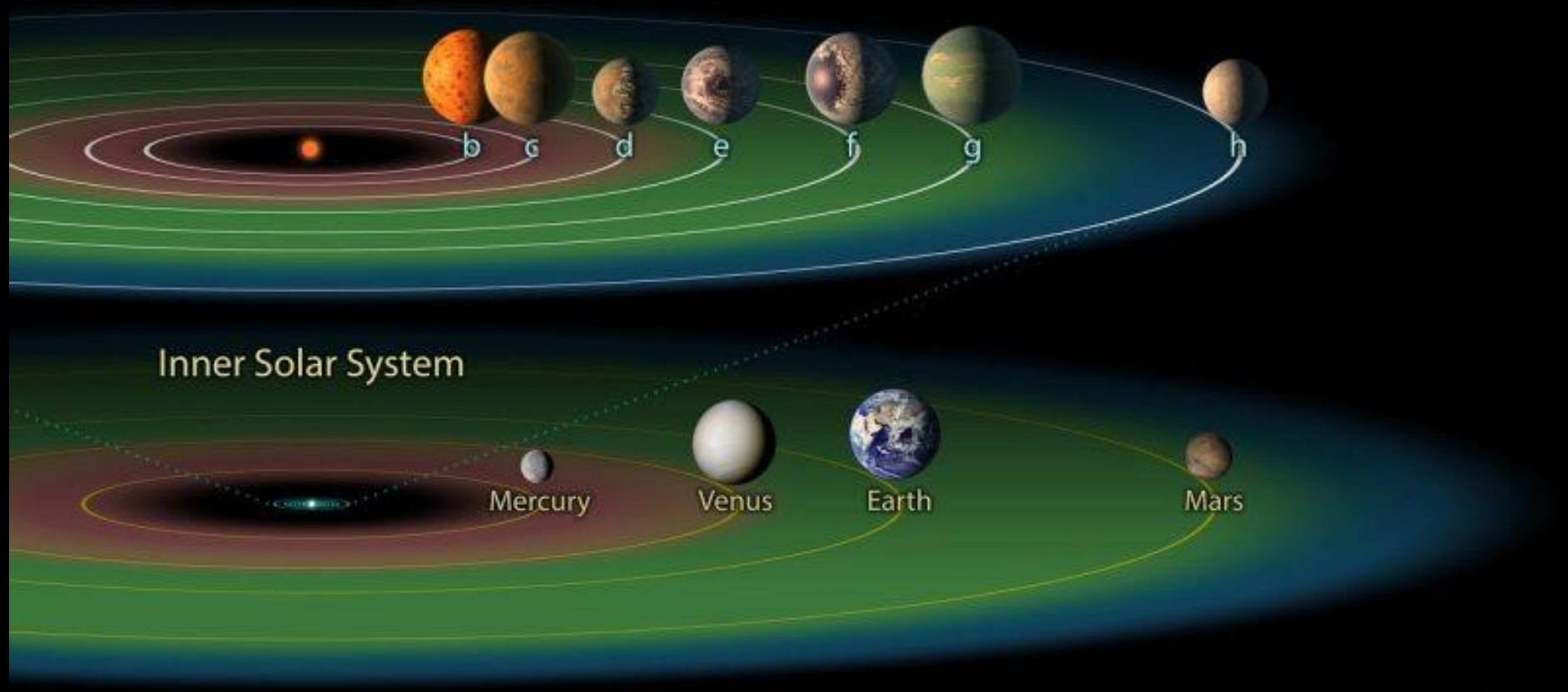
Credit: skyandtelescope



Credit: NASA

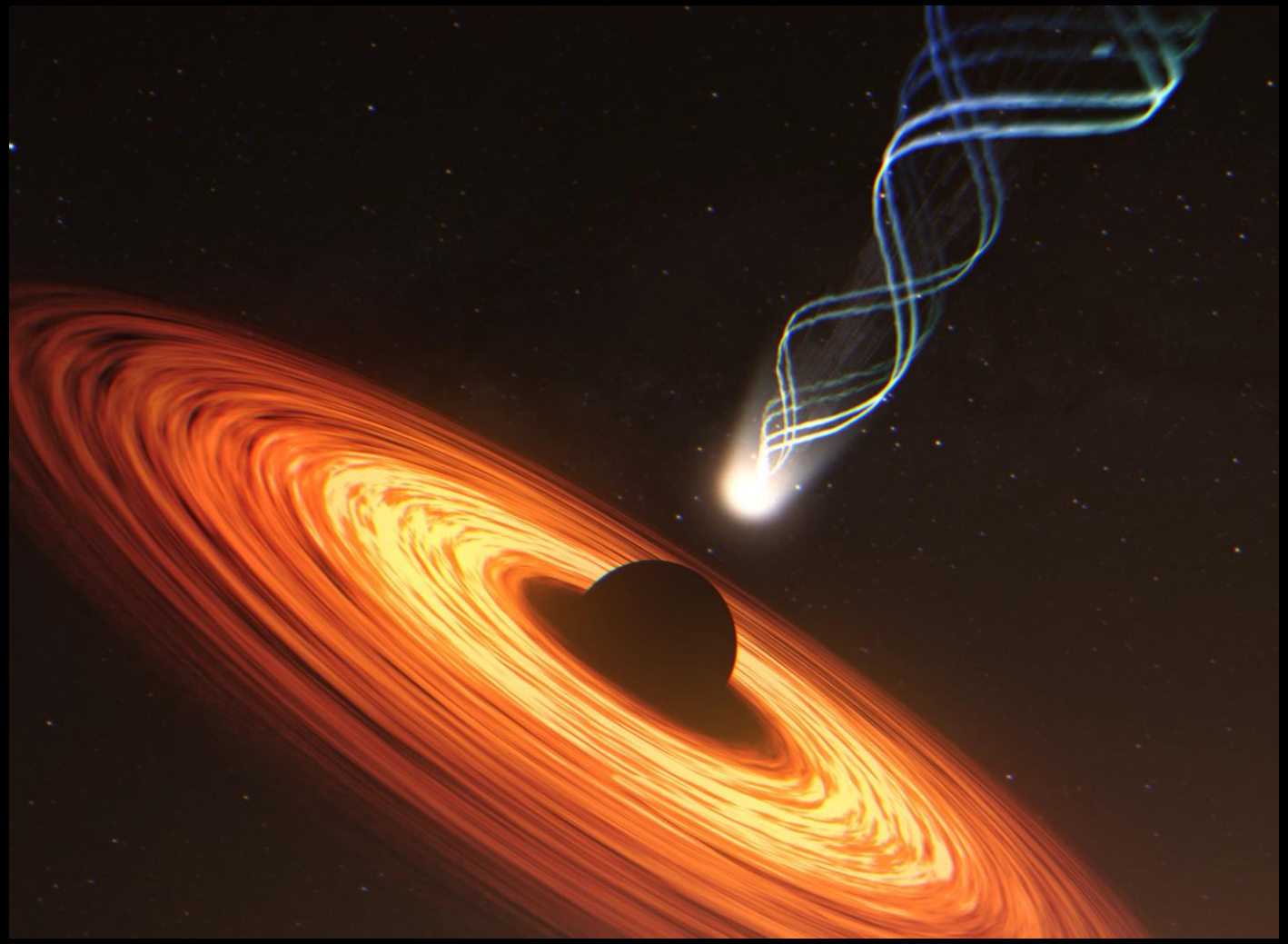
Credit: NASA

Exoplanets



Trappist-1 system. Credit: EarthSky

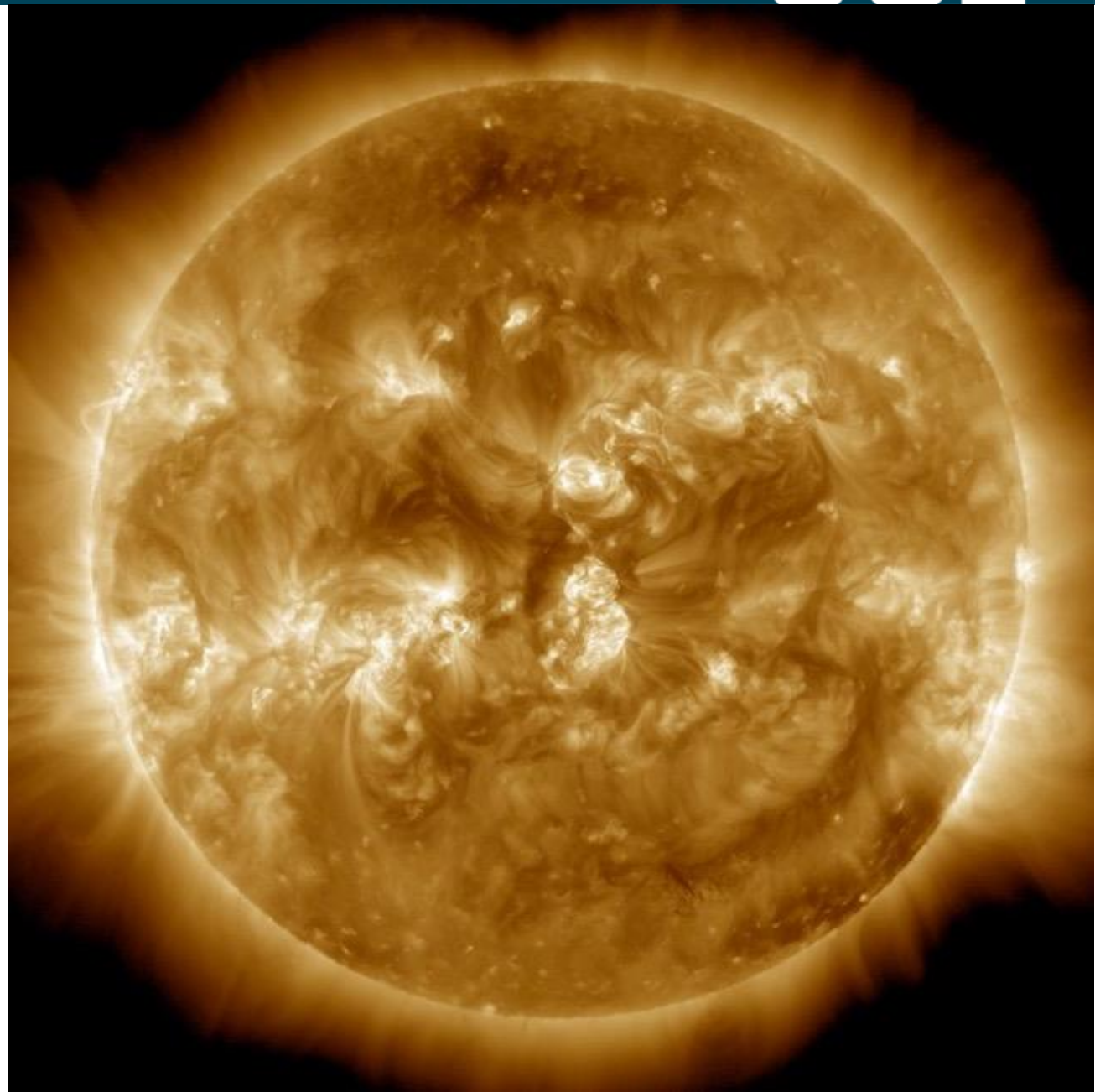
Black holes



Credit: NASA

Conclusion – Why we care about the Sun.

- The Sun acts as a window into astrophysical plasma processes. Studying these phenomena close-up provides an insight into the mechanics of much more elusive events.
- The Sun is volatile. Solar flares and coronal mass ejections cause space weather effects here on Earth. It is important we understand the physics behind these events.



RyanJFrench1 ryan.french.14@ucl.ac.uk

Explosive Energy Release on the Sun and Beyond

1 o'clock Space Lecture

Ryan French

UCL Mullard Space Science Laboratory