

Space Weather

Lecture 2: The Sun and the Solar Wind



Elena Kronberg (room 442)
elena.kronberg@lmu.de

The Sun: facts

- Age = 4.5×10^9 yr
- Mass = 1.99×10^{30} kg (330,000 Earth masses)
- Radius = 696,000 km (109 Earth radii)
- Mean distance from Earth (1AU) = 150×10^6 km (215 solar radii)
- Equatorial rotation period = $\simeq 25$ days
- Mass loss rate = 10^9 kg·s⁻¹
- It takes sunlight 8 min to reach the Earth



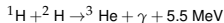
The Sun: facts

- Age = 4.5×10^9 yr
- Mass = 1.99×10^{30} kg (330,000 Earth masses)
- Radius = 696,000 km (109 Earth radii)
- Mean distance from Earth (1AU) = 150×10^6 km (215 solar radii)
- Equatorial rotation period = $\simeq 25$ days
- Mass loss rate = 10^9 kg·s⁻¹
- It takes sunlight 8 min to reach the Earth
- The radiation power is $\simeq 1.5$ kW·m⁻² at the distance of the Earth

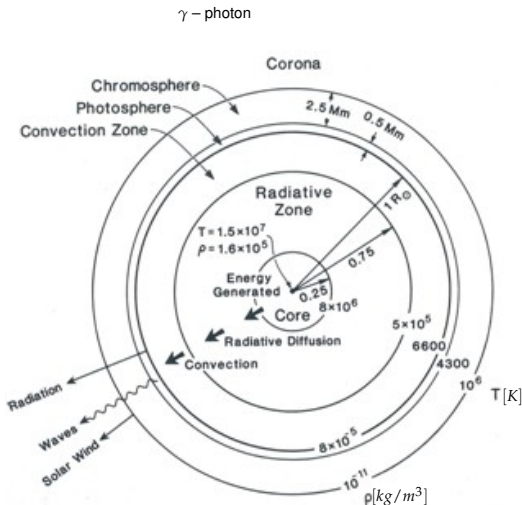


The solar anatomy

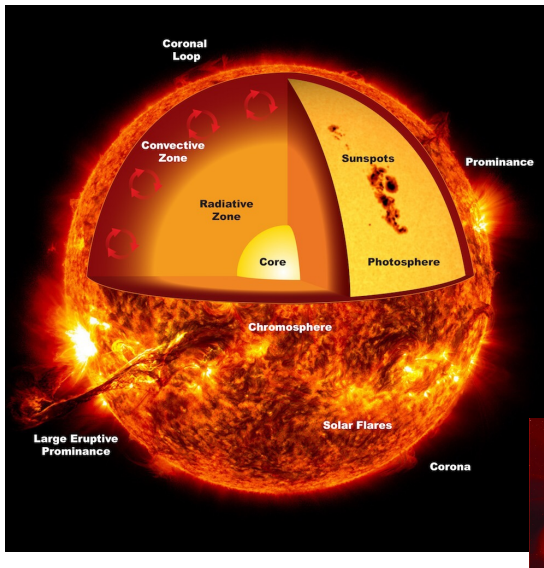
- **Core:** ${}^1\text{H} + {}^1\text{H} \rightarrow {}^2\text{H} + e^+ + \nu + 0.42 \text{ MeV}$



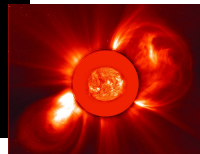
- The **radiative zone**:
electromagnetic radiation transports energy outwards
- The **convection zone**:
energy is transported by convection
- The **photosphere** – layer which emits visible light
- The **chromosphere** is the Sun's atmosphere.
- The **corona** is the Sun's outer atmosphere.



The solar anatomy



corona expands to $\sim 1 R_{\odot}$



The Sun and its magnetohydrodynamics

The induction equation is

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B}, \quad (1)$$

where $\mathbf{v}$ is the fluid velocity, $\mathbf{B}$ is the magnetic field strength, $\eta = 1/(\mu_0 \sigma_0)$ is the magnetic diffusivity and t is the time.

The magnetic Reynolds number is

$$R_m = \frac{vL}{\eta} = \mu_0 \sigma_0 vL,$$

where μ_0 is the permeability of free space and σ_0 is the electrical conductivity of the material and L is the length scale.

The Sun and its magnetohydrodynamics

The induction equation is

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B}, \quad (1)$$

where $\mathbf{v}$ is the fluid velocity, $\mathbf{B}$ is the magnetic field strength, $\eta = 1/(\mu_0 \sigma_0)$ is the magnetic diffusivity and t is the time.

The magnetic Reynolds number is

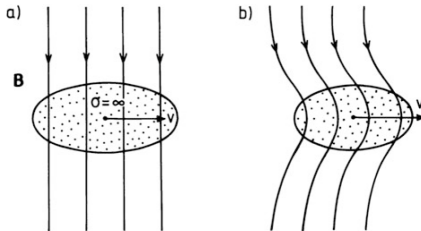
$$R_m = \frac{vL}{\eta} = \mu_0 \sigma_0 vL,$$

where μ_0 is the permeability of free space and σ_0 is the electrical conductivity of the material and L is the length scale.

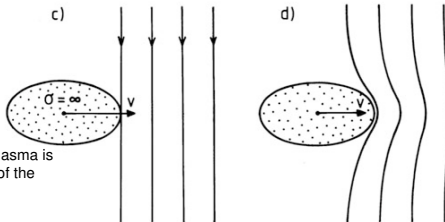
For most solar phenomena $R_m \simeq 10^6 - 10^{12} \Rightarrow$ the magnetic field is “frozen” to the plasma.

For the Earth's dynamo $R_m \simeq 10^3$, generation of the magnetic field in laboratory $R_m \ll 1$ due to small scales

Frozen-in condition



When plasma starts to move, the magnetic field lines will be frozen-in and follow the motion of the plasma.



A highly conducting plasma is approaching an area of the magnetic field.

Due to the high conductivity the field cannot penetrate the plasma and is pushed ahead of the plasma blob.

Credit: A. Brekke

The Sun and its magnetohydrodynamics

The momentum equation is

$$\rho \frac{d\mathbf{v}}{dt} = -\nabla p + \mathbf{j} \times \mathbf{B} + \rho \mathbf{g}, \quad (2)$$

where ρ is the plasma density, p is the plasma pressure and $\mathbf{g}$ is the gravitational acceleration.

Equating the left-hand side to the magnetic force gives an order-of-magnitude speed

$$v = \frac{B}{\sqrt{\mu_0 \rho}} = v_A,$$

where v_A is the *Alfvén speed* and is the typical speed to which magnetic forces can accelerate plasma through the Lorentz force law.

The Sun and its magnetohydrodynamics

The continuity equation

$$\frac{d\rho}{dt} + \rho \nabla \cdot \mathbf{v} = 0, \quad (3)$$

and energy equation

$$\frac{\rho^\gamma}{\gamma - 1} \frac{d}{dt} \left(\frac{p}{\rho^\gamma} \right) = Q - L \quad (4)$$

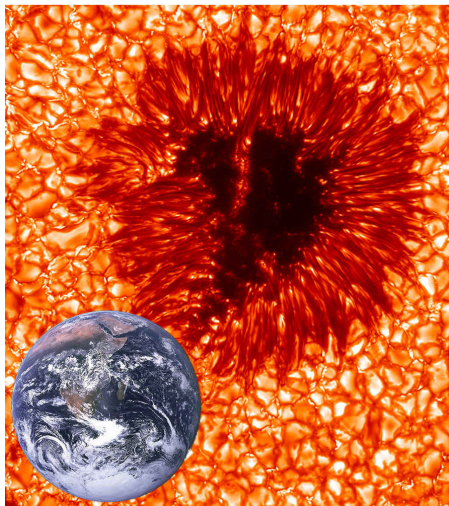
which describes how the entropy of a moving element of plasma changes because of energy input Q and loss L . γ is the adiabatic index.

Energy can change due to, e.g.,:

- the conduction of heat, which tends to equalize temperatures along the magnetic field
- the radiation and ohmic heating.

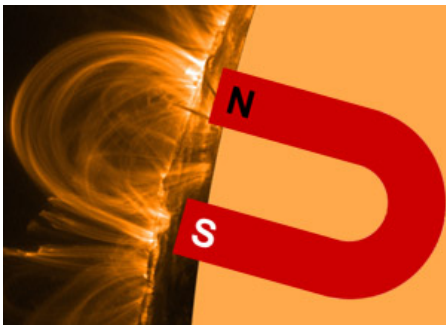
More details on MHD equations and their use in modeling of the Sun are e.g. in Priest, Magnetohydrodynamics of the Sun, 2014.

Photosphere: sunspots



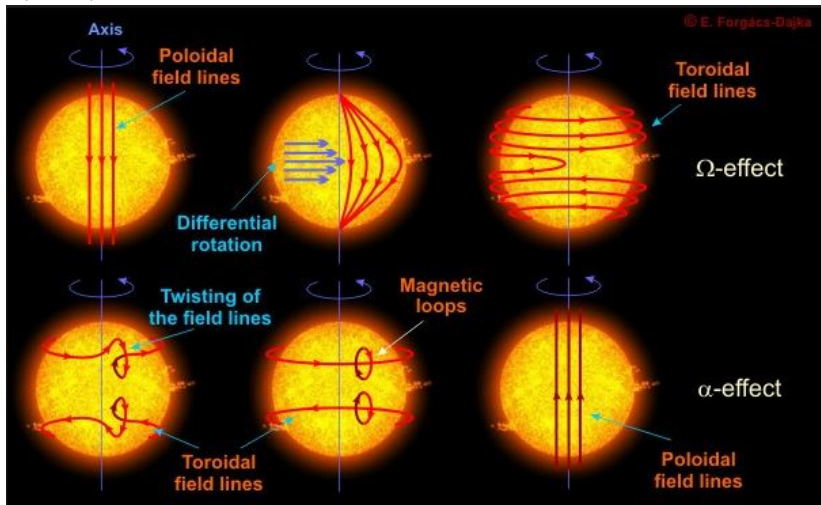
Sunspots are regions with reduced surface temperature caused by concentrations of magnetic field flux that inhibit convection

$$B=0.3 \cdot 10^8 \text{ nT}$$



Photosphere: sunspot generation mechanism

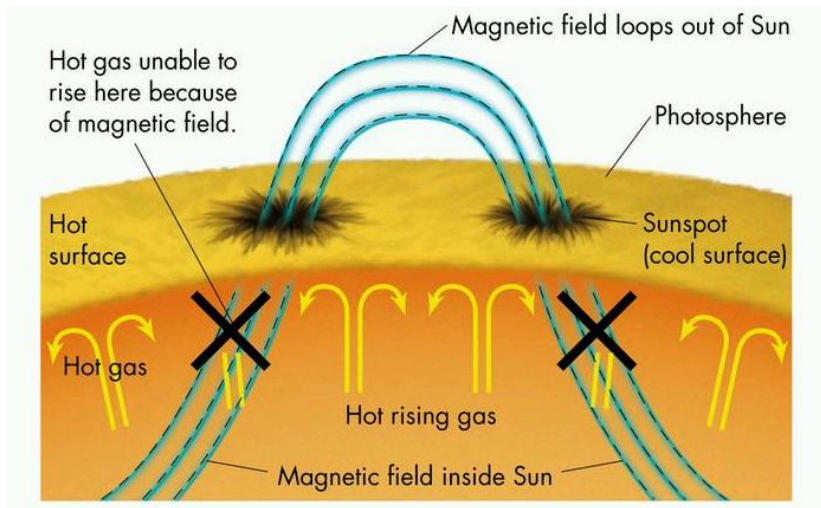
solar cycle – 11 years



Babcock-Leighton mechanism

Image: E. F. Dajka

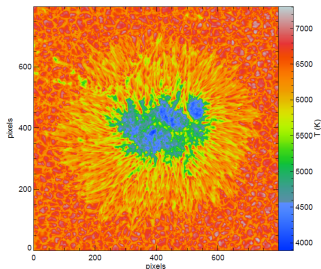
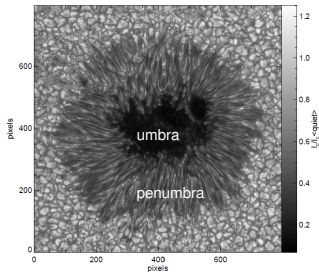
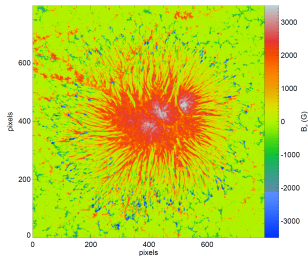
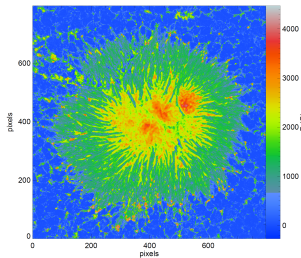
Photosphere: sunspot generation mechanism



frozen-in condition: hot gas does not penetrate the area with strong magnetic field

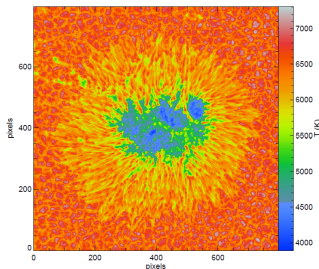
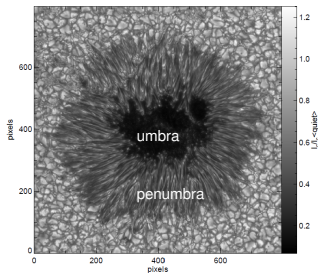
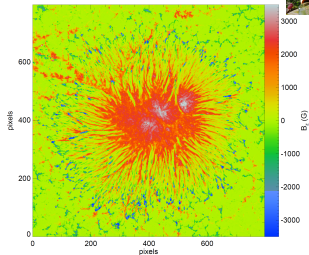
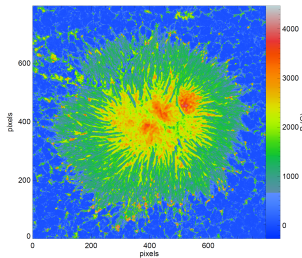
Image from oswego.edu

Photosphere: sunspots



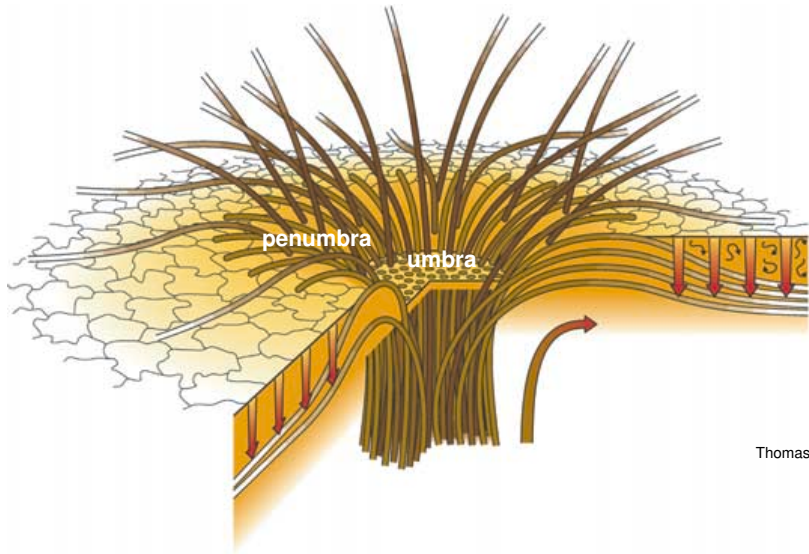
Tiwari, S., A&A, 2015, Solar Optical Telescope, Spectropolarimeter (vector magnetograph), Hinode

Photosphere: sunspots



Tiwari, S., A&A,
2015, Solar Optical
Telescope,
Spectropolarimeter
(vector
magnetograph),
Hinode

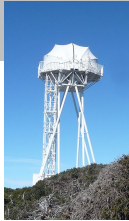
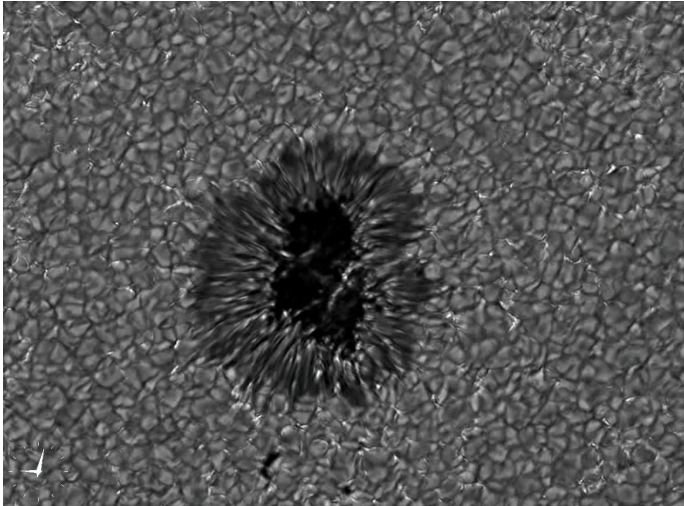
Photosphere: sunspot structure



Thomas et al., 2002

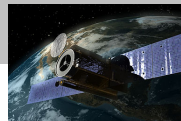
Photosphere: sunspots

- Quiet sunspot, granulas – the tops of giant convection cells



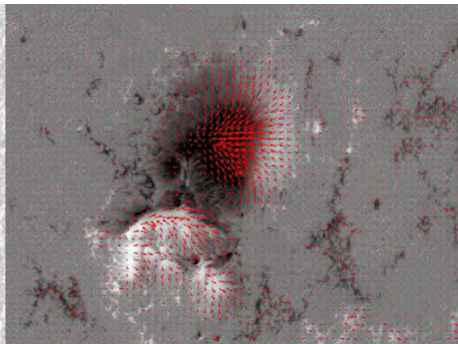
Credit: Peter Suetterlin and Rob Rutten and the Dutch Open Telescope (DOT) team

Photosphere: sunspots



- Huge Hurrican

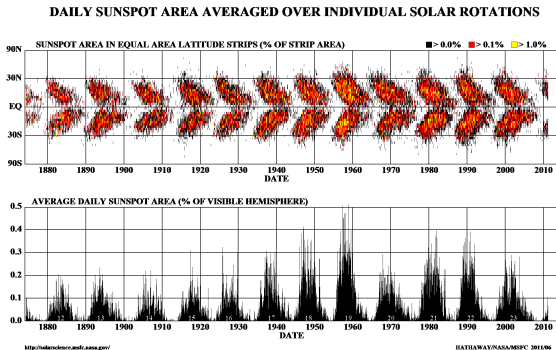
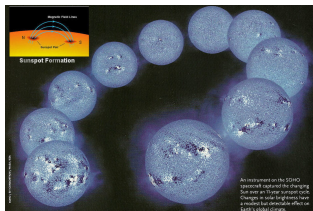
2006-12-14 22:00:06



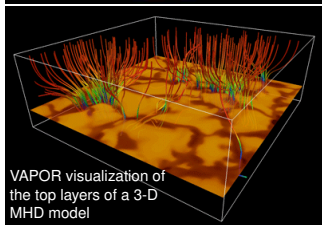
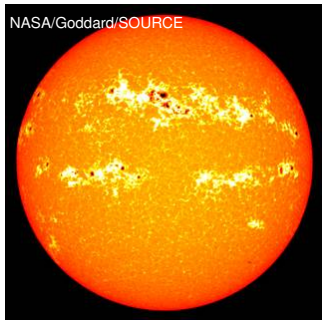
Credit: Team of Hinode
is a mission of JAXA,
NASA and UK space

Solar cycle

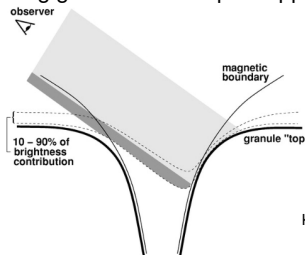
- Number of solar spots changes. Solar cycle spans from one minimum to the next – ~ 11 years.
- Hale cycle is complete magnetic cycle – ~ 22 years.



Why is the Sun brighter during solar maximum?



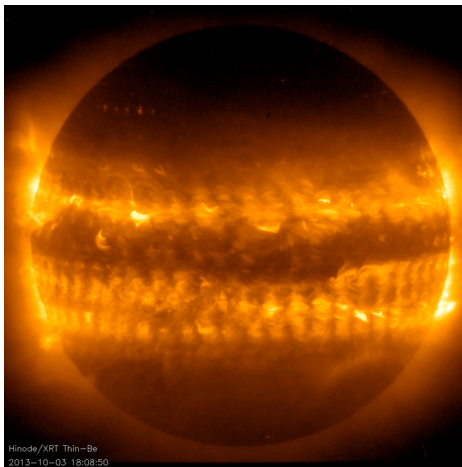
- Sunspots are accompanied by bright white spots – faculae – which cause an overall increase in solar irradiance.
- Faculae form in the canyons between granules and are produced by concentrations of magnetic field.
- Density of the gas is reduced by the presence of strong magnetic fields. The deeper layers of the granule become transparent. They are hotter and radiate more strongly, explaining the brightening.
- Sunspot magnetic fields are far stronger. They cool the surrounding gases and the spots appear dark.



Keller et al., 2004

Active regions

- An active region is an area with an especially strong magnetic field.
- Sunspots and faculae are indicators of active regions.
- They are prone to solar flares and Coronal Mass Ejections.

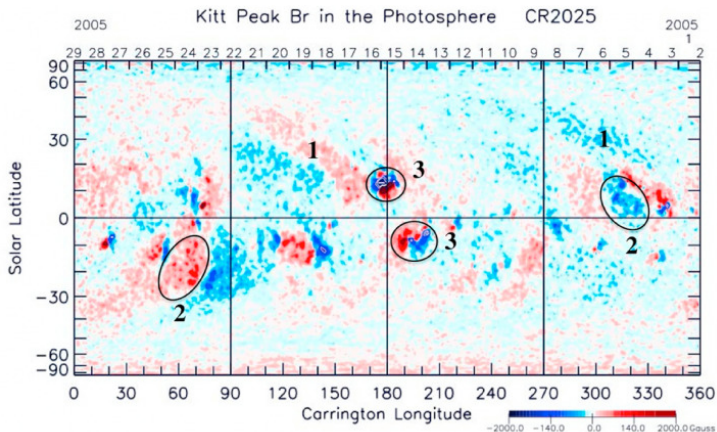


Credit: NASA

X-ray Telescope from
Hinode, 2 months of
images in 2013

What about single sunspots?

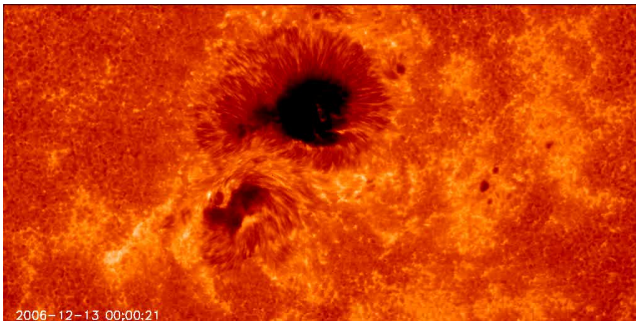
The origin of sunspots is a very difficult and complex problem!



Akasofu 2021

Chromosphere: solar flare

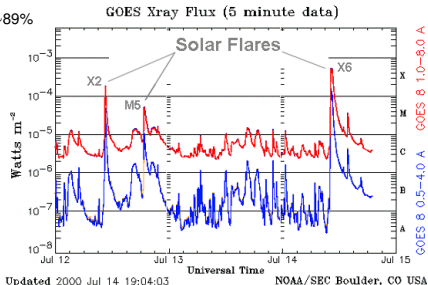
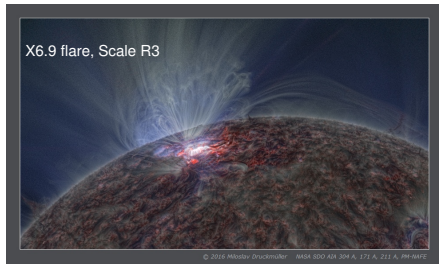
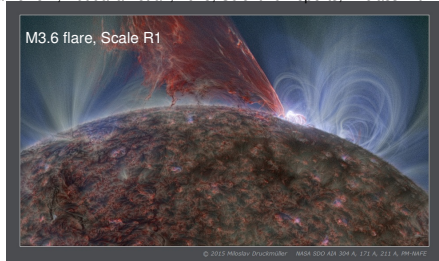
- Flare is sudden blast of electromagnetic radiation and charged particles emanating from the surface of the Sun.
- Associated X-rays and UV radiation can affect Earth's ionosphere and disrupt long-range radio communications.
- Direct radio emission at decimetric wavelengths may disturb the operation of radars and other devices that use those frequencies.
- It is a challenging task to predict solar flare (machine learning helps).



Credit: Hinode team,
Solar Optical
Telescope (SOT)

Chromosphere: solar flares

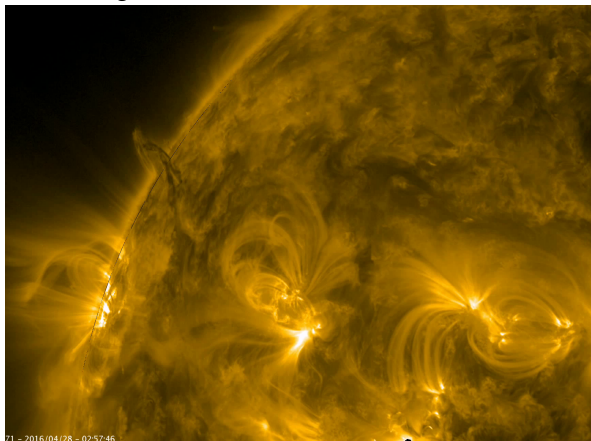
Operational prediction of solar flares using a transformer-based framework, Abdullallah et al., 2023, Scientific Reports, M-class with ~89%



- Scale R1 → M1 class. HF radio occasional loss of contact. LF navigation signals briefly degraded.
- Scale R3 → X1 class. HF radio communication: loss of contact for about an hour on sunlit side of Earth. LF navigation signals degraded for about an hour.

Chromosphere: prominence

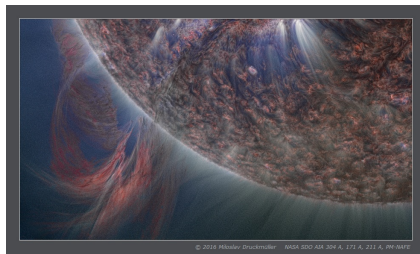
- A prominence is a large plasma and magnetic field structure extending outward from the Sun's surface, often in a loop shape.
- The magnetic field is embedded in plasma – frozen-in condition.
- Magnetic field strength is $10^6 - 10^7$ nT.



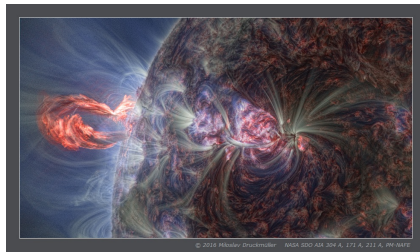
Chromosphere: prominence and filament

- Difference in view: prominence – against space, filament against Sun

Filament eruption, 2010

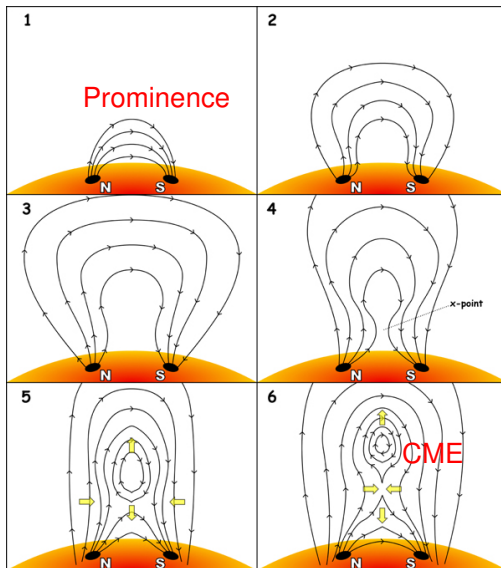


Prominence eruption, 2015

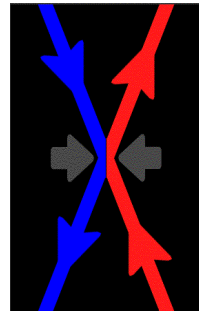


Prominence and Coronal Mass Ejection (CME)

CME is large expulsion of plasma and magnetic field from the Sun's corona.



Solar flare?



Credit: SSL Berkely

Solar flare and CME

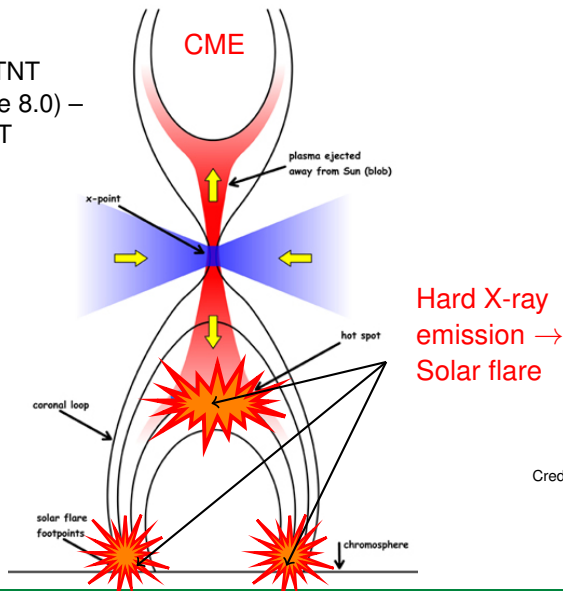
Energy comparison:

Large solar flare –

$\simeq 10^9$ of megatons of TNT

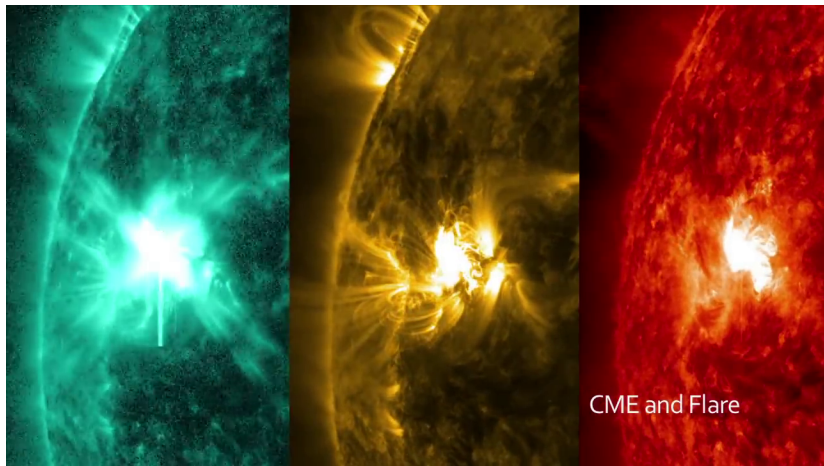
Earthquake (magnitude 8.0) –

$\simeq 10^3$ megatons of TNT

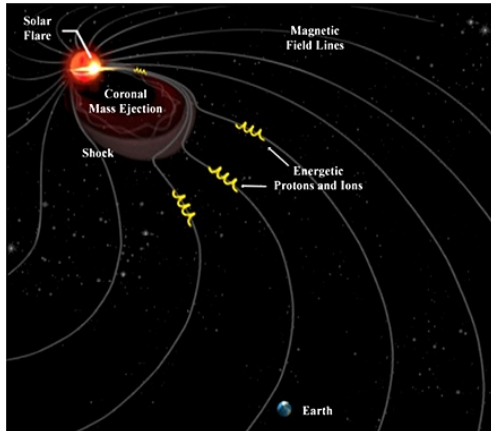


Credit: SSL Berkely

The difference between CMEs and solar flares?



Solar Particle Event (SPE) or Solar Energetic Particle (SEP) event or “solar radiation storm”

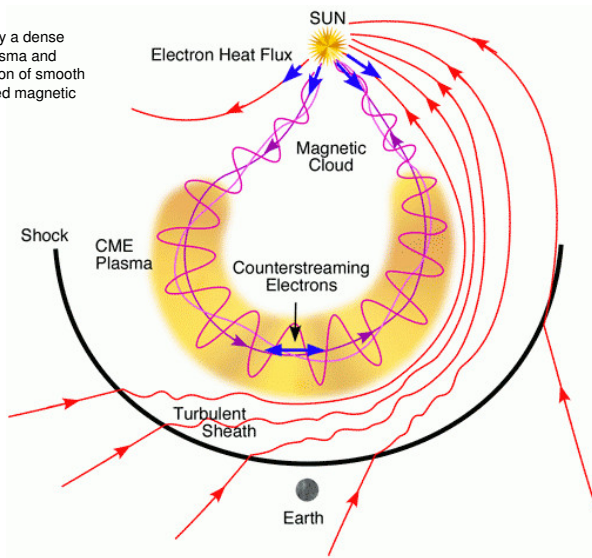


Takes from 10 min to several days to arrive to Earth's orbit (Podgorny, 2018)

- SPE occurs when particles (mostly protons) emitted by the Sun become accelerated either close to the Sun during a flare or in interplanetary space by CME shocks.
- The strength of SPEs and CMEs is reflected by Space Weather scale S.

Interplanetary CME (ICME) — typical structure

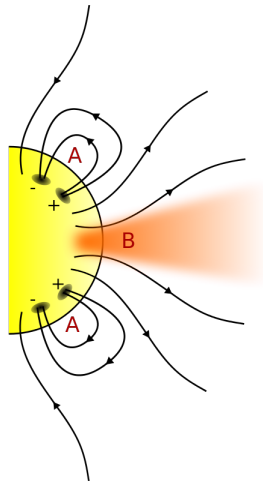
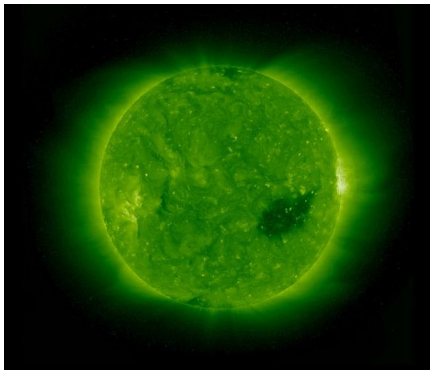
Shock wave followed by a dense (and hot) sheath of plasma and magnetic cloud — region of smooth rotation of the enhanced magnetic field vector, and low T_p



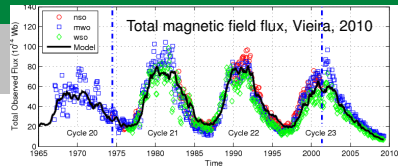
Coronal holes

Dark regions where the magnetic field is open and through which the solar wind is streaming outward.

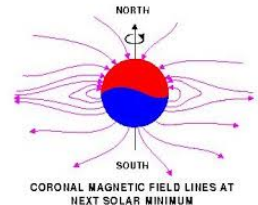
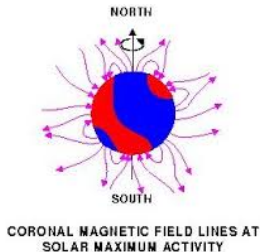
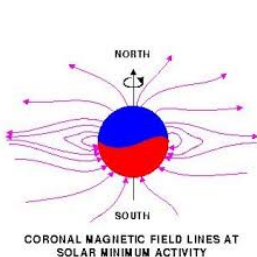
The strength of magnetic field at the poles is $\sim 10^5$ nT.



Solar magnetic field topology

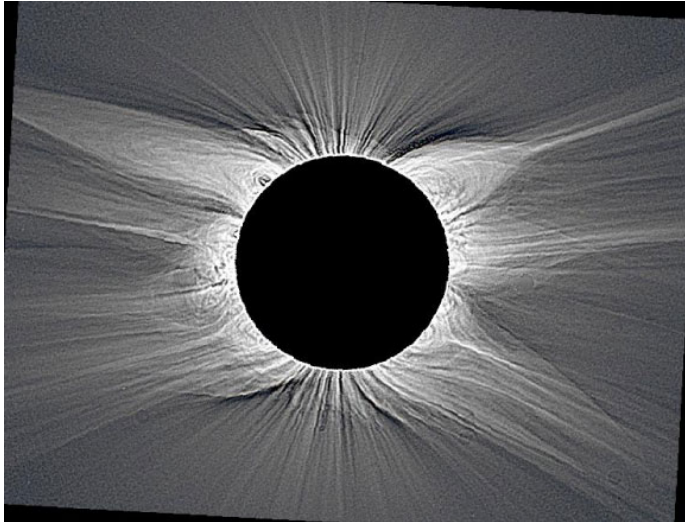


- The Sun has a complex magnetic field geometry.
- Coronal helmet streamers are large closed magnetic loops which connect regions of opposite magnetic polarity. They lead to formation of heliospheric current sheets.



Solar corona

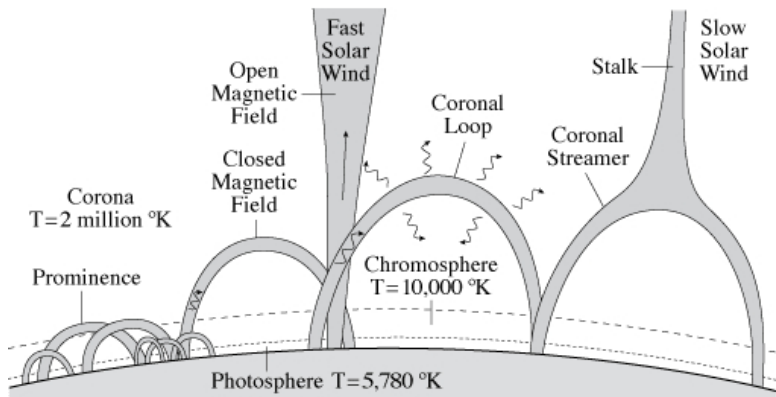
The total eclipse of 29 March 2006 in Libya



Credit: M. Druckmüller and P. Aniol

Solar corona

- Coronal loop is filled with hot plasma, prominence is cooler and denser.
- Prominence has cusps to hold plasma, closed magnetic field is empty of plasma.

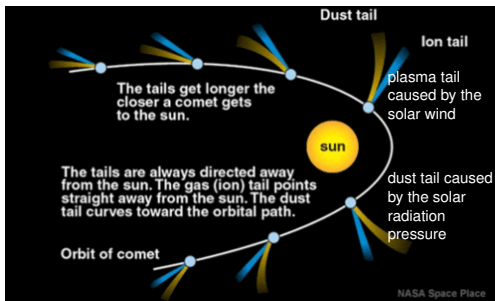
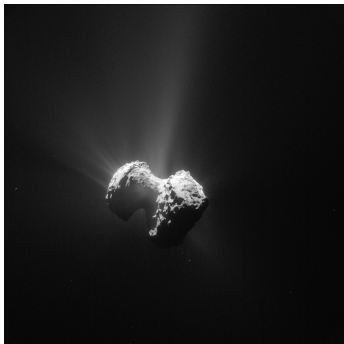


The solar wind

- Solar wind is a *plasma*, gas of charged particles with equal numbers of free positive and negative charge carriers
- Mainly electrons and protons, He (5%)
- Free charges make the plasma *highly electrically conductive*
- Density $n_{e,sw} \simeq 5 \text{ cm}^{-3}$ and temperature $T_{sw} \simeq 10^6 \text{ K}$ (room $\simeq 293 \text{ K}$)
- Interplanetary Magnetic field (IMF) $B_{sw} \simeq 5 \text{ nT}$ at the Earth
- Velocity $v_{sw} \simeq 300 - 800 \text{ km/s}$

Solar wind evidence

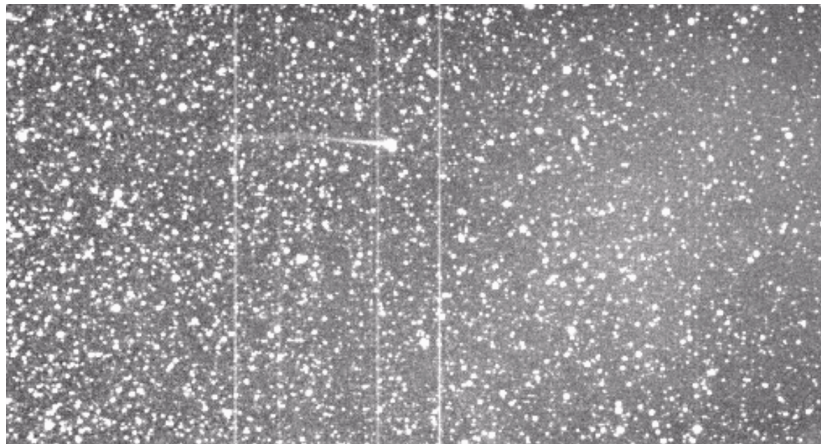
- Particles streaming from the Sun exert pressure upon interplanetary matter, evident from observations of comet tails.



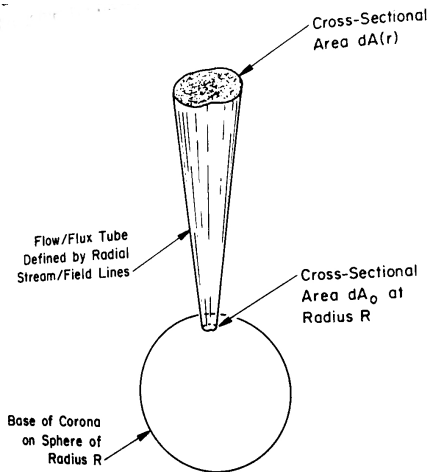
Churimov-Gerasimenko Comet observed by Rosetta.
Image Credit: ESA

Solar wind evidence

- Encke Comet loses its tail via interaction with CME as observed by STEREO-A in April 2007 (Credit: NASA)



Solar wind flux tube



Conservation of the magnetic flux within the tube

$$B(r) \left(\frac{r}{R} \right)^2 dA_0 = B_0 dA_0$$

or

$$B(r) = B_0 \left(\frac{R}{r} \right)^2$$

The solar corona and any fixed source are rotating at equator at an angular rate of

$$\begin{aligned} \omega &= \frac{2\pi \text{ rad}}{25.4 \text{ days}} \\ &= 2.7 \times 10^{-6} \text{ rad s}^{-1} \end{aligned}$$

Solar wind flux tube

The azimuthal plasma velocity in frame of reference rotating with the Sun

$$V_{\phi} = -\omega r$$

The magnetic field follows the plasma flow

$$\frac{B_{\phi}}{B_r} = \frac{V_{\phi}}{V_r} = \frac{-\omega r}{V(r)}$$

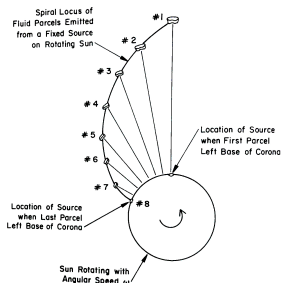
This gives a differential equation for the field lines near the solar equator

$$\frac{rd\phi}{dr} = \frac{-\omega r}{V(r)}$$

If $V(r)$ is constant and location of the source is at $\phi_0, r = R$ then

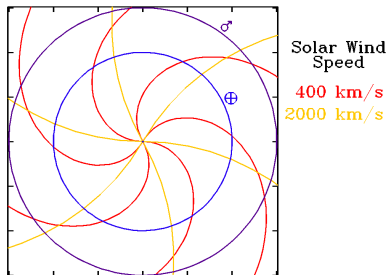
$$r - R = -\frac{V}{\omega}(\phi - \phi_0).$$

This geometry is known as the spiral of Archimedes.



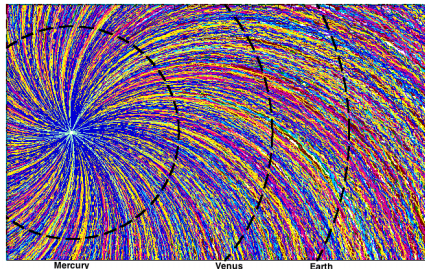
Interplanetary Magnetic Field (IMF) topology

- Due to the conservation of angular momentum of the plasma, the IMF lines trace out Archimedian spiral patterns (called Parker spiral).
- At Earth the IMF makes an angle $\phi \sim 45^\circ$ with respect to the Sun-Earth line
- $\tan \phi = R_{SE}\omega_S / V_{SW}$, where R_{SE} is the Sun-Earth distance and 1 AU (Astronomical Unit)= 150×10^9 m.



IMF topology

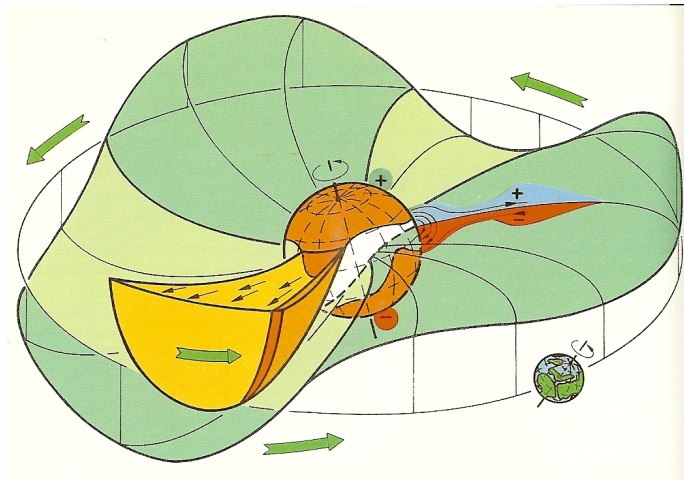
Image Courtesy: J. Borovsky (left) and Borovsky 2008, JGR



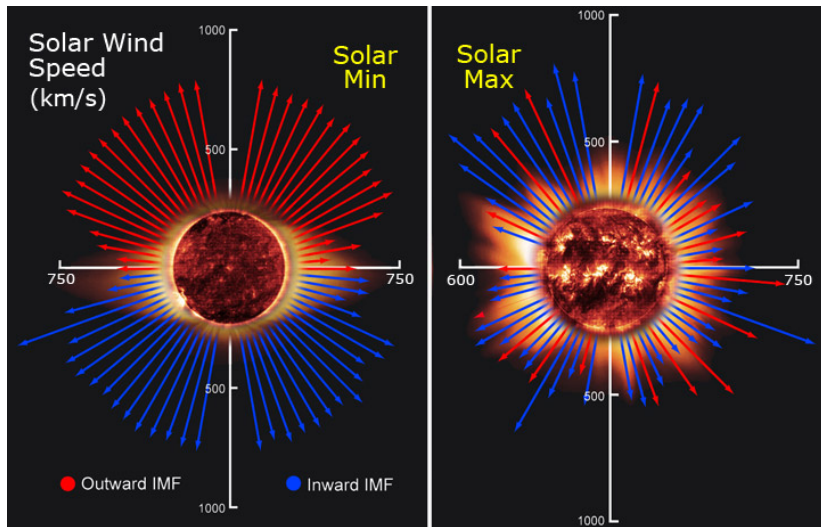
- A depiction (center) looking at the sides of the tubes. An end view (right) depicts the cross sections of the network of tubes.
- Cross-section sizes of the flux tubes correspond to the sizes of granules on the solar surface. The median diameter of a flux tube at 1 AU is 5.5×10^5 km (~ 86 Earth's radii).

IMF topology

- The heliospheric current sheet is the separation layer between positive and negative magnetic field lines, resembles a “ballerina’s skirt”.



Solar wind speed



Solar wind topology

- High speed streams (HSSs) are formed by solar wind originating from coronal holes.
- A stream interaction region (SIR, can also be called corotating interaction region (CIR)) forms at compressed boundary between fast and slow solar wind in HSS.
- Due to the tilt of the coronal magnetic field with respect to the Sun's rotation axis CIRs are formed during declining phase of solar cycle.

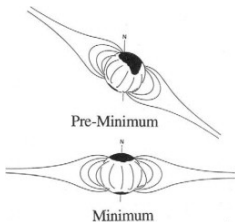


Image: Gosling 2014

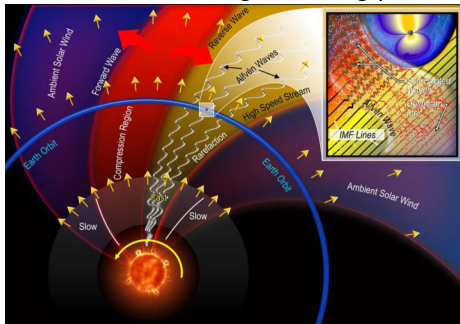
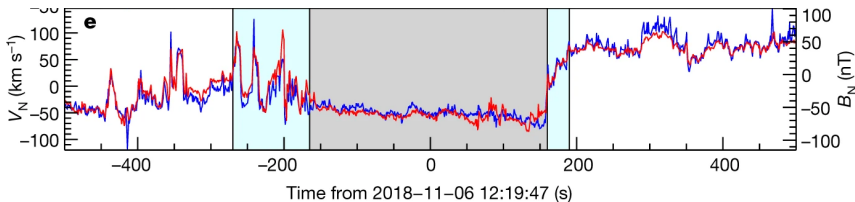


Image: Desai et al., 2007

Fluctuations in the solar wind

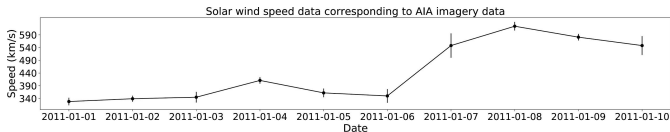
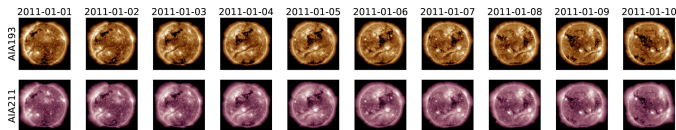
- HSSs contain a complex spectrum of wave-like oscillations in velocity, density, and magnetic field strength, with periods ranging from seconds to days (*Gurnett, 2001*).
- Often this perturbation is related to Alfvén waves:

$$\mathbf{b} = \pm \mathbf{v} \sqrt{\mu_0 \rho}, \text{ where } \mathbf{b} = \delta \mathbf{B} \text{ and } \mathbf{v} = \delta \mathbf{V}$$

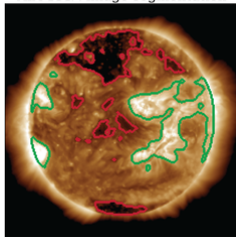


Observations at 35 solar radii by
the Parker Solar Probe from
Kasper et al., 2019

Prediction of the solar wind speed using deep learning

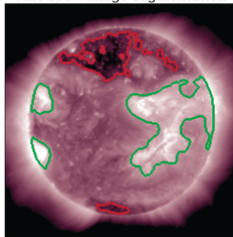


AIA 193Å image segmentation



2016-01-26 00:00:00

AIA 211Å image segmentation



2016-01-26 00:00:00

Segmented SDO EUV images
for generating coronal holes and
active regions masks
from Upendran et al., 2020

Question: Which direction does the solar wind have at the Earth's distance?

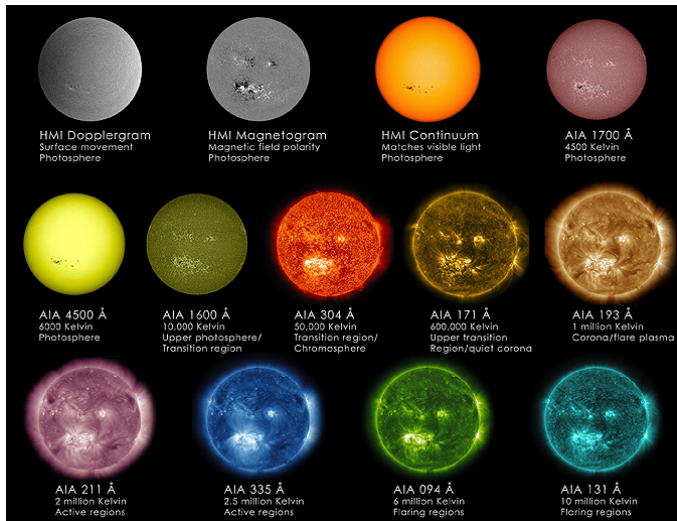
Frozen-in flux concept vs observations



Monitoring the Sun

Credit: NASA/SDO/Goddard Space Flight Center

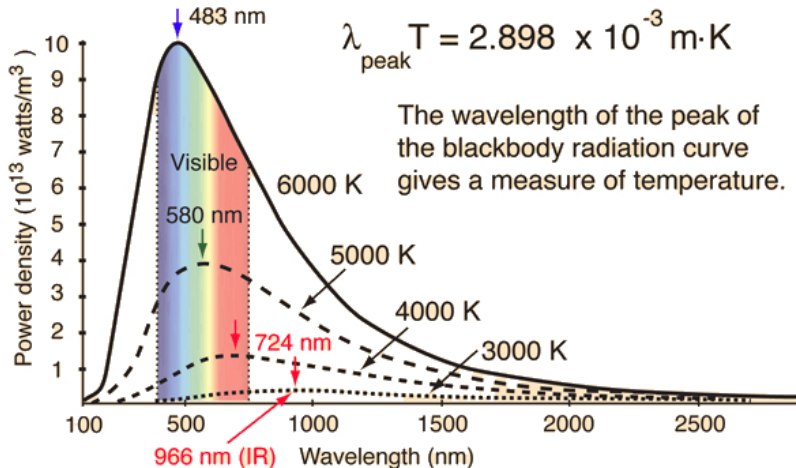
- Sun in different wavelengths seen by SDO



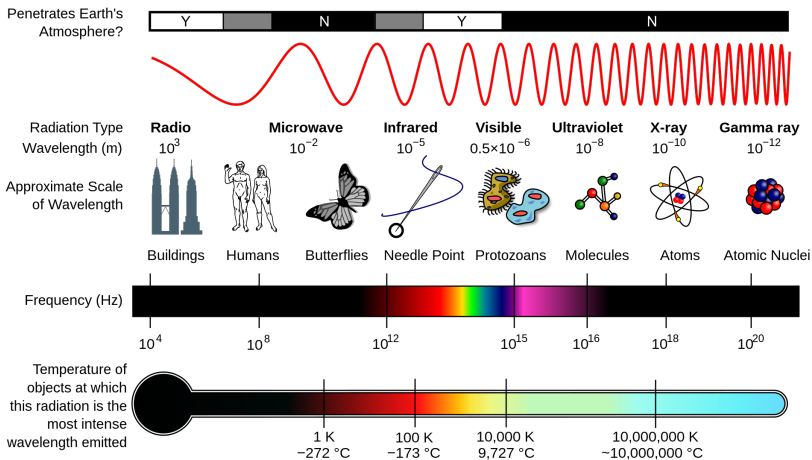
1 $\text{\AA}$ = 0.1 nm

Wien's law

Credit: Hyperphysics

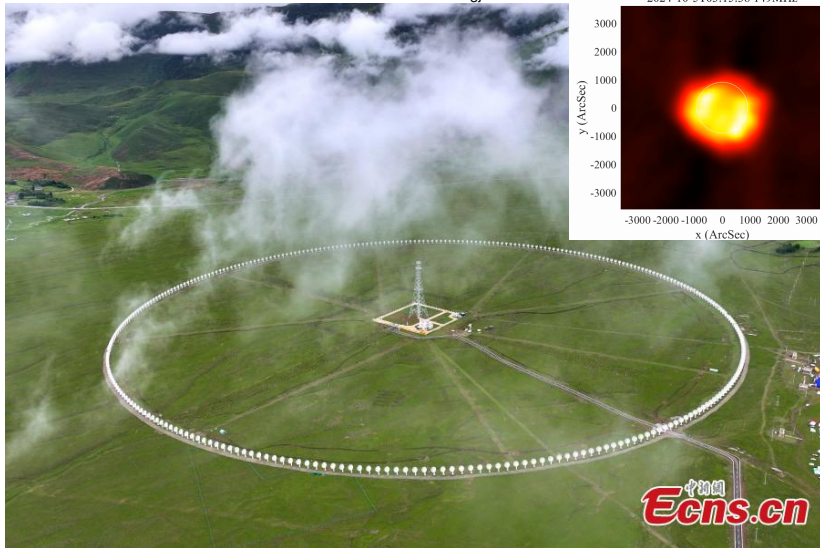


Electromagnetic spectrum



Sun in radio waves

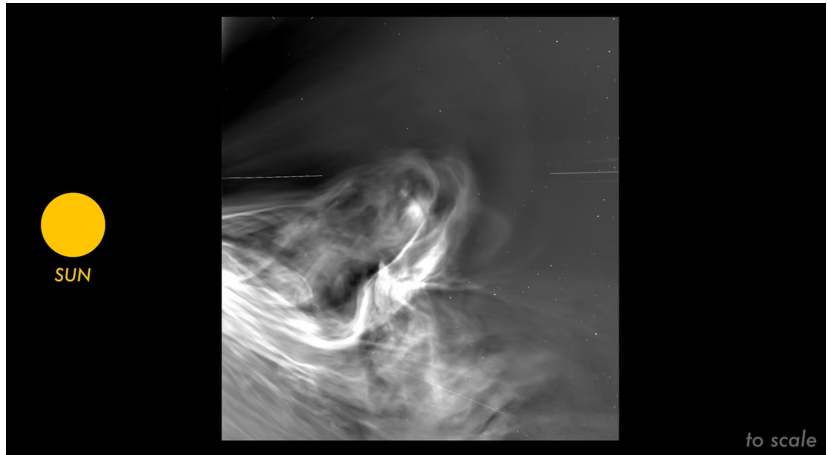
Photo: China News Service/Liu Zhongjun



Daocheng Solar Radio Telescope, Chinese Meridian Space Weather Monitoring Project II

The closest observations of the Sun

Parker Solar Probe (NASA) in December 2024



Monitoring of the solar wind

- <http://www.swpc.noaa.gov/products/ace-real-time-solar-wind>
- <http://www.swpc.noaa.gov/products/>
- <https://iswa.ccmc.gsfc.nasa.gov/IswaSystemWebApp/>
- http://hmi.stanford.edu/MHD/daily_mhd.html



Summary

- The variability of Sun is complicated and not easy to be predicted.
- Solar flares can directly lead to destructive consequences in radio communication, see consequences of Space Weather R-Scale in Lecture 1.
- Penetrating particles from solar radiation storms can lead to destructive consequences of S-Scale.
- We will learn later how the IMF direction and CMEs influence Space Weather.

- M. Kivelson and C. Russell, Introduction to Space Physics, 1995
- A. Brekke, Physics of the Upper Polar Atmosphere, 2013
- F. Menk and C. Waters, Magnetoseismology: Ground-based remote sensing of Earth's magnetosphere, 2013
- S. Tiwari et al., Depth-dependent global properties of a sunspot observed by Hinode using the Solar Optical Telescope/Spectropolarimeter, A&A, 2015
- Gurnett, D. A., Solar wind plasma waves, in Encyclopedia of Astronomy and Astrophysics (ed. P. Murdin), Institute of Physics and Macmillan Publishing, Bristol, pp. 2805-2813, 2001.