ASTR20A:
Introduction to Astrophysics I

Dr. Devontae Baxter

Lecture 9 | The Sun

Tuesday, October 28, 2025

Astrophysics Research Panel

October 30th @ 6PM at the Qualcomm Conference Center

Panelists:

- Adam Burgasser - Director of UCSD Cool Star Lab, specializes in oldest stars, brown dwarfs, and exoplanets, MS + Ph.D. in Physics @ Caltech
- Brian Keating - Host of the Into the Impossible Podcast, specializes in CMB + cosmology, Ph.D. in Physics @ Brown
- Ethan Nadler - Assistant Prof. + Postdoc scholar mentor, specializes in galaxy formation, dark matter, and cosmology, Ph.D. in Physics @ Stanford
- Julie Inglis - Postdoctoral Fellow, specializes in giant planet and substellar atmospheres, Ph.D. in Planetary Sciences @ Caltech

Ask for advice, undergraduate experiences, research concentrations and more!
Audience Q&A + Free Food (Mendocino Farms) + Touch a meteorite!

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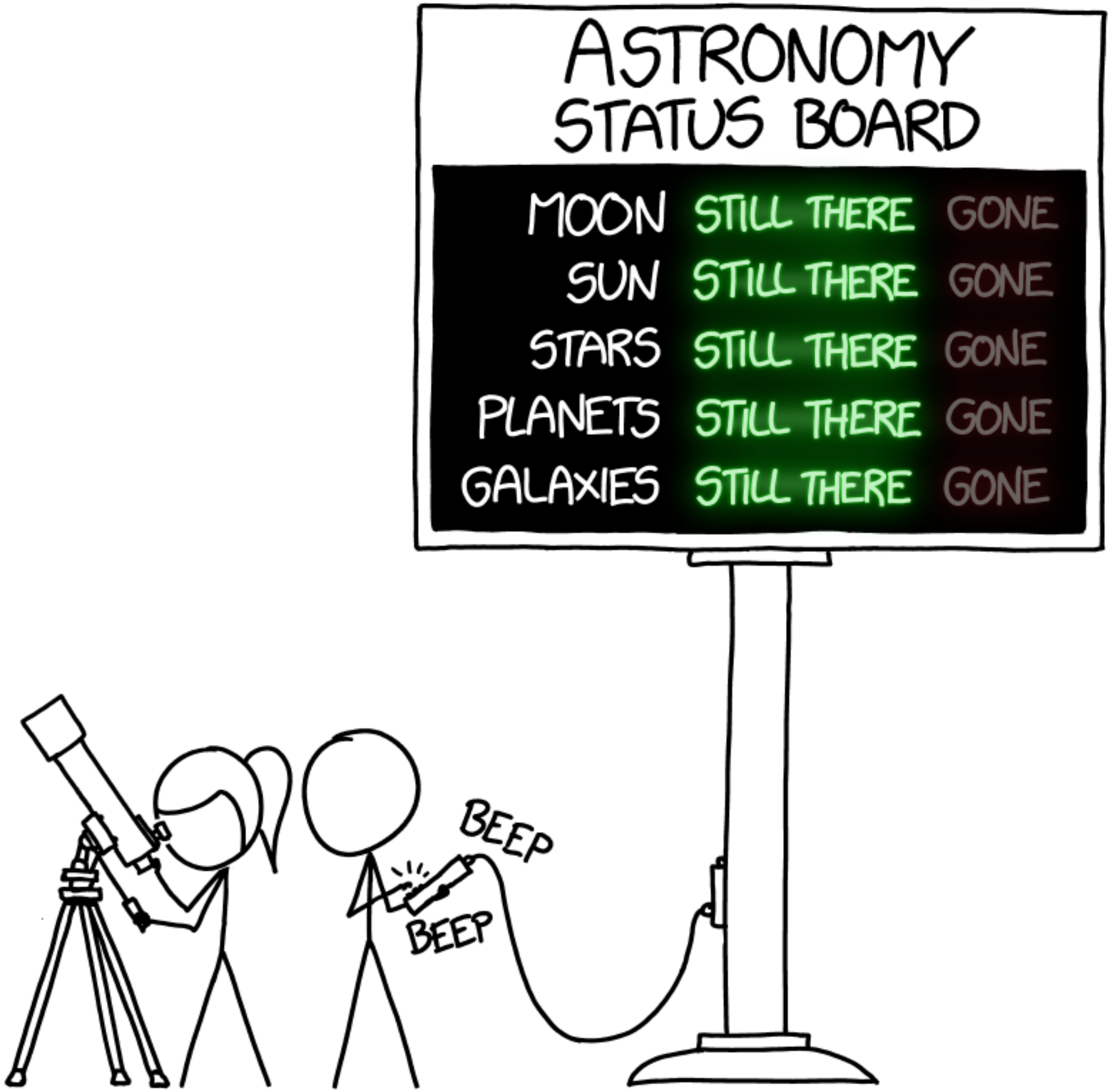
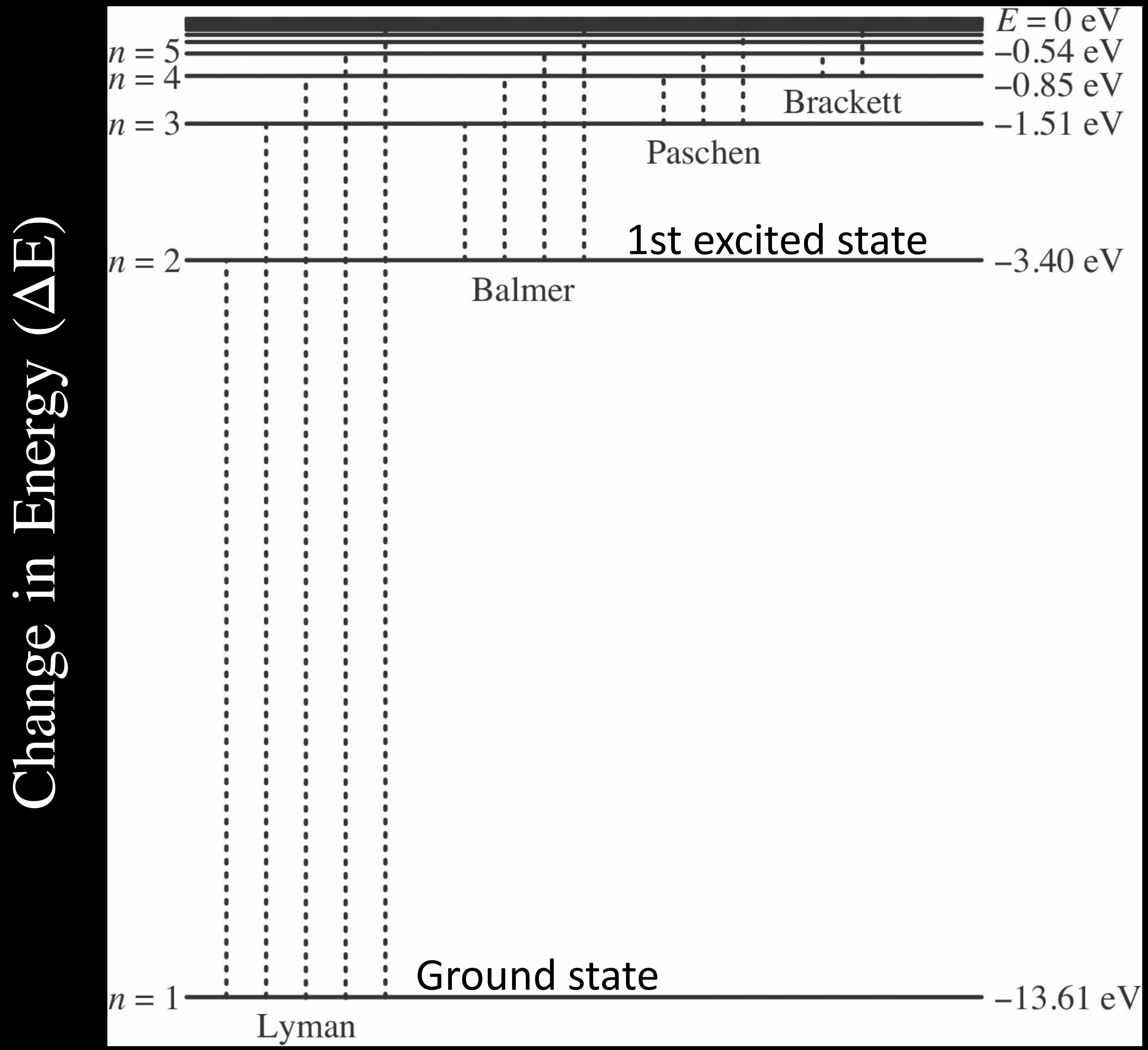
Announcements

- Homework #4 due **Wednesday, 10/29 by 11:59 pm via Gradescope.**
- **Reminder:** Only one of the two midterms will count towards your final grade.
- Homework #5 will be available on Canvas **tomorrow morning.**



Common misconceptions from the midterm



The dashed lines represent the various *spectral lines* of Hydrogen.

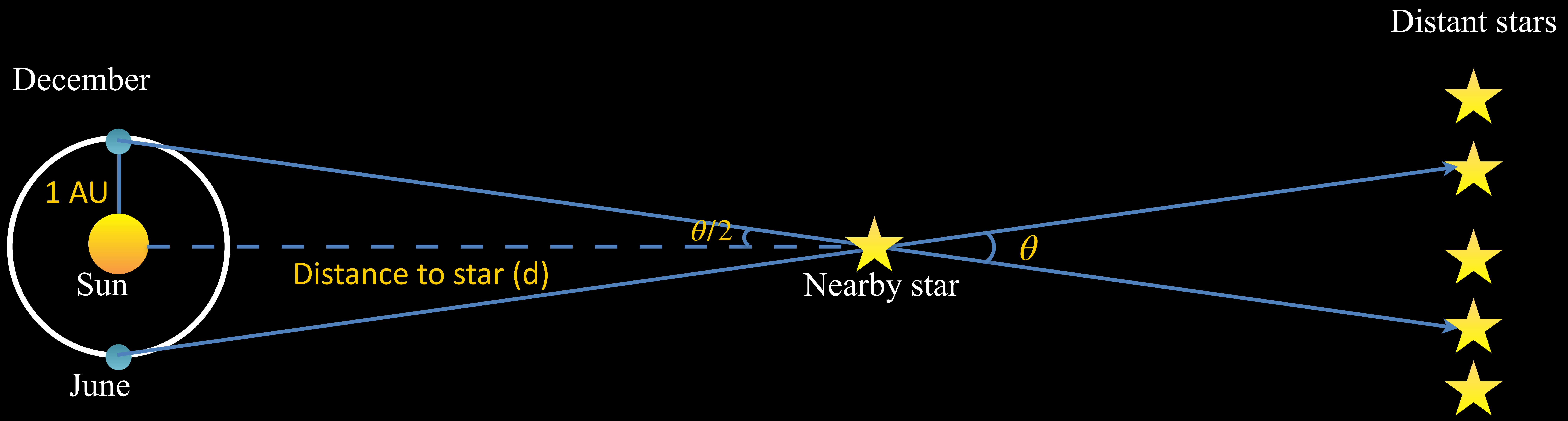
They correspond to transitions of electrons between the allowed orbits (or energy levels).

Transitions from low orbits to high orbits are called **absorption**

Transitions from high orbits to low orbits are called **emission**

Common misconceptions from the midterm

"**par**allax of one arc**sec**" – the parsec (distance corresponding to 1")



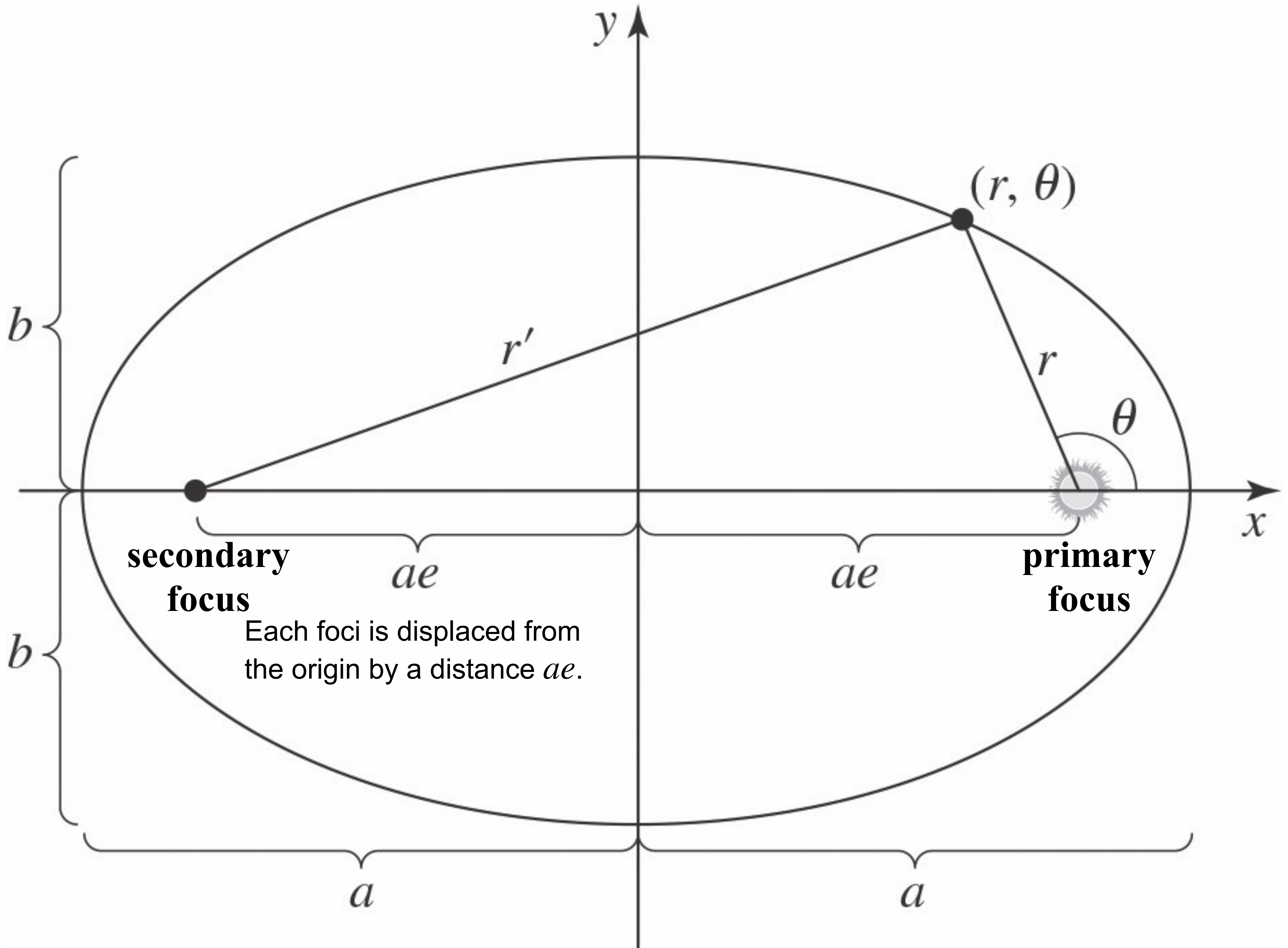
$$d = 1\ \text{parsec} \equiv \frac{1\ \text{AU}}{1''}$$

Common misconceptions from the midterm

When asked to plot some quantity A vs. some quantity B, the convention is that **B is the independent variable** and **A is the dependent** variable.

- The **dependent variable** is plotted along the **vertical axis.**
- The **independent variable** is plotted along the **horizontal axis.**

Common misconceptions from the midterm



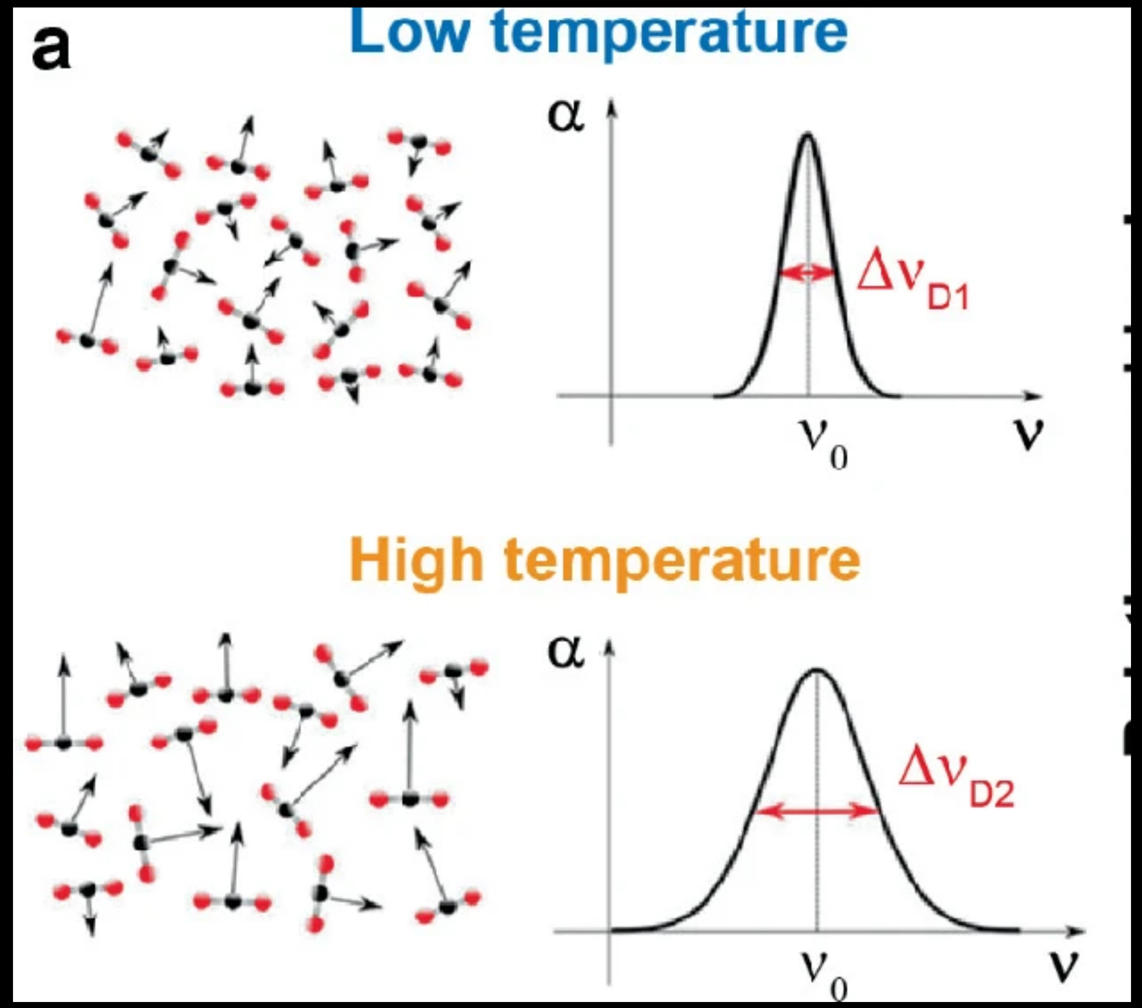
a: semi-major axis

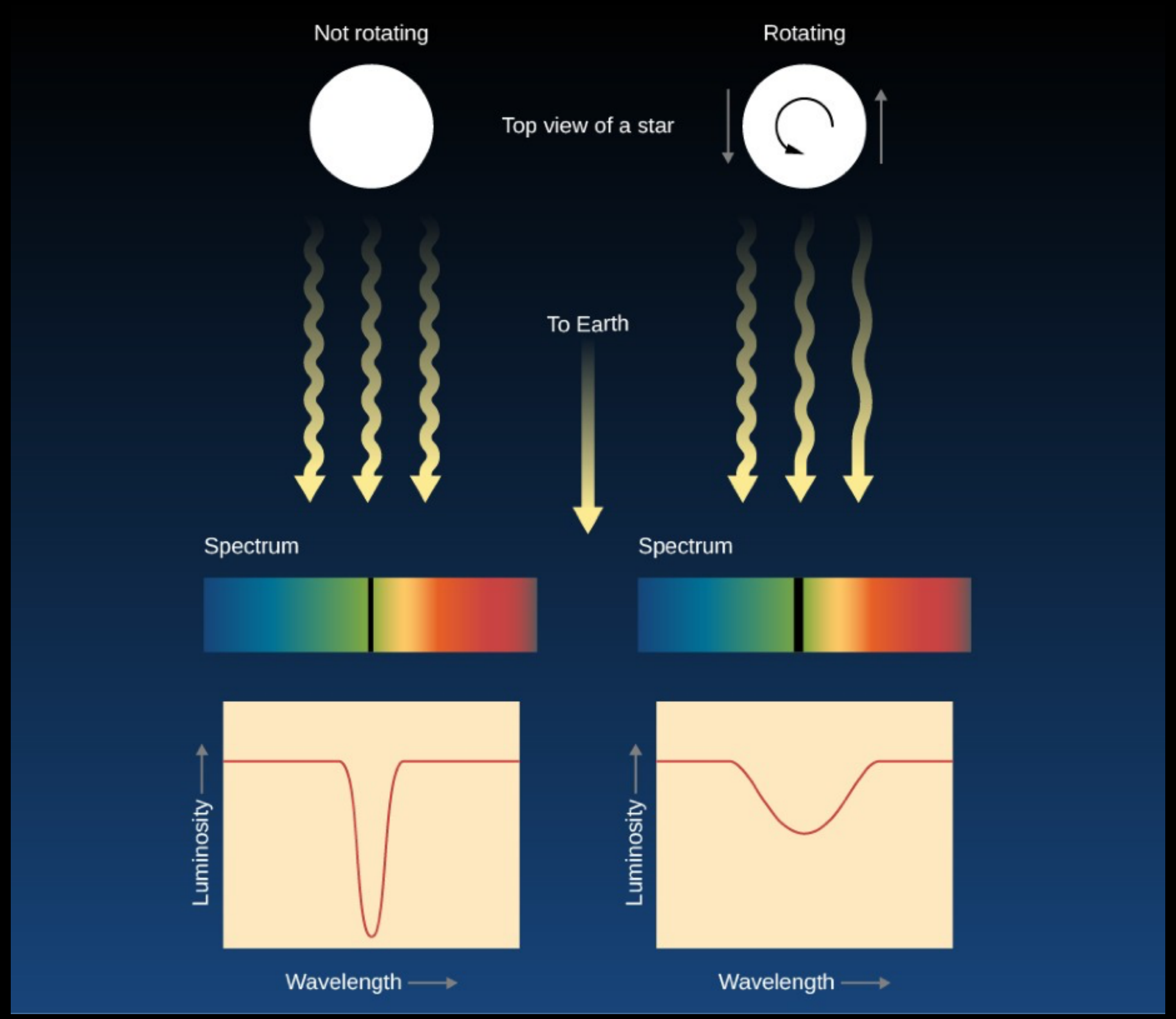
b: semi-minor axis

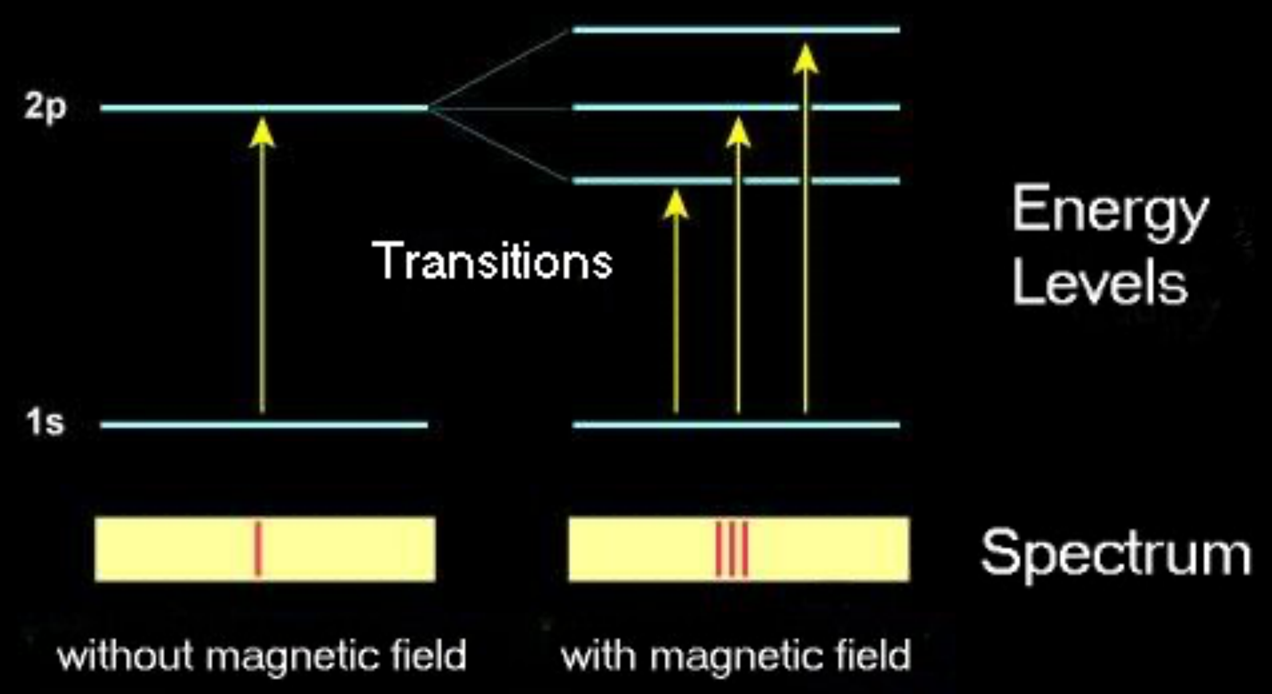
Recap of Lecture 8

In the previous lecture, we discussed the **Spectral Line Broadening** and **Astronomical Detection of Light.** The key concepts that we discussed were:

Spectral Line Broadening







$$\Delta t \cdot \Delta E \gtrsim \hbar$$

Astronomical Detection of Light

Refractors (prism) vs. Reflectors (mirrors)

Astronomical seeing (atmosphere blurs images)

Diffraction-limited resolution (also known as the “Rayleigh criterion”):

$$\theta_{\min}[\mathrm{rad}] = 1.22\frac{\lambda}{D}$$

Today’s lecture will center on the most important star to humankind — the Sun! ☀️


Questions?

Learning Objectives

- Explain the differences between the Photosphere, Chromosphere, and Corona.
- Identify surface features of the Sun (e.g., plages, filaments, sunspots, etc.)
- Explain the drivers of the Solar Cycle.
- Understand what causes the Solar Wind.

Observable Layers of the Sun - The Photosphere

- The observed surface of the Sun at visible wavelengths is called the **photosphere.**
- This is the layer were **nearly all observed photons escape**.
- **Extremely thin** (~400 km, or 0.06% of the Sun's radius)
  - Equivalent to 407 vertically stacked Sun God statues compared to the radius of the Earth.

- The **temperature below the photosphere increases with depth** — as does the degree to which atoms are ionized.

Observable Layers of the Sun - The Photosphere

- The photosphere **produces absorption lines in the spectrum of the Sun.**
  - Analyses of the solar spectrum revealed that by mass, the Sun is **73.4% hydrogen**, **25.0% helium**, and **1.6% heavier elements** (metals).
  -

Observable Layers of the Sun - The Photosphere

- This revelation was first made in 1925 by **Ceclia Payne-Gaposchkin**, author of the “most brilliant Ph.D. thesis in astronomy”.
  - Her discovery was made by **analyzing solar spectra through the lens of quantum mechanics.**
  - Unfortunately, ***her professor convinced her to dismiss her results*** as they conflicted with the prevailing belief at the time that the Sun and Earth had similar elemental abundances.
  - He later confirmed her results and received credit for her discovery!!!

Observable Layers of the Sun - The Photosphere

- Notice that the edges of the photosphere are fainter than the center.
  - We call this effect **limb darkening.**
- The primary source of *opacity* (what absorbs light from deeper layers) is H^- ion (a hydrogen atom with an additional electron.

The H^- ion is formed in a gas containing neutral hydrogen *and* free electrons through:

$$H + e^- \rightarrow H^- + \gamma$$

The second electron is loosely bound with an ionization energy of $\chi = 0.75\ \mathrm{eV}$, which corresponds to a wavelength of $\lambda = 1.7\ \mu\mathrm{m}$. As such, if this ion is present it can absorb photons from the UV to infrared.

Observable Layers of the Sun - Limb Darkening

- The average depth from which the observe photons originate depends on the column density of H^- along out line of sight.
- The photons at the center of the Sun's disk come from deeper, hotter layers of the photosphere.
- The photons at the limbs (or edges) of the Sun's disk come from higher, cooler layers of the photosphere.

Consequently, if we fit a Planck spectrum (i.e., *blackbody spectrum*) to the center of the Sun's disk we infer an effective temperature of $T \approx 6100\ \mathrm{K}$.

However, at the limbs the effective temperature is $T \approx 5000\ \mathrm{K}$.

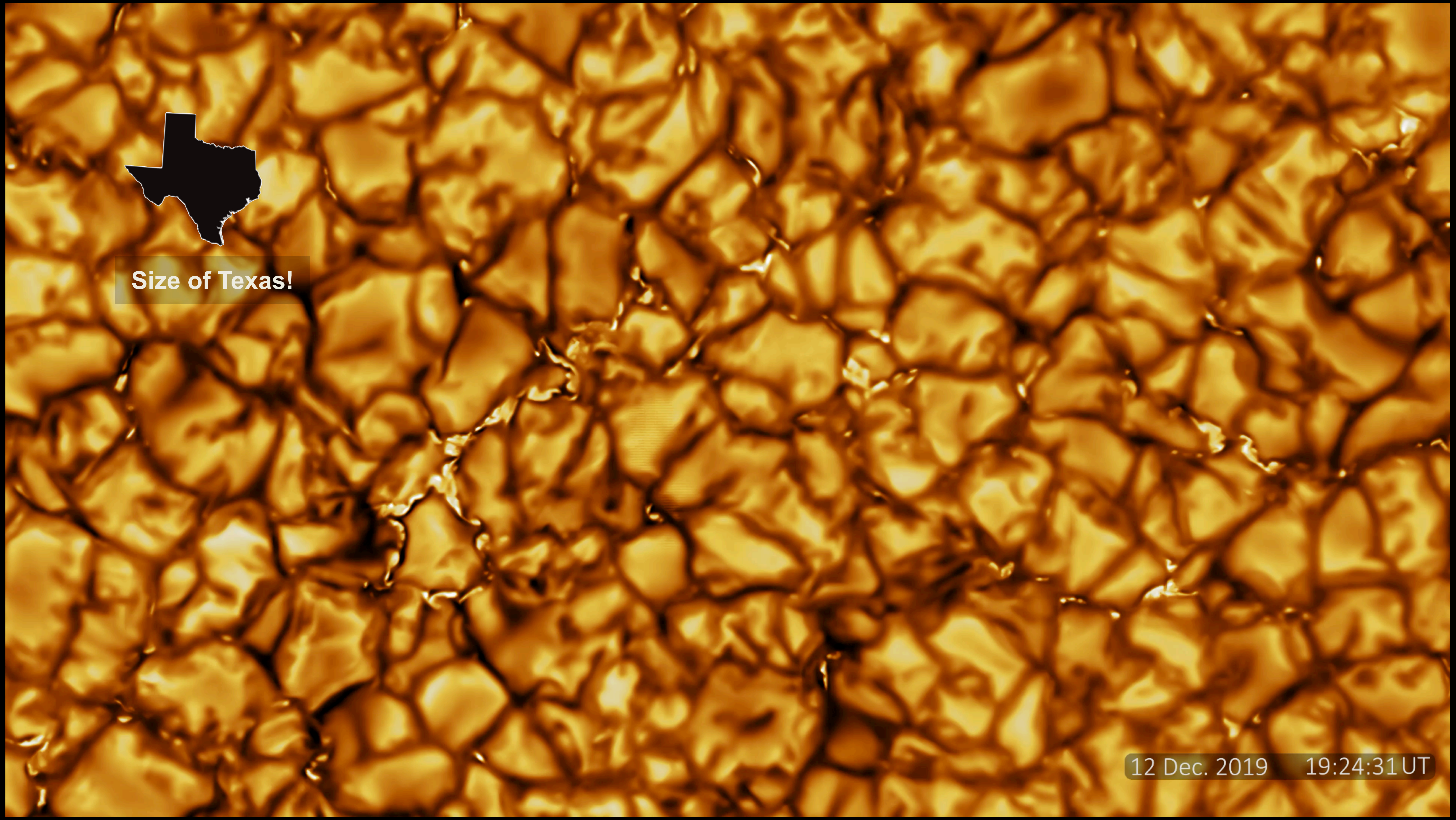
If we average over the entire disk we get a surface temperature of $T \approx 5700\ \mathrm{K}$.

Observable Layers of the Sun - Solar Granules

- When the Sun's disk is viewed at high angular resolution, the photosphere is seen to be broken up into granules.
- These are convection cells in the photosphere.
  - Hot gas rises to the top in the center, cools, and sinks back down on the edges.

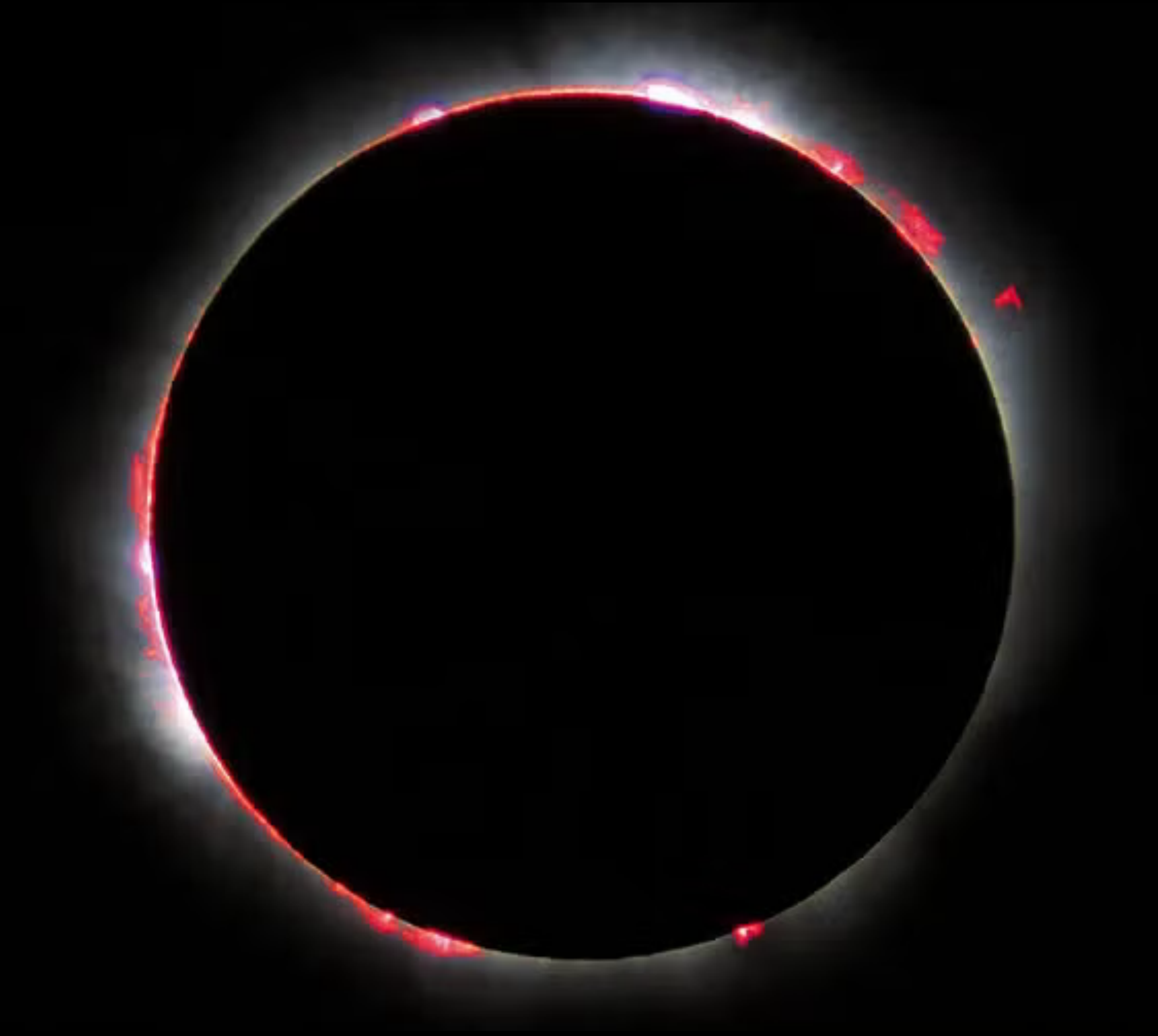
- The typical size of a granule is ~1000 km — approximately the size of Texas!

- The typical lifetime of a granule before it breaks up is only ~10 minutes.



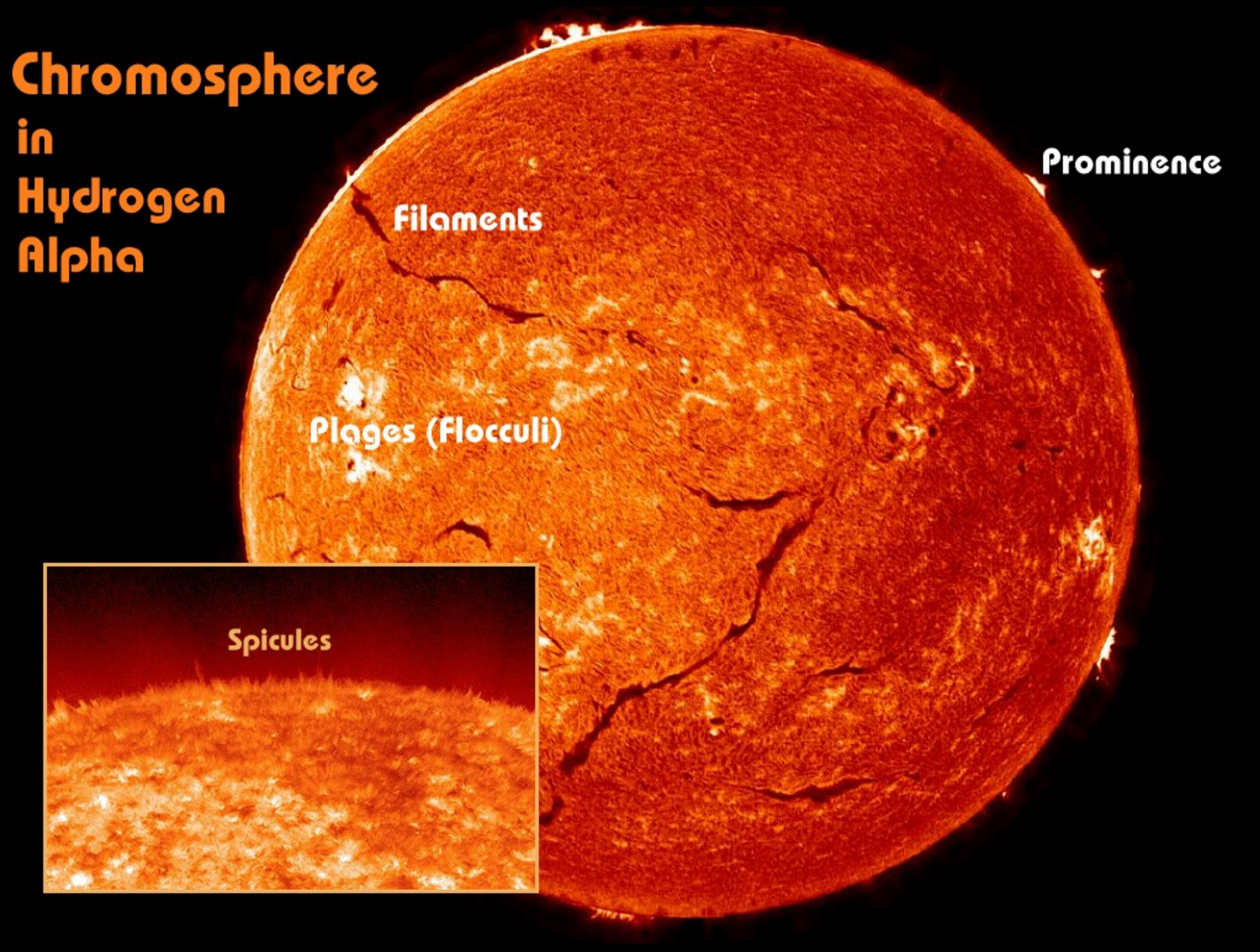
Observable Layers of the Sun - Chromosphere

- The chromosphere **sits directly above** the photosphere.
- The red and pink hues are due to Hydrogen-alpha (Balmer) emission.
- During an eclipse in 1868, Normal Lockyer measure a yellow emission line at $\lambda = 5876\ \text{Å}$.
  - This line did not correspond to any known element, so Lockyer called it "Helium" after the Sun god Helios.
  - 27 years later chemist isolated the element helium and its emission line was verified.



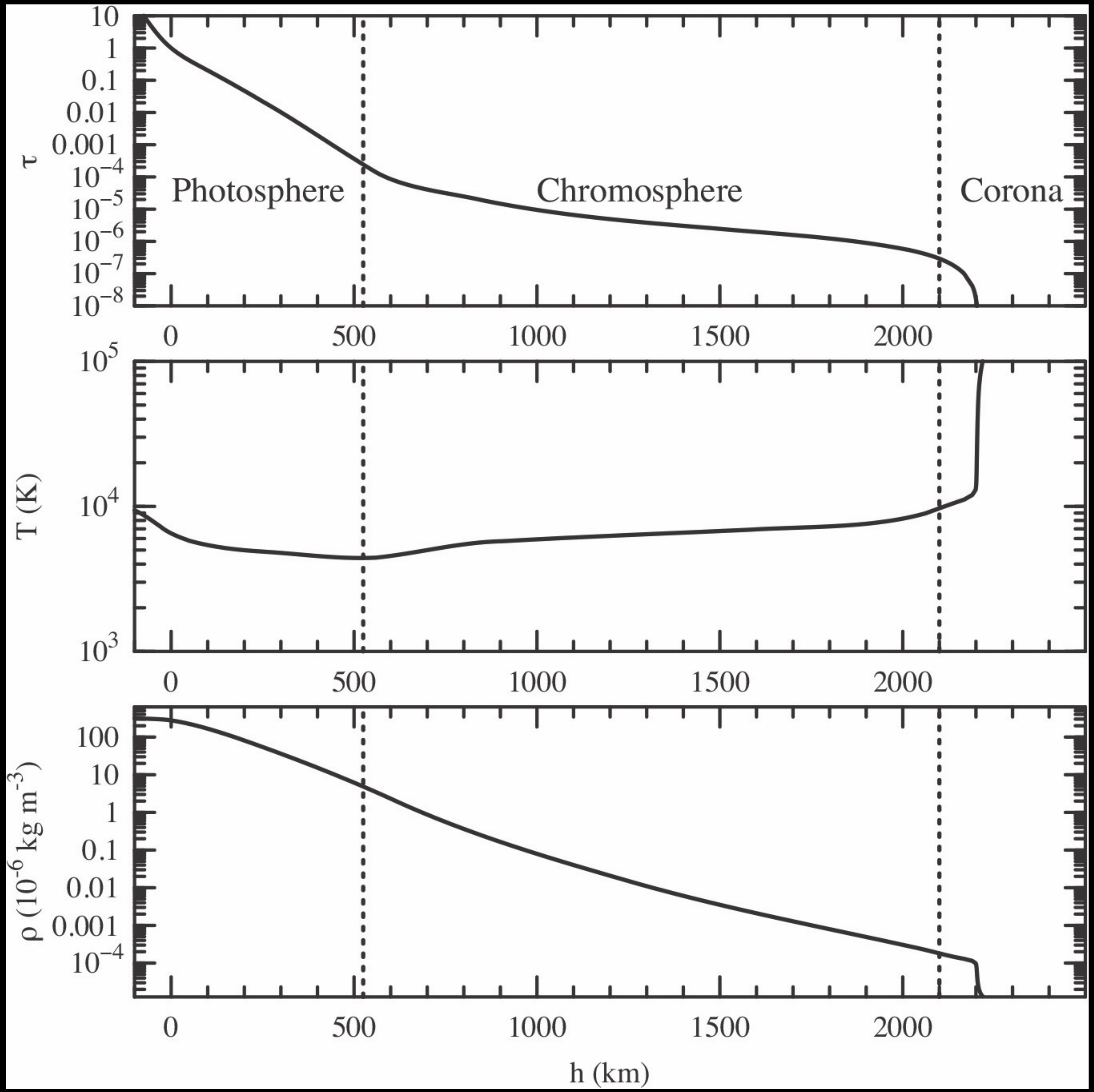
Observable Layers of the Sun - Chromosphere

- If we observe the chromosphere with a narrowband filter (e.g., H-alpha) we observe:
  - **Plages** – bright extended regions where the magnetic field is strong.
  - **Filaments** – dark, linear features corresponding to long clouds of *cool* gas.
    - They lifted above the chromosphere on magnetic field lines.
  - **Prominences** – filaments that extend beyond the Sun's limbs and seen against the relative darkness of space.
  - **Spicules** – narrow columns of gas moving vertically at speeds 10 km/s.



Observable Layers of the Sun - Corona

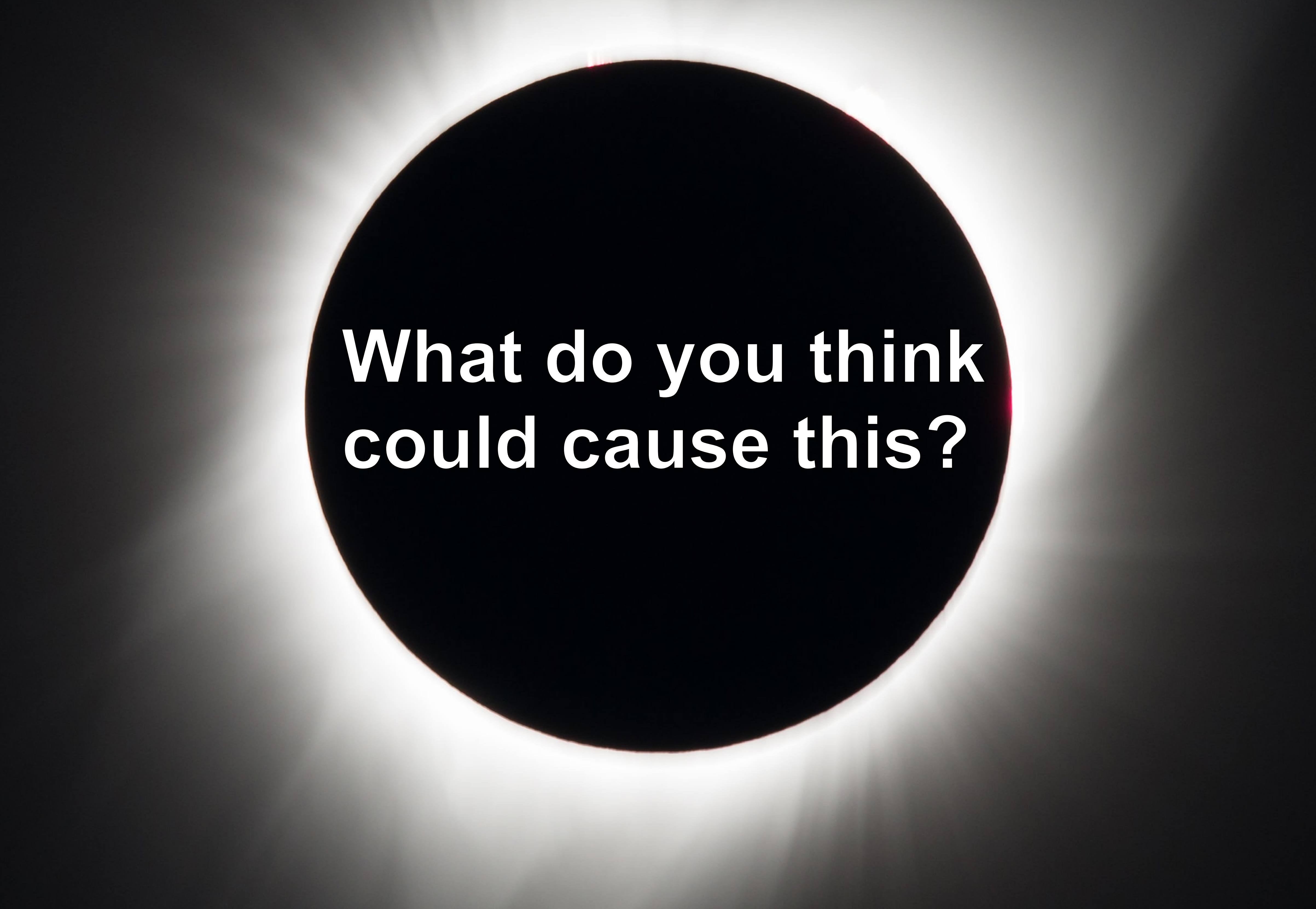
- The corona sits above the photosphere and extends out to 10-20 times the radius of the Sun!
- It's really, really hot too, ~1 million Kelvin!
- Notice from the left that it has a tiny optical depth (τ), **and it is not very dense.**



Questions?

Brain Break – Think-pair-share

The corona is incredibly hot (millions of Kelvin) and forms higher in the Sun’s atmosphere than the visible layer (photosphere & chromosphere).



Why don’t we feel the extreme heat on Earth?

Why is the Corona So Hot?

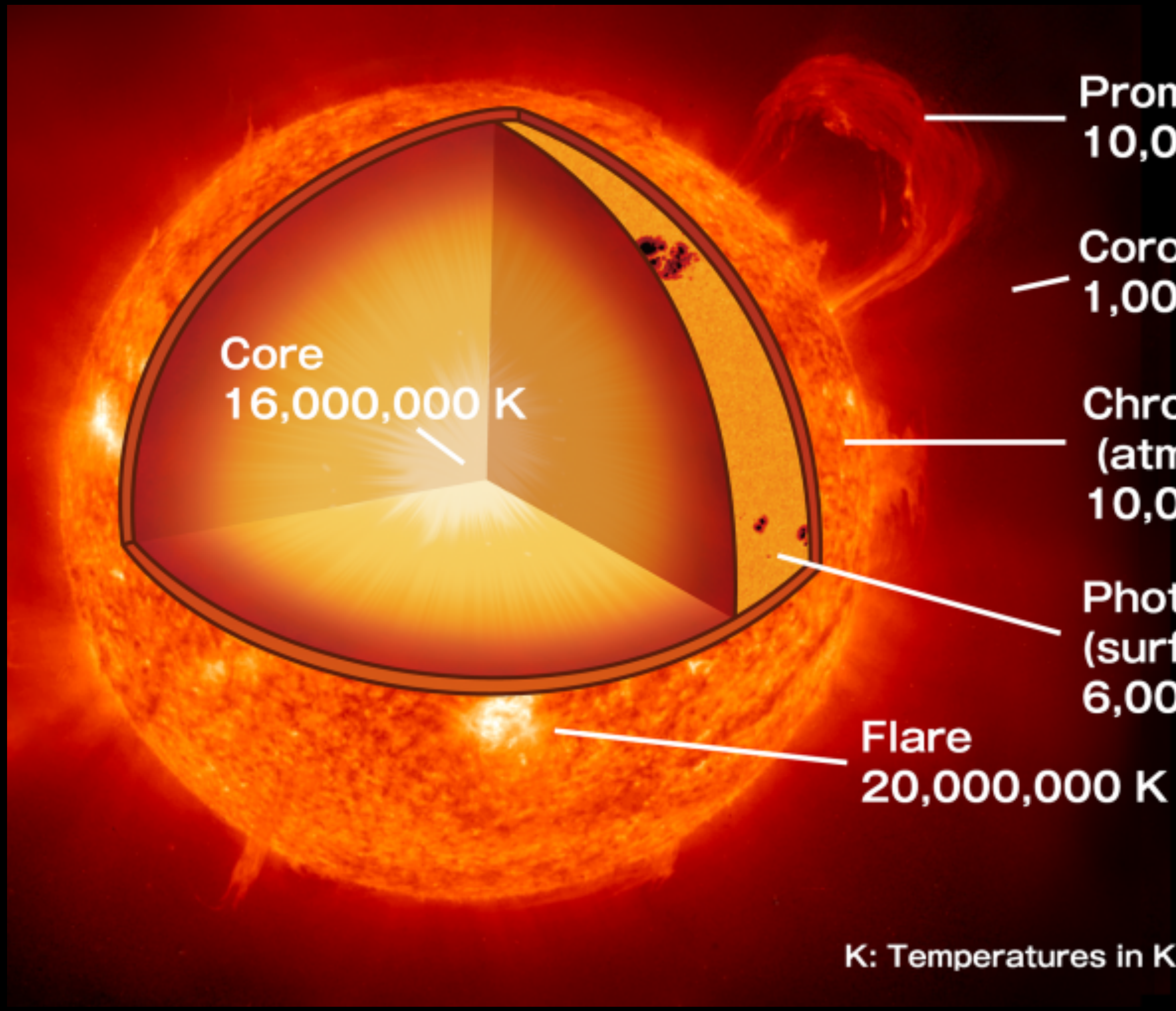
We don't know for certain.

However, there are two leading theories:

1) Magnetic reconnection

2) Heating by Alfvén waves

Both of these topics are beyond the scope of this course.



Solar Wind

Consider the **root mean square velocity** of protons in the **hot corona,**

$$v_{\mathrm{rms}} = \sqrt{\frac{3kT}{m_{\mathrm{p}}}} \approx 160\ \mathrm{km\ s^{-1}} \sqrt{\frac{T}{10^6\ \mathrm{K}}}$$

Comparing this to the **escape speed** at a distance r from the Sun's center,

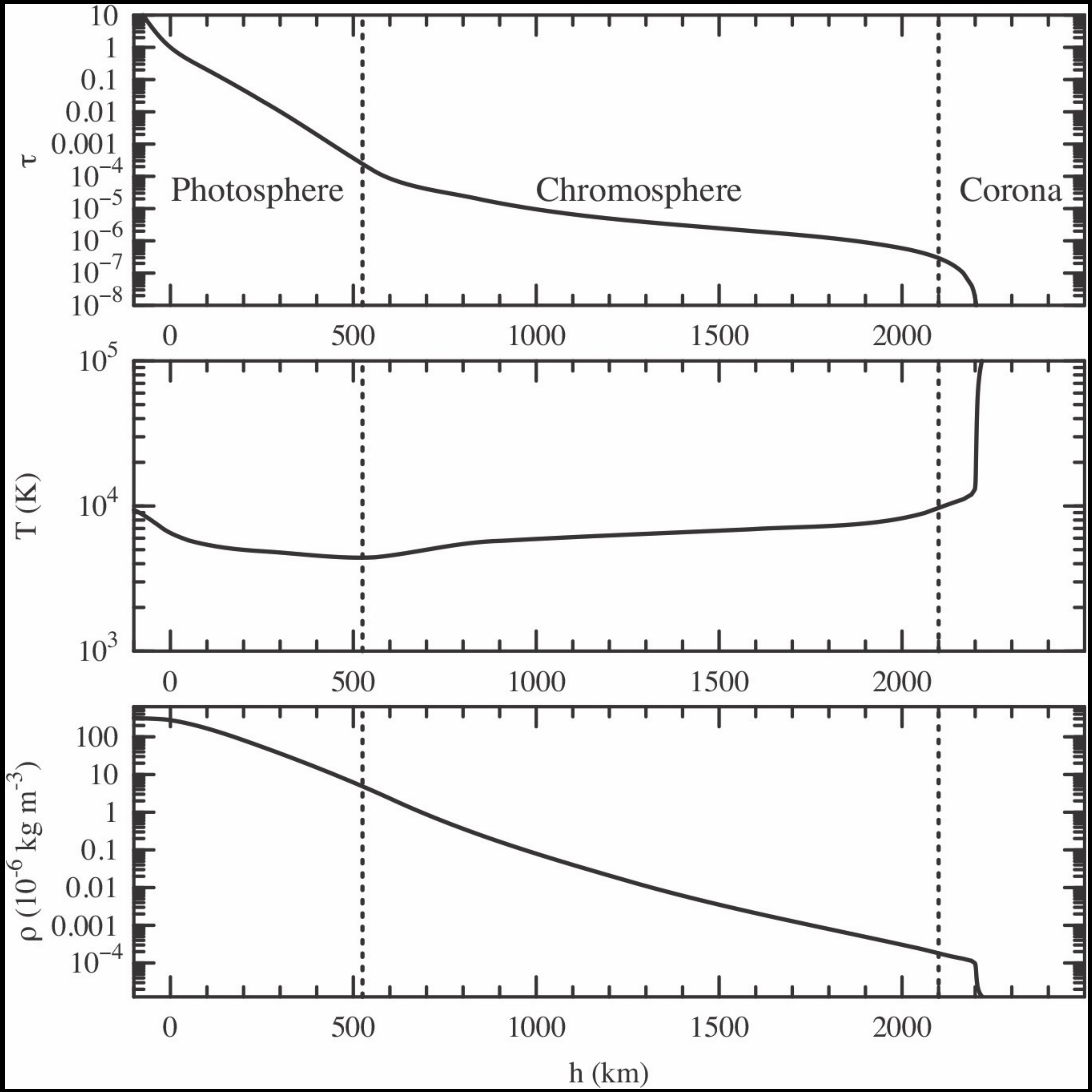
$$v_{\mathrm{esp}} = \sqrt{\frac{2GM_{\odot}}{r}} \approx 620\ \mathrm{km\ s^{-1}} \left(\frac{r}{R_{\odot}}\right)^{-1/2}$$

Solar Wind

$$v_{\mathrm{rms}} = \sqrt{\frac{3kT}{m_{\mathrm{p}}}} \approx 160 \text{ km s}^{-1}\sqrt{\frac{T}{10^6 \text{ K}}}$$

$$v_{\mathrm{esp}} = \sqrt{\frac{2GM_\odot}{r}} \approx 620 \text{ km s}^{-1}\left(\frac{r}{R_\odot}\right)^{-1/2}$$

As the escape speed decreases with distance from the Sun's center and the coronal temperature increases, **an increasing fraction of particles in the corona exceed the escape speed!**

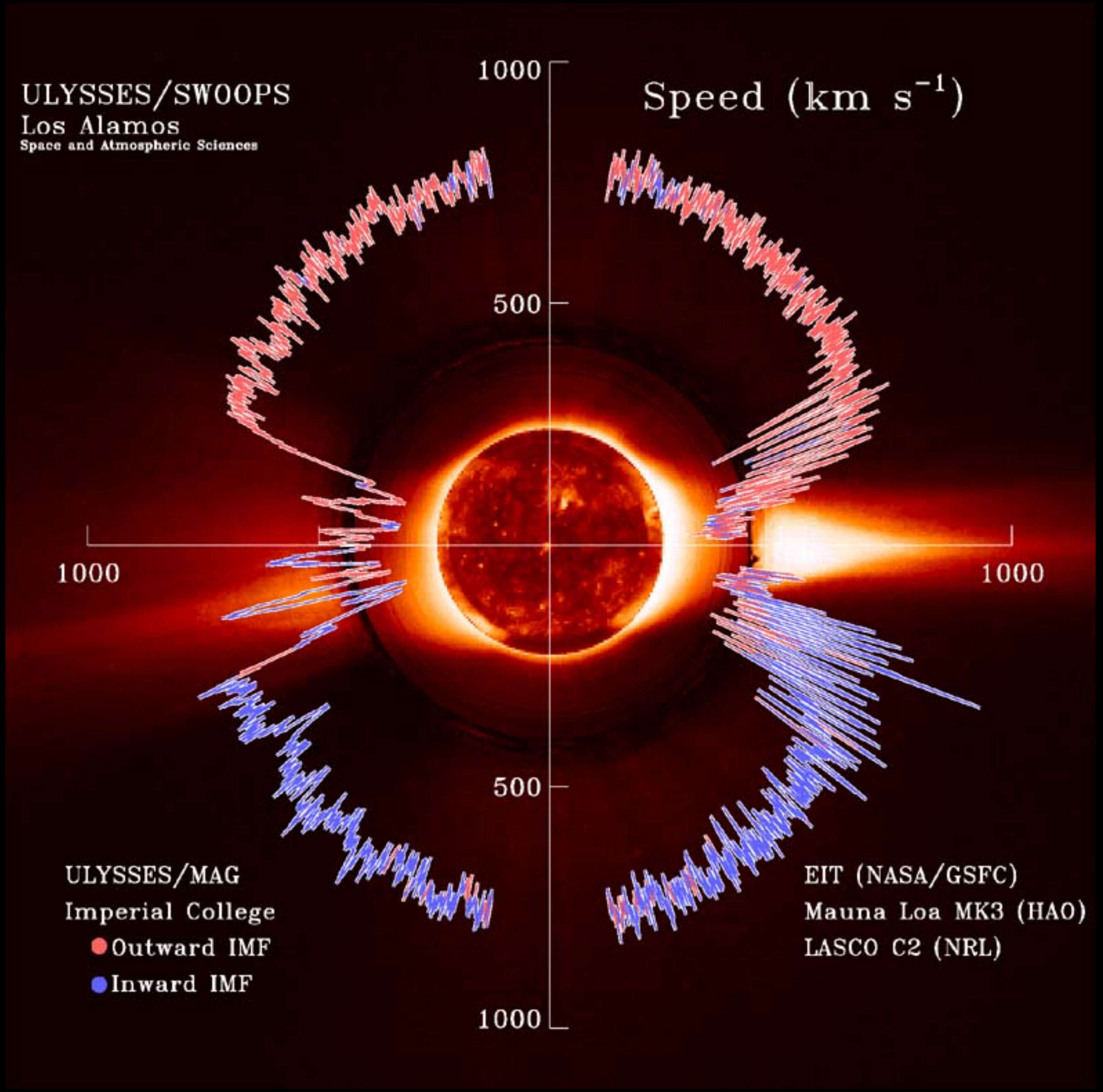


Solar Wind

The Sun is emitting a constant outward flow of particles called the "**Solar Wind**".

The speed of the solar wind varies depending on the Sun's latitude, but is between 250–750 km/s.

The number density of particles being emitted is $n \sim 10^7\ \mathrm{m}^{-3}$ (mass density is $\rho \sim 10^{-21}\ \mathrm{kg\ m}^{-3}$).



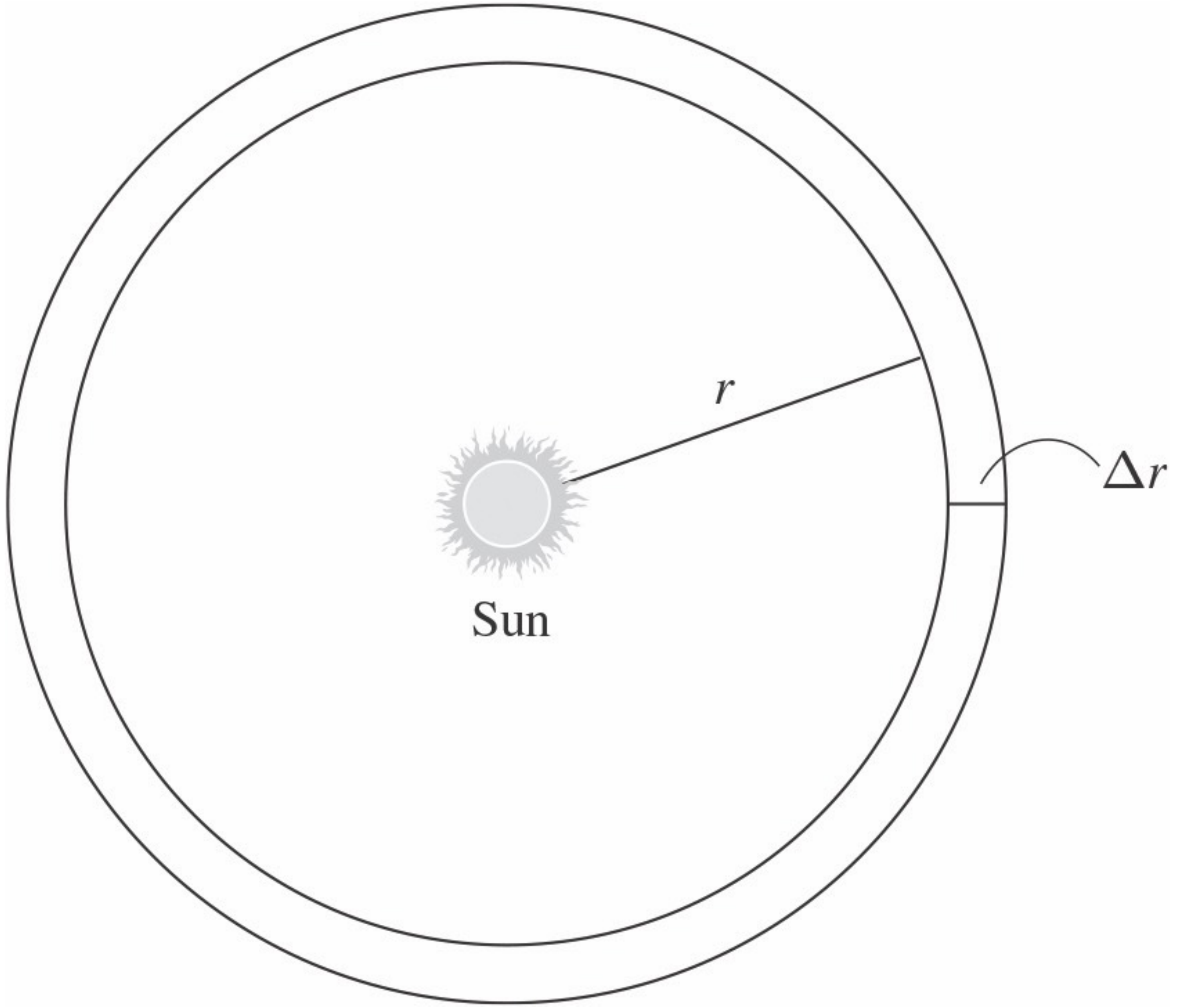
Mass Loss due to Solar Wind

If we assume that the solar wind is in a steady state (i.e., remains constant over time), we can compute the rate at which the Sun is losing mass.

Consider a thin shell of radius r and thickness Δr centers on the Sun.

The mass of the solar wind in the shell at any given instant is just the shell's volume times the density.

$$\Delta M = (4\pi r^2 \Delta r)\rho$$



Aside: Given this expression, how would we write **the instantaneous kinetic energy in the shell**?

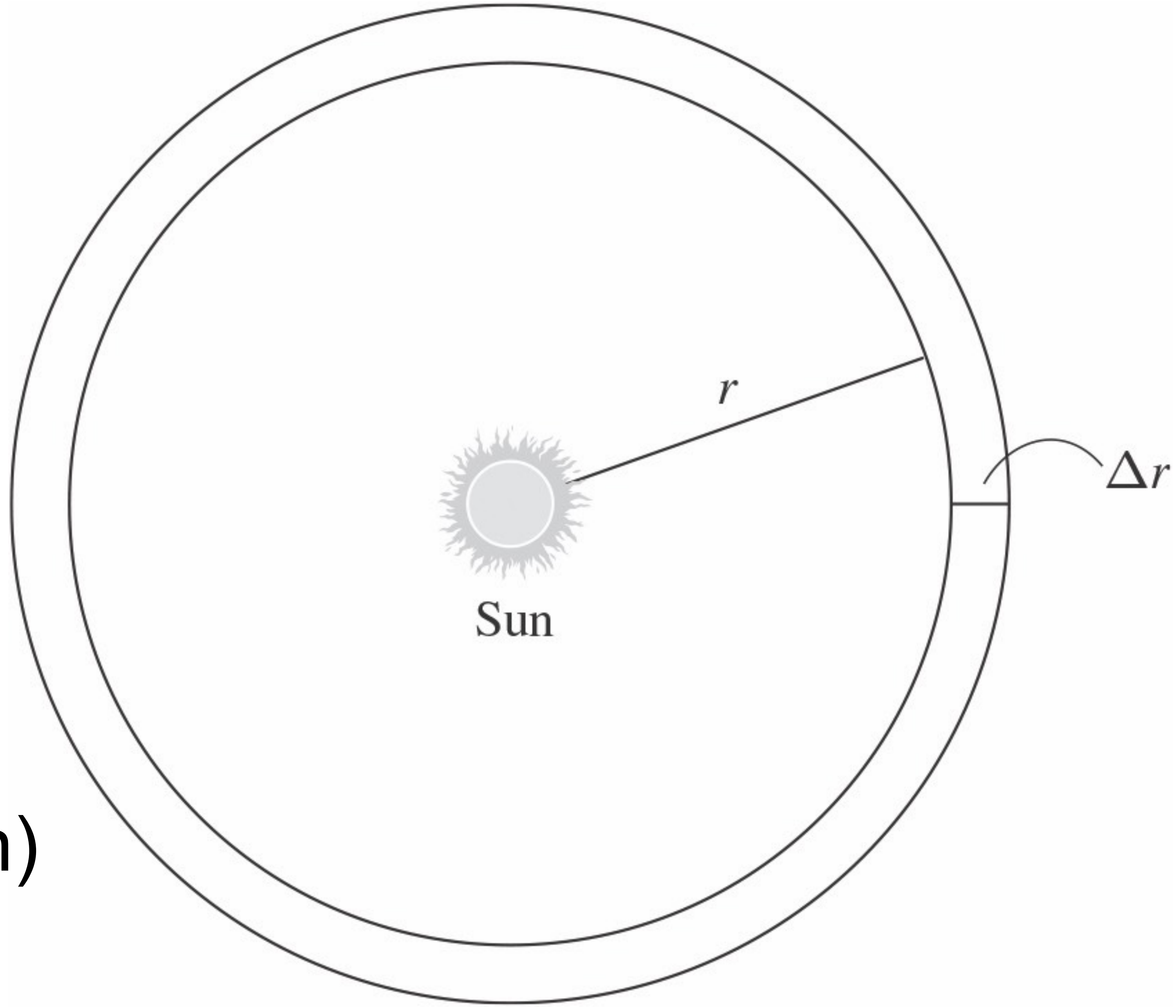
Mass Loss due to Solar Wind

The mass flux through the shell can be obtained by diving by the time Δt it takes a solar wind particle to move outward a distance delta r.

$$\frac{\Delta M}{\Delta t} = 4\pi r^2 \frac{\Delta r}{\Delta t}\rho \quad \text{(Mass Flux)}$$

As we let $\Delta t \to 0$, we can write this as a mass continuity equation for a steady state spherical flow:

$$\frac{dM}{dt} = 4\pi r^2 \frac{dr}{dt}\rho \quad \text{(Mass Continuity Equation)}$$



Mass Loss due to Solar Wind

dM/dt is the mass loss rate of the Sun ($\dot{M}_\odot$) and dr/dt is the wind speed (v), which is constant as long as no additional forces are acting on the wind particles.

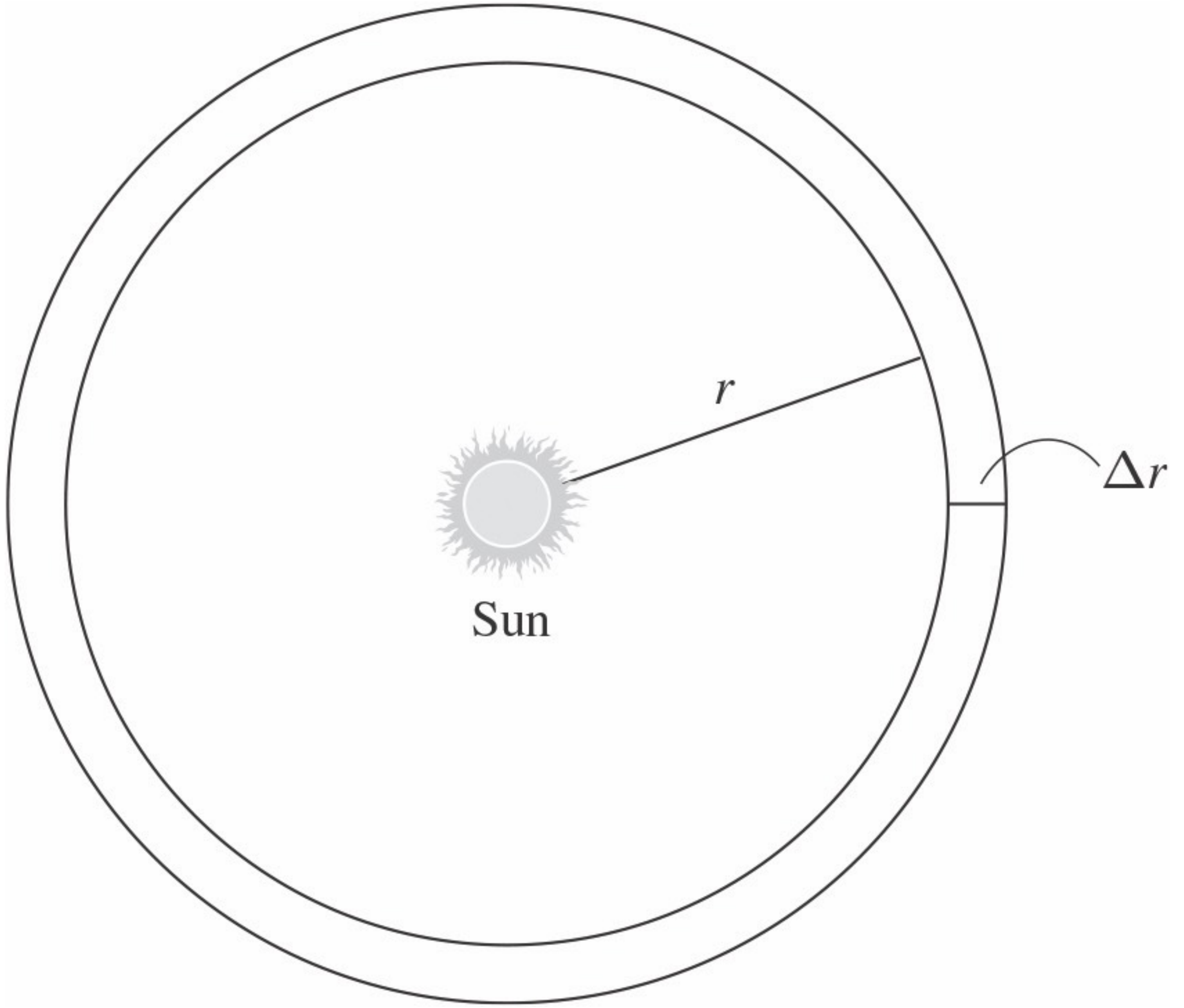
$$\dot{M}_\odot = \frac{dM}{dt} = 4\pi r^2 \frac{d}{dt}\rho = 4\pi r^2 v\rho$$

Plugging in measured values,

$$\dot{M}_\odot \sim 10^8 \text{ kg s}^{-1} \sim 10^{-14} \text{ M}_\odot \text{ s}^{-1}$$

Thus, the solar wind would drain the Sun of its mass in:

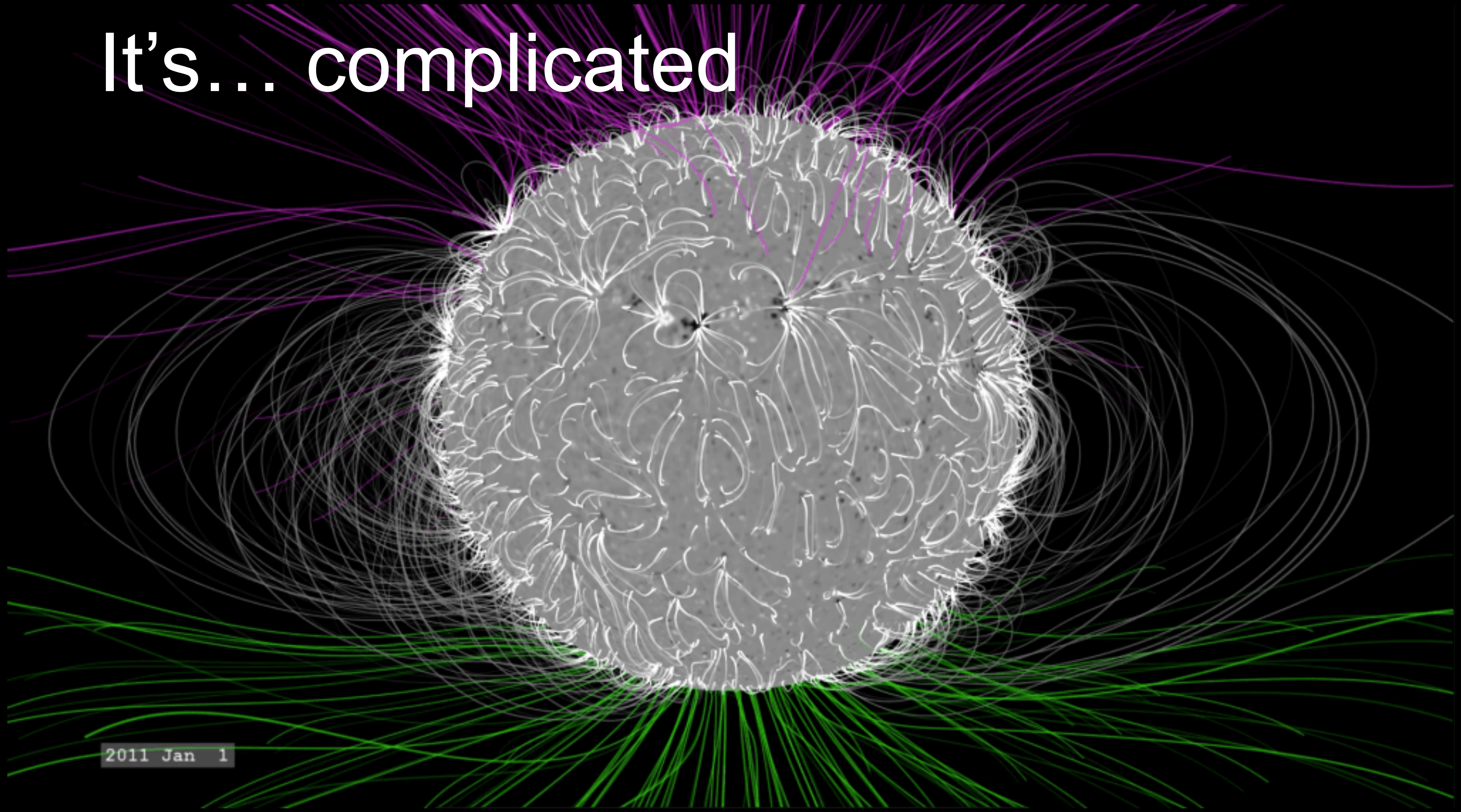
$$t_M = M_\odot / \dot{M}_\odot \sim 10^{14} \text{ yr}$$

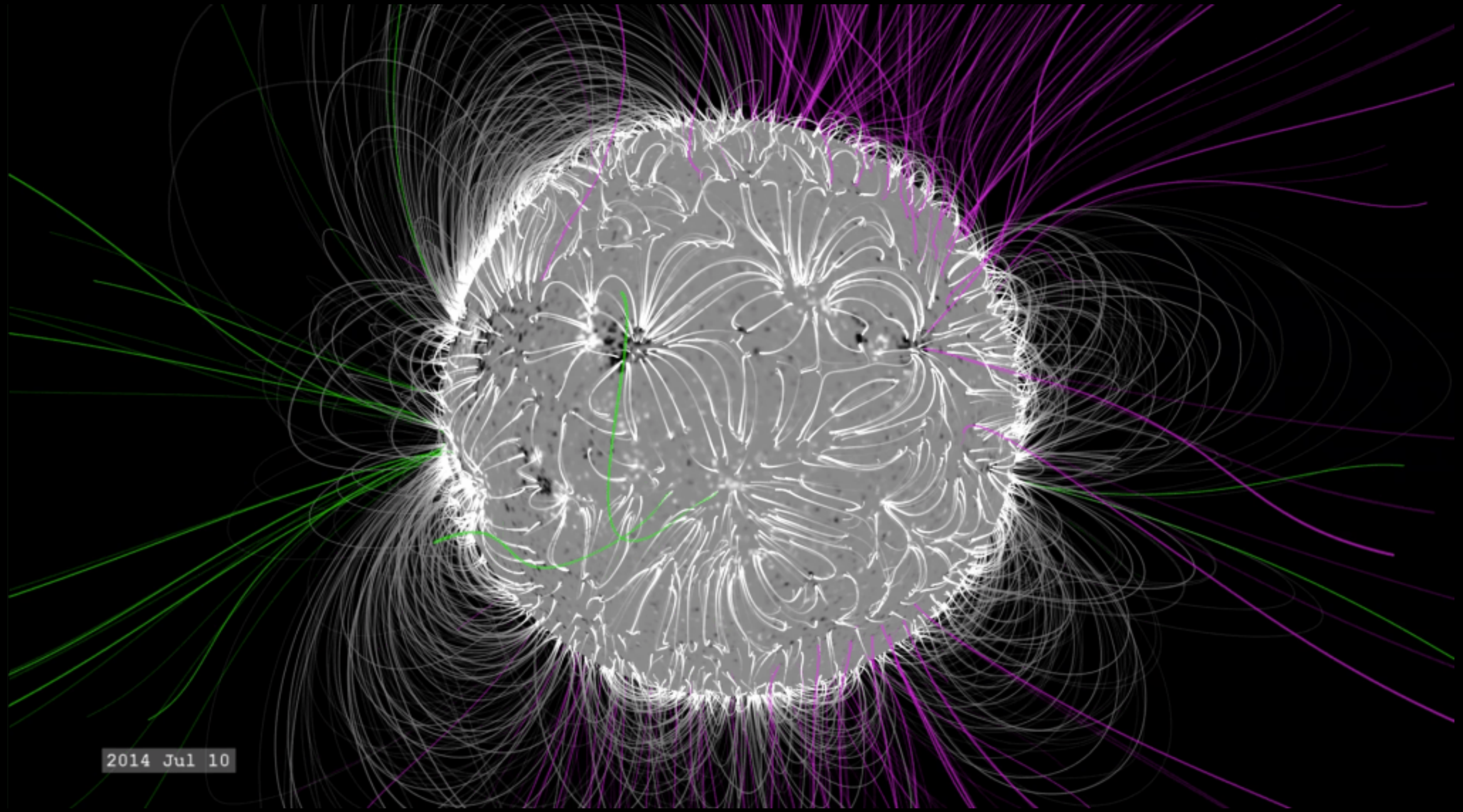


Solar Activity

This is the general term we use for the Sun's activity tied to its magnetic field. What does the magnetic field look like?

It's… complicated

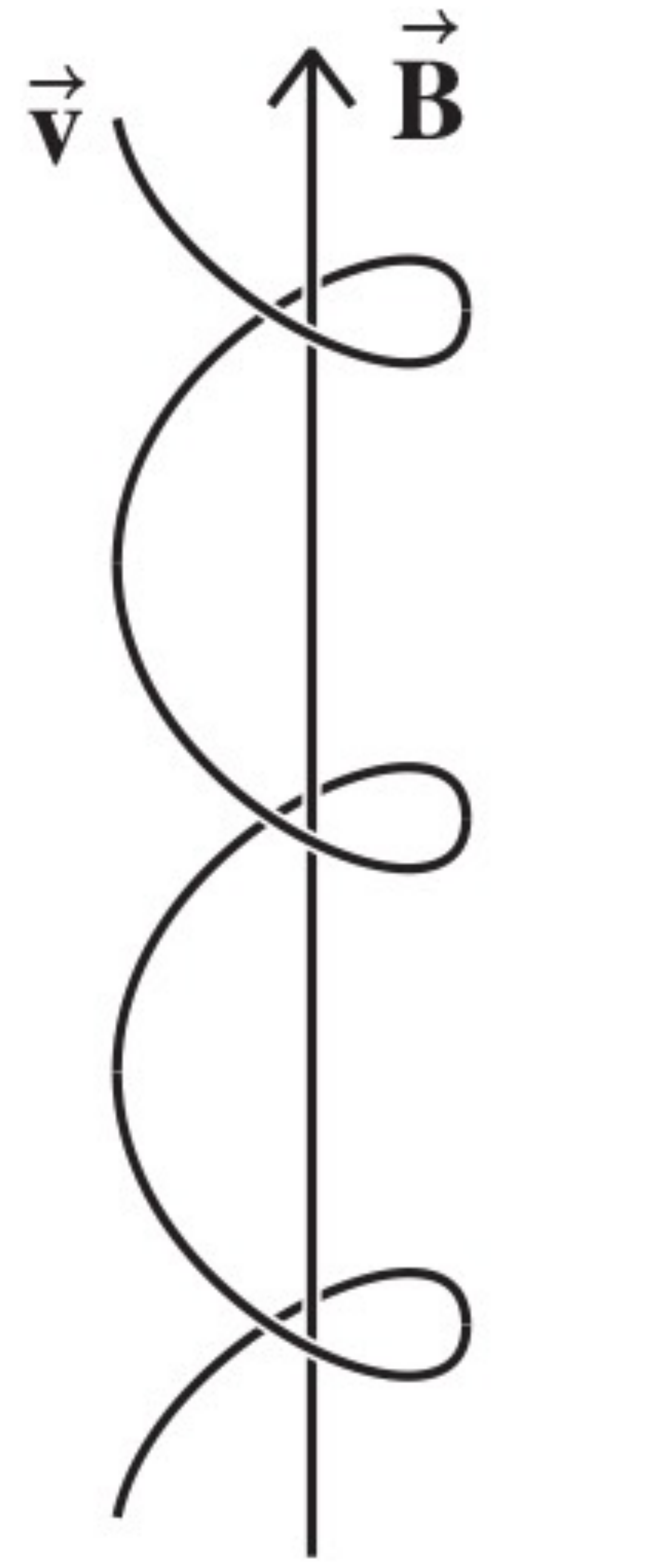




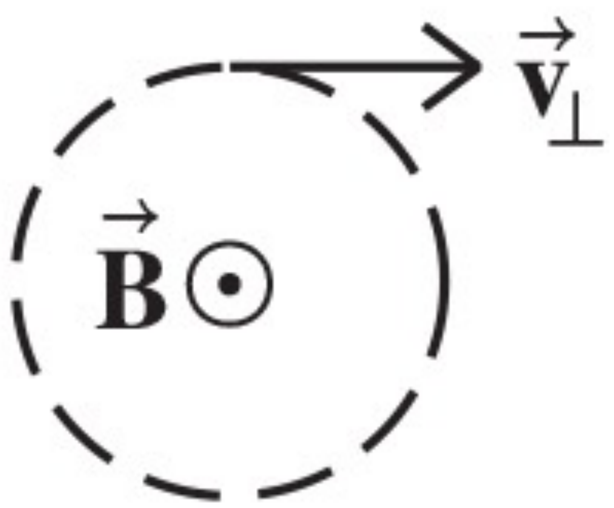
Review: a particle with charge q moving with a velocity $\vec{v}$ through a magnetic field will be accelerated by the Lorentz force, $\overrightarrow{F} = q\vec{v} \times \overrightarrow{B}$ ($\overrightarrow{B}$ is the strength of the magnetic field)

Particle motion in a magnetic field

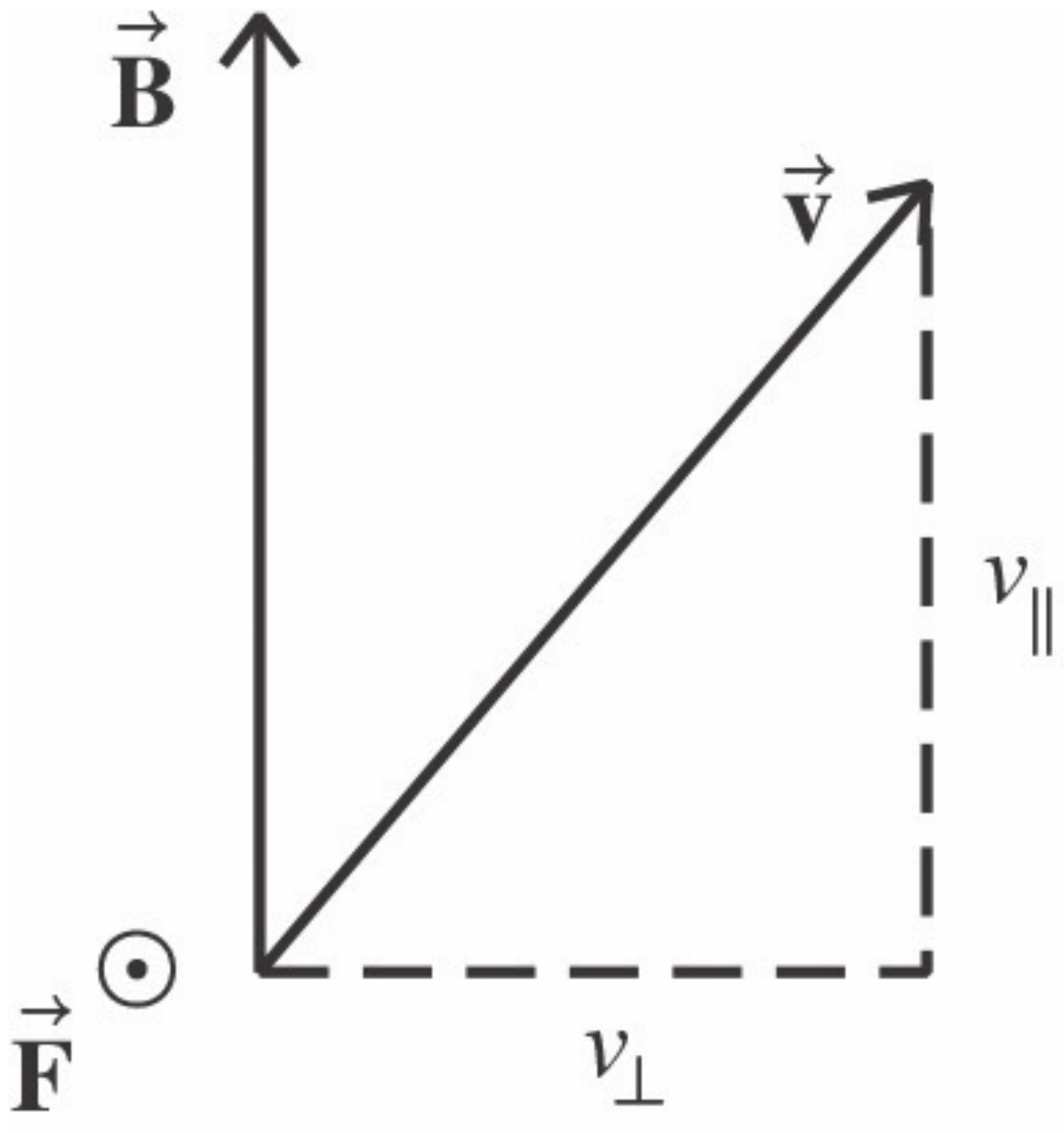
The Lorentz force causes the charged particle to move in a helix around magnetic field lines



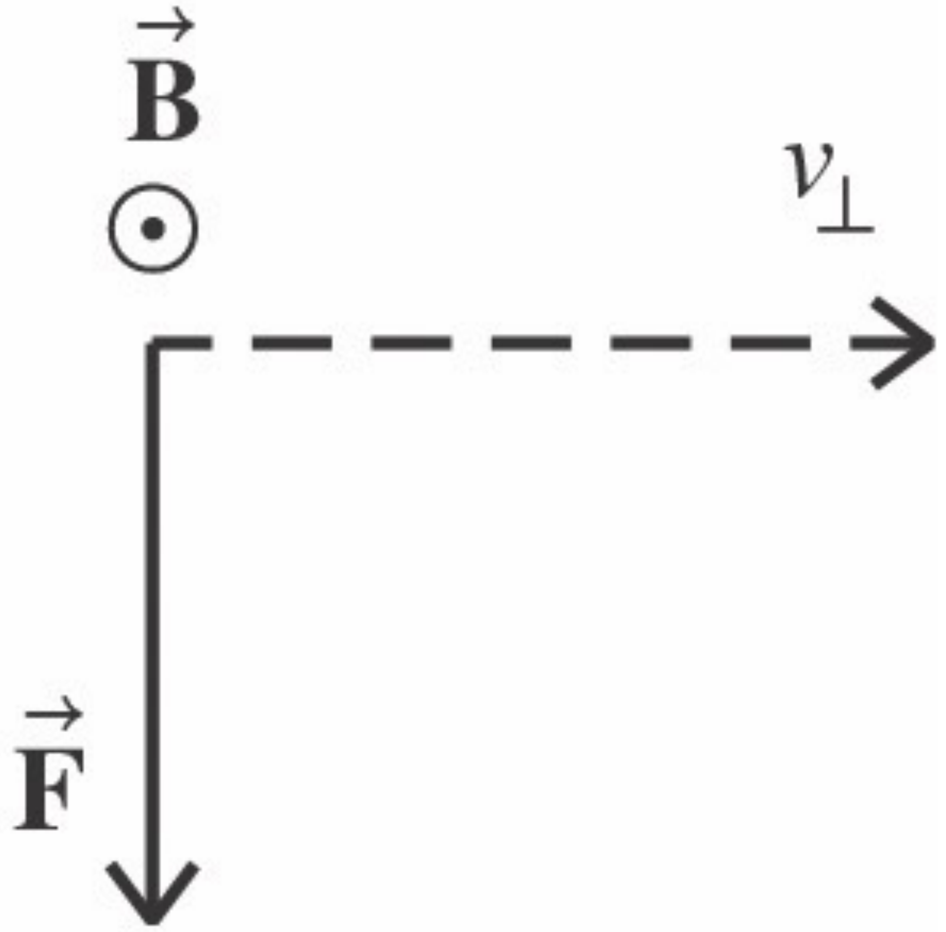
From the side



From above



From the side



From above

Particle motion in a magnetic field

From Newton's 2nd law, we see that an electron moving in circular motion will feel an acceleration:

$$a = \frac{q}{m} v_\perp B$$

Similarly, an object moving on a circular orbit experiences an acceleration:

$$a = v_\perp^2 / r$$

Relating the two equations, we find:

$$\frac{v_\perp^2}{r} = \frac{q}{m} v_\perp B$$

We can solve for the radius of the particle's orbit:

$$r_c = \frac{m v_\perp}{qB}$$ (Larmor radius)

Magnetic Pressure vs. Gas Pressure

The magnetic energy density (or magnetic pressure) is:

$$P_B = \frac{B^2}{2\mu_0} = 4.0 \times 10^5 \text{ N m}^{-2} \left(\frac{\text{B}}{1 \text{ T}} \right)^2$$

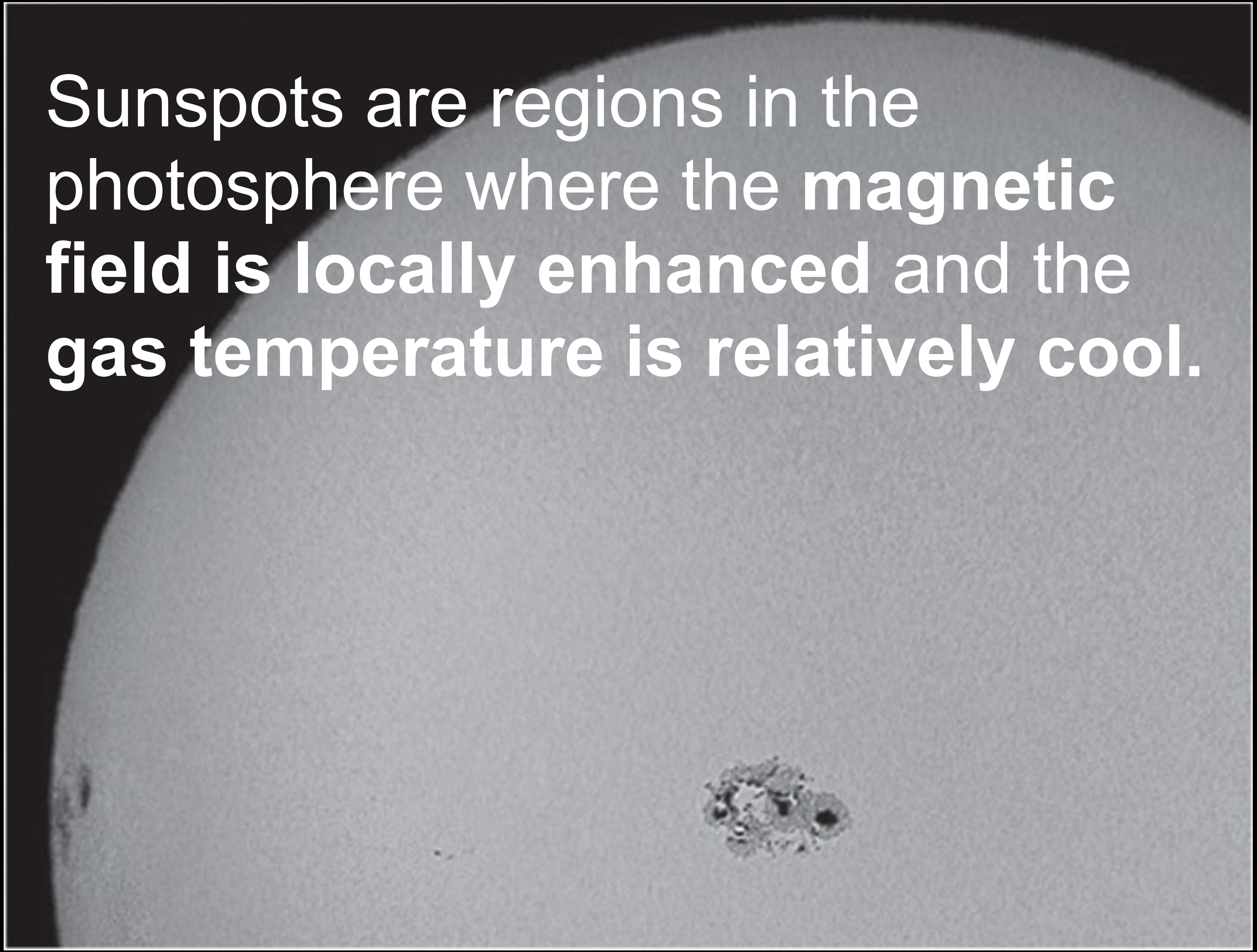
μ_0 is the permeability constant

$\mu_0 = 4\pi \times 10^{-7}$ kg m C^{-2}

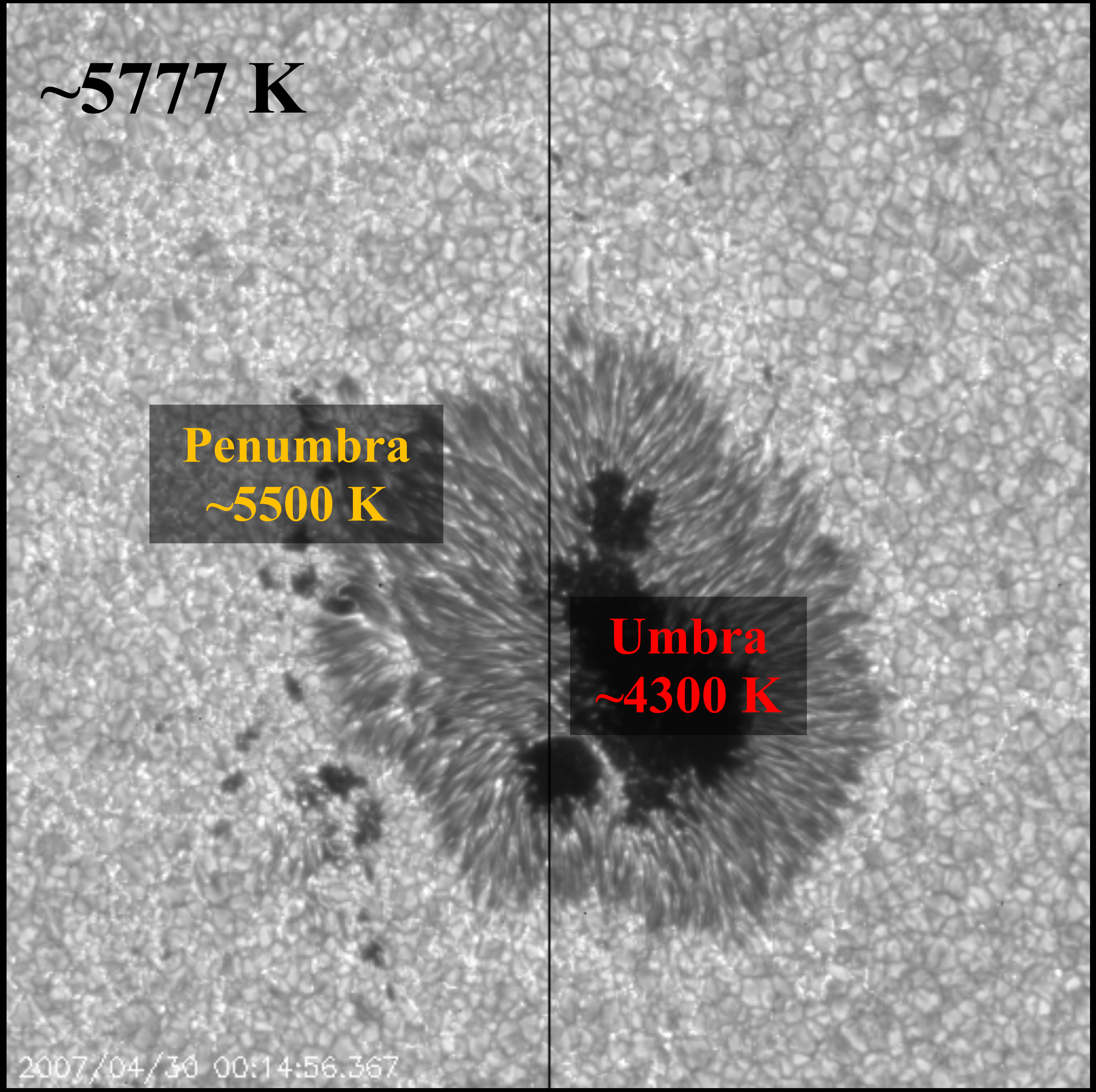
Within the Sun, the gas pressure is given by the ideal gas law:

$$P_{\text{gas}} = \frac{\rho k T}{\mu m_p} \approx \frac{5000 \text{ N m}^{-2}}{\mu} \left(\frac{\rho}{10^{-4} \text{ kg m}^{-3}} \right) \left(\frac{T}{6000 \text{ K}} \right)$$

Sun Spots



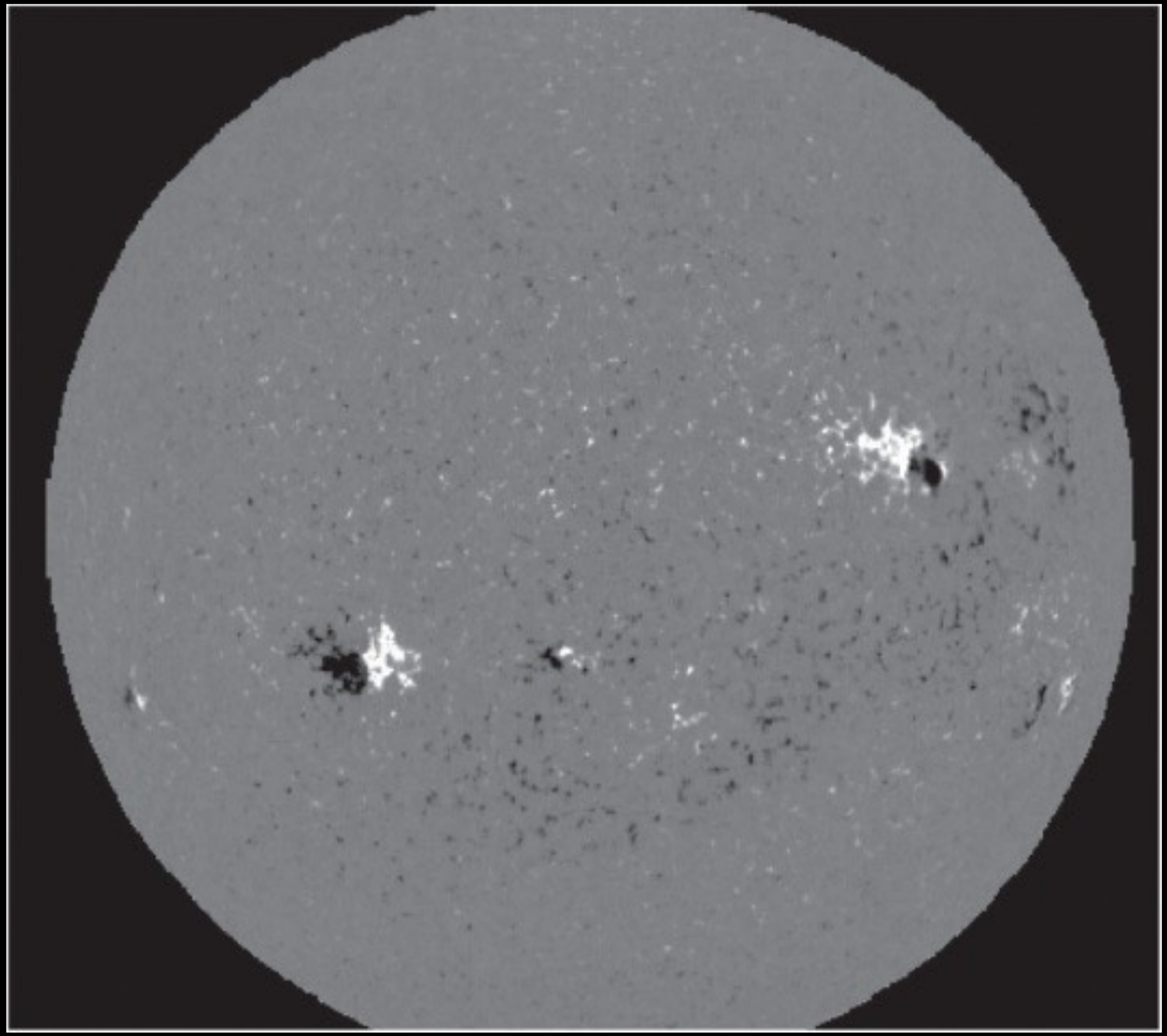
Sunspots are regions in the photosphere where the **magnetic field is locally enhanced** and the **gas temperature is relatively cool.**

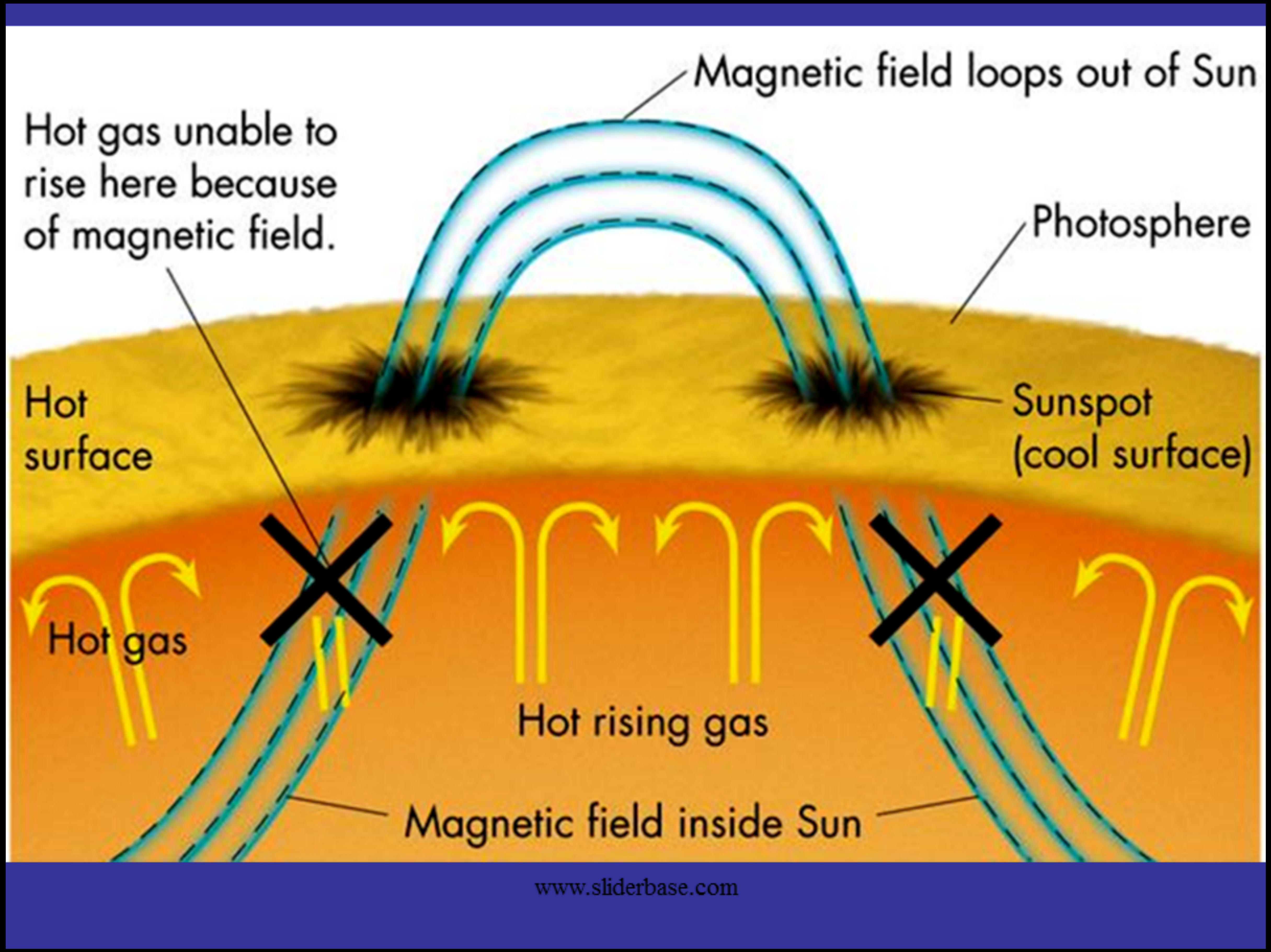


In other words, these are “cool” regions of the Sun where magnetic field lines are closely packed and break through the photosphere.

Sun Spots

Sunspots **come in pairs with opposite magnetic polarity.**



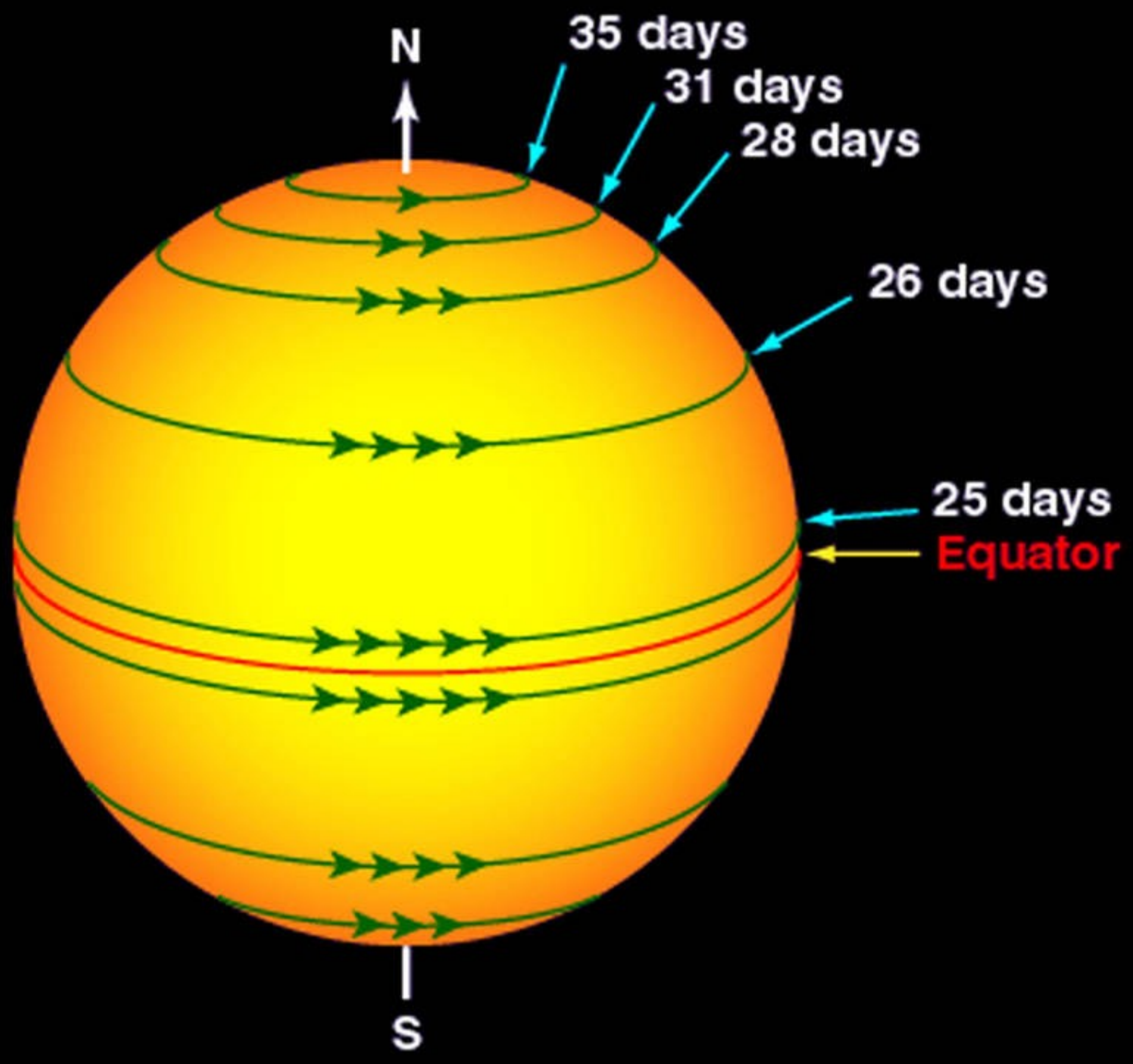


This **magnetogram** (left) shows the polarity around each pair of spots.

Differential Rotation

The Sun rotates at different speeds at different latitudes

- Unlike the Earth, the Sun is a fluid body, not a rigid one.
- This fluidity causes it to undergo differential rotation.
- The equatorial regions rotate faster than the polar regions.
- Galileo (and others) first discovered this tracking sunspots as they rotated at different latitudes on the Sun.

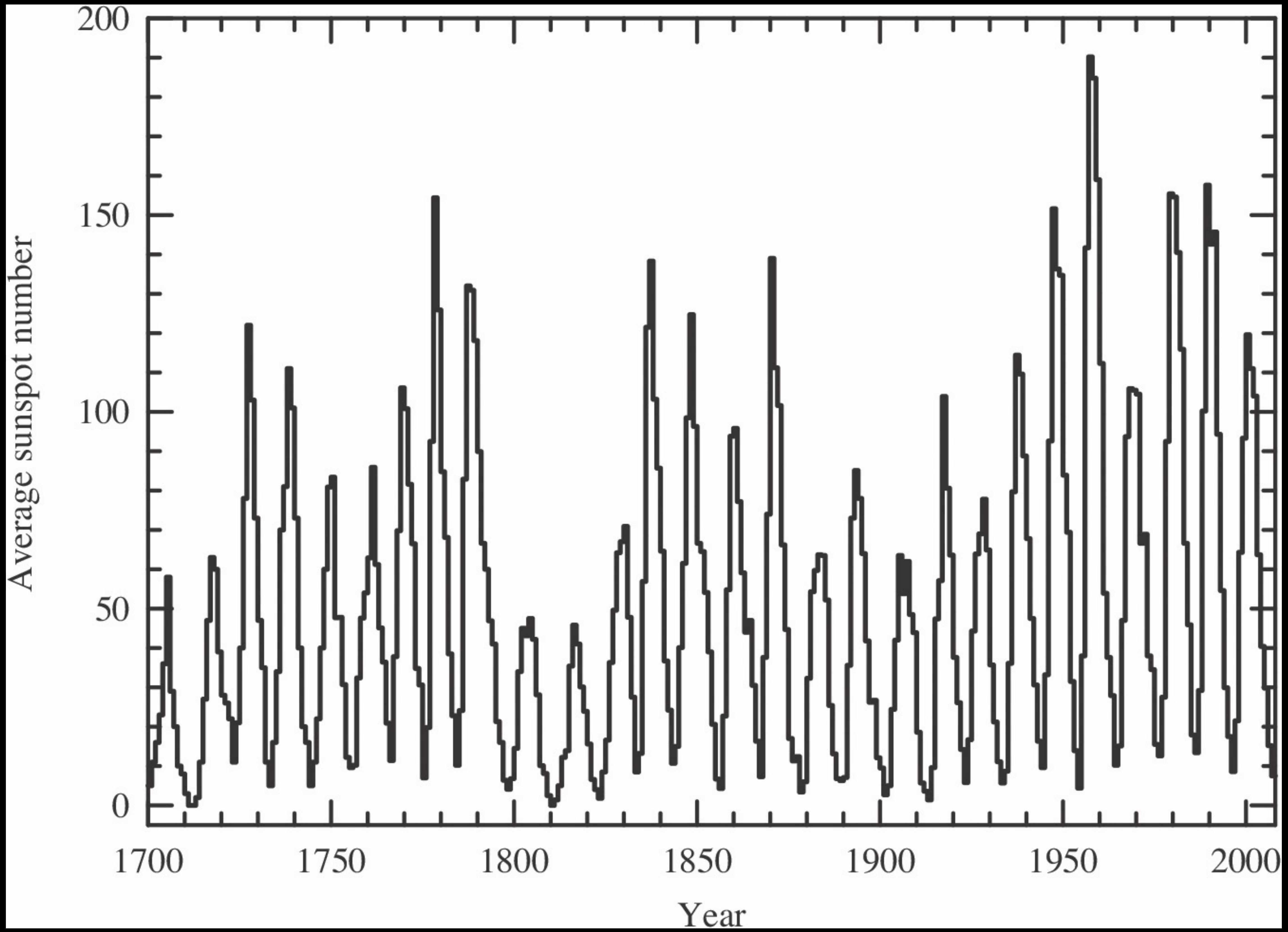


Sunspots through Time

Sunspot cycle: The timeframe in which the number of sunspots increase to a maximum and decrease to a minimum.

Every 11 years the magnetic field flips, like flipping a bar-magnet around so N-S direction is flipped.

The complete Solar cycle is the 22 year period in which the polarity of the poles return to where they started.



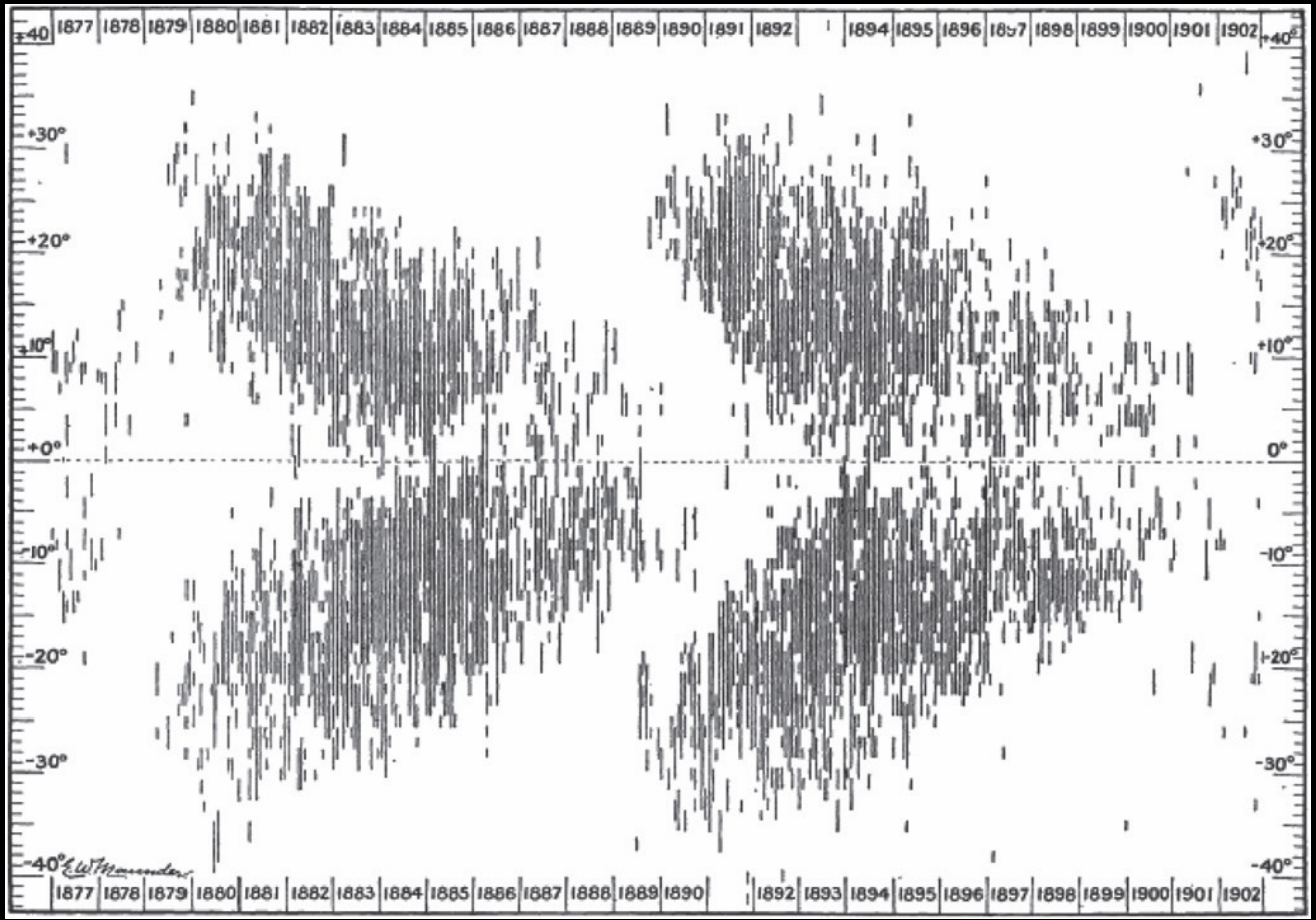
The cycle and flipping is due to the magnetic "dynamo" in the Sun's interior. As you saw earlier, the magnetic field (and its creation) is complicated

Migration of Sunspots

- Sunspots are created at latitudes > |30| degrees at the beginning of the activity cycle.

- They migrate towards the equator during the Sunspot cycle.

- Then they flip polarity and start again (makes a nice “butterfly diagram”)

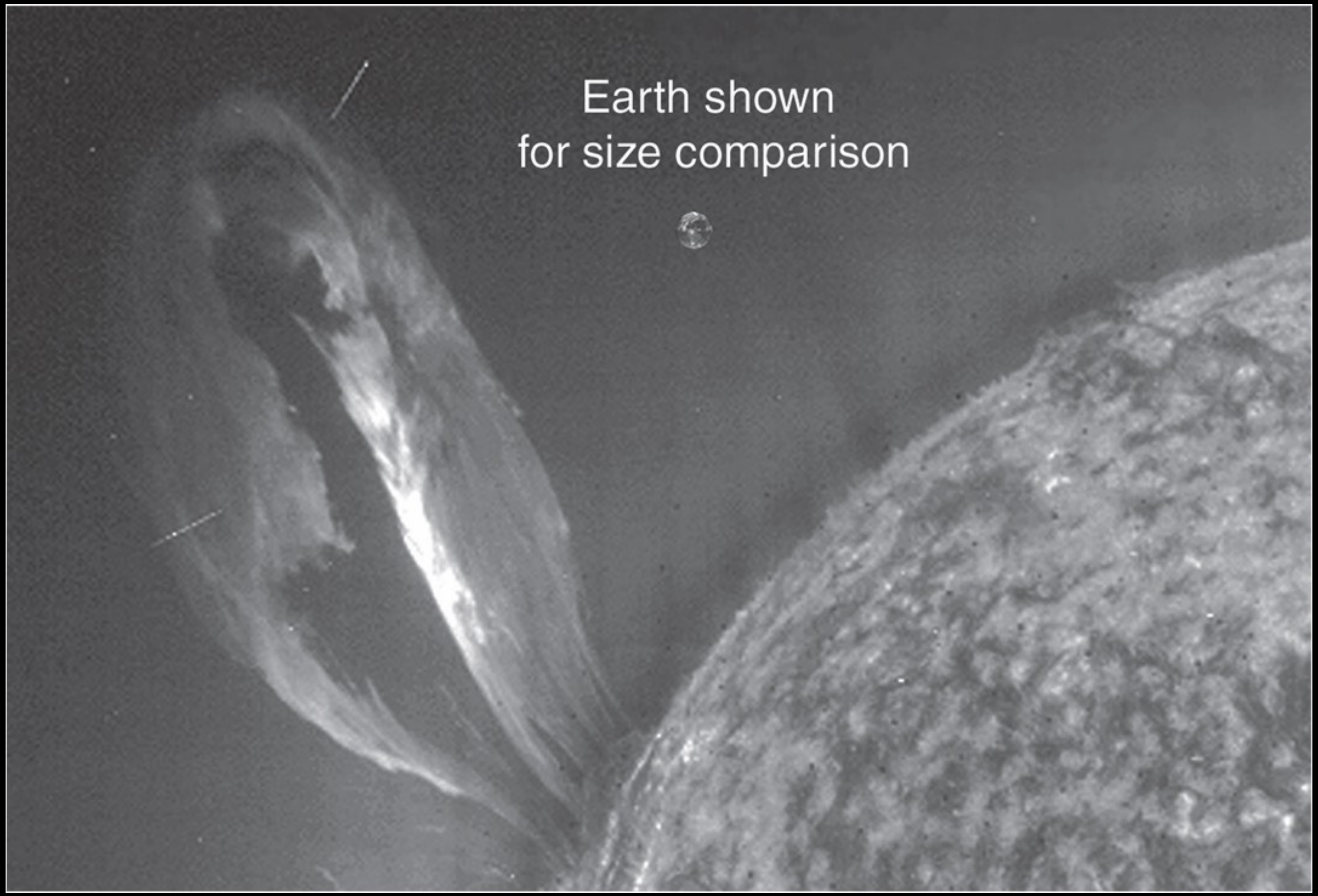



Questions?

Solar Prominences

Occasionally, kinked magnetic field lines in the photosphere erupt outward and create a loop, which produces a **bipolar magnetic region** (think sunspot pair).

If the poles of the region merge, it can accelerate ionized gas along the field lines and you get a **prominence** (shown here).



It is still bound to the sun, so it’s not considered ejected material.

Coronal Mass Ejection (CME)

An **erupting prominence** can cause a coronal mass ejection.

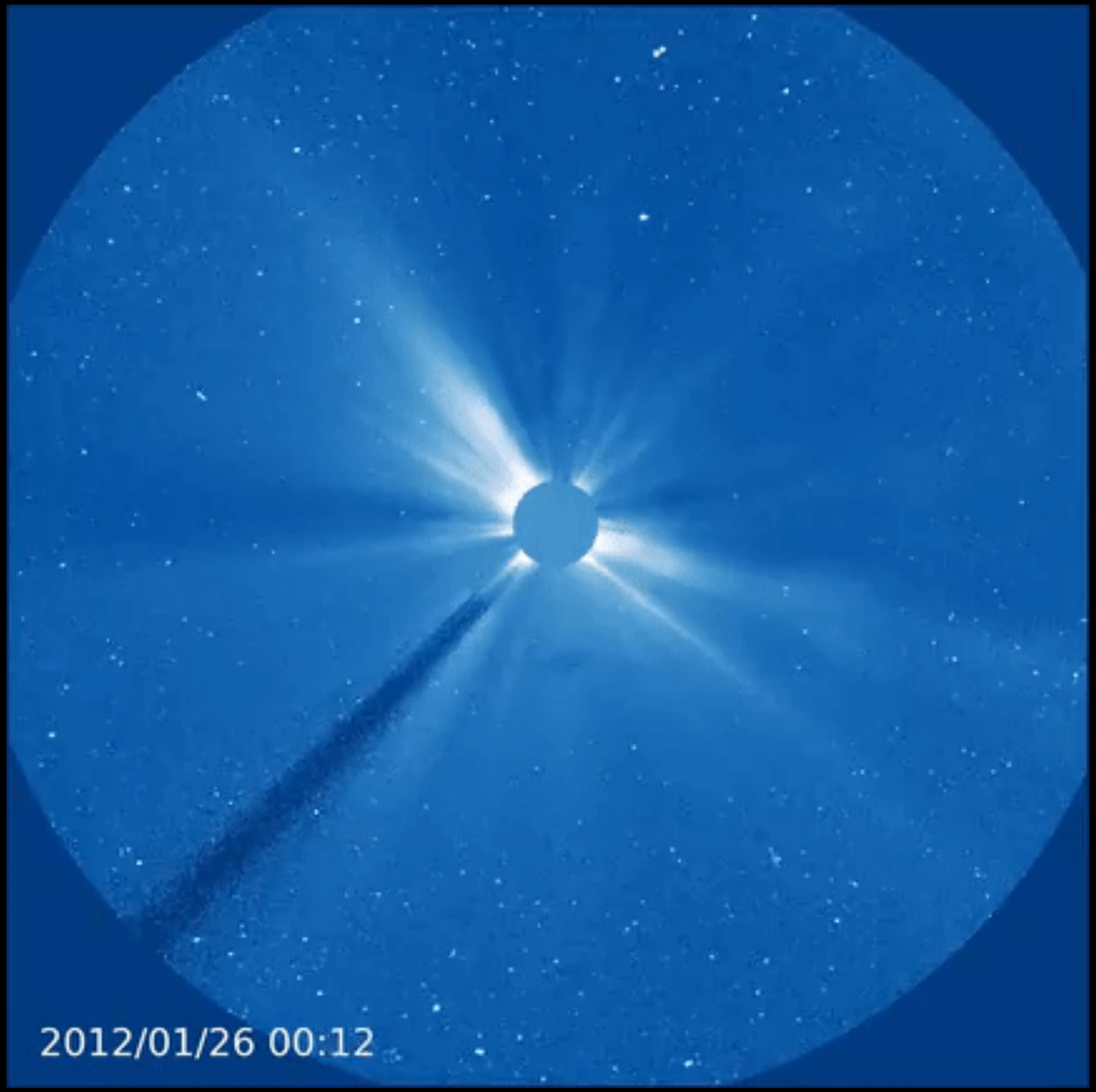
These big blobs of *ionized* gas occur a few times a day (depends on what part of the activity cycle we are in, from 1/ week to 2-3 per day)

The typically travel at ~ 500 km s^{-1}

A large CME contains $\sim 10^{13}$ kg of gas! ~10^{13} kg of gas!

Recall, $M_{\oplus} \sim 6 \times 10^{24}$ kg

Solar flares are even more energetic! They are chromospheric eruptions triggered by the sudden release of energy stored in teh Sun's B-field!



Solar Flare Observed by NASA’s Solar Dynamics Observatory


Questions?

Reminders

- **Homework #4 due Wednesday, 10/29 by 11:59 pm via Gradescope.**
- Log into canvas and submit your answer to the discussion question by the end of the day to receive participation credit.