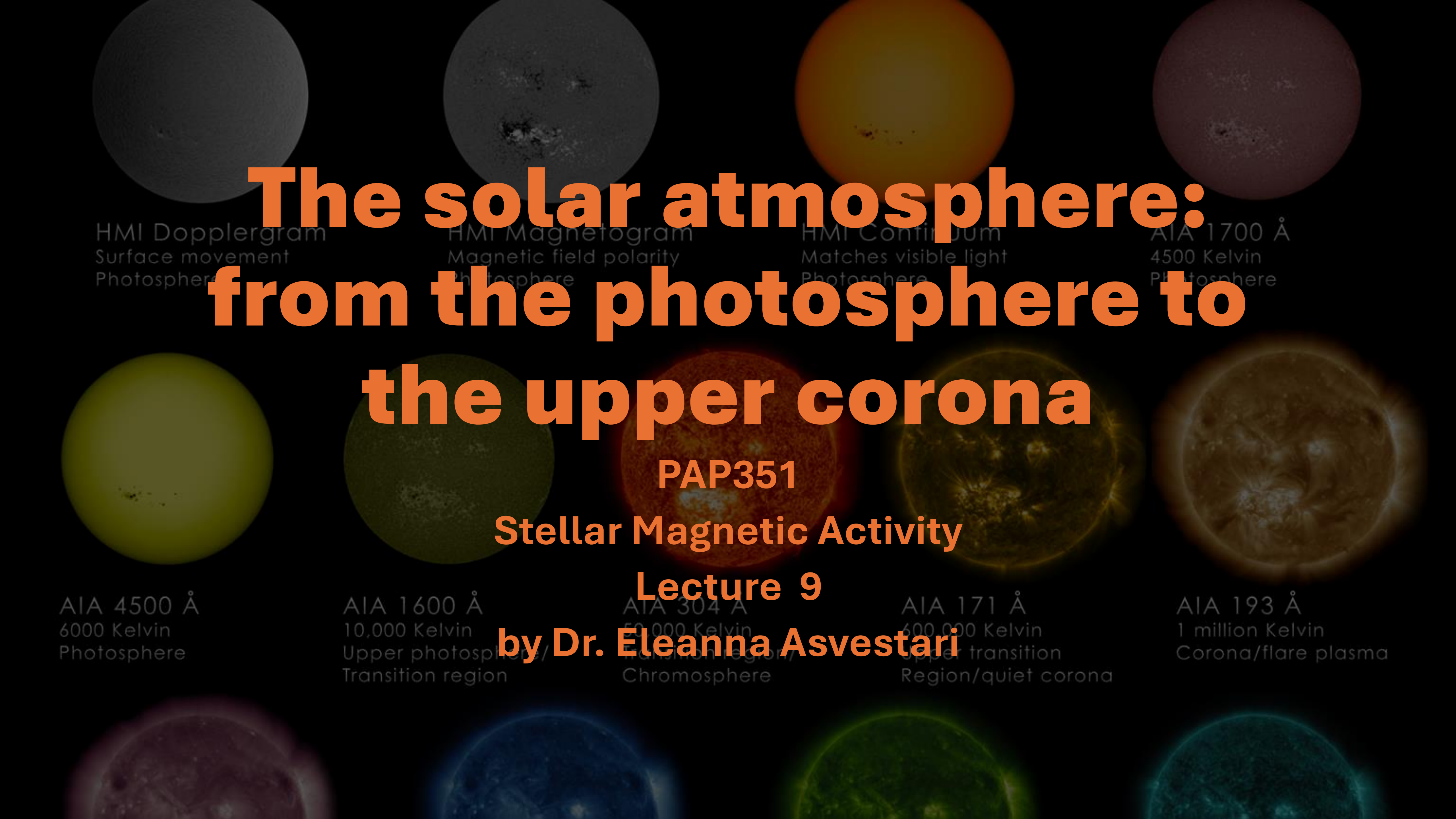


The solar atmosphere: from the photosphere to the upper corona

PAP351

Stellar Magnetic Activity

Lecture 9

by Dr. Eleanna Asvestari

Outline

- The structure of the solar atmosphere
- Photosphere: the basis of the coronal magnetic field
- The spiky chromosphere and the solar network
- The chromosphere of other starts
- The transition region and the elusive corona

The structure of the solar atmosphere

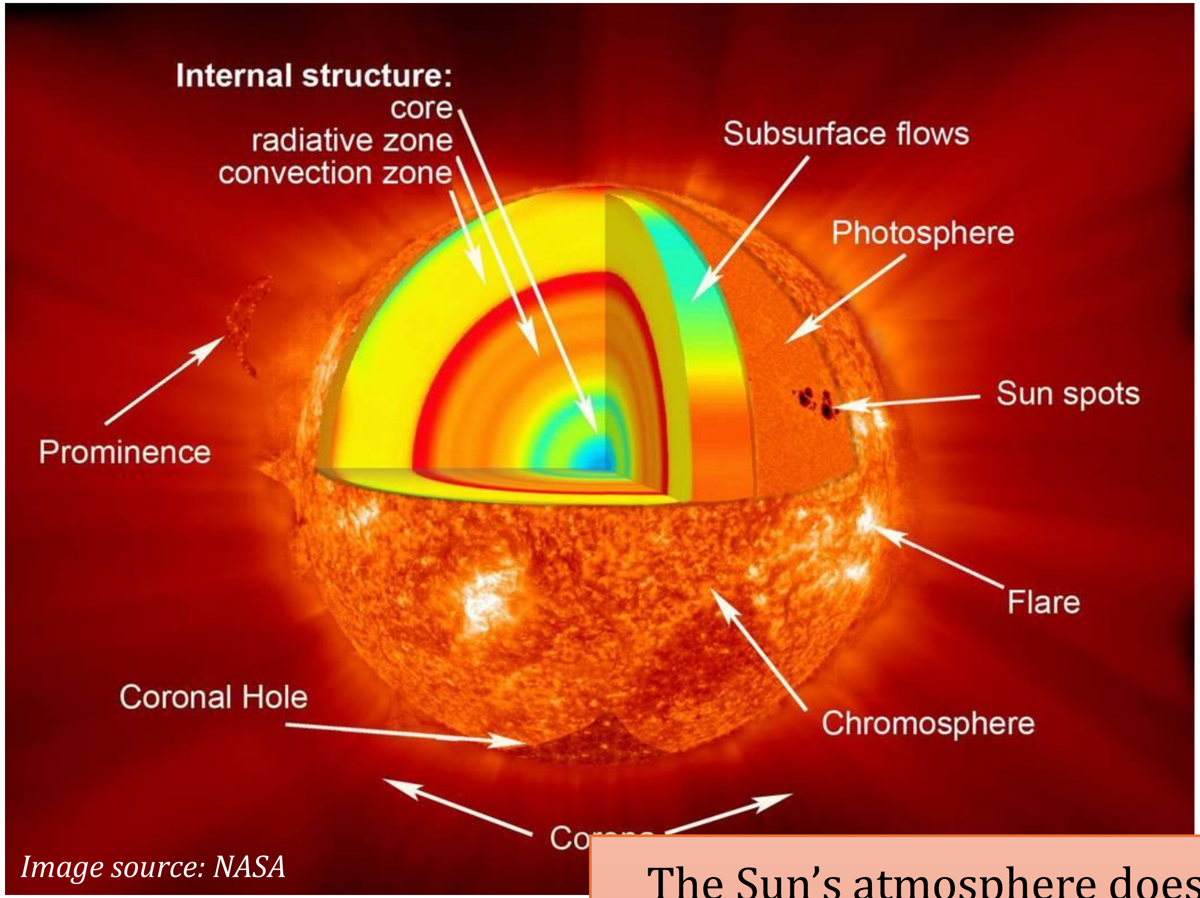


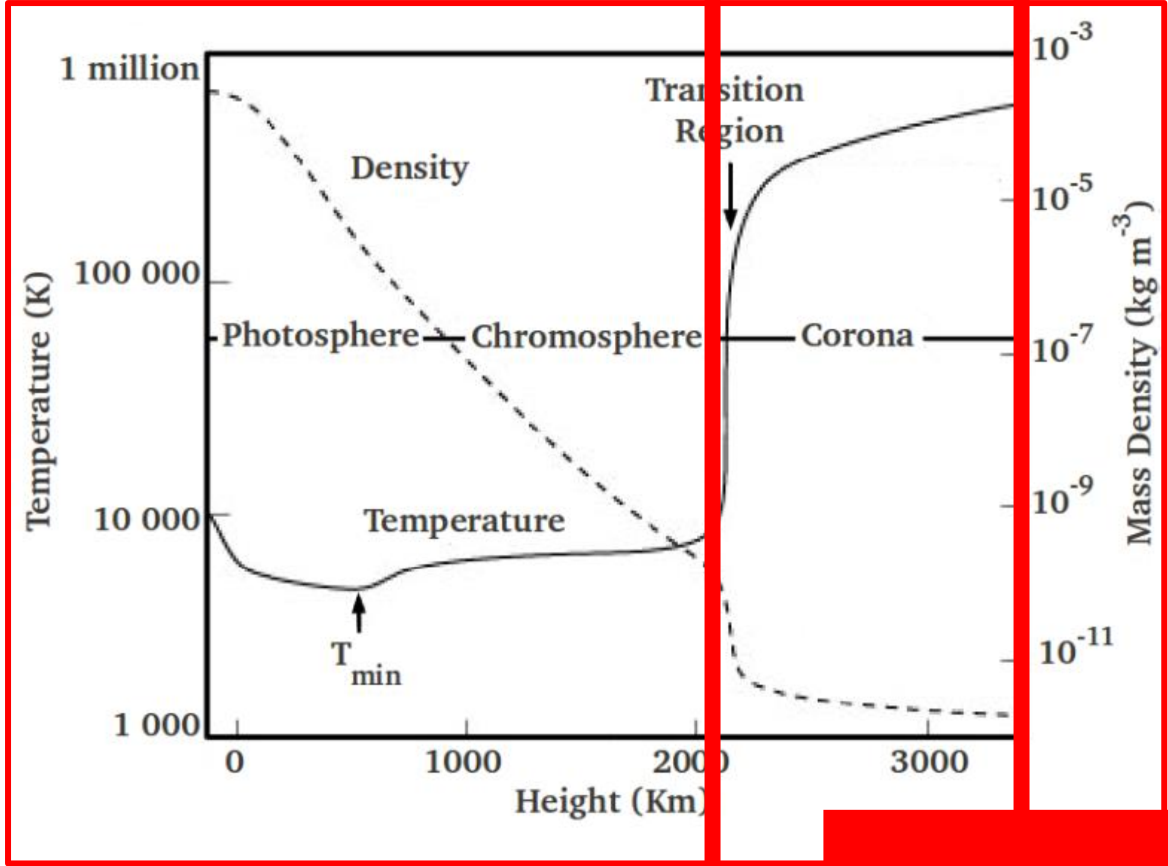
Image source: NASA

Photosphere → Chromosphere → Transition Region → Corona

the density drops exponentially

The Sun's atmosphere does not really end at the end of the corona region, but it extends far and away from the Sun all the way to the edge of our solar system! This means that all planets are cruising inside the Sun's atmosphere.

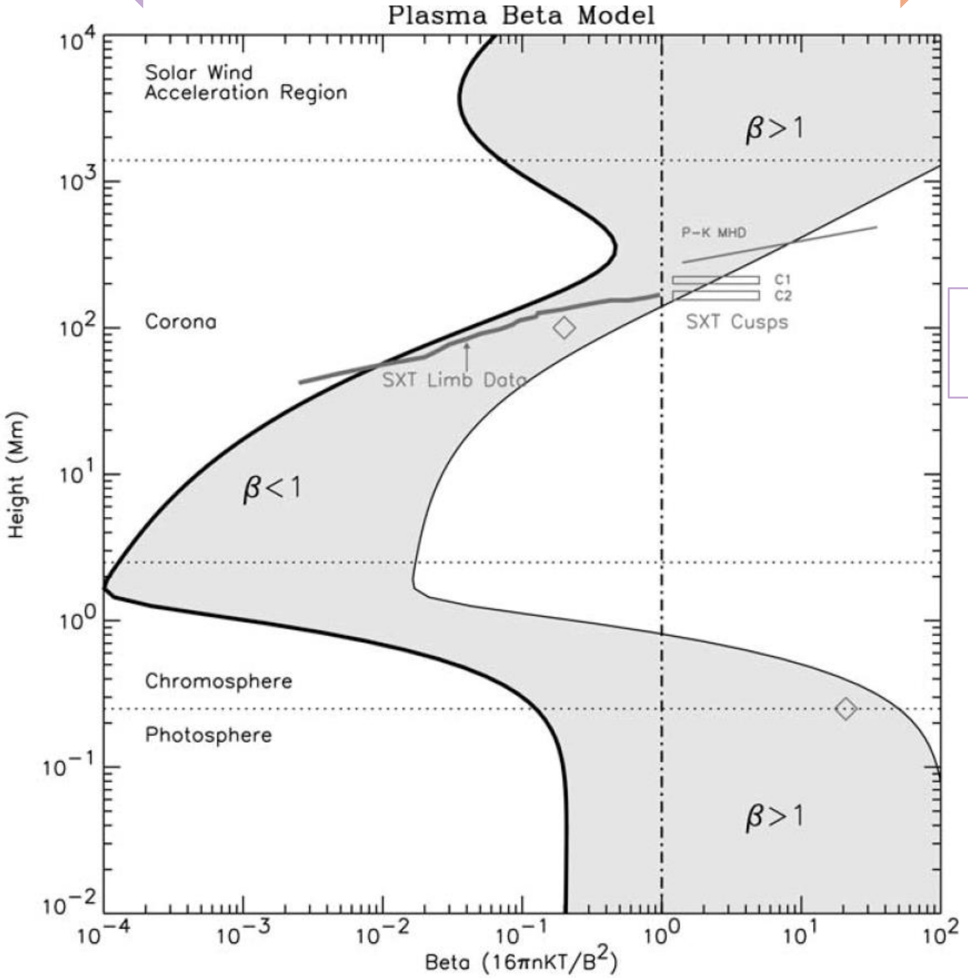
The structure of the solar atmosphere in plasma parameters



Why is the corona so hot?

Field dominates

Gas dominates



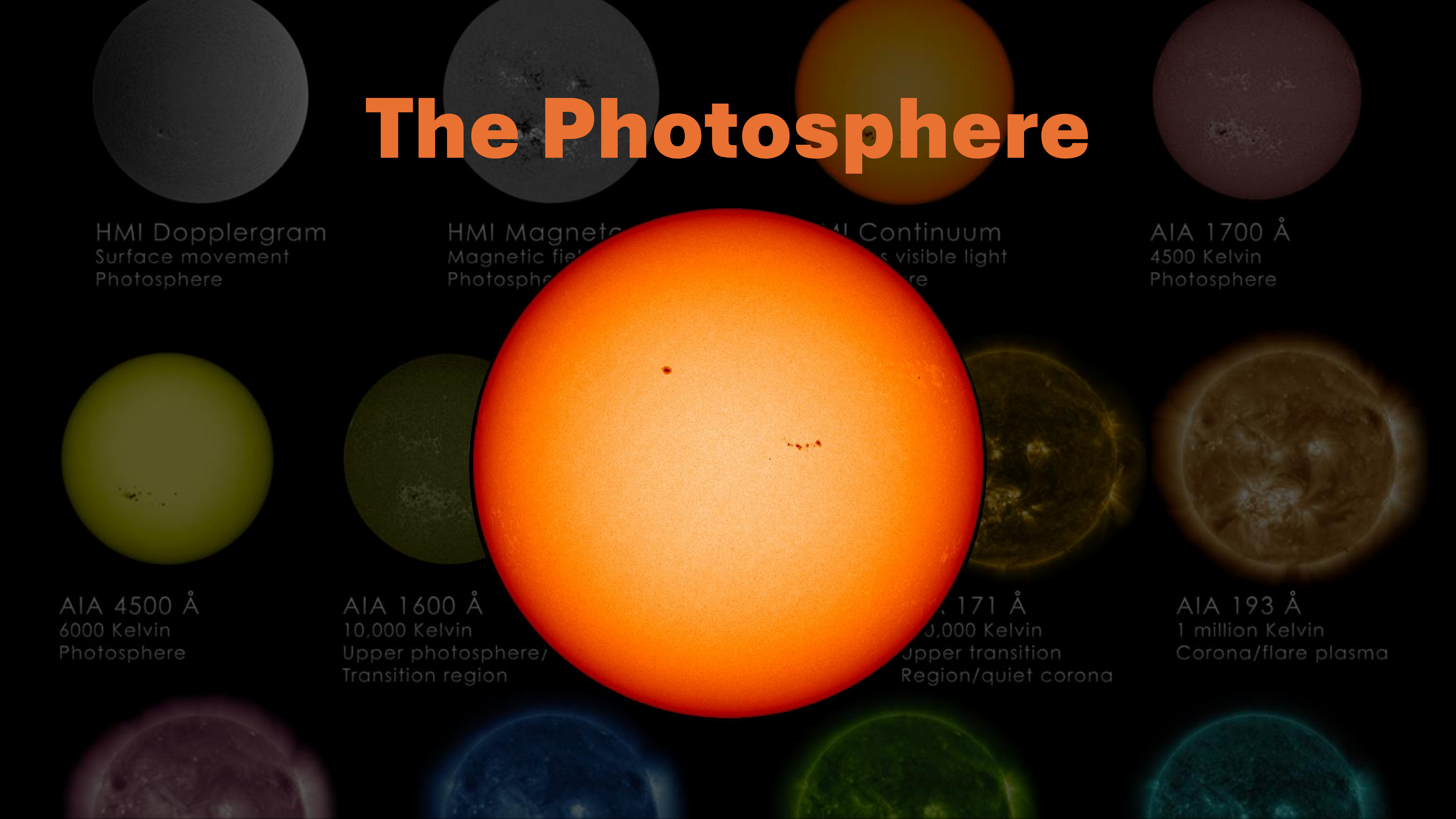
B-field follows solar wind flow

Gas follows magnetic field

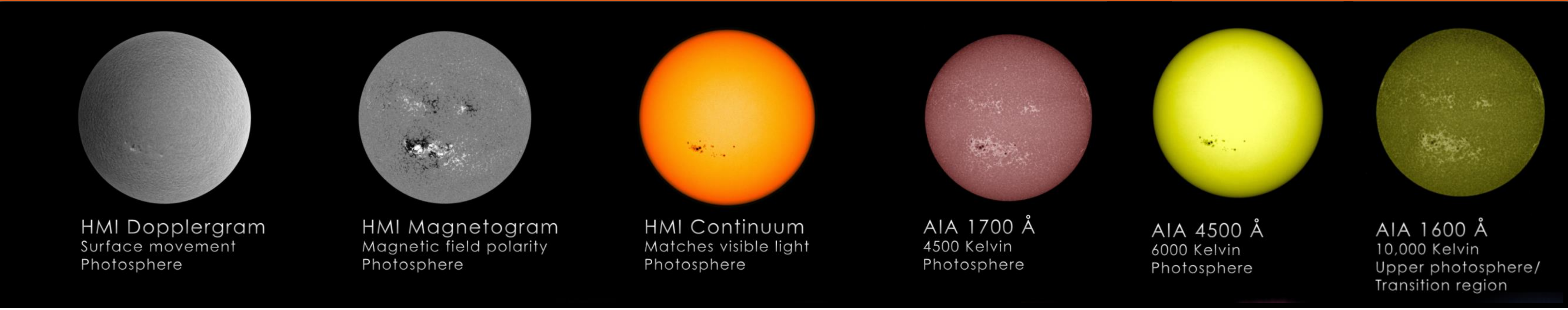
Gas flows drag magnetic field with them

Figure source: Garry, 2001

The Photosphere



Photosphere: the atmospheric floor



- The first layer of the Sun where radiation escapes!
- Extends up to the layer that reaches the temperature minimum (~500 km thickness).
- Dominated by visible-light emissions (3900 Å - 7600 Å)
  - Gas in an equilibrium state → Thermal emissions
- It behaves as a Black Body (BB): absorbs all incident radiation and re-radiates energy at spectrum that depends only on temperature (*T*).
- From the light emitted in the solar corona we estimate the total energy output of the Sun, known as the **solar constant**.

"The **total solar irradiance (TSI)** is the spectrally integrated radiative energy flux incident on the top of the Earth's atmosphere at the mean Sun–Earth distance of 1 a.u., and it describes the total radiative energy of the Sun received by Earth's system."

Chatzistergos et al., 2023

Solar constant: NOT a constant after all

Monitoring of solar irradiance from space since 1978 has shown that the TSI is variable in all time-scales.

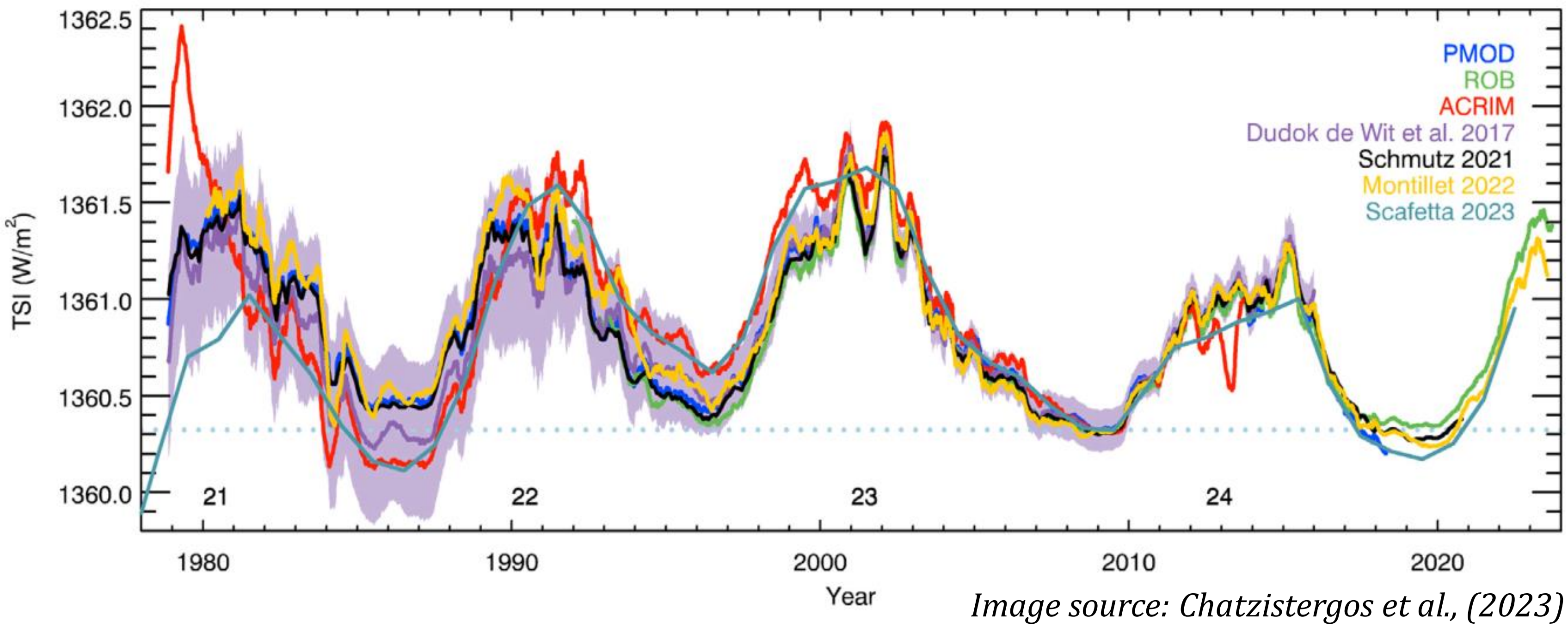


Image source: Chatzistergos et al., (2023)

What does this plot remind you of?

The TSI - aka the energy radiated by the Sun through the photosphere – follows the solar cycle!

Evolution of the total photospheric magnetic flux

What does this plot tell us?

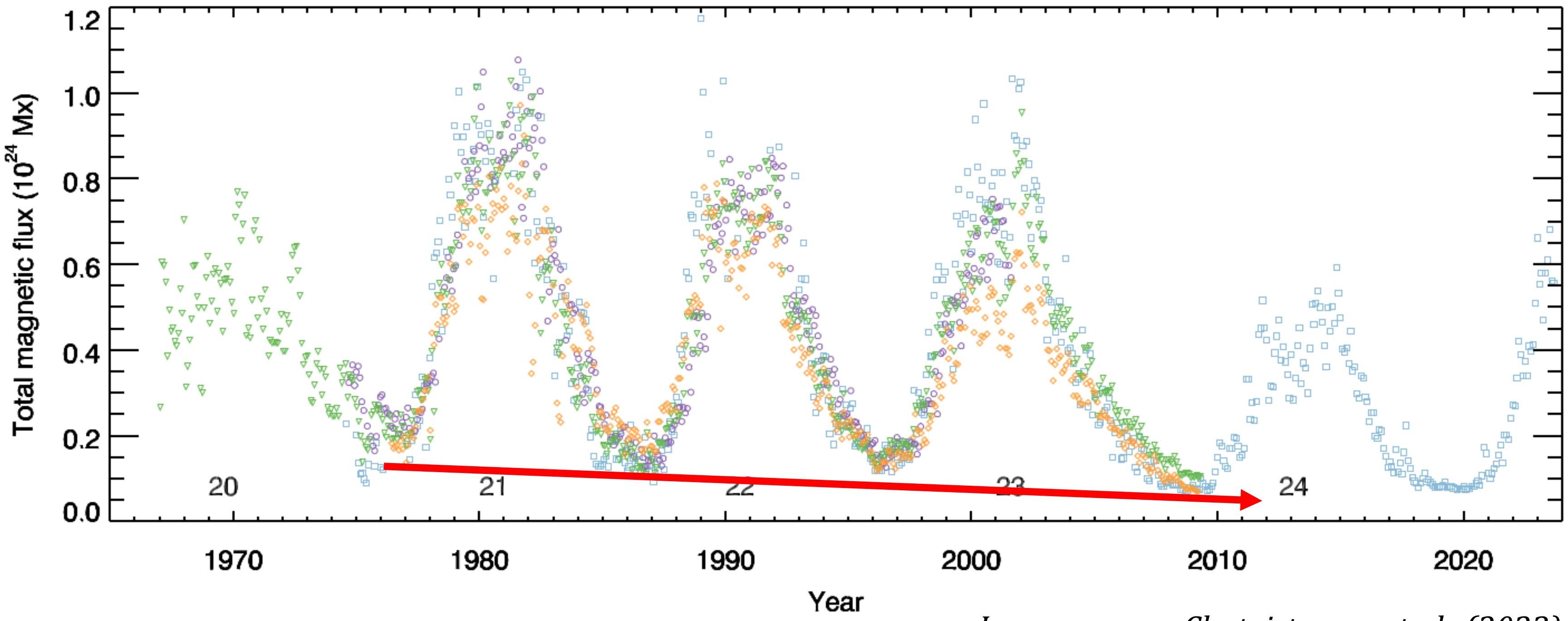
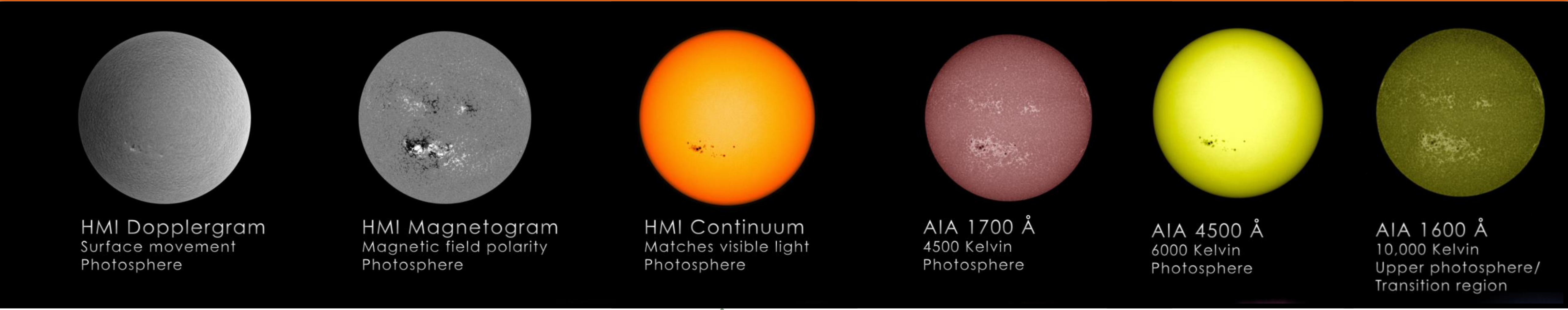


Image source: Chatzistergos et al., (2023)

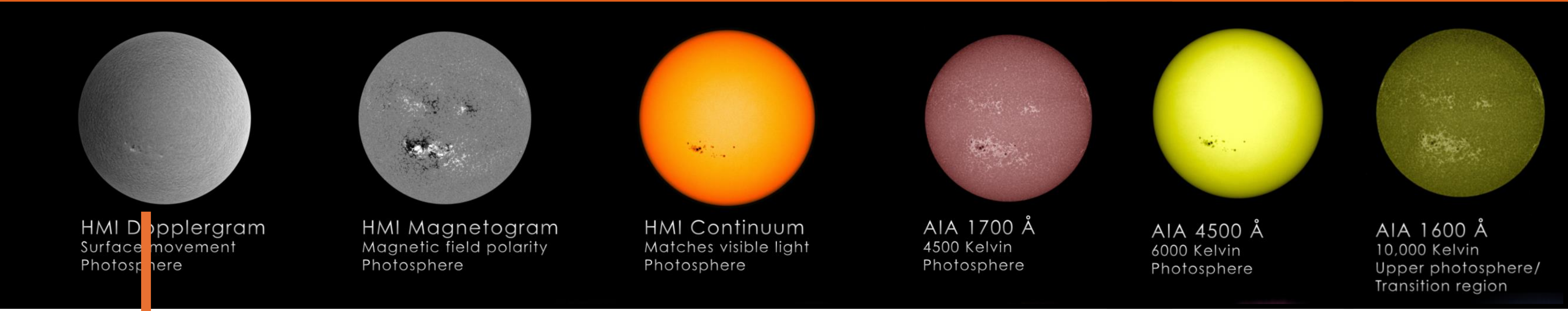
- The surface magnetic field also varies with the solar cycle.
- It exhibits a downward trend over solar cycles 20 to 24, during periods of quiet solar activity solar minima.

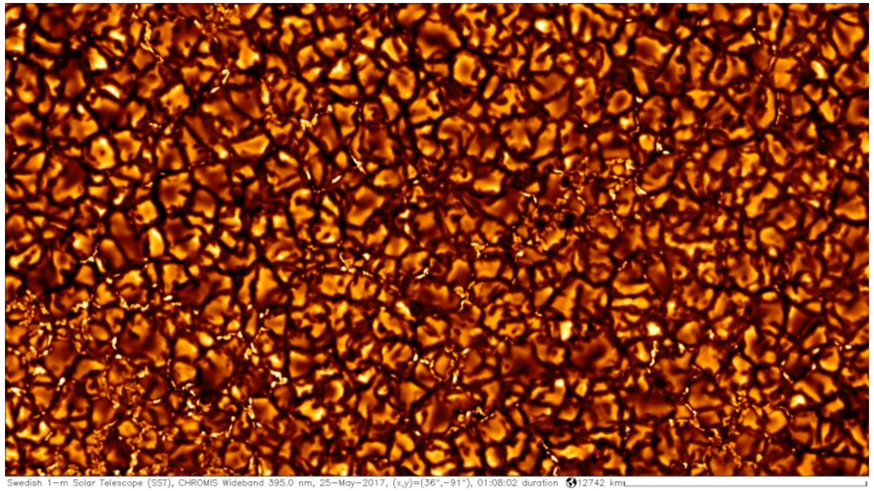
The photosphere, plain?



The photosphere **appears** featureless most of the time.

The photosphere, plain?





Video by Luc Rouppe and accesible via Wikimedia Commons

- Granulation
- Supergranulation

Direct evidence/ well observed (in the photosphere and the chromosphere respectively).

- Mesogranulation
- Giant cells

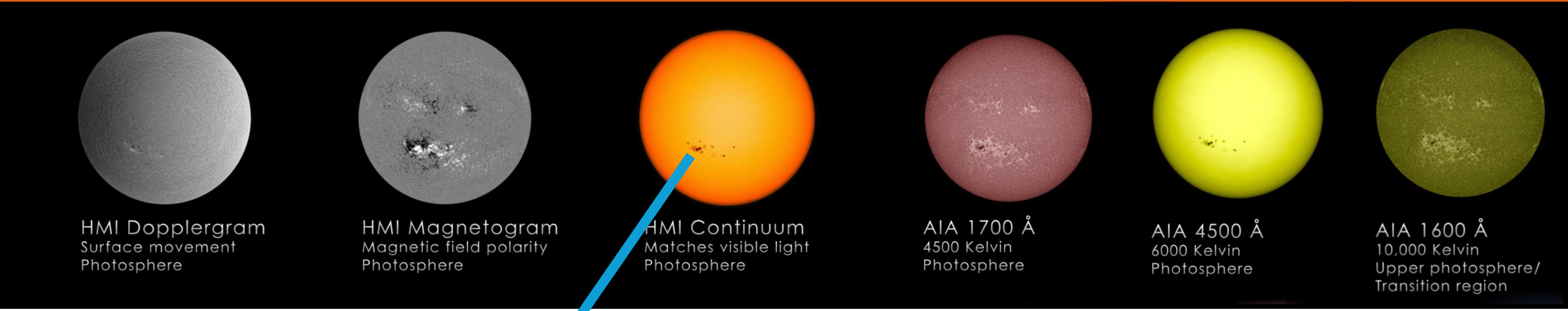
Less strong evidence/ needs further investigation

Granules:
↠Thousands of km to Mm
↠Live for tens of minutes
Supergranules:
↠ Tens of thousands of km to Mm
↠ Can last for a few days

Bright center = Up-flow
Dark border = Down-flow

Quiet Sun Magnetic Field

The photosphere, plain?



Umbra

Penumbra

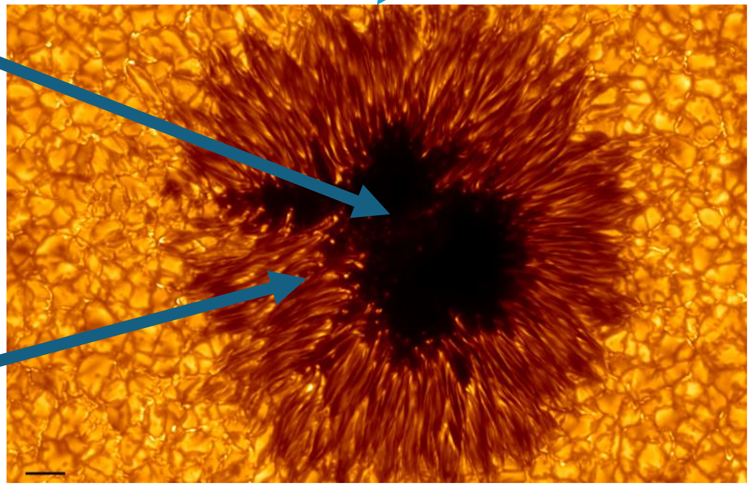


Image by Luc Rouppe, accesible via Wikimedia Commons

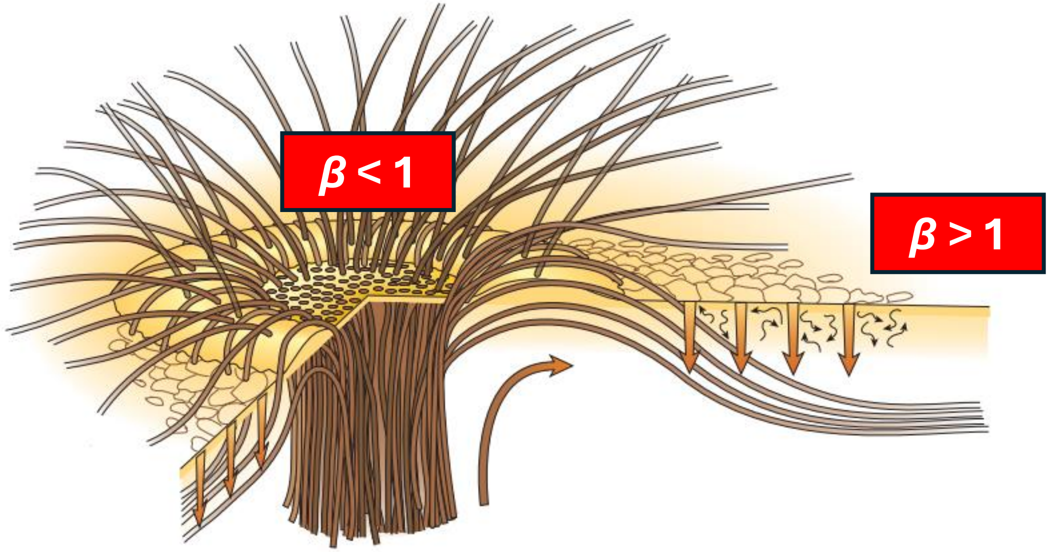
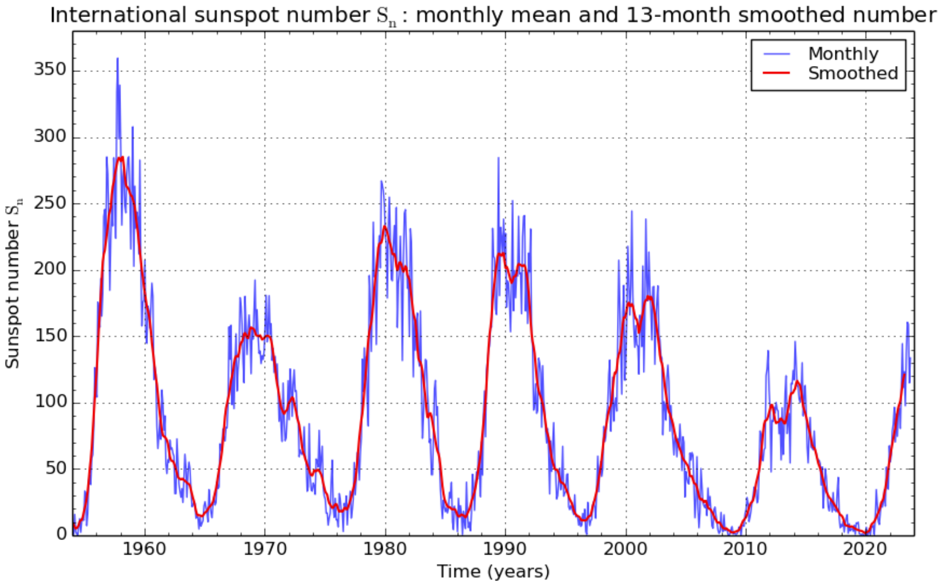
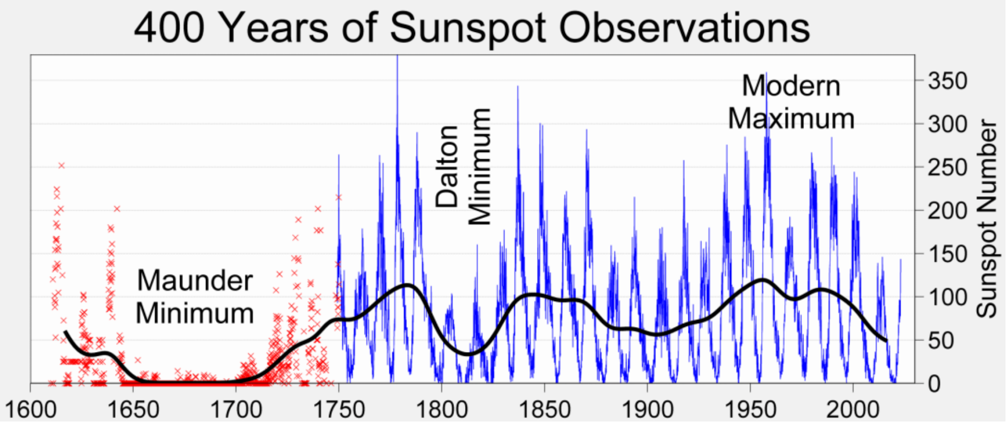


Image source: Thomas et al., (2002)

Let's refresh our memory from the previous lecture!

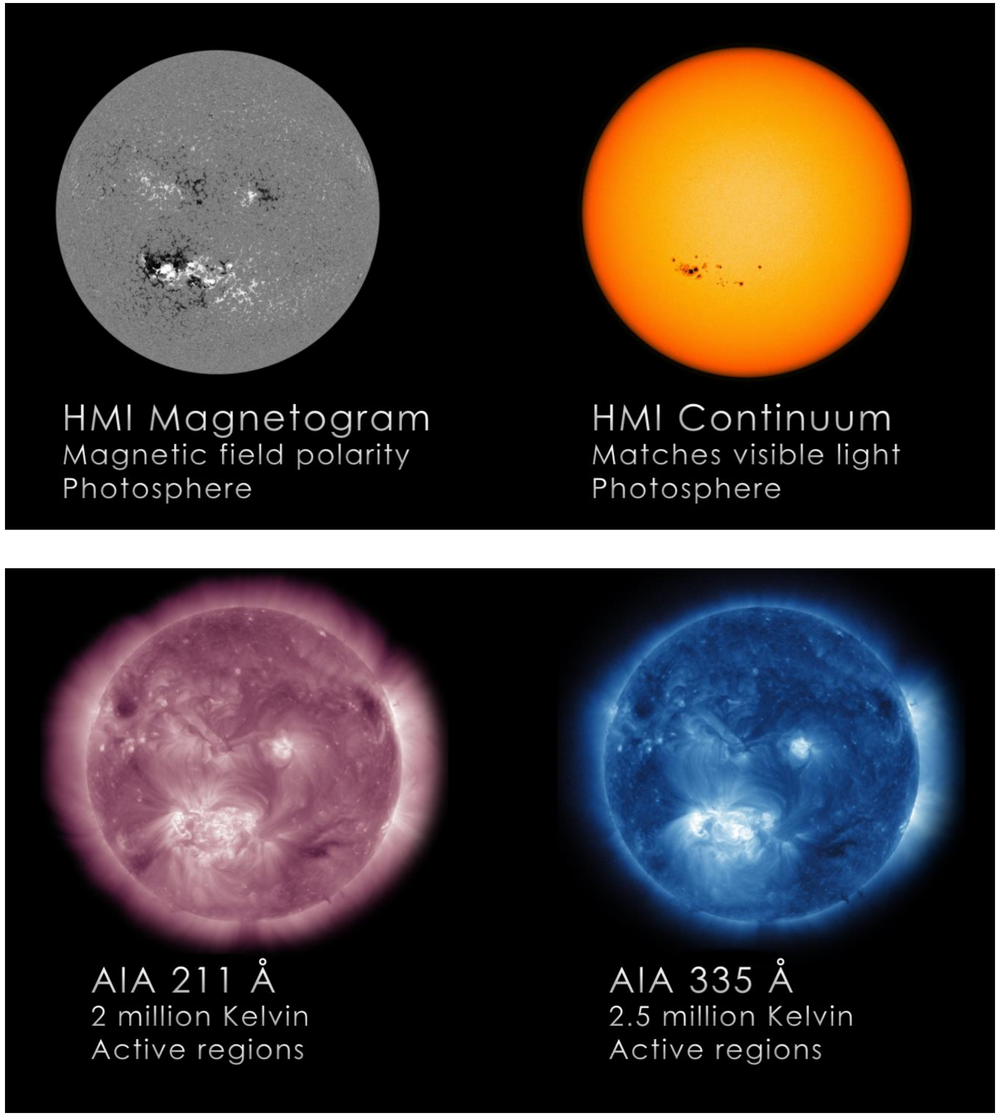


- Sunspots appear and disappear with the solar cycle!
- They are thus used as a direct proxy of the solar variability!
- They have been observed since ~1600 AC, and thus, are the oldest record of direct observations of the "inner" workings of our sun (solar dynamo)!



Created by Robert Rohde, via Wikipedia

Sunspot, Active regions, and Magnetic field loops



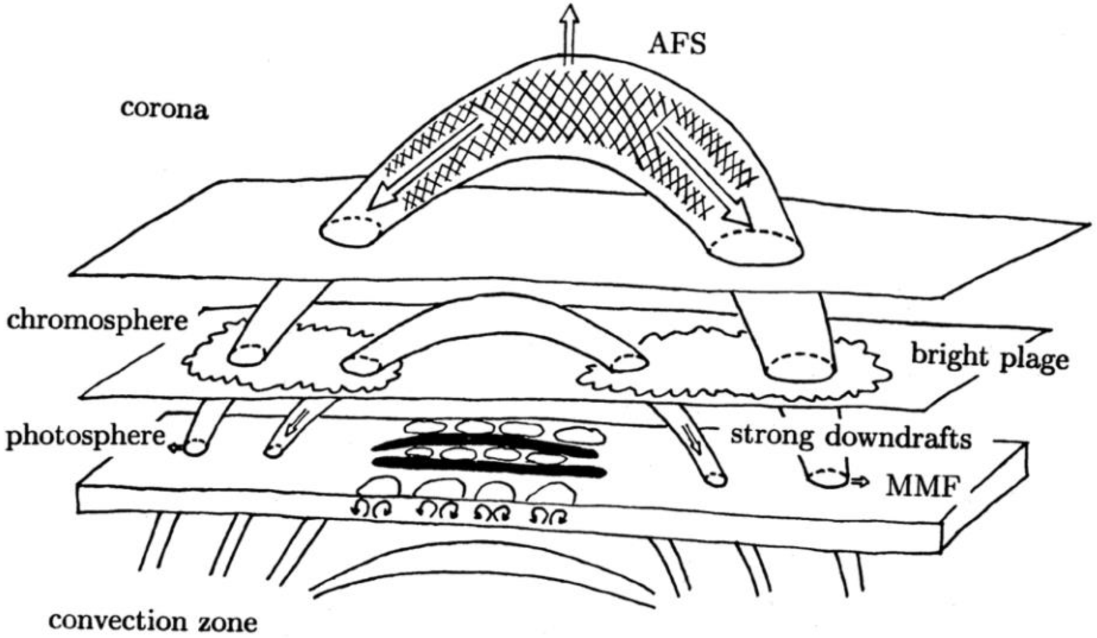
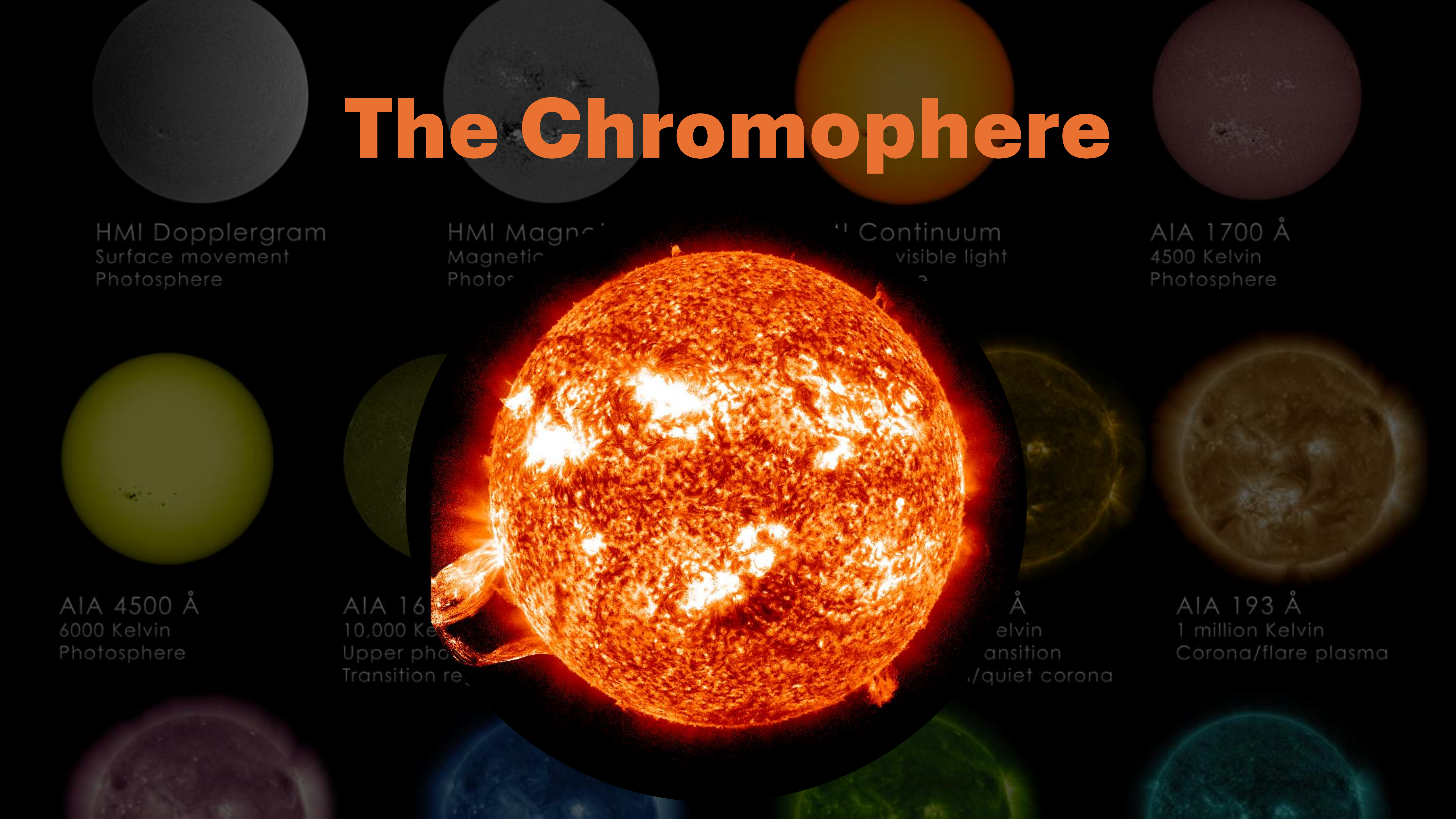


Image source: Toriumi & Wang (2019)

The Chromophere



Chromosphere

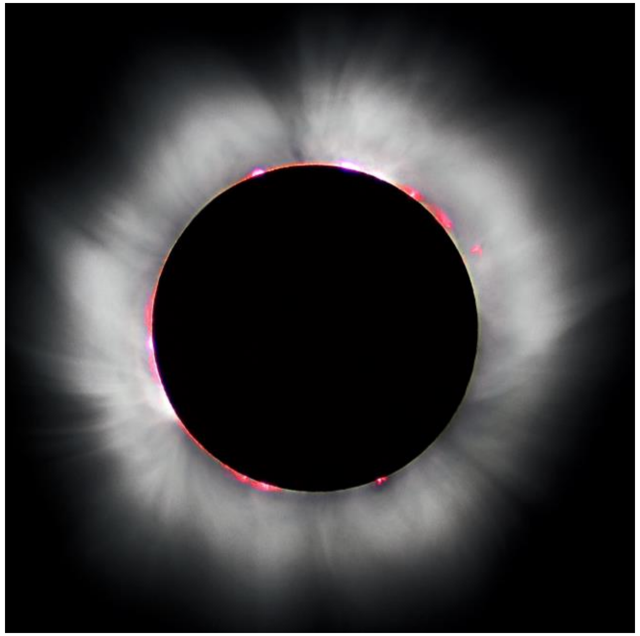
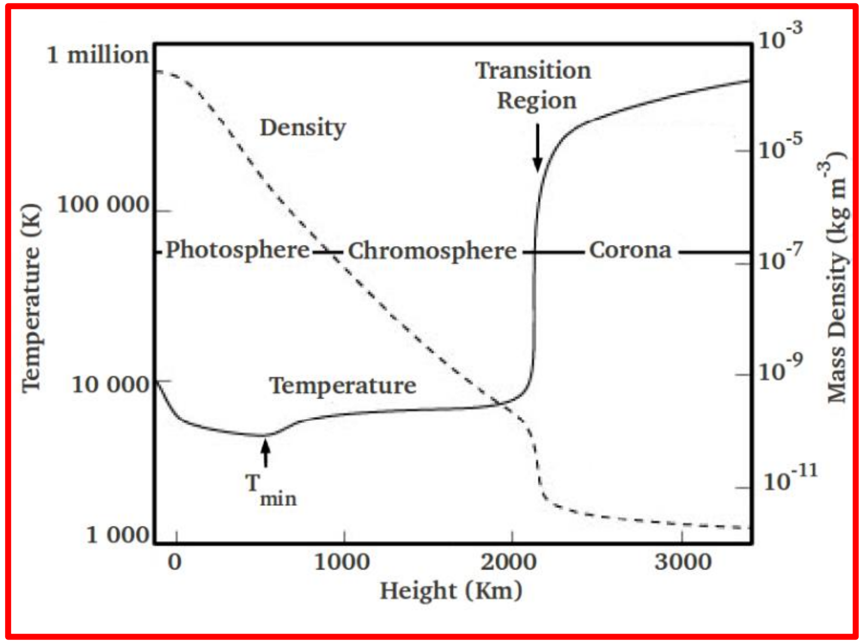
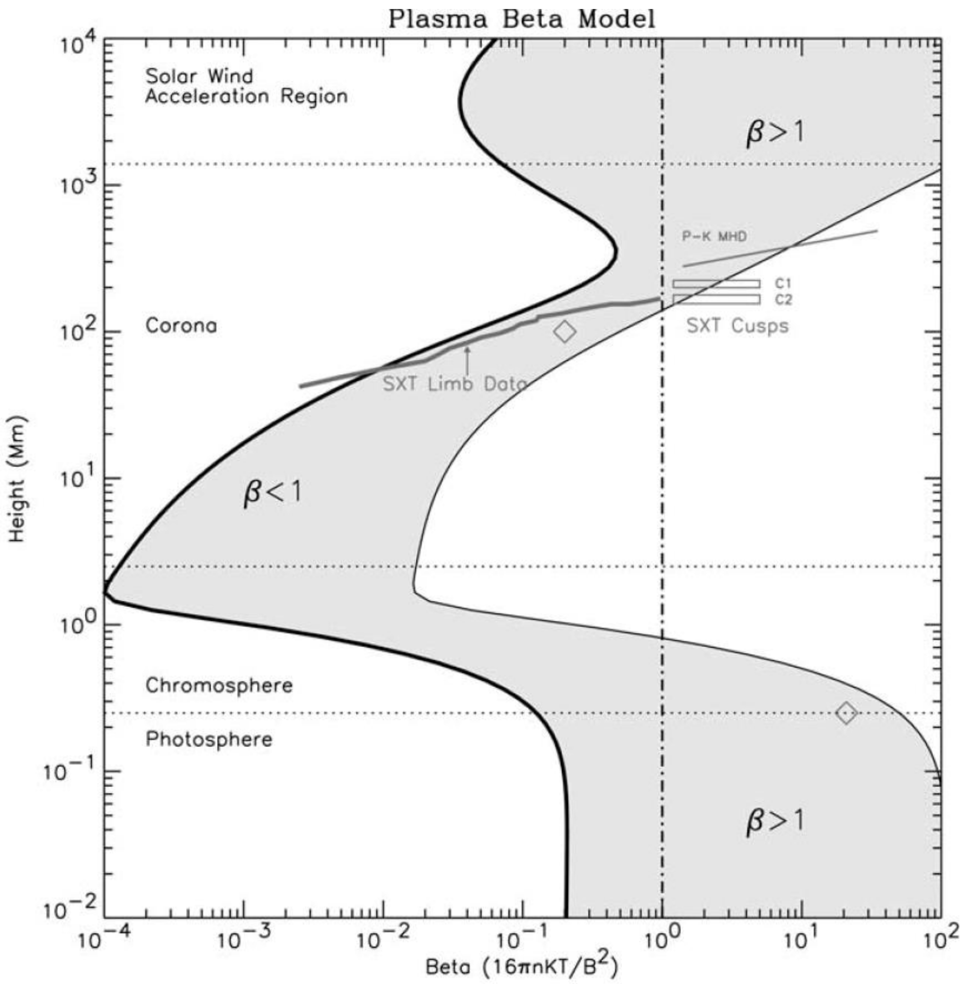


Image credit: Luc Viatour





The temperature in the chromosphere increases to a temperature plateau at around 7000 K.

The gas in the chromosphere is increasingly ionized
&
The magnetic field is a controlling power.

Chromospheric structures (1)

Network
(Active regions/ Sunspots)

Internetwork
(Fine magnetic field structures)

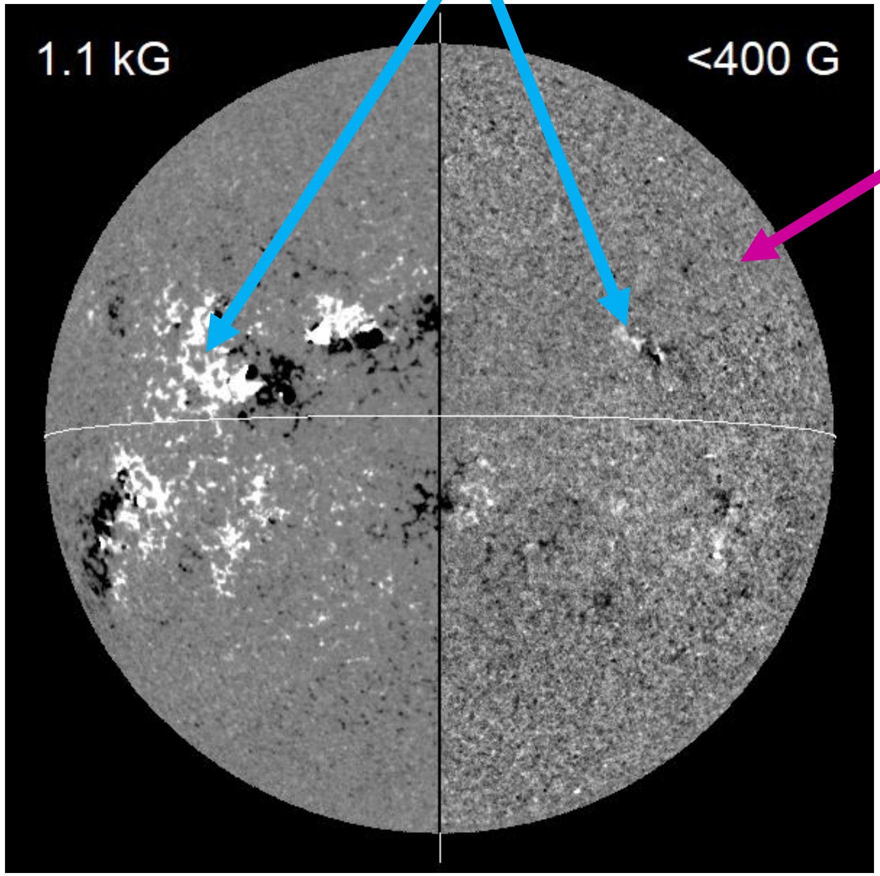


Image source: Solar Science Observatory, NAOJ

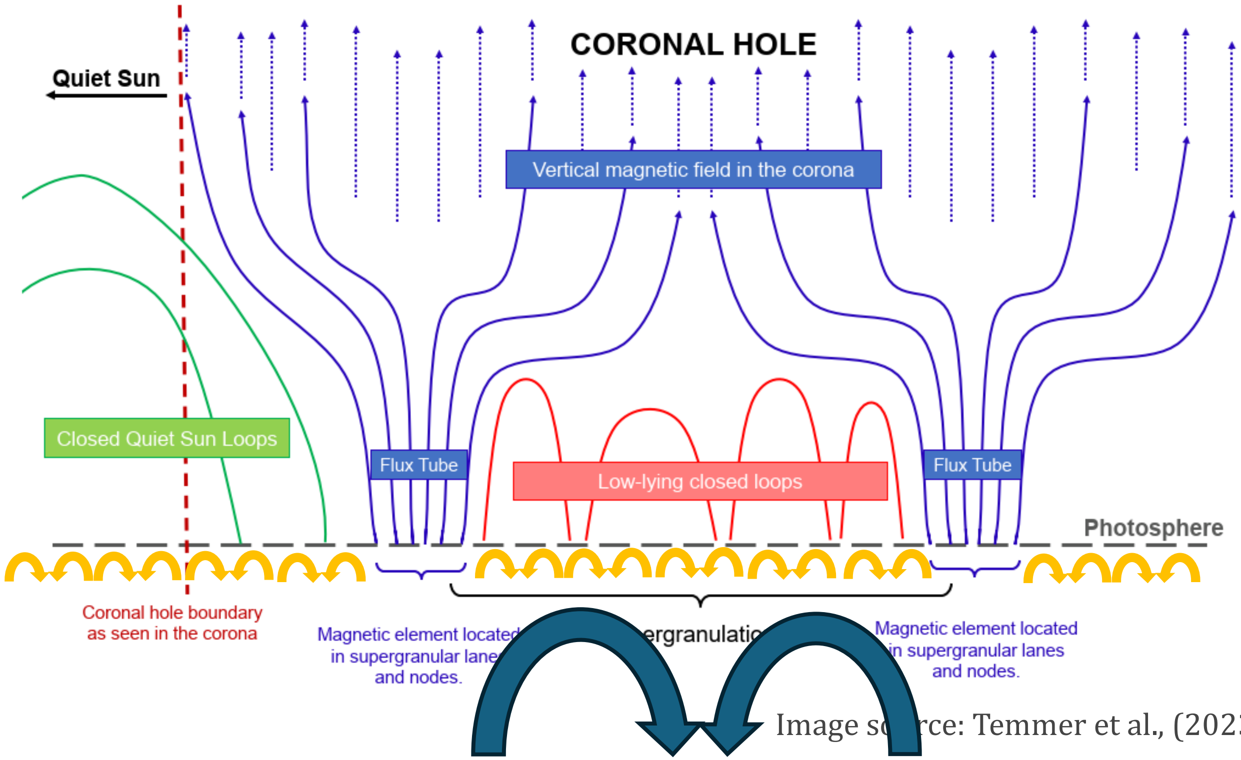
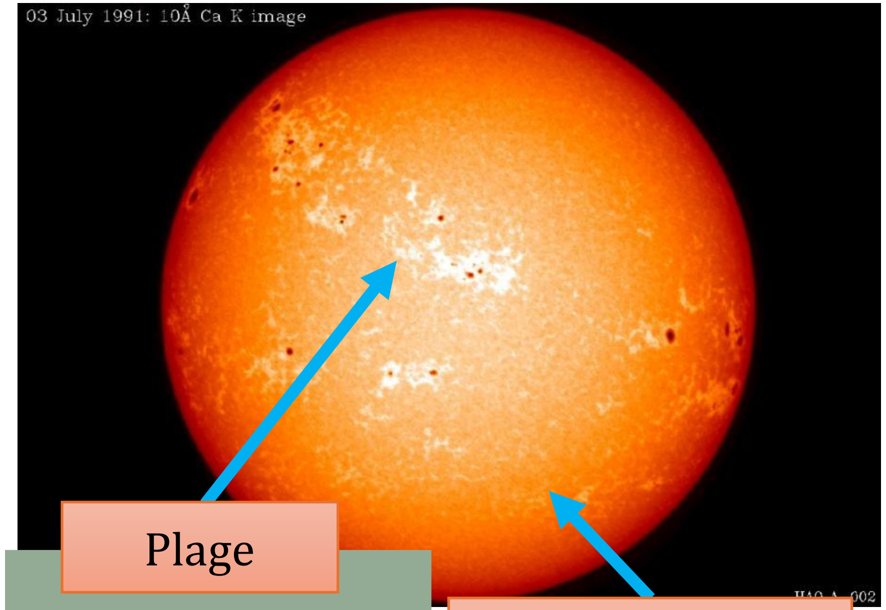
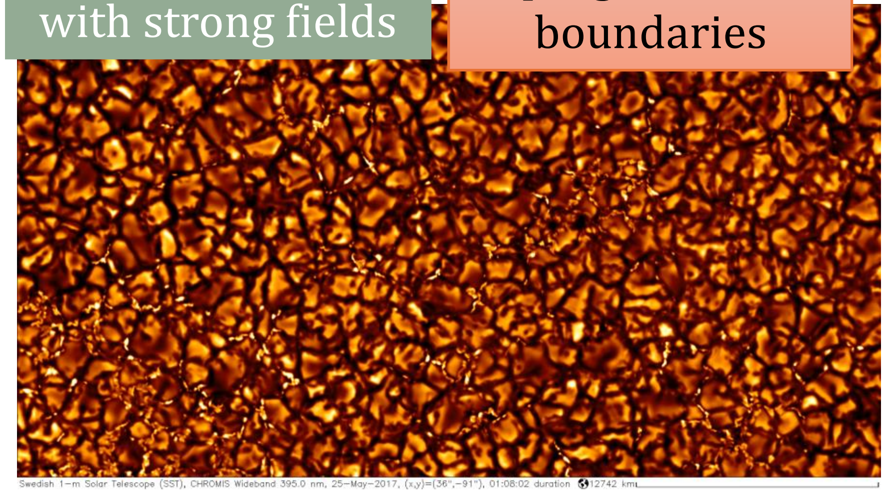


Image source: Temmer et al., (2023)

Chromospheric structures (2)





Video by Luc Rouppe and accesible via Wikimedia Commons

Spicules

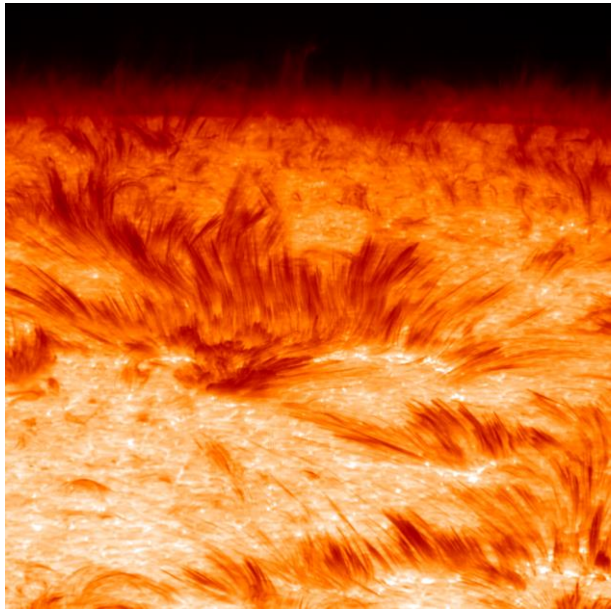


Image source: Luc Rouppe

- Highly dynamic structures present everywhere in the chromosphere, both in active and not so active regions.
- Divided in type-I and type-II

Type I

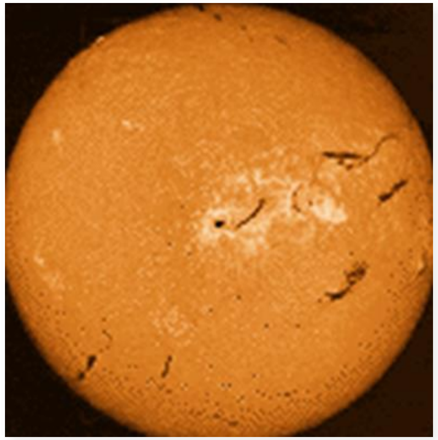
- Dynamic spicules located in active regions or in the quiet Sun near strong magnetic fields.
- 10-40km/s
- Periodic motion – lifetime: 3-5min
- "Due to the leakage of photospheric magnetoacoustic oscillations into the solar chromosphere (Bose et al., 2021)

Type II

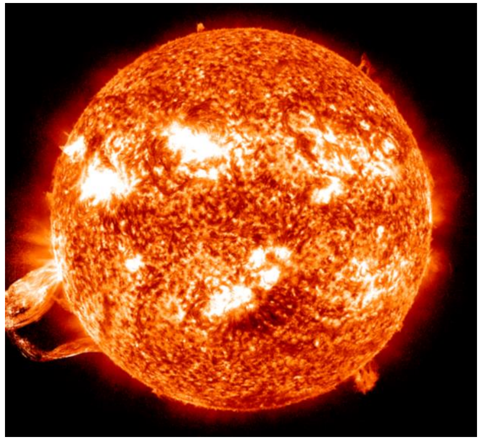
- More dynamic, involving sideways motion.
- 80–300 km/s
- Lifetime: ~1-3min

Chromospheric structures (3)

Filaments/Prominences



- In H-alpha observations they appear as dark & narrow bands.
- They are dark because they consist of cold & dense plasma.



- When observed in EUV they appear bright and can be observed at the solar limb as being suspended over the solar surface

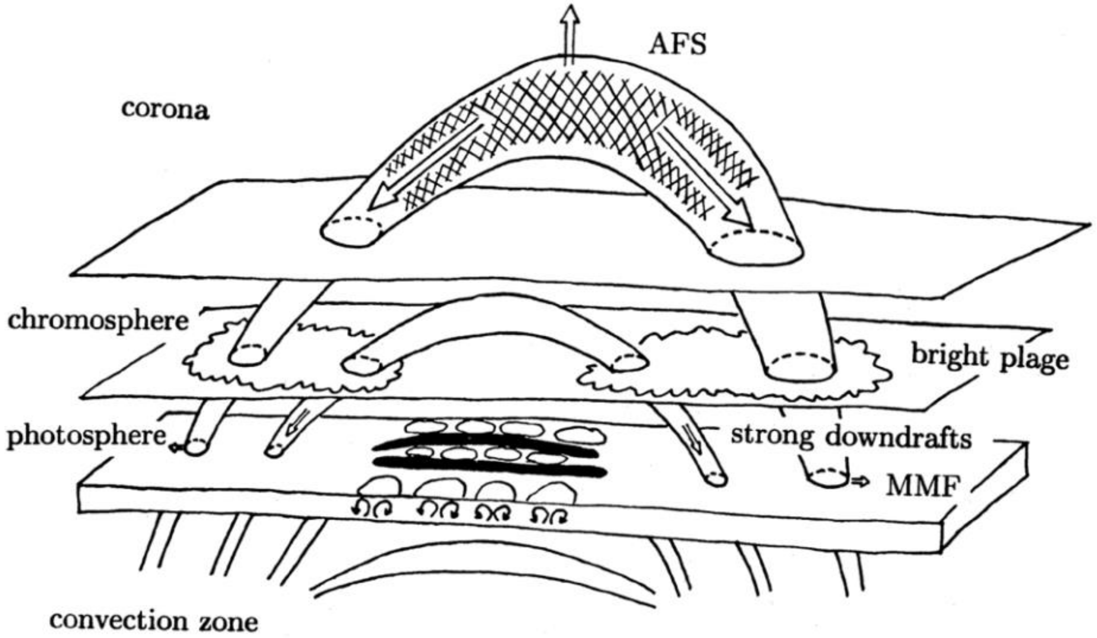


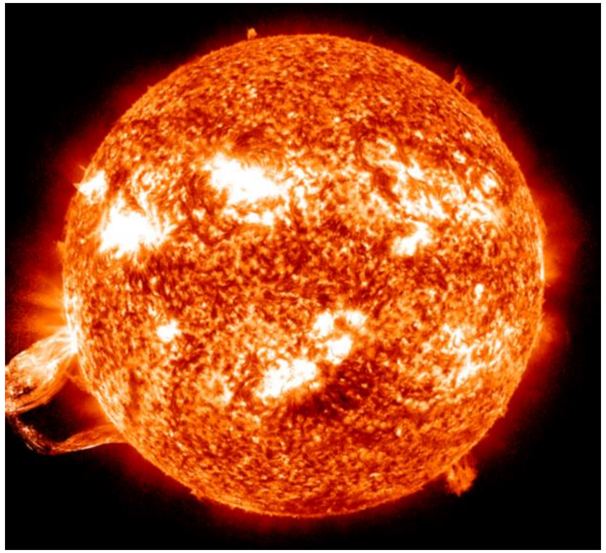
Image source: Toriumi & Wang (2019)

They can live for several months before they decay or erupt generating a solar storm.

Chromospheric structures (4)

How can they stay suspended in the chromosphere (and the low solar corona) which are less dense?

- The answer lies with their magnetic structure!
  - Lorentz Force opposing gravity.
  - Thermal shield against hot plasma that surrounds them.
- Their geometry is however still a subject of investigation.



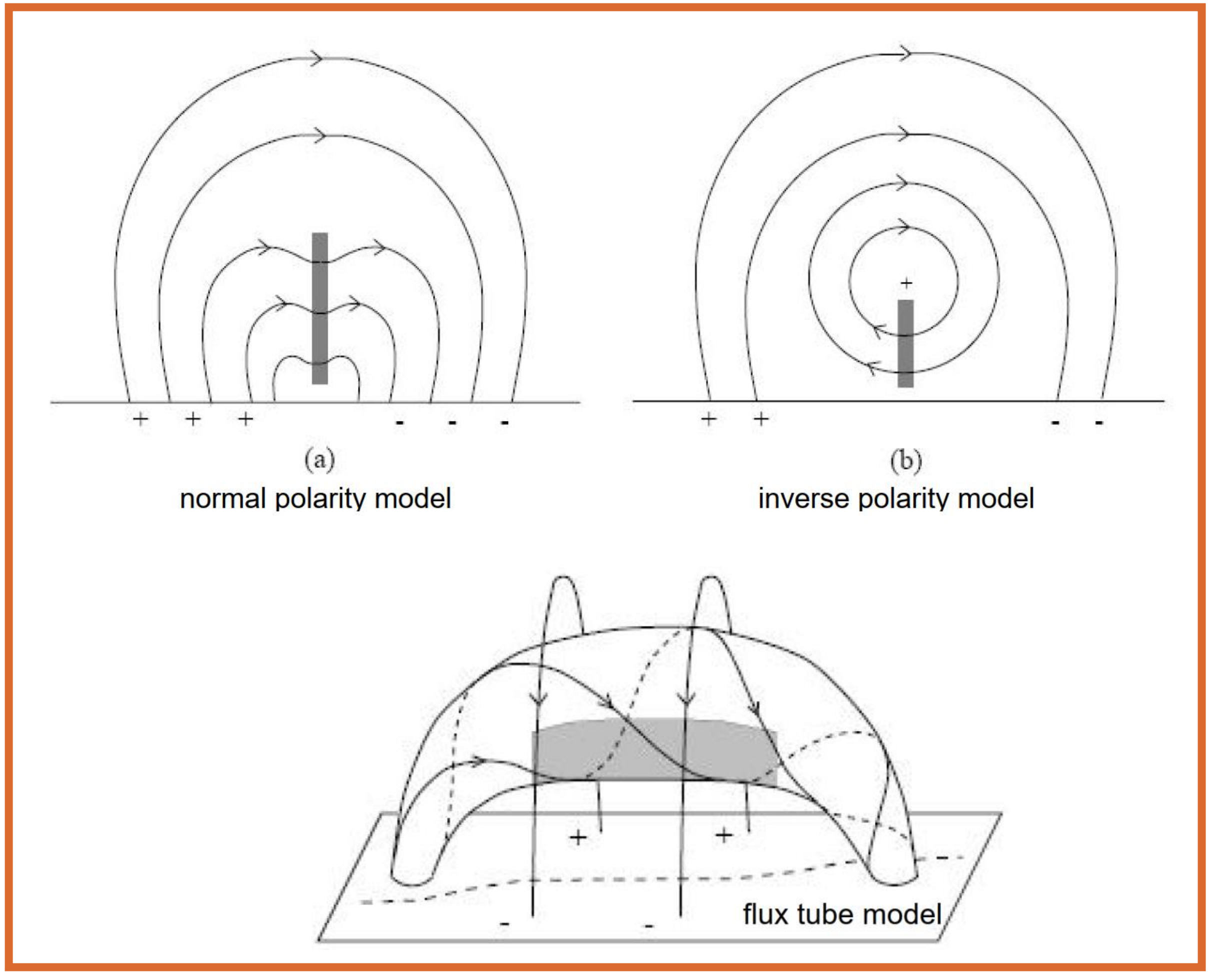


Image source: Dissertation by Clementina Sasso

Stellar Chromospheres

- Aside white dwarfs, almost all luminous stars have signatures that support the presence of a chromosphere.

- Stars with prominent and magnetically active chromospheres:
  - Stars in the lower main sequence
  - Brown dwarfs of F and later spectral types
  - Giant stars
  - Subgiant stars

- Stars without or with lost chromospheres:
  - Earlier-type, hotter stars (they have lost their convective envelope)

- Having a magnetised chromosphere does not mean it is similar to the solar chromosphere.

We observe them in emission lines of HI, HeI, MgII, and CaII and at Ultraviolet (UV), Infrared (IR), and radio wavelengths.

There is evidence of a correlations between chromospheric and higher-temperature emission features with the rotation period and age of the star.
→ As the star ages its magnetic field strength decreases an this affects emissions and rotation.

The Transition Region

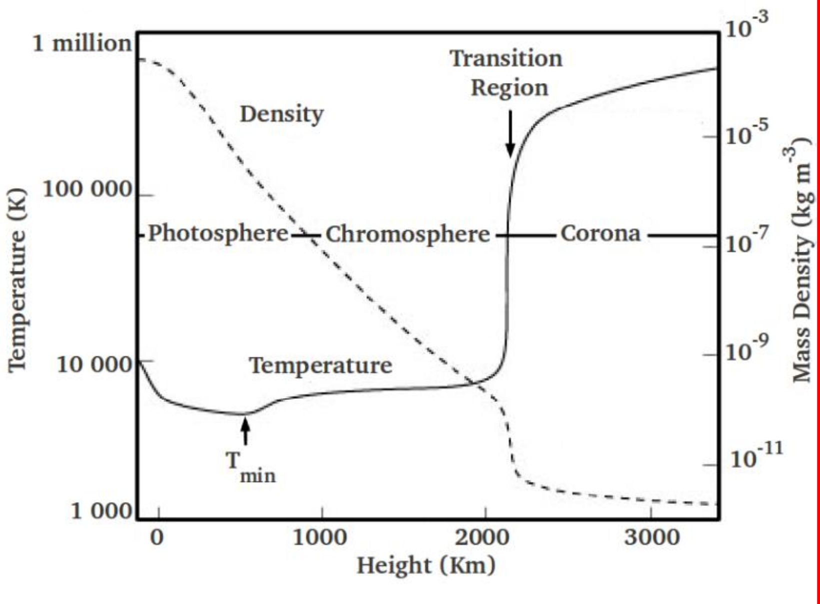
Transition region: From "cold" to Ultra-hot atmosphere

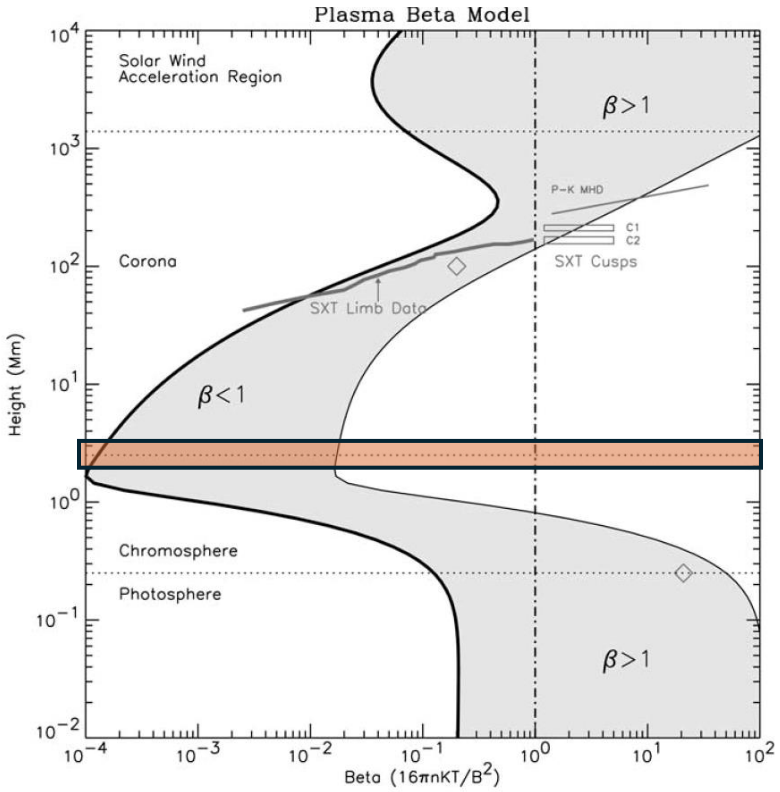
It is a narrow region between the chromosphere and the corona, where the:

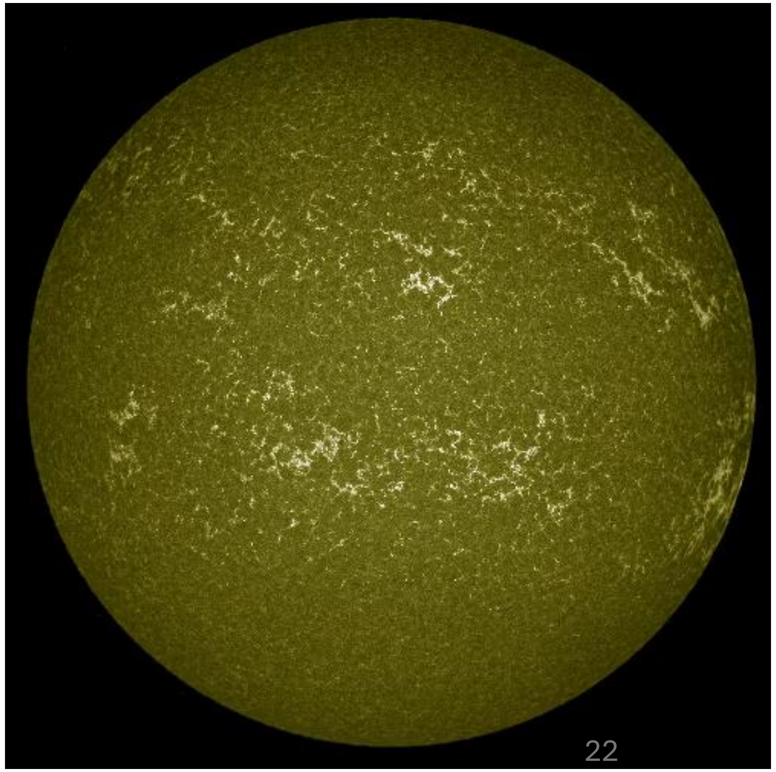
1. temperature suddenly increases dramatically.
2. density suddenly drops abruptly
3. The plasma β starts increasing

- Optically thin (radiative transfer is reduced compared to the photosphere and the chromosphere).
- Its height is not fixed but depends on the local conditions (what lies below: ARs, supergranular cells etc.)

The blinking TR
The brightness in the TR is highly variable with time.







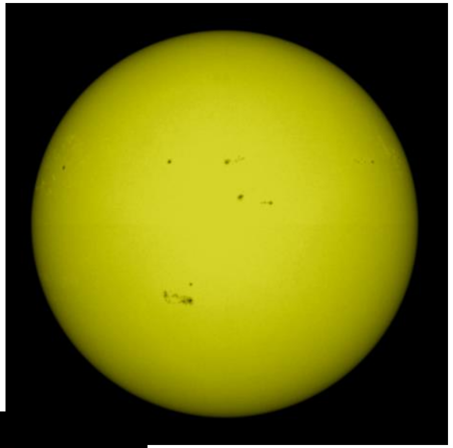
The Solar corona

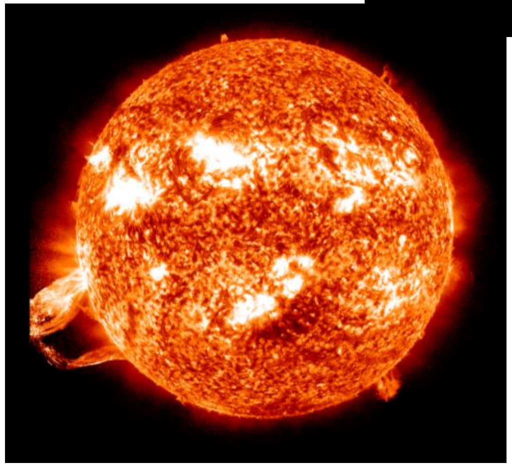
The “Why did it get so hot up here?” Corona

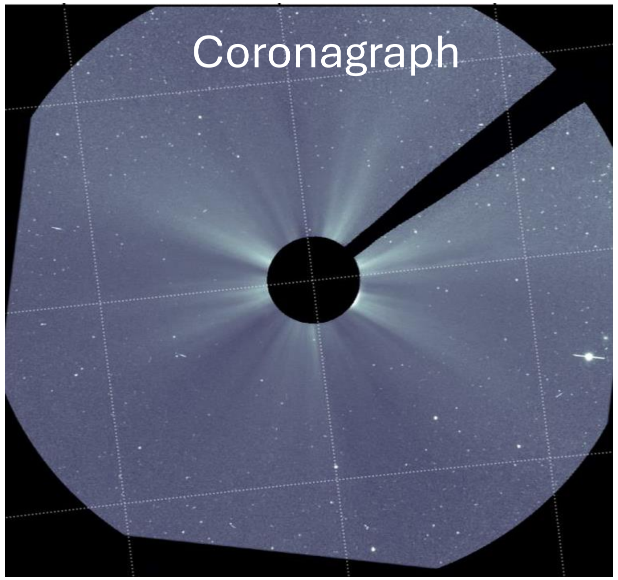
If the Corona is so hot, why is it invisible?

- Very hot gas – 1-3 million Kelvin
- Low density

→ Dim

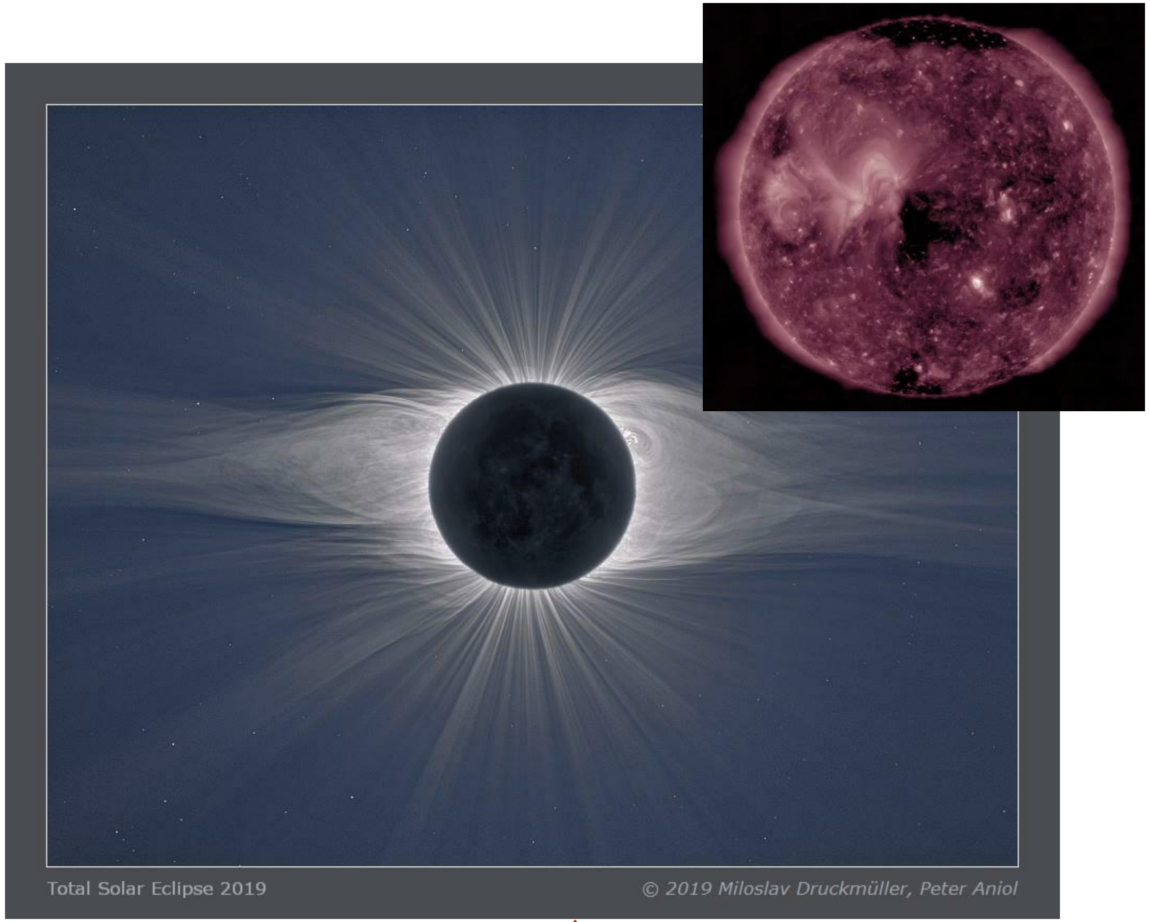




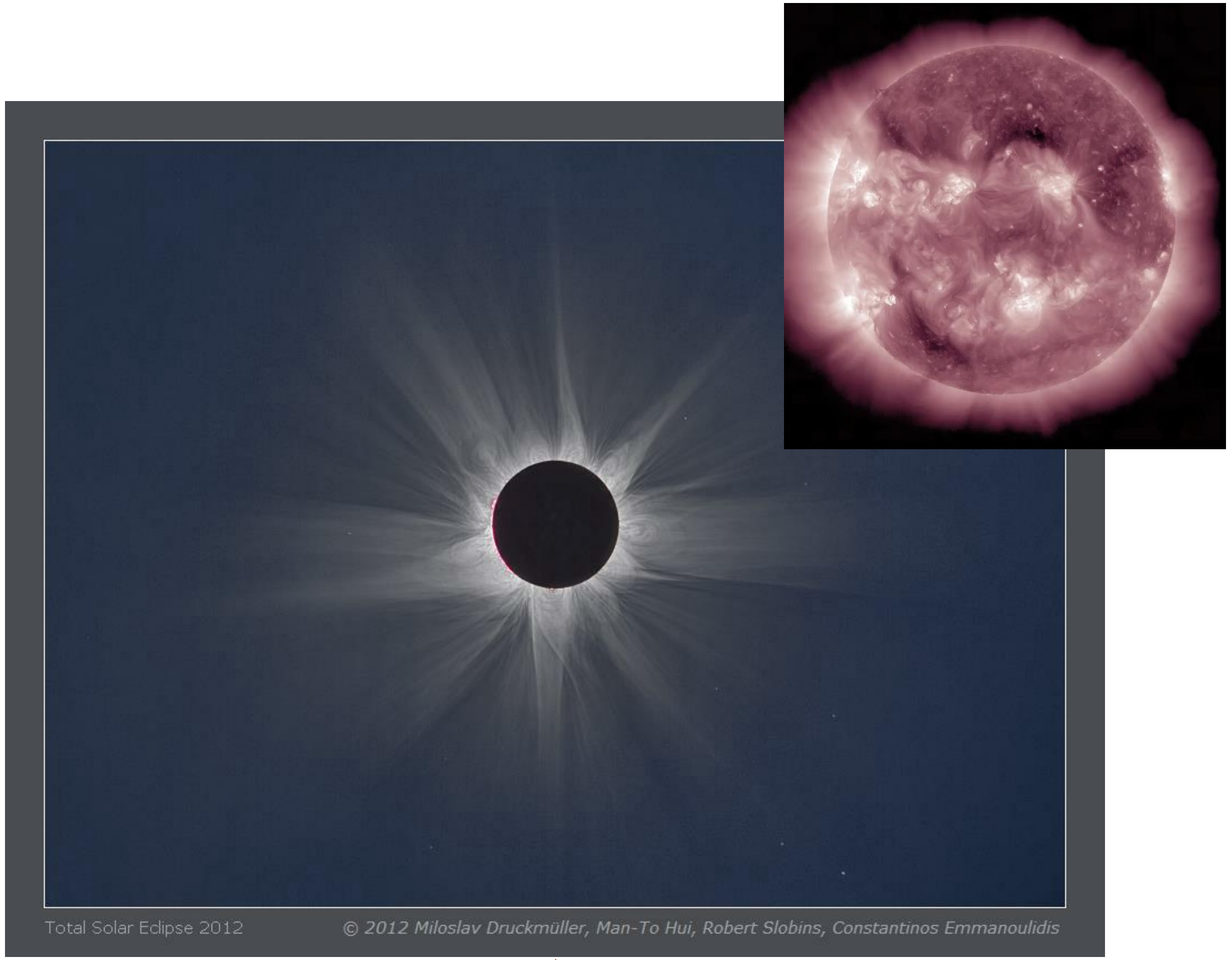


- Highly conductive, magnetically-dominated plasma
- Solar magnetic field stretches outward in the corona, forming both low lying closed, loop-like structures, and high lying loop structures.

The corona at different solar activity levels



During Solar Minimum



During Solar Maximum

Coronal Holes: a key structure in the corona

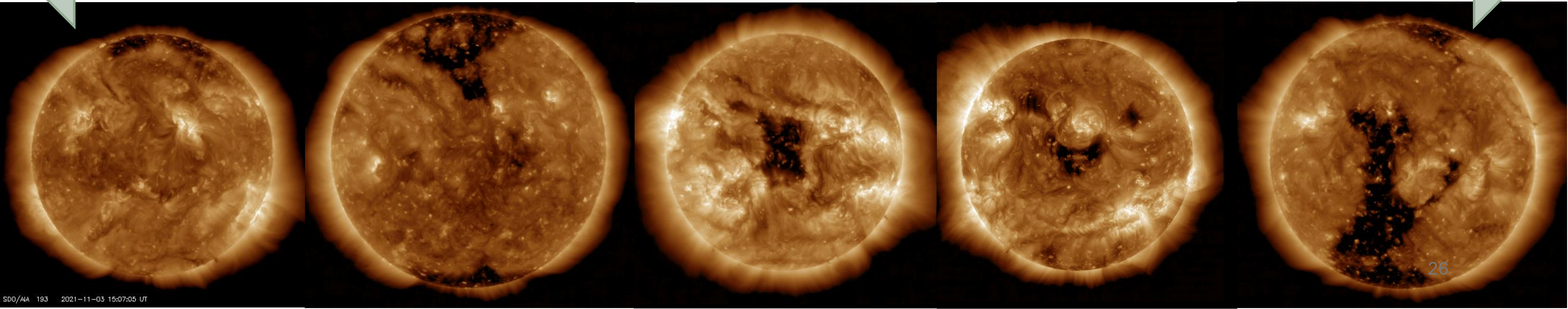
Image from Mitchell, Oregon (sharpened)

Image source: Mikic et al. 2018

- Dark patches on the solar surface.
- Low density regions above the solar limb.
- Open-field footpoints of time steady solar wind flows.
- Their location and size varies with the solar cycle.

BUT not all areas of open-field footpoints will match the two areas mentioned above.

Solar Minimum — Solar Maximum — Solar Minimum



The global magnetic field in the solar corona

Assumption 1: In most areas in the solar corona (and especially in strongly magnetised active regions) the plasma β is really small.

$$\beta = \frac{Gass\ Pressure\ (P)}{Magnetic\ Pressure\ (\frac{B^2}{2\mu_0})} \ll 1$$

Magnetic Pressure dominates

Assumption 2: The solar corona is quasi static. This means that it evolves very slowly in time.

In quasi-static equilibrium of low-β plasma the magnetic pressure dominates over plasma pressure and non-magnetic forces, i.e. gravity and kinematic plasma flow pressure.

Momentum Equation from ideal MHD theory

$$\rho\left(\frac{\partial \vec{v}}{\partial t} + (\vec{v}\,\vec{\nabla})\vec{v}\right) + \vec{\nabla}P - \frac{1}{c}(\vec{J}\times\vec{B}) + \rho\vec{g} = 0 \qquad \Rightarrow \vec{J}\times\vec{B} = 0$$

The corona is free of Lorenz forces

The global magnetic field in the solar corona

Ampere's law

$$\vec{J} \times \vec{B} = 0$$

$$\vec{J} = \vec{\nabla} \times \vec{B}$$

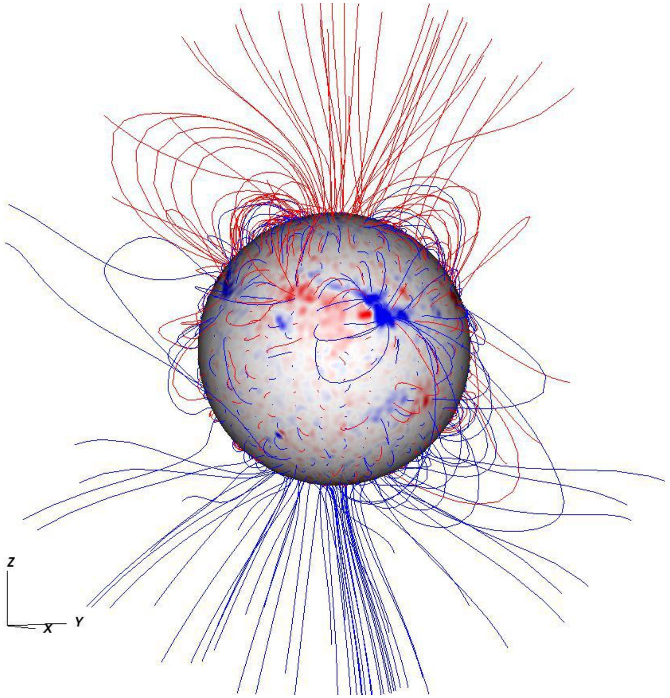
$$\left(\vec{\nabla} \times \vec{B}\right) \times \vec{B} = 0$$

$$\vec{\nabla} \times \vec{B} = 0$$

Potential (current free) Field approximation (PFSS)

$$\vec{B} \parallel \vec{\nabla} \times \vec{B}$$

Force-Free (FF) Field approximation



Example of a PFSS reconstruction of the solar corona using EUHFORIA – WSA (credit: Eleanna Asvestari).

PFSS

- Provides a coarse view of the coronal magnetic field structure.
- It cannot be used though for modelling the magnetic field at active regions where the field is strongly non-potential.
- Computationally cheap.
- Only magnetic field topology – No plasma

NLFF

- Good approximation for reconstructing the coronal field of active regions with significant free magnetic energy.
- Only magnetic field topology – No plasma

The most advanced coronal model

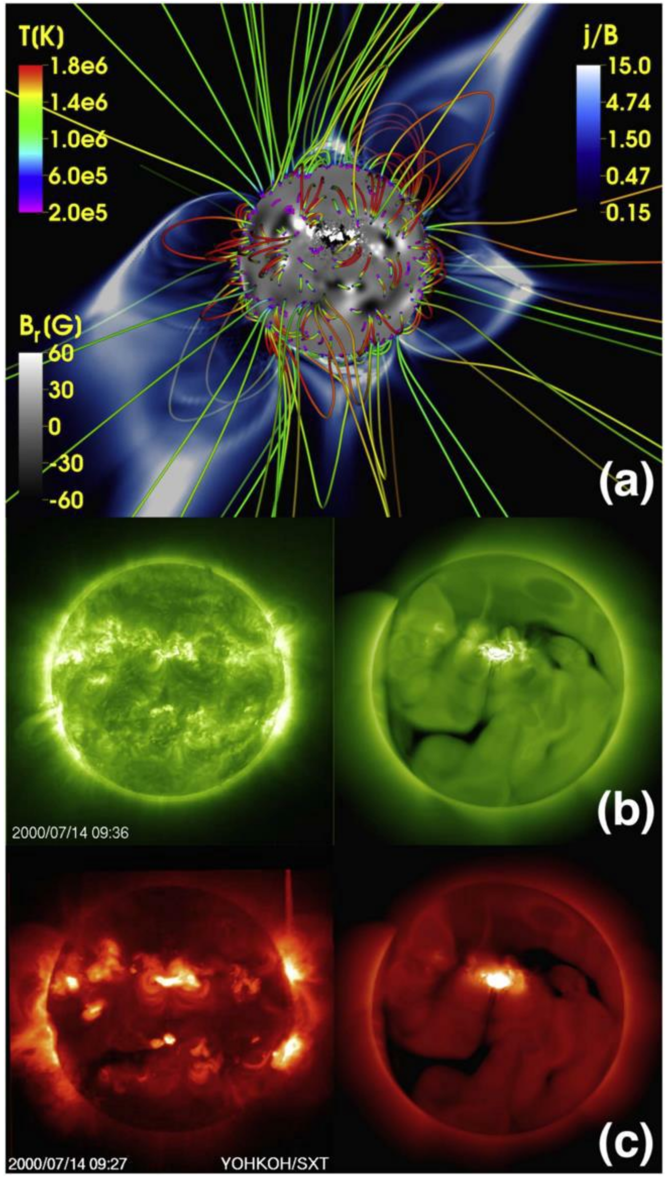
Thermodynamic Resistive MHD model

It is good in:

1. Modelling the location and evolution of Coronal Holes
2. Reproduction of streamer structure
3. Modelling the location of the Heliospheric Current Sheet

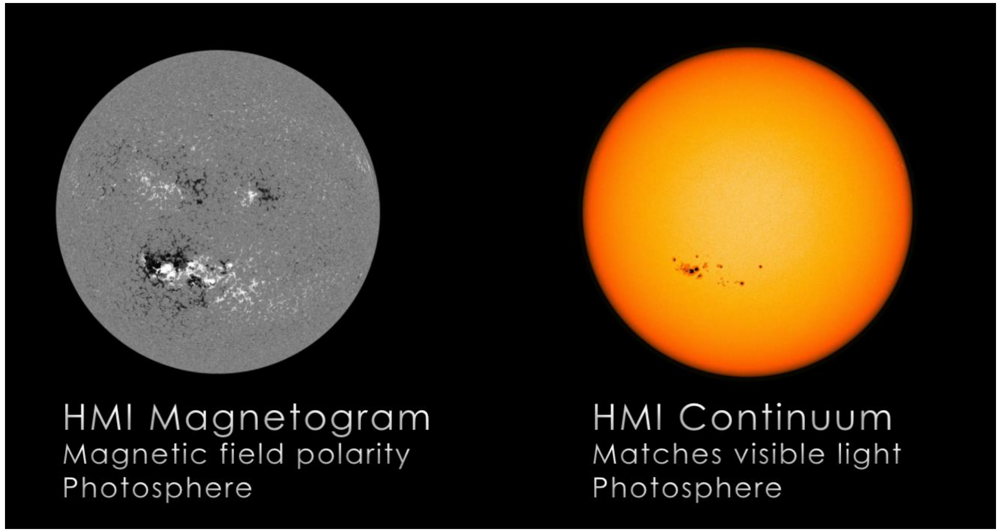
Plus:

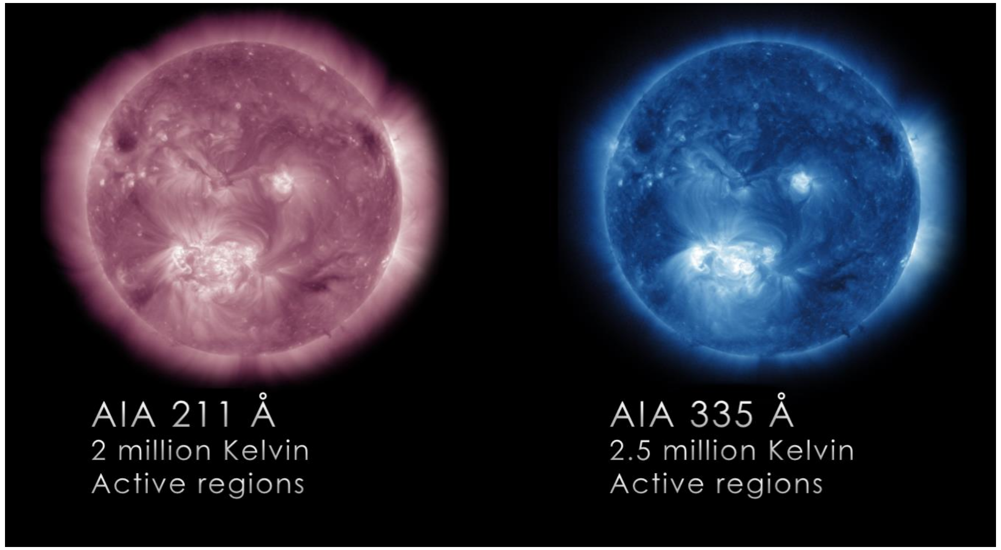
1. Radiative losses
2. Anisotropic thermal conduction
3. EUV and X-ray emission can be modelled



Images taken from Török et al., 2018 ApJ

Active regions & Classifications





Mount Wilson Magnetic Classifications	
α	Denotes a unipolar sunspot group.
β	A sunspot group having both positive and negative magnetic polarities, with a simple and distinct division between the polarities.
βγ	A sunspot group that is bipolar but in which no continuous line can be drawn separating spots of opposite polarities.
δ	A complex magnetic configuration of a solar sunspot group consisting of opposite polarity umbrae within the same penumbra.
γ	A complex active region in which the positive and negative polarities are so irregularly distributed as to prevent classification as a bipolar group.

Active Region Classifications

- Mount Wilson (Hale) classification - Sketches

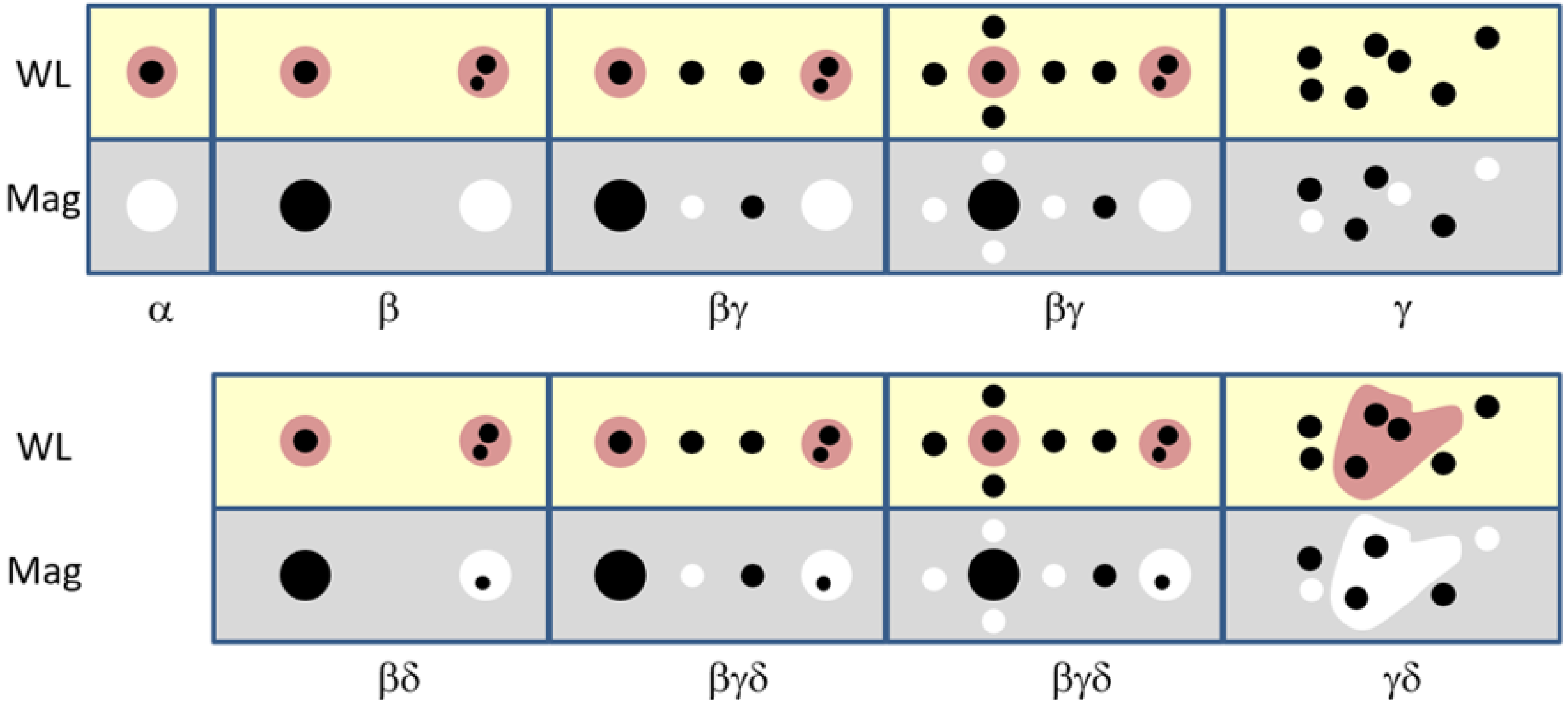


Image source: https://www.stce.be/educational/classification

After todays lecture you should be able to…

… describe the structure of the low atmosphere of the Sun.

→ …list the properties of the photosphere, explain its importance for the coronal and interplanetary magnetic field, and describe the structures observed there.

→ …list the properties of the chromosphere and describe the structures observed there.

→ …explain what we know about the chromosphere of other stars.

→ …list the properties of the transition region and the solar corona and describe the magnetic structures that exist there.

→ Derive the simplest approximation of the coronal magnetic field.

References

For reading:

- Space Physics an Introduction, Russell C.T., Luhmann J.G., Strangeway R.J.
  Chapter 4: Sections 4.1-4.5
- An Introduction to Stellar Magnetic Activity, Basri G.,
  Chapters 2 - 4 (4.1 -4.2)

Image sources:

- Solar Dynamic Observatory
- NASA
- Dissertation by Clementina Sasso
- Chatzistergos et al., 2023 https://doi.org/10.1016/j.jastp.2023.106150
- Gary, G.A., 2001 https://doi.org/10.1023/A:1012722021820
- Mikić, Z. et al., 2018 https://doi.org/10.1038/s41550-018-0562-5
- Temmer et al., 2023 https://doi.org/10.1016/j.asr.2023.07.003
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- Toriumi & Wang, 2019 https://doi.org/10.1007/s41116-019-0019-7
- Török et al., 2018 https://doi.org/10.3847/1538-4357/aab36d

Disclaimer: Some material is borrowed from material I developed for the ”Space Applications of Plasma Physics” and a guest lecture’s slides for the ”Advanced Plasma Physics”