

# Introduction to the Solar Interior and Atmosphere

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NASA/MSFC

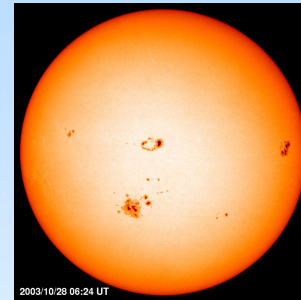


# The Solar Interior

# Solar Interior and Atmosphere(s)

The Outer layers (Atmospheres) of the Sun:

- Photosphere



- Chromosphere



- Corona



Never look at the Sun Directly  
with your unprotected eyes!!

# Formation of the Sun

Initially, have a blob of gas...

...and gravity:

$$F = \frac{GMm}{r^2}$$

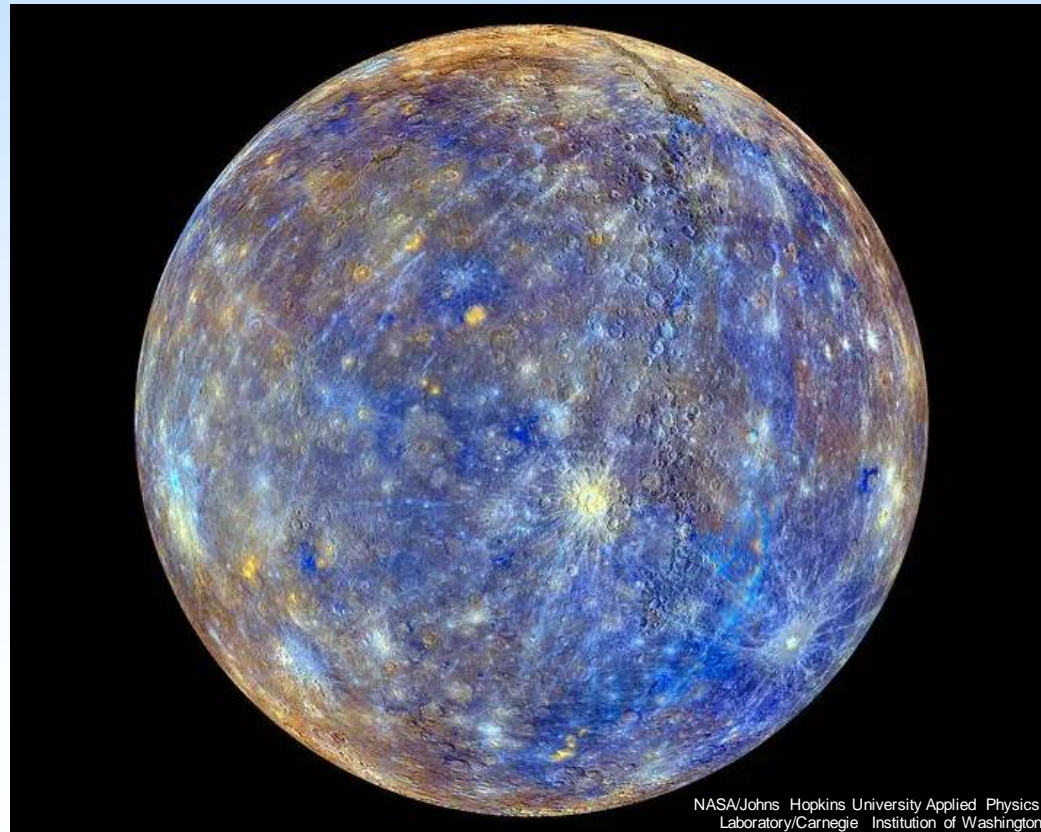
$$\mathbf{F} = \frac{GMm}{r^2} \hat{\mathbf{r}}$$



(<https://photojournal.jpl.nasa.gov/target/Other?subselect=Spacecraft%3AGalileo+Orbiter%3A>)

Length ~ 20 km  
(Gaspra, from Galileo.)

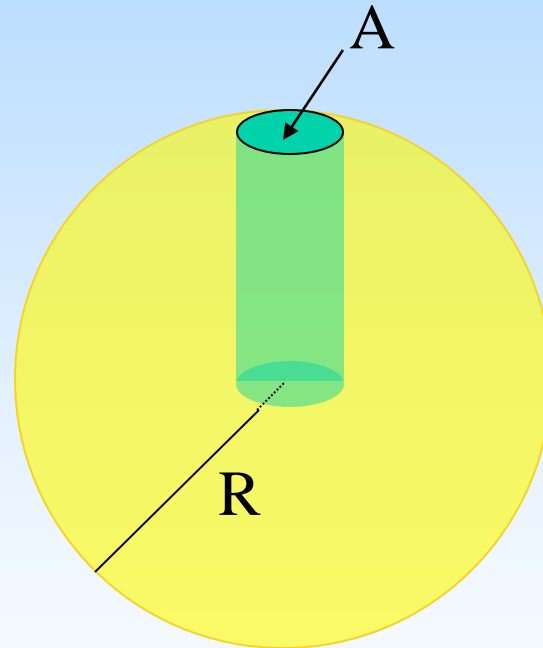
Diameter ~5000 km  
(Mercury, from  
Messenger)



NASA/Johns Hopkins University Applied Physics  
Laboratory/Carnegie Institution of Washington

# Interior Temperature Structure

# Sun's Central Core Temperature (Estimate)



# Sun's Central Core Temperature (Estimate)

- $m = \rho AR$
- $F = G(m/2)M/R^2$
- $p = F/A = G\rho M/2R$
- $p/\rho = GM/2R$
  
- $pV = NkT$
- $p/\rho = kT/m_H$
  
- $GM/2R = kT/m_H$
- $T = Gm_H M/(2kR)$

$m, A, \rho$  = column mass, area, ave density

$R, M$  = solar radius, mass

$F$  = column force

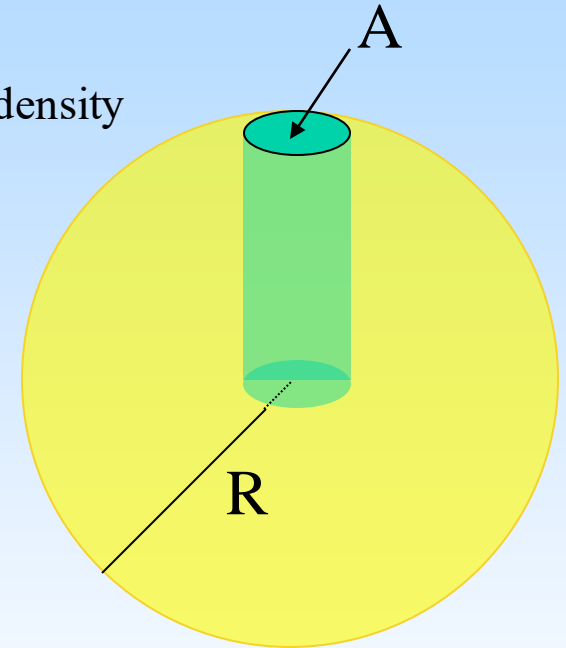
$G$  = gravitational constant

$P, T$  = solar center pressure,  
temperature

$N$  = number of column particles

$k$  = Boltzmann's constant

$m_H$  = hydrogen mass



- $T = 1 \cdot 10^7 \text{ K}$

Might this *gravitational contraction* mechanism power the Sun (stars)??

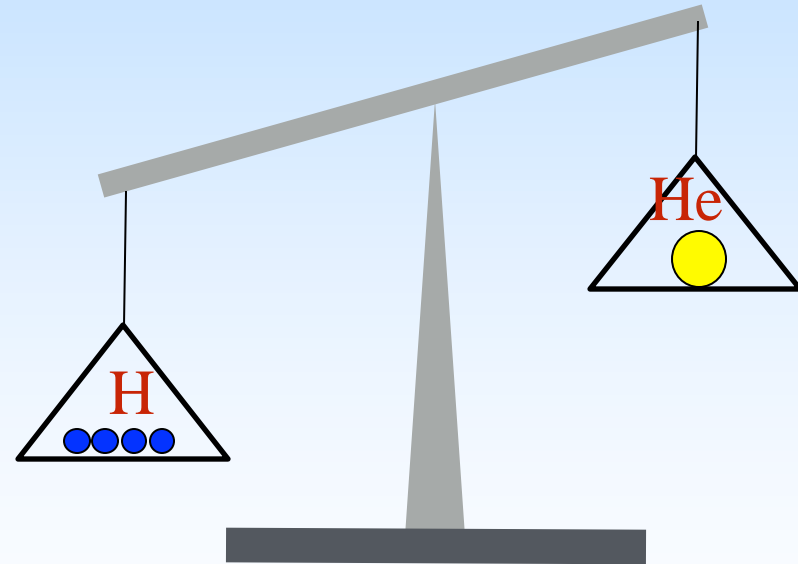
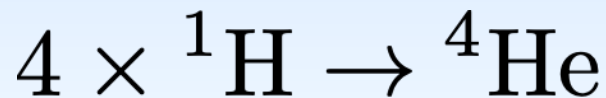
=> Solar lifetime of  $\sim 3 \times 10^7$  years

**Problem!!**

Need at least  $3 \times 10^8$  years  
(mid-1800s)

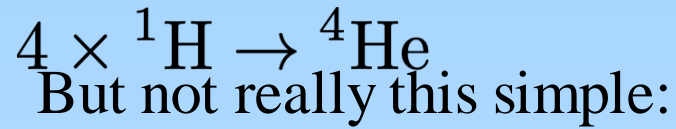
So this is *not* the main story for core and interior conditions

- Core conditions (temperature, density,...) sufficient to generate *fusion*.
- Processes are complicated, but one of the consequences is:



Mass “mismatch” of 0.0285 amu  $\sim 5 \times 10^{-26}$  g...

...which appears as *energy* via  $E=mc^2$ .



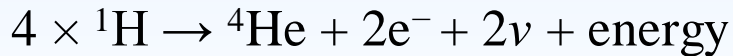
A realistic case is the “p-p cycle”:

- ${}^1\text{H} + {}^1\text{H} \rightarrow {}^2\text{D} + e^+ + \nu + \text{energy}$
- ${}^2\text{D} + {}^1\text{H} \rightarrow {}^3\text{He} + \text{energy}$  (in the form of  $\gamma$  radiation)

and after this process occurs twice:

- ${}^3\text{He} + {}^3\text{He} \rightarrow {}^4\text{He} + {}^1\text{H} + {}^1\text{H} + \text{energy}$

So the net result is:



where the released energy is 26.73 MeV (in photons, and in the neutrinos).

$4 \times {}^1\text{H} \rightarrow {}^4\text{He}$   
But not really this simple:

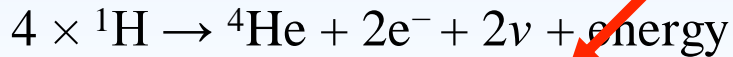
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- ${}^3\text{He} + {}^3\text{He} \rightarrow {}^4\text{He} + {}^1\text{H} + {}^1\text{H} + \text{energy}$

So the net result is:



Neutrinos

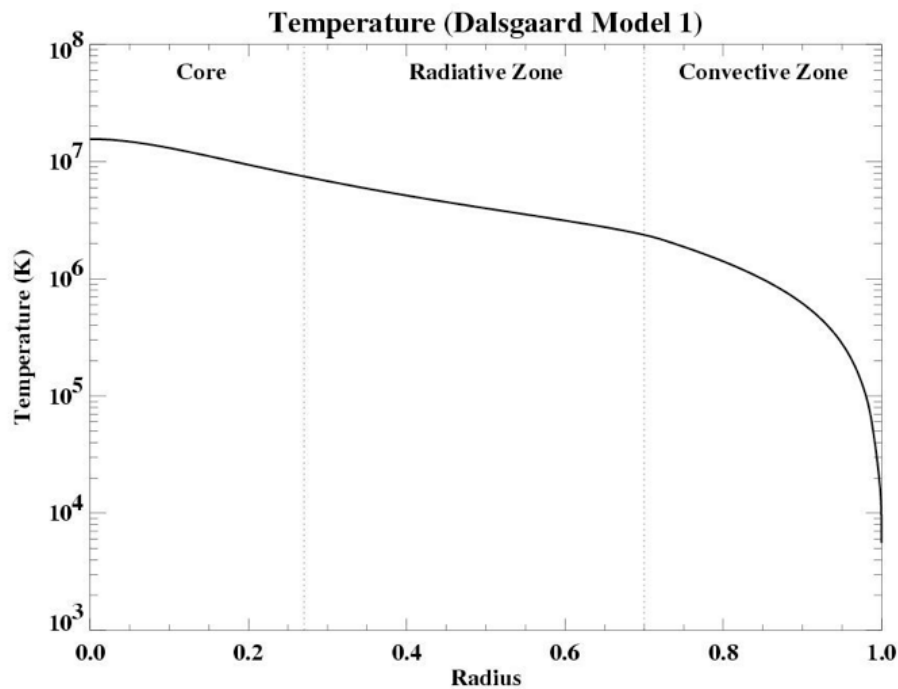


where the released energy is 26.73 MeV (in photons, and in the neutrinos).

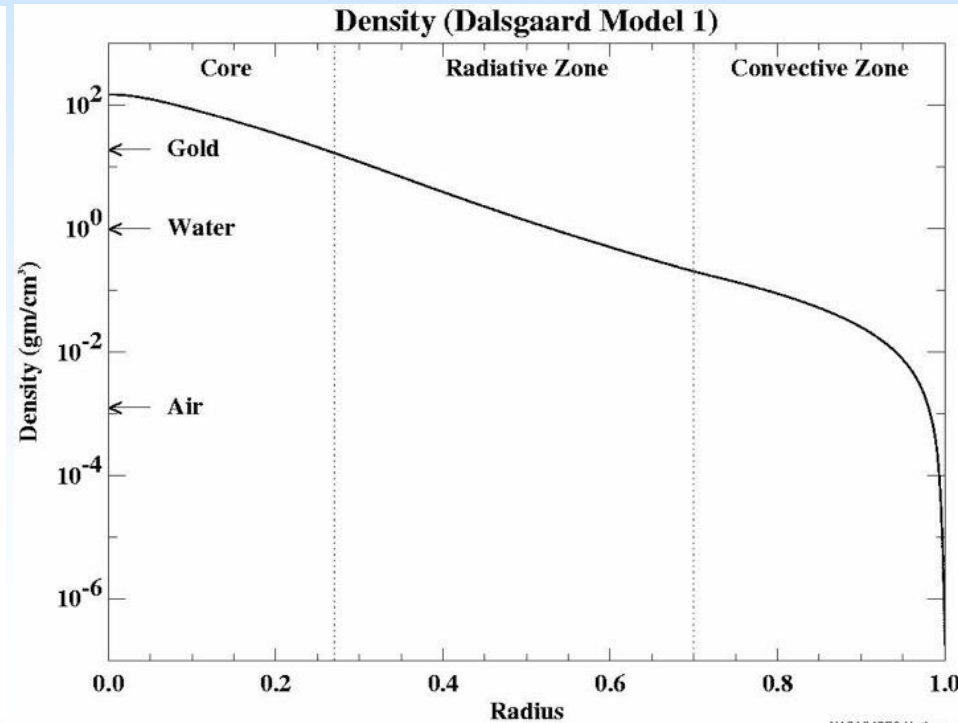
Get the full structure by solving equations for:

- Mass conservation
- Hydrostatic equilibrium
- Energy transport via radiation
- Energy production

These are not trivial(!), but get solutions....



NASA/MSFC Hathaway



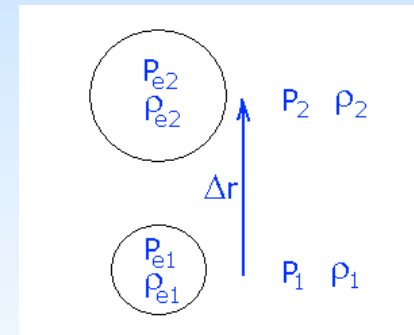
NASA/MSFC Hathaway

Considering with various physical inputs (e.g., under what conditions particles will be ionized, radiation's interaction with those particles, etc.), come out with three basic interior zones:

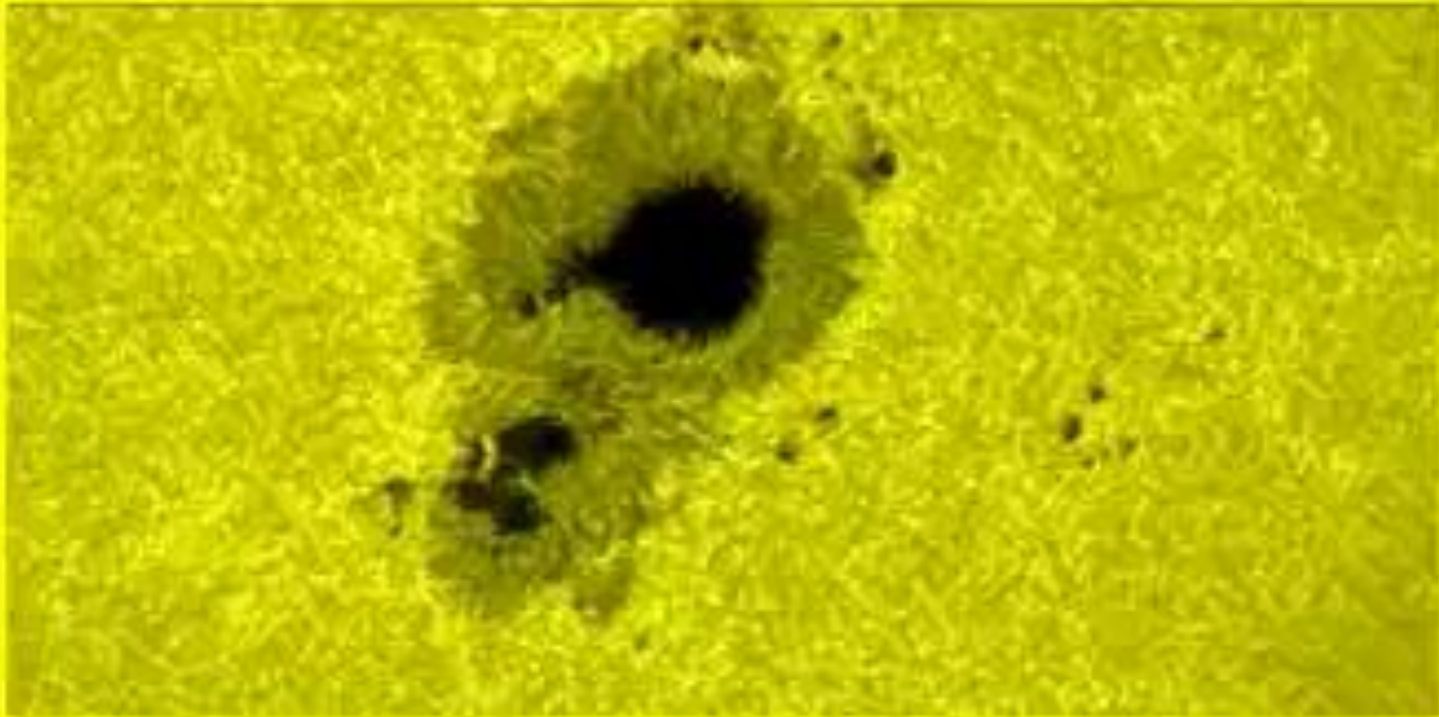
- The core: hot enough for many of the H nuclei to be undergoing fusion. The fusion creates photons that move away from the center. By about 0.25 of the radius from the center, hardly any fusion is still taking place as a result of decreasing temperature and density with radius, and so this can be considered the approximate limit of the core region.
- Radiative zone: Where energy transfer is via photons scattering off of electrons. The material is extremely dense, and photons diffuse out over a long period of time ( $\sim 10^5$  yrs) toward the surface. The temperature and density continue to fall with radius. This continues until about 0.7 of the solar radius.
- The convection zone takes up the last  $\sim 25\%$  of the solar radius.
- Then reach the photosphere.

- Convective instability sets in when:

$$\left| \frac{dT}{dr} \right|_{outside} > \left| \frac{dT}{dr} \right|_{adiabatic}$$

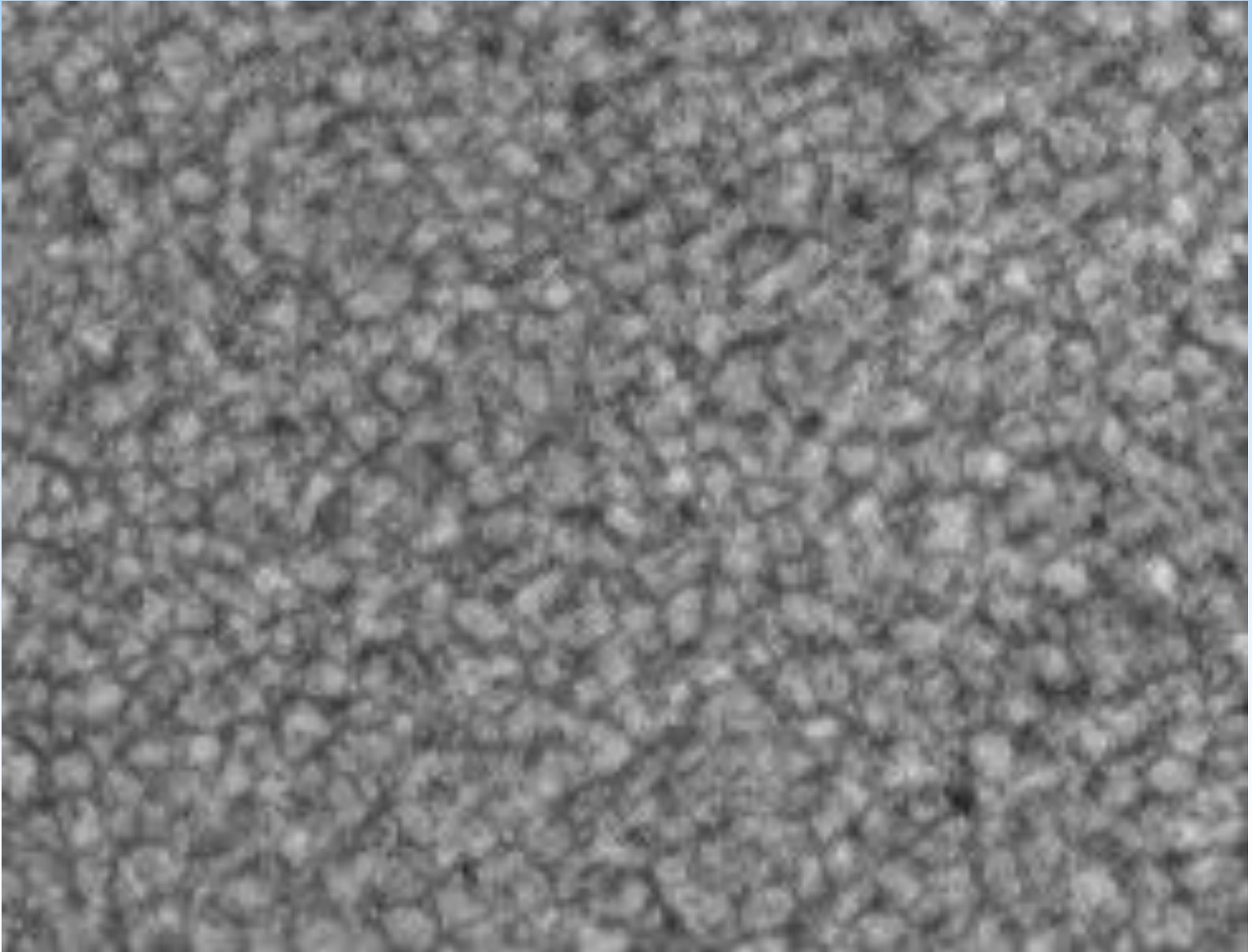


# Hinode SOT Granulation Movie

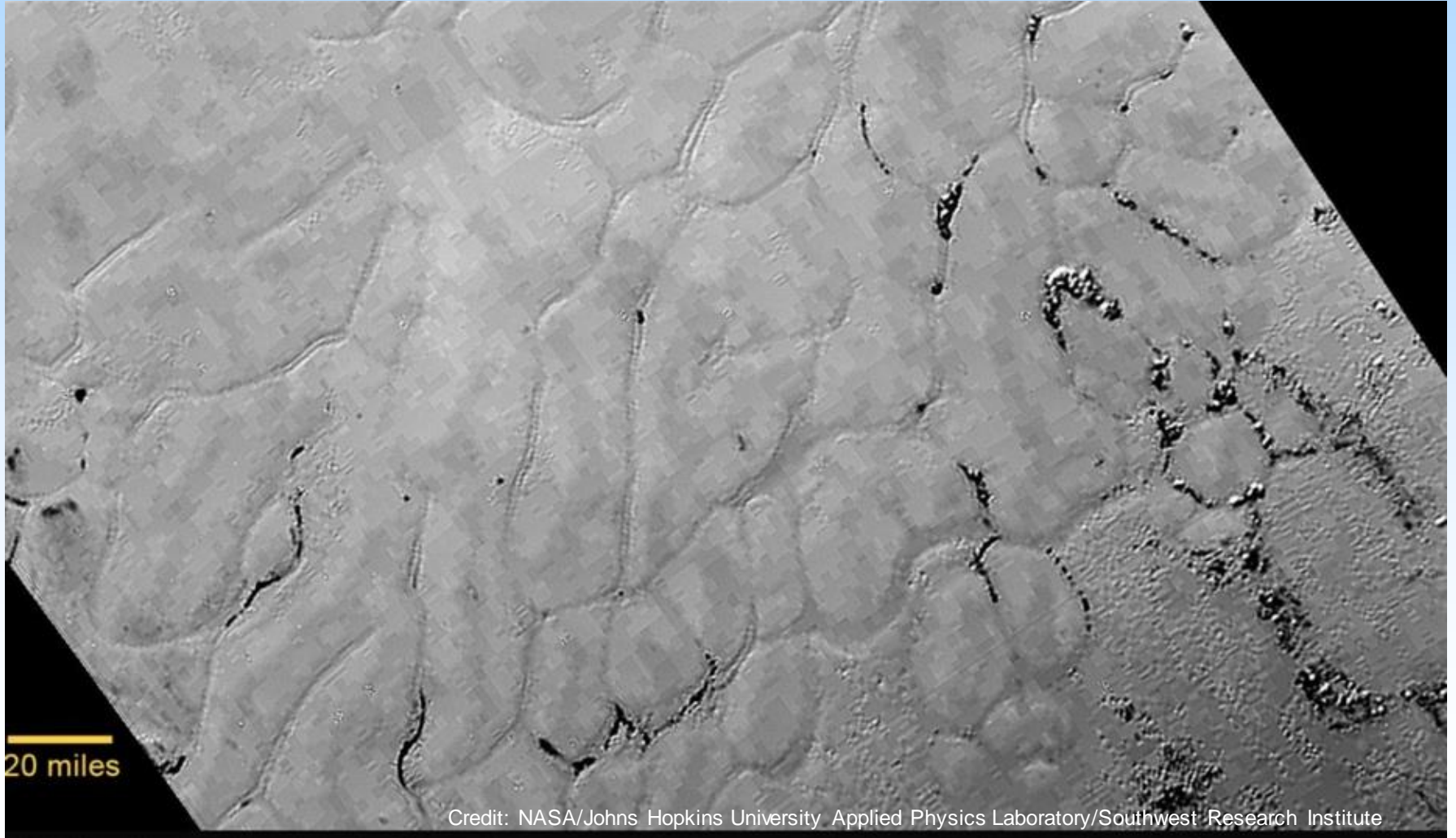


NASA/Goddard Space Flight Center Scientific Visualization Studio

## BBSO Granulation (near IR; 60 min)



# Convection on *Pluto* too??



Credit: NASA/Johns Hopkins University Applied Physics Laboratory/Southwest Research Institute

# From the Interior to the Photosphere

Recall that in the interior the density is so high that photons run into particles; they are scattered off of those particles, or absorbed and reradiated away from them.

Going out from the center, the material density goes down. Eventually the density becomes so low that a photon has a 50-50 chance of running into a particle or escaping out into space. This defines *the photosphere*.

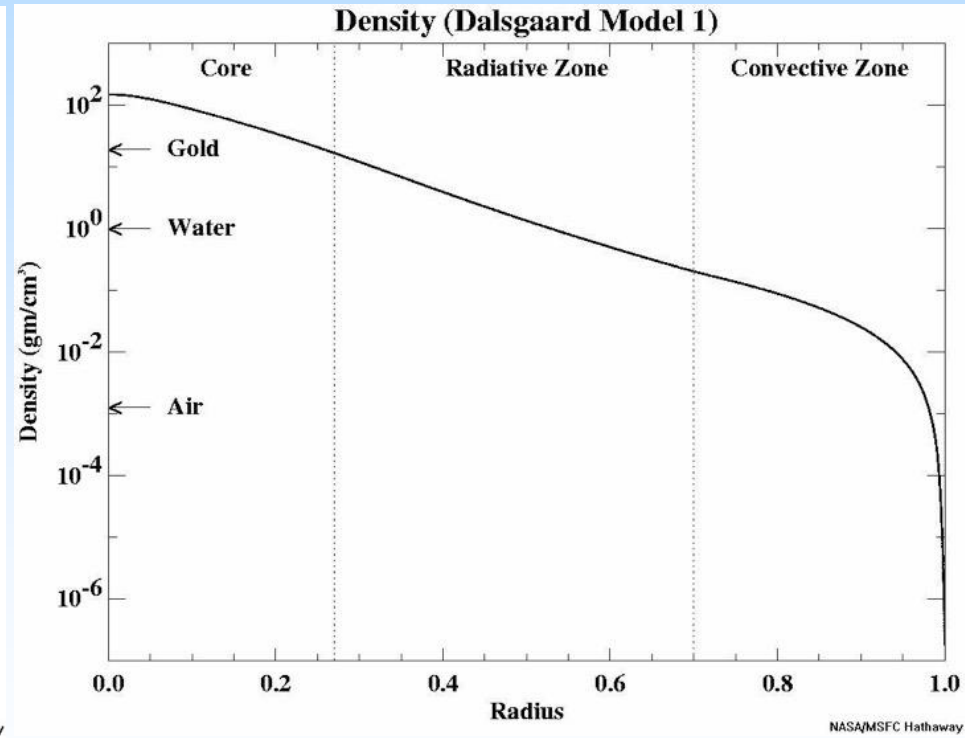
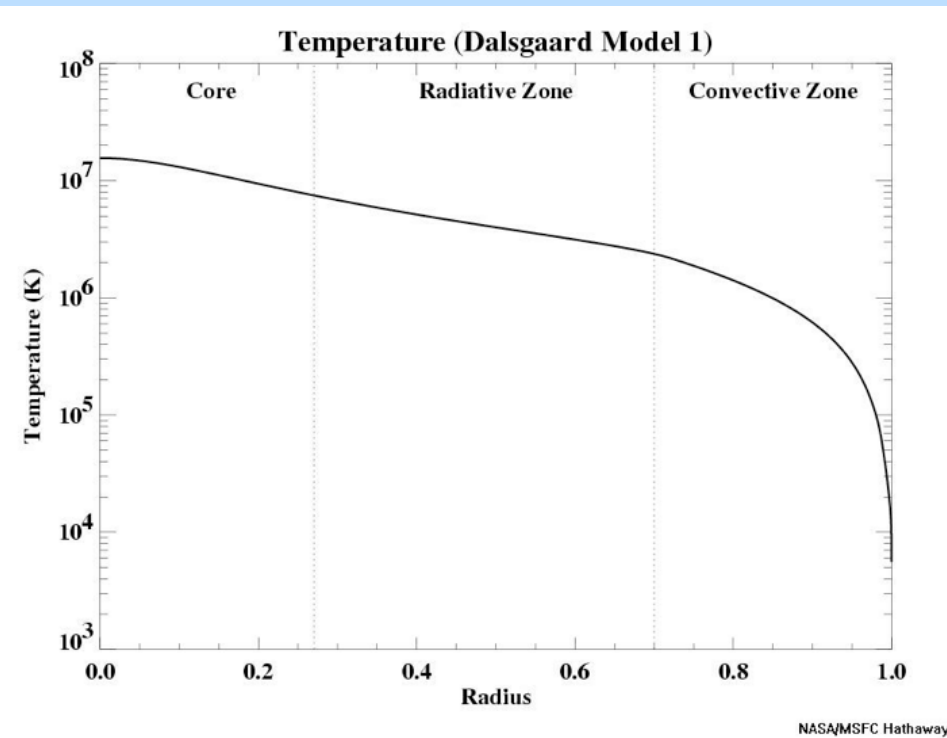
Temperature has dropped to about 6000 K.

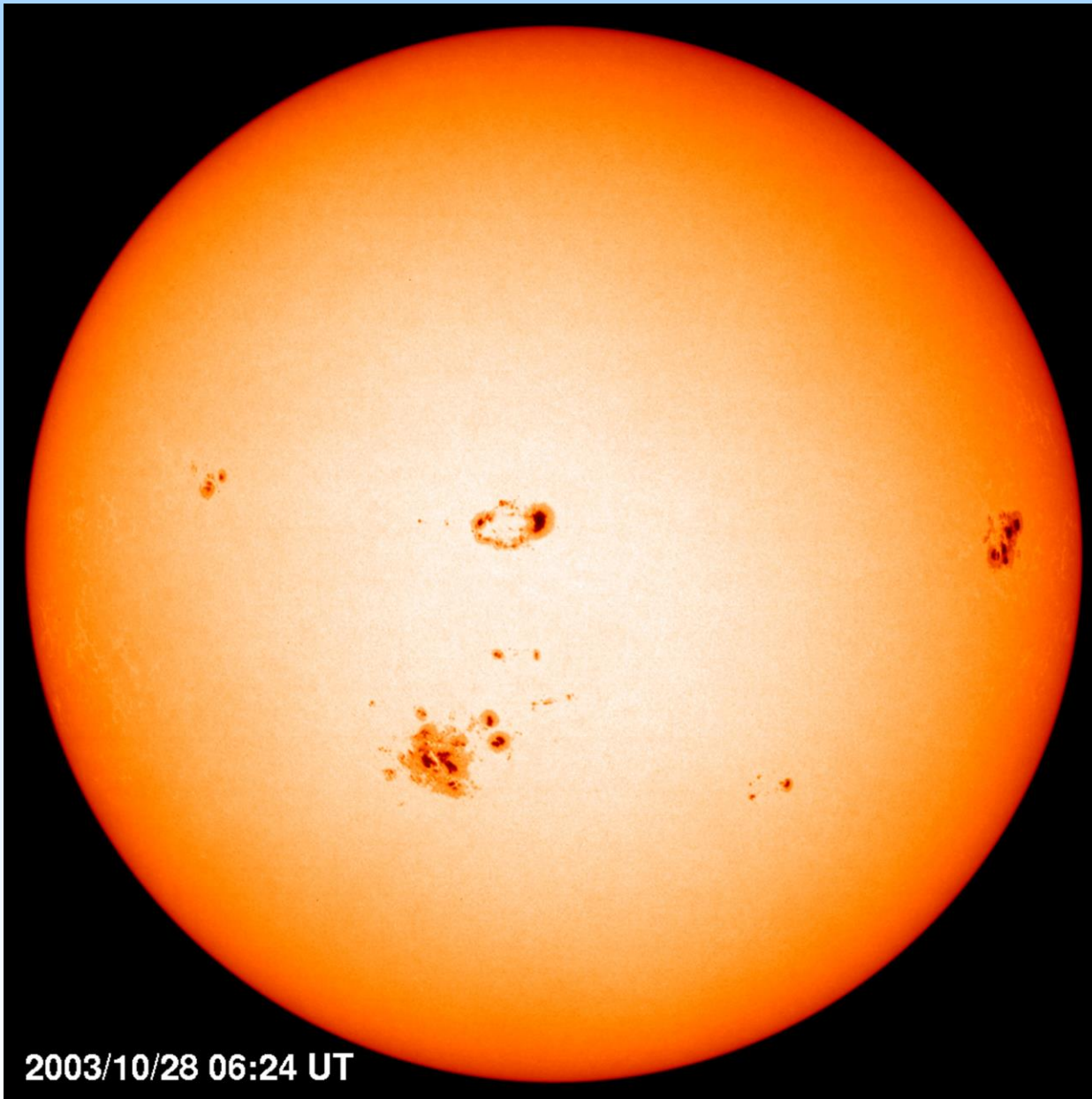
The photosphere edge is comparatively sharply defined.

Granules from convection bubble up, with slight variations in the temperature.

The photosphere can be considered the lowest solar atmosphere.

# The Solar Interior's Temperature and Density Distribution





2003/10/28 06:24 UT

The Photosphere

# Is the Theoretical Interior Structure Correct?

The above-discussed solar interior is based on physics principles, and on solving equations subject to various assumptions, etc. That is, it is largely theoretical. But is it correct? How can we check these ideas?

Two approaches:

Particles from the interior; the “solar neutrino problem.”

Helioseismology

# The Solar Neutrino Problem

Recall, from the p-p cycle (fusion process in the core of the Sun), the net result is:  $4 \times {}^1\text{H} \rightarrow {}^4\text{He} + 2e^- + 2\nu$ .

Neutrinos are *extremely* small. Their mass is also extremely small; close enough to zero to be unmeasurable until (maybe) recently.

Can calculate the expected flux, by using the amount of energy liberated according to theory, and the luminosity of the Sun (i.e., how bright the Sun is). This flux at the Earth's surface is  $F(\nu) \sim 8 \times 10^{10}$  neutrinos  $\text{cm}^{-2} \text{ s}^{-1}$ .

This is a *huge* flux; many of them are going through you right now!

Essentially all neutrinos pass through us, and even the Earth.

# The Solar Neutrino Problem (continued)

But there are experiments to detect them: Bury huge containers of chlorine (cleaning fluid). This is because a neutrino interaction with Cl is known:  $^{37}\text{Cl} + \nu \rightarrow ^{37}\text{Ar} + \beta$ .

The argon can be detected and counted. Based on the particle physics properties of neutrinos, the interaction cross section can be calculated. An experiment was run in Homestake Mine in South Dakota, US over 1970-1995. It showed that the measured neutrino flux was  $\sim 1/3$  of the theoretical value.

This experiment was repeated, with high accuracy. The flux was lower than expected. This is the *Solar Neutrino Problem*.

This problem was solved, with the help of a supernova in 1987A, in the Large Magellanic Cloud, a nearby galaxy.

The neutrinos go through three states, only  $1/3$  of them are expected to be detected by the above experiment.

So the solar core theory is supported by neutrino observations.

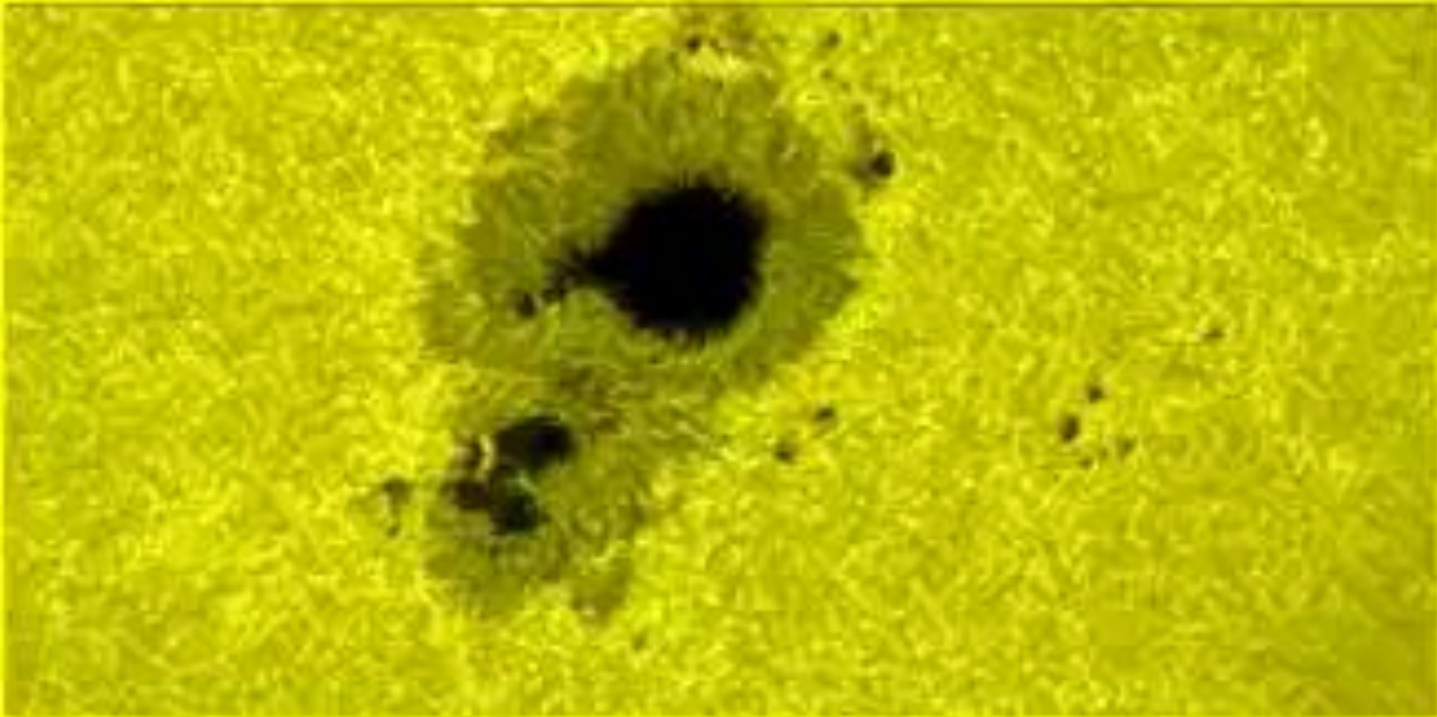
This led to Nobel Prizes in 2002 and 2015.

# Helioseismology

The Sun rings like a bell! Found in the early 1960s using Doppler techniques.

Through careful measurements, the oscillations can be decomposed into a spectrum of discrete values. That is, only some period-wavelength combinations show up, while others do not.

# Hinode SOT Granulation Movie



NASA/Goddard Space Flight Center Scientific Visualization Studio

# Helioseismology (continued)

Explanation in the 1970s: Waves trapped in the interior of the Sun (or in the base of the solar atmosphere).

By using the physics of waves, we can learn about the interior structure of the Sun.

Trapped acoustic (sound) waves travel with a speed,  $c_s$  of  $c_s^2 = \gamma P / \rho$ , so  $c_s \sim T$ .

The temperature in the interior of the Sun drops with distance from the center. The details of how it drops depend on the specifics of the model of the interior.

# Helioseismology (continued)

So, can learn about the interior models in this way:

Use a model, with some set of assumptions, to derive a model solar atmosphere.

Input acoustic waves into that model, and measure the period/wavelength distributions that come out.

Compared those theoretical period/wavelength distributions with the observed ones.

If the theory does not match the observations, then tweak the model and/or the assumptions and repeat the process.

In this way, the model details of the Sun's interior can be refined to a high degree of accuracy.

# Some Helioseismology Results:

Helped establish the standard model for the solar interior.

Contributed to solving the solar neutrino problem.

Refined values for the depth of the convection zone.

Gave information on the rotation speed of the Sun as a function of depth.

Told us about the *tachocline*, a region of strong shear flows at the base of the convection zone.

# Sunspots, an Introduction

Localized dark regions on the Sun. First regularly seen by Galileo in 1609/1610.

Individual sunspots live for a few days to a few weeks

Darkest part is called the *umbra*. This is often surrounded by a less-dark *penumbra*.

They often form in groups.

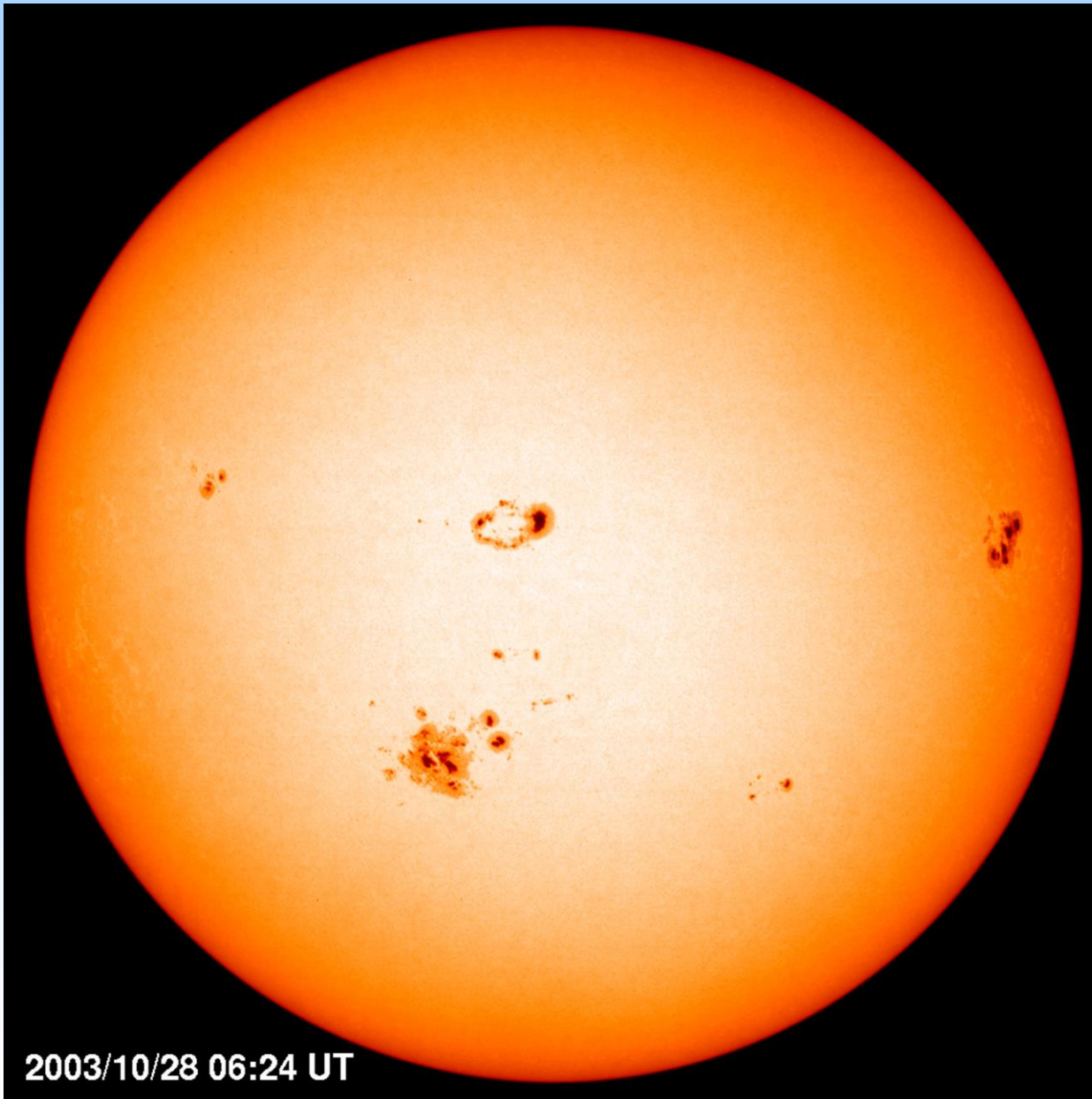
Several spots together make an *active region* (although in some cases a single spot can make an active region).

Spots are dark because they are cooler than the surrounding photosphere (~4000 K compared to ~6000 K).

Spots are cool because they are locations of particularly strong magnetic field.

The number of spots on the Sun in a given year varies, with some years having, on average, more spots than others.

The spot-number variation is cyclic, with a period of ~11 year. This is the 11-year solar sunspot cycle, or simply: *the solar cycle*. <sup>33</sup>



2003/10/28 06:24 UT

The Photosphere

# The Sun's Magnetic Field, an Introduction

The magnetic field of the Sun originates in the interior (probably the base of the convection zone).

It extends through the surface, throughout the corona, and throughout the heliosphere.

They often form in groups.

Several spots together make an *active region* (although in some cases a single spot can make an active region).

Spots are dark because they are cooler than the surrounding photosphere (~4000 K compared to ~6000 K).

Spots are cool because they are locations of particularly strong magnetic field.

# Solar Rotation, and long-term Sunspot Behavior

Can use sunspots to track solar rotation.

The Sun rotates at different rates, depending on the latitude. This is called *differential rotation*. It is a vital factor in solar activity.

The equator of the Sun makes one rotation in approximately 25 days, while at the poles one rotation requires approximately 30 days.

Differential rotation wraps the magnetic field at different latitudes, making those latitudes prone to activity.

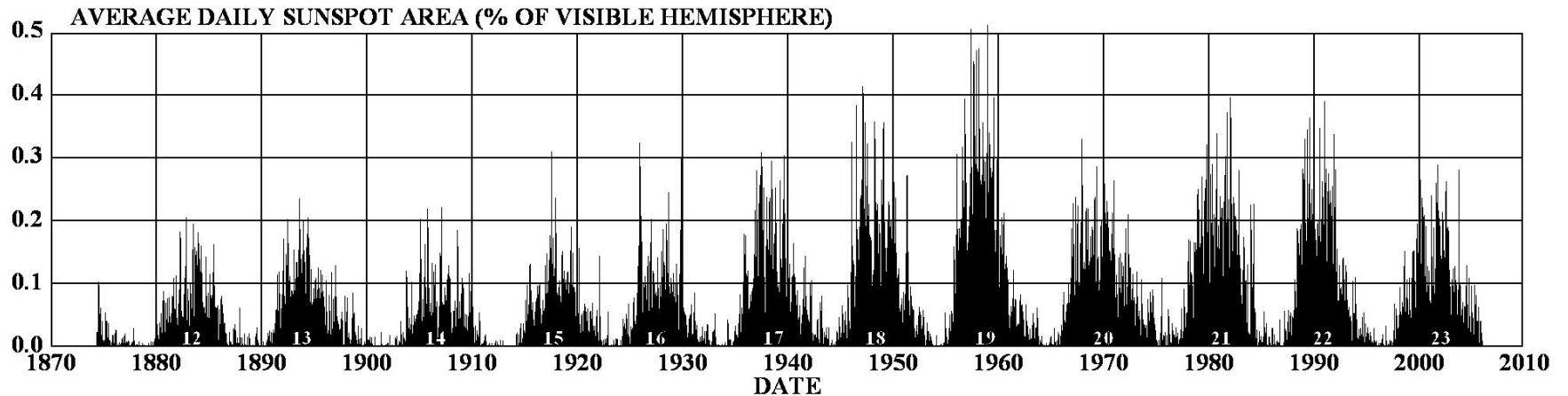
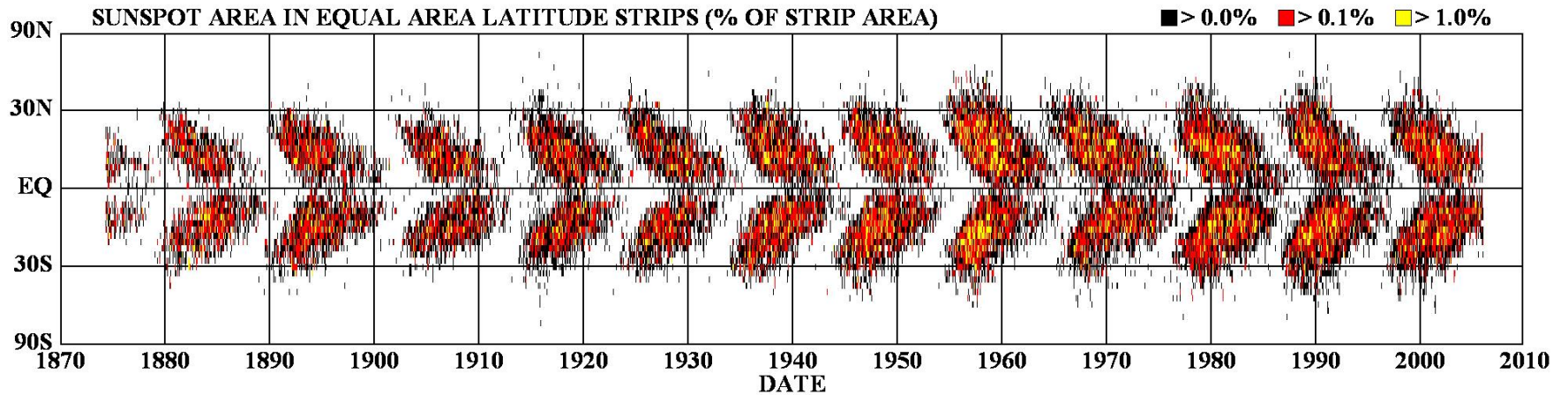
Sunspots occur where the field expands through the surface at locations where the field is strong.

Over the 11-year solar cycle, the latitude at which most spots appear changes, starting at high latitudes ( $\sim 45^\circ$ ), and ending near the equator.

This results in the *butterfly diagram*.

The general orientation of the magnetic-field polarity of the north and south hemispheres changes each cycle (that is, the north pole is positive one cycle, and then negative the next). Thus *the magnetic solar cycle* is about 22 year.

# DAILY SUNSPOT AREA AVERAGED OVER INDIVIDUAL SOLAR ROTATIONS



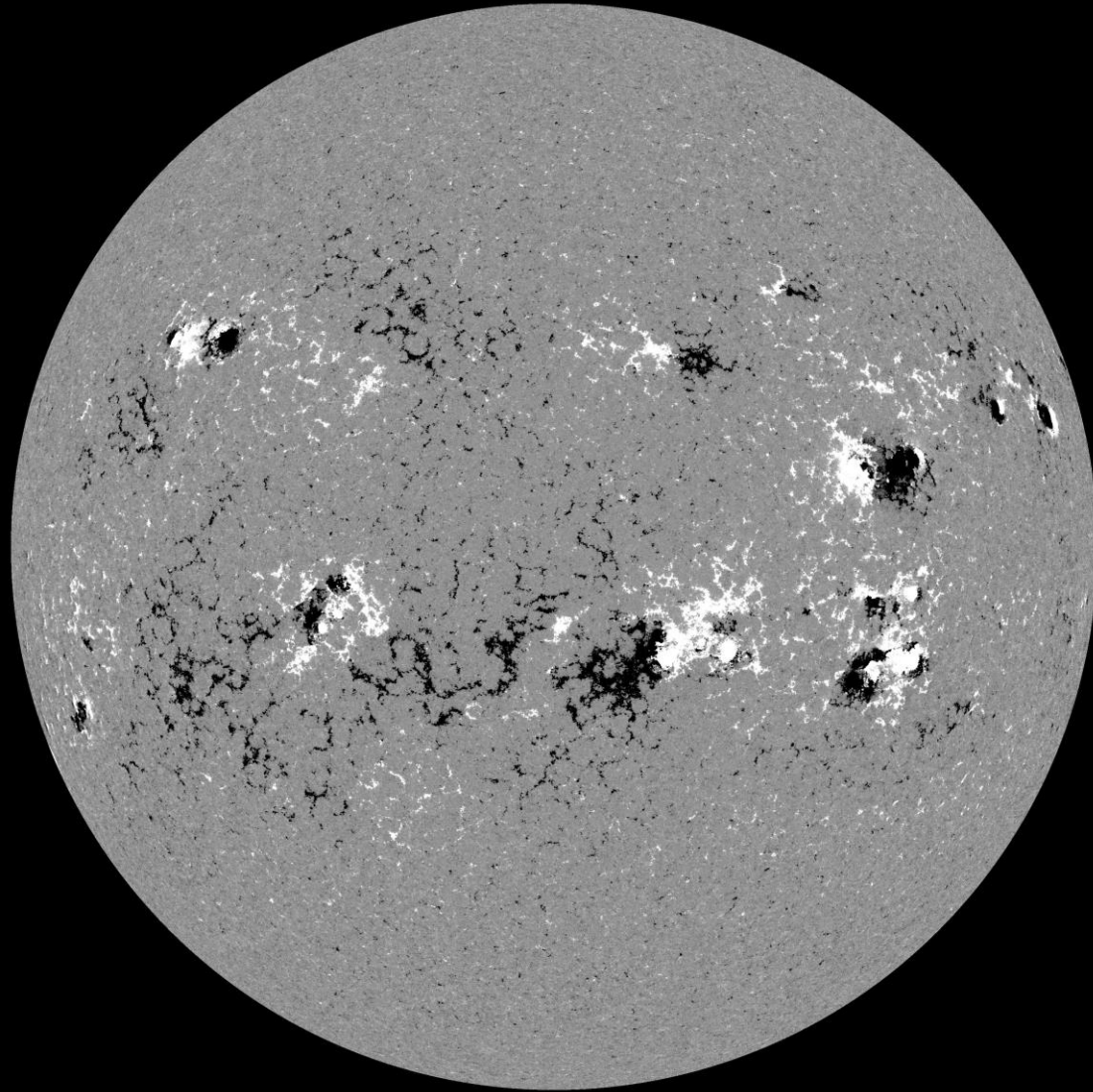
# The Solar Dynamo (generating and renewing the magnetic field and solar cycle)

The evidence is that the solar magnetic field is made somewhere around the base of the convection zone, at or near the tachocline in the boundary between the radiative zone and the convection zone.

There is velocity shear at this location because — from helioseismology — the radiative zone rotates rigidly, while the convection zone rotates differentially.

The *Babcock model* (or Babcock-Leighton model) explains many of the features of the sunspot cycle.

# Magnetogram (HMI)



**Convective Zone**

**Radiative Zone**

**Core**

**Prominence**

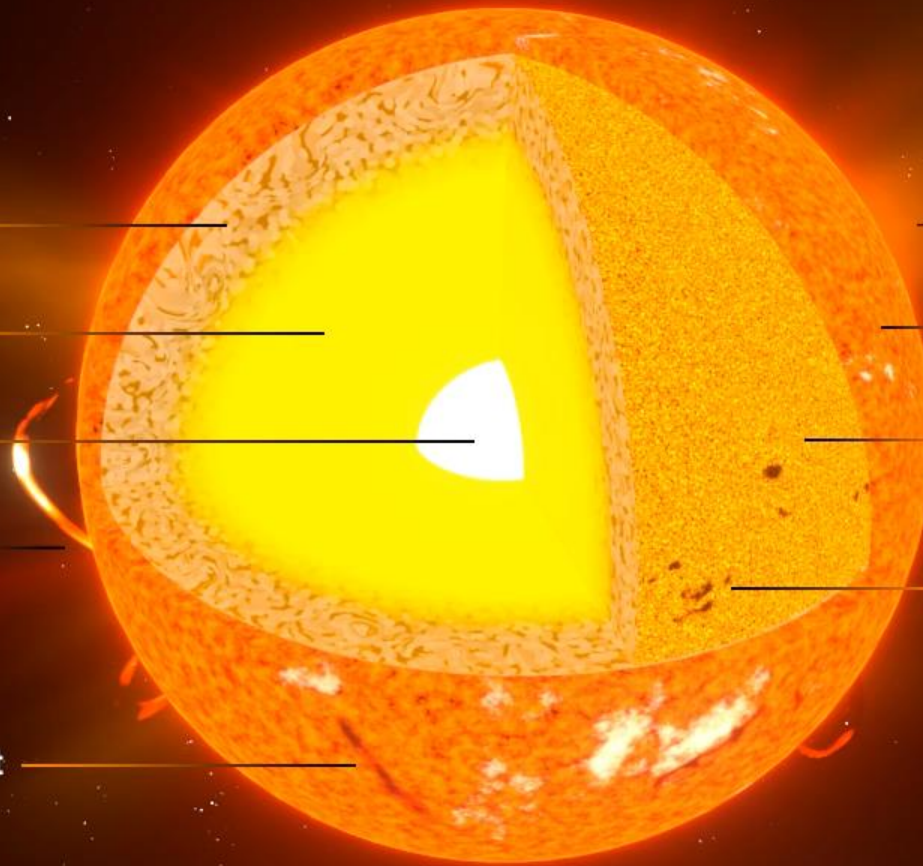
**Filament**

**Corona**

**Chromosphere**

**Photosphere**

**Sunspot**



(Blank)

# The Solar Atmosphere

# Overview of the Solar Atmosphere

- Below the photosphere, the Sun is opaque at visible wavelengths.
- For this reason, we call the photosphere the “surface” of the Sun, even though it is totally gas/plasma; certainly far from solid!
- At and/or beyond this surface (i.e., at larger radii from the center) is the solar atmosphere.
- The photosphere is often referred to as one of the three atmospheres of the Sun. These atmospheres are the photosphere, the chromosphere, and the corona.
- The atmosphere is much more tenuous than the interior, although its density varies a lot too, as we will see.
- The temperature of the chromosphere is hotter than the photosphere, and the corona is much hotter than both.
- Why the corona is so hot is probably the main outstanding question in solar astronomy for the last 80 years.

# The Photosphere

(Already partially discussed, and so just a quick summary)

- Temperature of average photosphere:  $\sim 6000$  K.
- Granules fill the surface in most places; they are convection cells  $\sim 1000$  km in diameter, and they have lifetimes of a few minutes.
- Sunspots are cooler areas,  $\sim 4000$  K, that live for days to weeks. They form due to intense concentrations of magnetic field. They show the rotation of the Sun.
- Spots occur in active regions, which are locations of enhanced magnetic field.

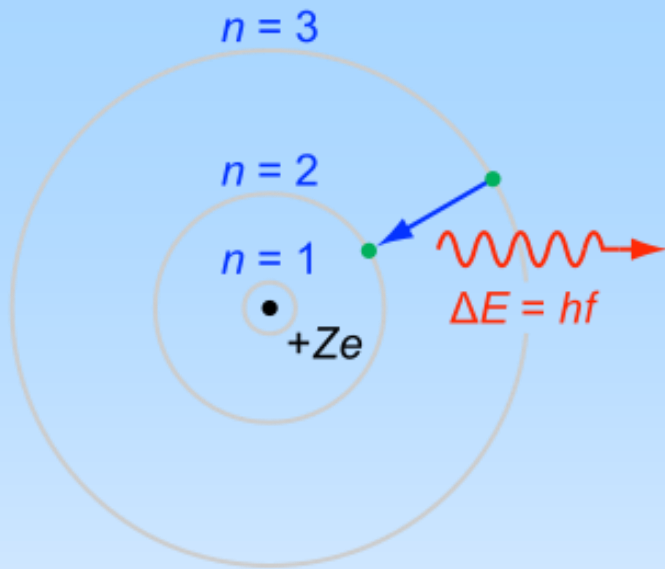
# The Chromosphere

- Less dense than the photosphere.
- Hotter than the photosphere;  $\sim 10^4$  K.
- Very narrow region; compared to the interior and the atmosphere. It extends about  $\sim(2-5) \times 10^3$  km beyond the photosphere.
- It can be seen as a bright red rim beyond the solar limb at the start and end of solar eclipses.
- This gives it its name, from the Greek for color sphere.

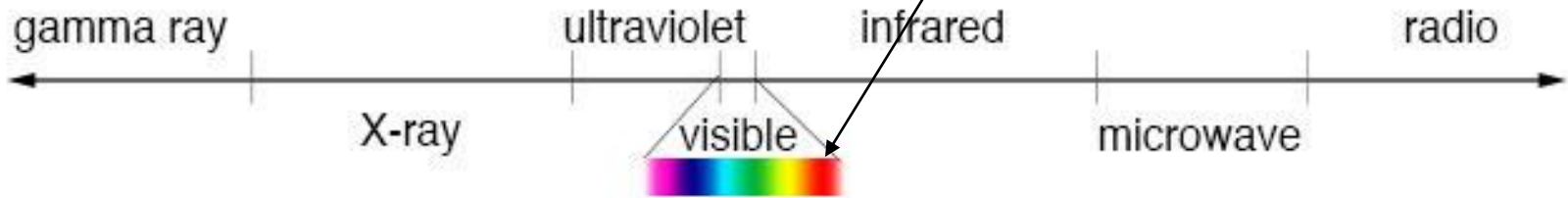


Alphonse Sterling, 2016 Mar 9, Indonesia  
ZenithStar 66 + EOS700D, 1/1000 s

Chromosphere

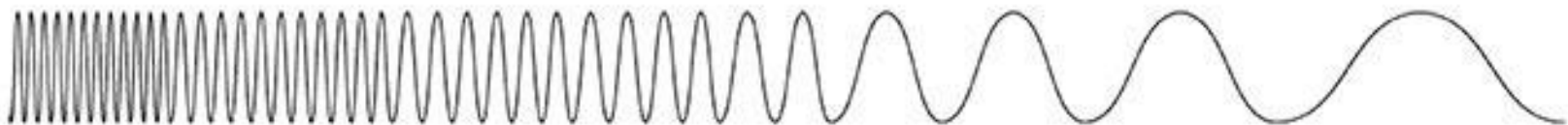


H-alpha ( $H\alpha$ ) transition in hydrogen atom; 656.3 nm.



shorter wavelength  
higher frequency  
higher energy

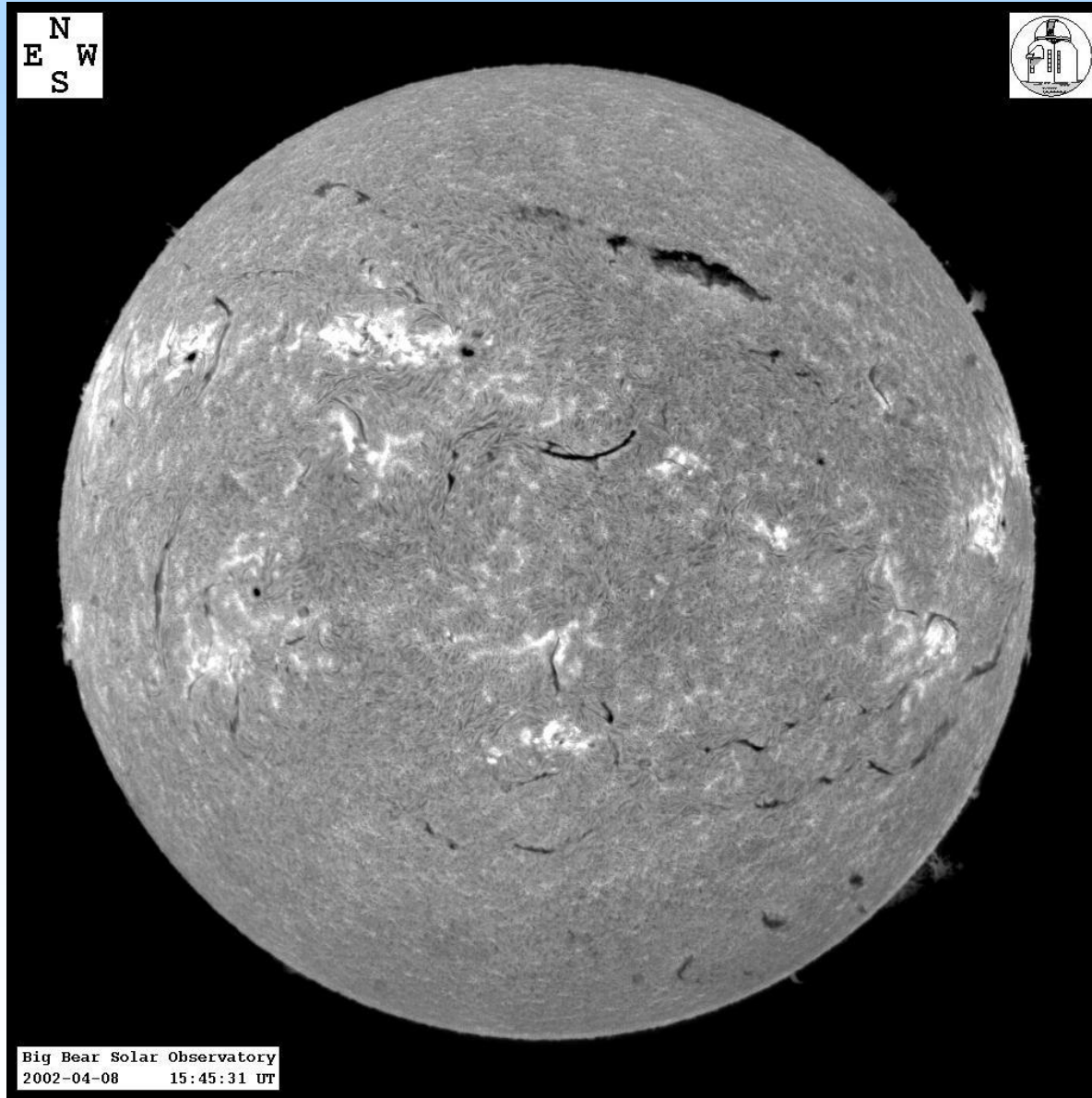
longer wavelength  
lower frequency  
lower energy



# The Chromosphere (continued)

- The chromosphere can be observed in visible light, using an H-alpha filter (or spectrohelioscopes/spectroheliographs).
- Because of this, the chromosphere was a major focus of solar physics from the early 1900s until at least the 1970s. (From the 1970s we started having more and more observations of the Sun from space, which shifted the focus.)
- The chromosphere shows very different features than the white-like photosphere, which look bland in comparison; e.g., ARs, filaments, prominences, plage....
- Active areas show a lot more detail and structure in the chromosphere than in the photosphere.
- Besides H-alpha, the chromosphere can also be studied from the ground in Ca, and also at radio wavelengths. (More options are available from space, including UV.)

# Chromosphere in H $\alpha$





# **Solar Flare**

## **1971 October 10**

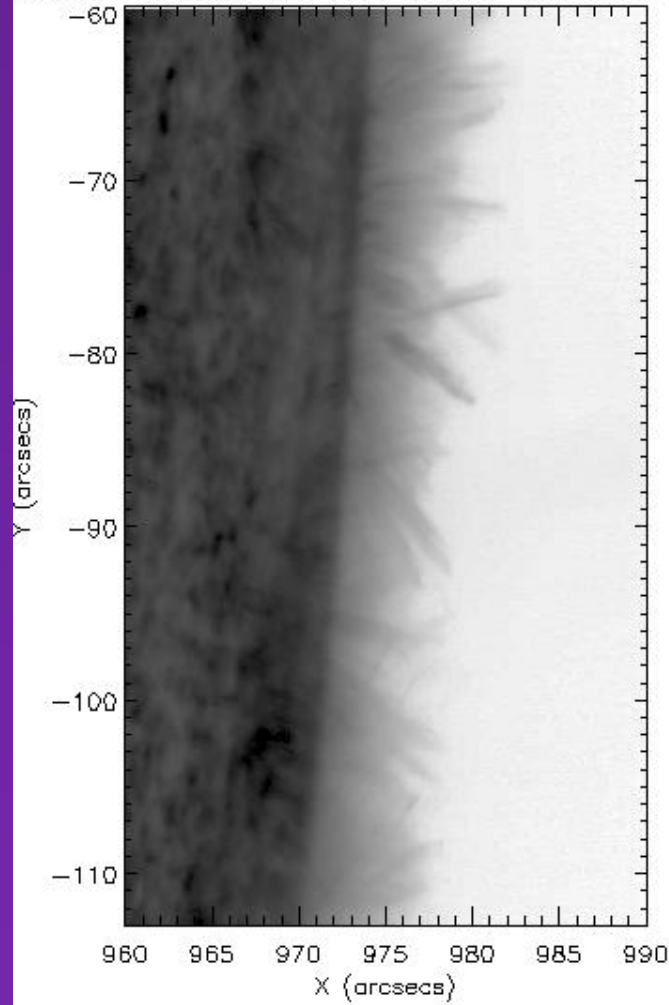
**Big Bear Solar Observatory**



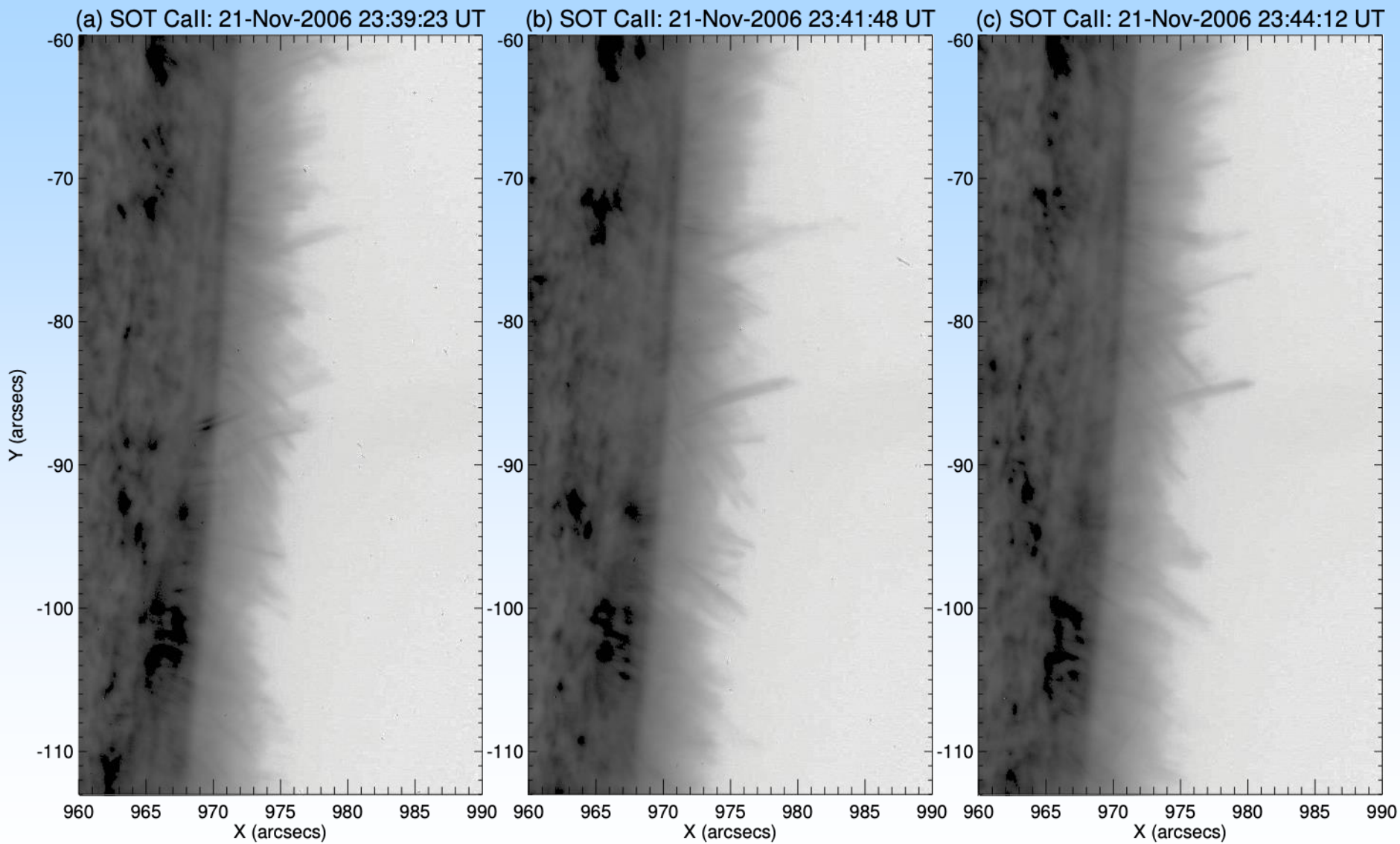
# The Chromosphere (continued)

- Close-up views of the solar limb show that the chromosphere is filled with dynamic spike-like features. These are called chromospheric *spicules*.
- Spicules are *very* common, with  $\sim$ few  $\times 10^5$  —  $10^6$  always on the Sun. They make up a large part of the chromosphere.
- Spicules live on average (very rough averages)  $\sim 5$  min. They shoot out from the surface and reach about 5000 km beyond the photosphere.
- On the solar disk, the spicules are sometimes called “mottles” instead of spicules. They form a distinctive pattern around approximately circular cells.
- The cells are the edges of supergranules, which are convective features similar to granules, but about 30 times larger (radius of granules  $\sim 1000$  km; of supergranules  $\sim 30,000$  km). They are locations of enhanced magnetic field.
- The physics of spicules is still hotly debated!!

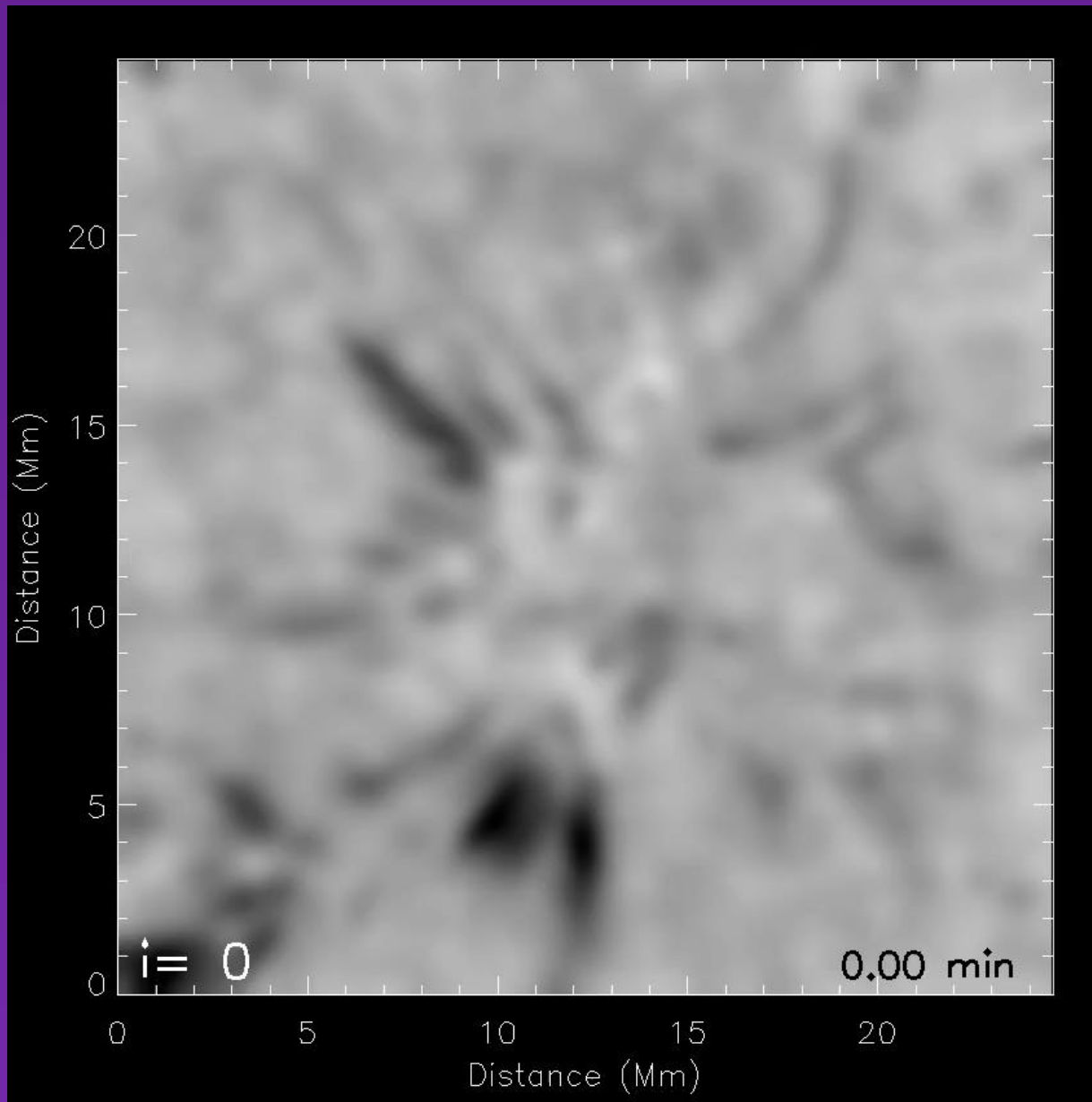
Hinode SOT/WB 21-Nov-2006 22:58:02.574 UT



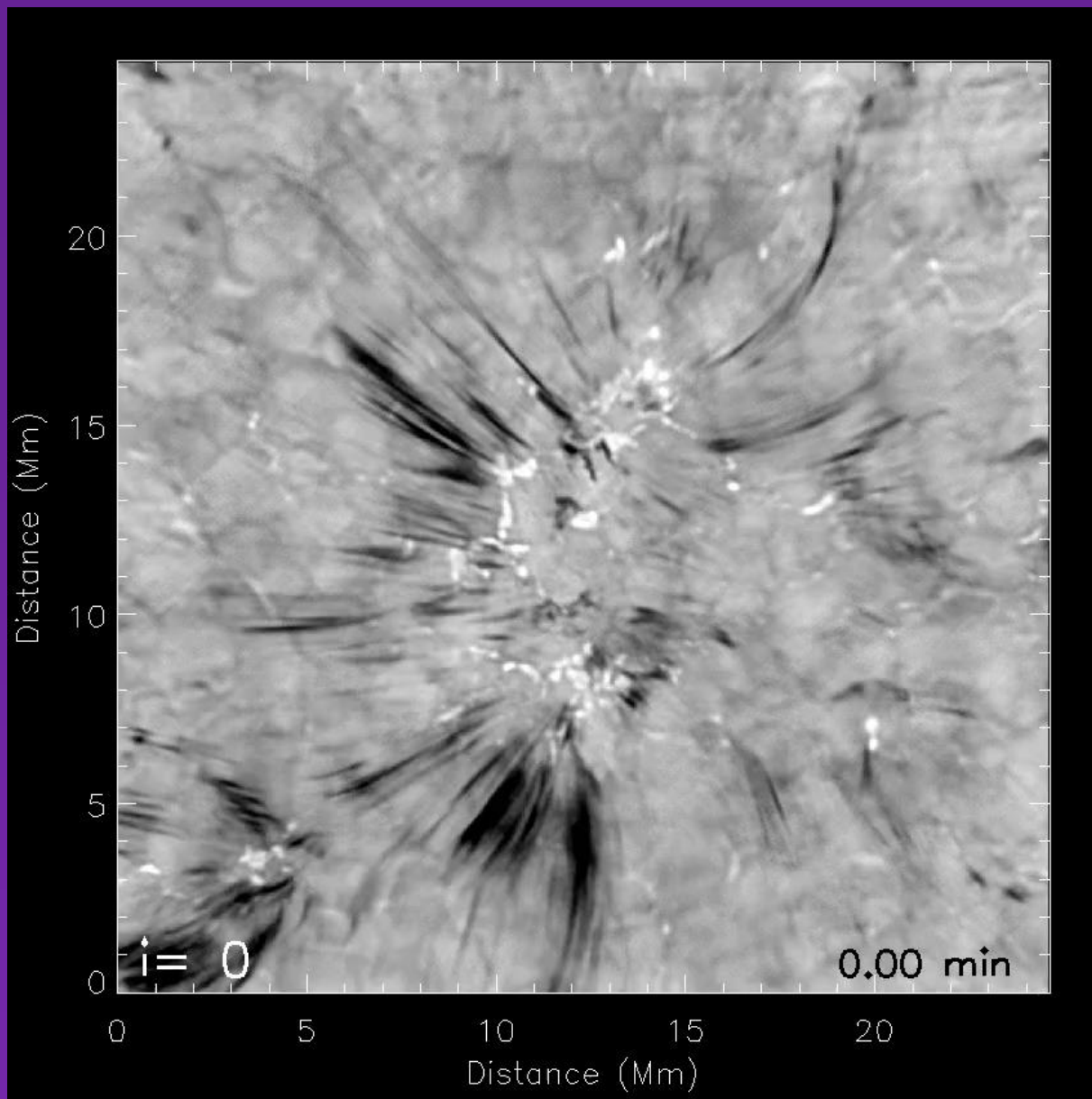
(Data set studied in Zhang et al. 2012)



(Sterling 2021)



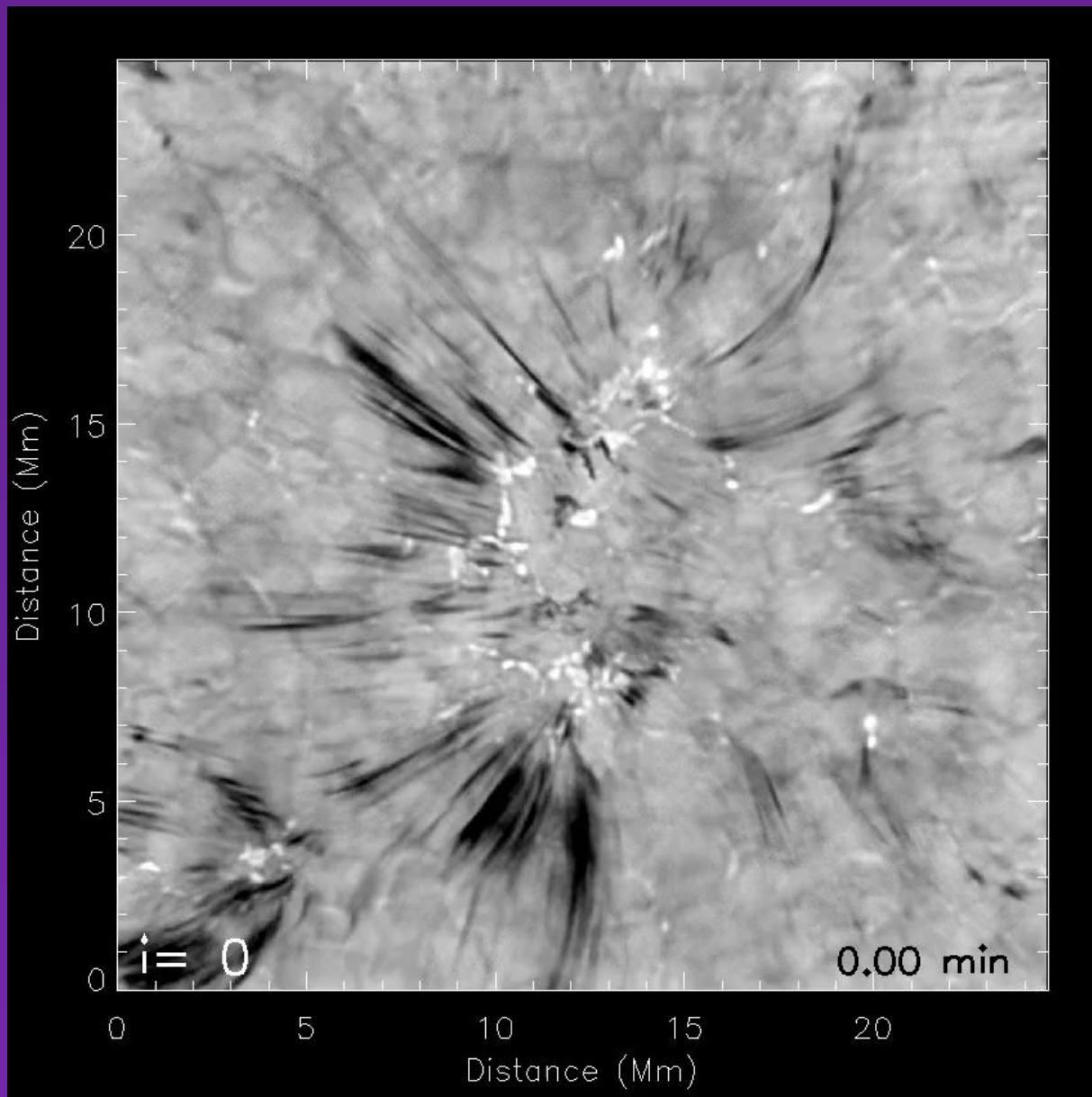
(Sterling+2020) (cf. Samata+2019, Pereira+2013)



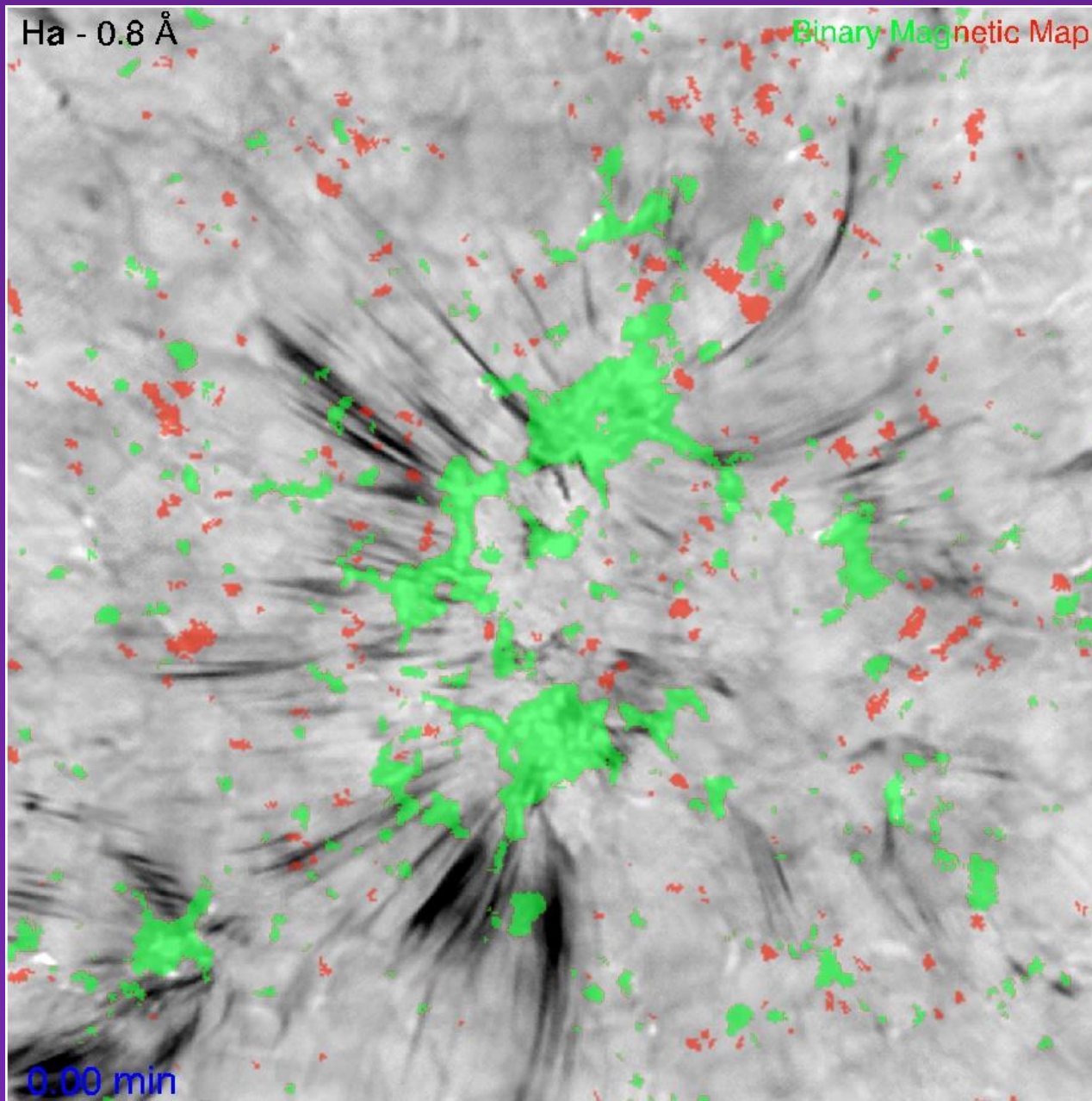
Sterling et al. (2020) (data from Samanta et al. 2019; Goodie Solar Telescope, Big Bear Solar Observatory)

# The Magnetic Field in the Chromosphere (Cont)

- The magnetic field concentrates at the edges of the supergranule cells. This magnetic structure is called the *magnetic network*.
- Spicules are rooted in the network, and extend outward into the corona following the magnetic field.

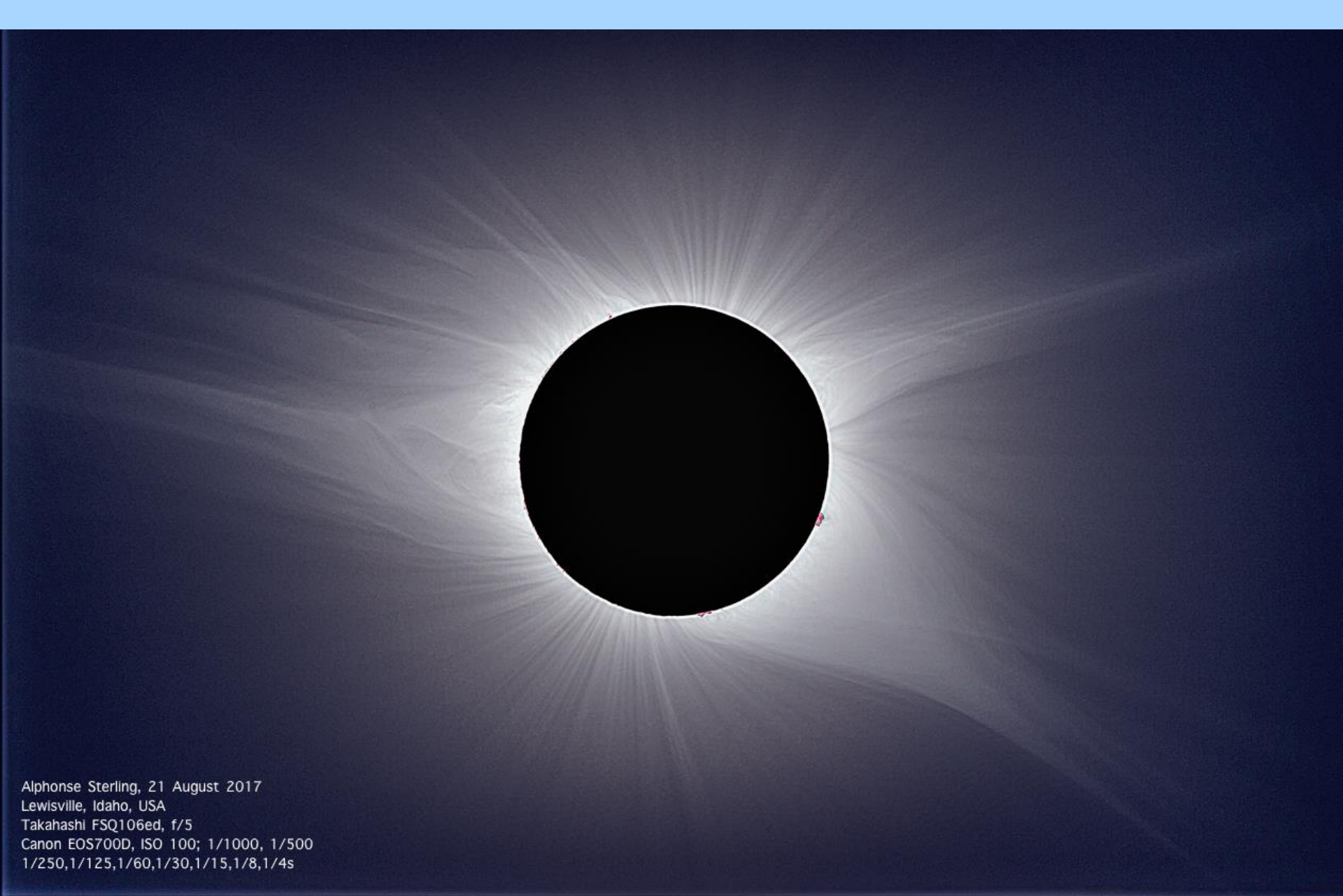


Sterling et al. (2020) (data from Samanta et al. 2019; Goodie Solar Telescope, Big Bear Solar Observatory)



# The Corona

- Its name is from the Latin for “crown.”
- The corona visible during total solar eclipses extends several solar radii.

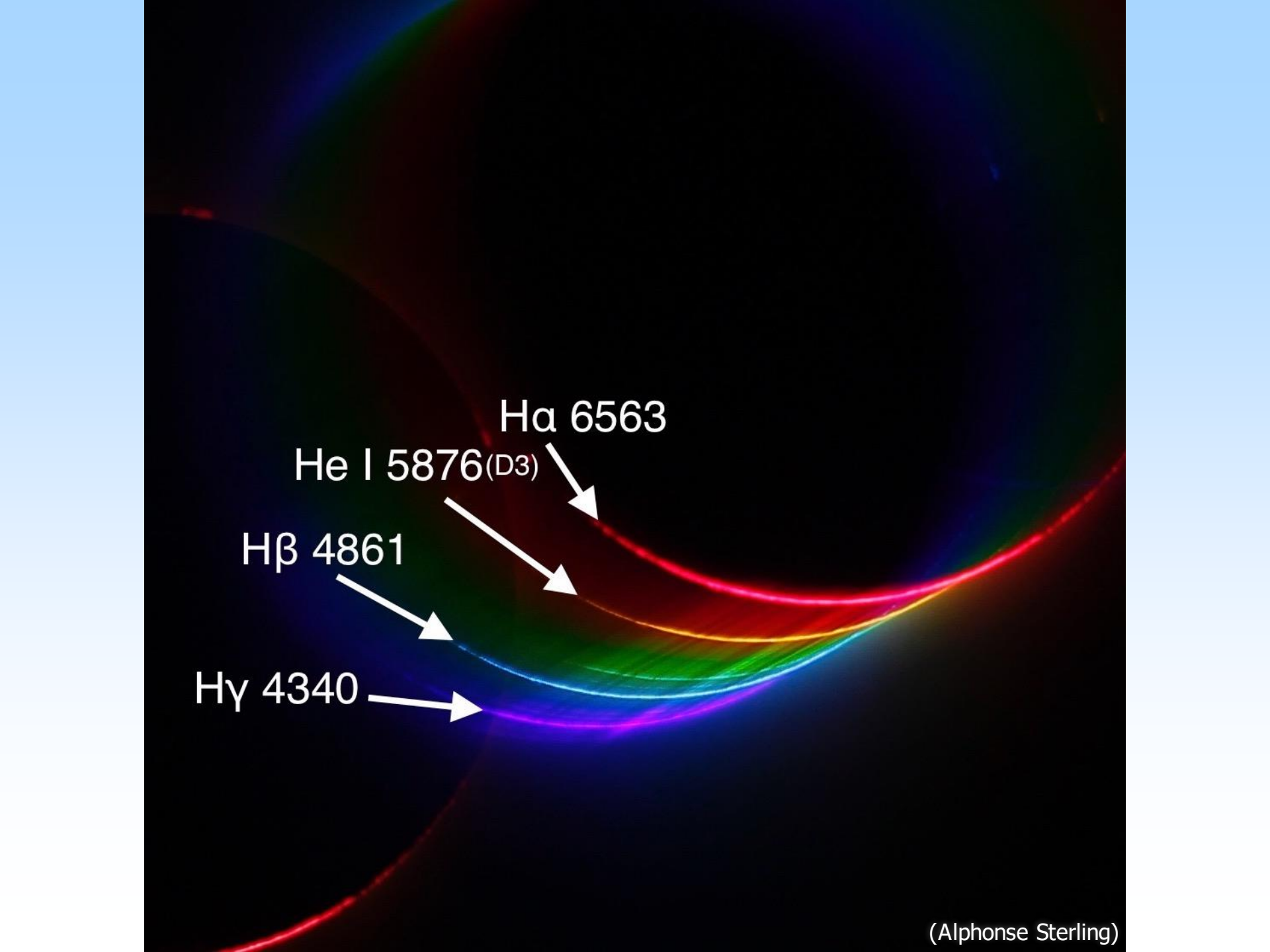


Alphonse Sterling, 21 August 2017  
Lewisville, Idaho, USA  
Takahashi FSQ106ed, f/5  
Canon EOS700D, ISO 100; 1/1000, 1/500  
1/250,1/125,1/60,1/30,1/15,1/8,1/4s

Corona – The Sun's outermost atmosphere

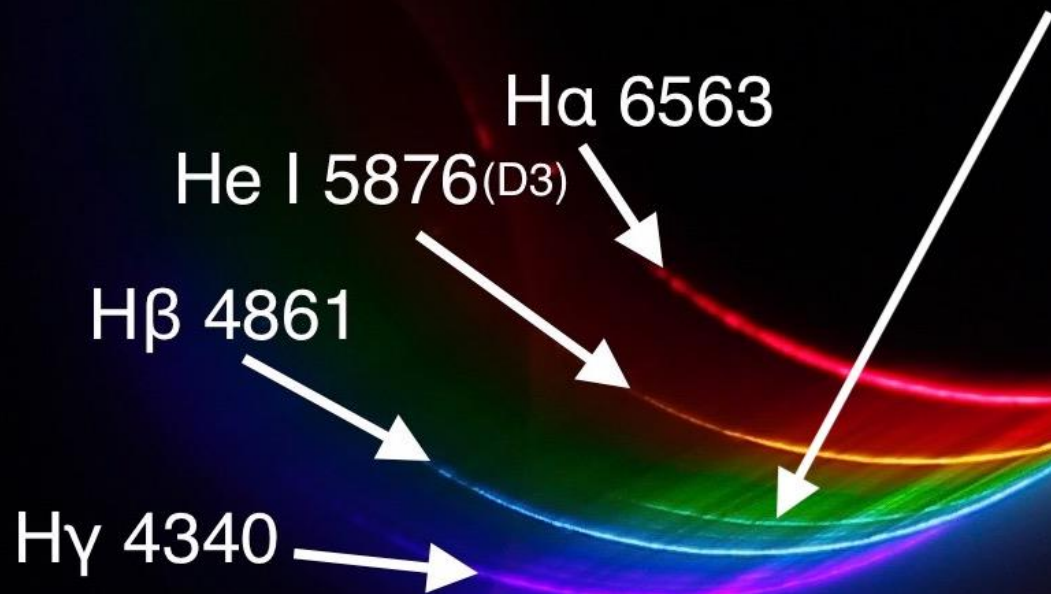
# The Corona

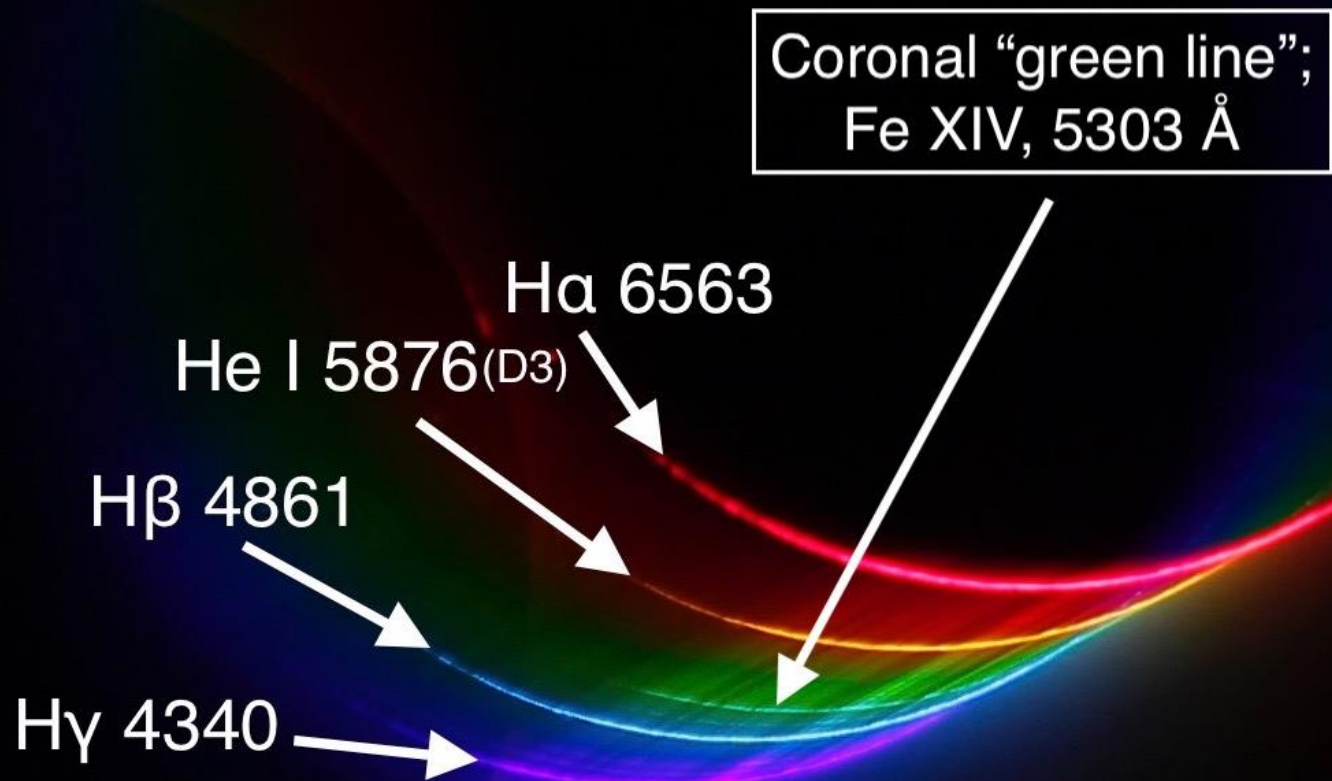
- Expected to be cool, but found strange spectral lines, first during 1869 eclipse.

A photograph of a star's spectrum showing several prominent emission lines. The lines are curved and colored according to their wavelength: Hγ (4340) is violet, Hβ (4861) is blue-green, He I (5876) is yellow-green, and Hα (6563) is red. The background is dark with some faint, diffuse light.

H $\alpha$  6563  
He I 5876<sub>(D3)</sub>  
H $\beta$  4861  
H $\gamma$  4340

(Alphonse Sterling)

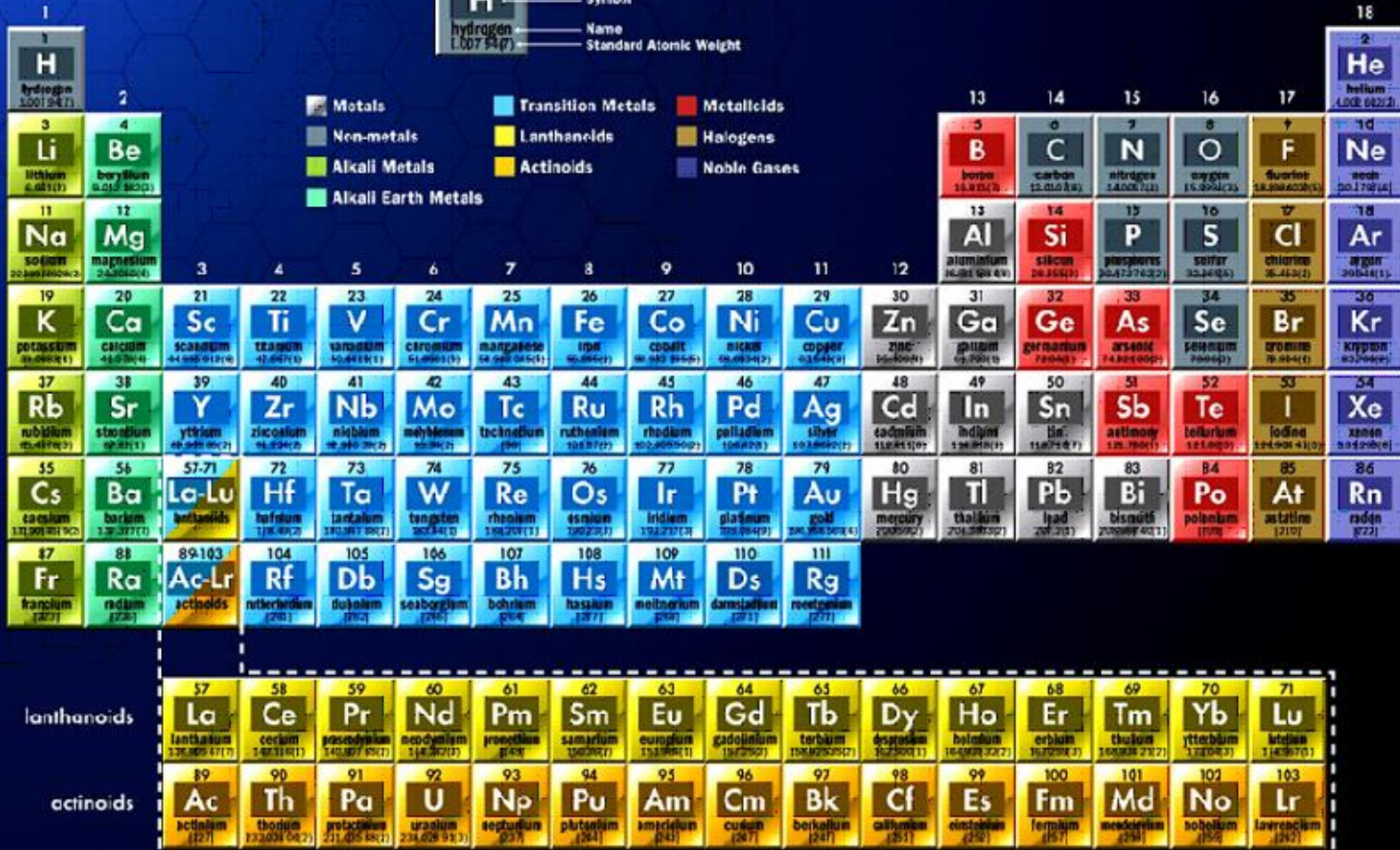




# The Corona

- Expected to be cool, but found strange spectral lines, first during 1869 eclipse.
- Many explanations considered, including a “new” element: *coronium*.
- **But this didn't work....**

# The Periodic Table



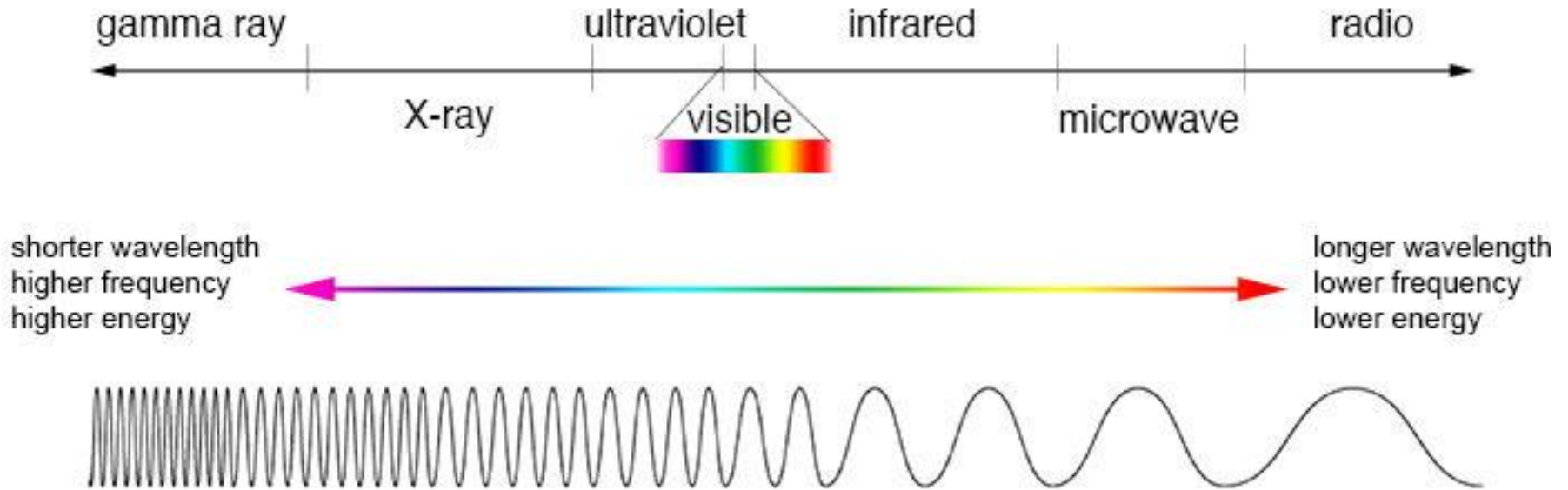
# The Corona: Continued...

- The mystery spectral lines found to be due to highly-ionized familiar elements ~1940.

So this was a sloooow process: 1869 eclipse observations, and 1939~1943 explanation!!

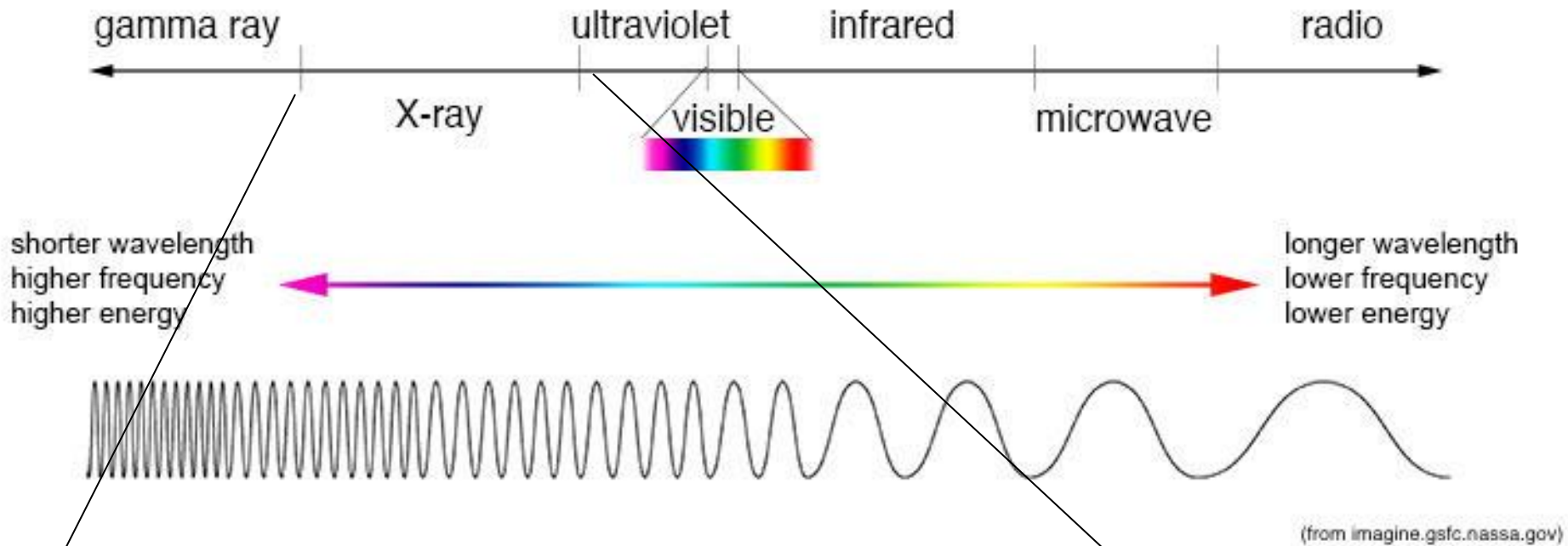
- Structured with loops; late 1960s and 1970s observations from balloons, Skylab, etc.
- This structure due to the magnetic field.

# The Electromagnetic Spectrum



(from [imagine.gsfc.nasa.gov](http://imagine.gsfc.nasa.gov))

# The Electromagnetic Spectrum

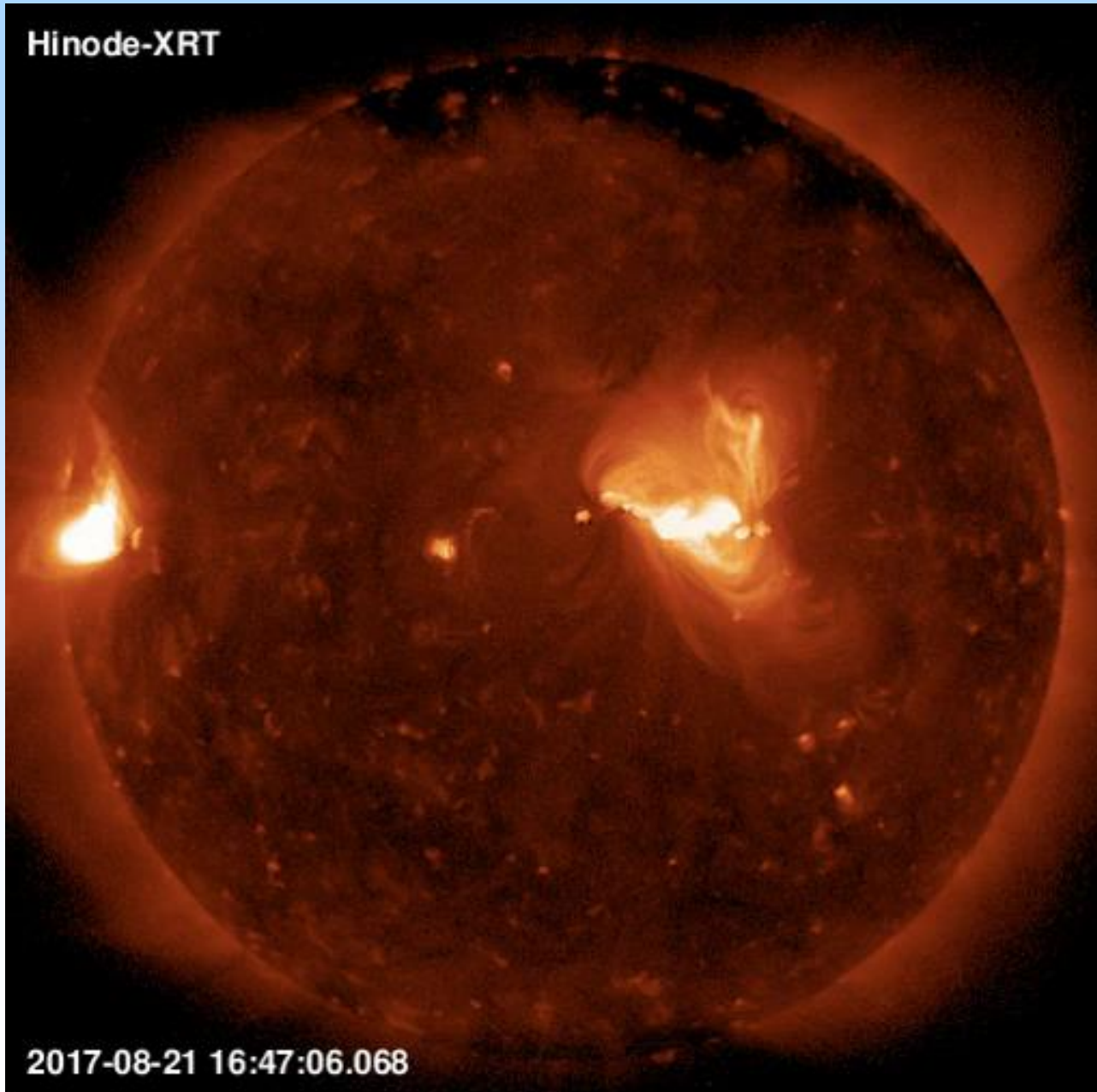


Hard X-ray ( $\sim 1\text{--}0.1 \text{ \AA}$ ); Soft X-ray ( $\sim 10\text{--}1 \text{ \AA}$ ); Extreme UV ( $\sim 1000\text{--}100 \text{ \AA}$ )

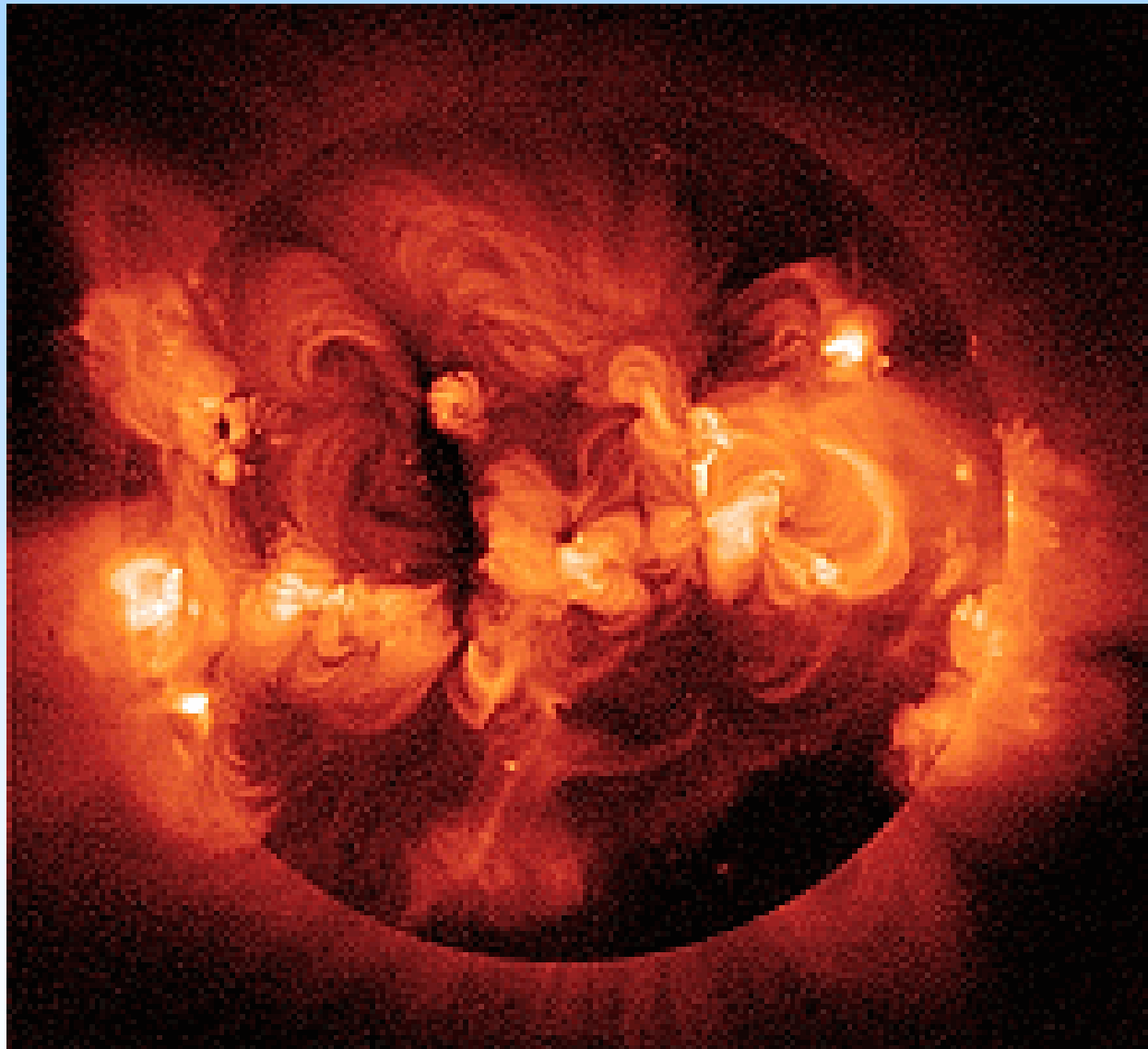


[https://www.esa.int/ESA\\_Multimedia/Images/2006/09/Hinode\\_Solar-B\\_mission\\_to\\_study\\_the\\_dynamic\\_Sun-](https://www.esa.int/ESA_Multimedia/Images/2006/09/Hinode_Solar-B_mission_to_study_the_dynamic_Sun-) credit: JAXA/ESA

Hinode-XRT

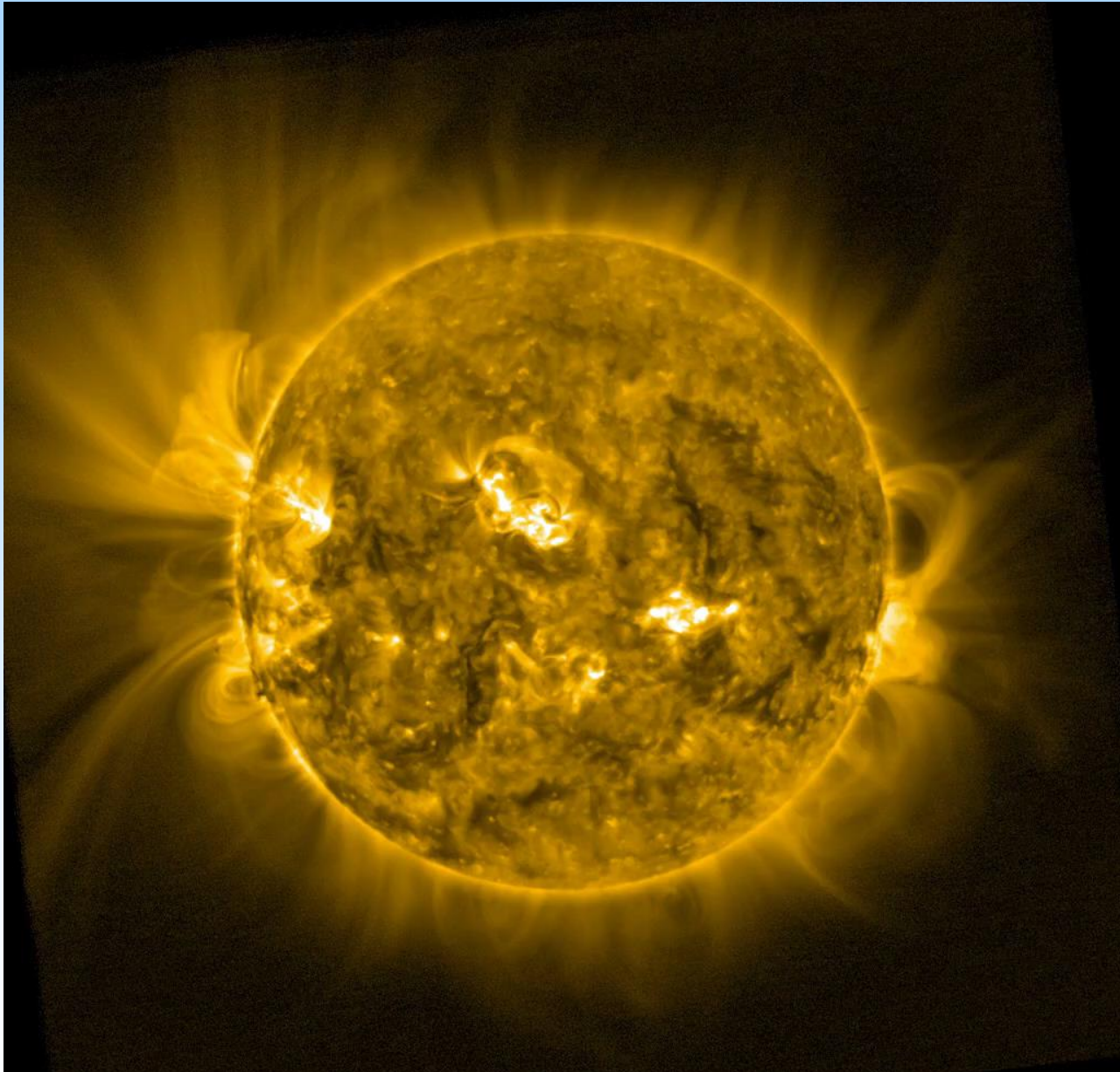


2017-08-21 16:47:06.068



NASA

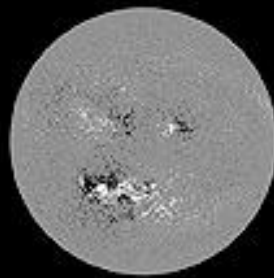
The Corona from Yohkoh/SXT



PROBA2/SWAP 17.4nm 2014-06-28 01:15:35



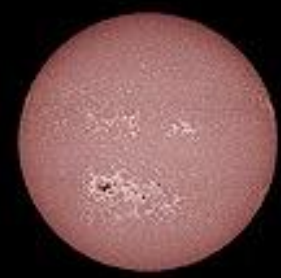
HMI Dopplergram  
Surface movement  
Photosphere



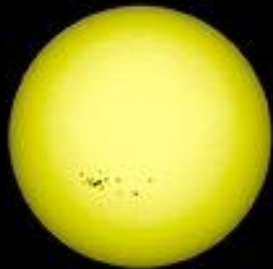
HMI Magnetogram  
Magnetic field polarity  
Photosphere



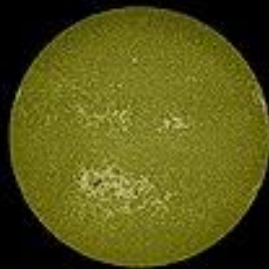
HMI Continuum  
Matches visible light  
Photosphere



AIA 1700 Å  
4500 Kelvin  
Photosphere



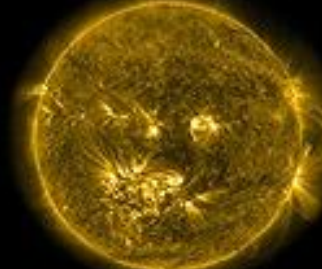
AIA 4500 Å  
6000 Kelvin  
Photosphere



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



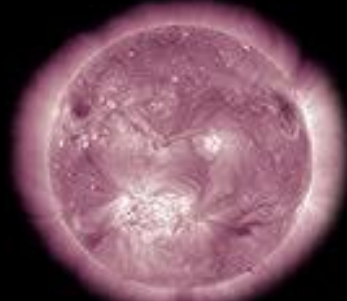
AIA 304 Å  
50,000 Kelvin  
Transition region/  
Chromosphere



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



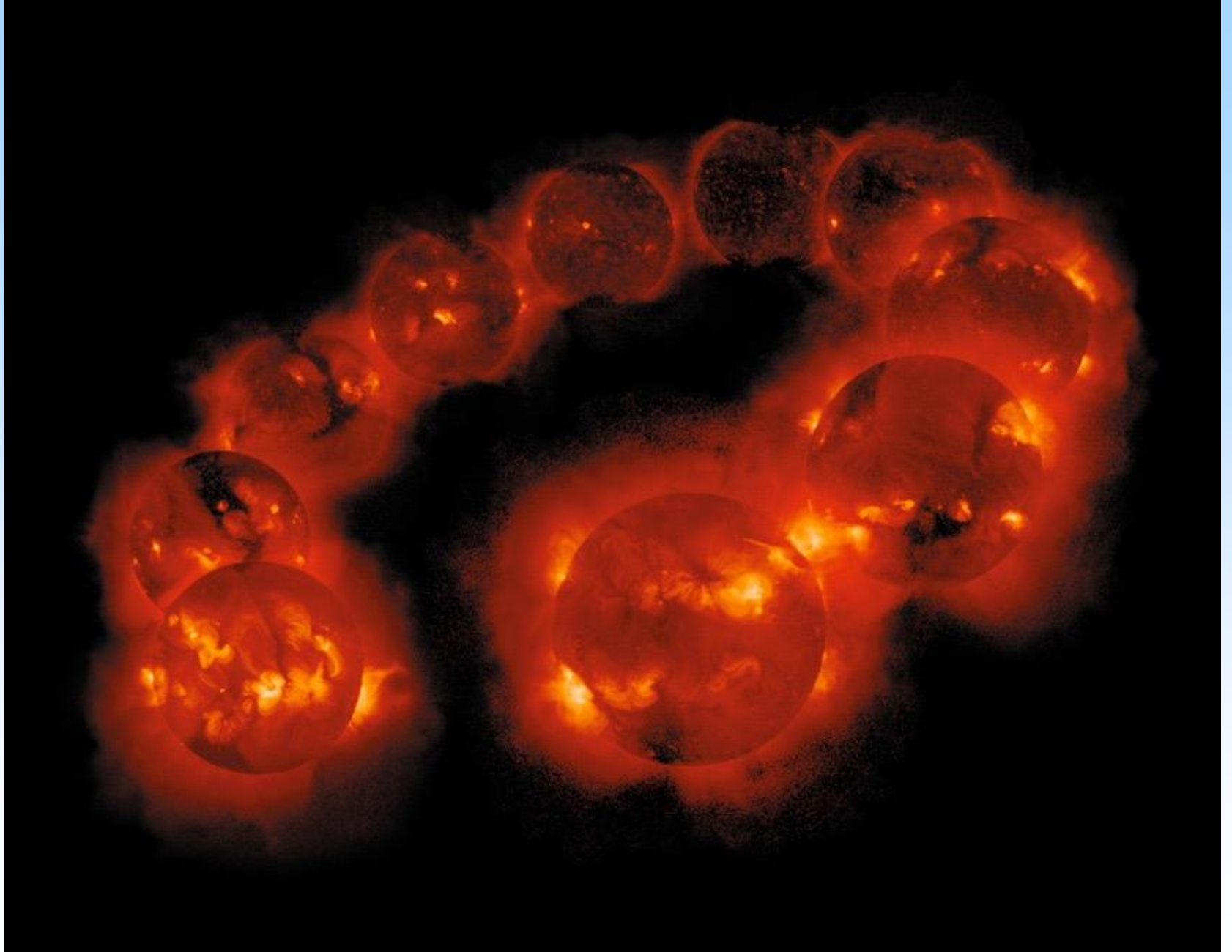
AIA 131 Å  
10 million Kelvin  
Flaring regions

# The Corona (continued)

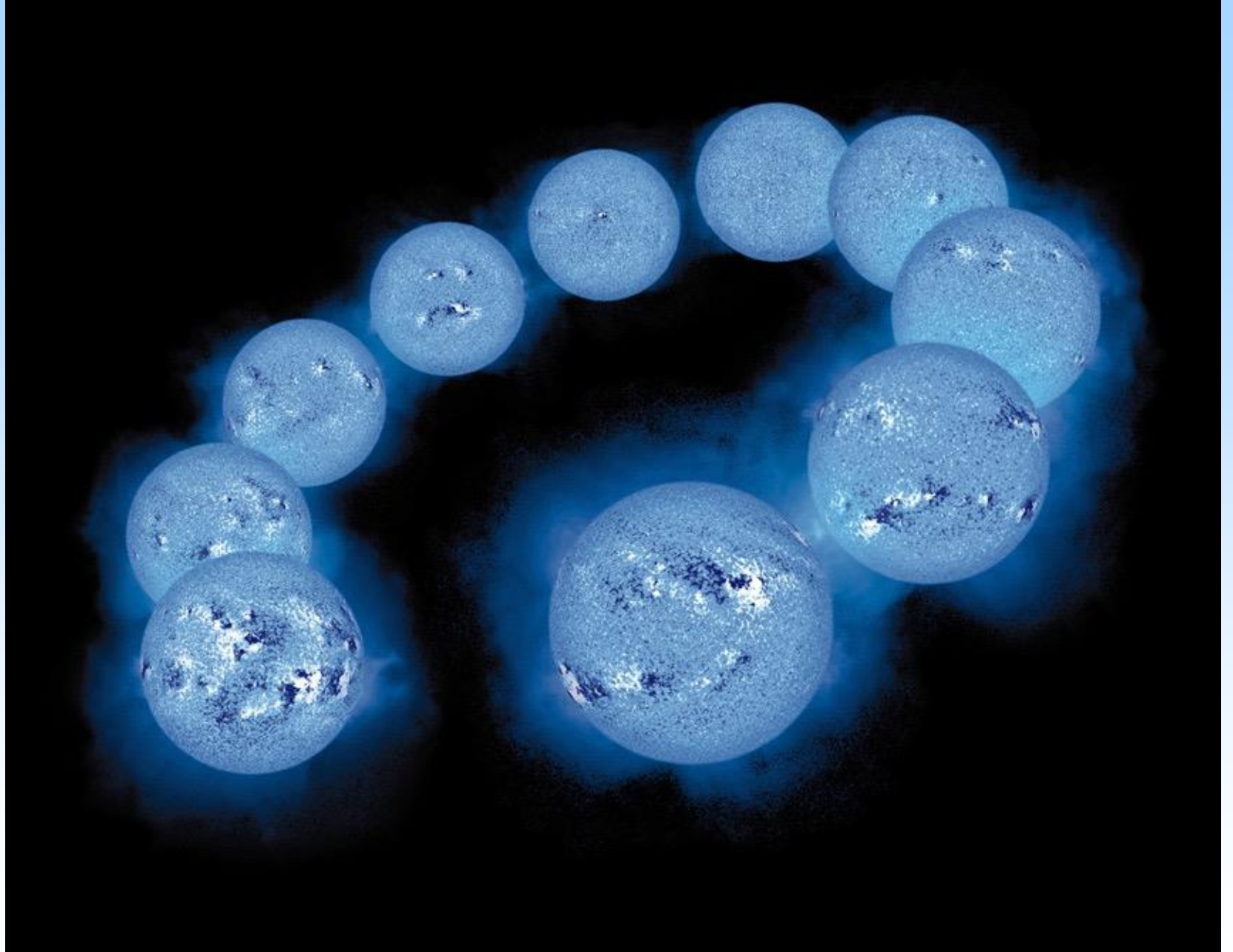
- 100 to 1000 times less dense than the chromosphere.
- Hotter than the photosphere and chromosphere  $\sim 10^6$  K.
- Its structure is determined by the magnetic field.
- Active regions are bright in the corona, the dark locations are *coronal holes*, where the magnetic field opens out into the heliosphere.
- The corona shows dramatic changes over the solar cycle.

# Corona (continued): The Magnetic Sun

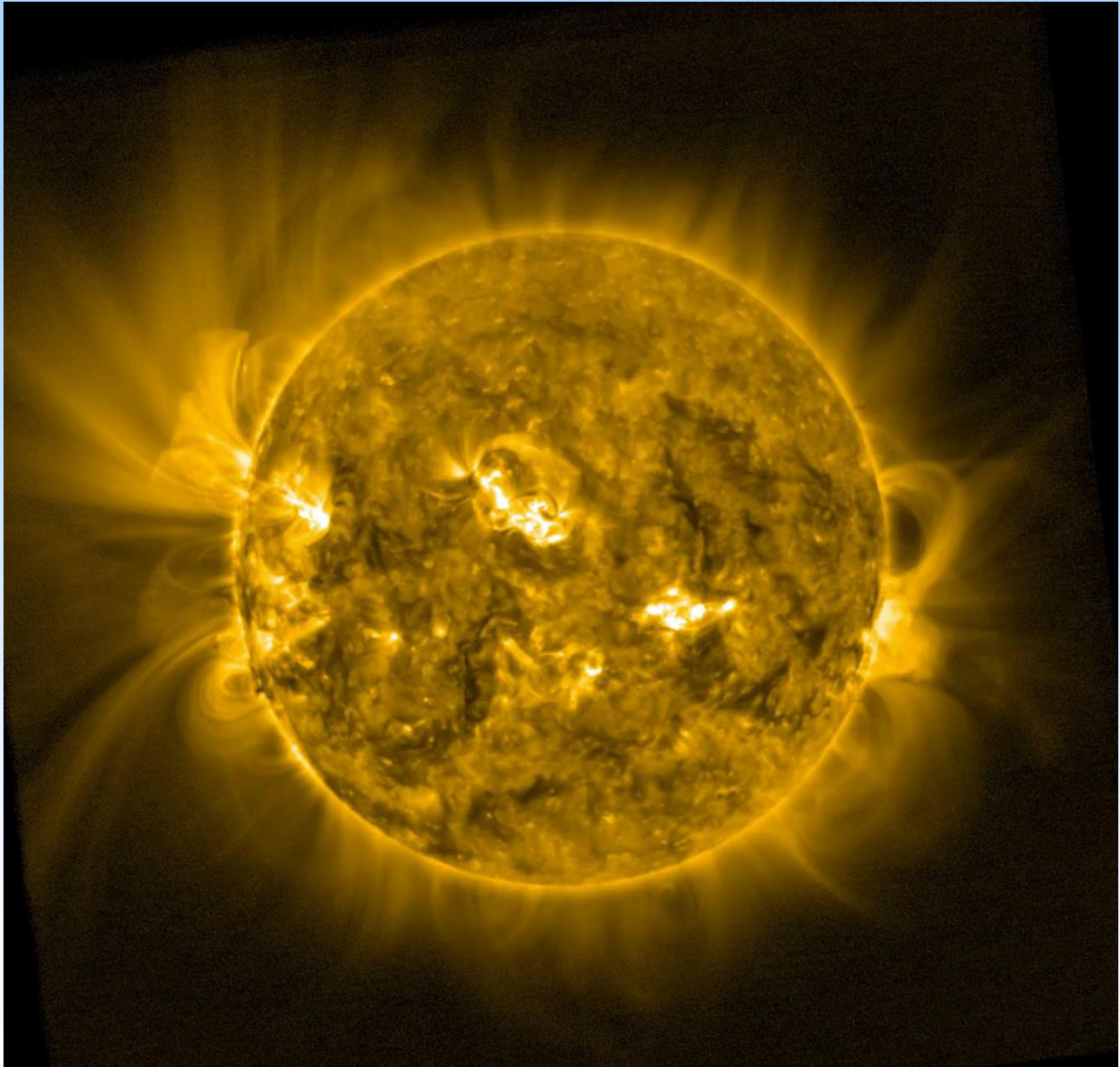
- In most solar locations - including in most of the corona - the magnetic field and plasma are tied together; we say that the field is *frozen into* the plasma. (Plasma can flow along field lines, but not normal to it.)
- The field and the plasma move together. Which dominates depends upon the *plasma beta*, the ratio of plasma pressure to magnetic pressure.
- In the convection and low photosphere beta is generally high, so that the plasma dominates. The atmosphere (upper chromosphere and corona) is *low beta*, so that the field determines the structure.



Credit: The solar X-ray images are from the *Yohkoh* mission of ISAS, Japan. The X-ray telescope was prepared by the Lockheed-Martin Solar and Astrophysics L

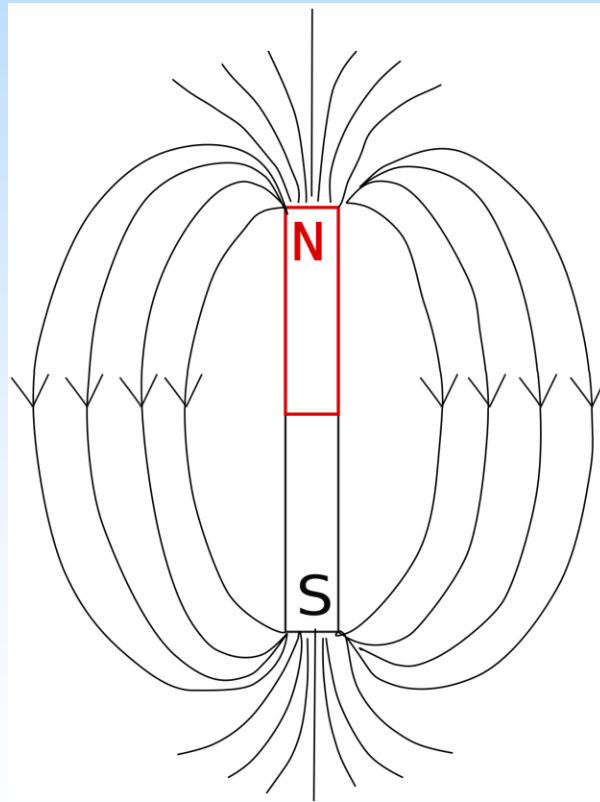


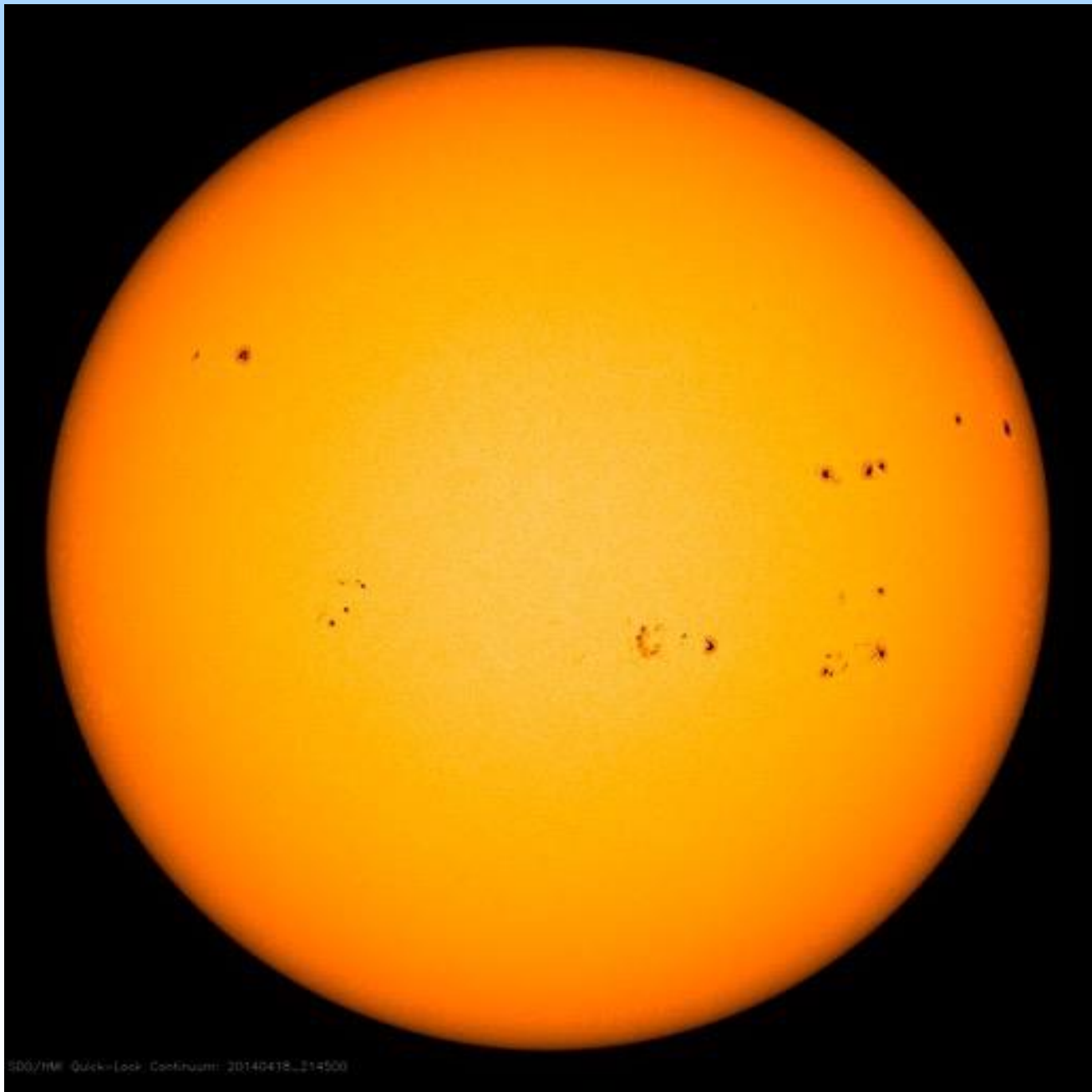
# Magnetism and the Sun - some more details



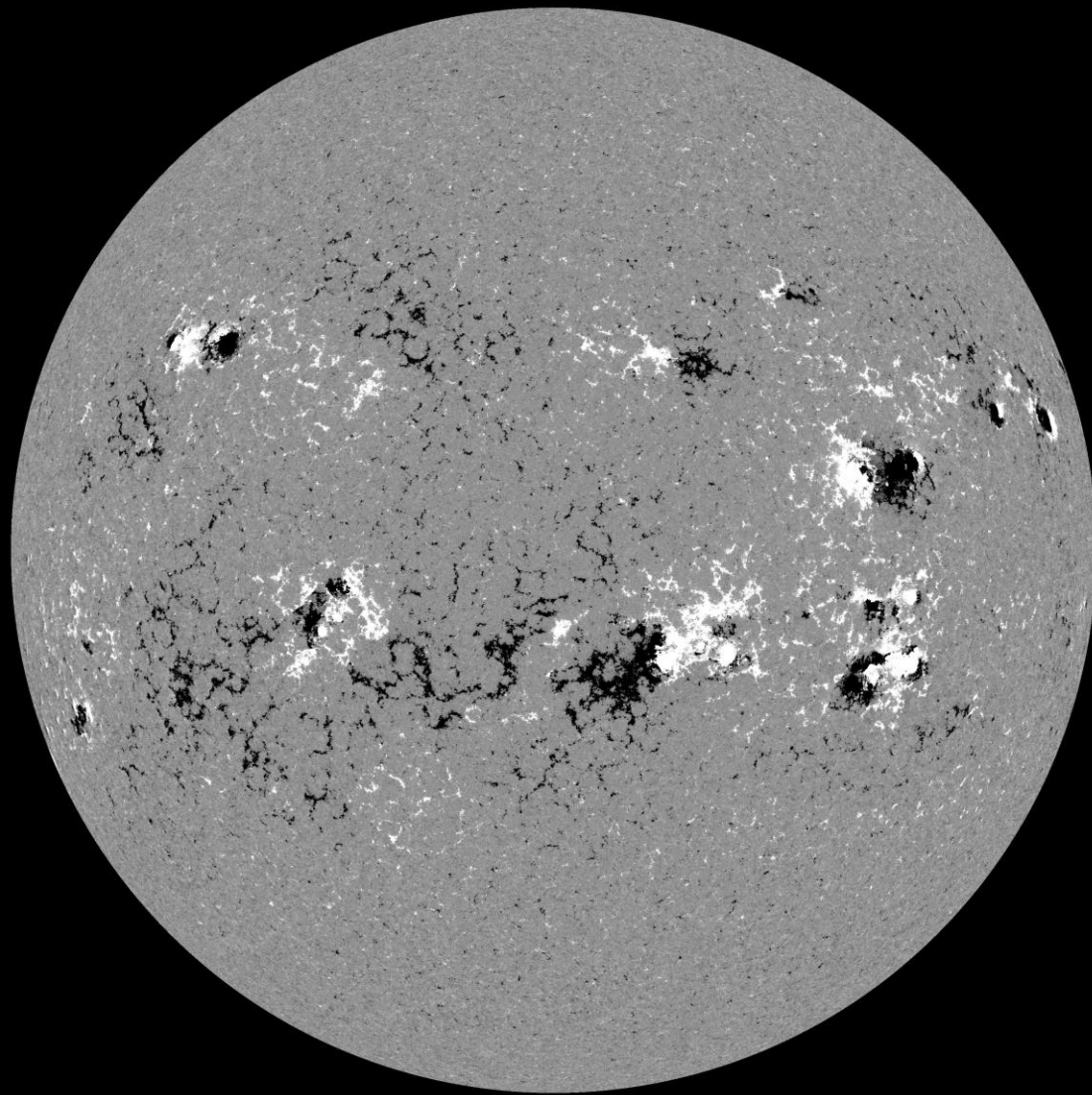
PROBA2/SWAP 17.4nm 2014-06-28 01:15:35

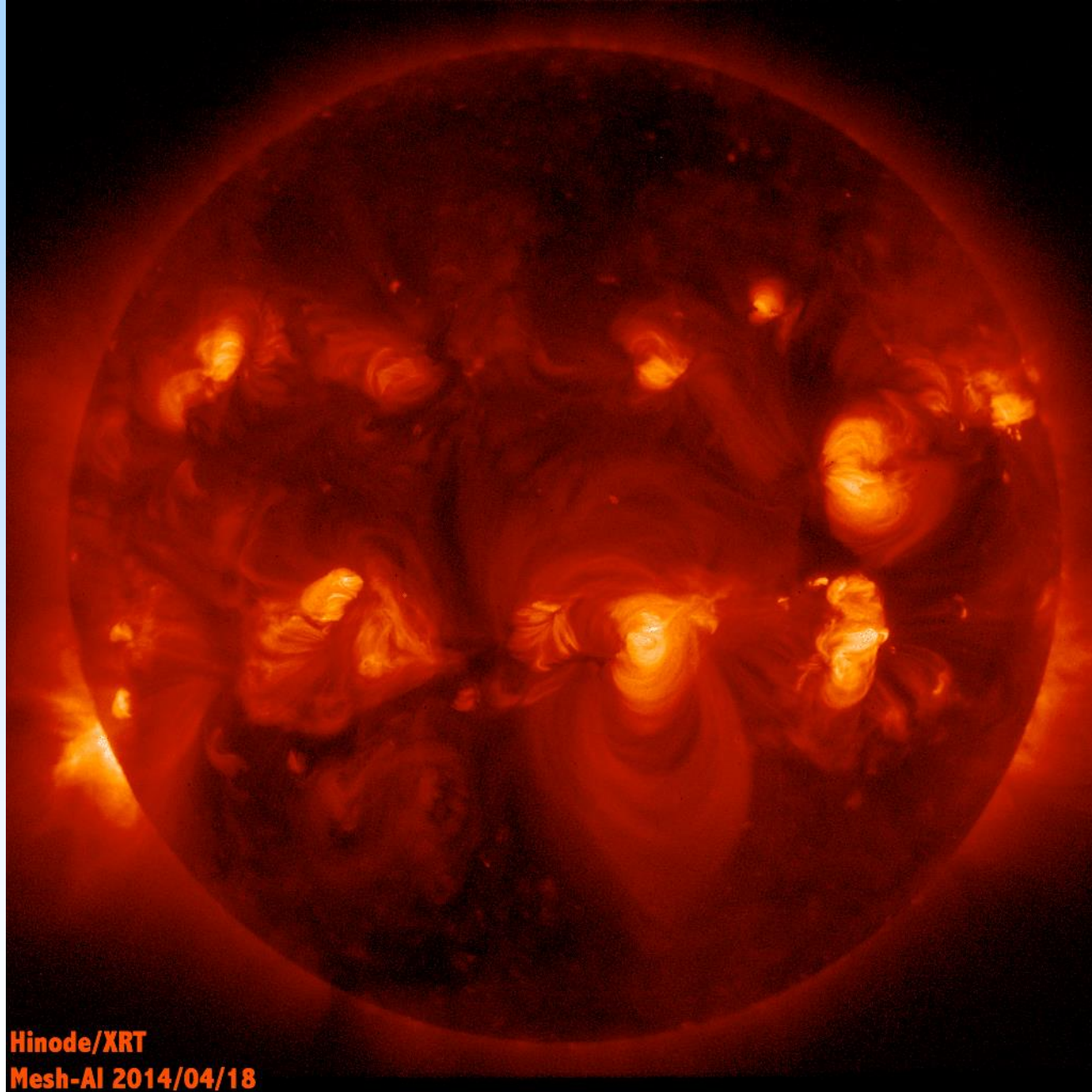
*Magnetism* is responsible for many of the changing features of the Sun.





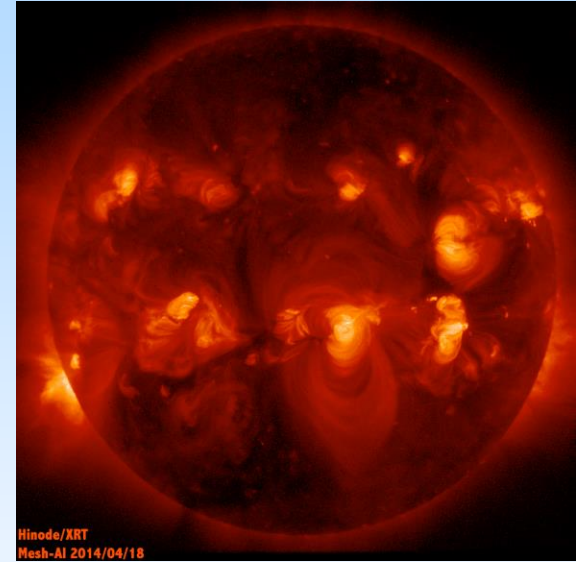
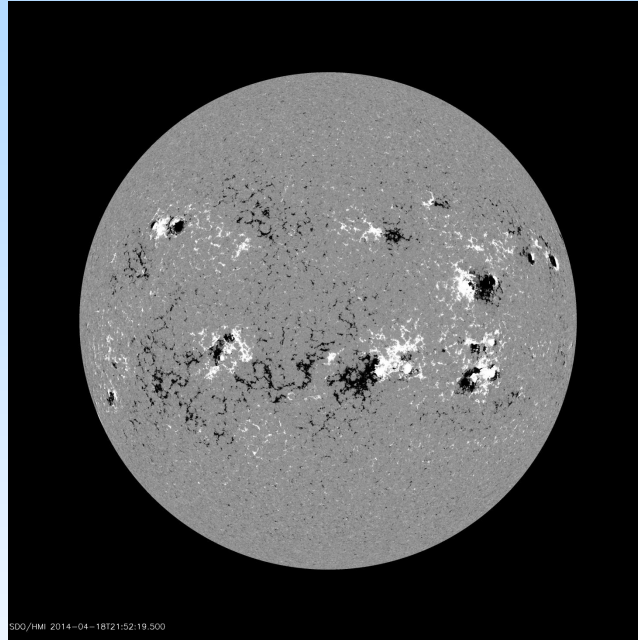
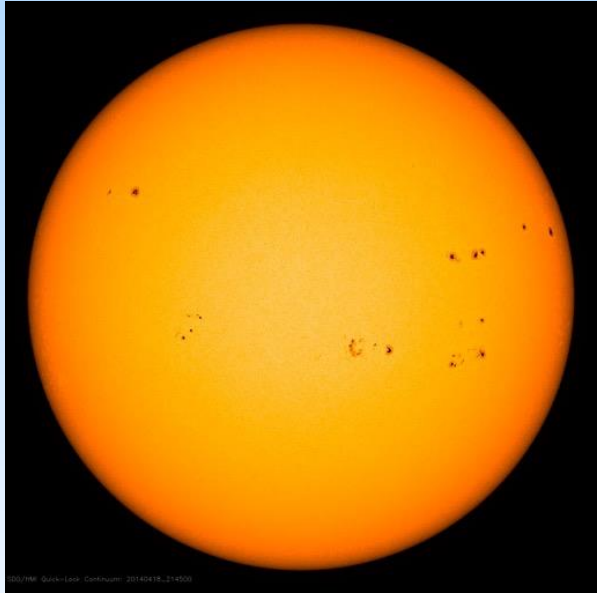
G00/HM Quick-Look Continuum: 20140418\_114500





Hinode/XRT

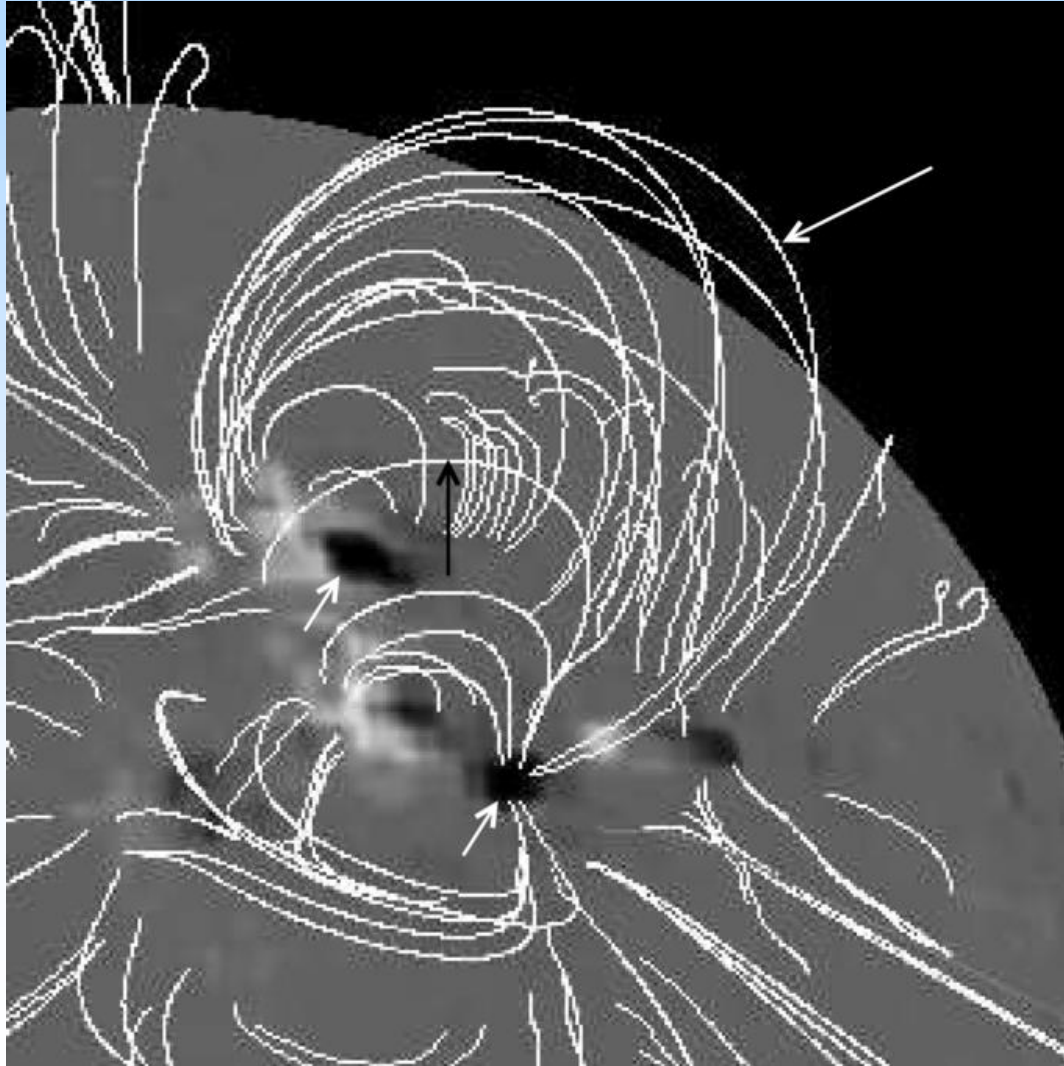
Mesh-AI 2014/04/18



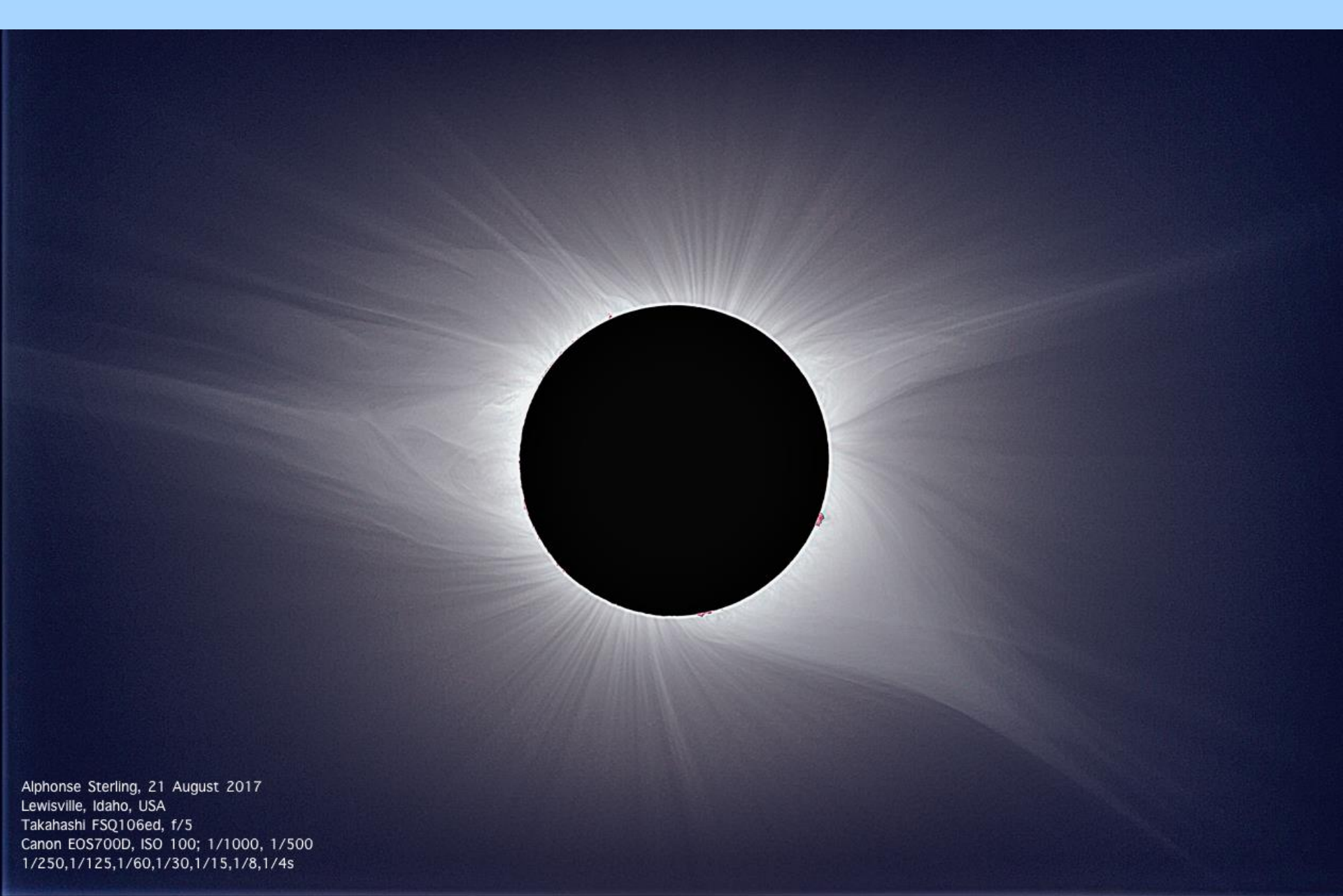
FMS 150505

Assume force free (and zero currents), leads to force-free potential field (PFSS)

$$j = 0 \Rightarrow \nabla \times B = 0 \Rightarrow B = \nabla \phi \Rightarrow \nabla^2 \phi = 0$$



(From Sterling et al. 2014)



Alphonse Sterling, 21 August 2017  
Lewisville, Idaho, USA  
Takahashi FSQ106ed, f/5  
Canon EOS700D, ISO 100; 1/1000, 1/500  
1/250, 1/125, 1/60, 1/30, 1/15, 1/8, 1/4s

Corona – The Sun's outermost atmosphere

# The Corona: Continued Again...

Now, let's consider again the temperature structure between the photosphere and the corona.

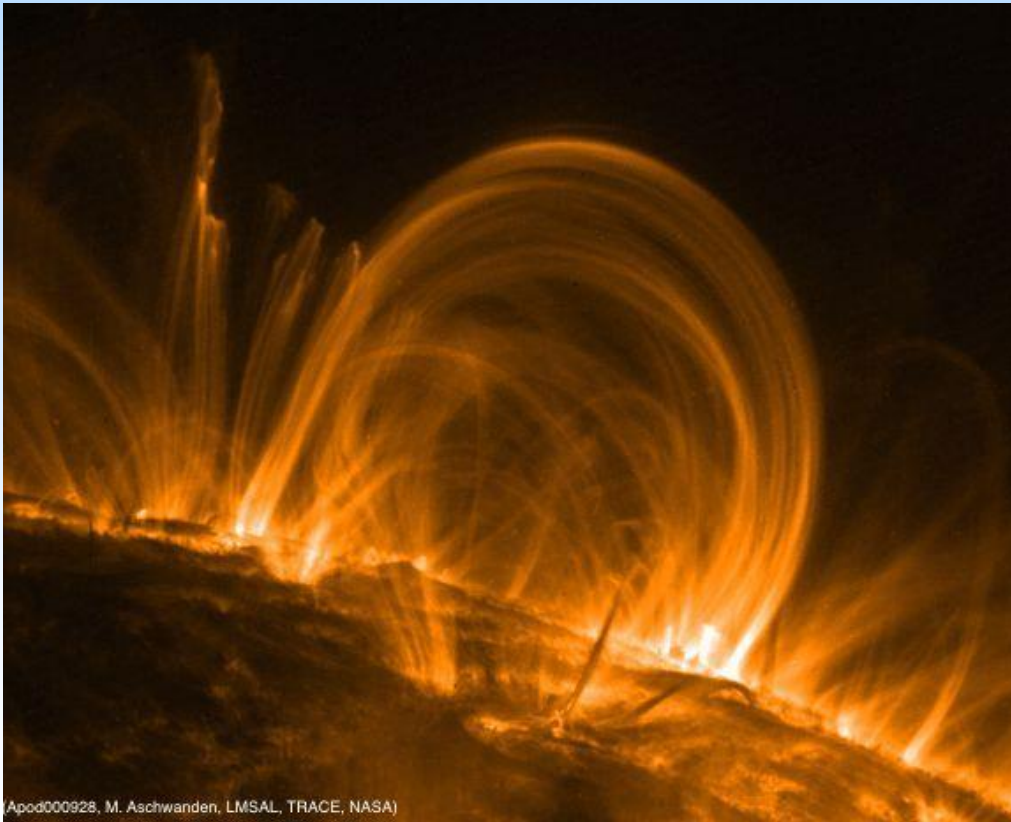
Next question: What makes the corona hot??

And the answer for now is...

*Magic!!*

Actually, a hot corona is not as mysterious as it seems....

Just assume a hot corona. Now, what does the temperature structure look like?



Energy balance equation:

$$H - R = C$$

R=Radiation losses; “known.”

C= Thermal Conduction;  
form known.

H= the “magic” Heating.

**Recipe: Adjust H until predictions of energy-balance equation match observations.** (Rosner, Tucker, Vaiana 1978.)

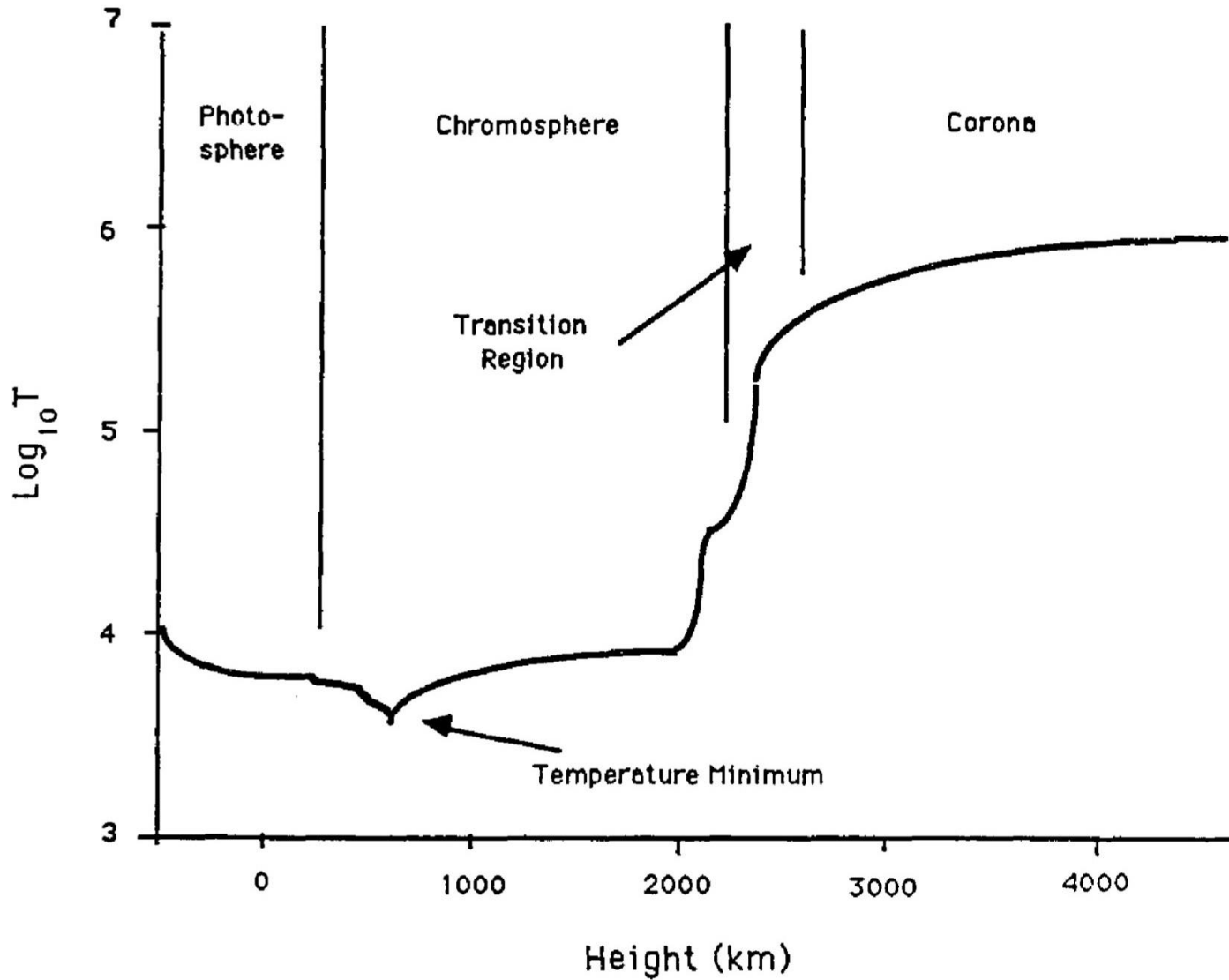
# Form of Thermal Conduction:

$$\mathbf{C} = \nabla \cdot \mathbf{F}_c$$

$$\mathbf{F}_c = -\kappa_0 T^{5/2} \nabla T$$

In 1-dimension (along a loop), this is:

$$F_c = -\kappa_0 T^{5/2} \frac{dT}{dz}$$



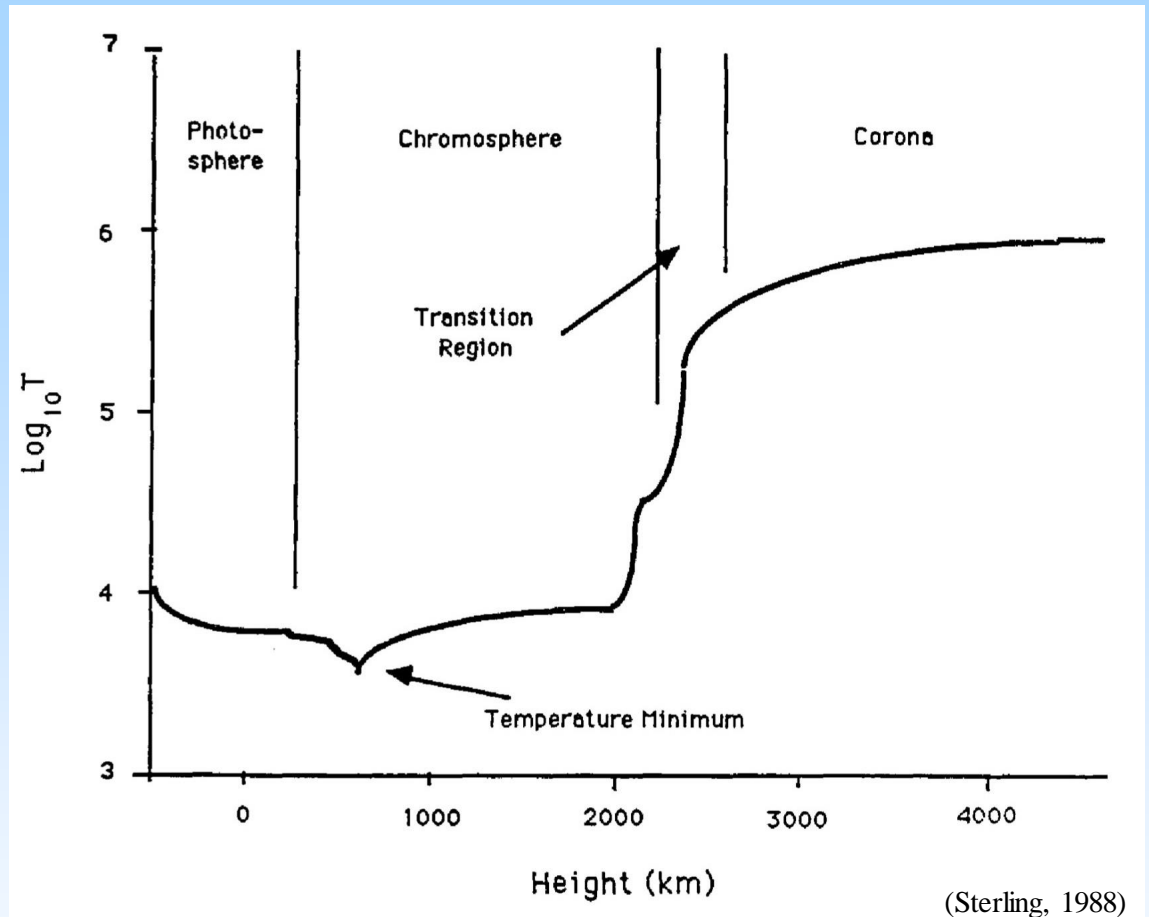
(Sterling, 1988)

$$H - R = C$$

At around  $T \sim 10^5$  K:

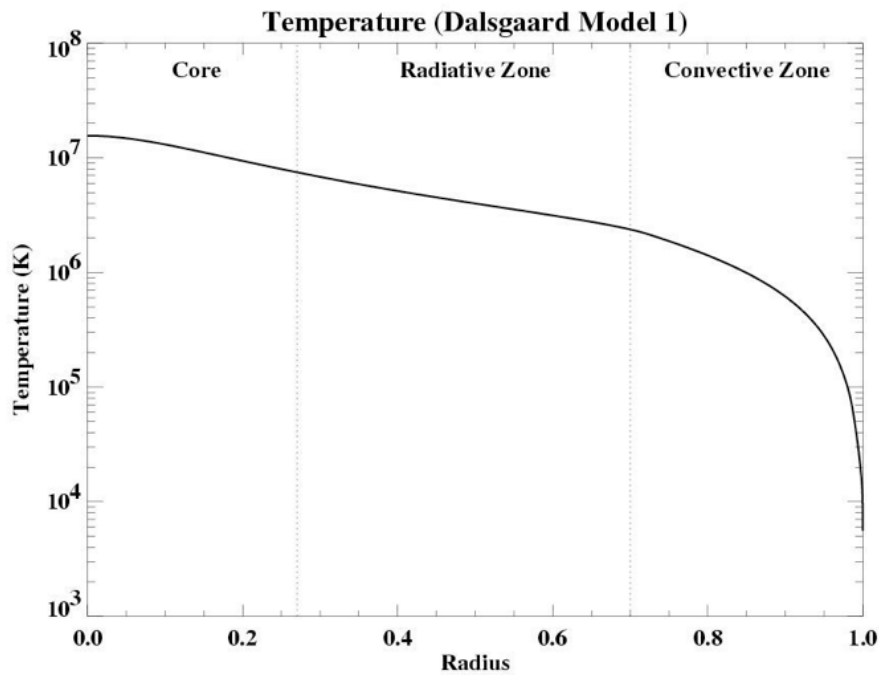
$$-R \approx C$$

$$R \approx \frac{d}{dz} \left[ \kappa_0 T^{5/2} \frac{dT}{dz} \right]$$

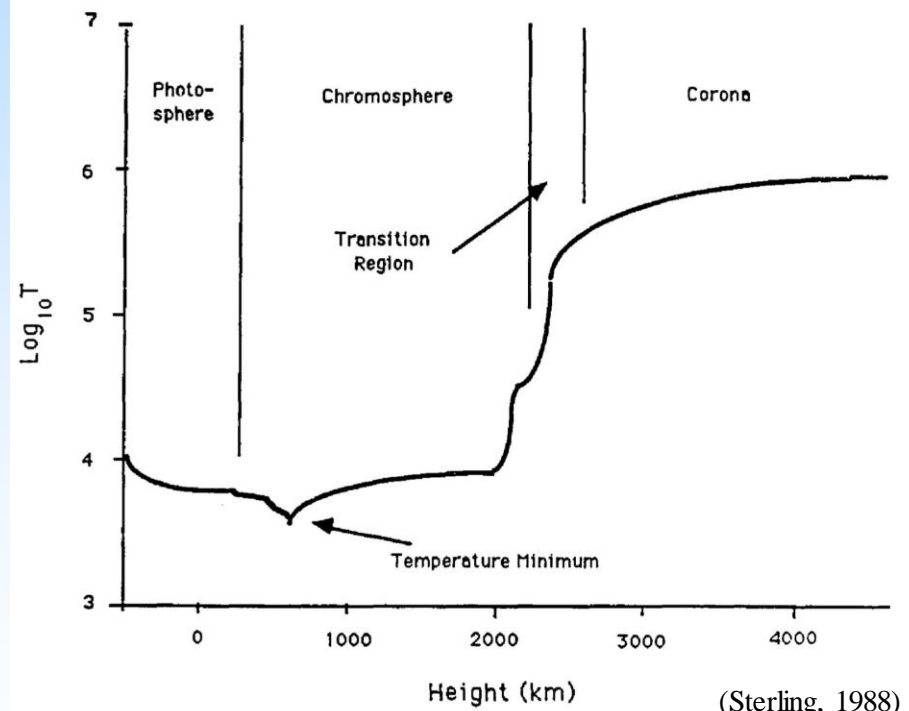


Strong radiation in this temperature range means a steep temperature gradient is needed for energy balance. This leads to a “thin” transition region.

# The Sun's Temperature Structure



NASA/MSFC Hathaway



(Sterling, 1988)

# Coronal Heating - Briefly:

Currently there are two leading concepts receiving attention for heating the corona:

- *Magnetic reconnection*. Photospheric motions twist up the coronal field. This twist accumulates in coronal loops. The field undergoes reconnection, which is a process by which the field reconfigures to a simpler topology (less potential  $\rightarrow$  more potential), releasing energy in the process.
- *Wave heating*. Photospheric motions inject *Alfvén waves*, which are transverse waves that propagate along the field at the Alfvén speed:  $v_A = (B^2/8\pi)^{1/2}$  onto the coronal field. Somehow (more magic!) the energy is transmitted from the waves into the coronal plasma, heating it.

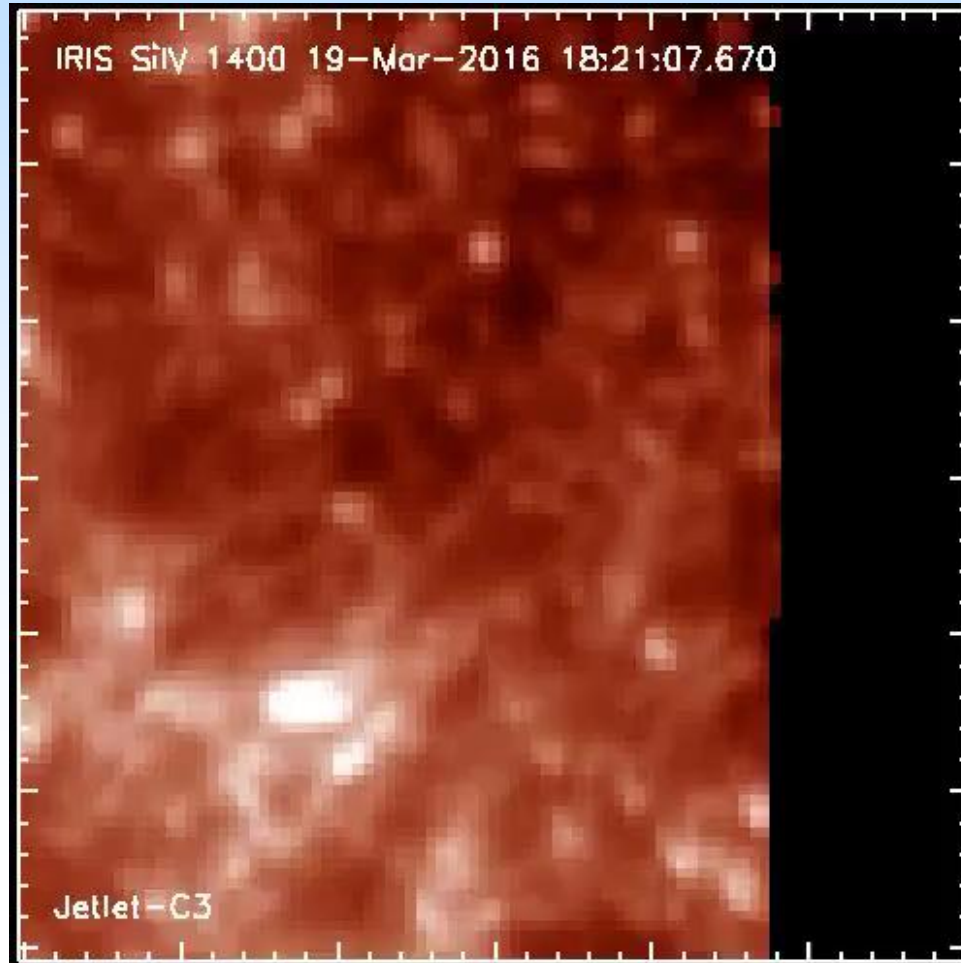
# The Transition Region:

- Between the chromosphere and the corona.
- Thin region.
- Emits in UV, so also must go to space to see details.
- The IRIS satellite is designed to observe the transition region.

# But, are the above assumptions correct??

- (Just considering the atmospheric portion)
- There are many assumptions, including:
  - 1-dimensional calculations
  - Static atmosphere
  - Etc.

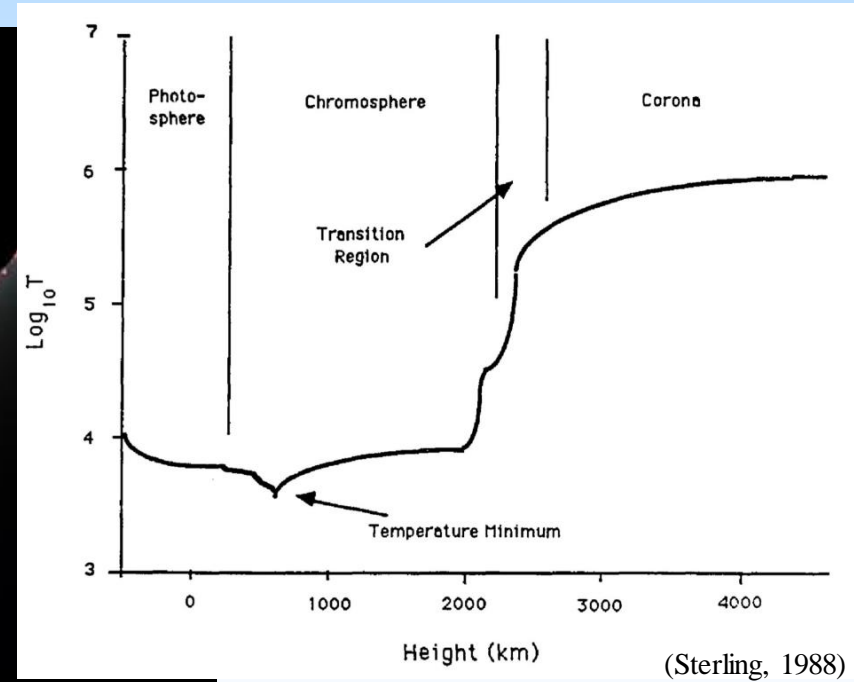
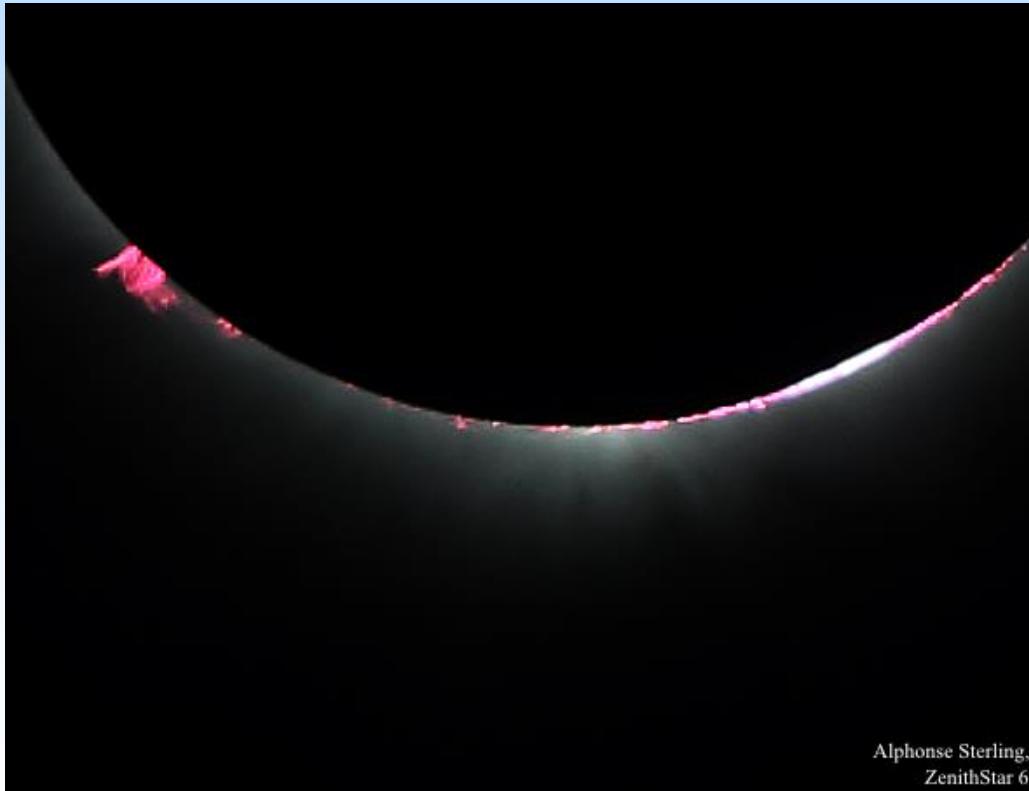
The “IRIS” satellite observes the transition region, and finds it to be highly dynamic. It’s not static, like in the simplest models!



(Panesar et al. 2018)

# Another example: Prominences/Filaments

Chromospheric material suspended in the corona



# Summary

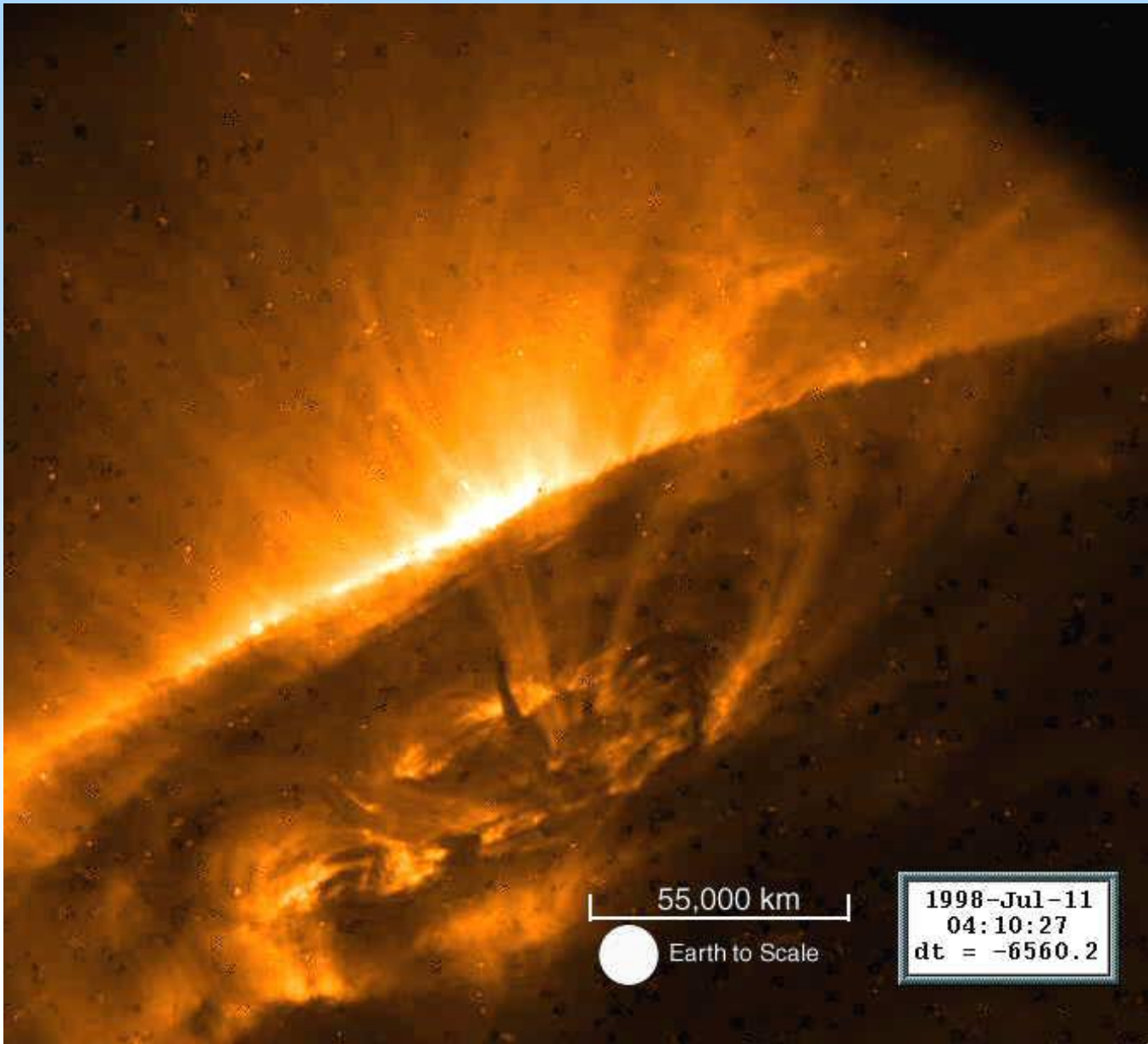
- General structure of the Sun is well understood.
- There are still fundamental questions that remain to be resolved. Two that I have touched on here are:
  - Coronal heating: The mechanism must be magnetic, but how the magnetic energy is converted to thermal energy is still vigorously debated.
  - How does energy build up and violently release to cause solar eruptions, leading to flares and CMEs?
  - And there are many others!

Image:  
Alphonse Sterling  
21 August 2017,  
Lewisville, Idaho

(Blank)

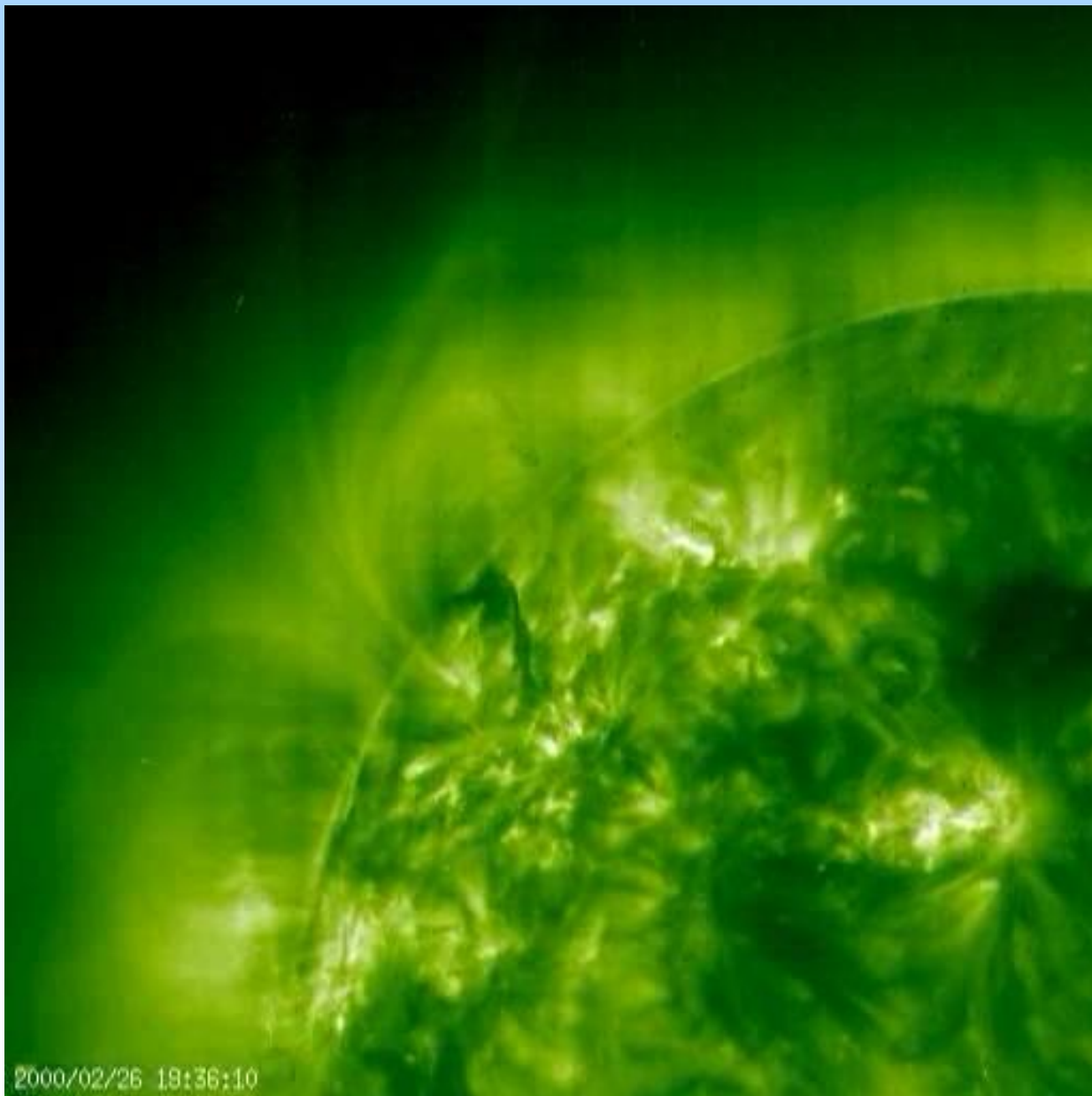
(Backup Slides)

# Solar Eruptions



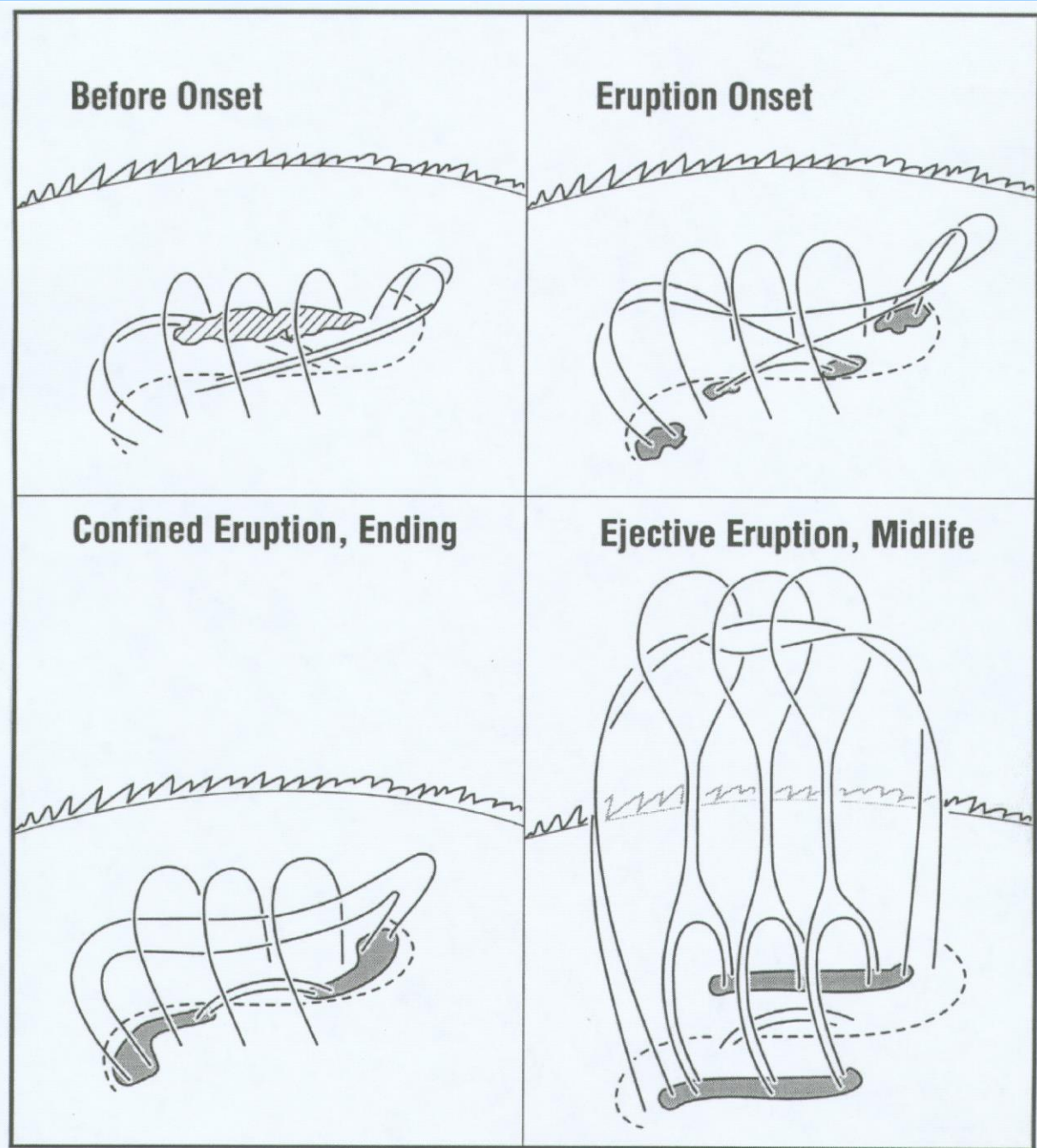
55,000 km  
● Earth to Scale

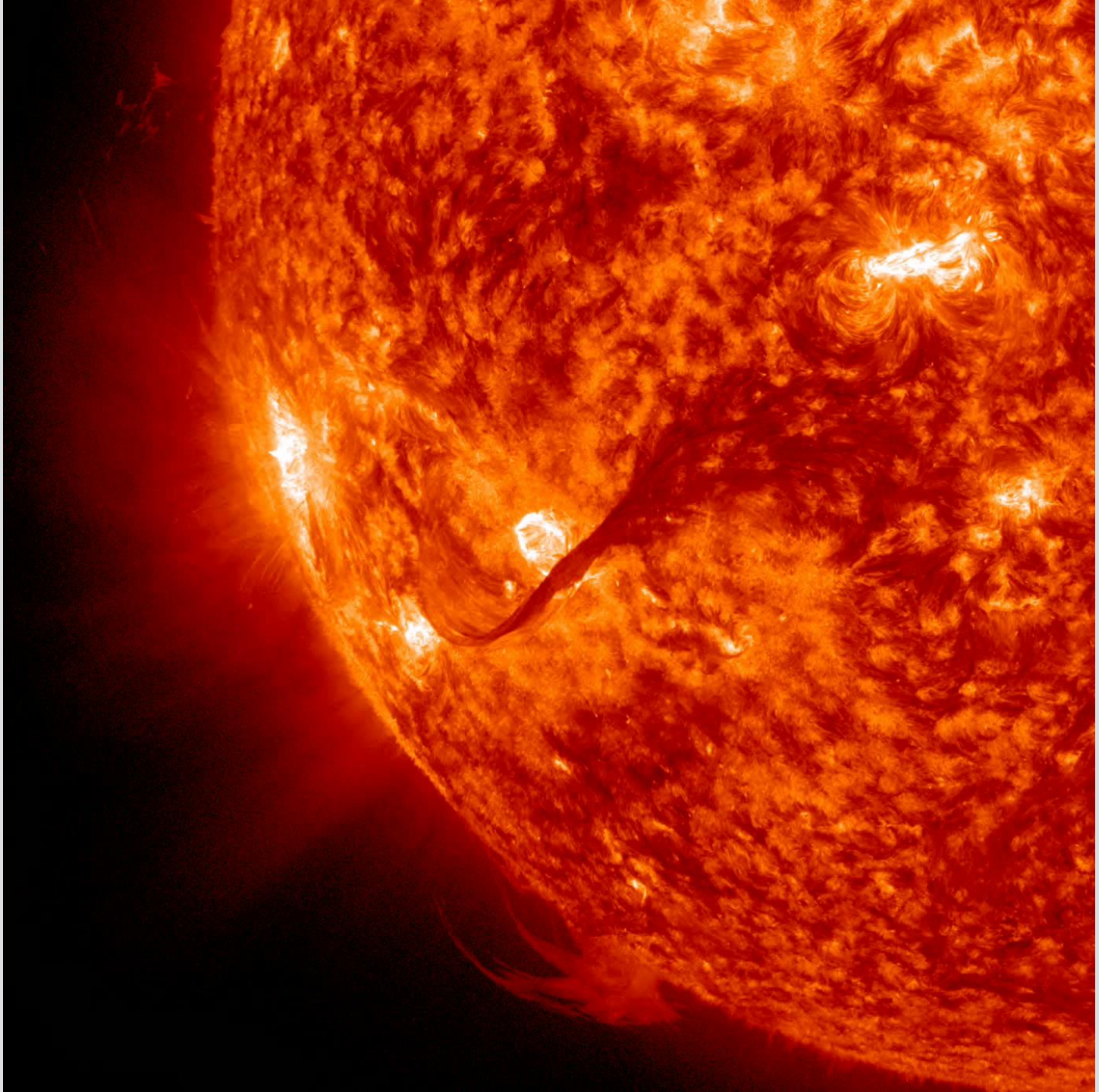
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04:10:27  
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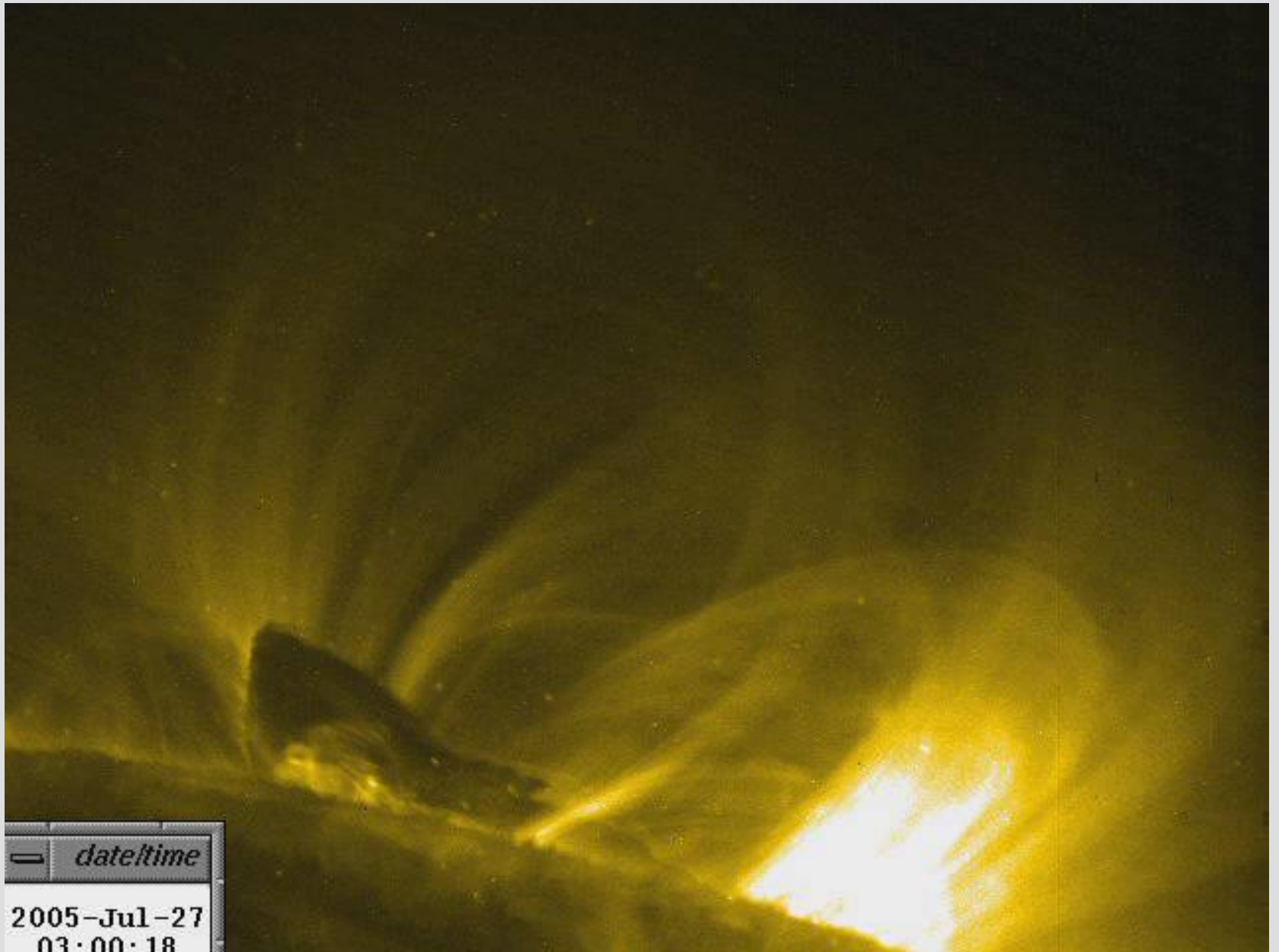
(Sterling & Moore 2004)

(Moore et al. 2001)

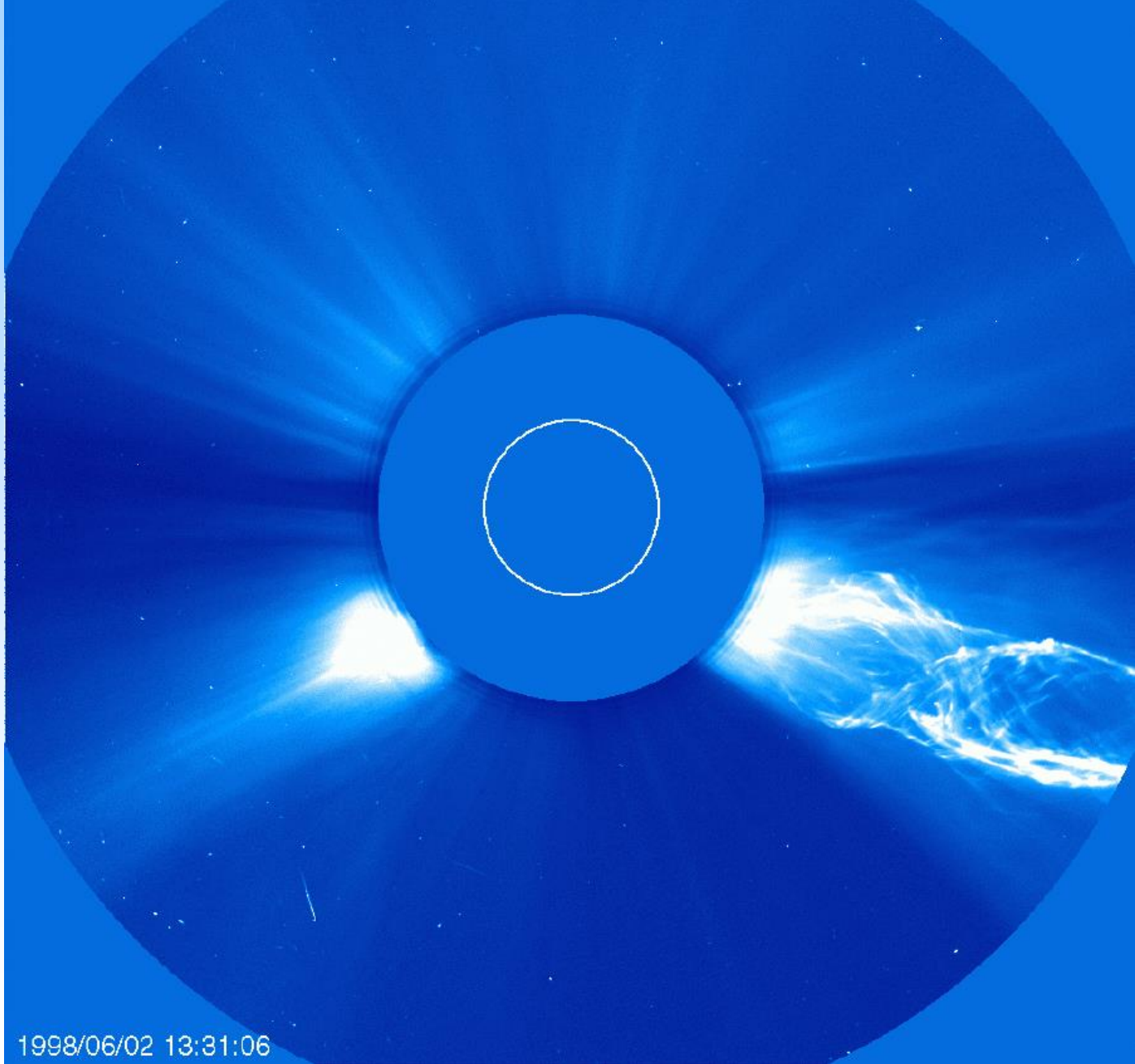




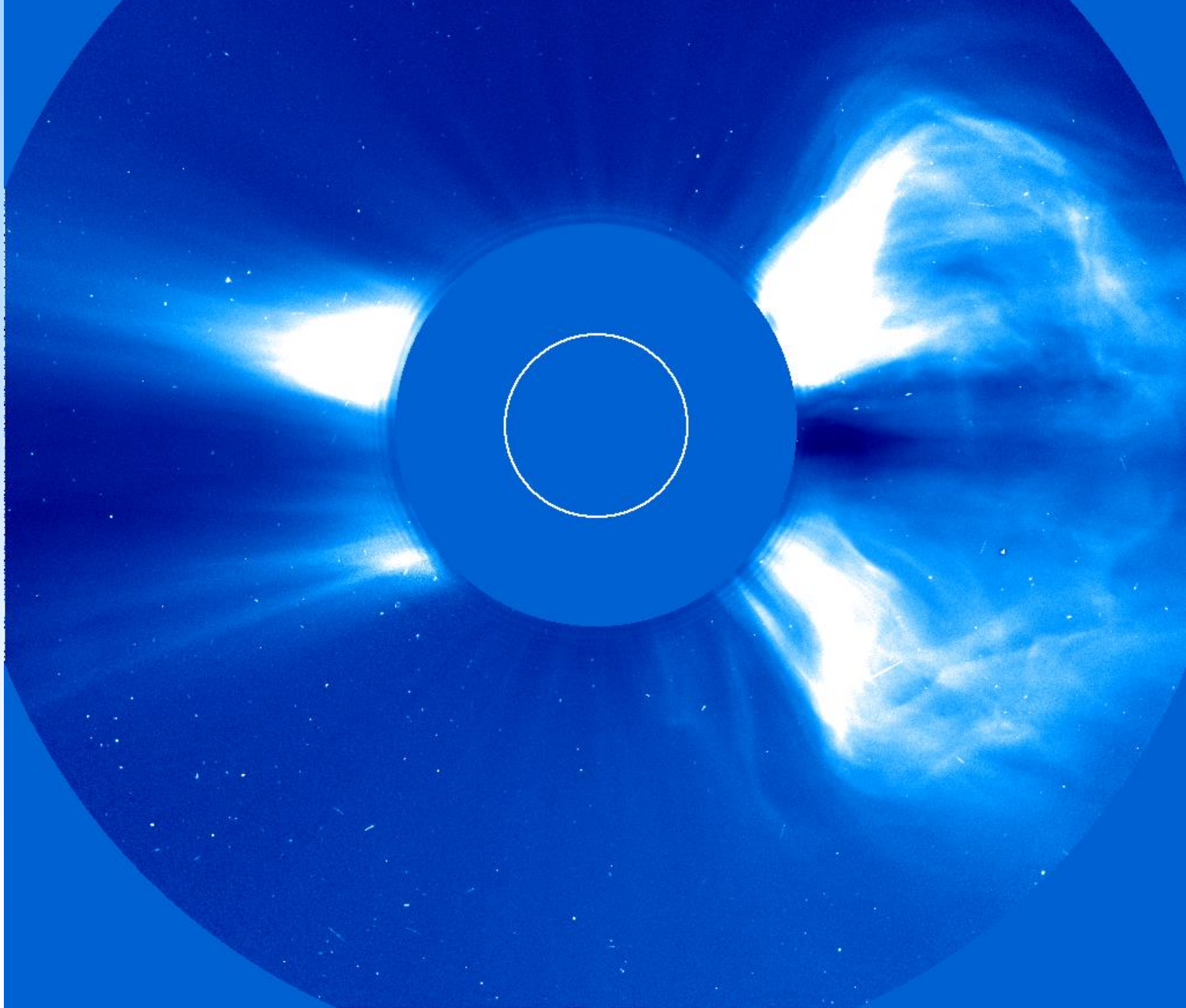
(TRACE 171)



*datetime*  
2005-Jul-27  
03:00:18



1998/06/02 13:31:06



1998/01/26

