Part 2: Stars

- Thursday, February 9 Reading: Chapter 6 [Ed. 9, 10, 11, 12]
  - The nature of light: How we use spectra to measure the properties of stars
- Tuesday, February 14 Reading: Chapters 8, 9.1, 9.5 or Orion Nebula
  - Stars: distance, luminosity, mass, composition. Star formation. HW2 assnd
- Thursday, February 16 Reading: Chapter 7.1 — 7.2 or 7.3 on the Sun
  - Stars: Our Sun.
- Tuesday, February 21 Reading: Chapters 7 or 9 on fusion, 9.2 — 9.5
  - Stars: Stellar models, energy generation, main sequence life
- Thursday, February 23 Reading: Chapters 10.1 — 10.3
  - Stars: Evolution from main sequence to white dwarf or Type II supernova
- Tuesday, February 28 Reading: Chapters 10.4, 11 HW 2 due
  - Stars: Type I supernovae; white dwarf stars, neutron stars, black holes
- Wednesday, March 1 Help session from 4 — 6 PM in Welch 3.502
- Thursday, March 2 Exam 2 (Part 2)
- Monday, March 6 Help session from 4 — 6 PM in RLM 4.102
- Tuesday, March 7 Exam 3 (Parts 1 + 2)
- Thursday, March 9 Exam 4 (Parts 1 + 2)

The Sun

Average distance from Earth:
1.4960×10^8 km = 1.0000 AU
Maximum distance from Earth:
1.5210×10^8 km = 1.0167 AU
Minimum distance from Earth:
1.4710×10^8 km = 0.9833 AU
Average Angular diameter seen from Earth:
0.53° = 32 minutes of arc

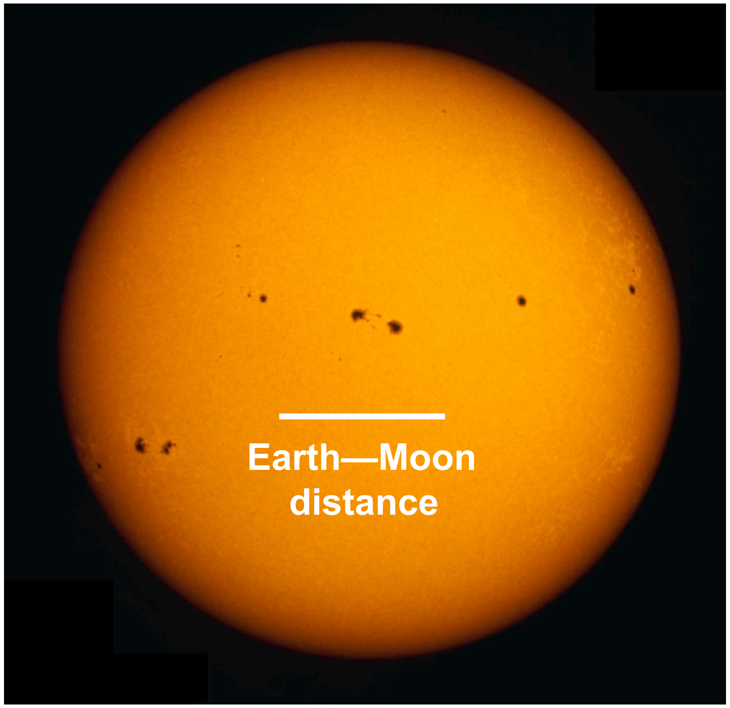
Period of Rotation: 25 days at equator
Period of Rotation: 27.8 days at latitude 45°

Radius: 6.960×10^5 km
Mass: 1.989×10^{30} kg
Average density: 1.409 g/cm^3

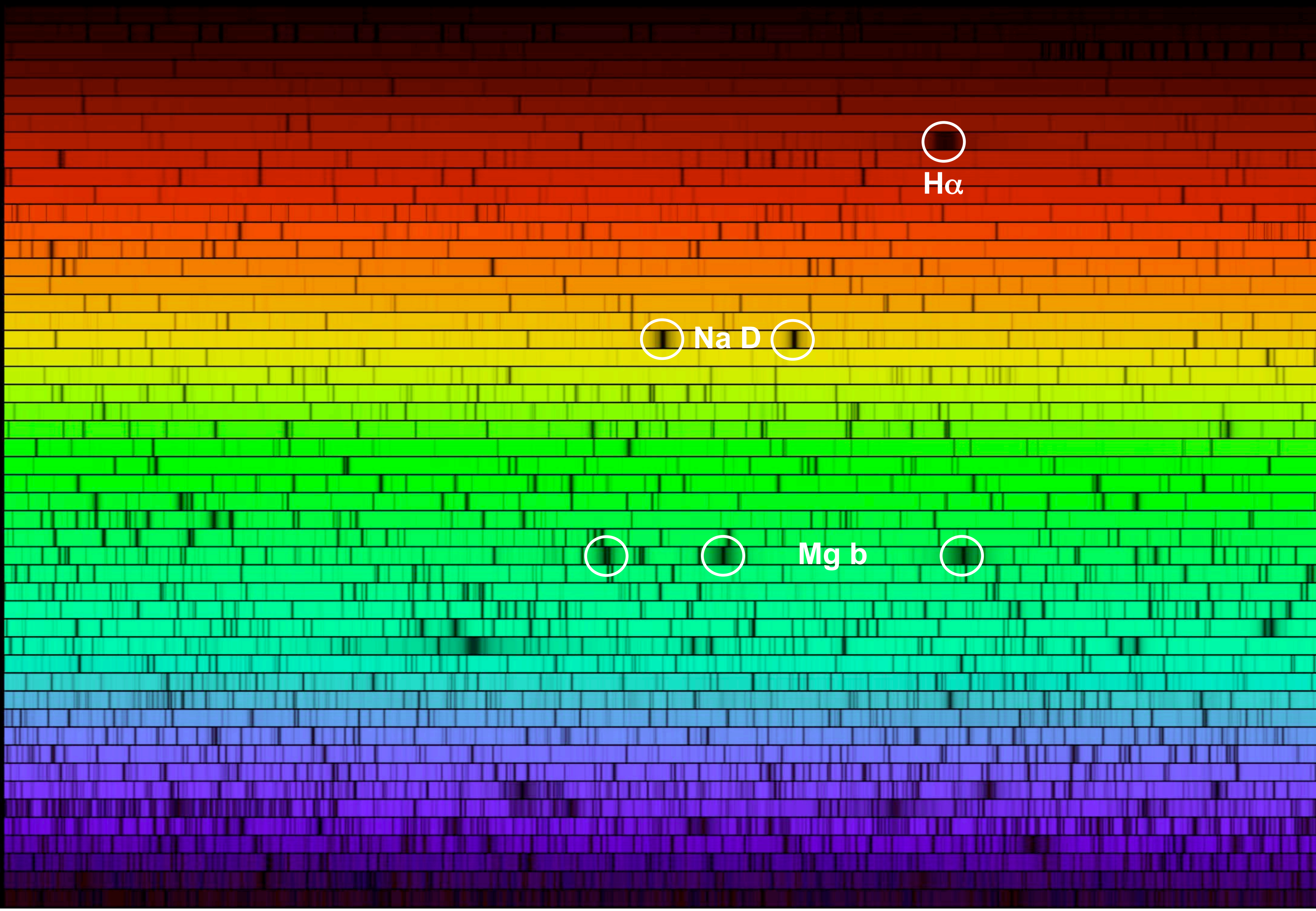
Escape velocity at surface = 618 km/s

Surface temperature = 5800 K
Central Temperature = 15 million K
Spectral type = G2 main sequence

Apparent visual magnitude = -26.74
Absolute visual magnitude = 4.83



The spectral type of the Sun is G2



Abundance of Elements in the Sun's Atmosphere

Element	% by No. of Atoms	% by Mass
Hydrogen	91.0	70.9
Helium	8.9	27.4
Carbon	0.03	0.3
Nitrogen	0.008	0.1
Oxygen	0.07	0.8
Neon	0.01	0.2
Magnesium	0.003	0.06
Silicon	0.003	0.07
Sulfur	0.002	0.04
Iron	0.003	0.01

Note: Abundances are different in the Sun's core, because much of the hydrogen has already been converted to helium.

Conduction, Radiation, and Convection

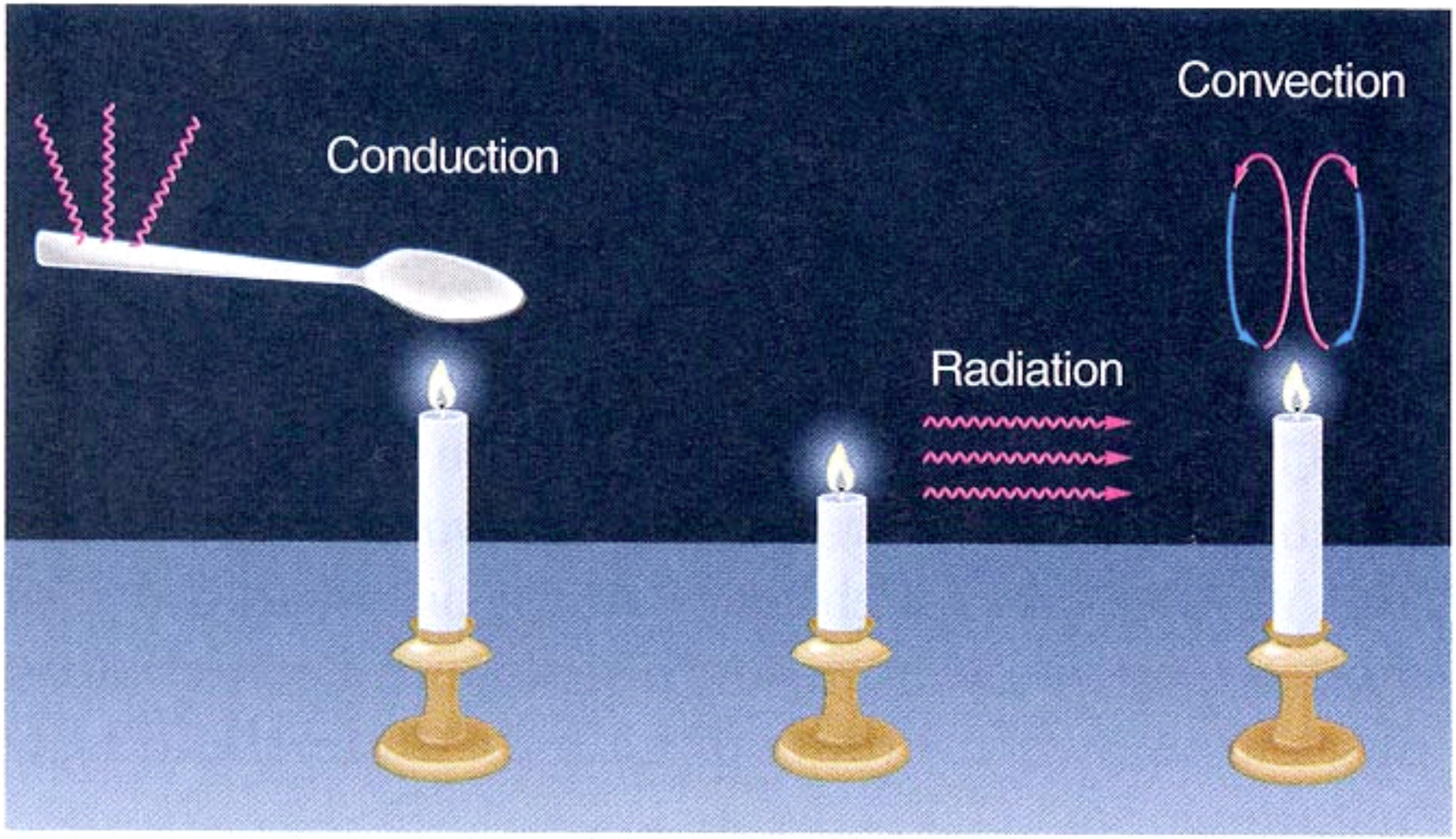
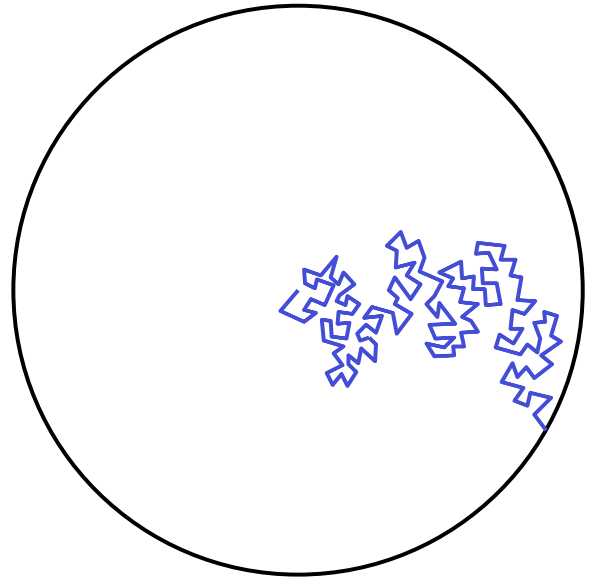


Figure 9-20
The three modes by which energy may be transported from the flame of a candle, as shown here, are the three modes of energy transport within a star.

Energy Flows by Radiation or by Convection

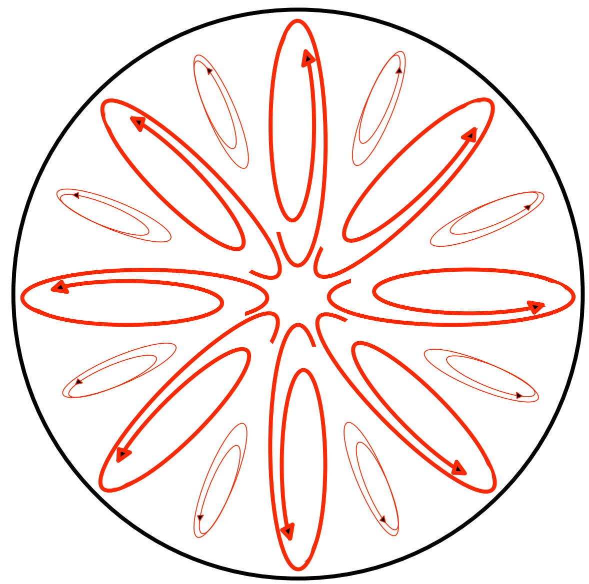
Radiative Diffusion:

Photons are repeatedly absorbed and reradiated in random directions. A single, high-energy photon that is made by nuclear reactions takes a million years to get to the Sun's surface, by which time it has been converted into about 1600 photons of visible light. Note: the light travel time from the center of the Sun to the surface is only about 2 seconds!



Convection:

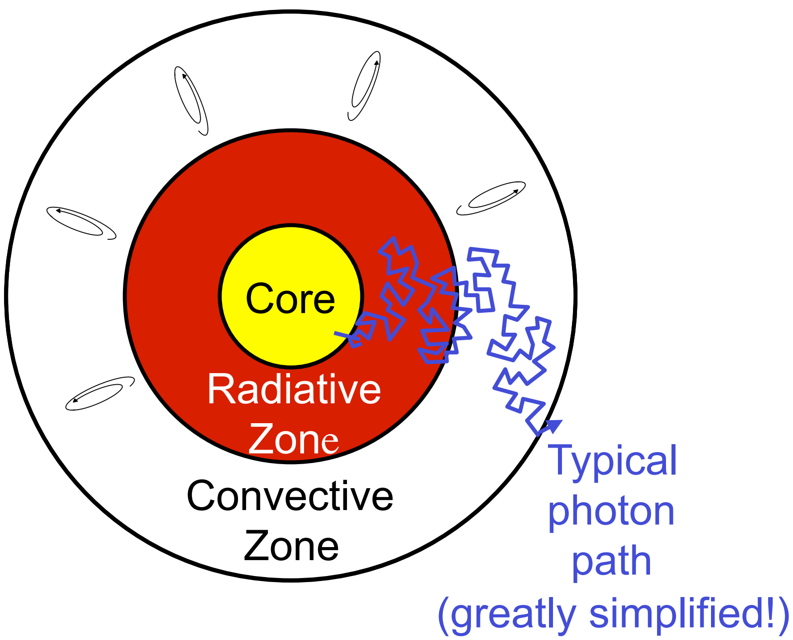
Energy can also be carried out from center of a star by the motion of hot gas.

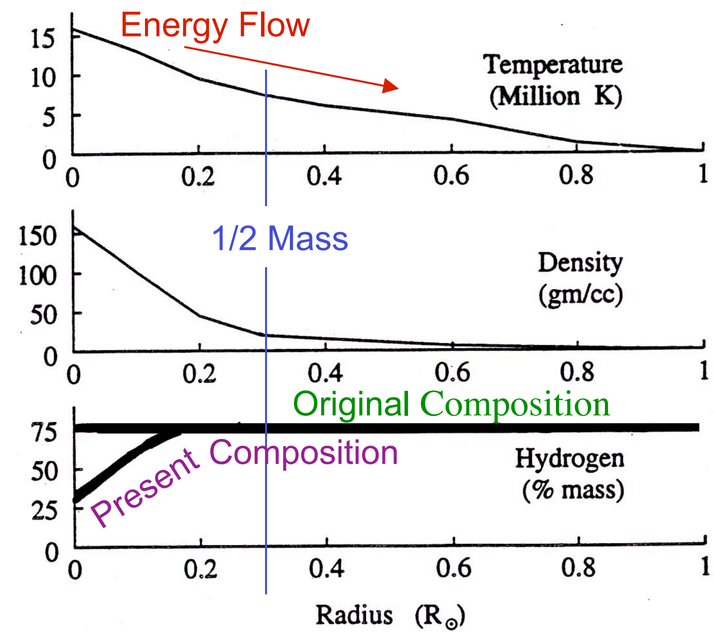


Inside the Sun

The Sun is a typical main sequence star, about half way through its 10 billion year life.

In its internal structure, the Sun resembles other main sequence stars of the same mass. In the core, where temperatures are hot enough, energy is released by the fusion of hydrogen to helium (next lecture). This energy flows outward, first by radiation and then mostly by convection, before it reaches the photosphere and escapes as light.





The graphs show how temperature, density, and composition change with radius inside the Sun.

Conduction, Radiation, and Convection

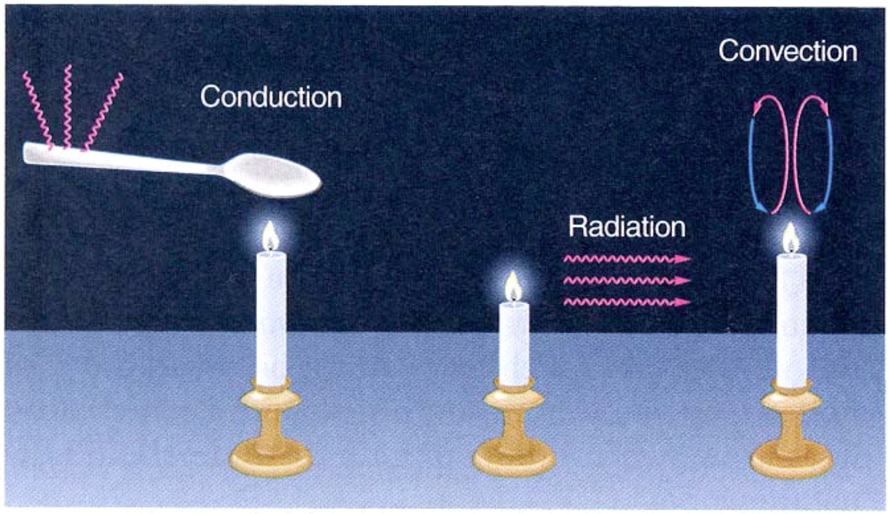


Figure 9-20
The three modes by which energy may be transported from the flame of a candle, as shown here, are the three modes of energy transport within a star.

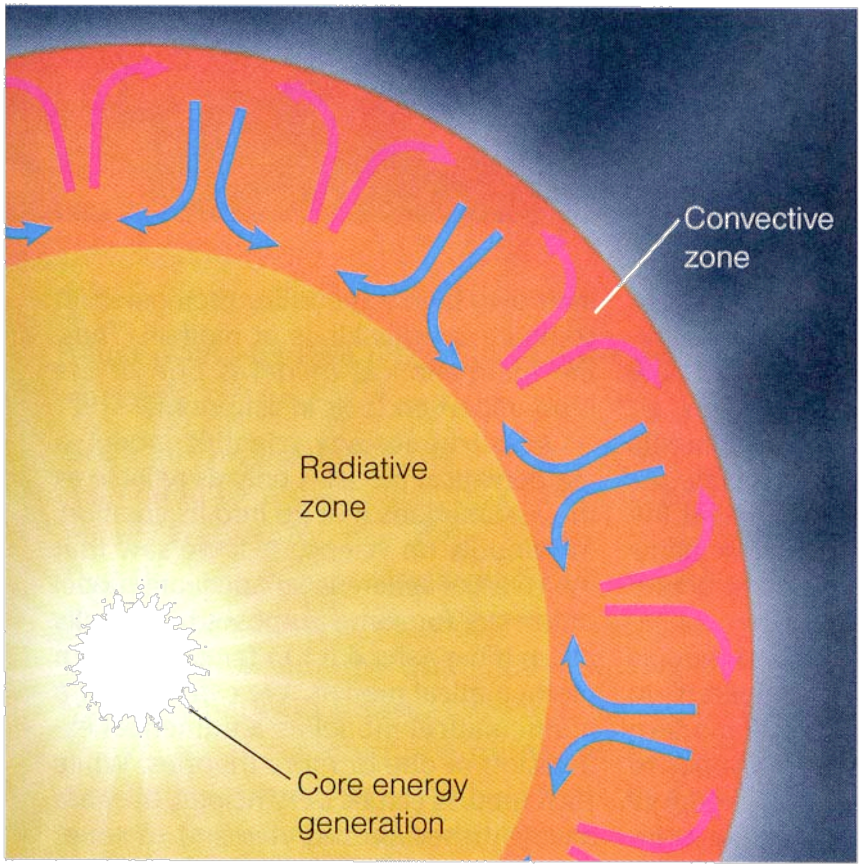
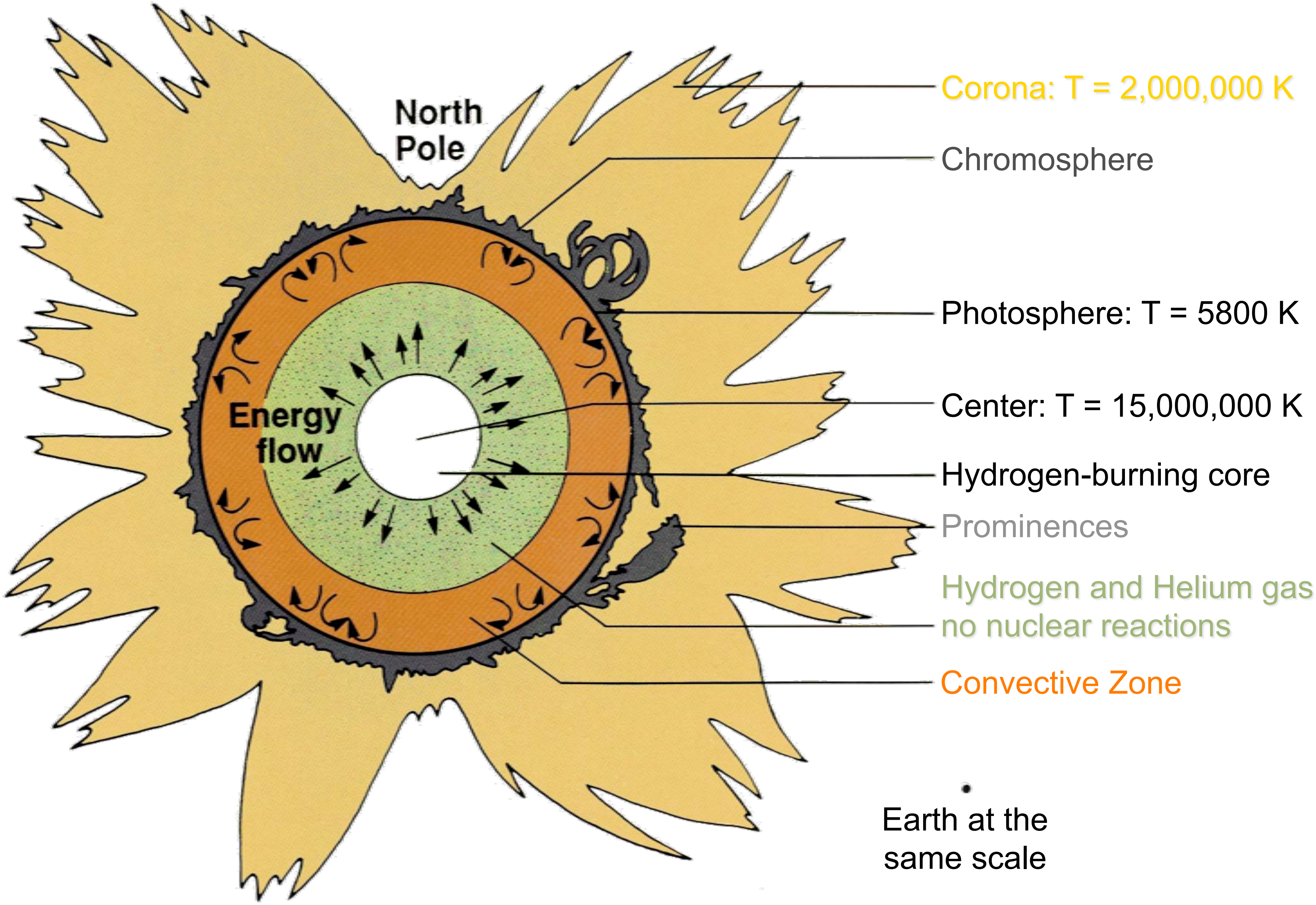


Figure 9-21
A cross section of the sun. Near the center, nuclear fusion reactions generate high temperatures. Energy flows outward through the radiation zone as photons. In the cooler, more opaque outer layers, the energy is carried outward by rising convection currents of hot gas (red) and sinking currents of cooler gas (blue).

Cross Section of the Sun



The Sun's Atmosphere

Photosphere

The **photosphere** is the deepest layer from which photons can easily escape. Most light from the Sun is emitted in the photosphere. The temperature of the photosphere decreases smoothly with altitude to a minimum of about 4400 K. There, absorption lines are formed.

Chromosphere

In the **chromosphere** the temperature increases to a maximum of about 10,000 K. Because the density is low, the **chromosphere** is transparent. During a solar eclipse, it can be seen as a pink layer just above the photosphere.

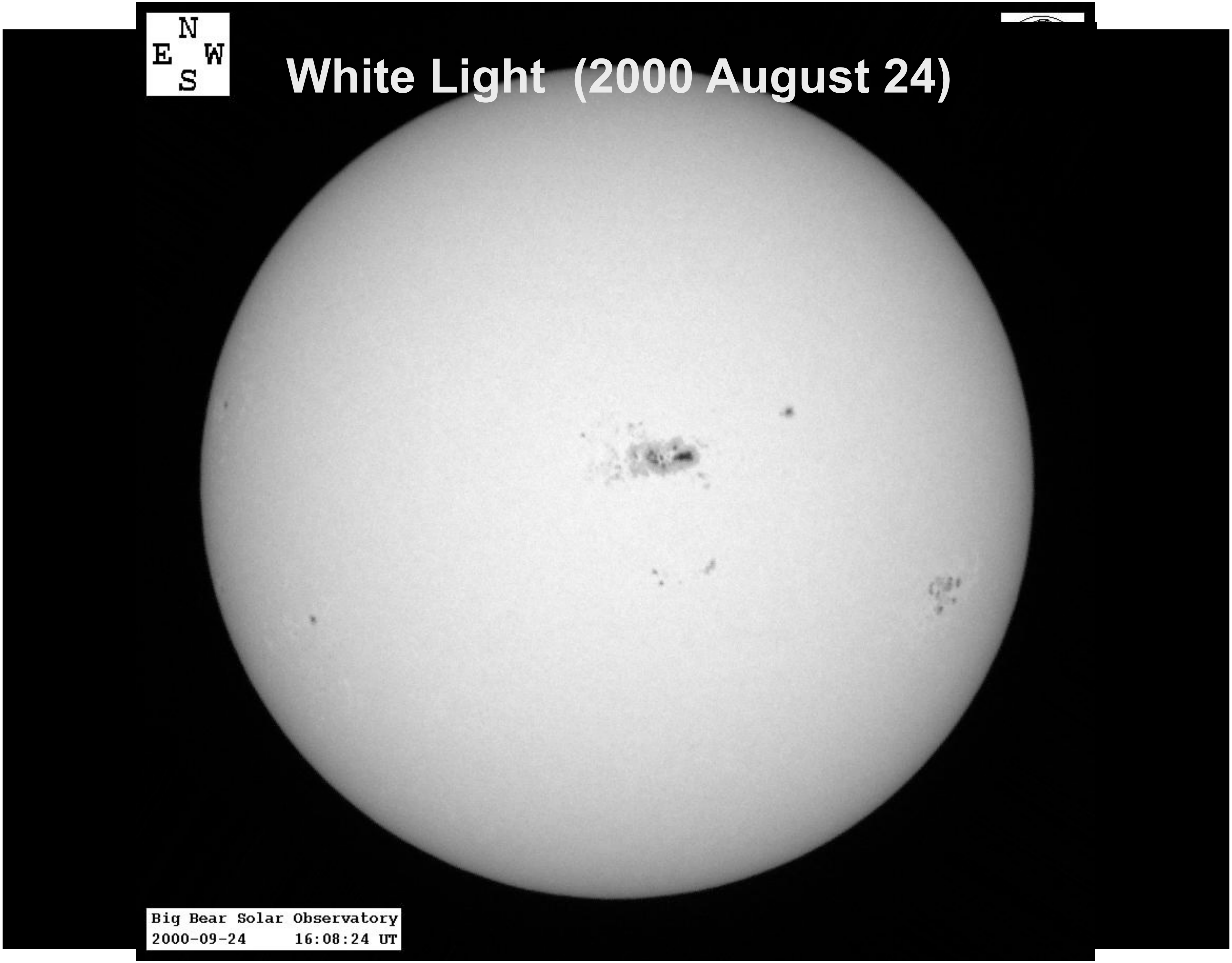
Corona

The **corona** has a temperature of more than 1,000,000 K, and extends out to about 10 $R_{\odot}$. It is difficult to observe the corona except during an eclipse.

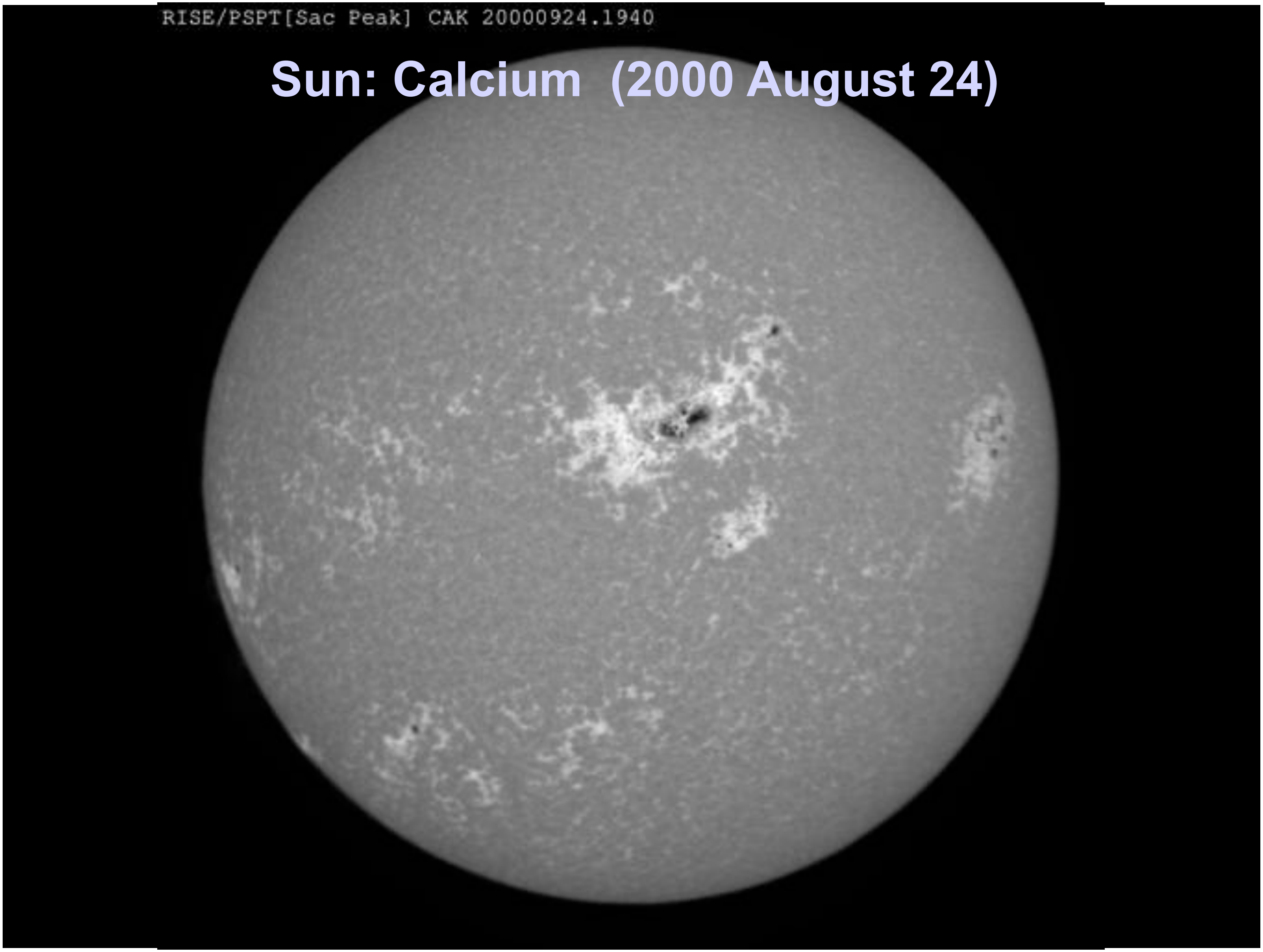
Solar Wind

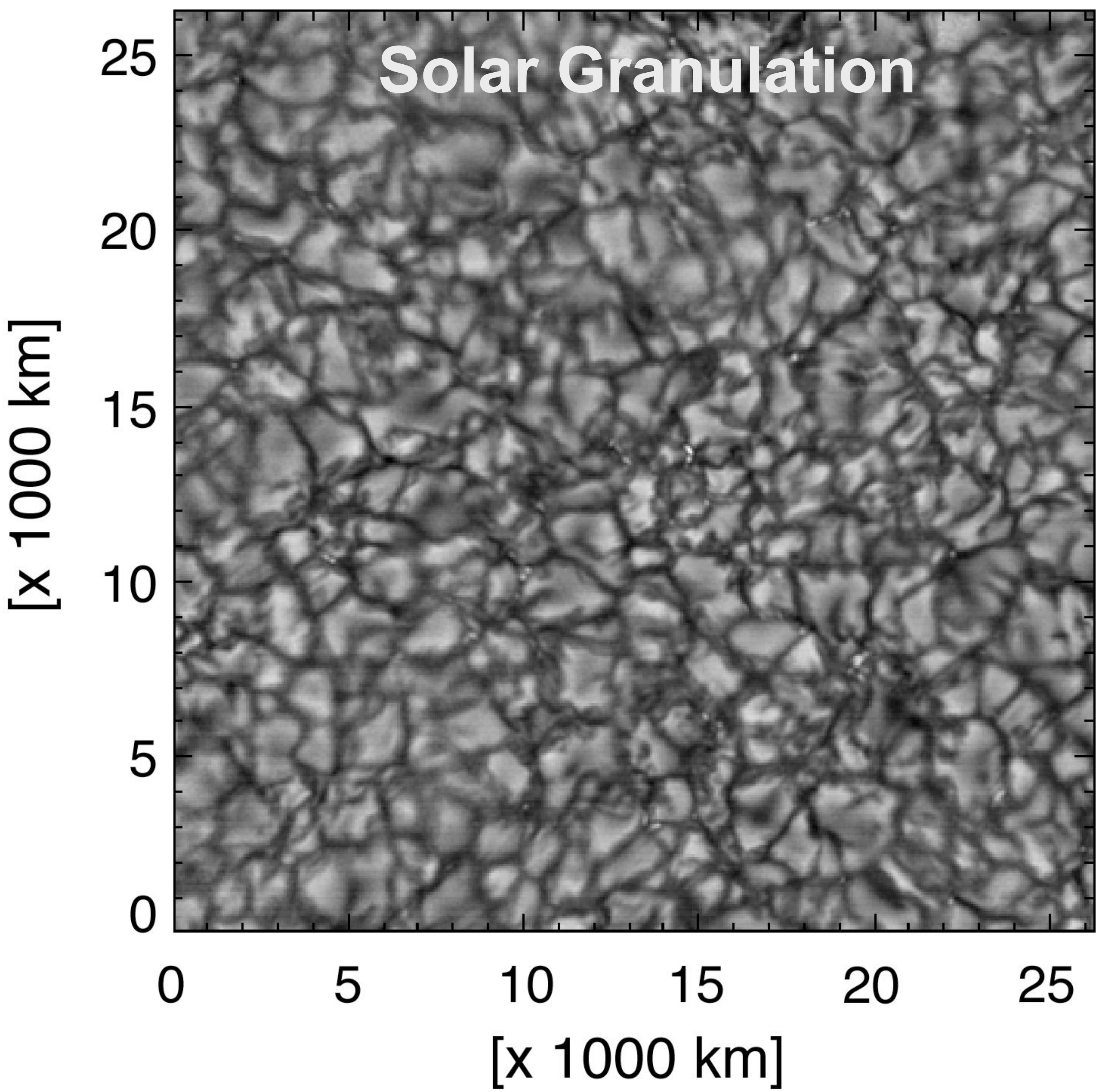
Beyond the corona, atoms of ionized gas stream outward along the magnetic field at speeds of 350 km/s (when quiet) to 1000 km/s (in eruption). The **solar wind** blows by and affects the Earth. Well beyond the orbit of Pluto, it mixes with the interstellar gas that fills the Milky Way.

White Light (2000 August 24)



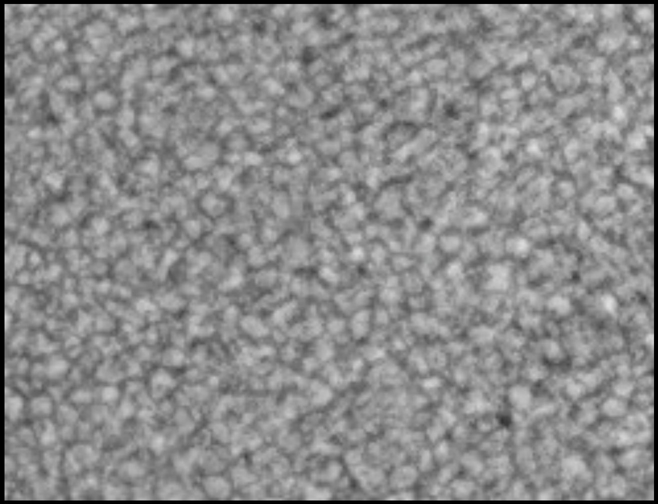
Sun: Calcium (2000 August 24)



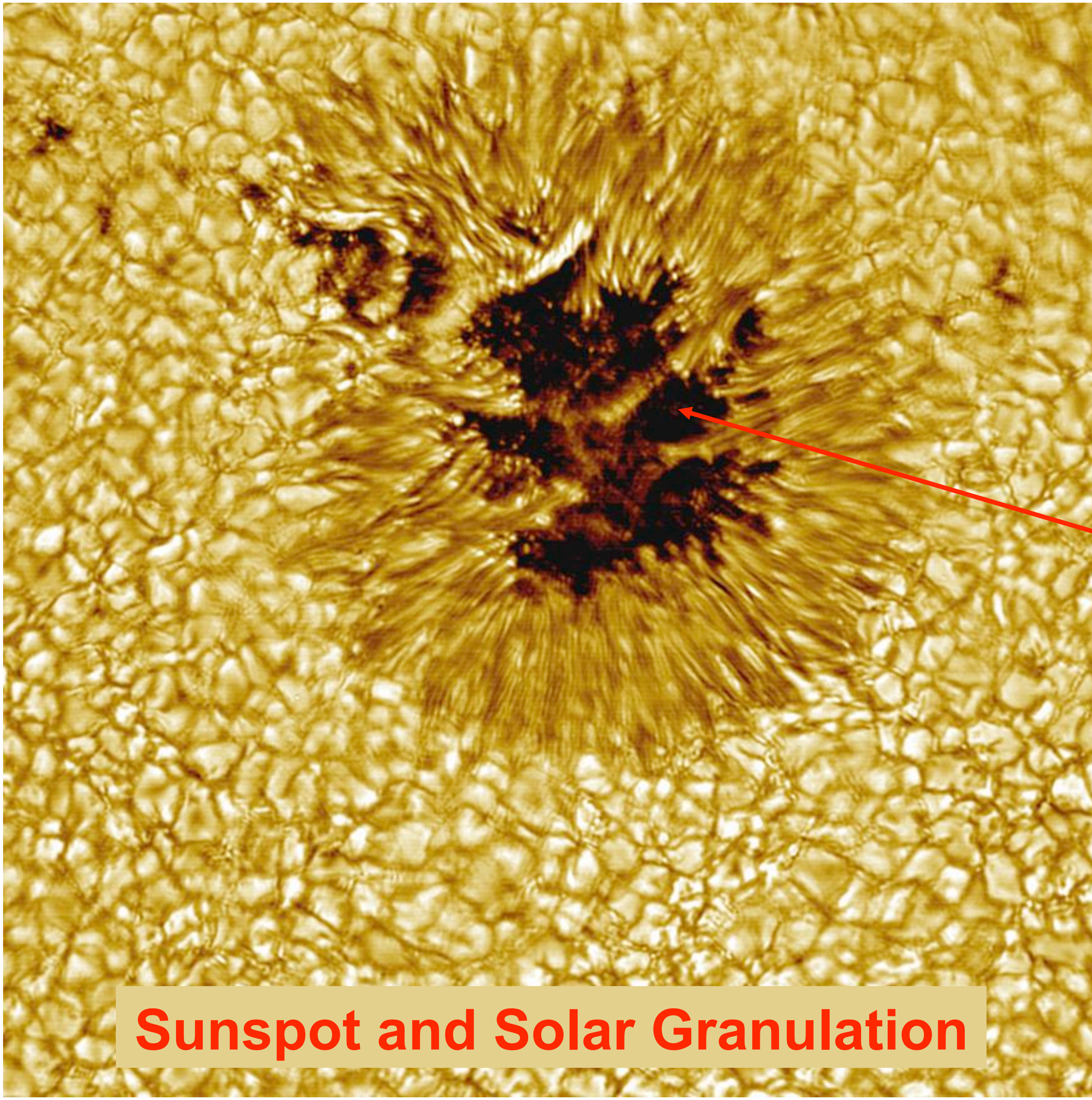


Solar Granulation
25
20
15
10
5
0
[x 1000 km]
0
5
10
15
20
25
[x 1000 km]

Solar Granulation



Solar granules are typically the size of Texas and last 10 — 20 minutes. They carry the heat outward from the Sun's interior by convection.

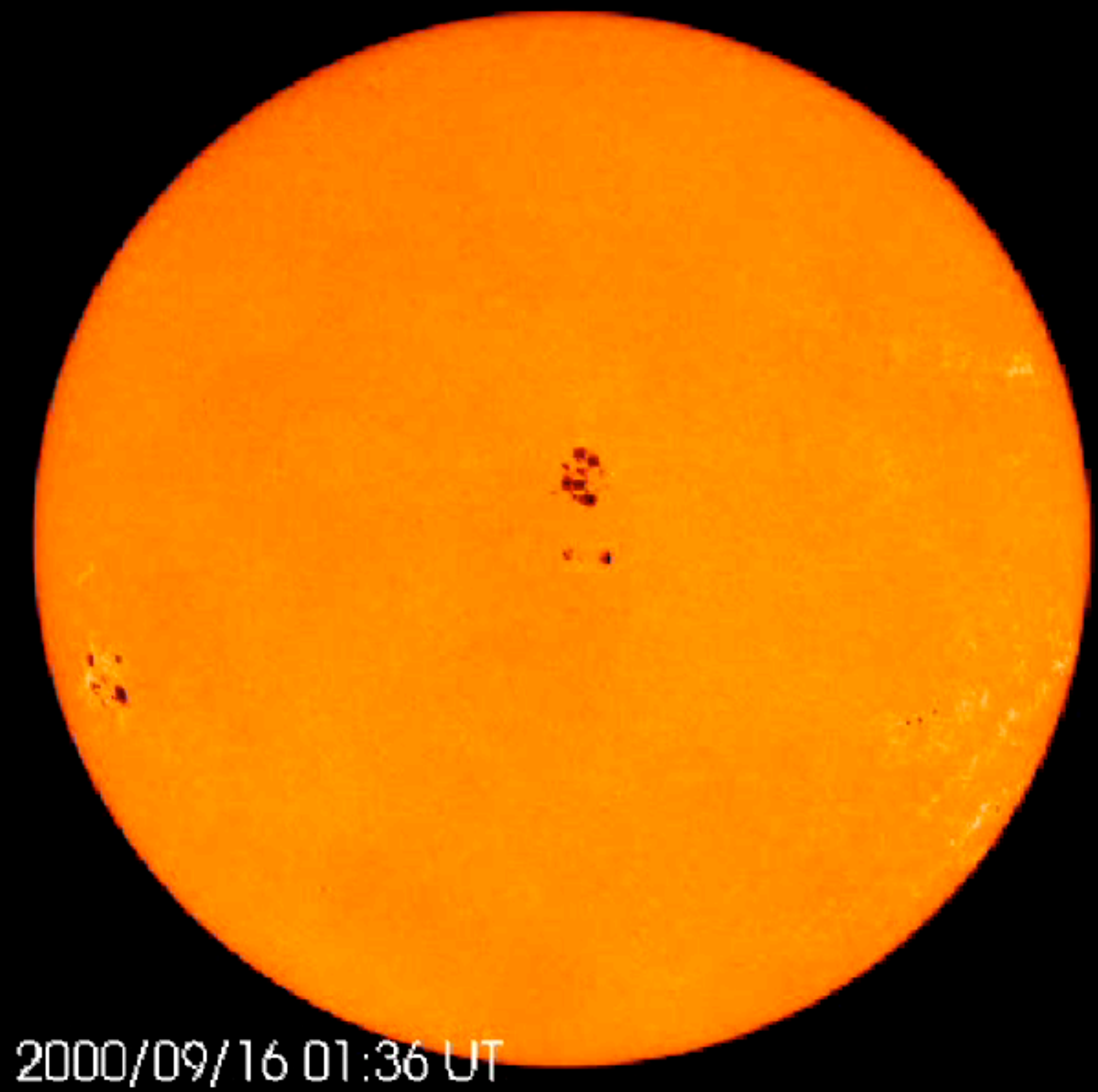


Sunspots are cool areas where magnetic fields stop convection from carrying the normal energy out to the surface.

The umbra is at about 4240 K compared to 5800 K in the photosphere.

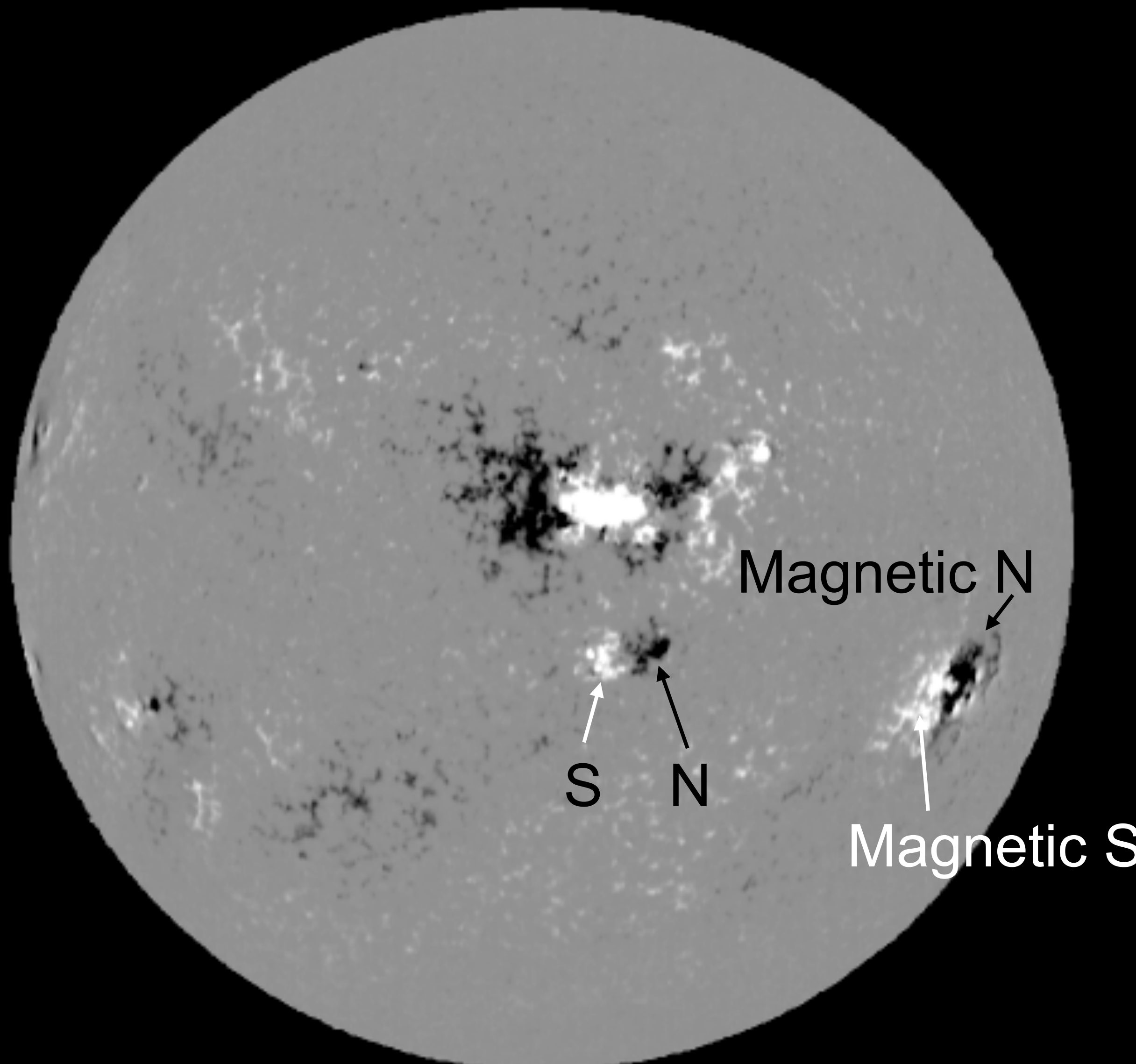
Sunspots are darker than the photosphere but they are still bright.

Solar Rotation

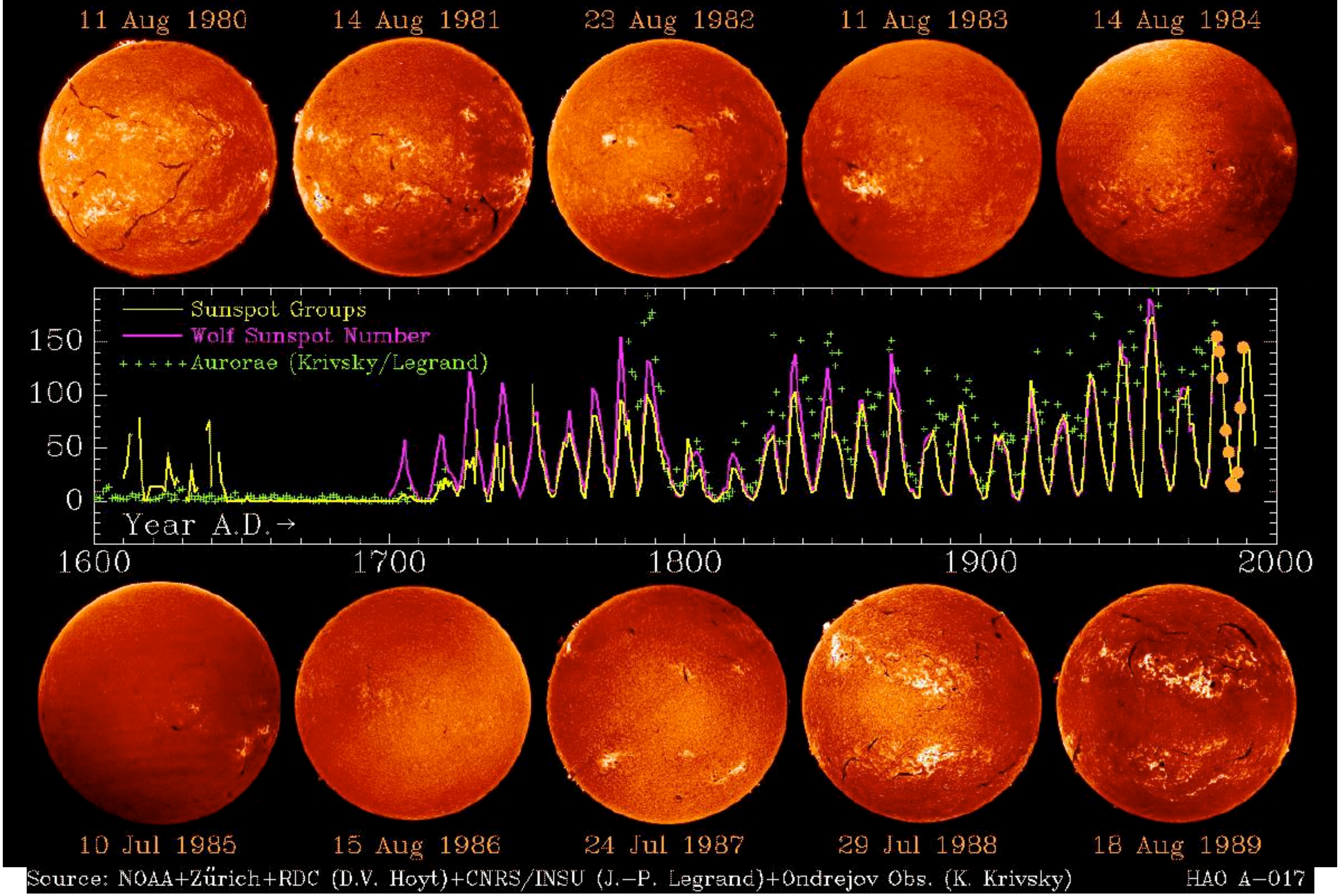


The Sun rotates once in 25 days at the equator and more slowly at higher latitudes.

Sun: Magnetogram 2000 August 24



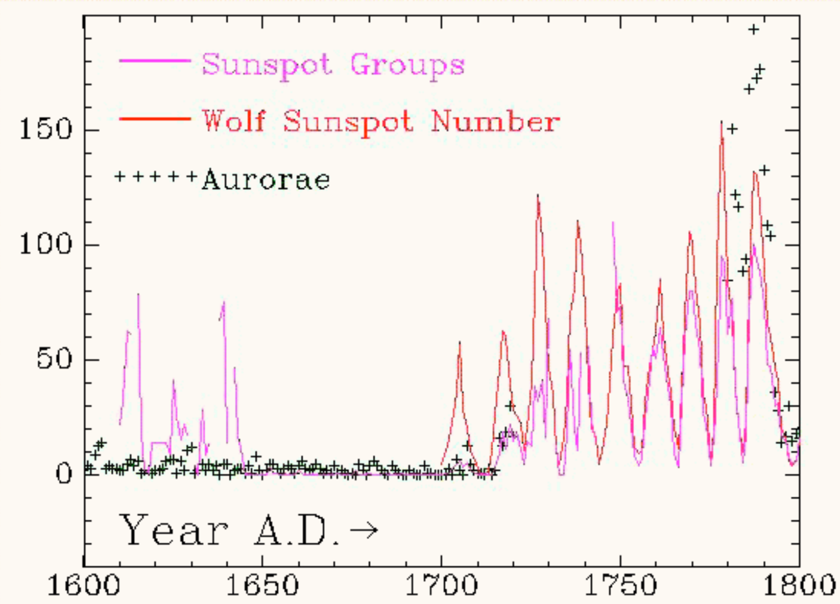
Sunspot Numbers Increase and Decrease with a Period of 11 Years



Solar Cycle: The Maunder Minimum

1645–1715: The Maunder minimum

Sunspots observations continued in the seventeenth century, with the most active observers being the German Johannes Hevelius (1611–1687) and the French Jesuit Jean Picard (1620–1682). Very few sunspots were observed from about 1645 to 1715, and when they were their presence was noted as a noteworthy event by active astronomers. Historical reconstructions of sunspot numbers indicate that the dearth of sunspots is real, rather than the consequence of a lack of diligent observers. A simultaneous decrease in auroral counts further suggest that solar activity was greatly reduced during this time period.

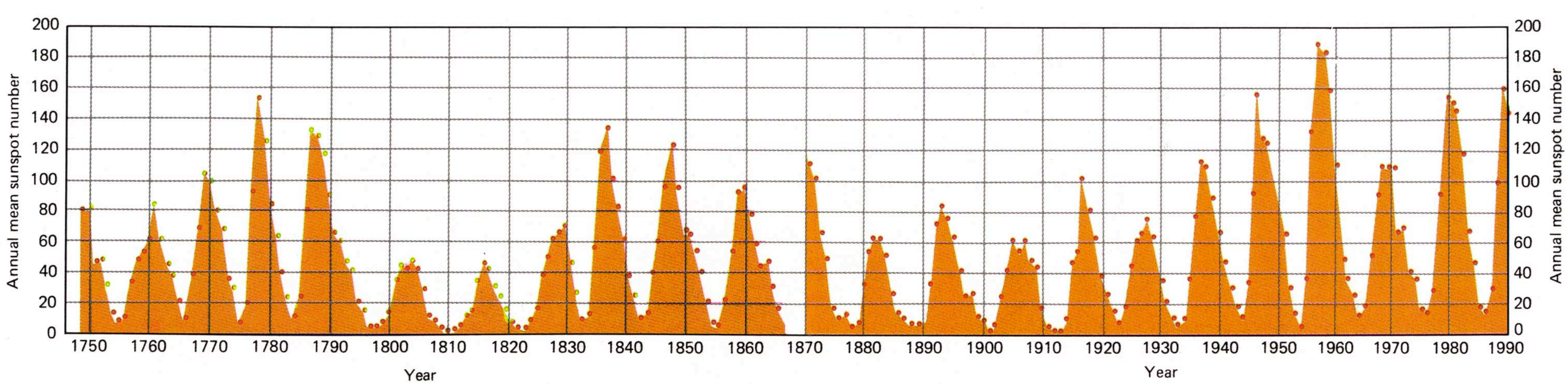


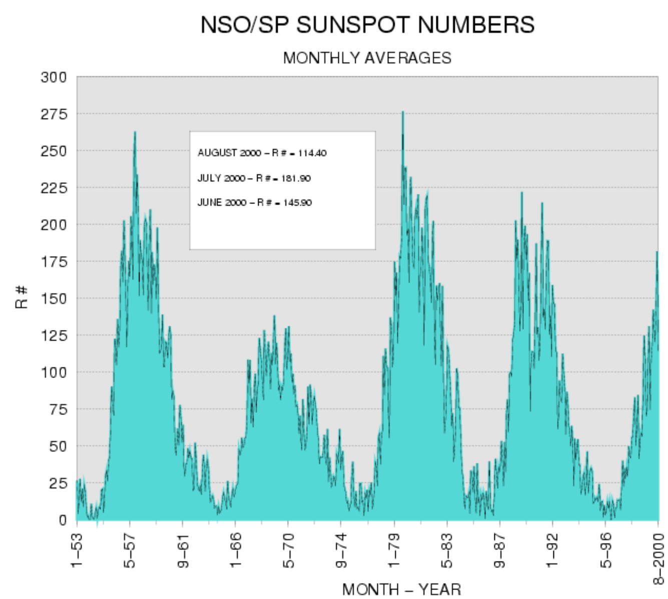
Variation in observed sunspot numbers during the time period 1600–1800. The red curve is the Wolf sunspot number, and the purple line a count of sunspot groups based on a reconstruction by D.V. Hoyt. The green crosses are auroral counts, based on a reconstruction by K. Krivsky and J.P. Legrand.

This period is now known as the Maunder minimum, after the solar astronomer E.W. Maunder, who was most active in investigating the dearth of sunspot sightings by astronomers active in the second half of the seventeenth century. The documented occurrence of exceptionally cold winters throughout Europe during those years may be causally related to reduced solar activity, although this remains a topic of controversy.

During the “Maunder minimum” the Sun got fainter by only about 0.2 %. This was enough to cause the “little ice age” on Earth.

Sunspot Cycle (1748 — 2000)





Babcock Model For Solar Activity

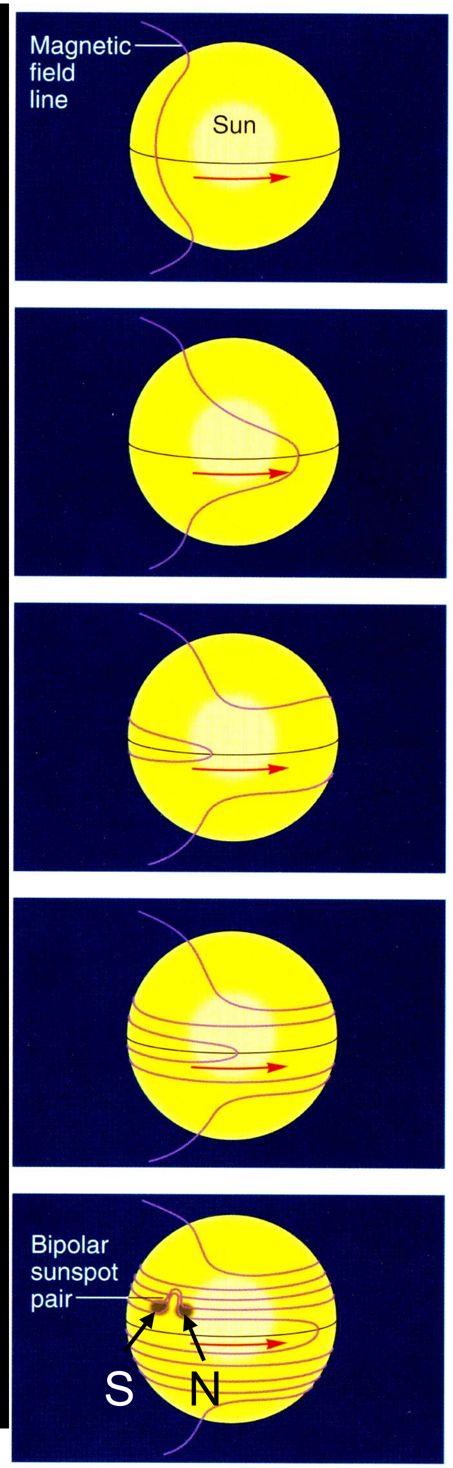
The Sun is an electrically conducting plasma.

Convection stirs up vast electrical currents and creates a magnetic field via the dynamo effect.

Differential rotation winds up the magnetic lines of force tighter and tighter during an 11-year sunspot cycle.

Stretched magnetic field lines get unstable, break out through the surface, and inhibit convection.

The cooling spots look dark.



Sunspots generally come in pairs of opposite magnetic polarity.

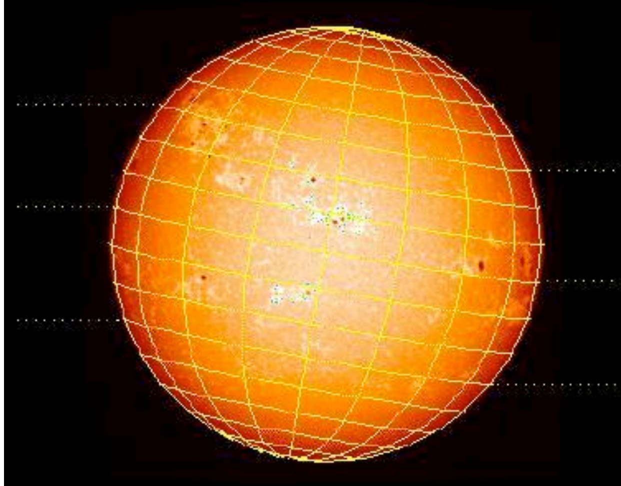
Early in a cycle, sunspots form at mid-latitudes. Later they form closer to the equator.

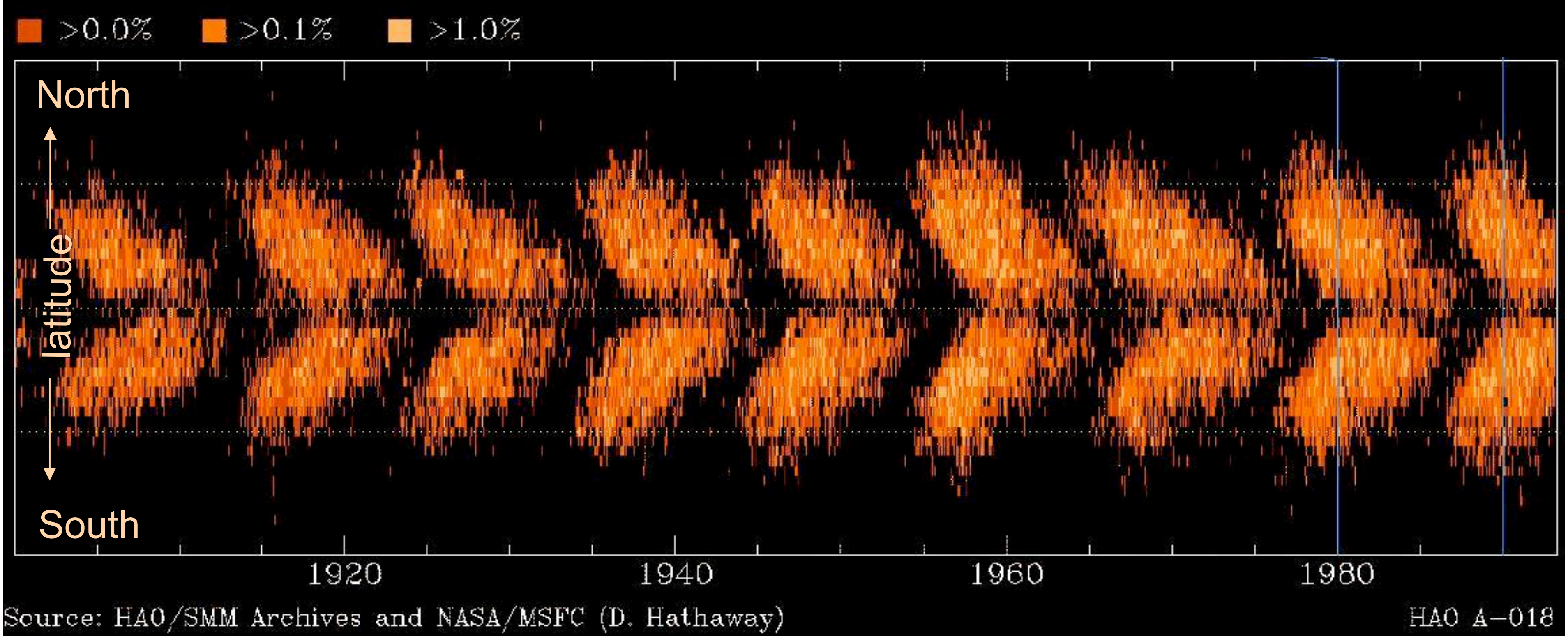
During a sunspot cycle, more and more spots form and decay as the magnetic lines of force recombine.

Eventually, the magnetic field dissolves in chaos and reforms with the opposite polarity.

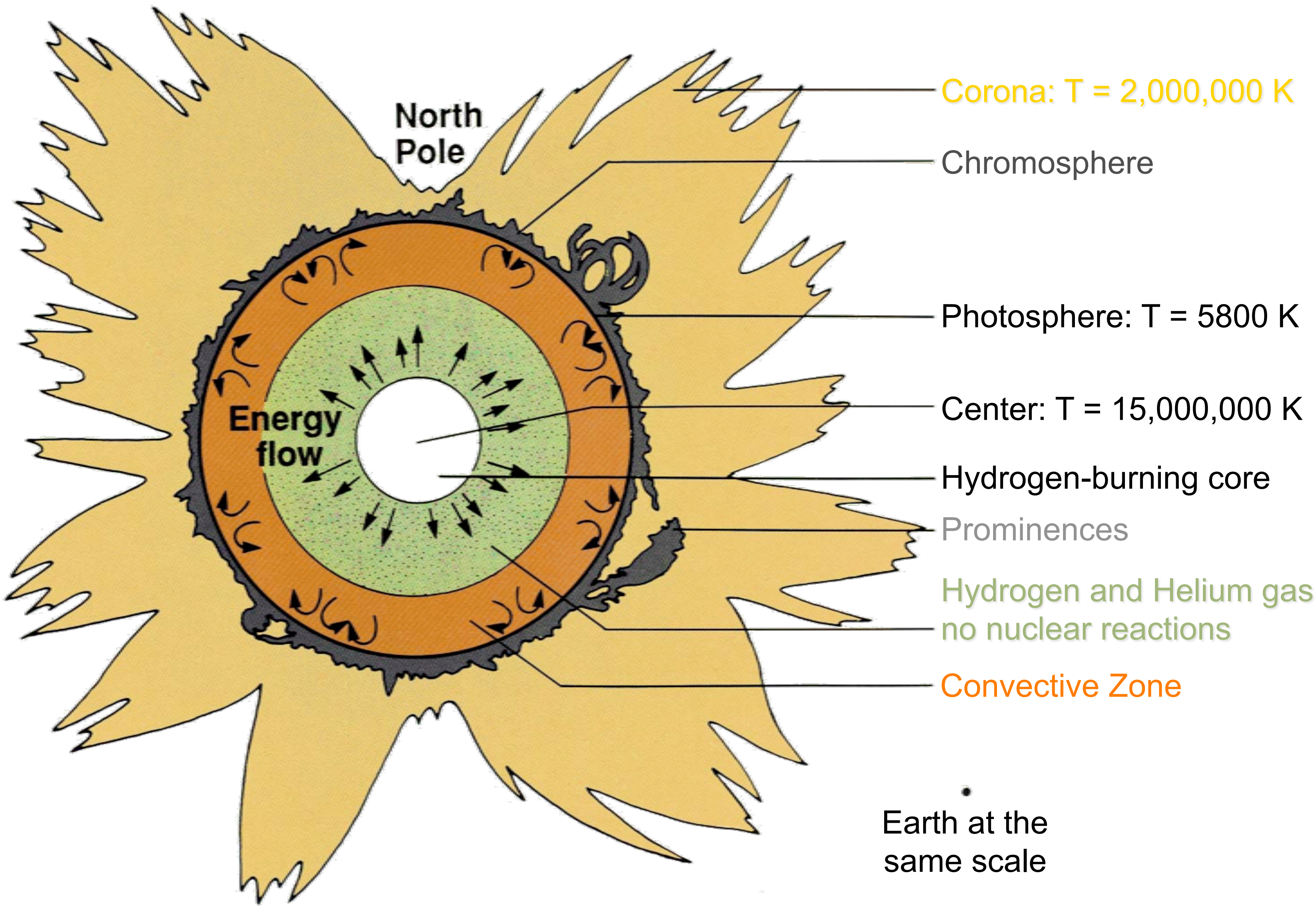
So the full magnetic field cycle takes 22 years.

Spot Activity Moves Toward the Equator During a Solar Cycle

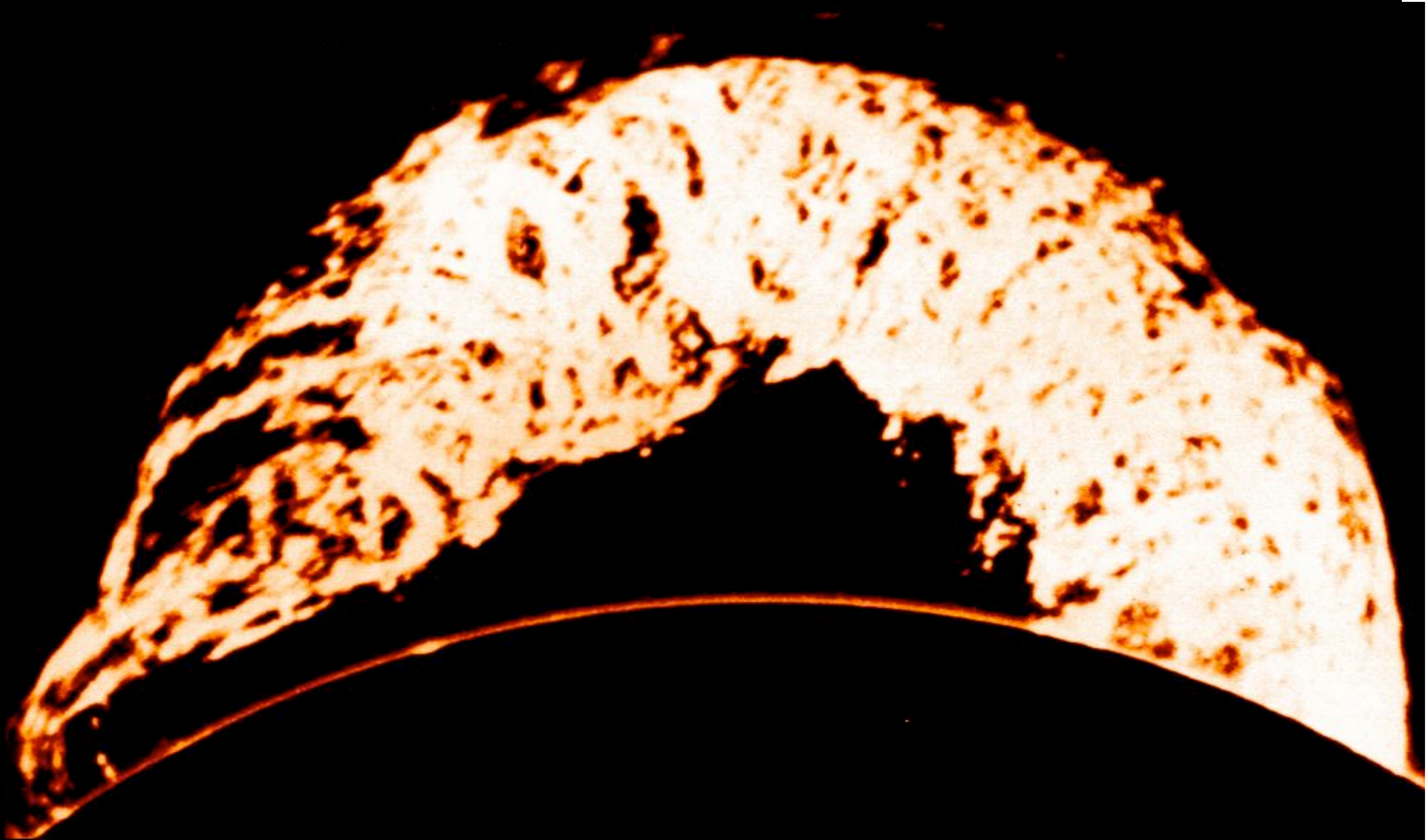




Cross Section of the Sun

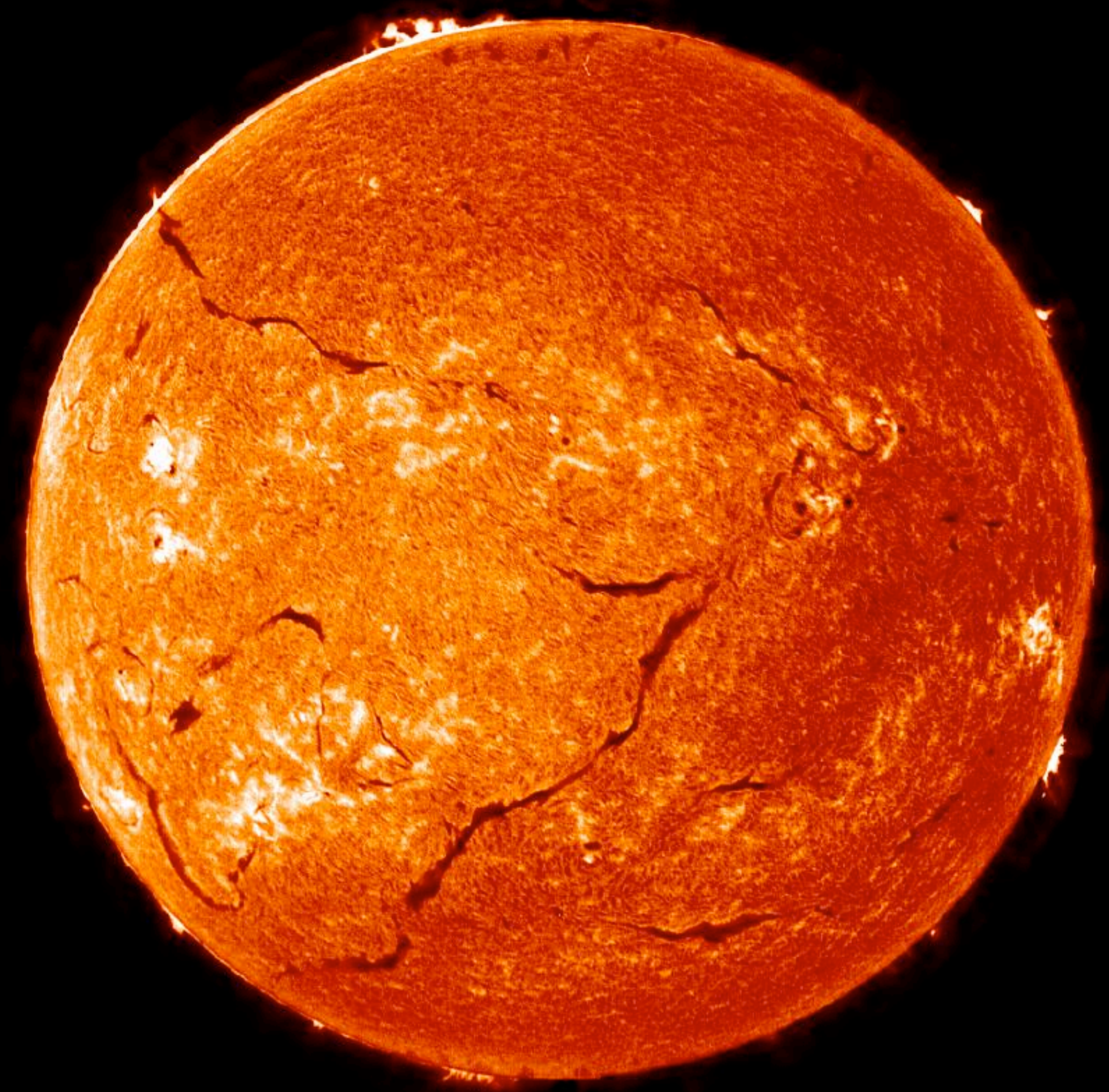


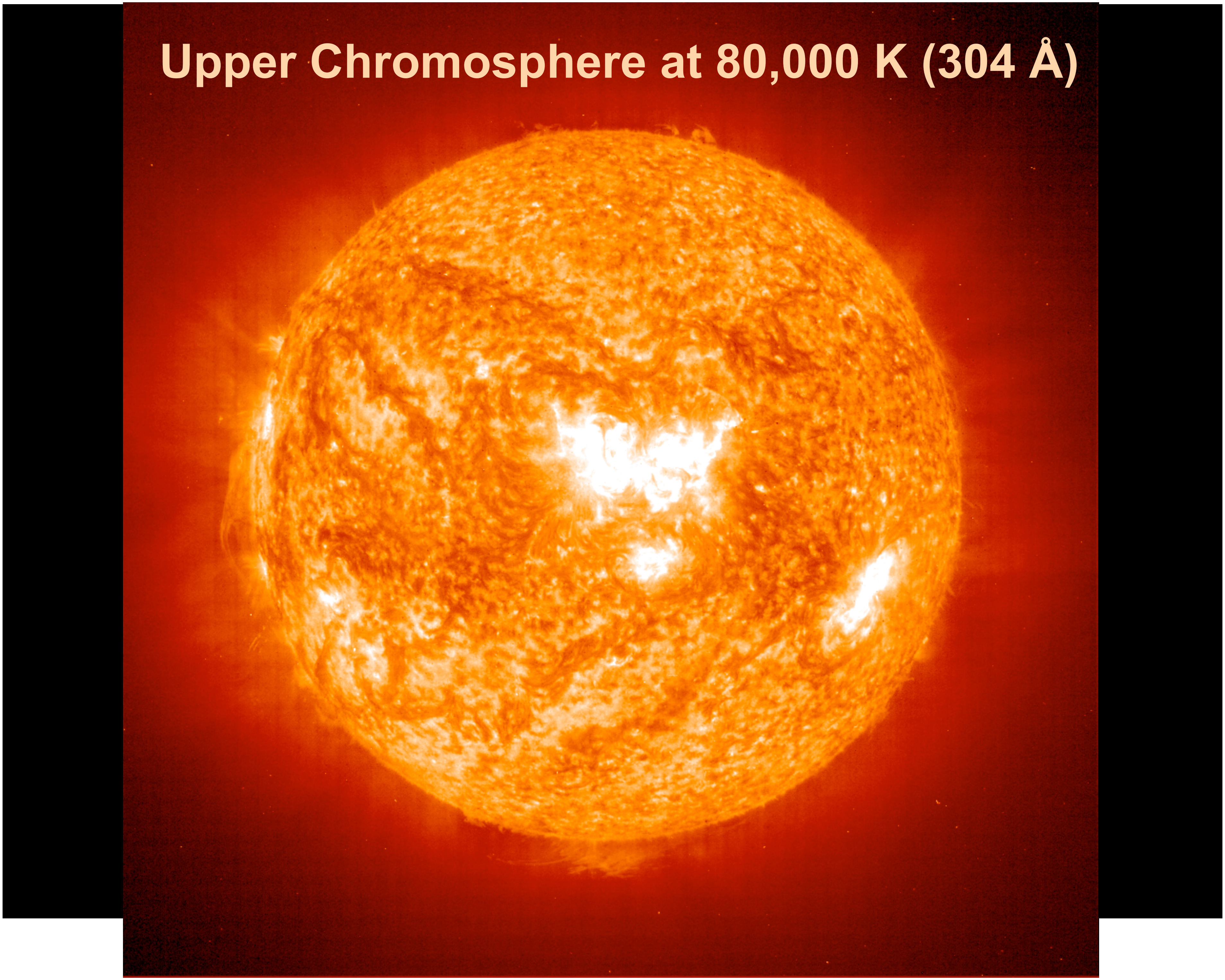
Eruptive Prominence (1946, June 4)

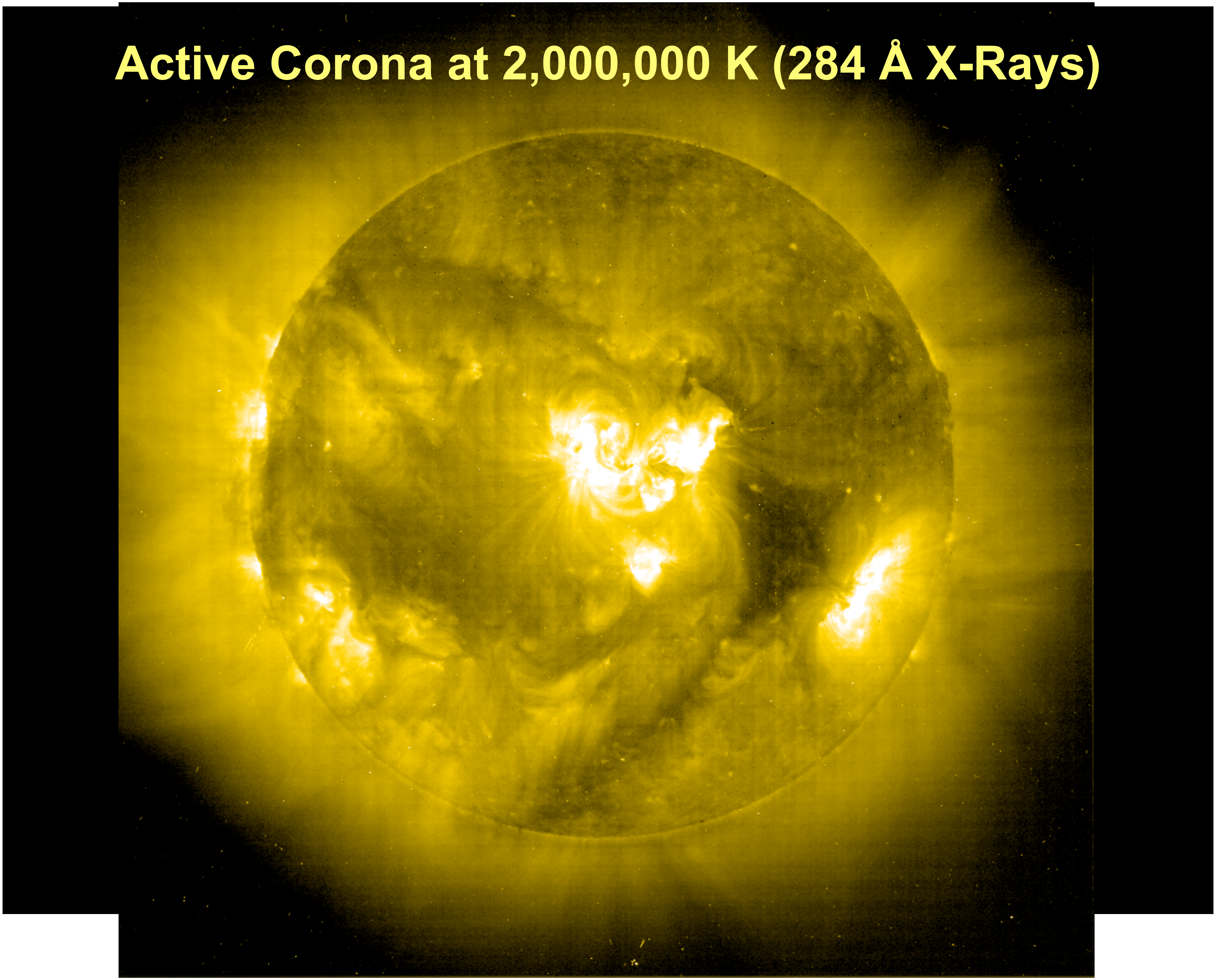


This giant prominence is 200,000 km high. The Earth would easily fit under it.

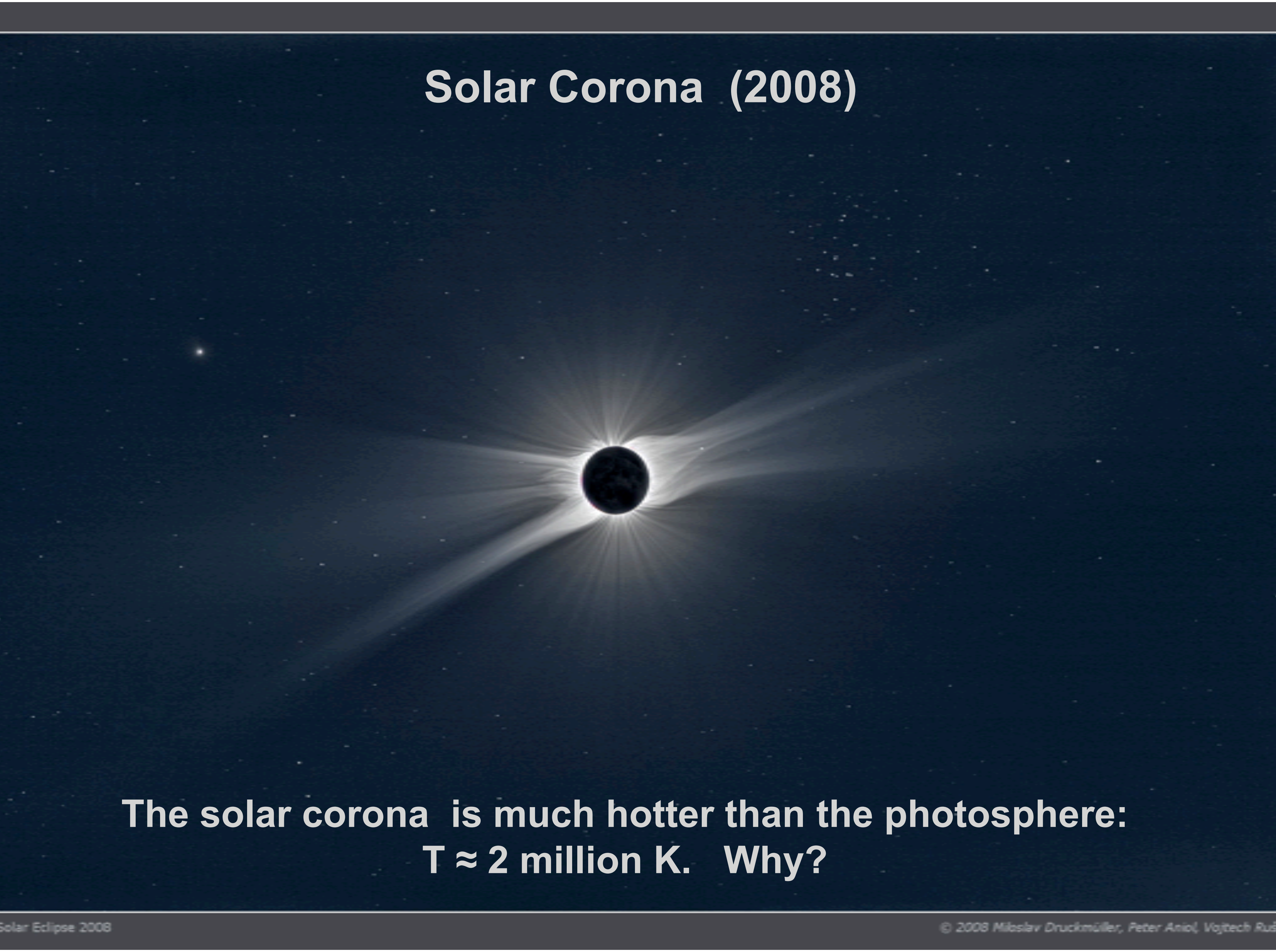
Sun: Hα (1980, August 11)




Upper Chromosphere at 80,000 K (304 Å)


Active Corona at 2,000,000 K (284 Å X-Rays)

Solar Corona (2008)



The solar corona is much hotter than the photosphere:
$T \approx 2$ million K. Why?

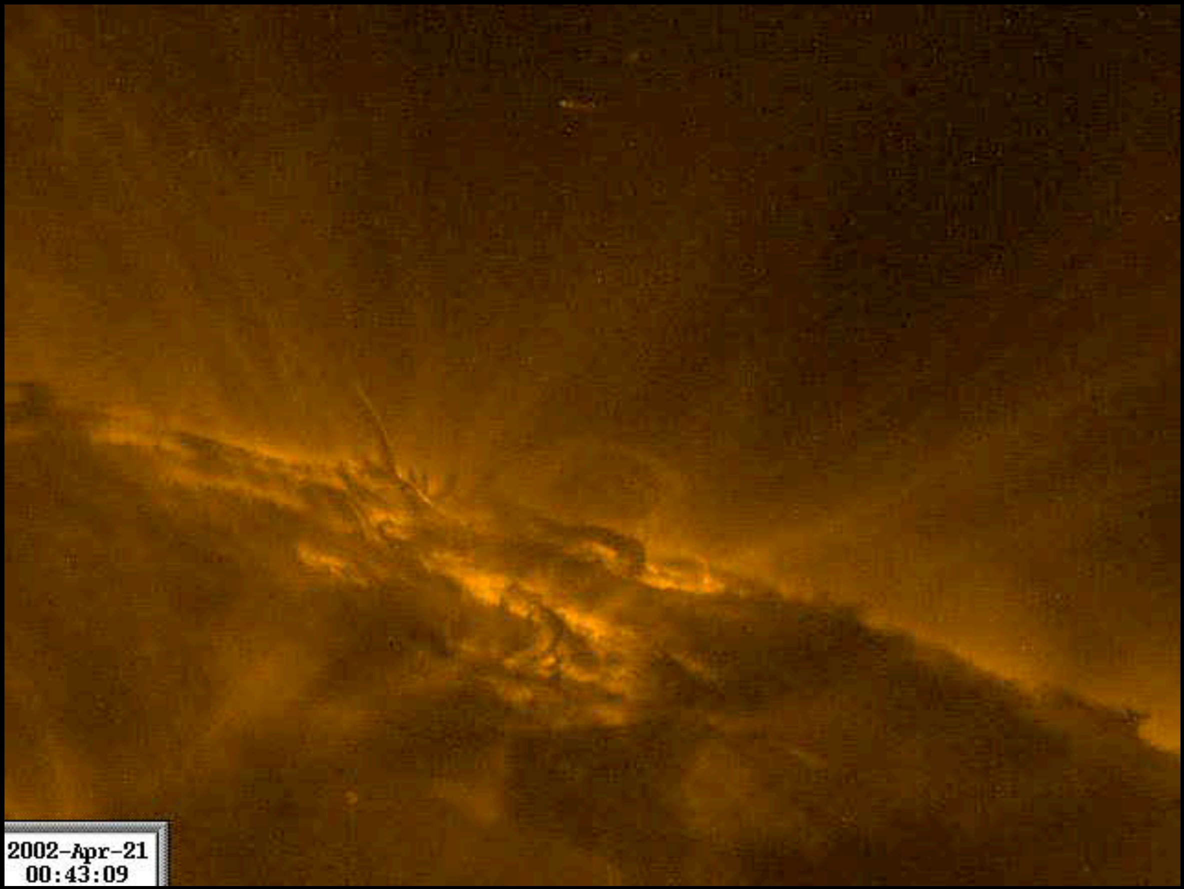
The photosphere has temperature T = 5800 K. How does the corona get so hot (T > 1 million K)?

This movie from the TRACE X-ray satellite shows dynamic arches in the lower corona.

Hot gas loops through the arches, controlled by magnetic fields.

This feeds energy from magnetic fields into the corona and heats it.

The photosphere has temperature T = 5800 K. How does the corona get so hot (T > 1 million K)?



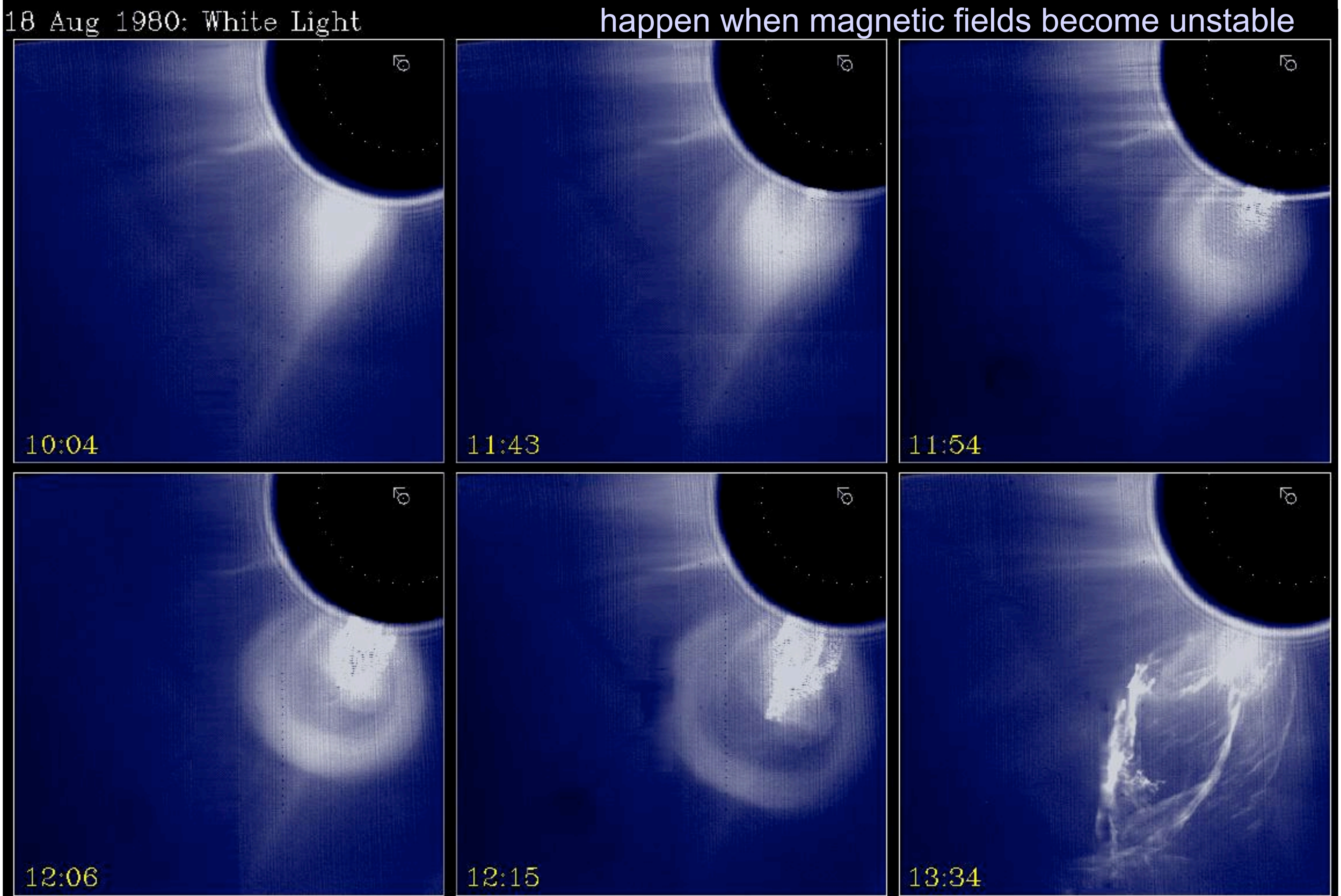
This movie from the TRACE X-ray satellite shows dynamic arches and a flare.

Hot gas loops through the arches, controlled by magnetic fields.

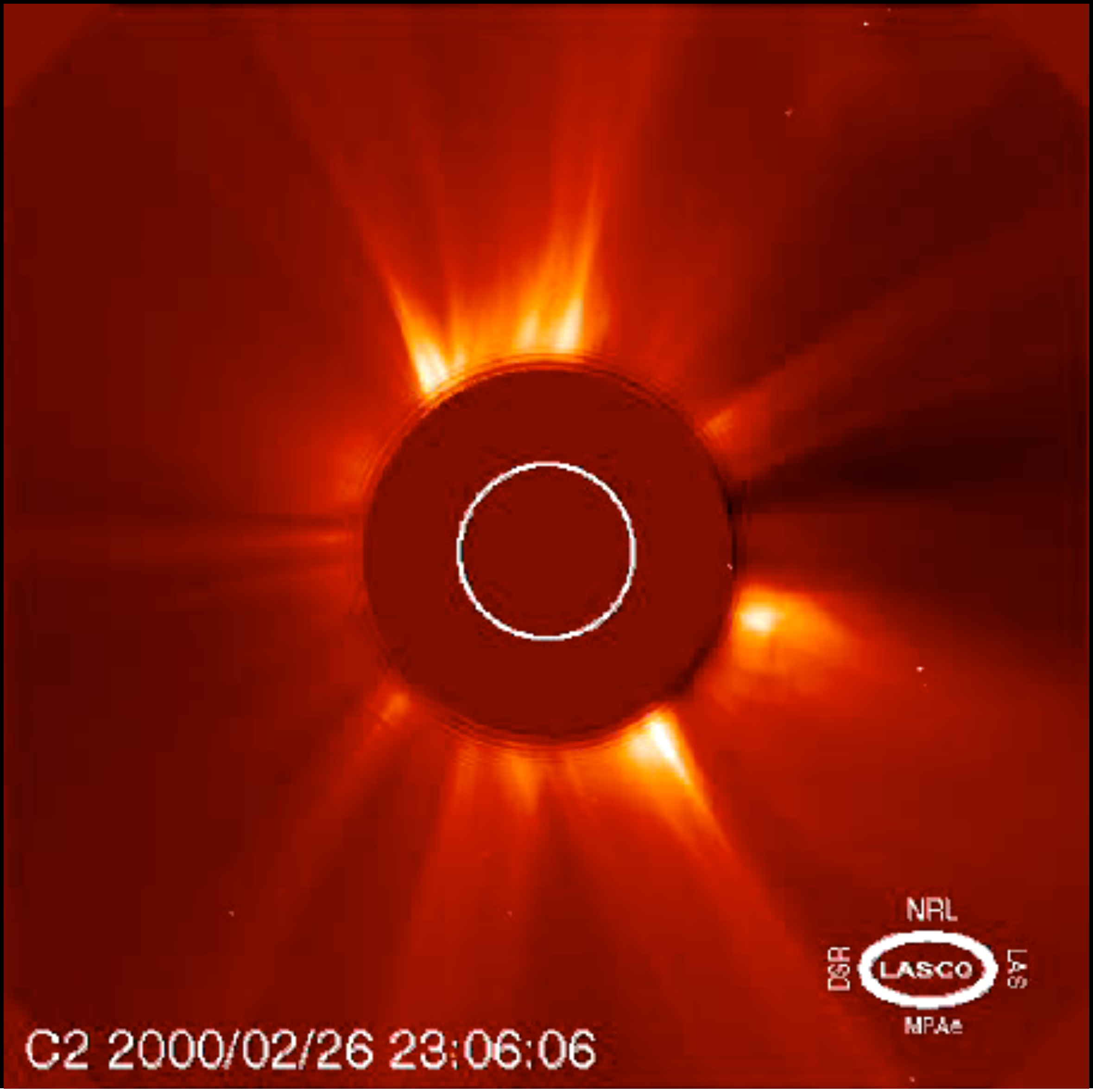
This feeds energy from magnetic fields into the corona and heats it.

Coronal Mass Ejections (Typically 10^{12} kg at 400 km/s)

happen when magnetic fields become unstable

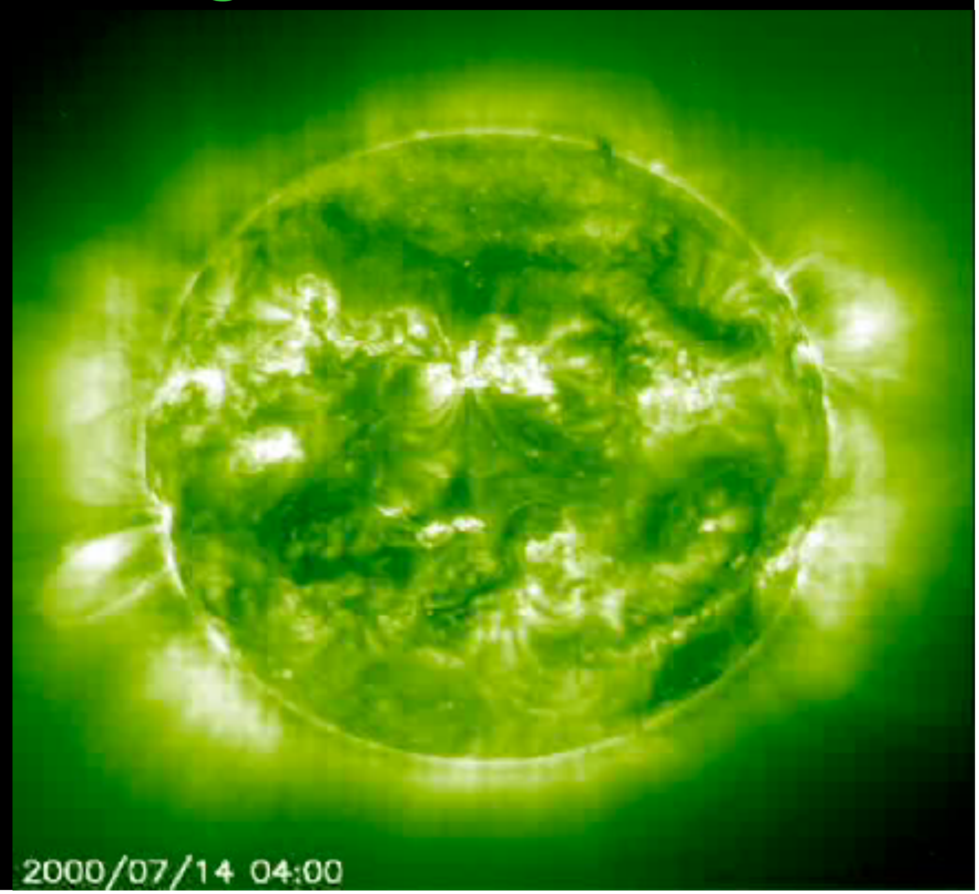


Coronal mass ejections (typically 10^{12} kg at 400 km/s) happen when magnetic fields become unstable.



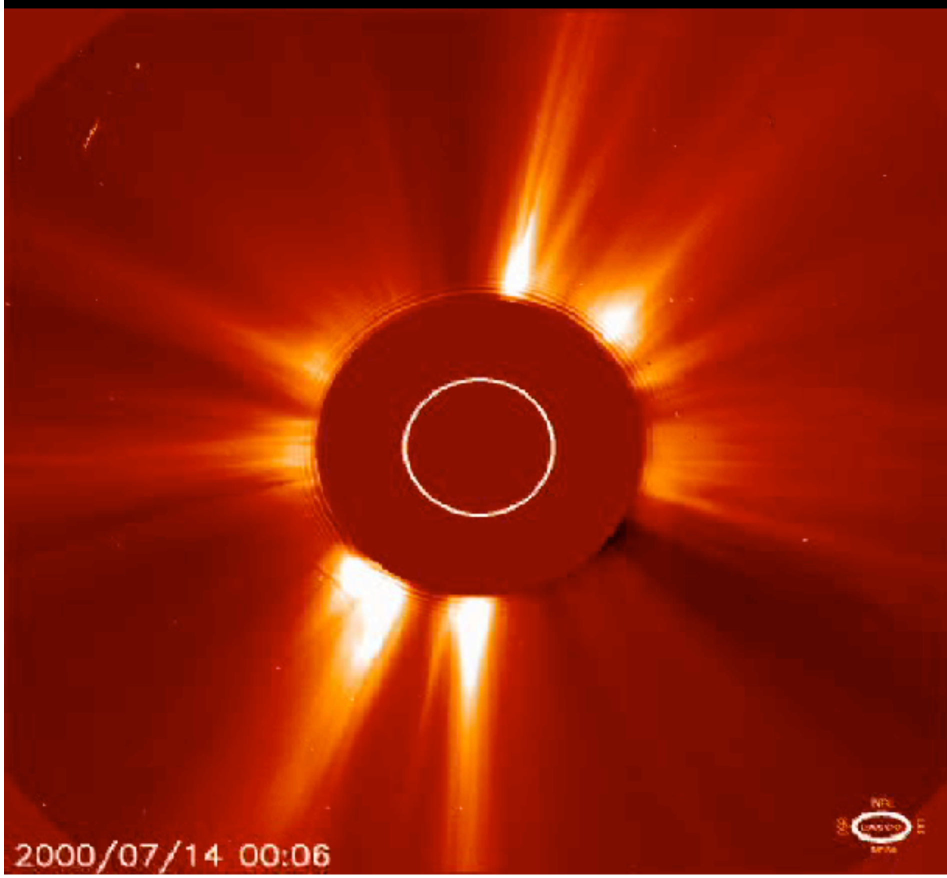
Visible Light (Calcium) and X-Ray Flares

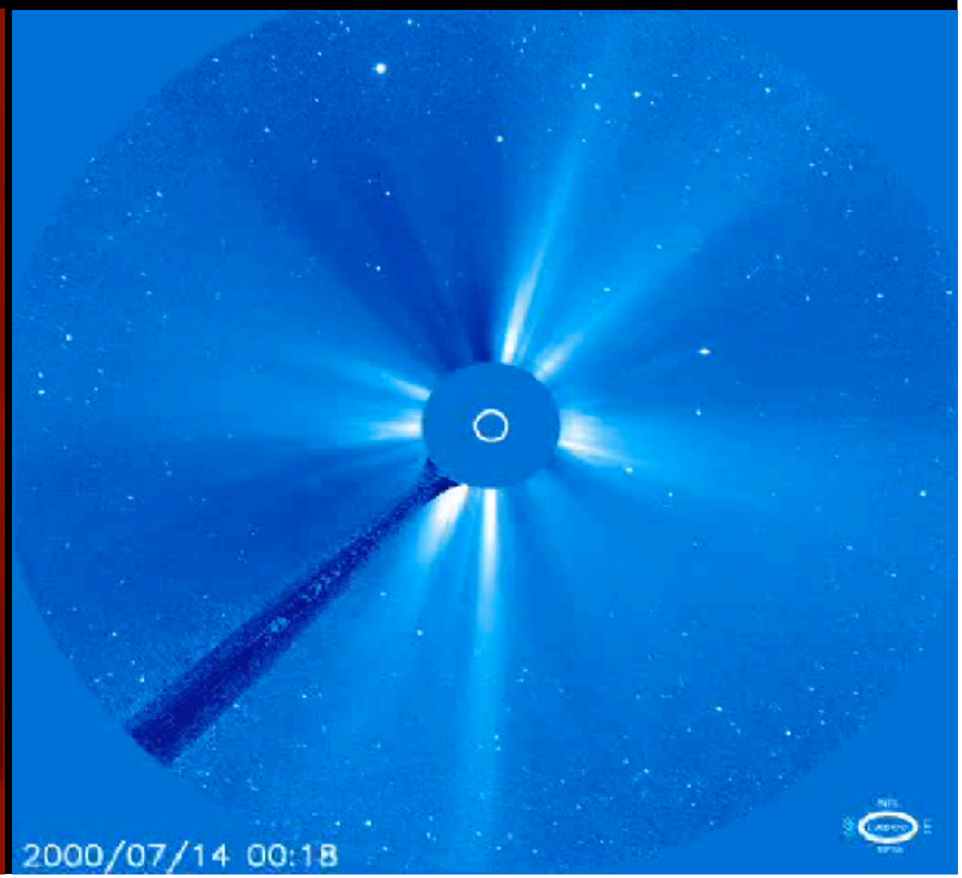
The X-ray flare is followed by an intense particle shower shown again in the next slide.



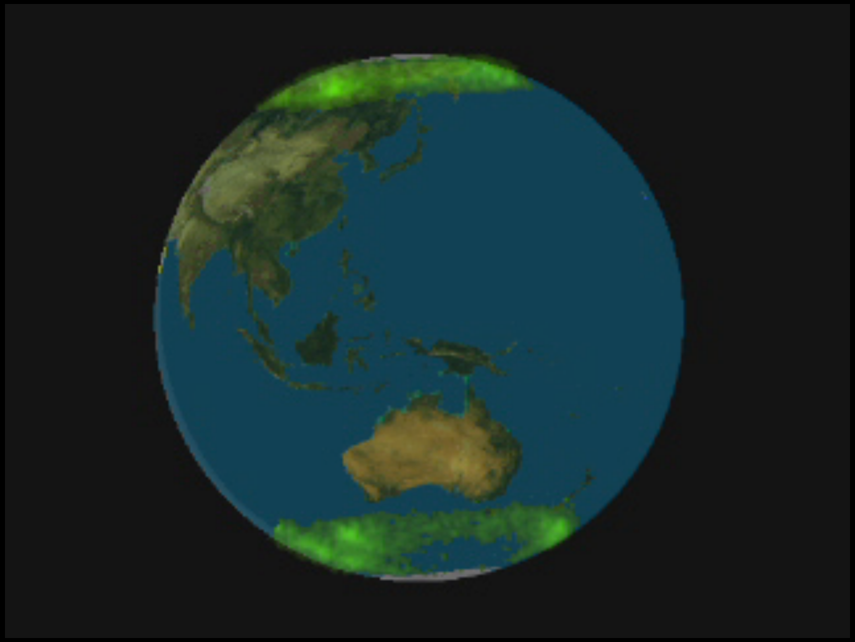
Coronal Mass Ejection And Particle Storm

This coronal mass ejection was followed about half an hour later by a particle storm that zapped the SOHO coronagraph detectors.





When solar particle storms hit the Earth, they make aurorae both in the north and in the south.



When solar particle storms hit the Earth, they make <u>aurorae.</u>

Aurora australis and constellation Orion photographed by astronauts on Space Shuttle Endeavour in April 1994.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Effects of Solar Activity on the Earth

Solar flares emit x-rays
that can disrupt radio communications on Earth 8 min later.

Solar flares emit charged particles.
When they get to the Earth, typically after a few hours or days,

- they cause aurorae (northern and southern lights) when they are funneled down to the Earth's polar regions by the Earth's magnetic field;
- they disrupt radio communications;
- they can create surges in electrical power lines that cause blackouts;
- they can kill unprotected astronauts in space.

Tree ring widths show an 11-year periodicity, so the Earth's climate (e. g., rainfall) is also affected slightly by the solar cycle.

There was at least one period (1645 — 1715) when sunspots disappeared. This “Maunder minimum” coincides with the “Little Ice Age” in Europe.

The Sun has been stable for 4 billion years.

Life on Earth has flourished because
the Sun has been stable for over 4 billion years.

Consider:
A change in Earth's mean temperature of only a few tens of degrees
would result in
a global iceball or a hot desert.

Why
stars on the Main Sequence are so stable
will be a major subject of the lecture on stellar structure and evolution.