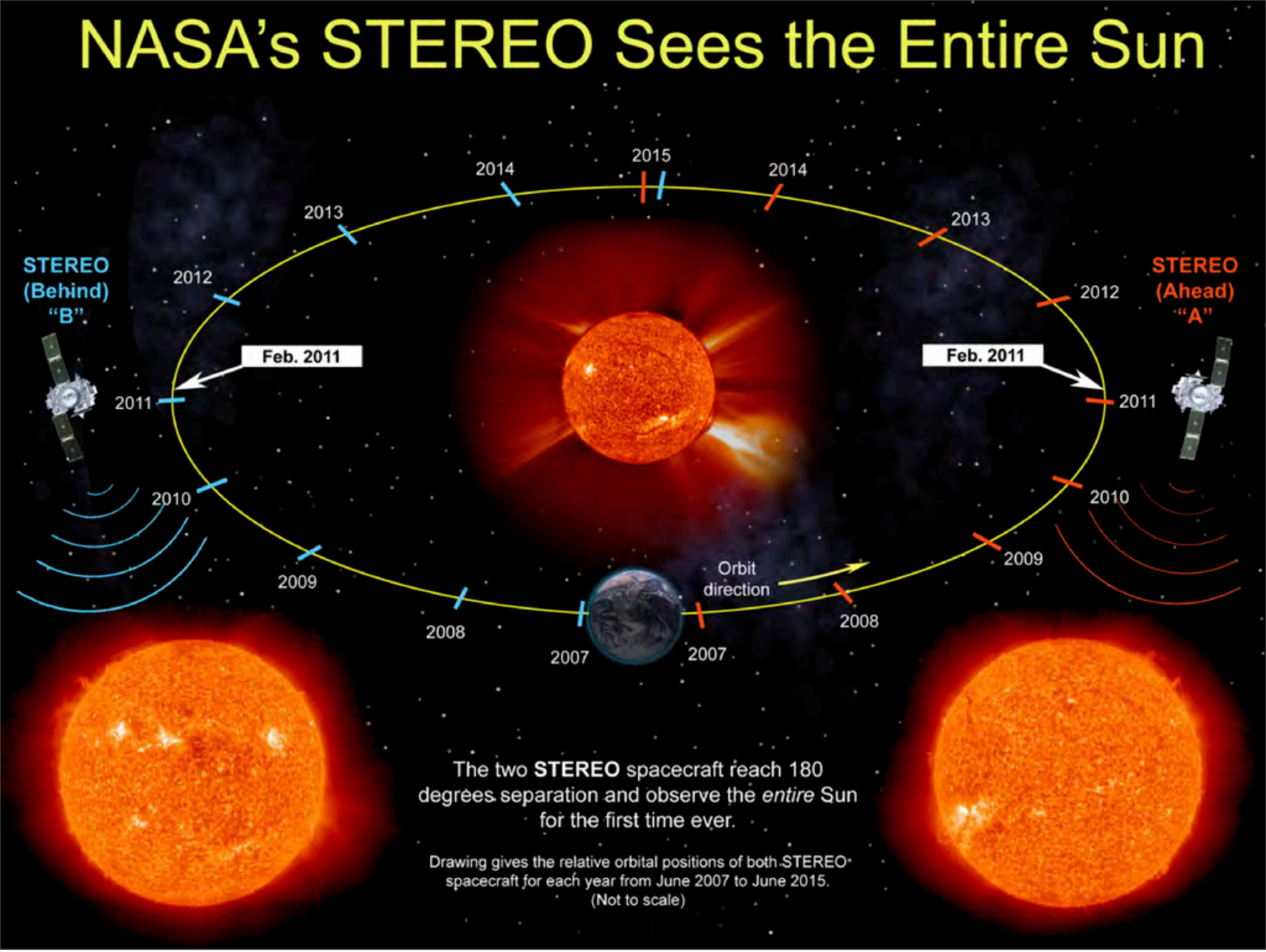
The Sun

Our very own star

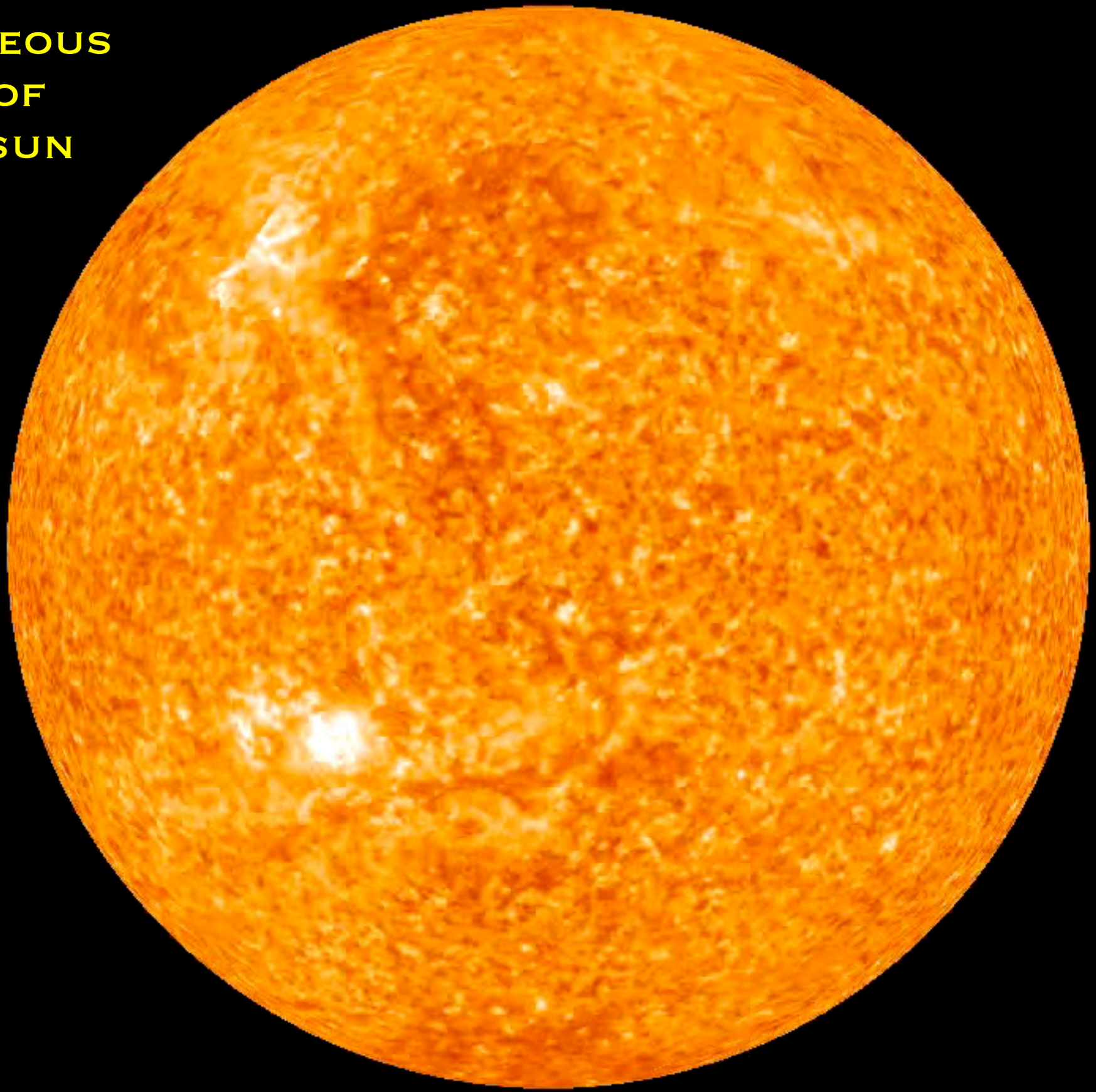
NASA's STEREO Sees the Entire Sun



The two **STEREO** spacecraft reach 180 degrees separation and observe the *entire* Sun for the first time ever.

Drawing gives the relative orbital positions of both STEREO spacecraft for each year from June 2007 to June 2015.
(Not to scale)

SIMULTANEOUS IMAGE OF ENTIRE SUN



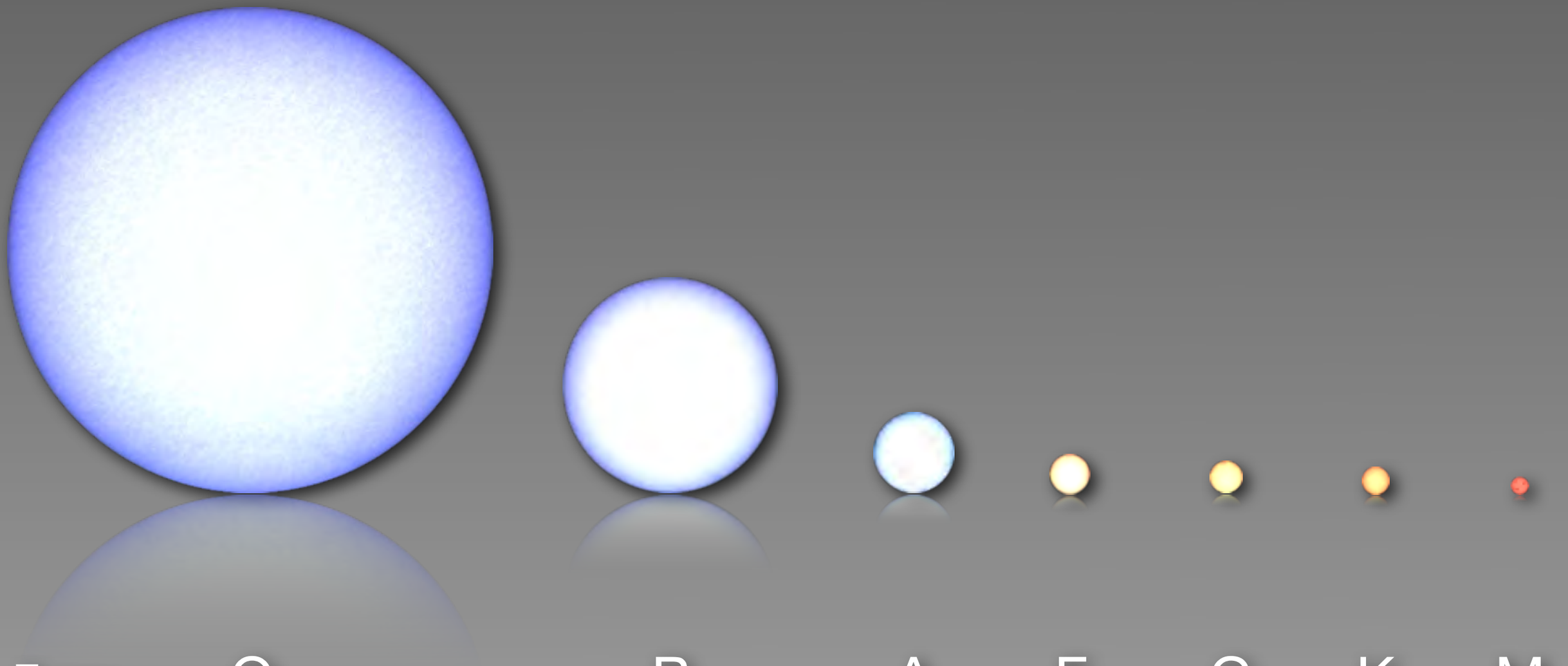
Our own star

- An "Average" Star, one of hundreds of billions in the galaxy (but it's our very own!).

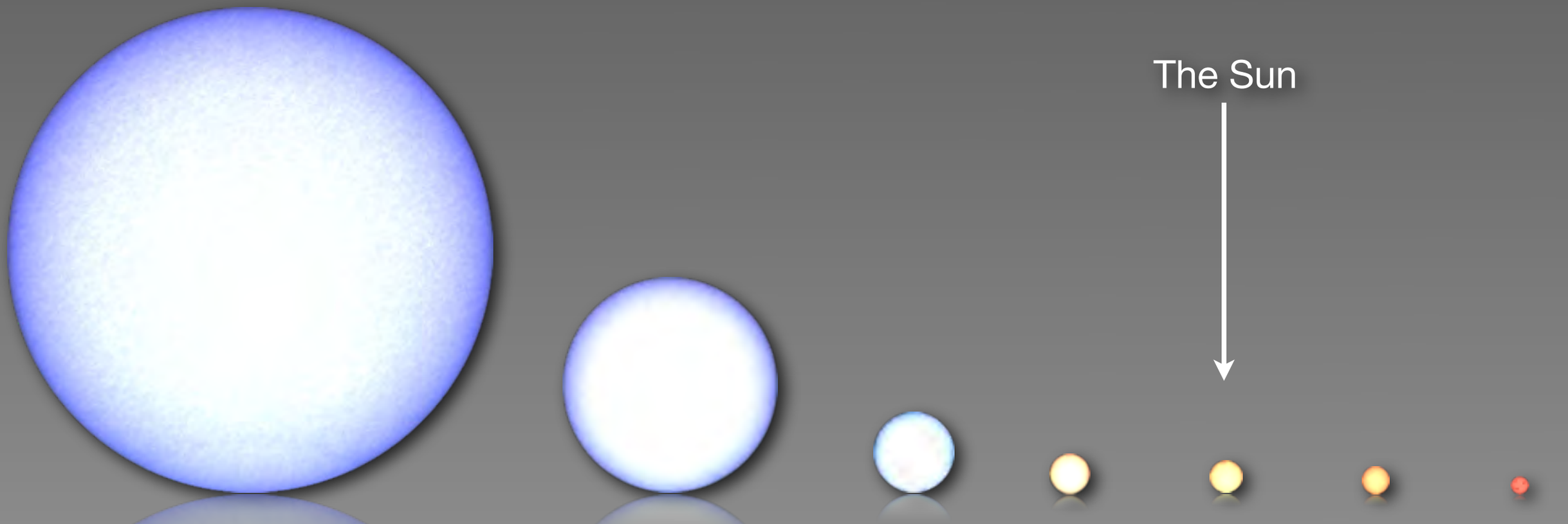
- Made **entirely** of gas. Far too hot for liquids or solids:
  - Surface: 6000 K
  - Center: 10 million K

- Composed of 70% hydrogen, 28% Helium, 2% everything else (C, N, O, Fe, etc.)

The stellar family portrait



The stellar family portrait

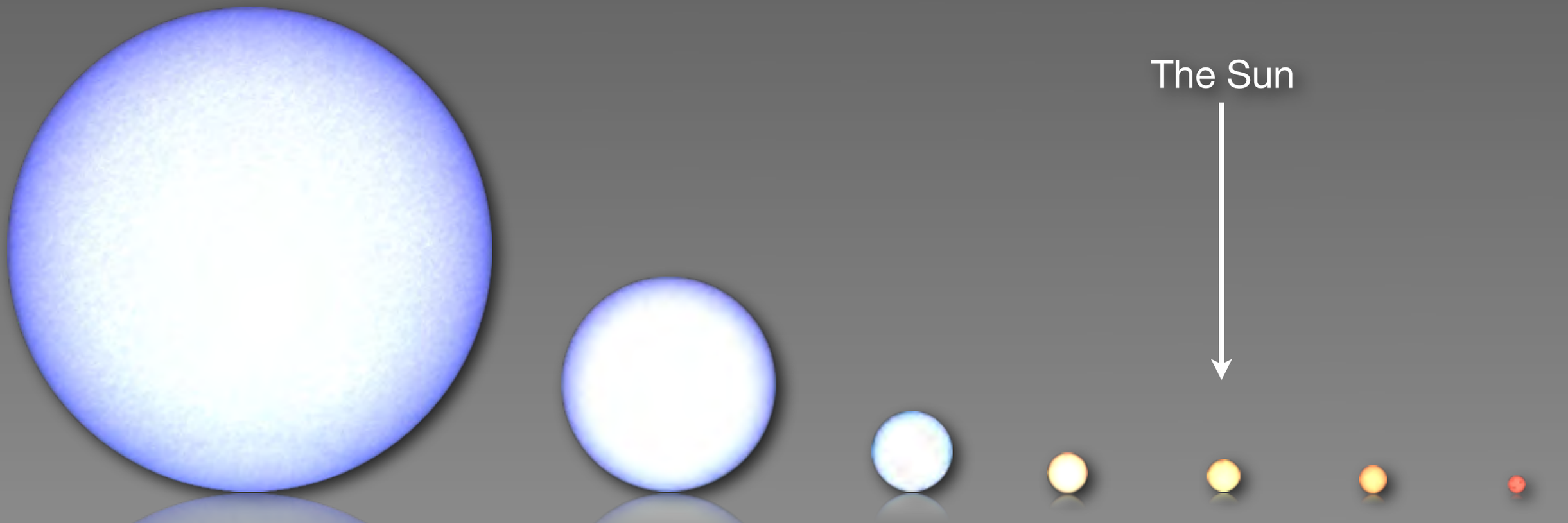


Type: O B A F G K M

1.0 M_{sun}

5800 K

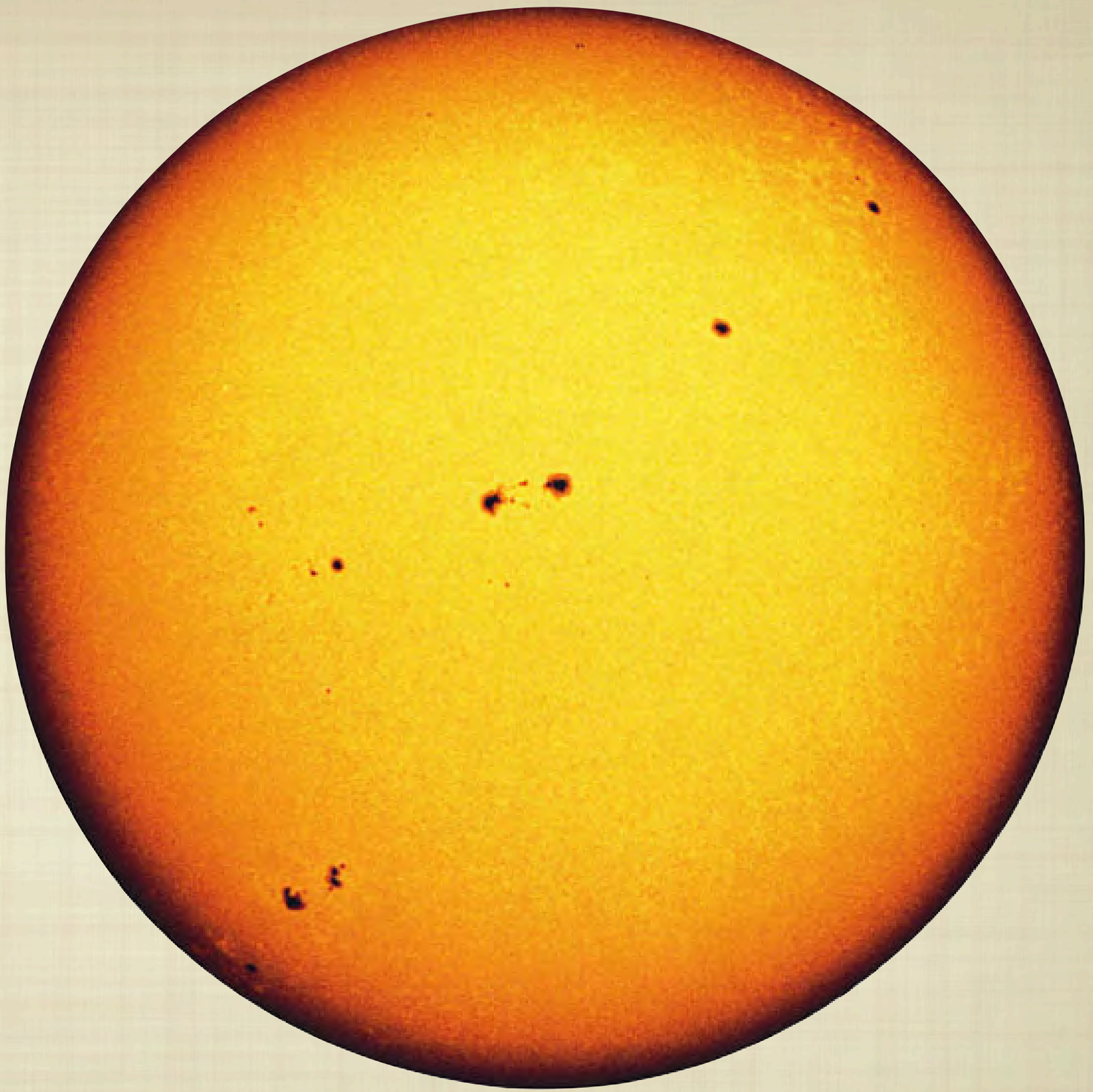
The stellar family portrait



Type:	O	B	A	F	G	K	M
	40 M_{sun}				1.0 M_{sun}		0.1 M_{sun}
	35000 K				5800 K		3000 K

- Radius: 6.9 x 10^8 m (109 times Earth)

- Mass: 2 x 10^{30} kg (300,000 Earths), 99.9% of mass in solar system



Why does the Sun Shine?

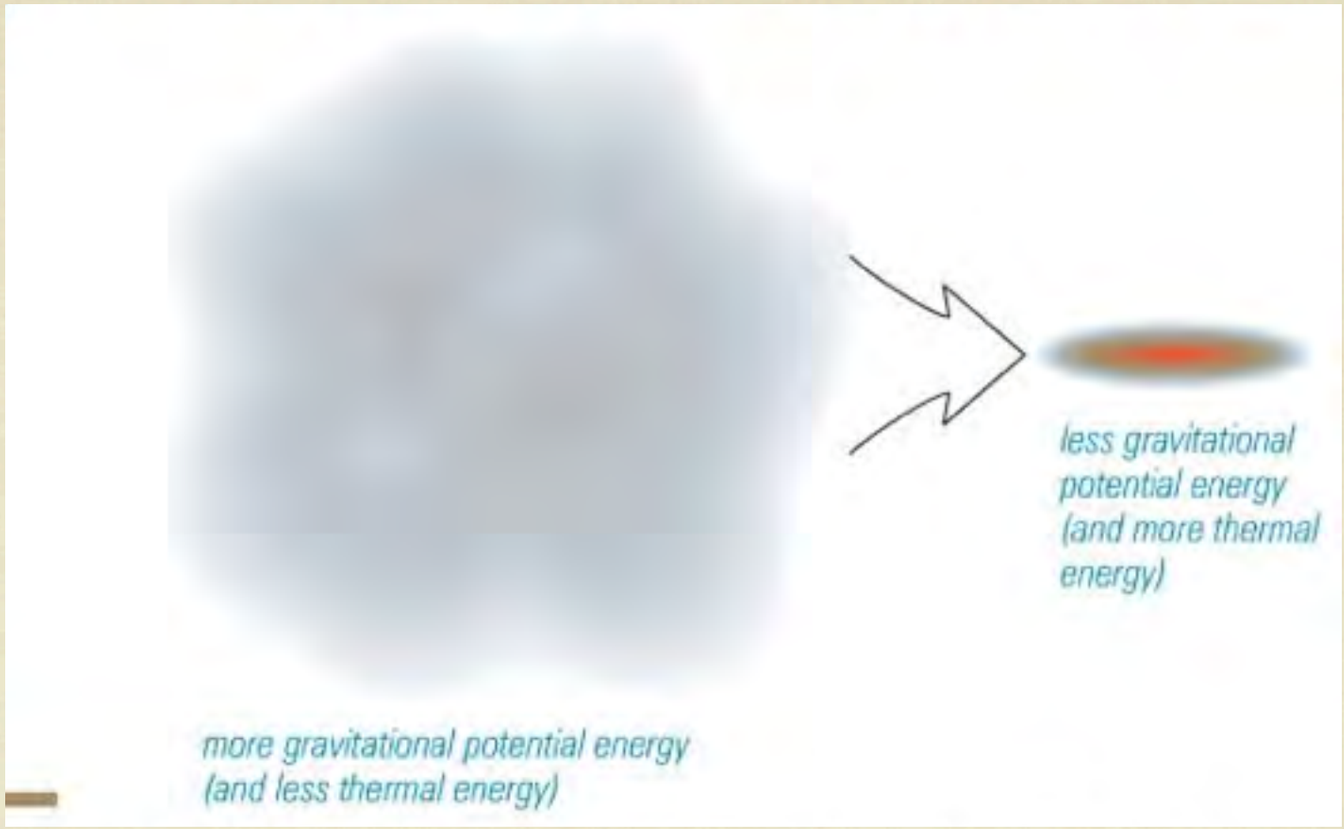
- Powered by Human Sacrifice?
- The Aztecs thought so.
- But... it's still shining 500 years later.

Why does the Sun Shine?

- Is it on fire, maybe made of Wood, or Coal?

- The chemical energy in the sun would only last for **10,000 years**! It's been going for 5 billion!

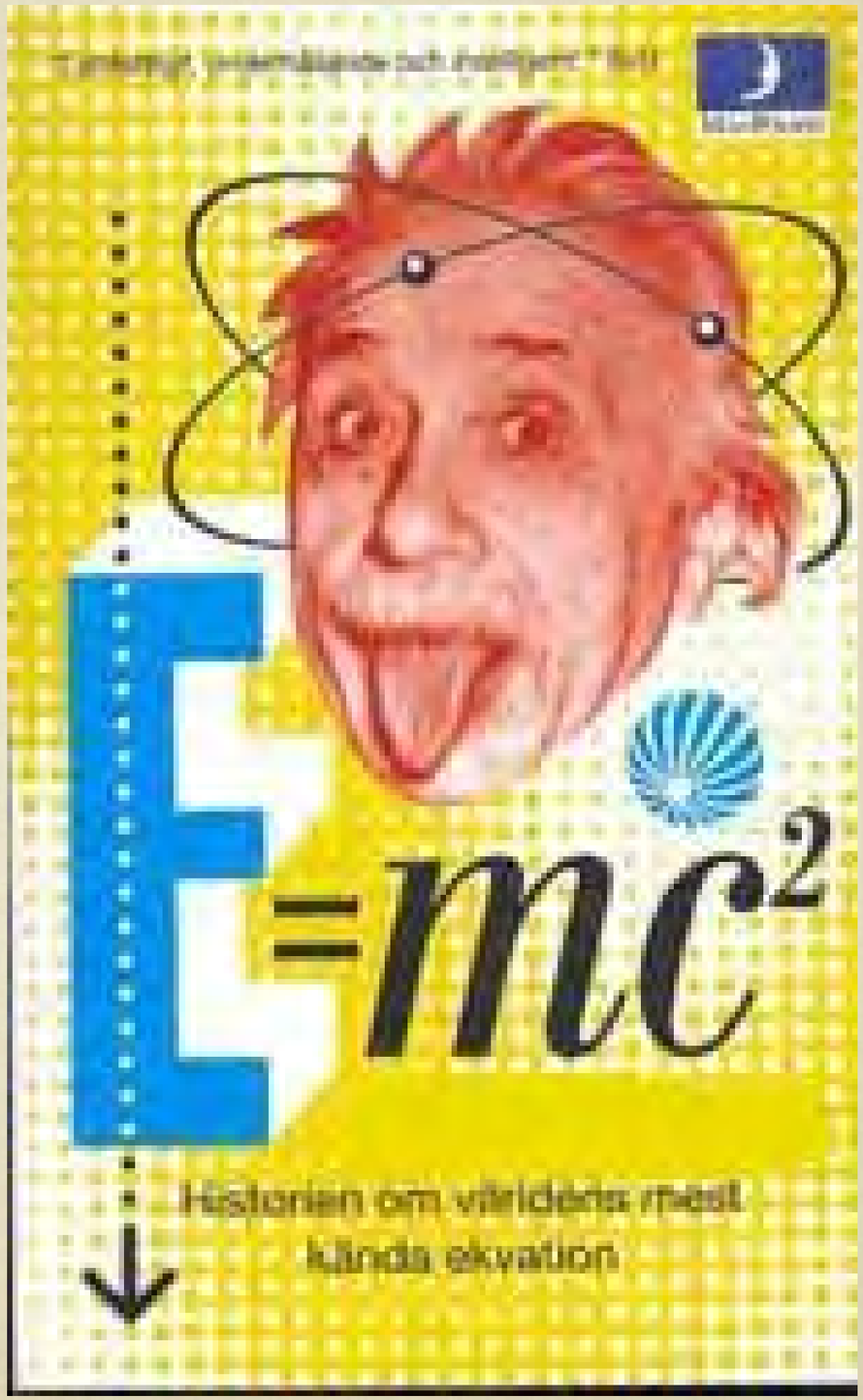
Why does the Sun Shine?



- Due to gravitational contraction? Works for Jupiter!
- It would run out of energy in **25 million years.**

Why does the Sun Shine?

- What else is there?
- Mass Energy! $E=mc^2$
- Much greater source of energy than any other!
- One gram of matter holds energy of 15,000 barrels of oil!



- “ The sun is a mass of incandescent gas,
  A gigantic nuclear furnace
  Where hydrogen is built into helium
  At a temperature of millions of degrees”

  — They Might be Giants,
  Why Does the Sun Shine?

What keeps it shining?

- Sun is in "Hydrostatic Equilibrium".

- It's large mass creates intense pressure in the center, which makes it HOT (millions of degrees).

- Overcomes Coloumb Barrier leads to nuclear fusion, which generates photons and energetic particles.

- Sun's luminosity is 400,000,000,000,000,000,000,000,000 Watts! (also known as ... 4×10^{26} Watts).

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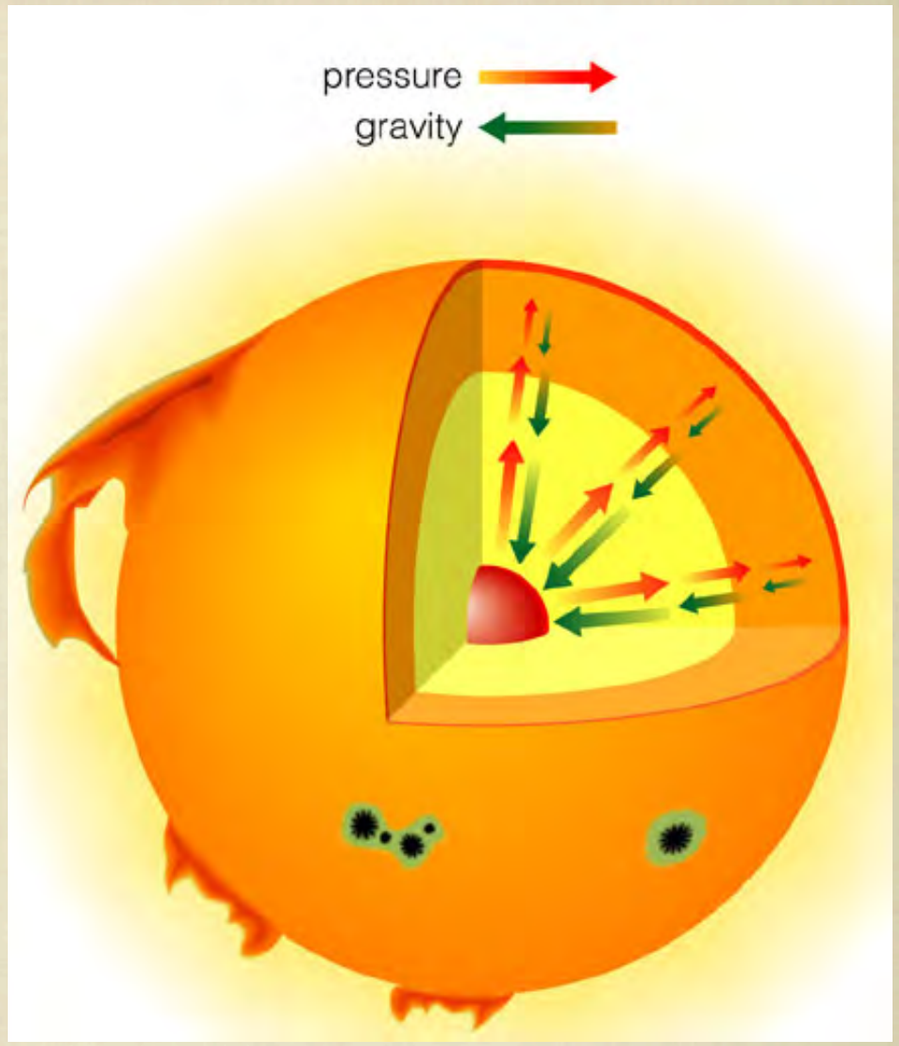

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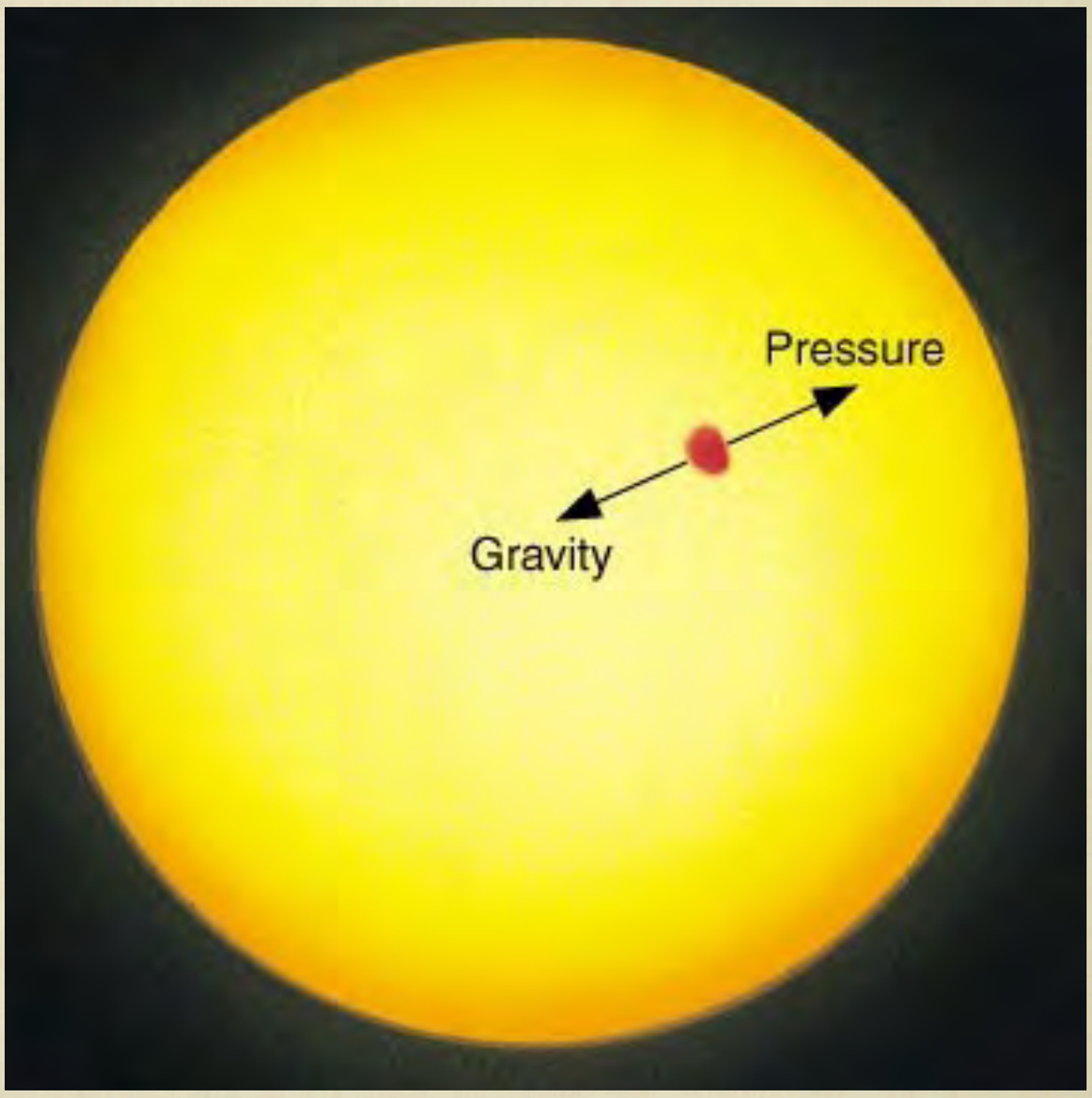
Gravity vs. Pressure

- It's a battle: gravity fighting against pressure.
- Pressure created by the heat, heat produced by the nuclear reactions!



The solar thermostat

Temperature Decreases

Fusion Rate Decreases

Core compresses

Temperature Restored

A

B

C

D

- What would happen inside the Sun if a slight rise in core temperature led to a rapid rise in fusion energy?

A) The core would expand and heat up slightly

B) The core would expand and cool

C) The Sun would blow up like a hydrogen bomb

A

B

C

D

- What would happen inside the Sun if a slight rise in core temperature led to a rapid rise in fusion energy?

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✪ B) The core would expand and cool

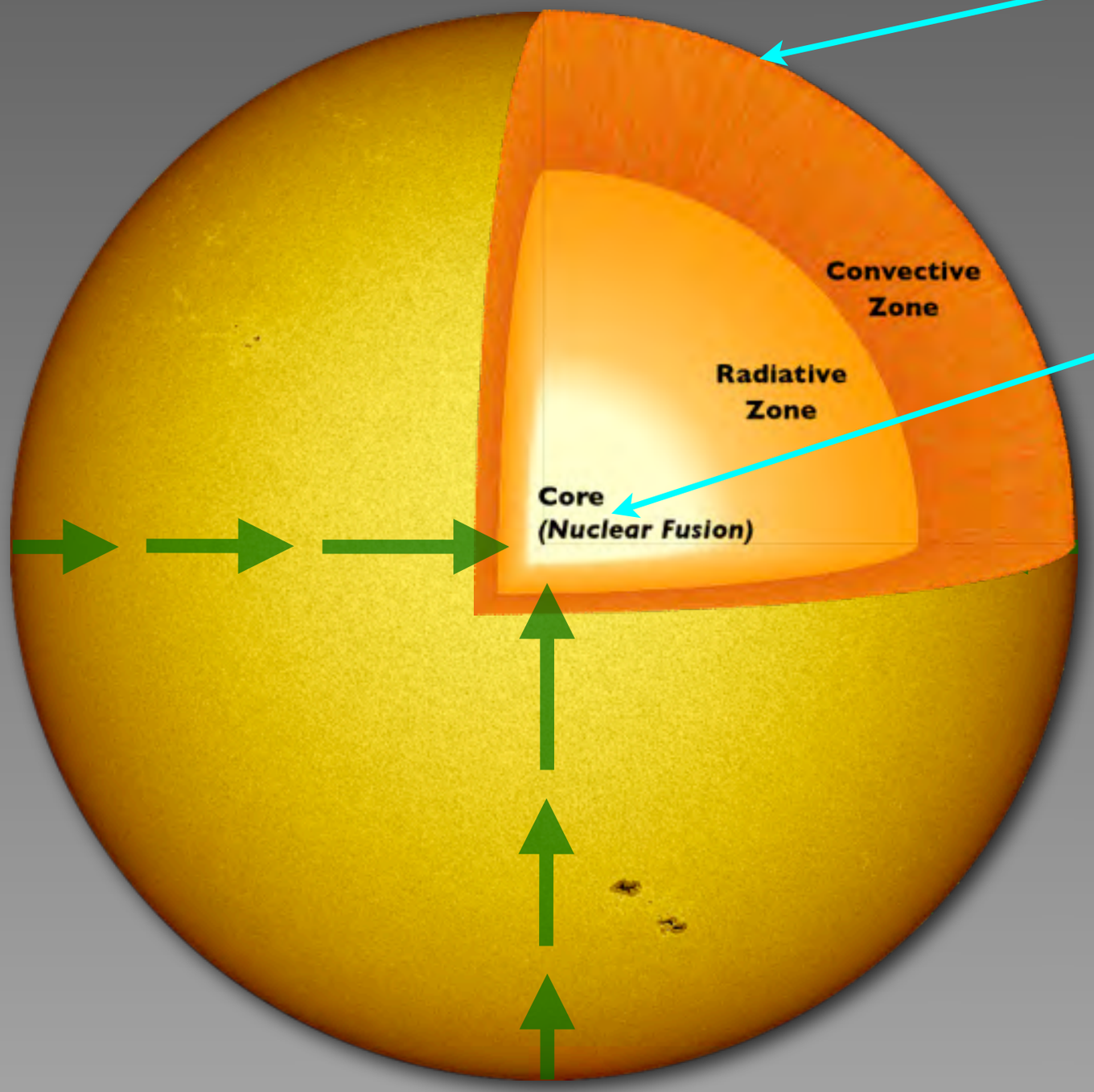
C) The Sun would blow up like a hydrogen bomb

What makes stars shine?

gravity

5,800 K

16,000,000 K



1200 K

What started The Sun shining?

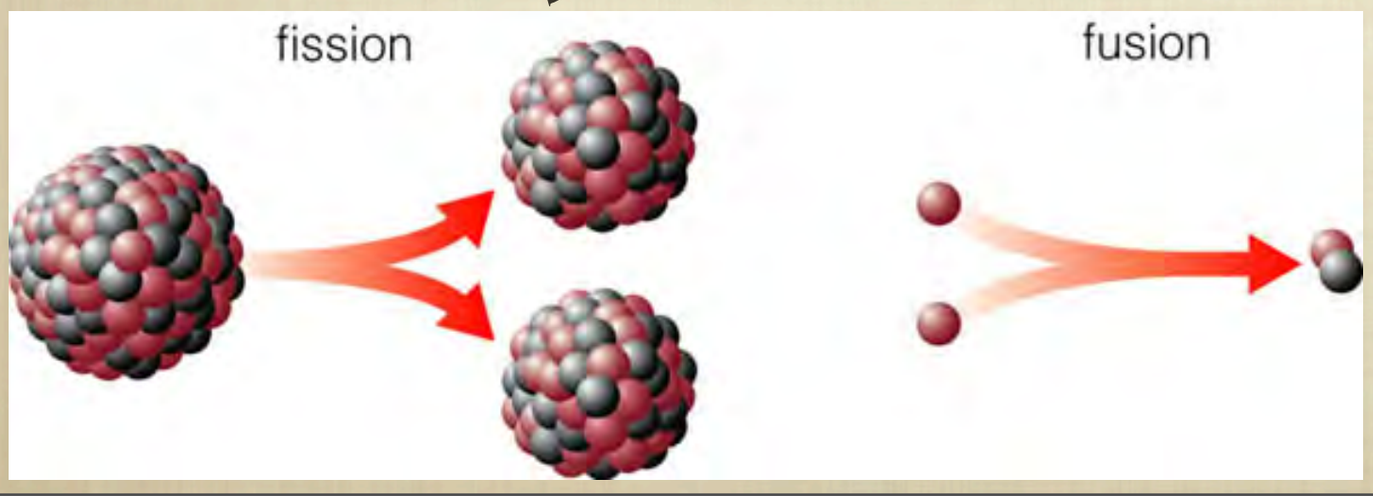
- Gravitational contraction!

- (even though it doesn't explain why it shines now).

- Contracting material heated up, until hot enough for nuclear "fusion" to occur.

Nuclear Reactions

- **Fusion:**
  - two light nuclei joined into one nucleus
    - powers the Sun
- **Fission:**
  - massive nucleus splits in smaller nuclei
    - powers nuclear reactors (Davis-Besse)



Hydrogen Fusion by the Proton–Proton Chain

Step 1

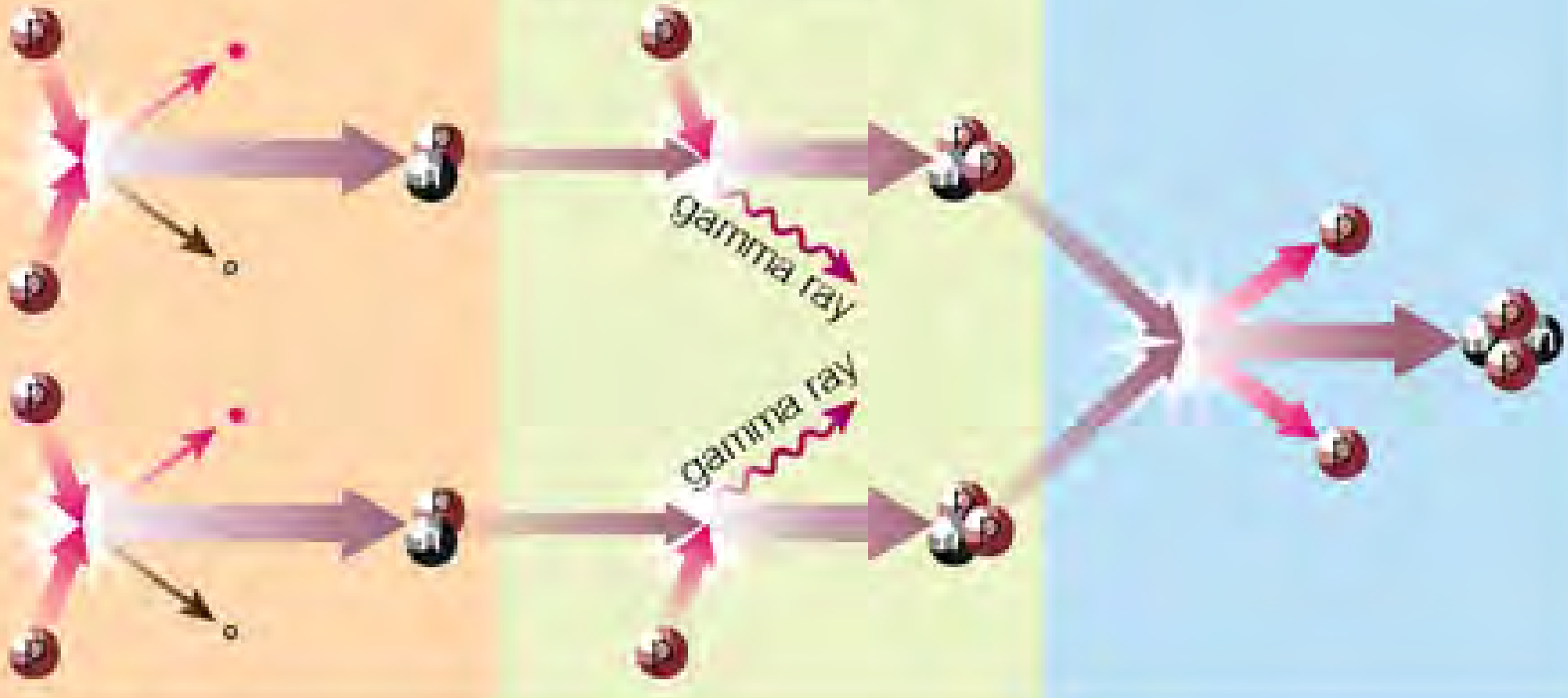
Two protons fuse to make a deuterium nucleus (1 proton and 1 neutron). This step occurs twice in the overall reaction.

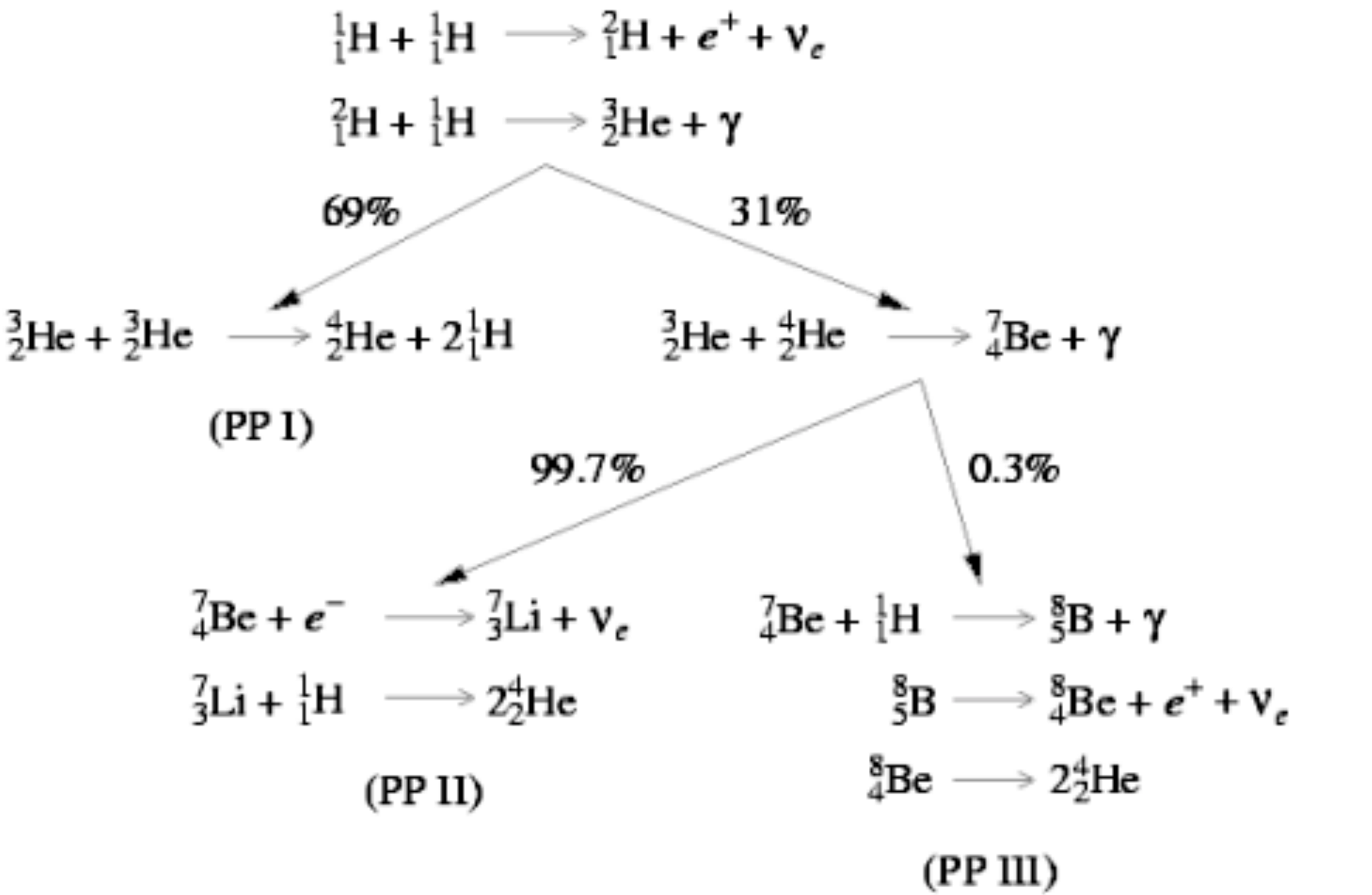
Step 2

The deuterium nucleus and a proton fuse to make a nucleus of helium-3 (2 protons, 1 neutron). This step also occurs twice in the overall reaction.

Step 3

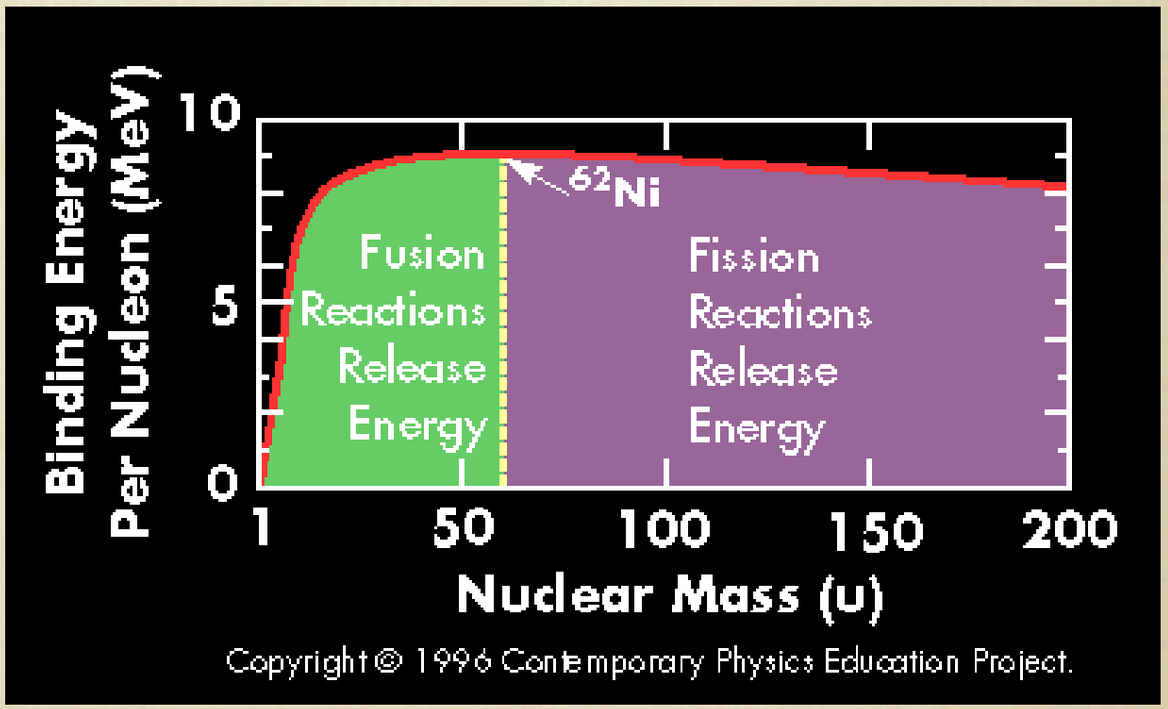
Two helium-3 nuclei fuse to form helium-4 (2 protons, 2 neutrons), releasing two excess protons in the process.




$^1_1H + ^1_1H \longrightarrow ^2_1H + e^+ + \nu_e$
$^2_1H + ^1_1H \longrightarrow ^3_2He + \gamma$
69%
31%
$^3_2He + ^3_2He \longrightarrow ^4_2He + 2^1_1H$
(PP 1)
$^3_2He + ^4_2He \longrightarrow ^7_4Be + \gamma$
99.7%
0.3%
$^7_4Be + e^- \longrightarrow ^7_3Li + \nu_e$
$^7_3Li + ^1_1H \longrightarrow 2^4_2He$
(PP II)
$^7_4Be + ^1_1H \longrightarrow ^8_5B + \gamma$
$^8_5B \longrightarrow ^8_4Be + e^+ + \nu_e$
$^8_4Be \longrightarrow 2^4_2He$
(PP III)

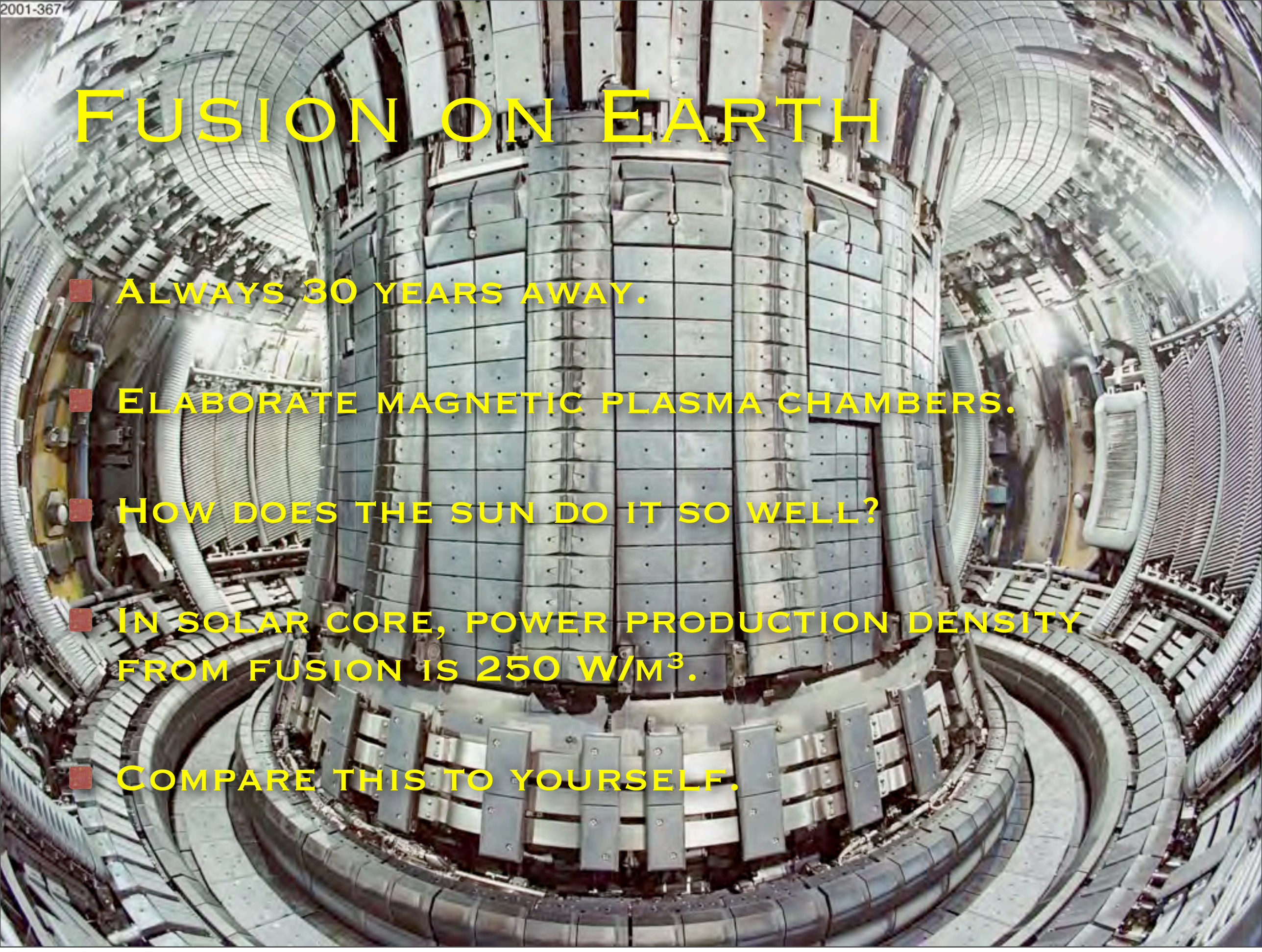
Converting Mass to Energy

- **Nuclear reactions change mass of constituents**
  - Mass increase consumes energy
  - Mass decrease releases energy
- **Mass decreases in**
  - **Fission of heavy nuclei**
    - Can occur spontaneously
    - natural radioactivity
  - **Fusion of light nuclei**
    - Like charges repel
    - Fusion requires high speed
    - Temperature > 10 million K



Fusion: Sun's Energy Source

- **Sun's core:**
  - Temperature = 15 million K
  - Hot enough to fuse hydrogen
- **p-p chain (proton-proton)**
  - Series of fusion reactions
  - Converts:
    4 hydrogen to 1 helium
  - mass of 4 H great than mass of 1 He: **this mass decrease is the energy source!! Only 0.7% difference**



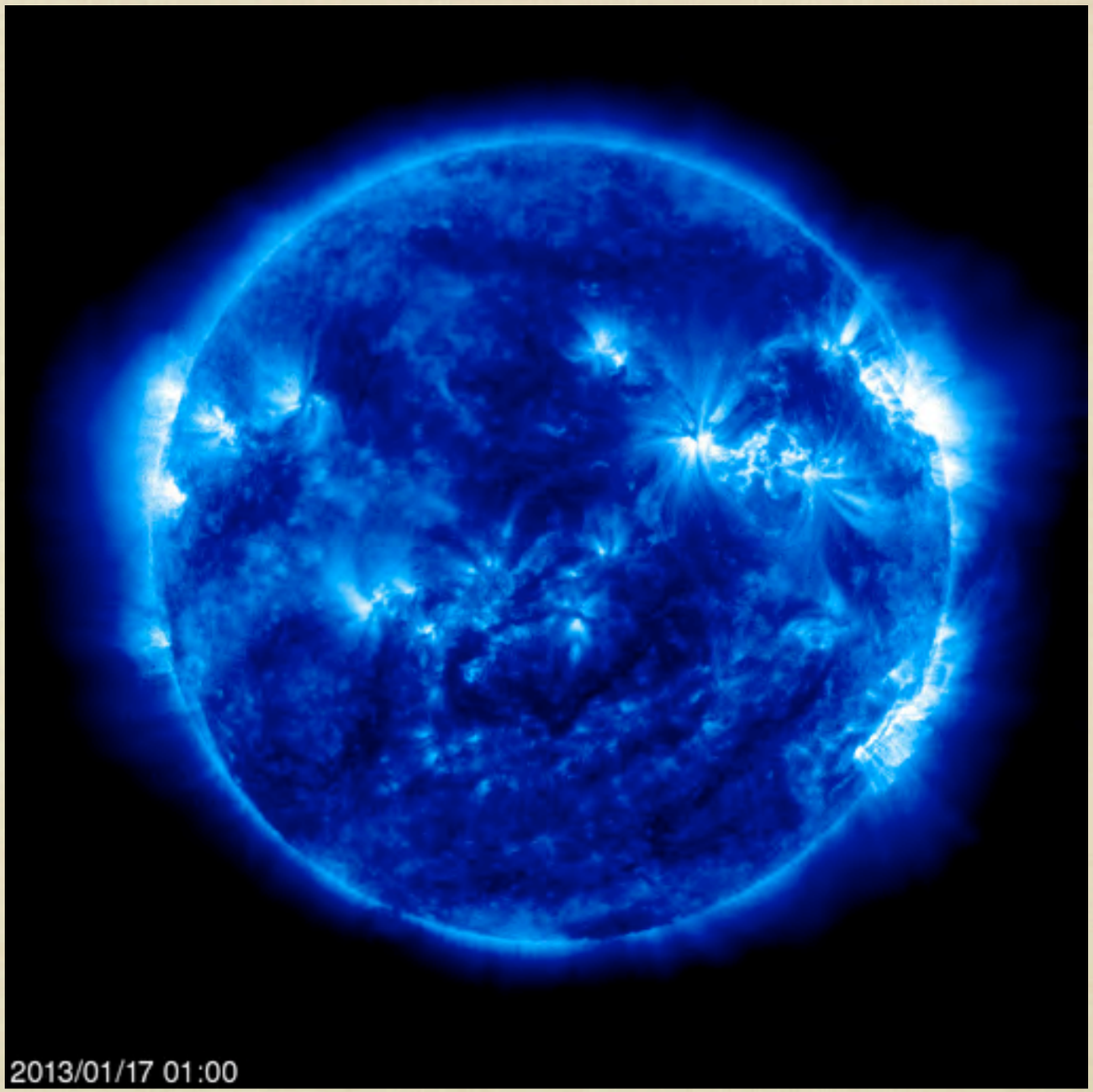
Fusion on Earth

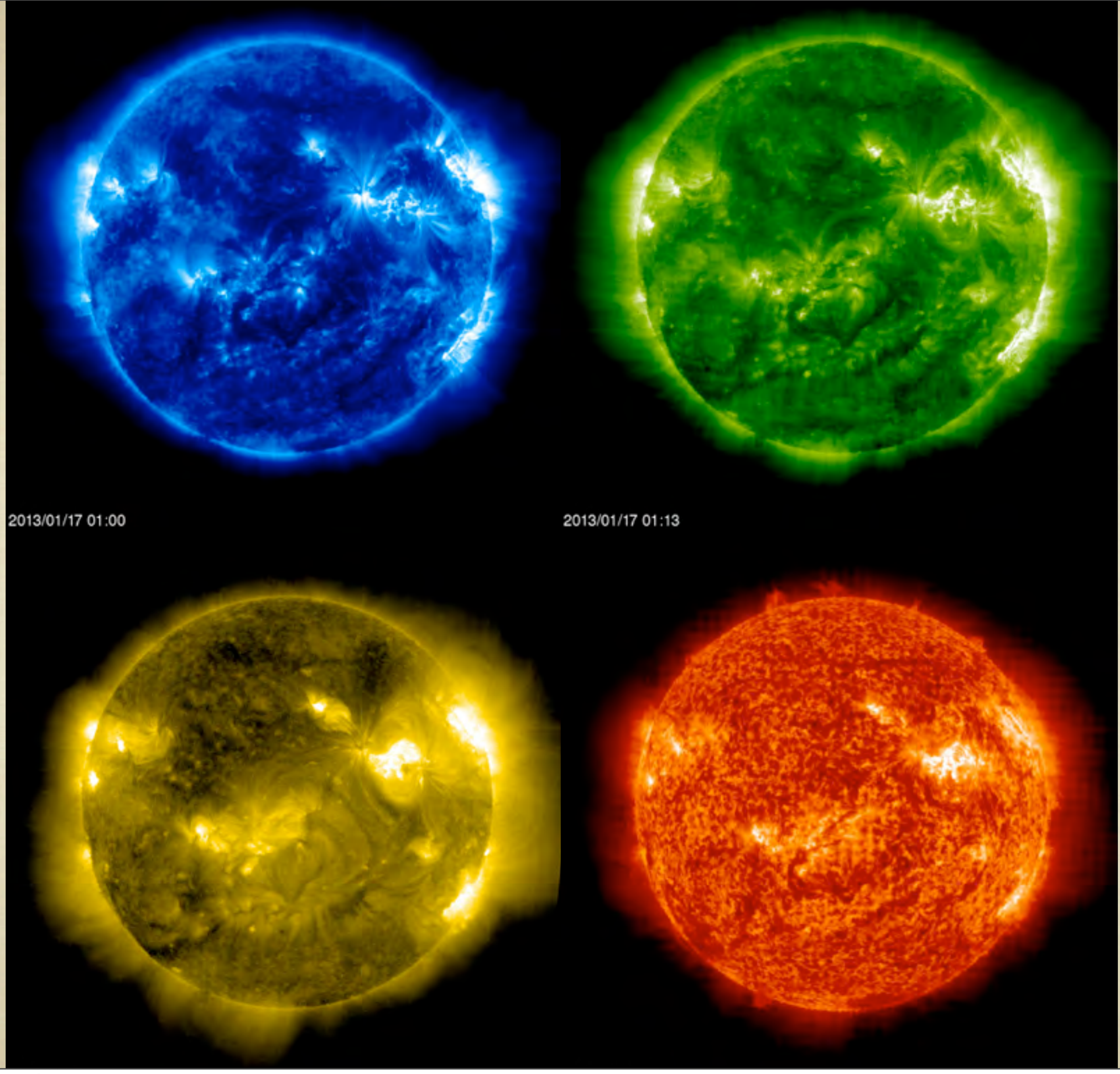
- Always 30 years away.
- Elaborate magnetic plasma chambers.
- How does the sun do it so well?
- In solar core, power production density from fusion is 250 W/m^3.
- Compare this to yourself.

Sun: latest View

8 hrs ago!

From the SOHO spacecraft

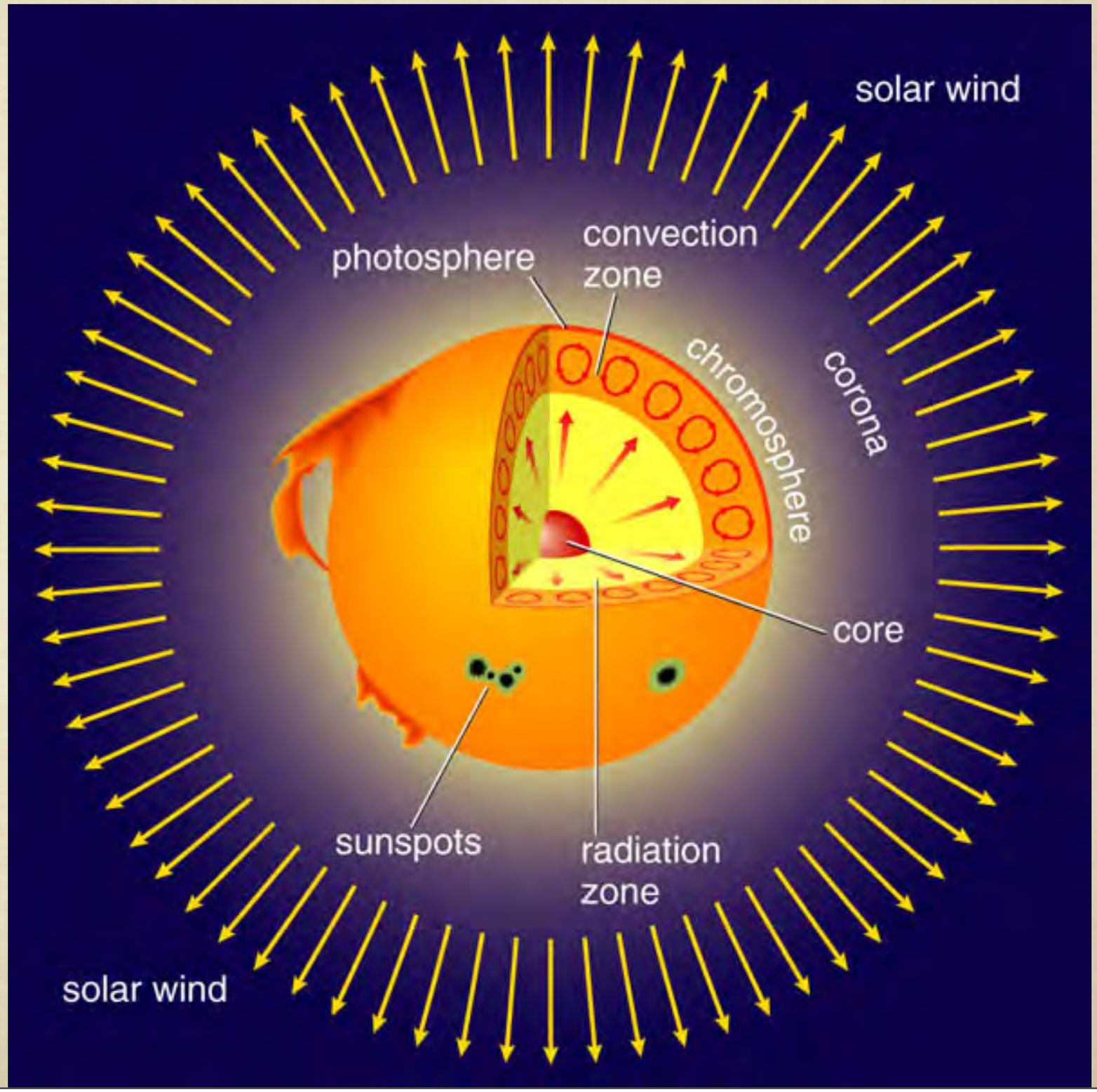



2013/01/17 01:00
2013/01/17 01:13

More SOHO

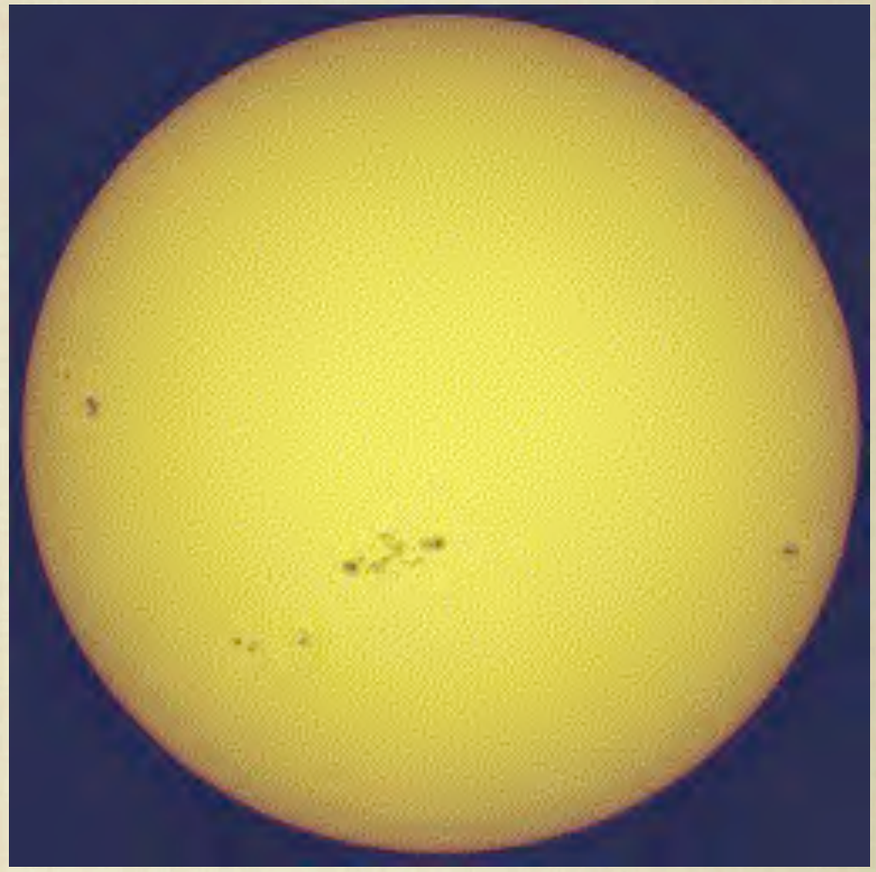
Major Regions of the Sun

- **Interior**
  - Core
  - Radiative Zone
  - Convective Zone
- **Atmosphere**
  - Photosphere
  - Chromosphere
  - Corona
  - Solar Wind



Photosphere

- Effective "surface" of sun
  - not solid, just the region we see by eye
- Thin atmospheric layer
  - Few hundred km
- Low density gas
  - 0.01% Earth's atmosphere
- Close-up shows granulation
  - convection cells
- Sunspots
  - Somewhat Cooler than surrounding gas. appear dark

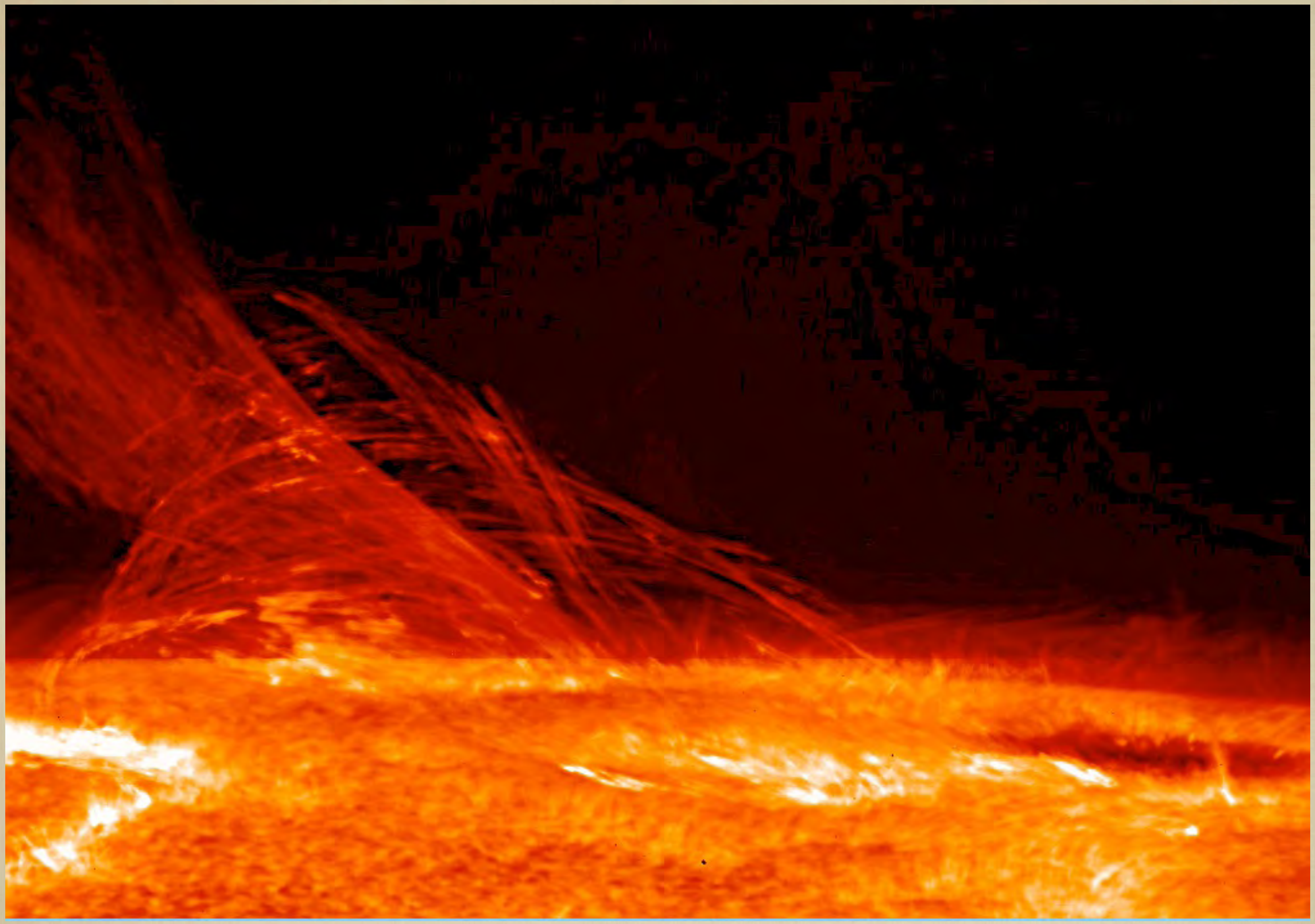


The sun's atmosphere

- Photosphere: 6000K lower layer.

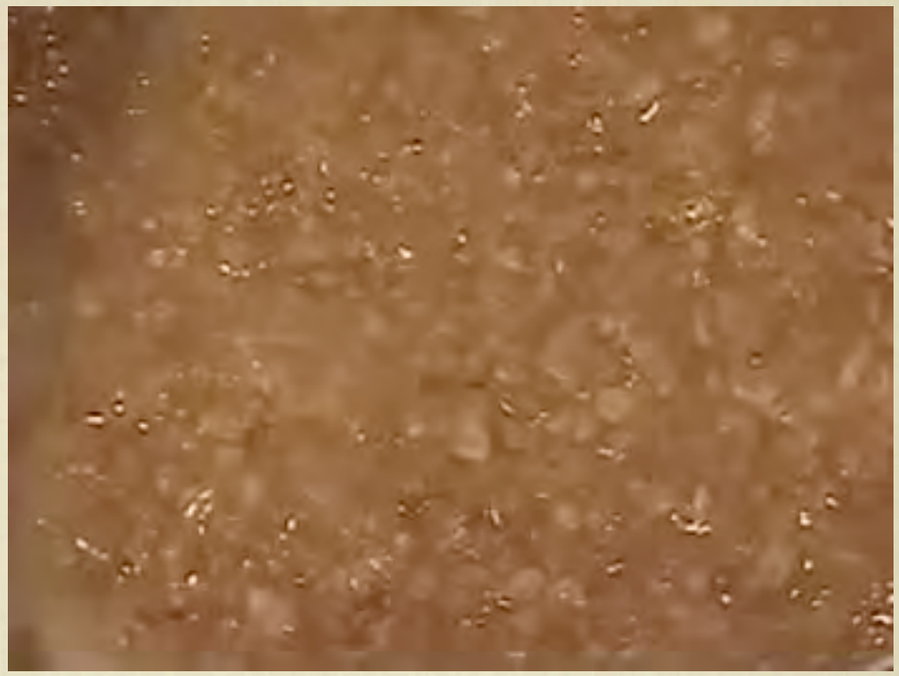
- Chromosphere: 10,000 K "middle layer"

- Corona: 1 million K "outermost layer", extends to several million KM above the surface!



Spacecraft Hinode

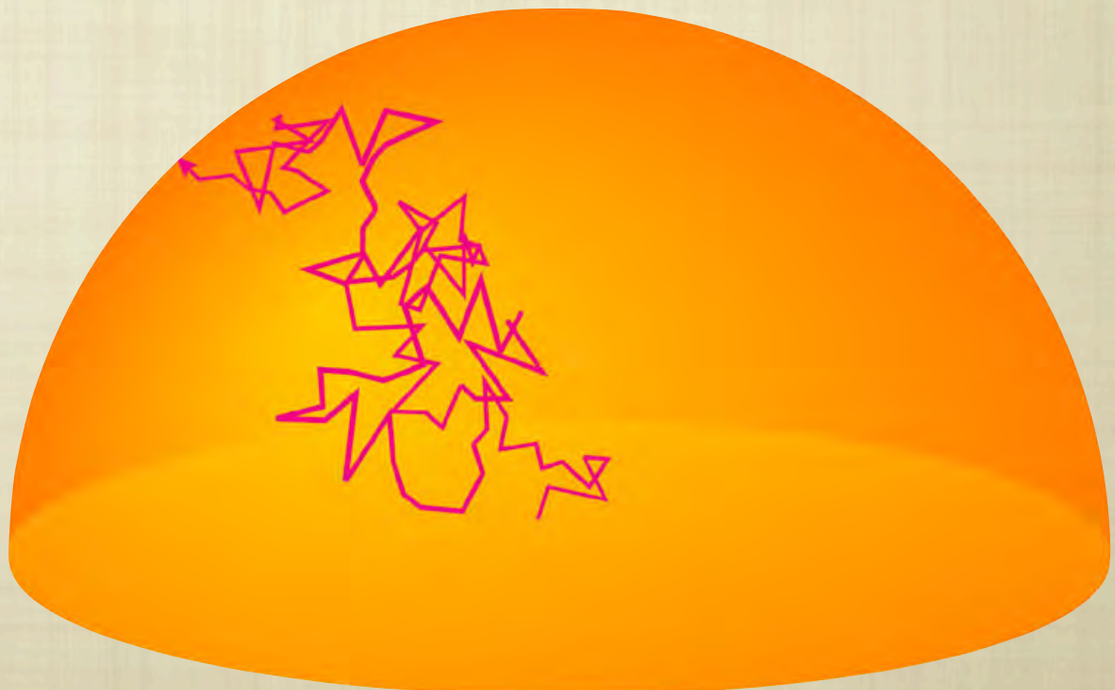
How does energy get out of the sun?



- Convection (think of boiling oatmeal).

- Radiation:
  A random walk.

- takes a photon a few **million** years to reach the surface!



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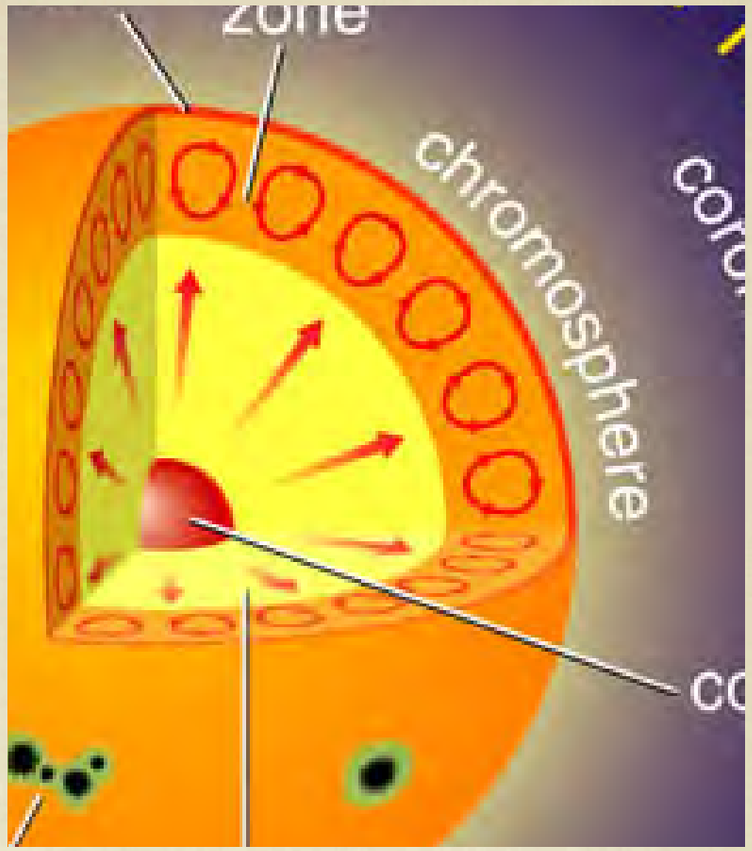
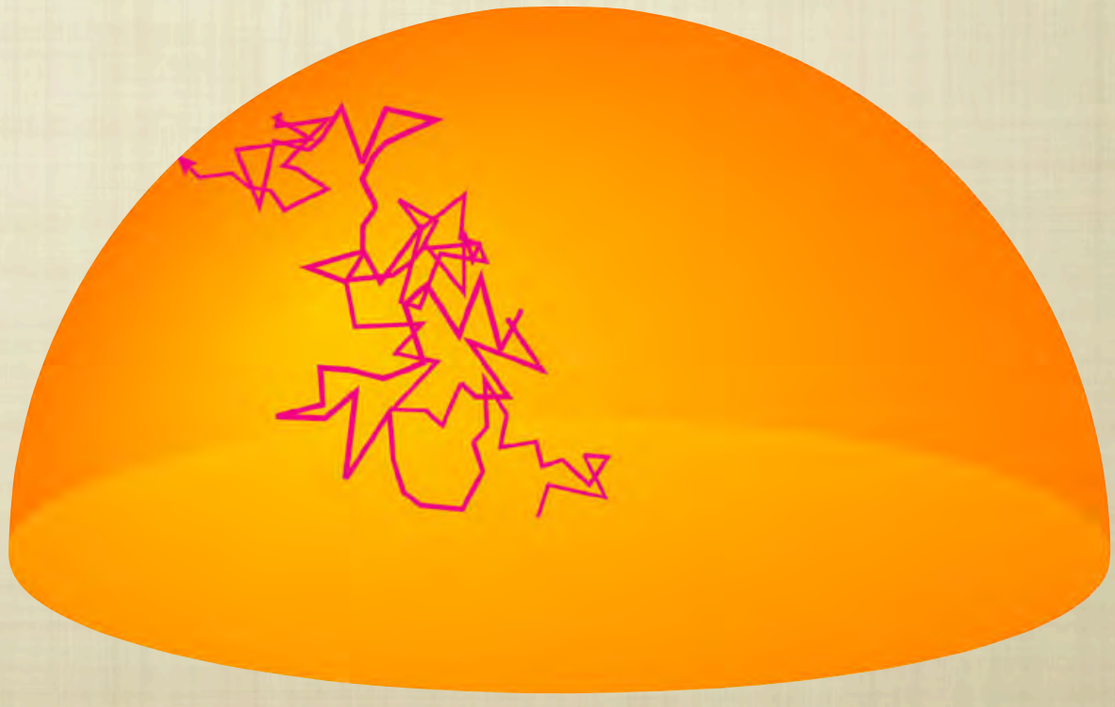
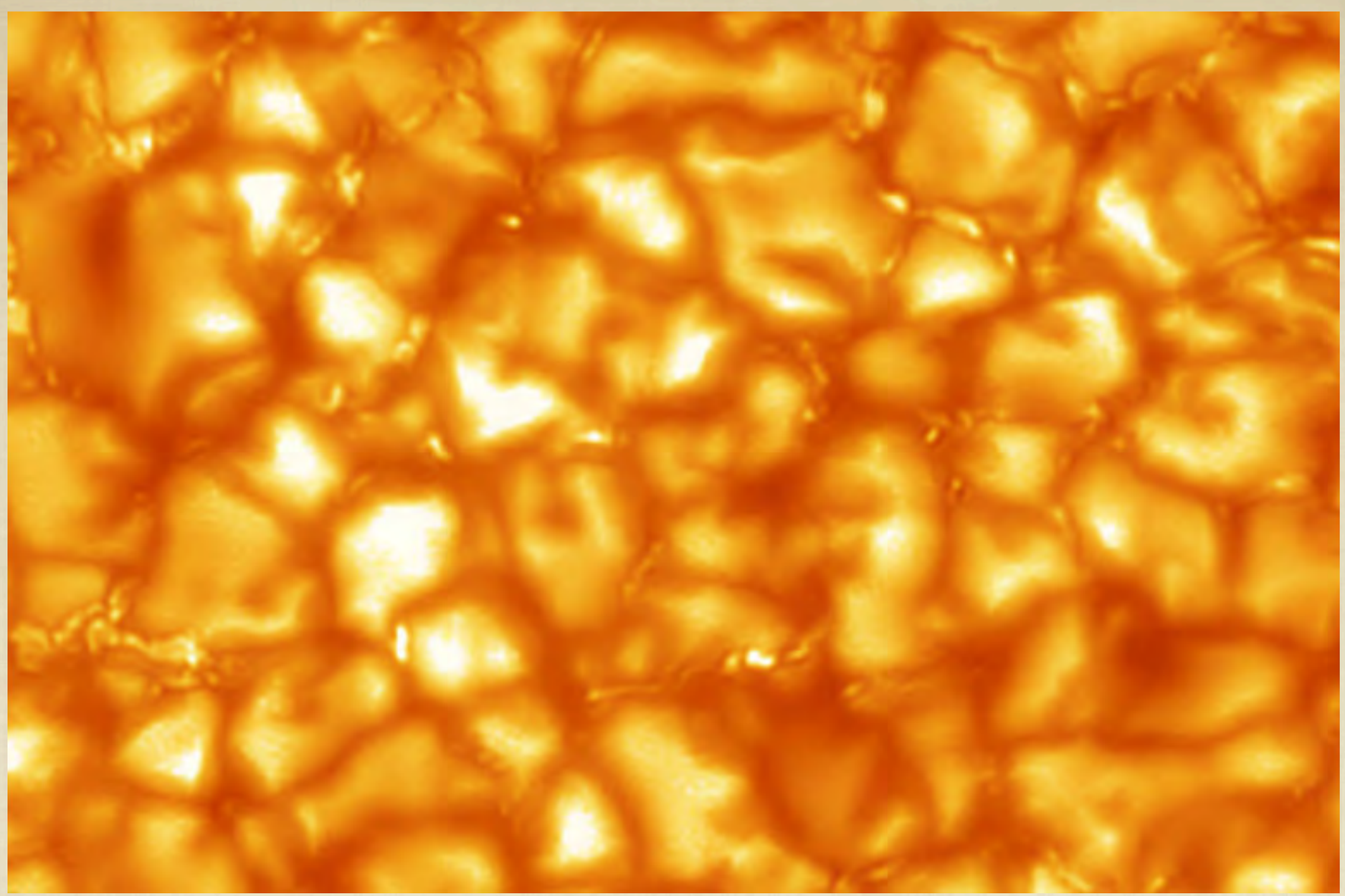
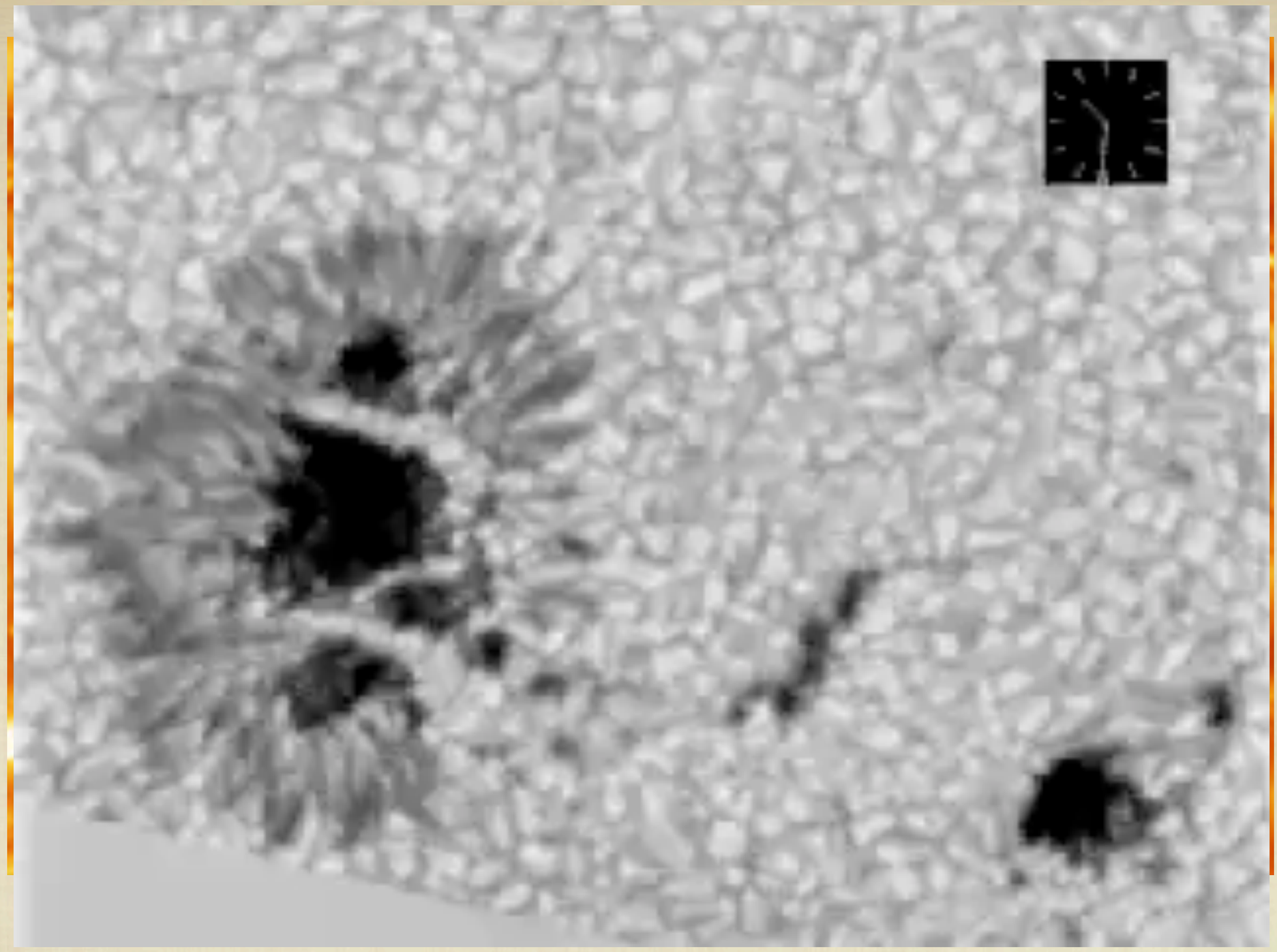






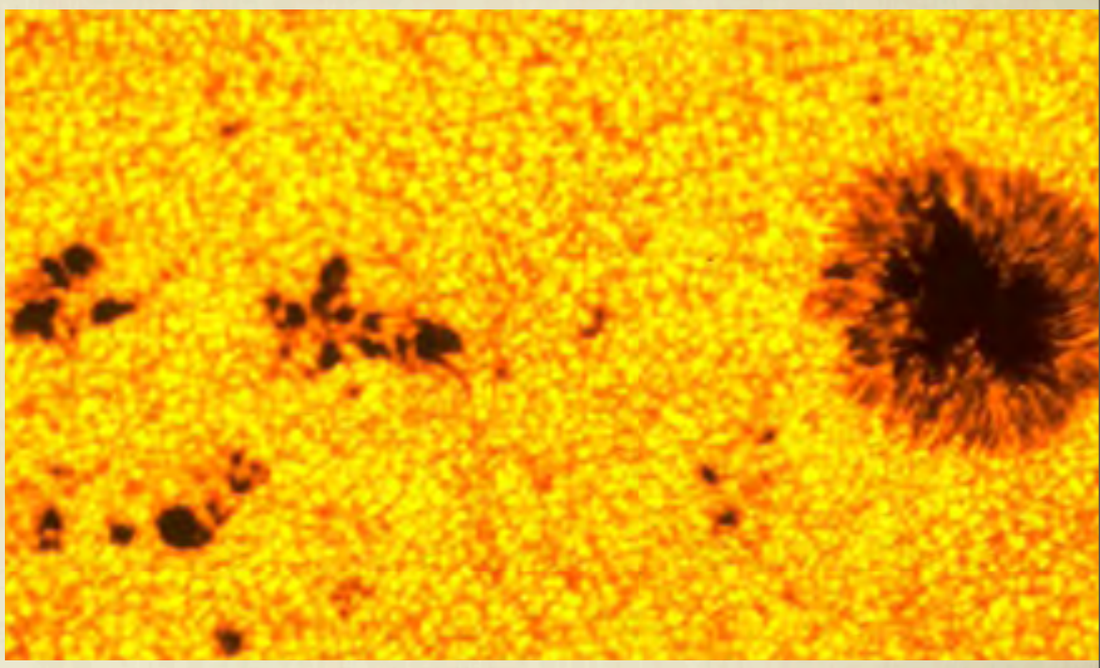
Bright Blobs: where hot gas reaches the surface by convection

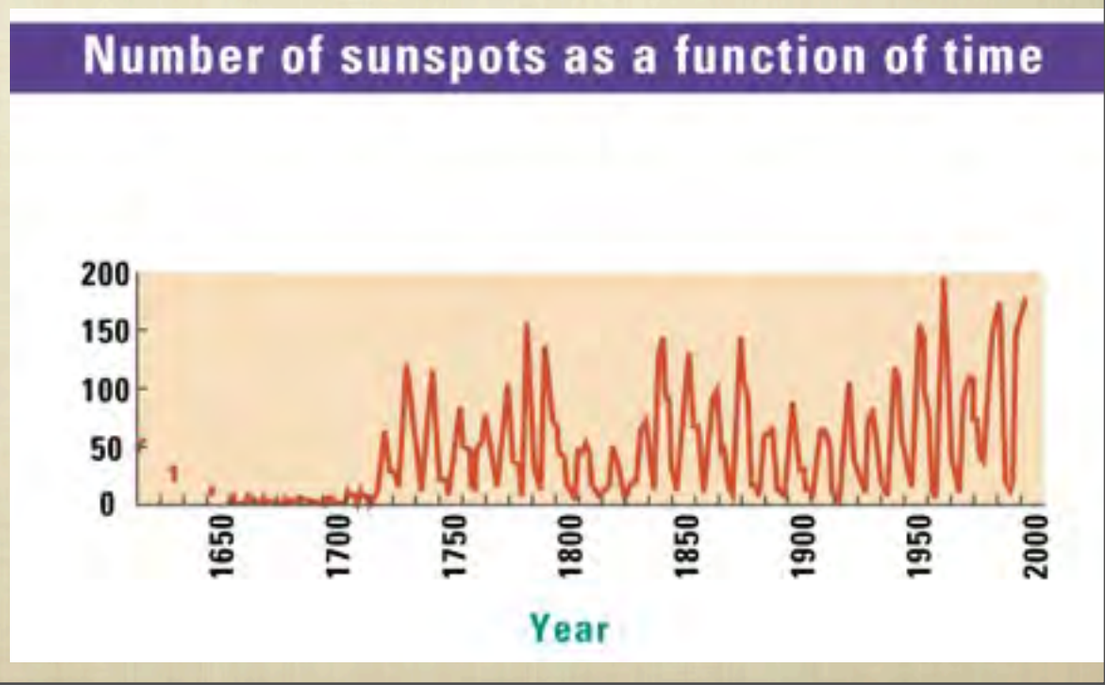


Bright Blobs: where hot gas reaches the surface by convection

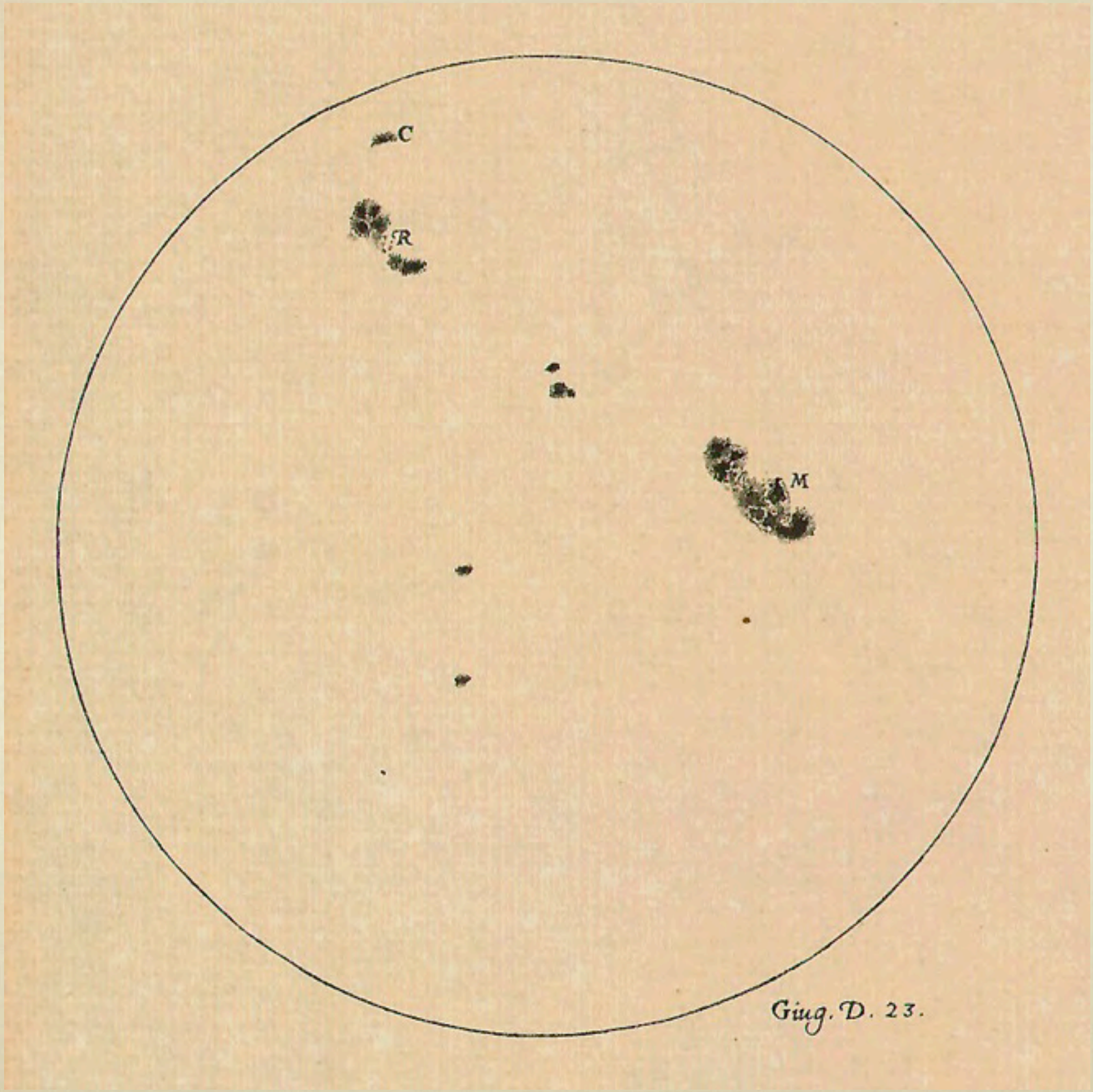
Atmospheric Features

- **Sunspots**
  - Often larger than Earth
  - Occur in groups
  - Associated with magnetic fields
- **Galileo used to measure solar rotation**
  - 25 days at equator (longer at poles)
- **Number of sunspots is cyclical, with 11 year period (actually 22)**
  - Correlated with solar activity: greatest activity at sunspot maximum, least at minimum





Galileo's Sunspot Drawings

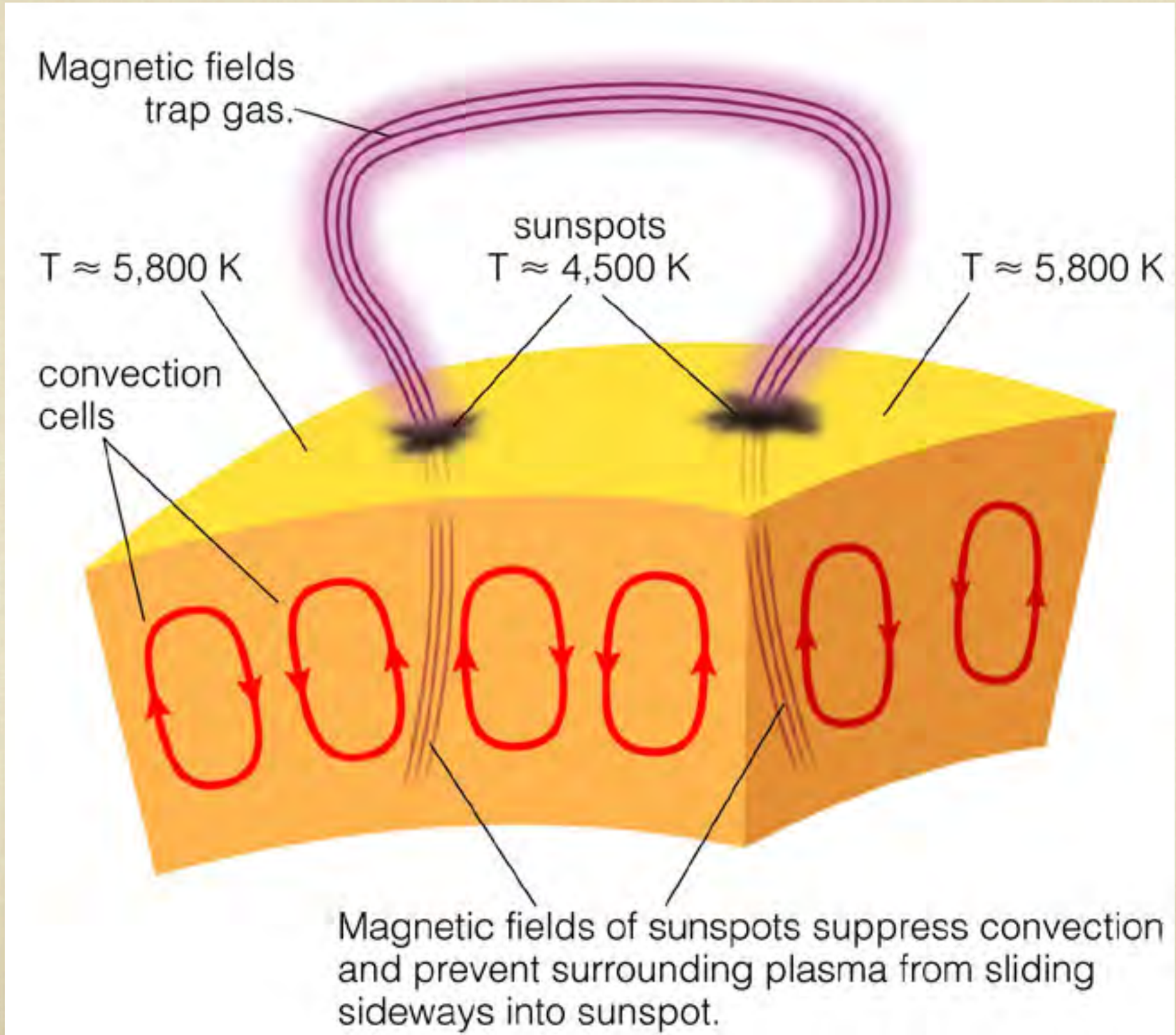


Solar Rotation

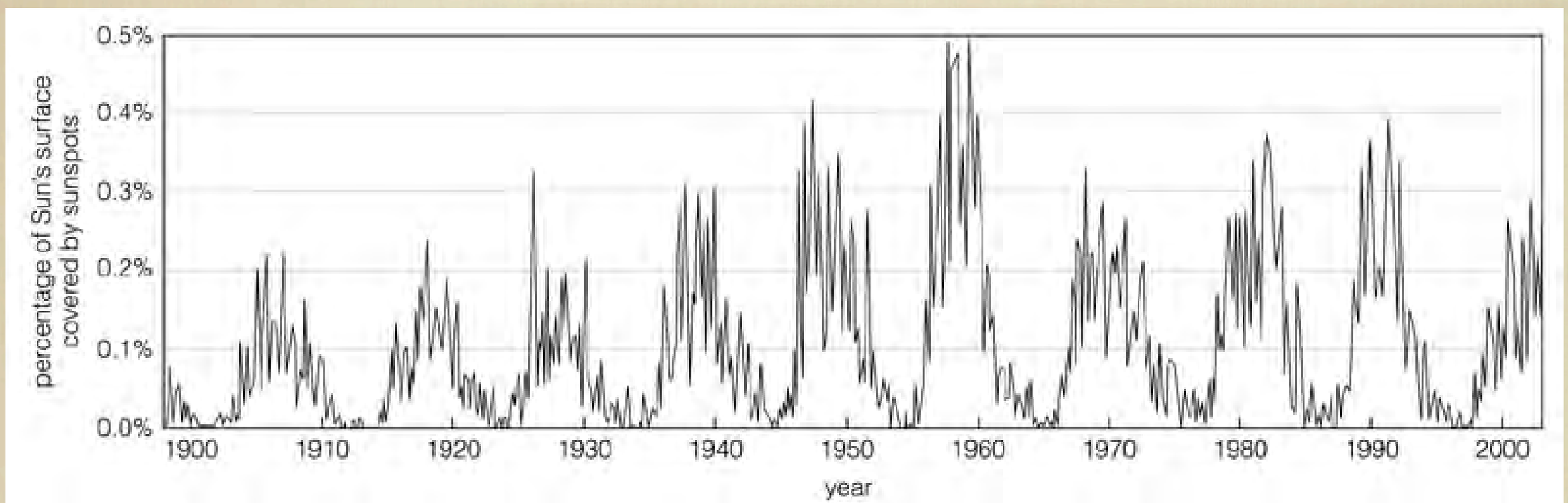
Slower at Poles

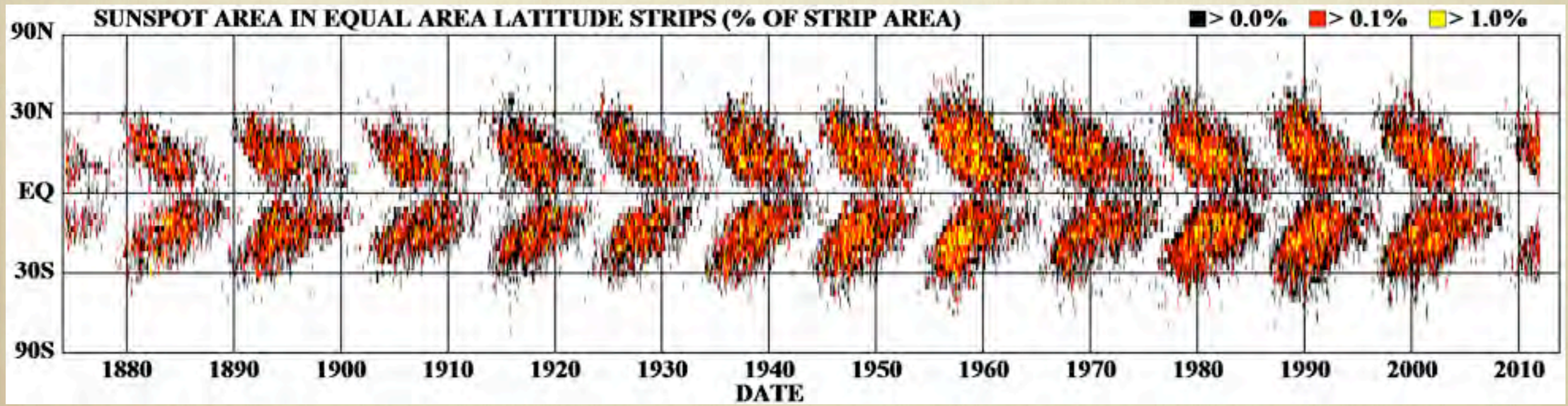
Fastest at Equator

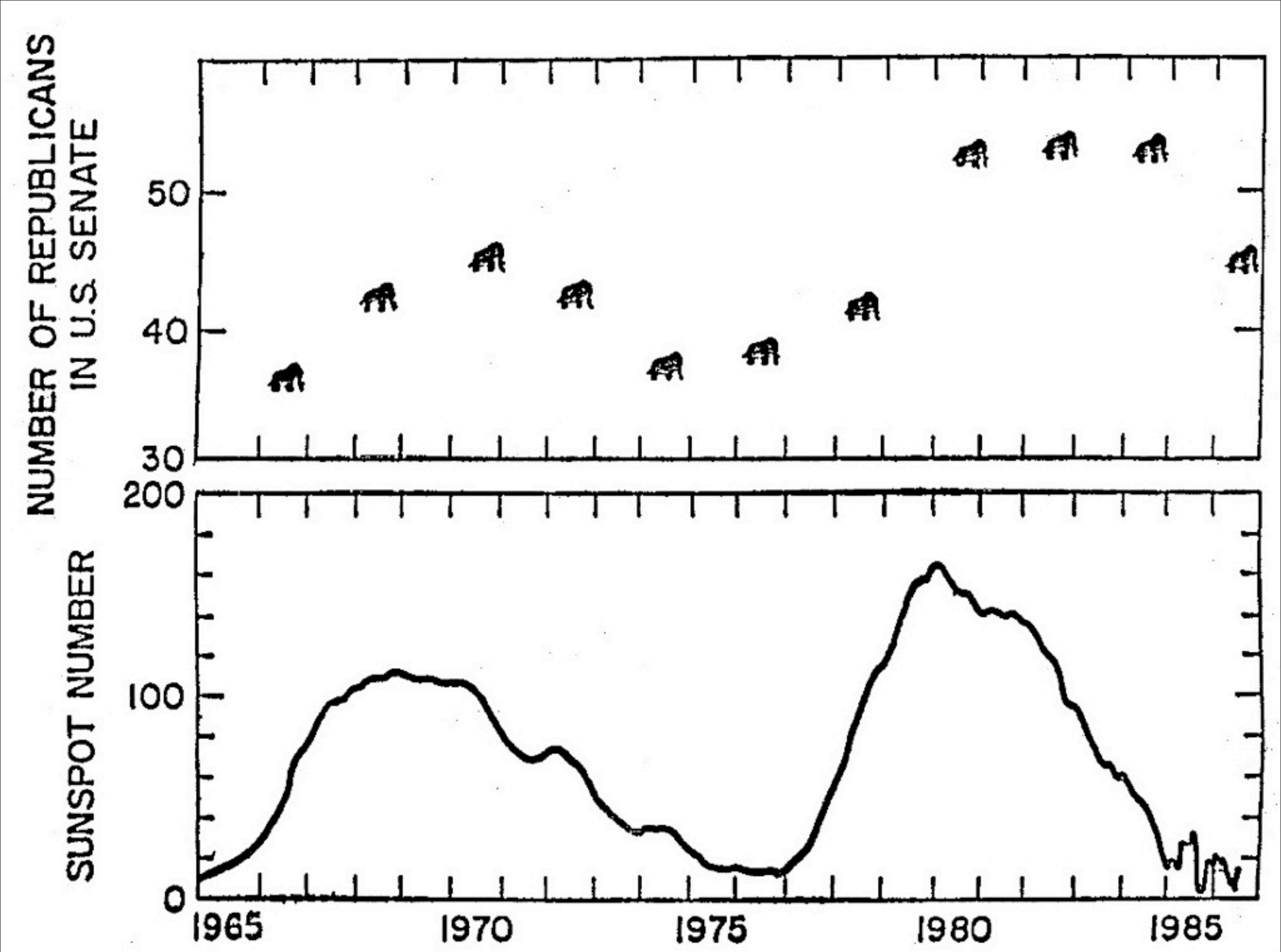
Magnetic Fields

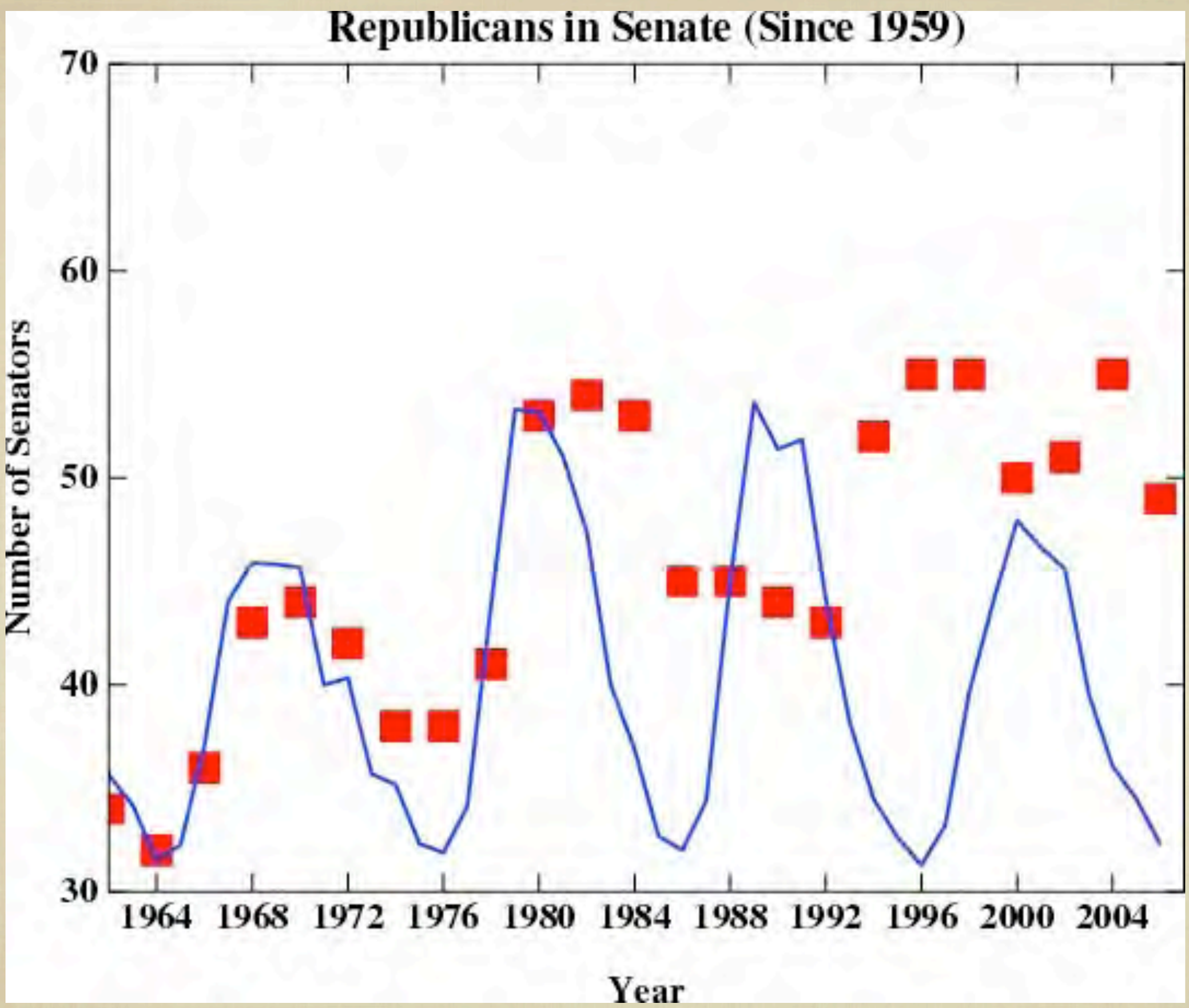


Sunspot Cycle






NUMBER OF REPUBLICANS
IN U.S. SENATE
50
40
30
200
SUNSPOT NUMBER
100
0
1965
1970
1975
1980
1985

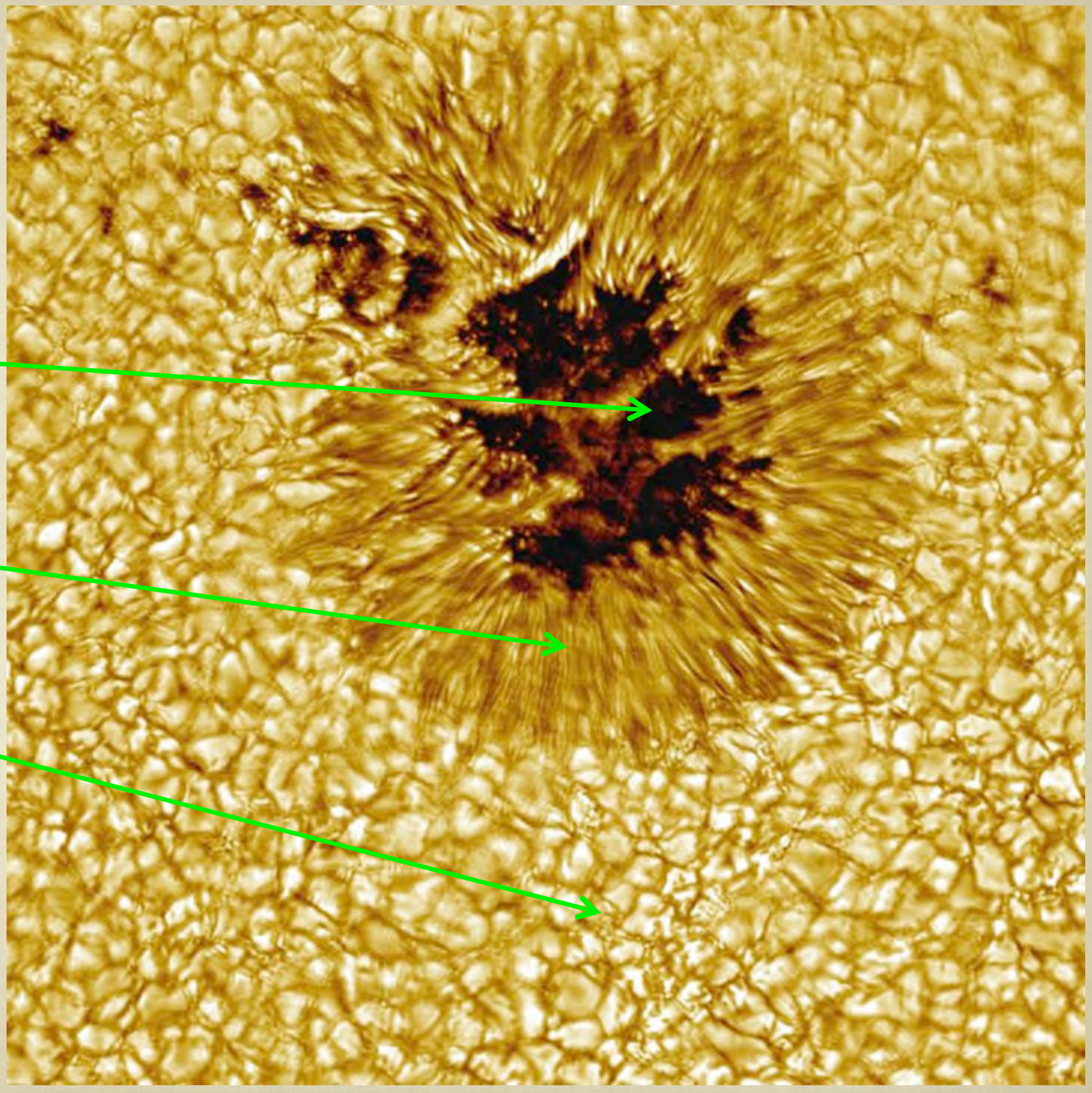

Republicans in Senate (Since 1959)
Number of Senators
70
60
50
40
30
1964
1968
1972
1976
1980
1984
1988
1992
1996
2000
2004
Year

Sunspot + Granulation

Umbra
(T ~ 3900K)

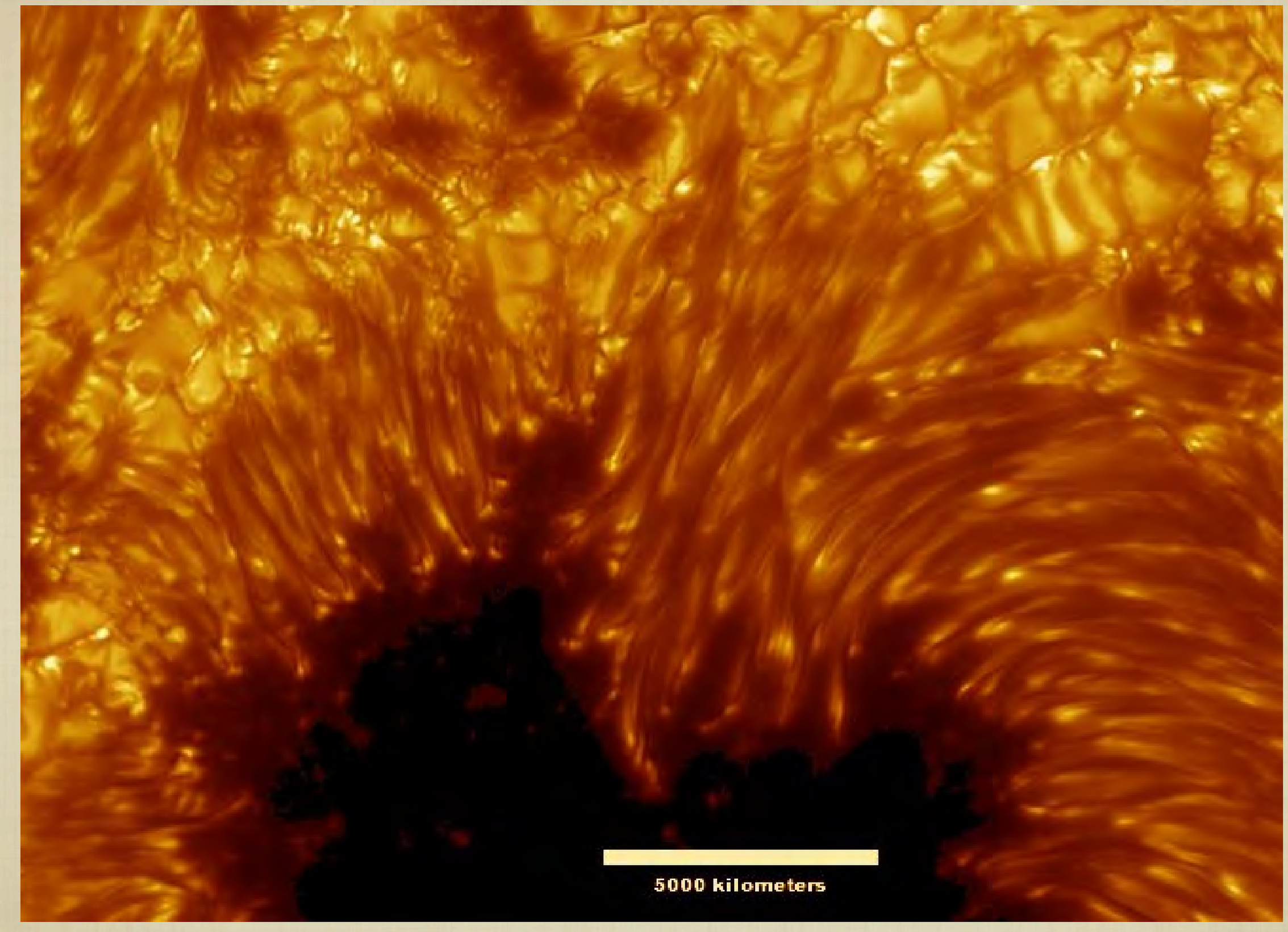
Penumbra

Photosphere
(T ~ 5770K)



NOAO/NSO

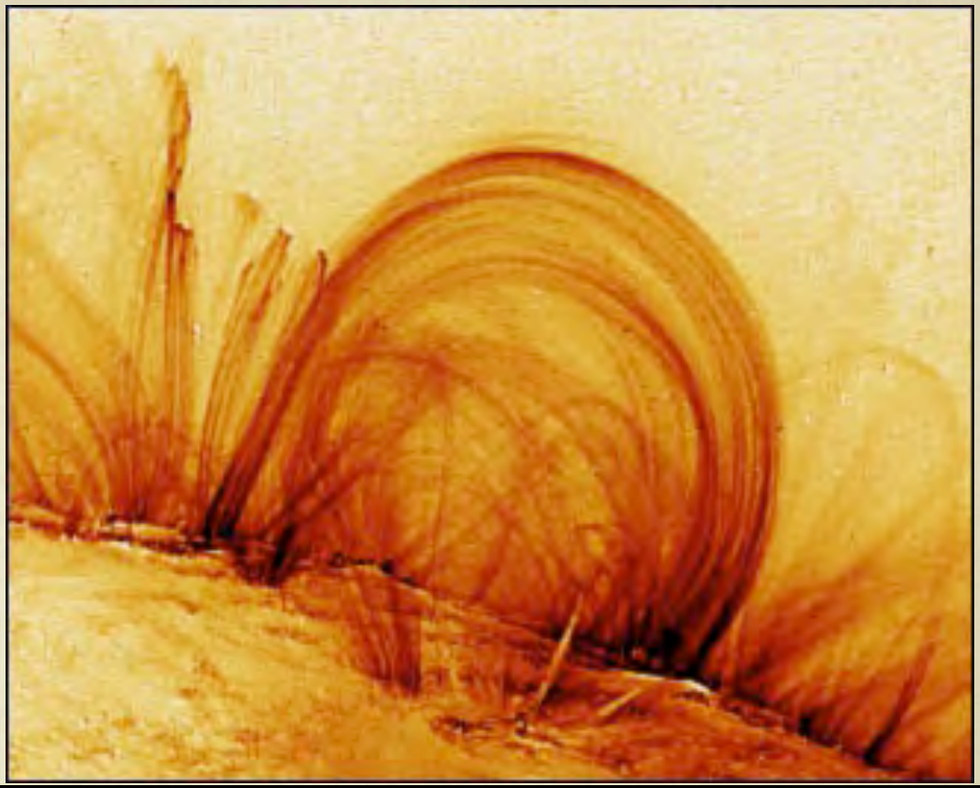
Most Detailed Sunspot Image Ever!



Swedish Vacuum Telescope

Atmospheric Features

- Prominences
  - Loops of hot gas
  - Base near sunspots
  - Trace magnetic fields



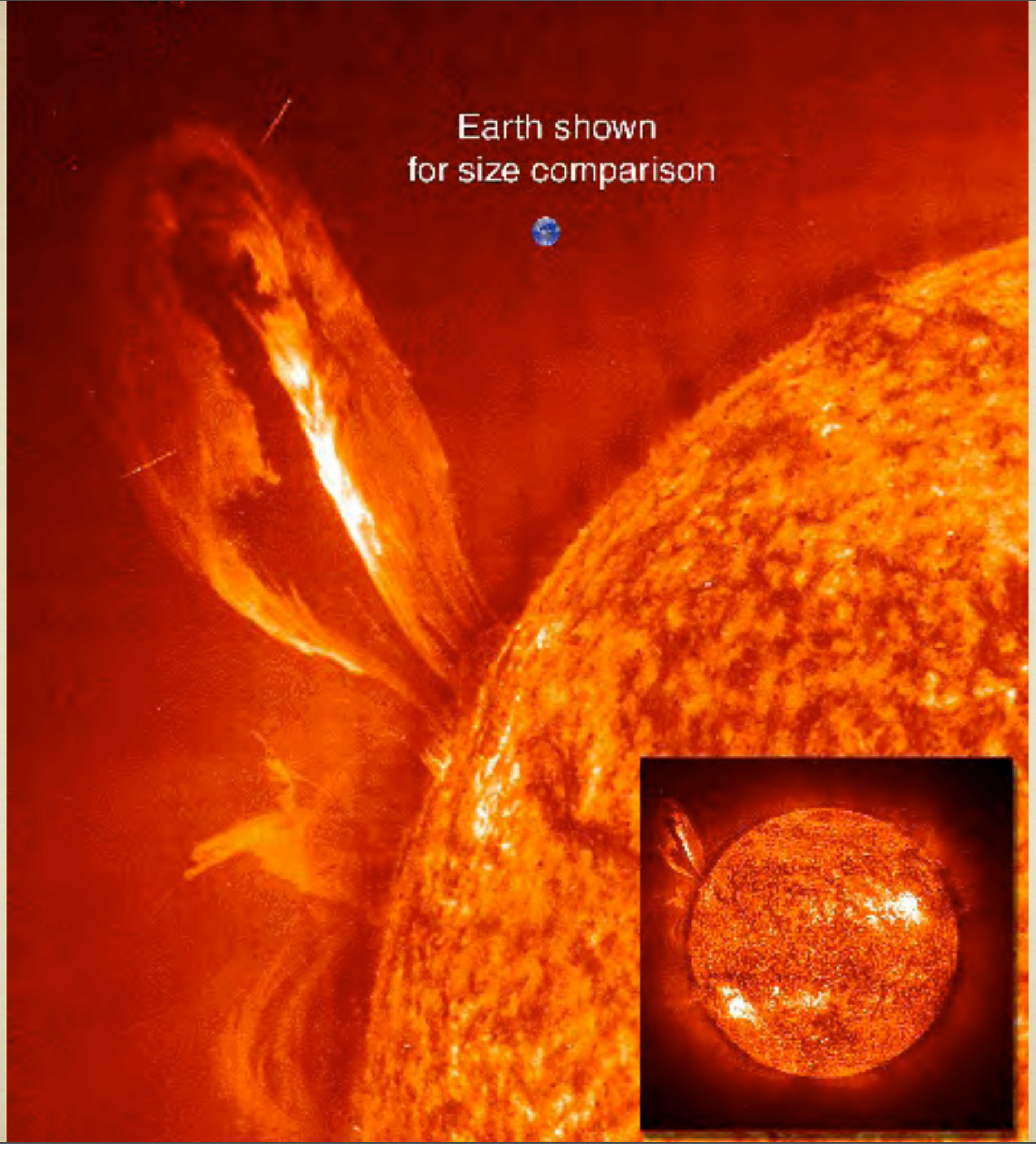


Image Credit:
NASA/SOHO

Solar Wind

- Gas flows away from sun
  - 10 million tons/yr
  - protons & electrons
  - speed 400-800 km/s
- Material goes outward into solar system
  - Hits Earth's atmosphere
    - makes it glow (aurorae)
    - trapped in Earth's magnetic field lines

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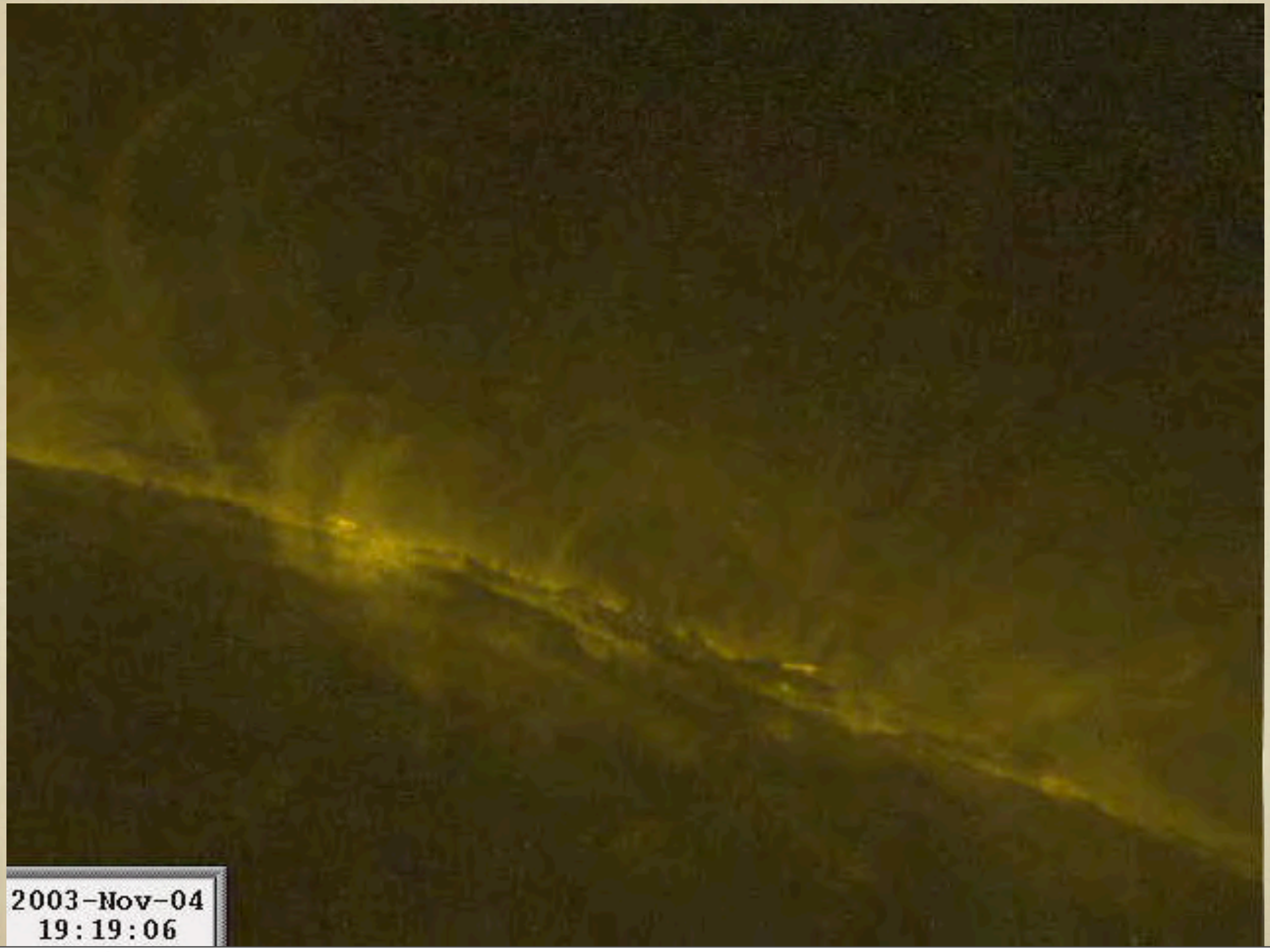
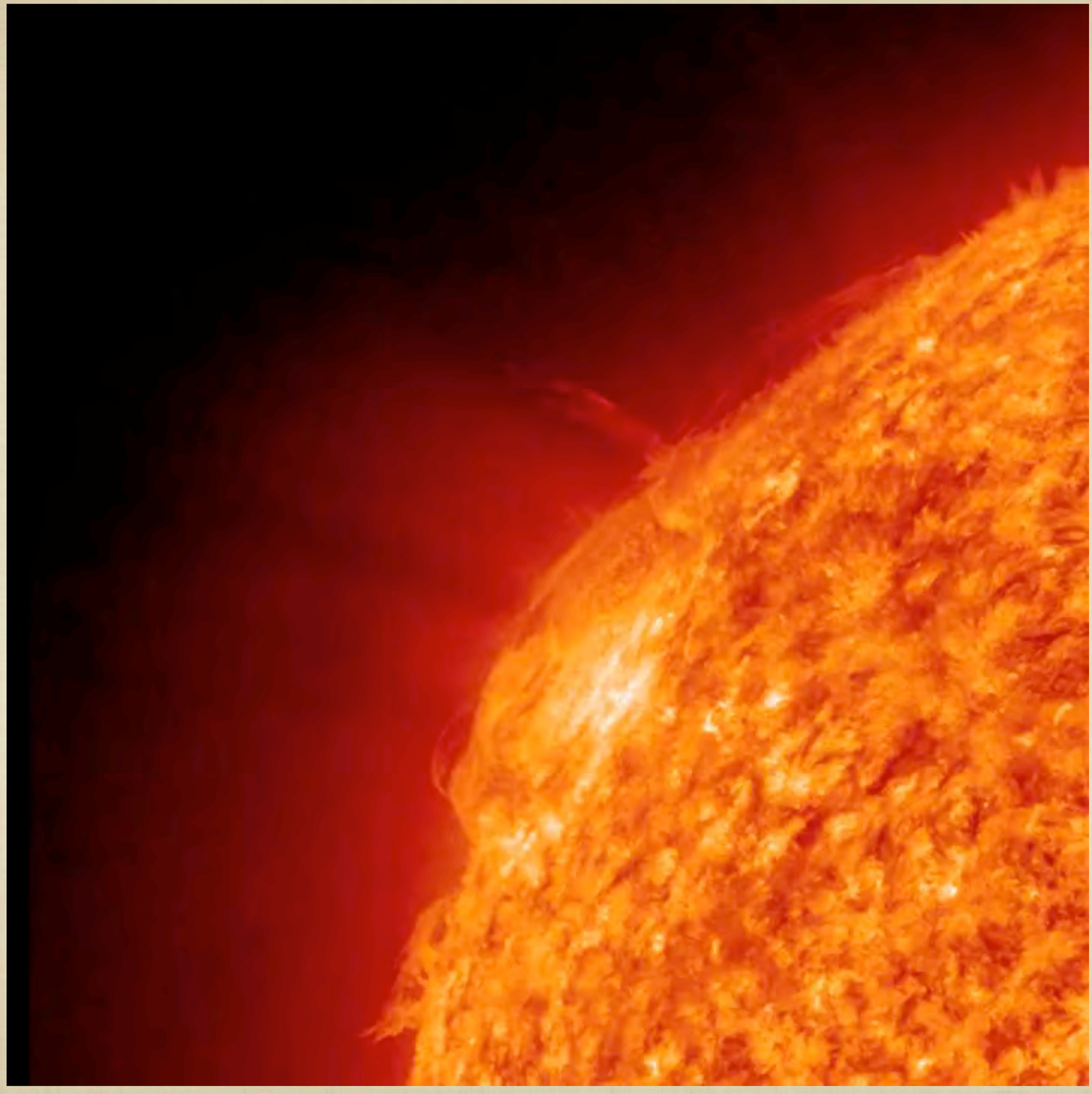
Solar Flare

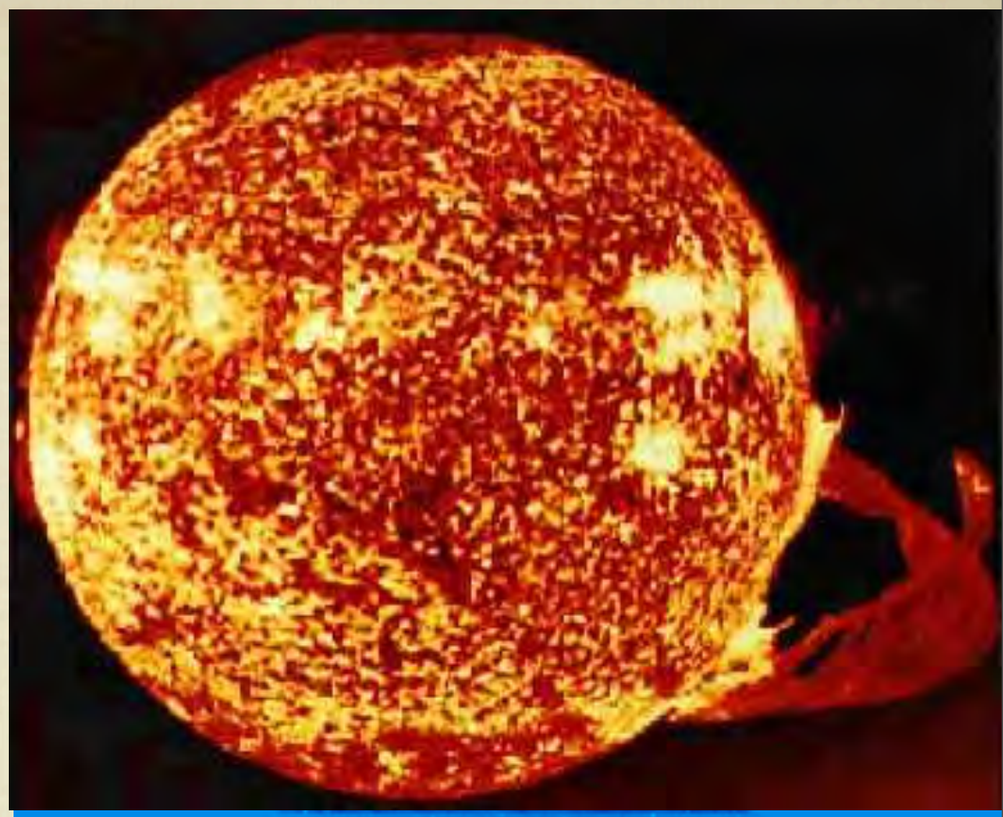
Image Credit:
NASA/TRACE

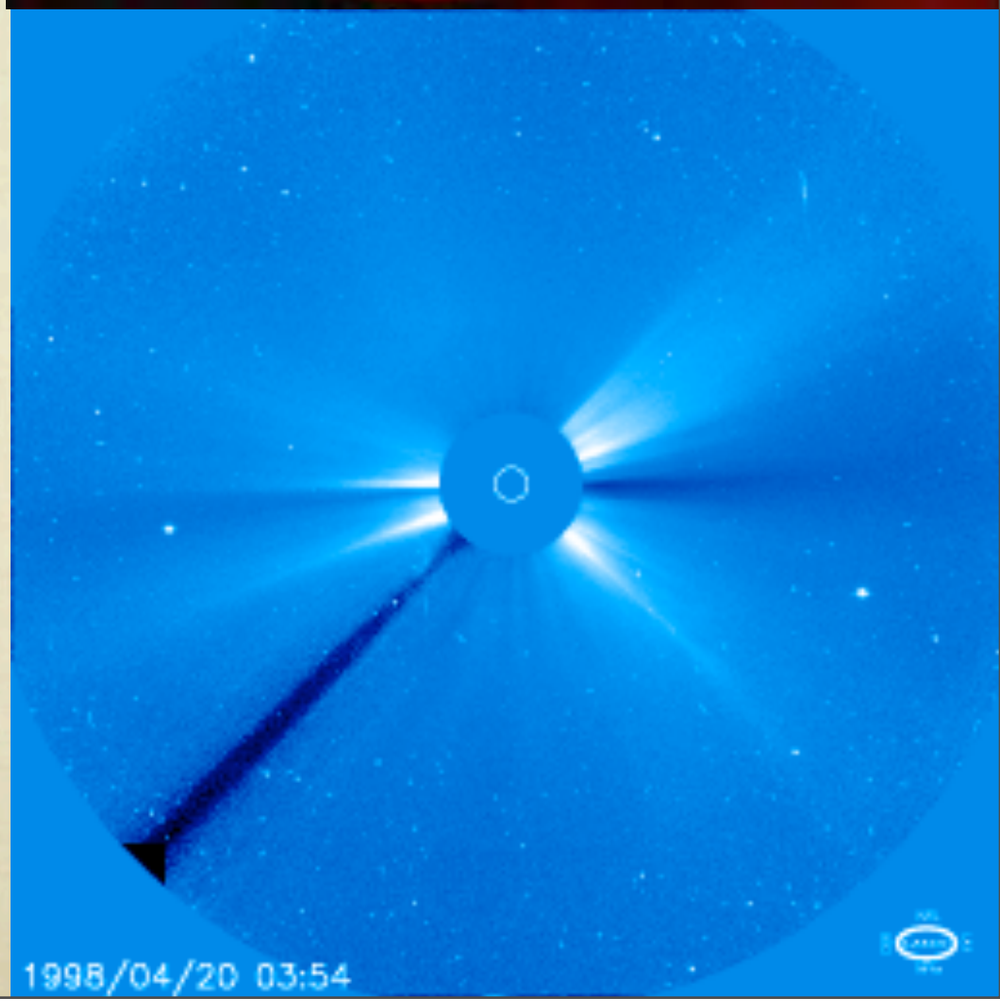




Solar Flares

- Eruptions caused by magnetic fields
  - may last 5-10 min
  - release huge amounts of energy
    - gas heated to 10^7 K, produces X-rays and UV radiation
- Coronal Mass Ejections
  - very large flares
  - large mass of gas ejected from corona





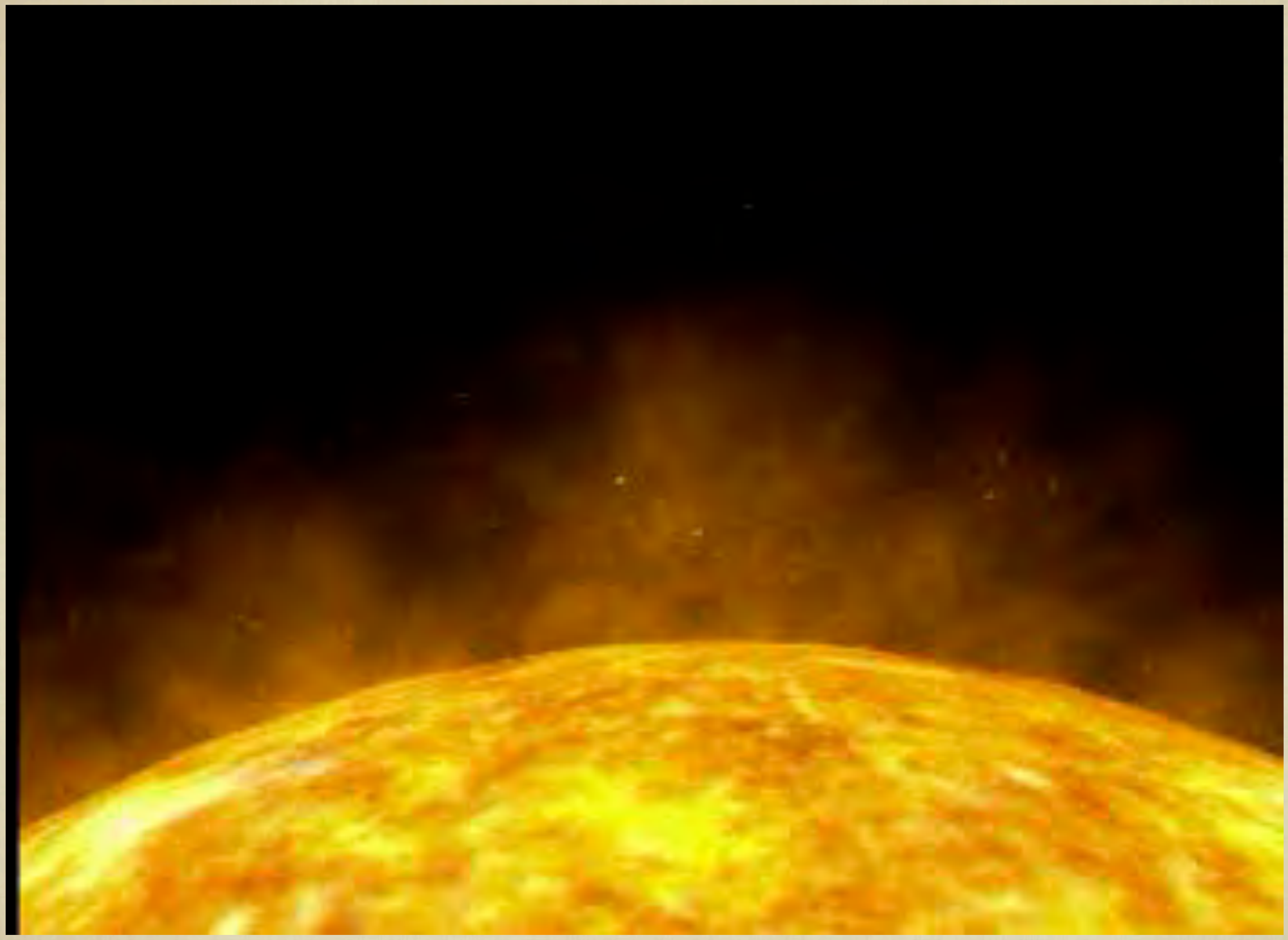
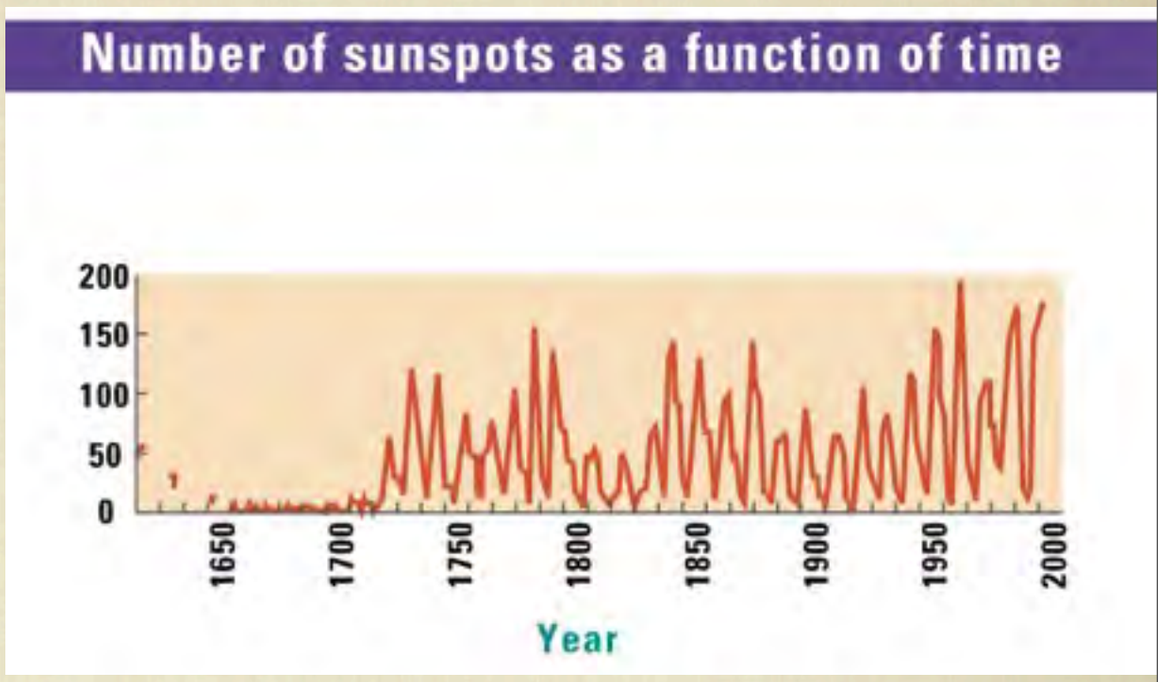


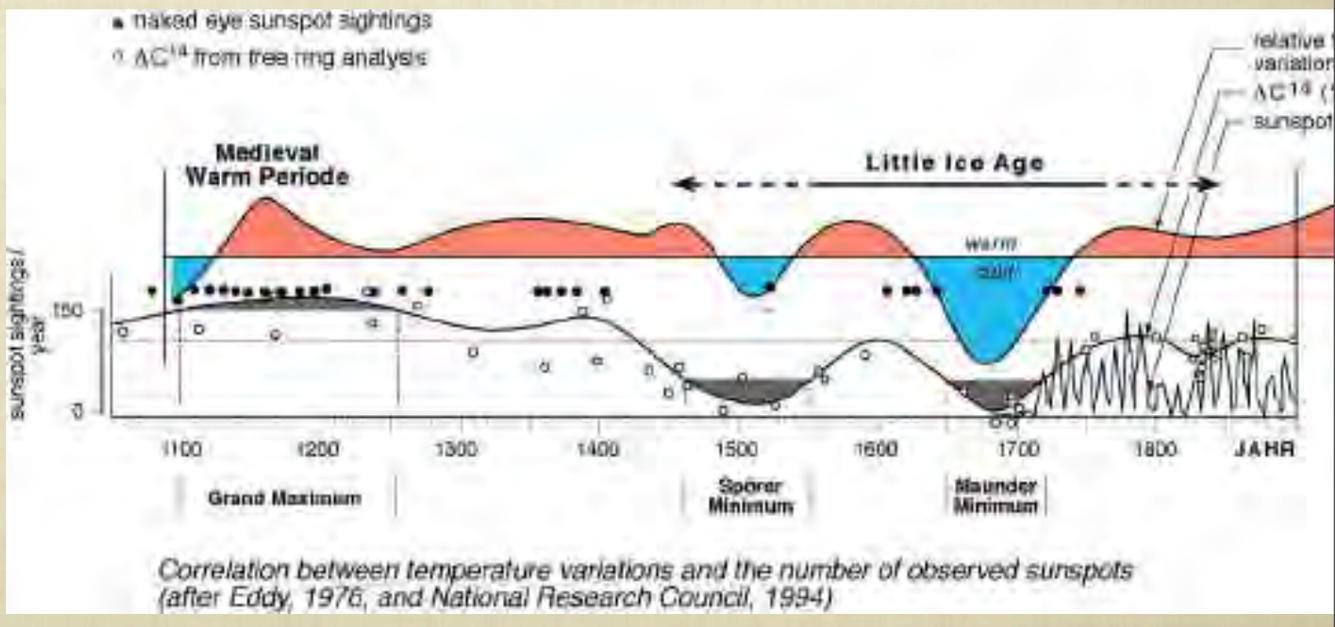
Image Credit:
NASA/SOHO

Image Credit:
NASA/SOHO

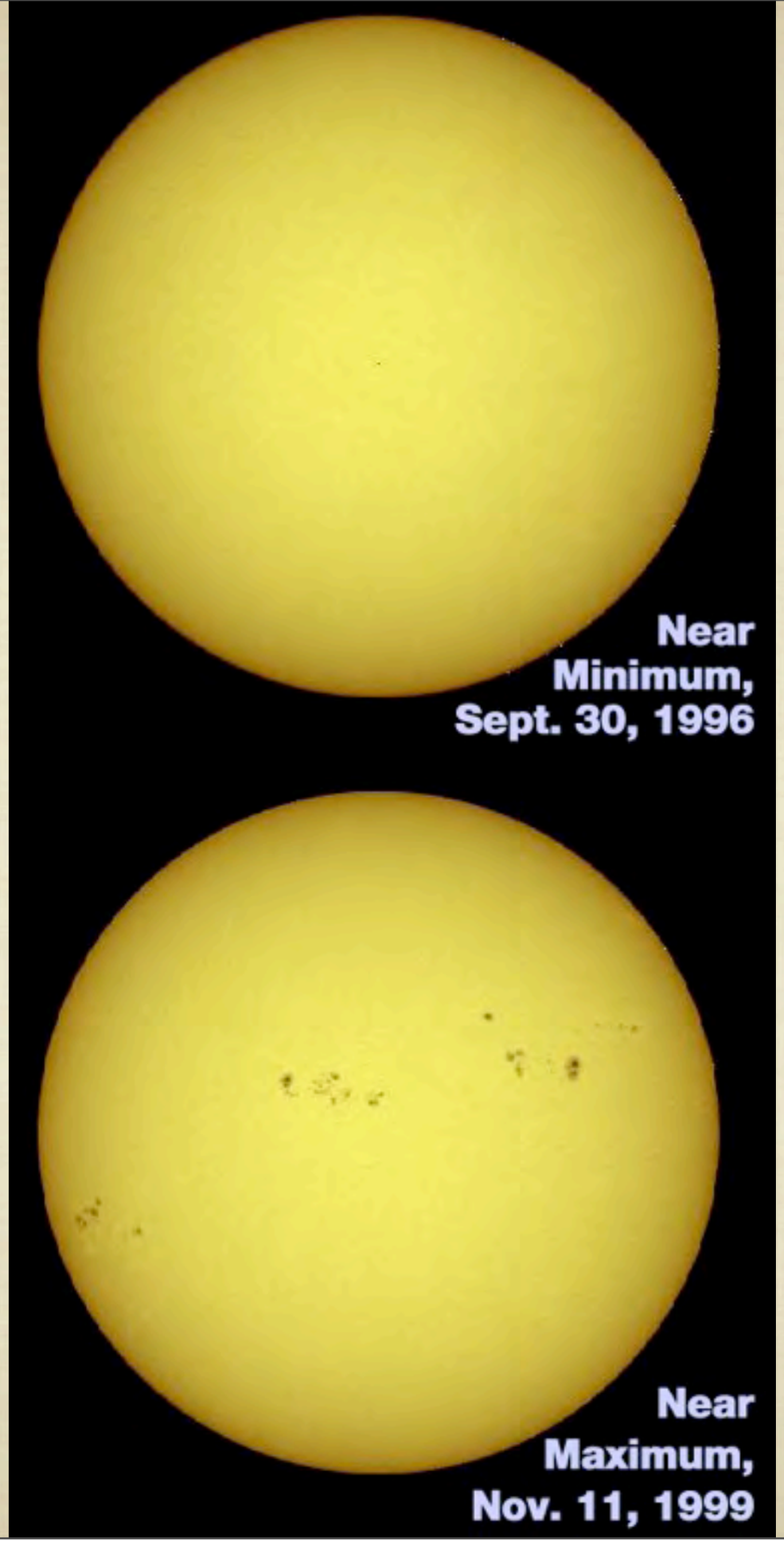
Solar Variability & Earth's Climate

- Solar Luminosity Varies by 1%
  - Highest at sunspot maximum
  - Lowest at minimum activity
- Maunder minimum 1650-1700
  - Very few sunspots
  - "Little Ice Age" in Europe
    - extreme cold temps
    - shorter growing season
- Still learning how Sun affects Earth's climate





Correlation between temperature variations and the number of observed sunspots (after Eddy, 1976, and National Research Council, 1994)


Near
Minimum,
Sept. 30, 1996
Near
Maximum,
Nov. 11, 1999

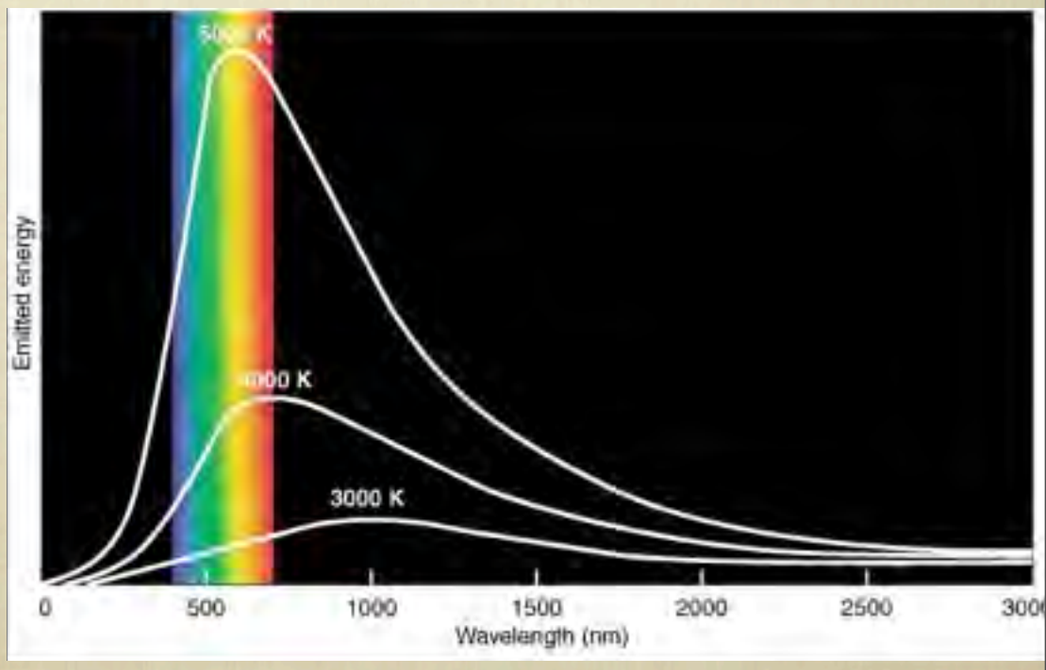
Thursday, January 17, 13

Blackbody Radiation

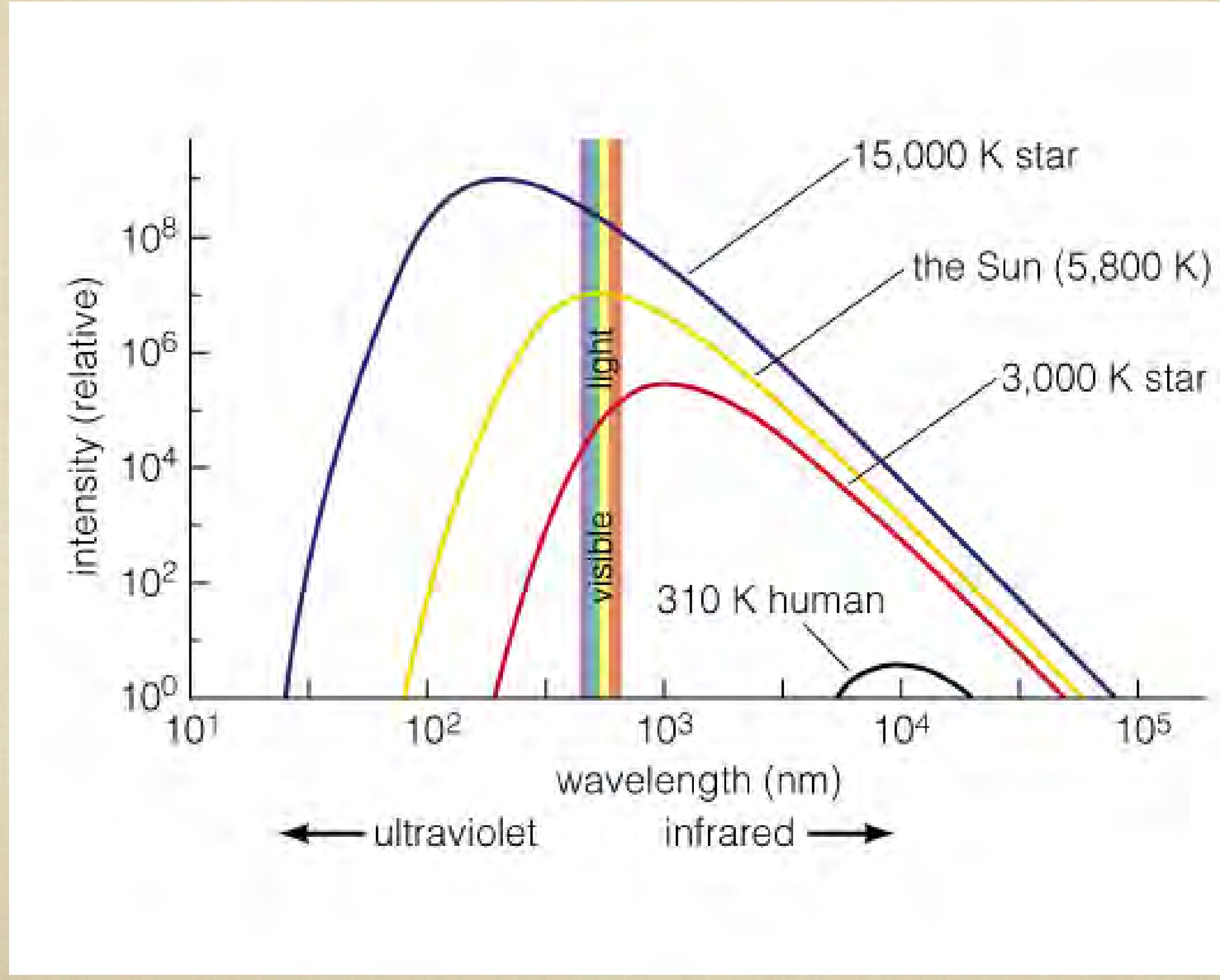
- A perfect absorber is "black"
  - Absorbs all light shining on it
  - Absorbed light (energy) heats object
  - Temperature increases until:

emitted energy = absorbed energy

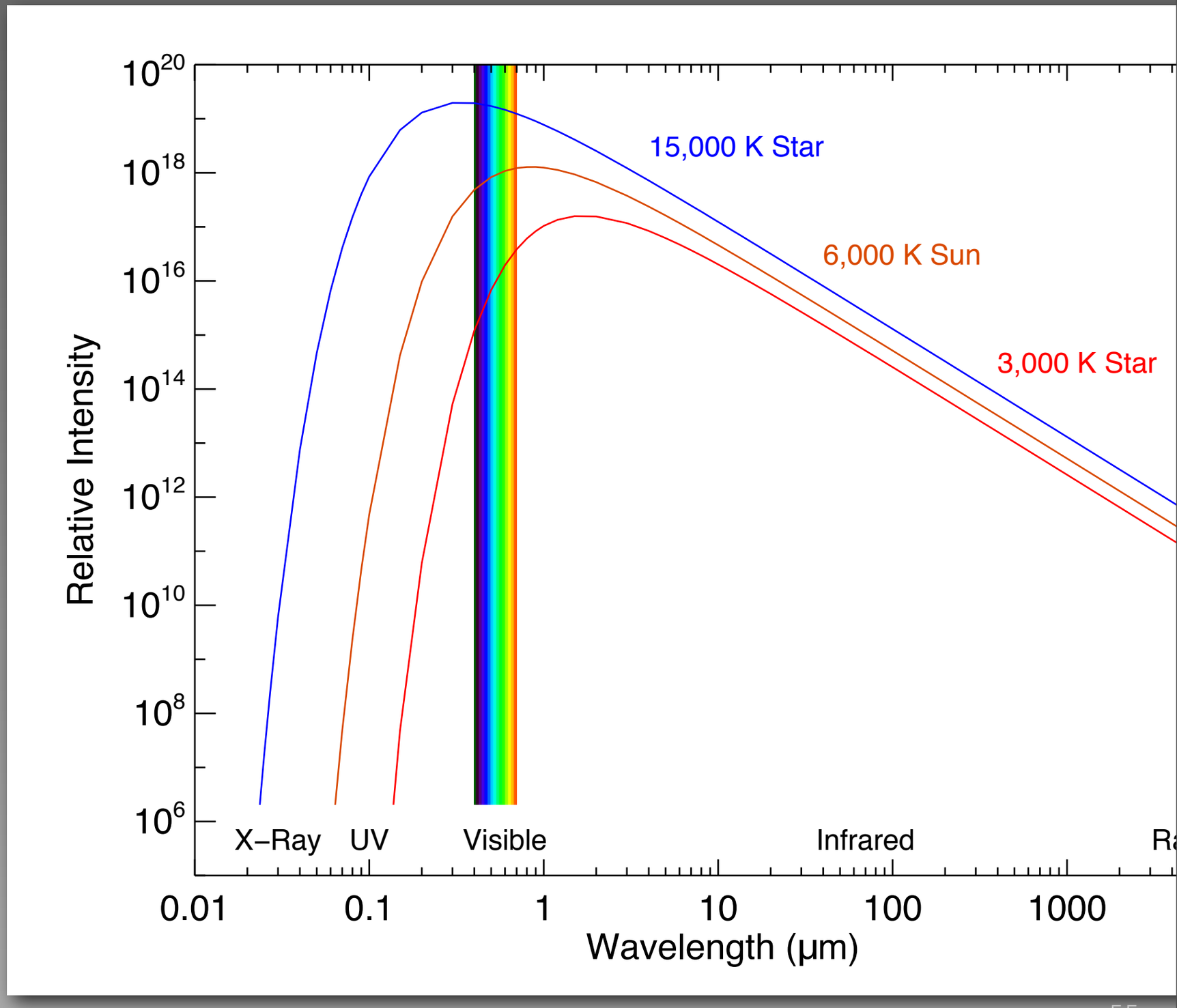
  - Emitted radiation called Blackbody Radiation
- The thermal radiation emitted by most objects, include **stars** is similar to blackbody



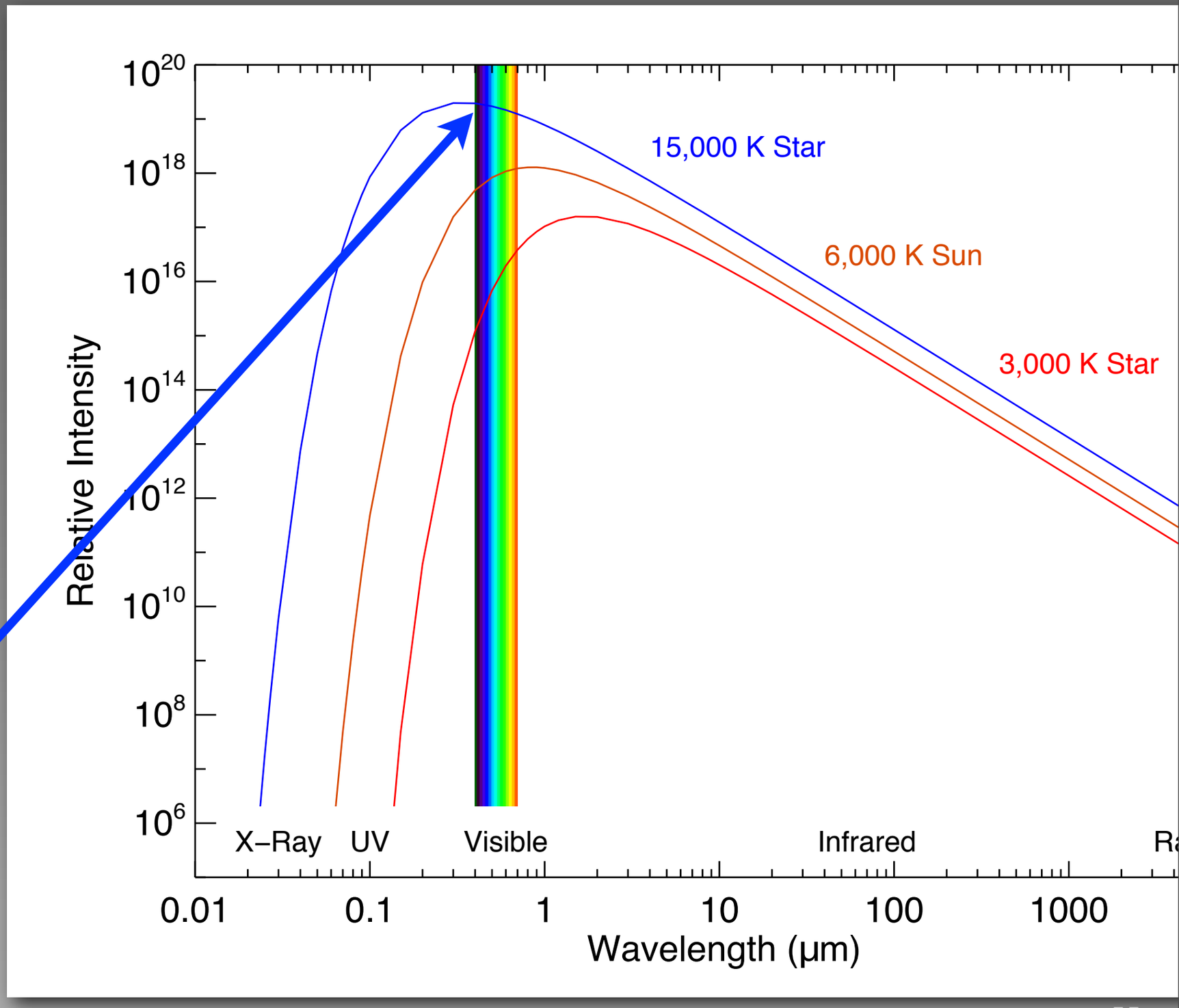
Thermal Radiation



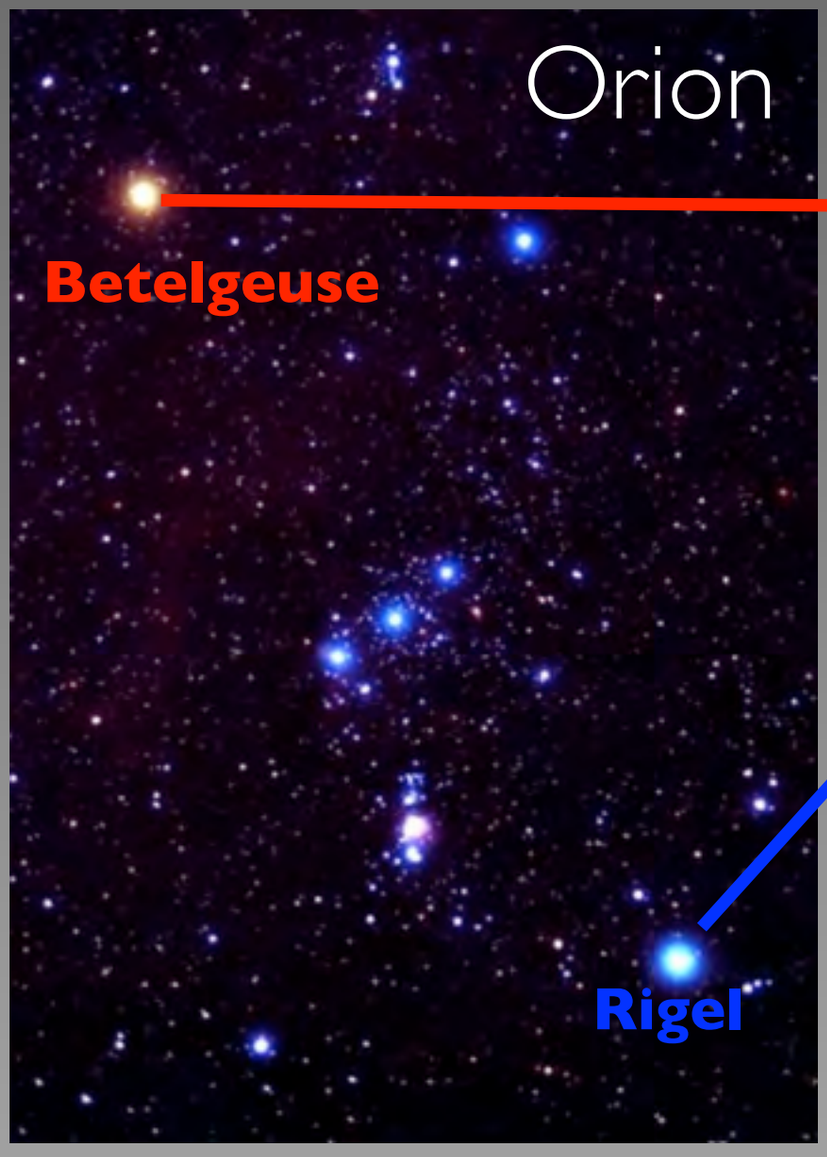
All "solid" objects emit light

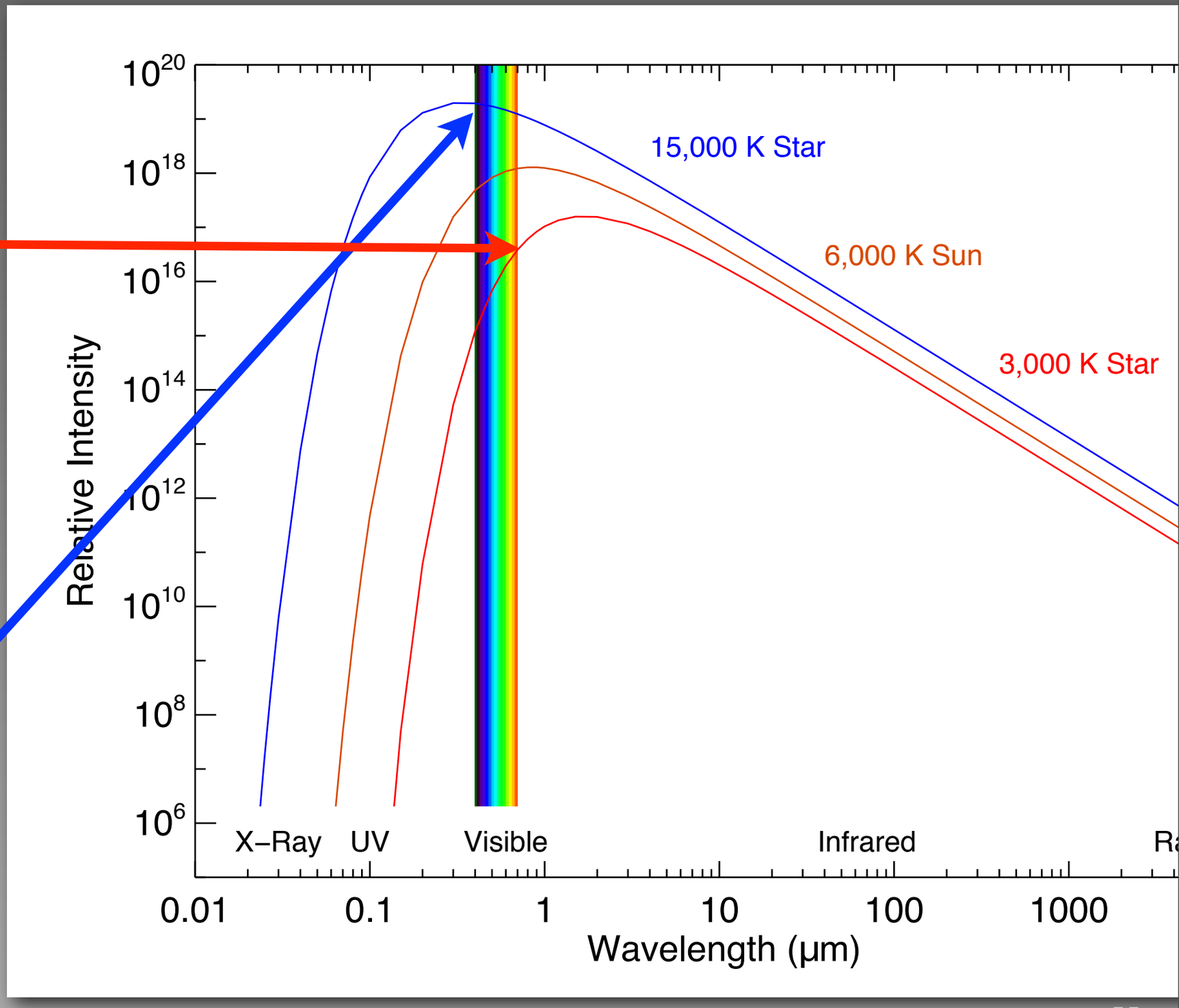


All "solid" objects emit light



All "solid" objects emit light





Planck Function

- Wien's law, rayleigh-Jeans Tail, known empirically.

$$I(\lambda, T) = \frac{2hc^2}{\lambda^5} e^{-\frac{hc}{\lambda k T}} \qquad B_\lambda(T) = \frac{2ckT}{\lambda^4},$$

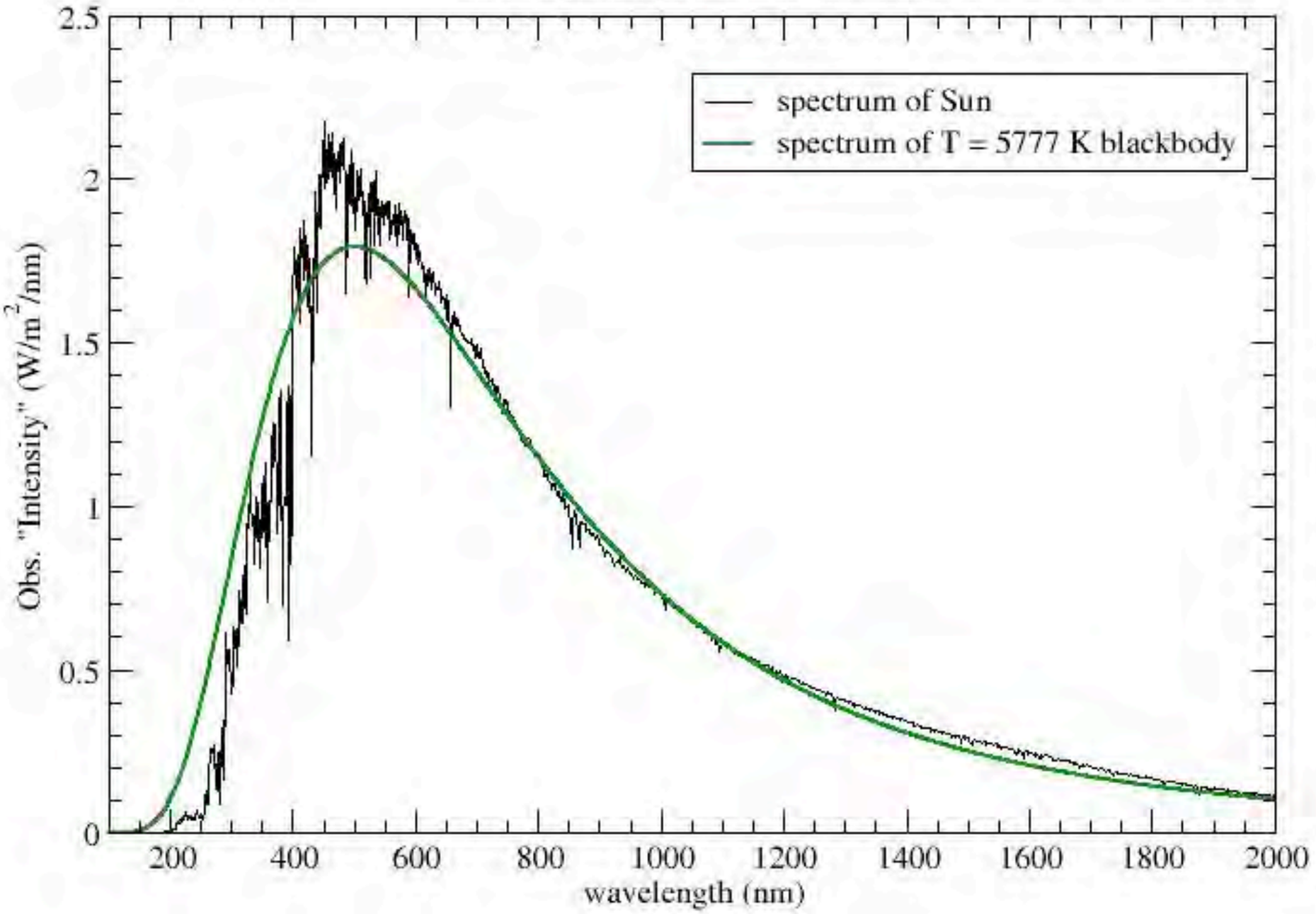
- Planck derived the function in 1900, to account for laboratory measurements of the spectra of heated objects.

- Required a minimum "quantum of action" and it's associated constant... first serious step to quantization of light

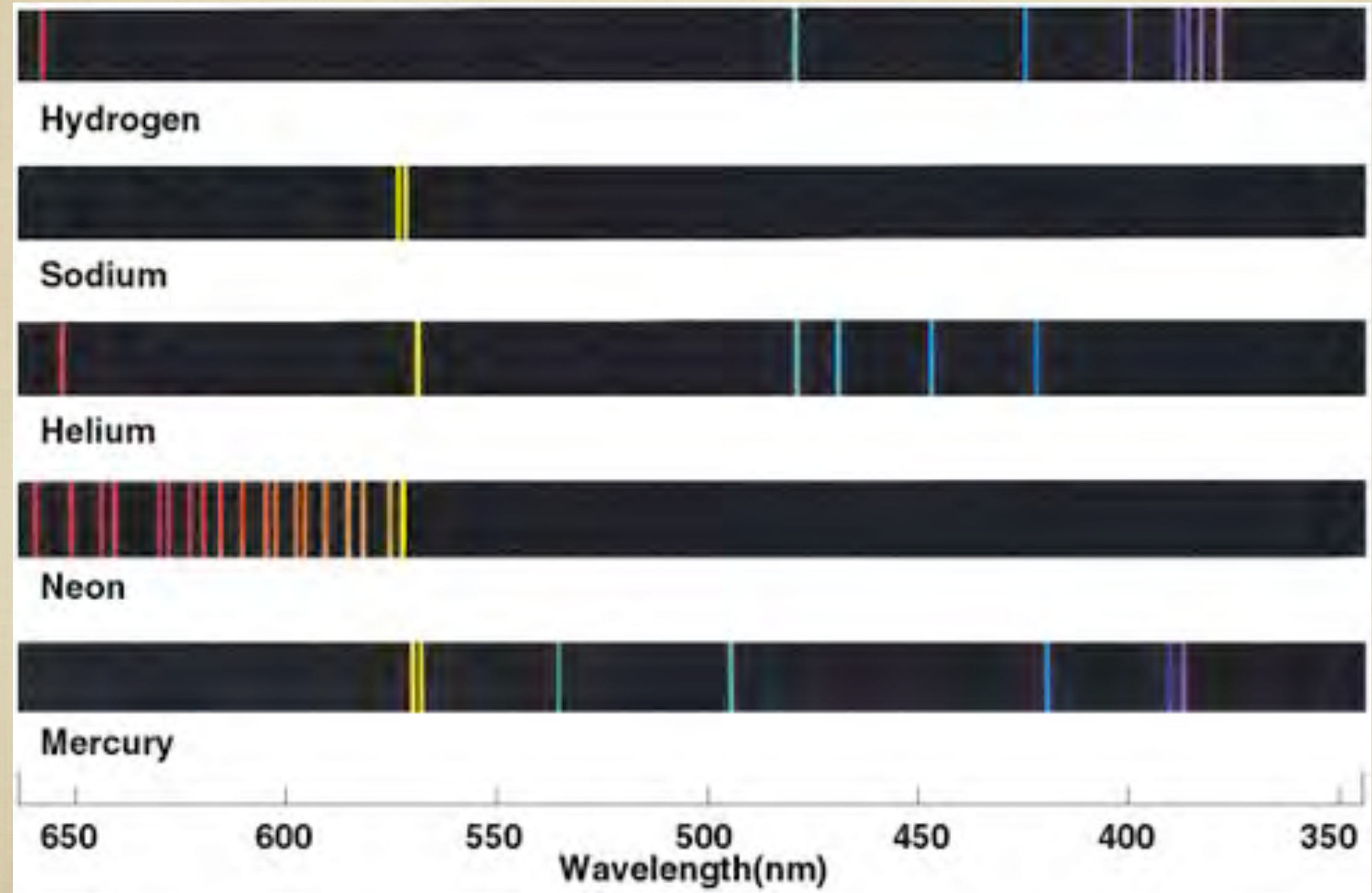
$$B_\lambda(T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{hc/\lambda kT} - 1}$$

Sun's Spectrum vs. Thermal Radiator

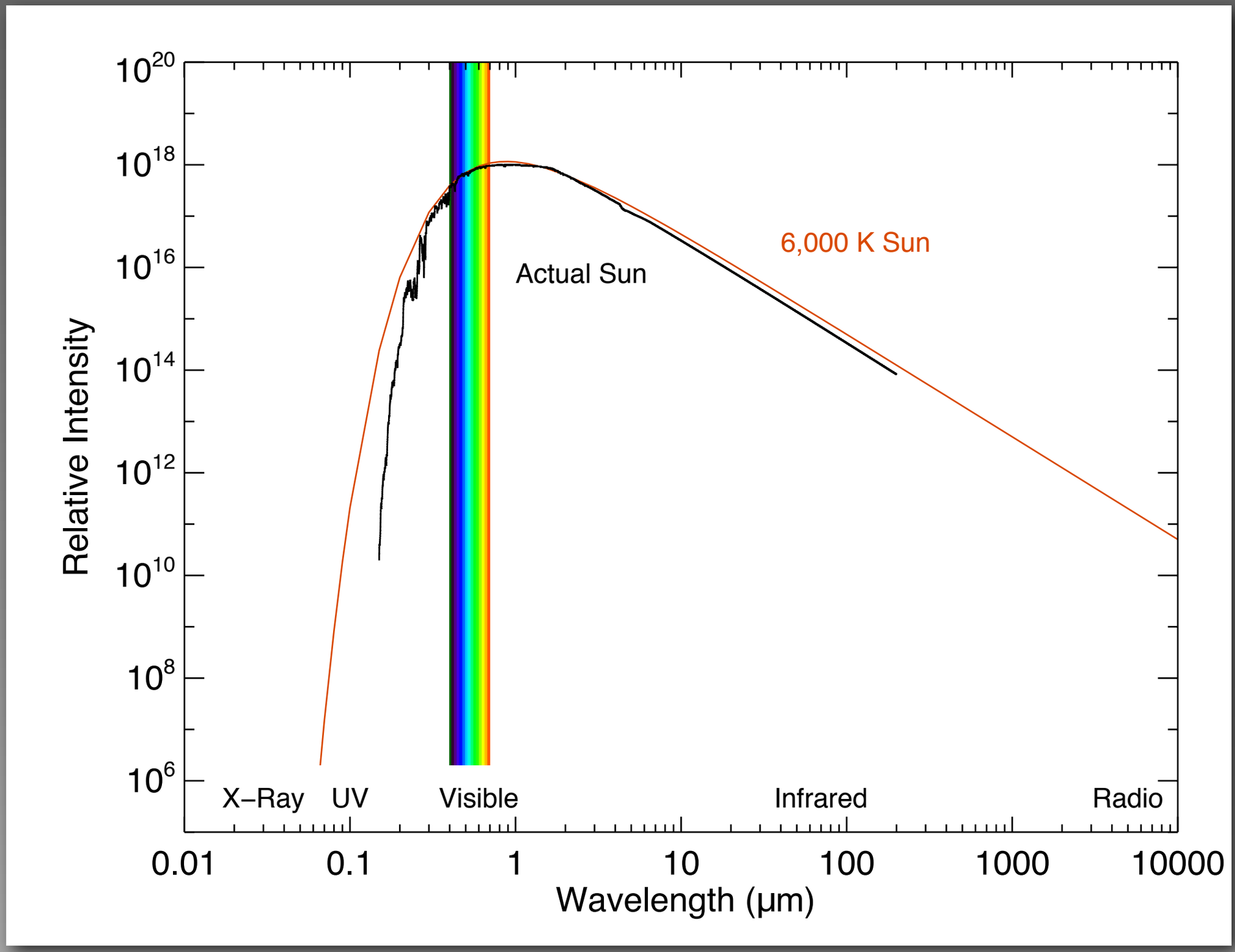
of a single temperature T = 5777 K



Spectra


Hydrogen
Sodium
Helium
Neon
Mercury
650
600
550
500
450
400
350
Wavelength(nm)

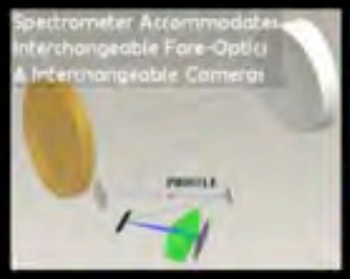
The Sun's spectrum is not so simple

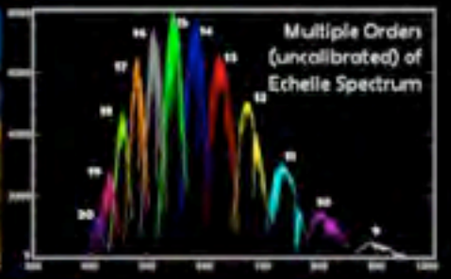


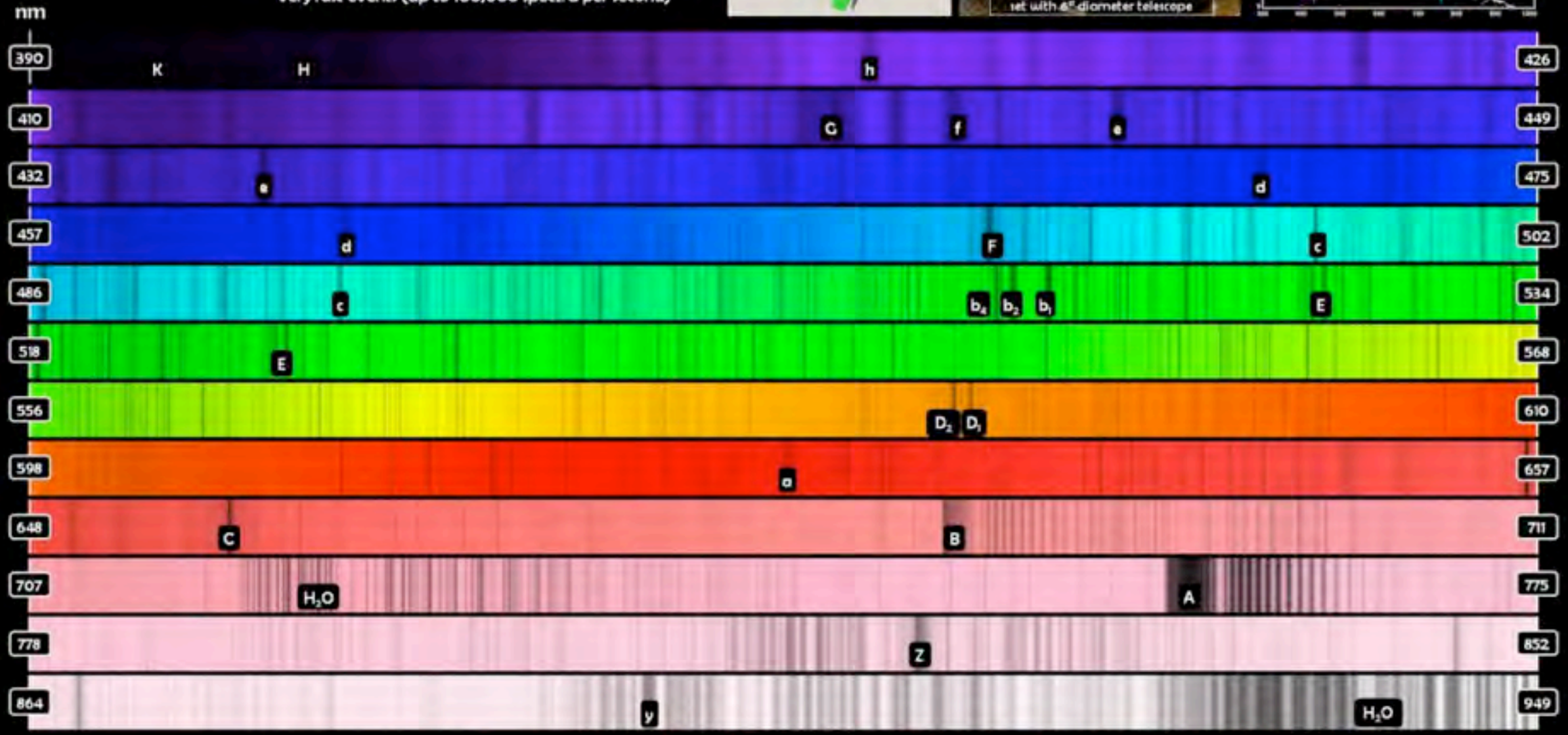
The Solar Spectrum

with the major Fraunhofer lines

High Speed Echelle Spectrometer developed for recording very fast events (up to 100,000 spectra per second)

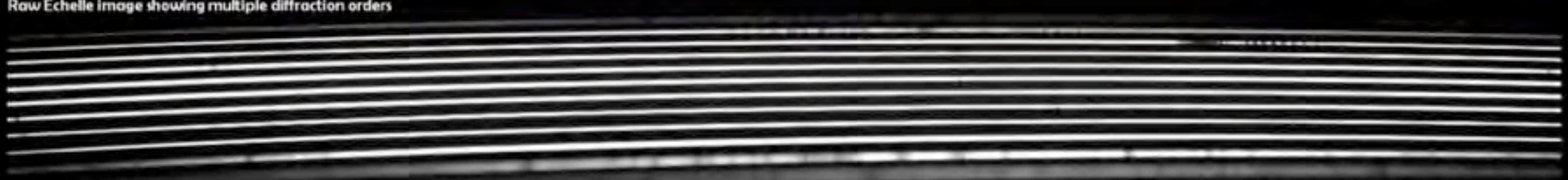






K	H	h	G		f	e	d	F	c	b_4	b_2	b_1	E	D_2	D_1	a	C	B		A	Z	y	
Ca+	Ca+	Hδ	Ca	Fe	H	Fe	Fe	Hβ	Fe	Mg	Fe	Mg	Mg	Fe	Na	Na	O_2	H_2	O_2	H_2O	O_2	O_2	O_2	H_2O
393.368	396.847	410.175	430.774	430.790	434.0	438.355	466.814	486.134	495.761	516.733	516.891	517.270	518.362	527.0	588.995	589.592	627.661	656.281	686.719	720.0	759.370	822.696	898.765	940.0

Raw Echelle image showing multiple diffraction orders



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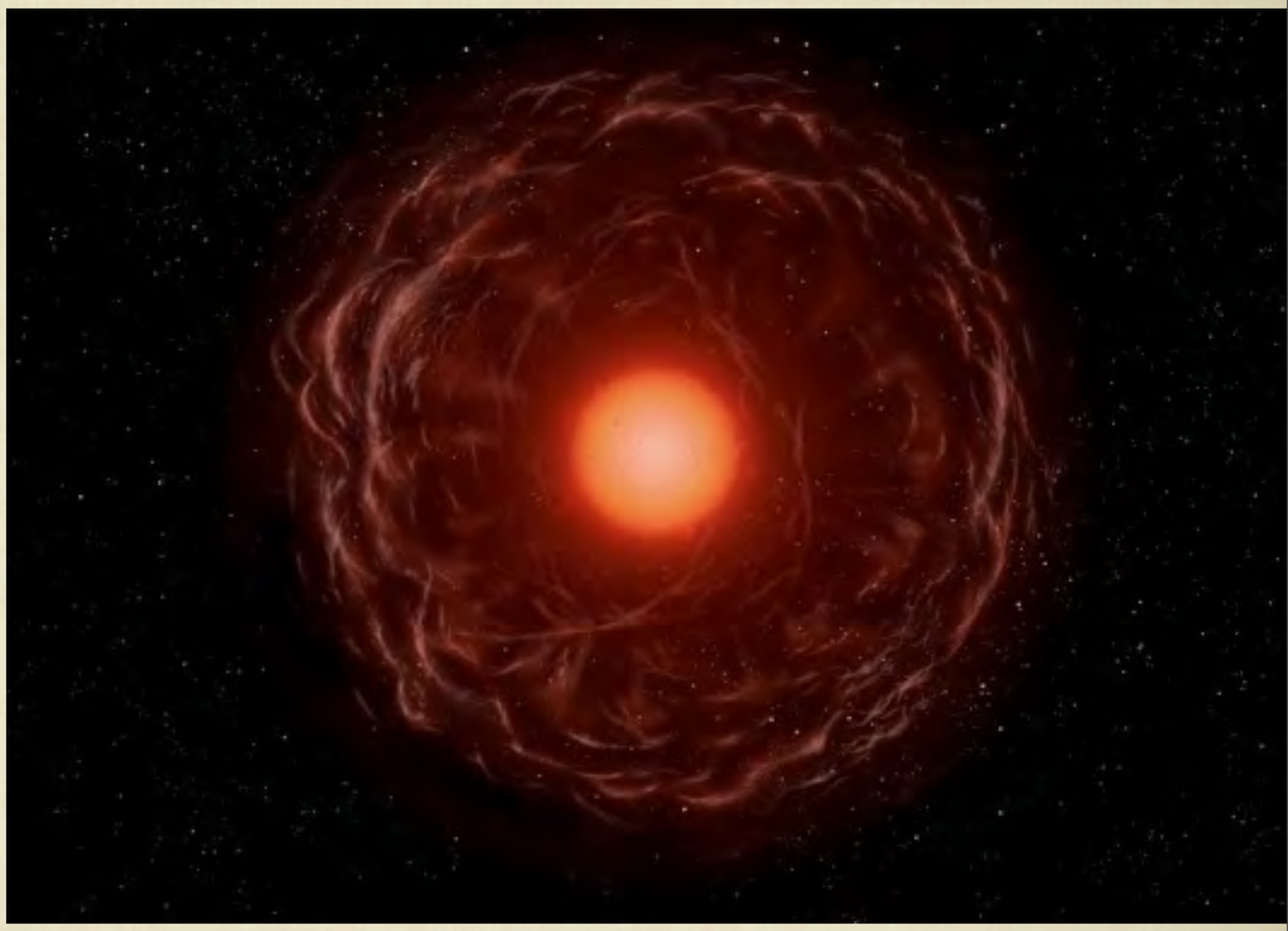
Fate of the Sun

- Sun has a finite lifetime (why?) around 10 billion years. Currently around halfway through.

- A.D. 5,000,000,000: Sun's luminosity will go up by 1000x! Earth temperature 1000K.

- Sun will swell to the earth's orbit, before turning into a white dwarf.



Planetary Nebulae