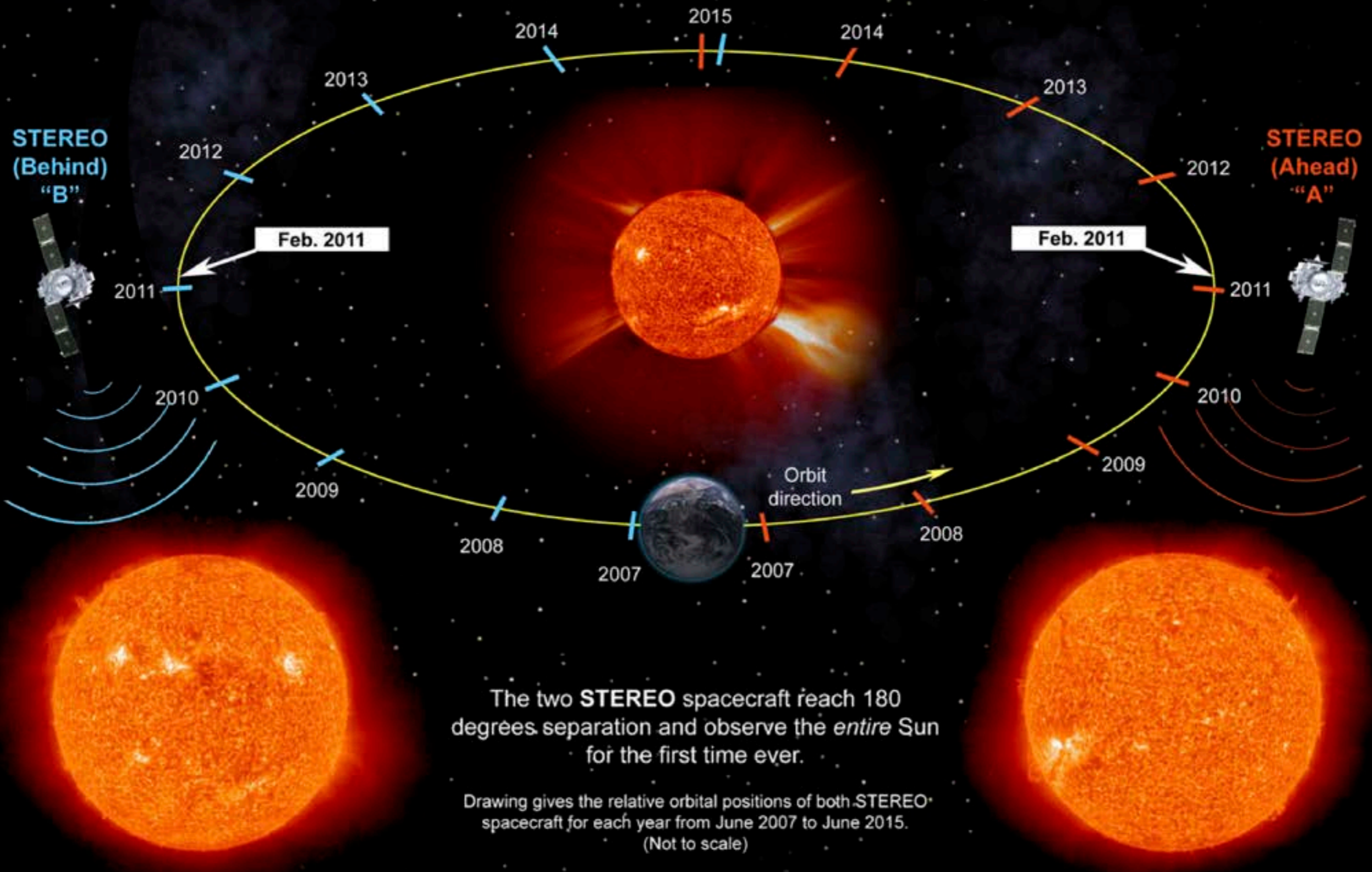


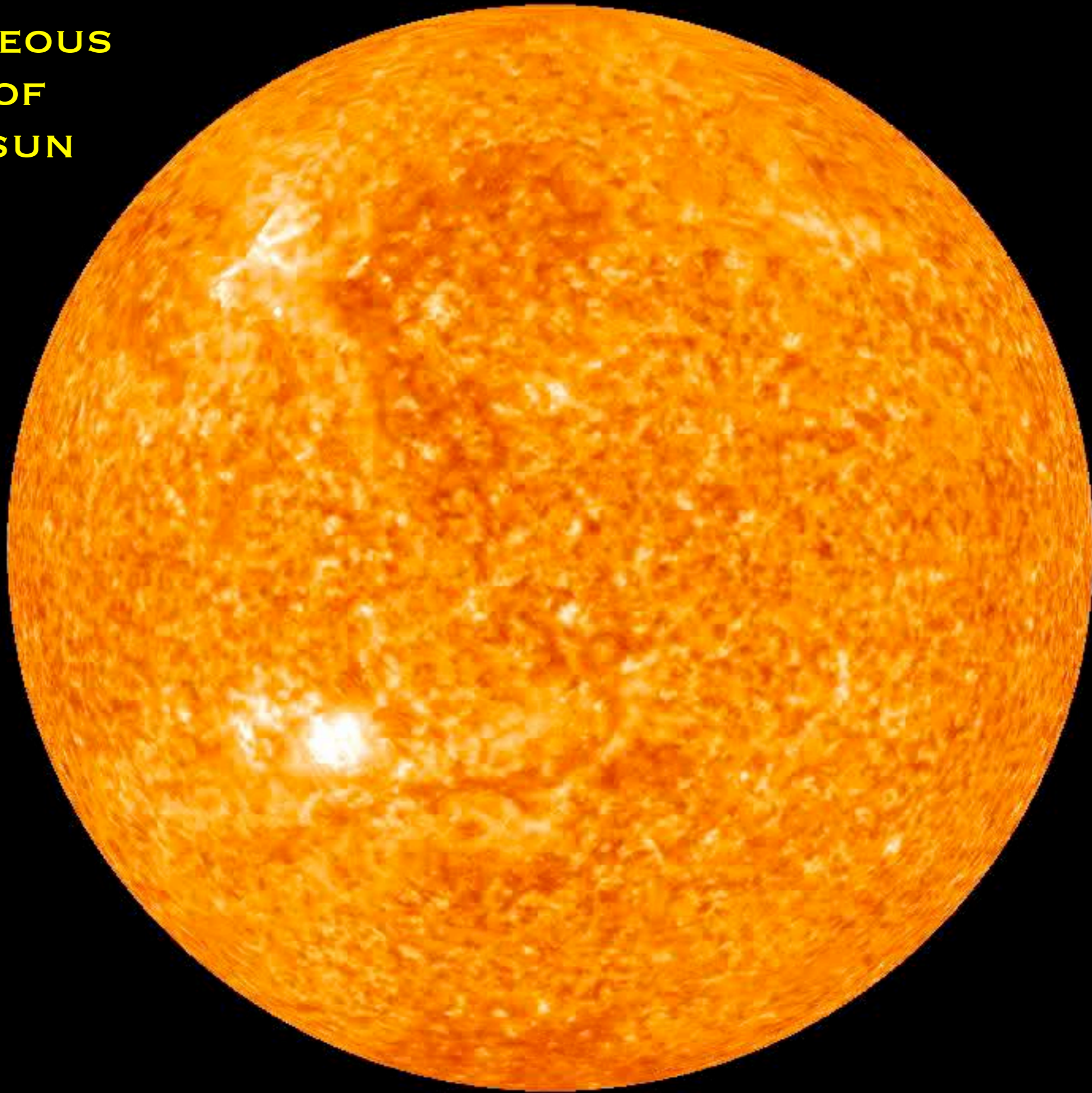


**THE SUN**  
**OUR VERY OWN STAR**

# NASA's STEREO Sees the Entire Sun



**SIMULTANEOUS  
IMAGE OF  
ENTIRE SUN**

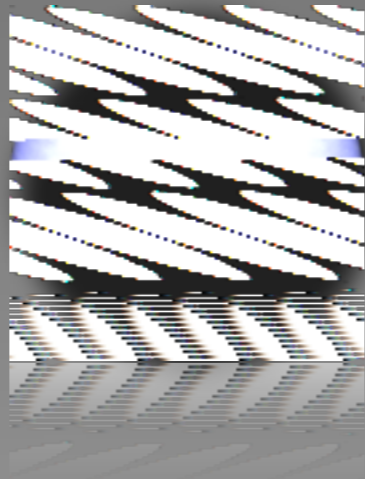
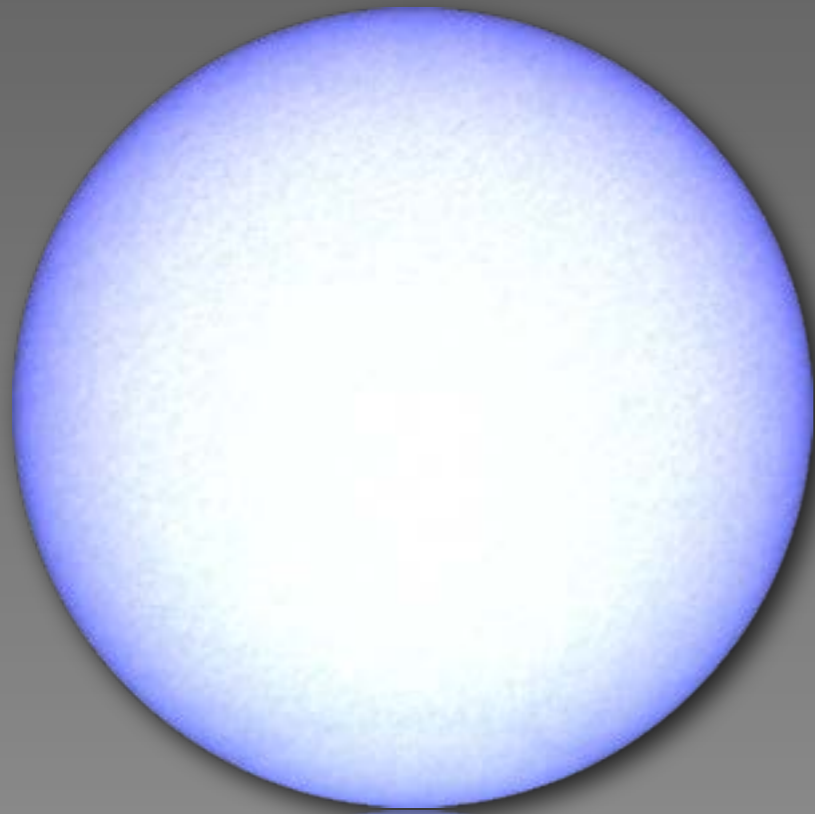


# OUR OWN STAR

- AN “AVERAGE” STAR, ONE OF HUNDREDS OF BILLIONS IN THE GALAXY (BUT IT’S OUR VERY OWN!).
- MADE ENTIRELY OF PLASMA GAS. FAR TOO HOT FOR LIQUIDS OR SOLIDS
- SURFACE: 6000 K
- CENTER: 14 MILLION K
- COMPOSED OF 70% HYDROGEN, 28% HELIUM, 2% EVERYTHING ELSE (C, N, O, FE, ETC.)



# The stellar family portrait



Type:

O

B

A

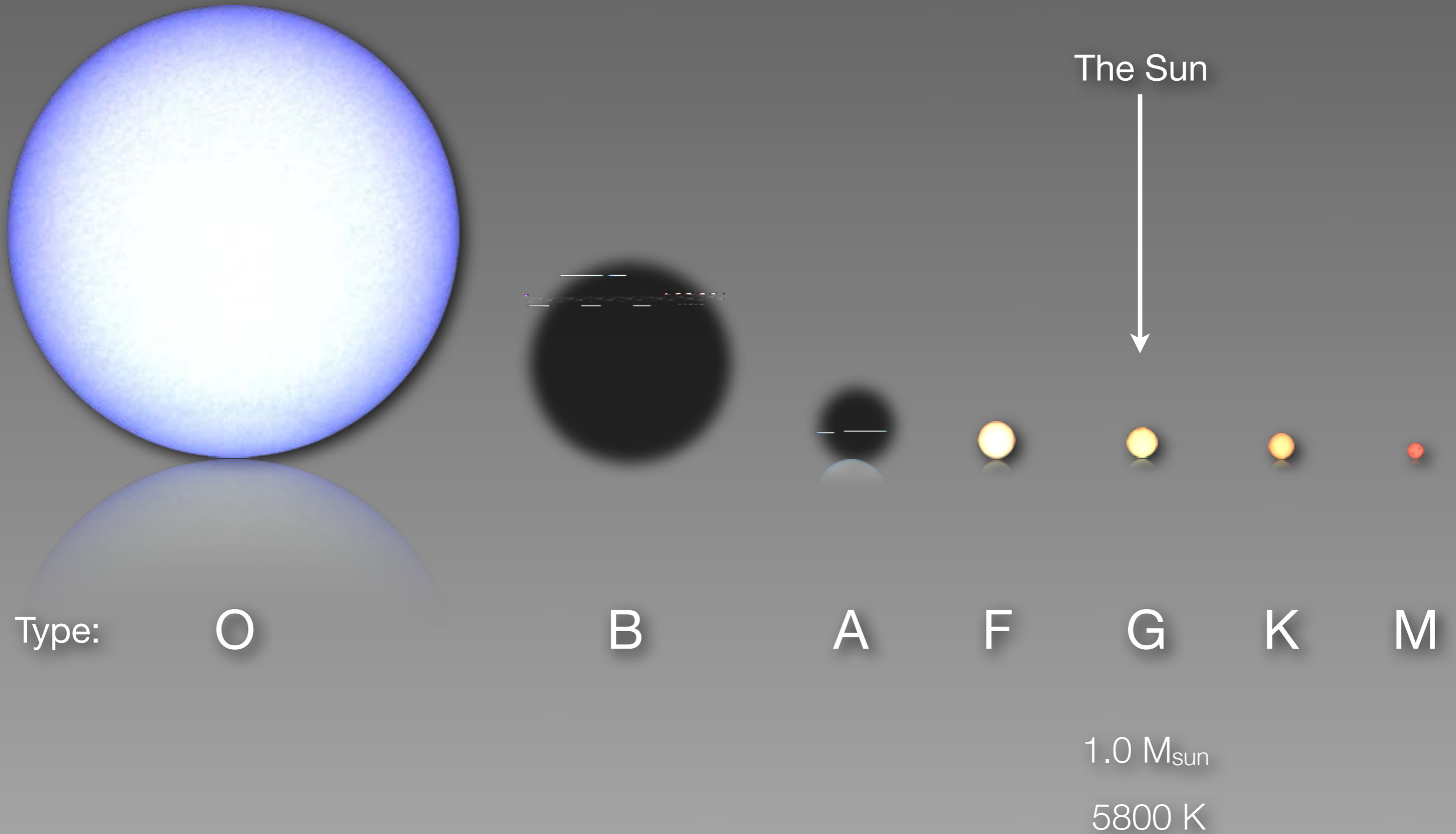
F

G

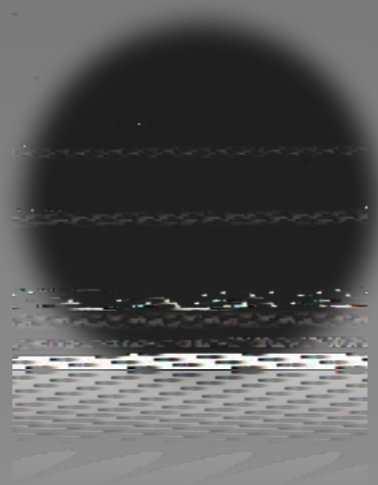
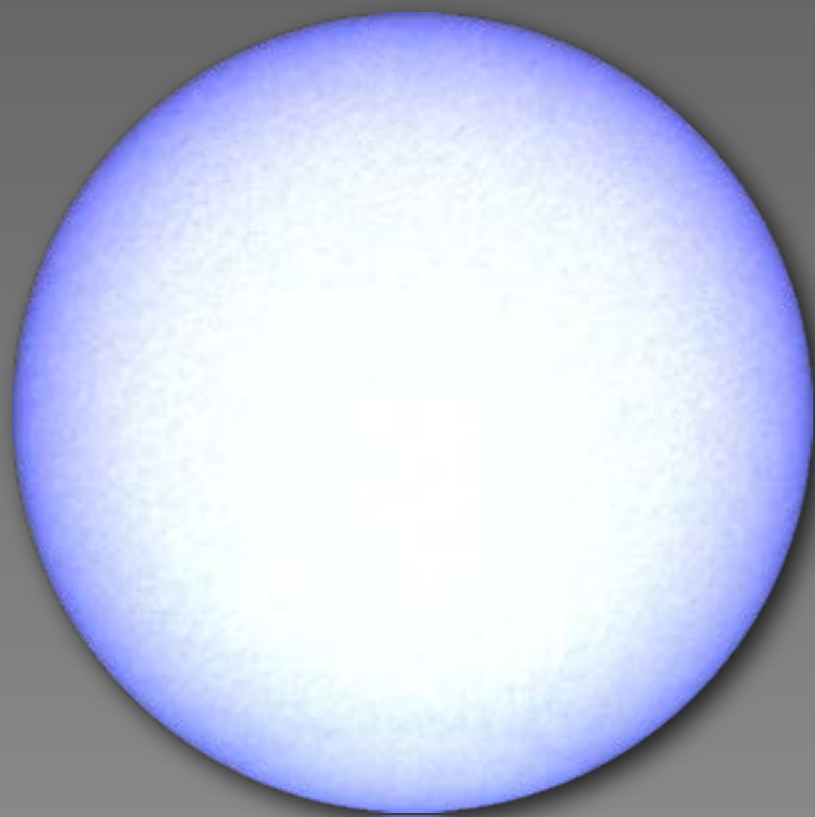
K

M

# The stellar family portrait



# The stellar family portrait



Type:

O

B

A

F

G

K

M

40  $M_{\text{sun}}$

35000 K

1.0  $M_{\text{sun}}$

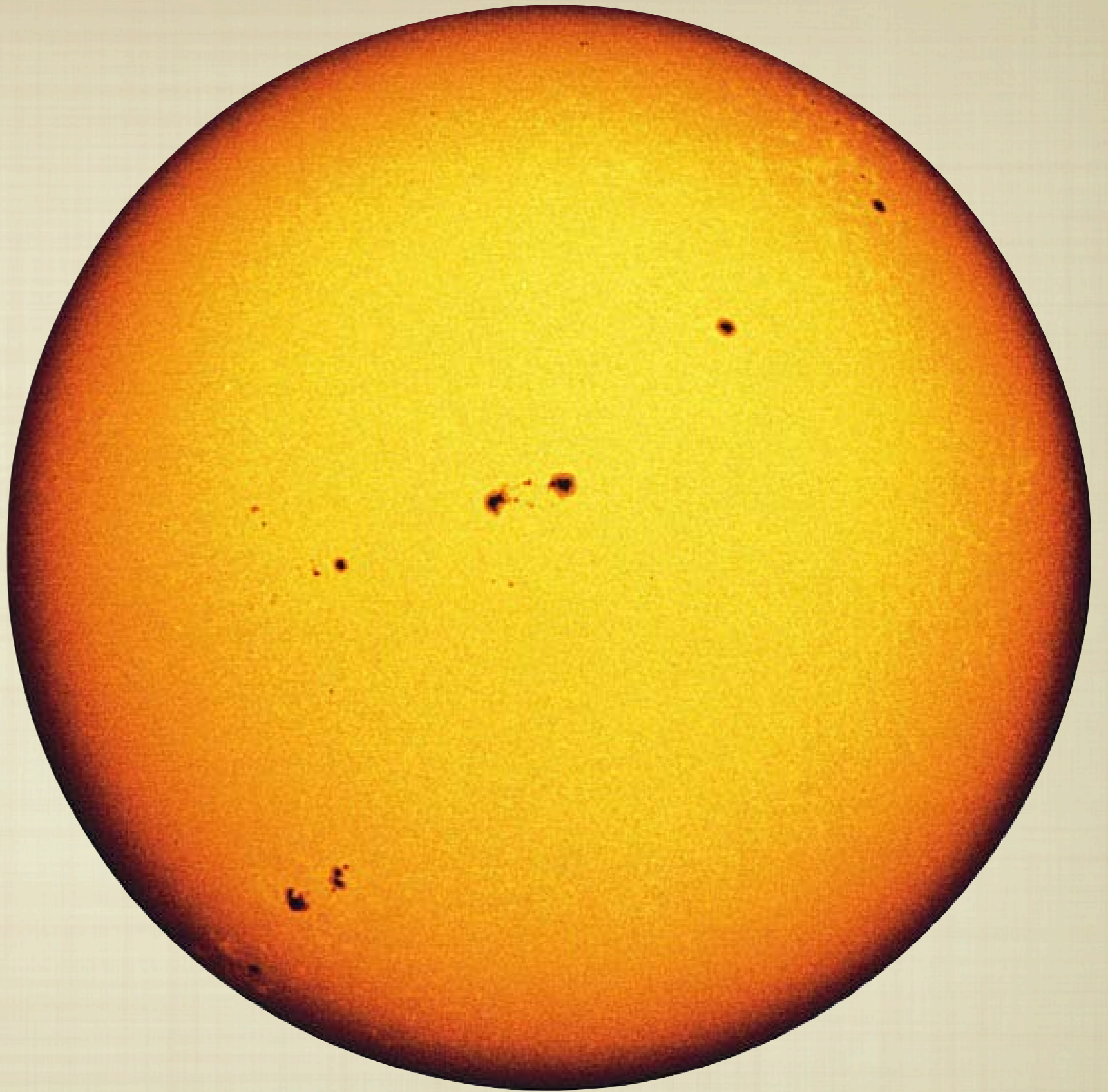
5800 K

0.1  $M_{\text{sun}}$

3000 K

■ **RADIUS:**  
 $6.9 \times 10^8 \text{ M}$   
(109×EARTH)

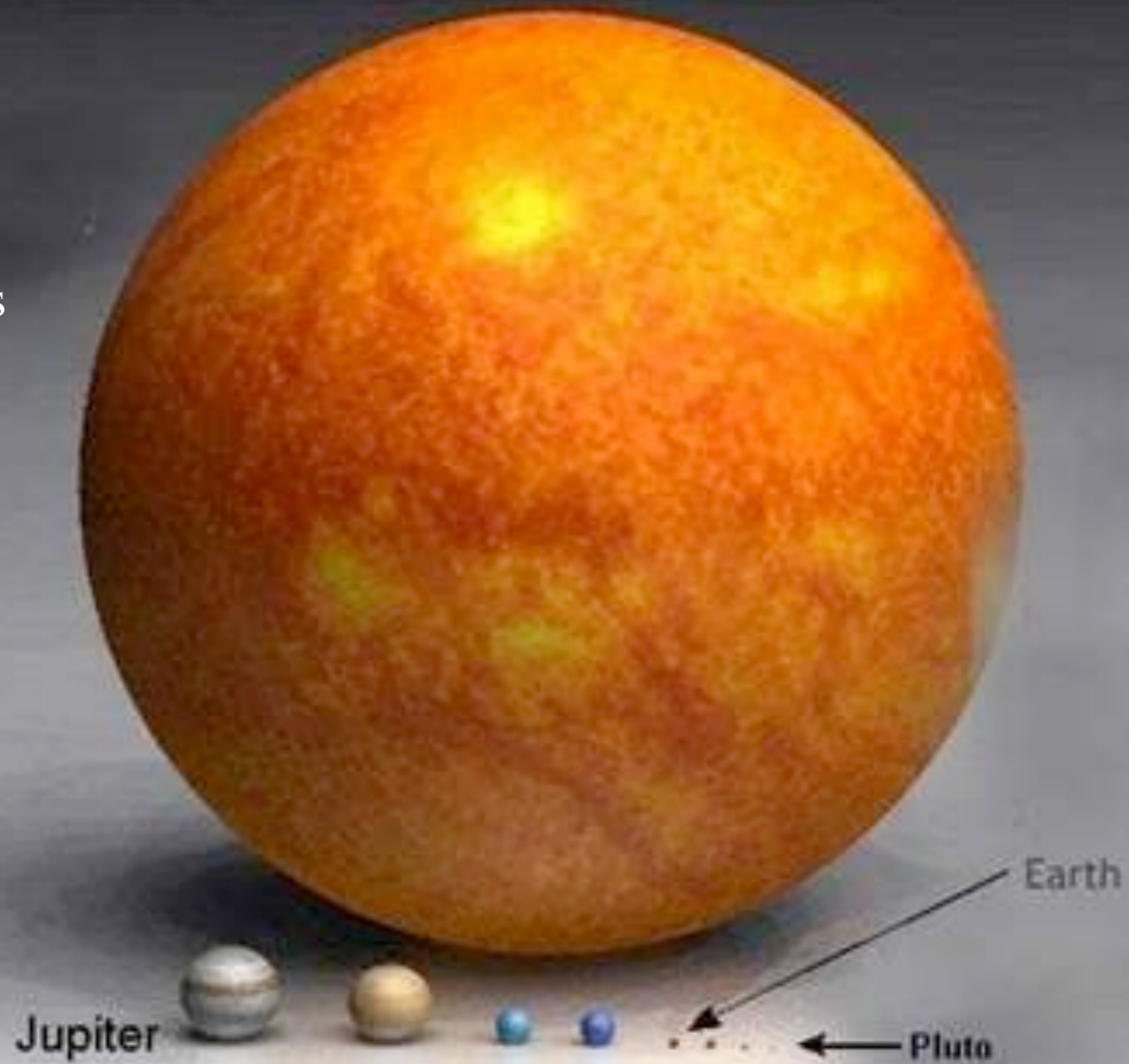
■ **MASS:**  
 $2 \times 10^{30} \text{ KG}$   
(300,000  
EARTHS),  
99.9% OF  
MASS IN SOLAR  
SYSTEM





# The Size of the Sun

Sun  
109 Earth's



# WHY DOES THE SUN SHINE?

- POWERED BY HUMAN SACRIFICE?
- THE AZTECS THOUGHT SO.
- BUT... IT'S STILL SHINING 500 YEARS LATER.

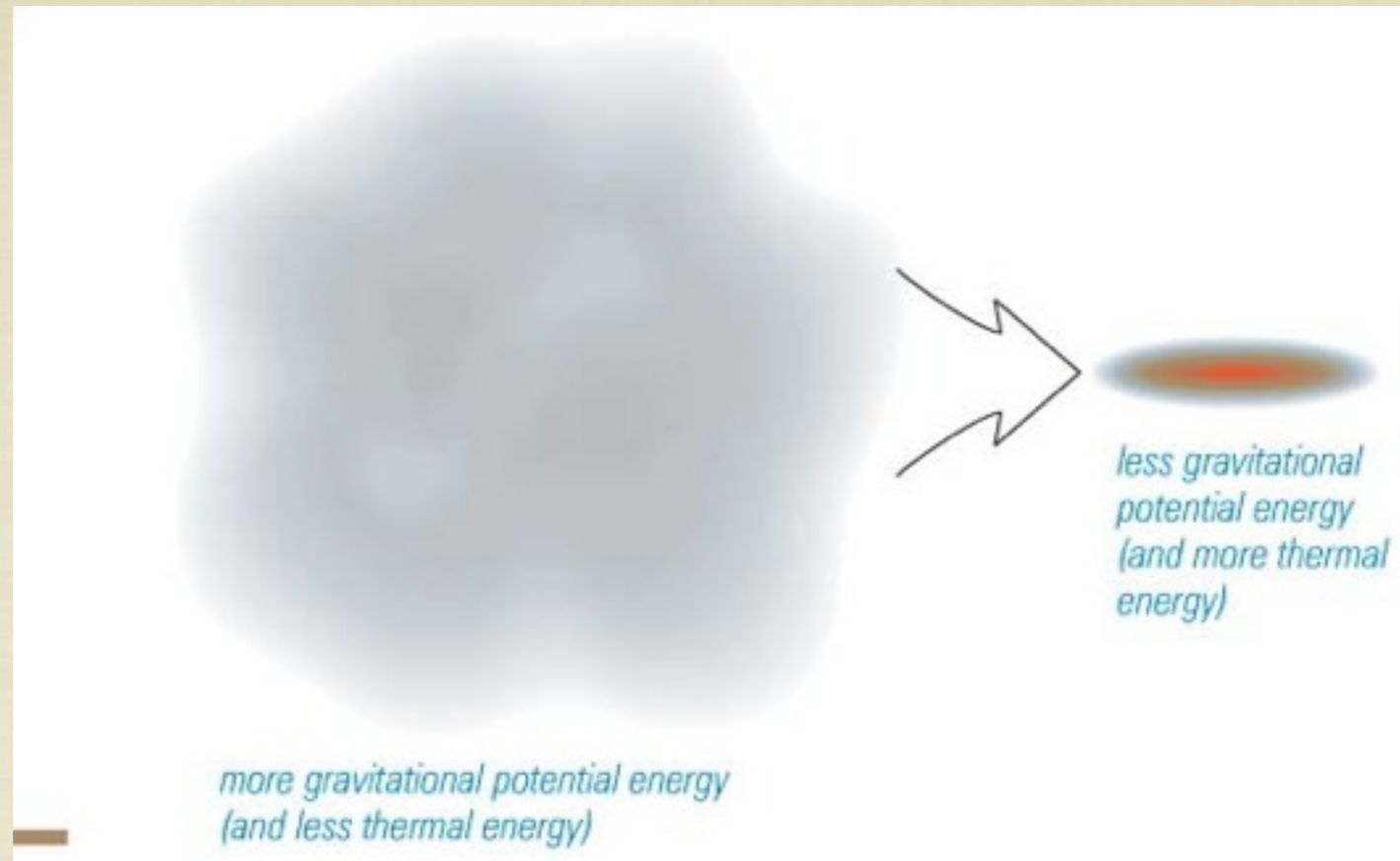


# WHY DOES THE SUN SHINE?



- 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!**

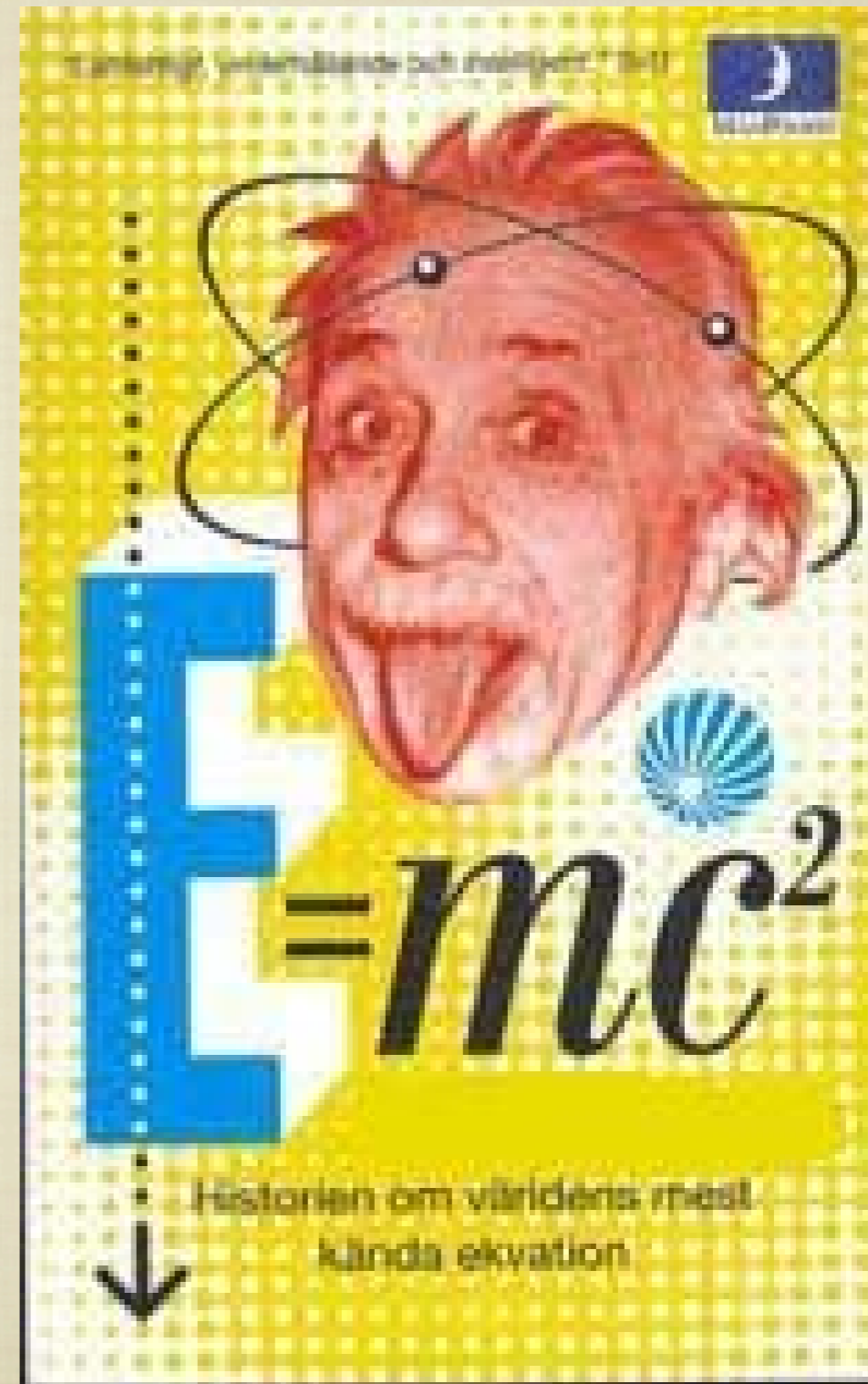
# WHY DOES THE SUN SHINE?



- **DUE TO GRAVITATIONAL CONTRACTION? WORKS FOR JUPITER!**
- **IT WOULD RUN OUT OF ENERGY IN 25 MILLION YEARS.**

# WHY DOES THE SUN SHINE?

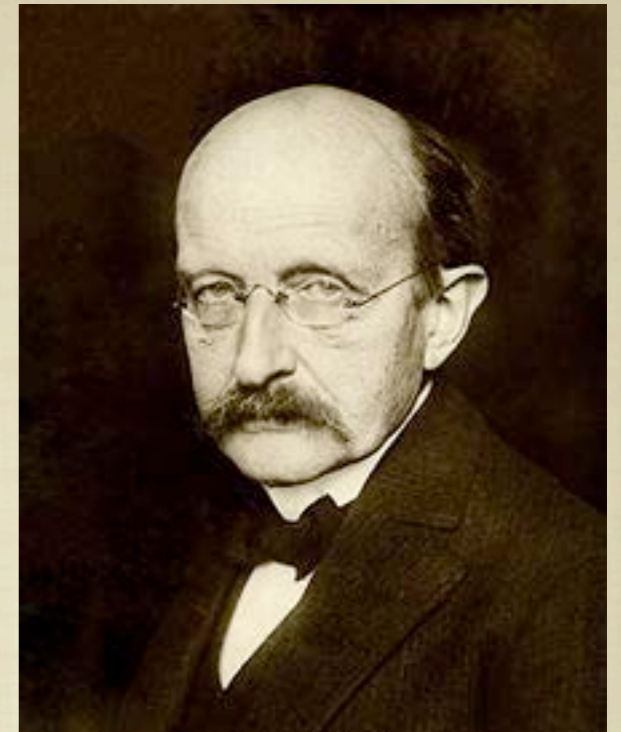
- WHAT ELSE IS THERE?
- MASS ENERGY!  $E=MC^2$
- MUCH GREATER SOURCE OF ENERGY THAN ANY OTHER!
- ONE GRAM OF MATTER HOLDS ENERGY OF 15,000 BARRELS OF OIL!



# HOW DOES THE SUN SHINE?



# PLANCK FUNCTION



- WIEN'S LAW, RAYLEIGH-JEANS TAIL, KNOWN EMPIRICALLY.

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

- PLANCK DERIVED THE FUNCTION IN 1900, TO ACCOUNT FOR LABORATORY MEASUREMENTS OF THE SPECTRA OF HEATED OBJECTS.
- REQUIRED A MINIMUM “QUANTUM OF ACTION” AND ITS ASSOCIATED CONSTANT... FIRST SERIOUS STEP TO QUANTIZATION OF LIGHT

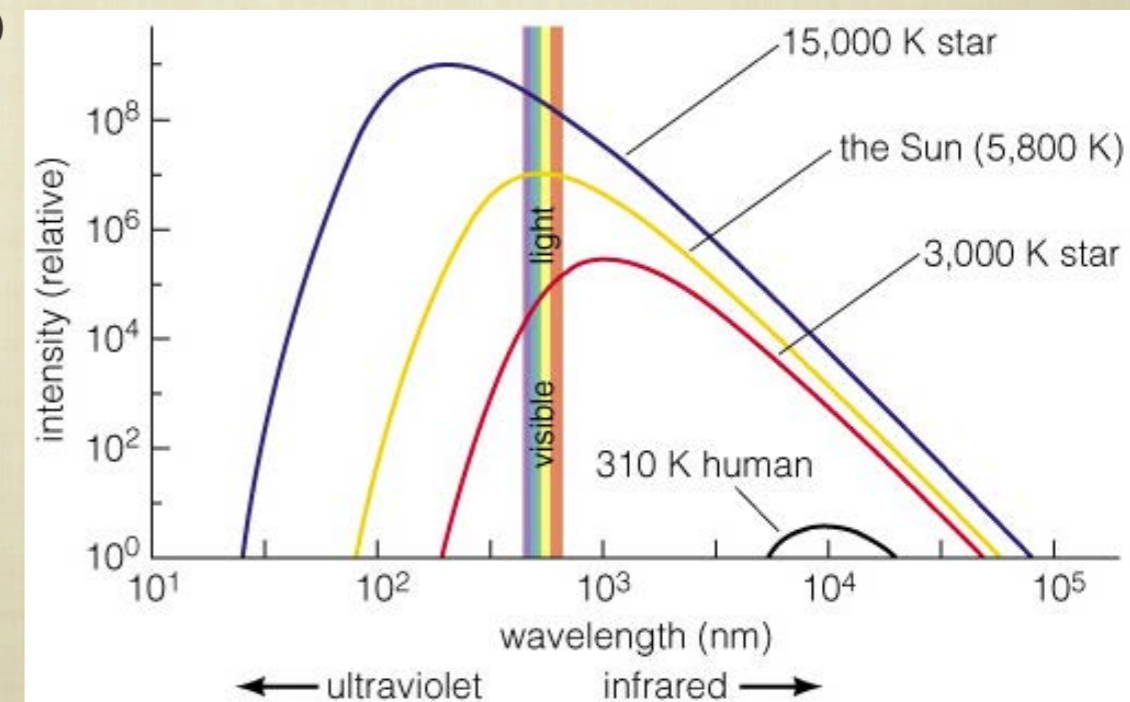
$$B_\lambda(T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{hc/\lambda kT} - 1} \quad \lambda_{\text{peak}} = \frac{2.9 \times 10^6 \text{ nm K}}{T}$$

# BLACKBODY RADIATION

- A PERFECT ABSORBER IS “BLACK”
- ABSORBS ALL LIGHT SHINING ON IT
- ABSORBED LIGHT (ENERGY) HEATS OBJECT
- TEMPERATURE INCREASES UNTIL:

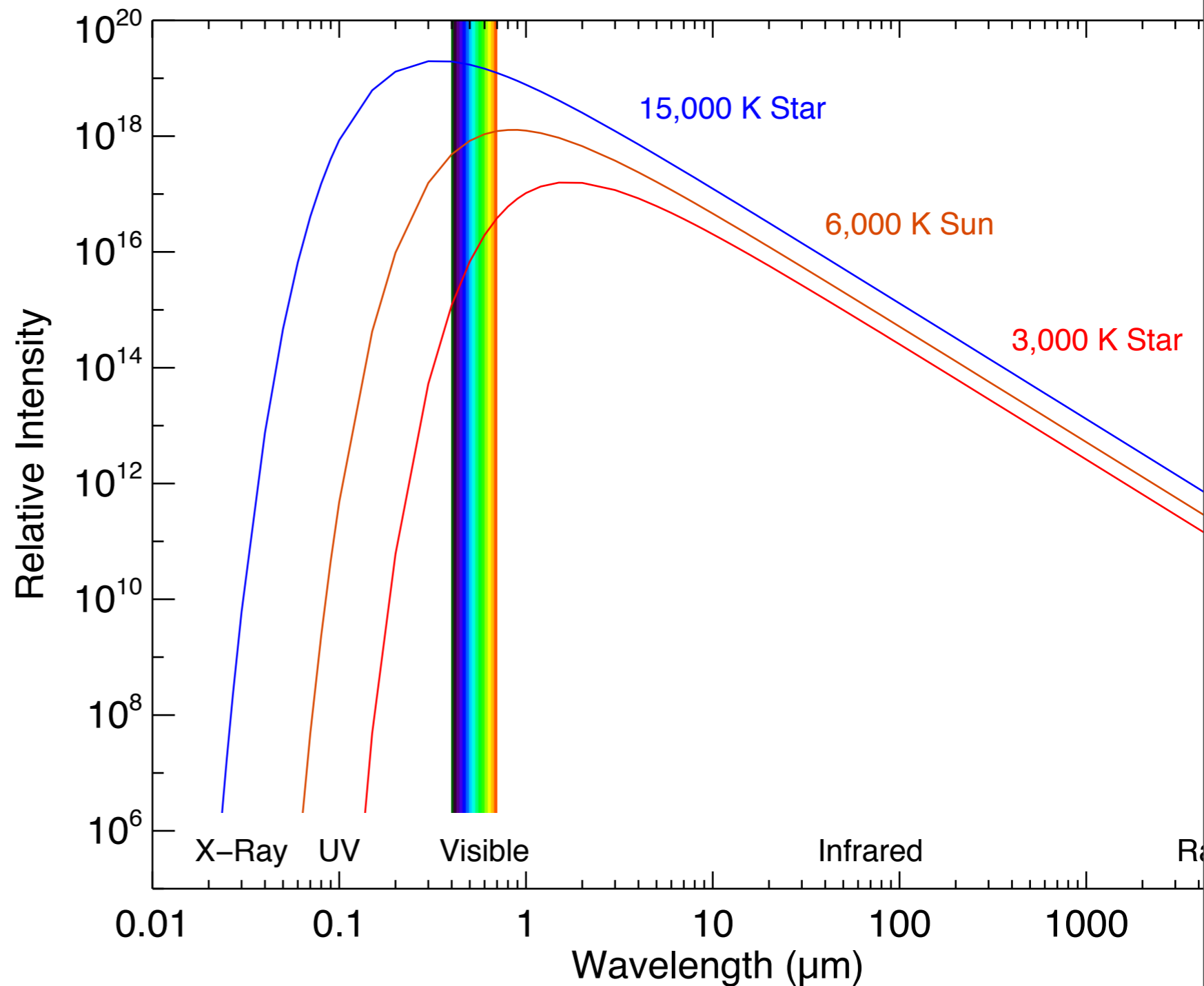
**EMITTED ENERGY = ABSORBED ENERGY**

- EMITTED RADIATION CALLED **BLACKBODY RADIATION**
- THE THERMAL RADIATION EMITTED BY MOST OBJECTS, INCLUDE STARS IS SIMILAR TO BLACKBODY

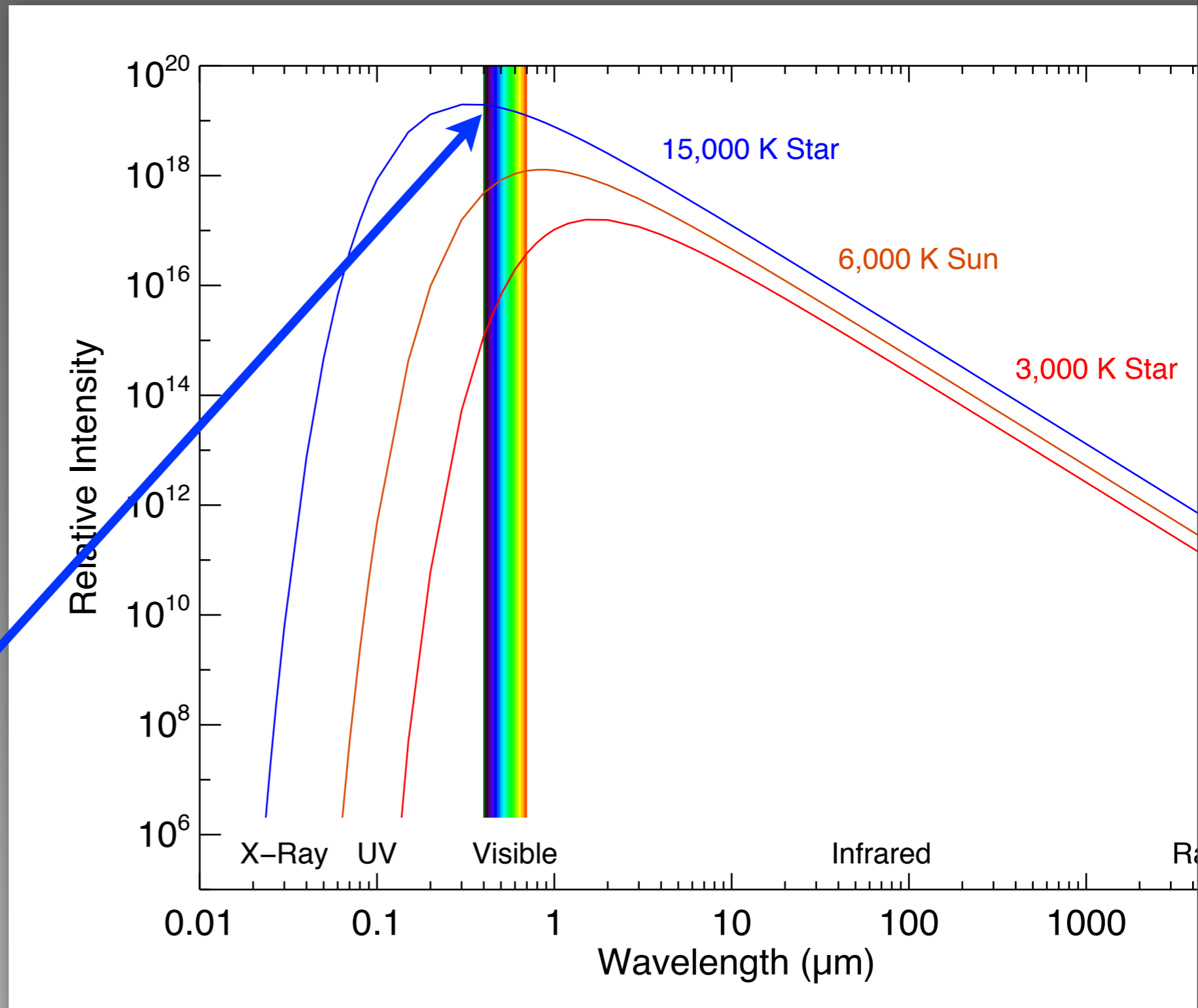




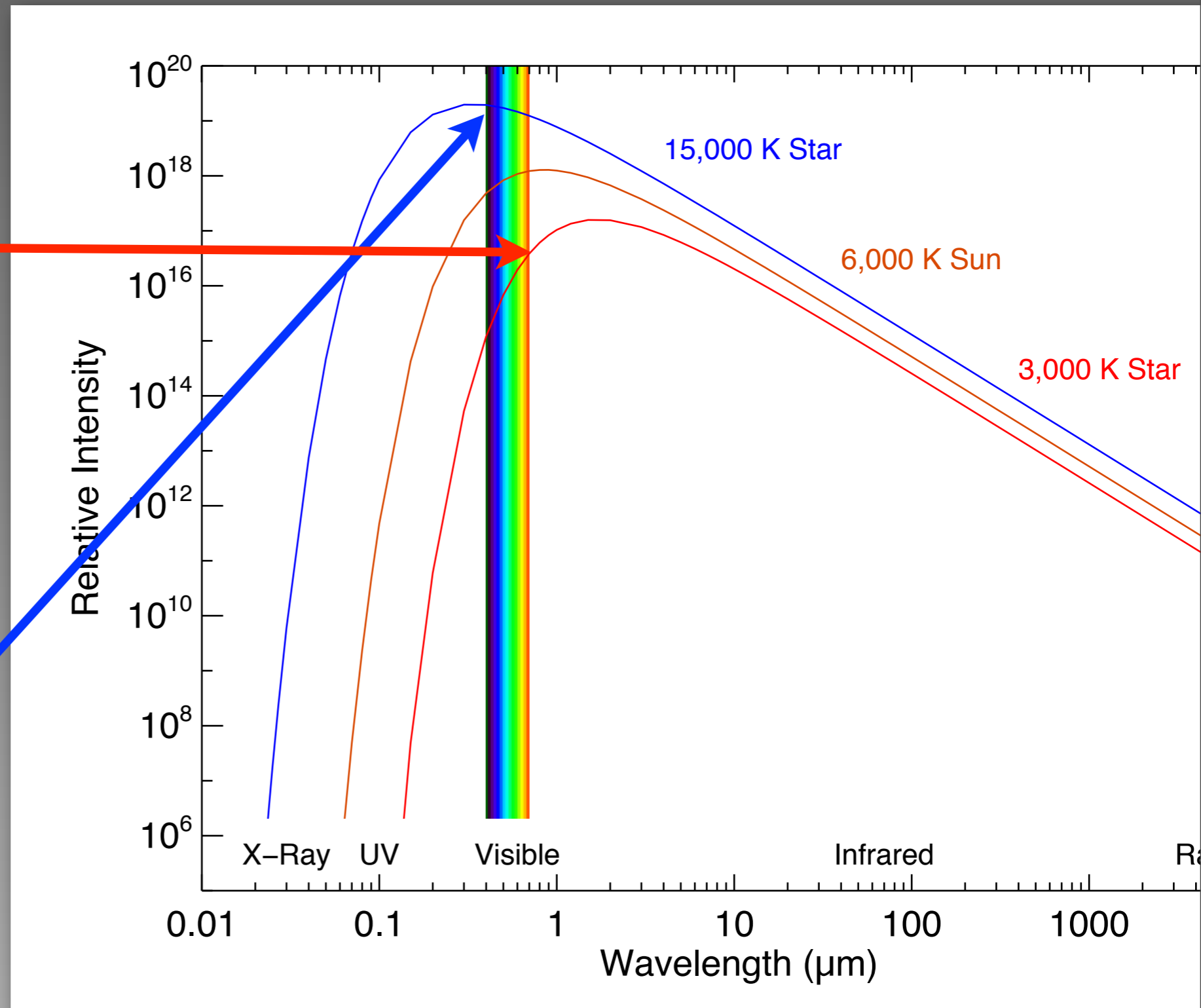
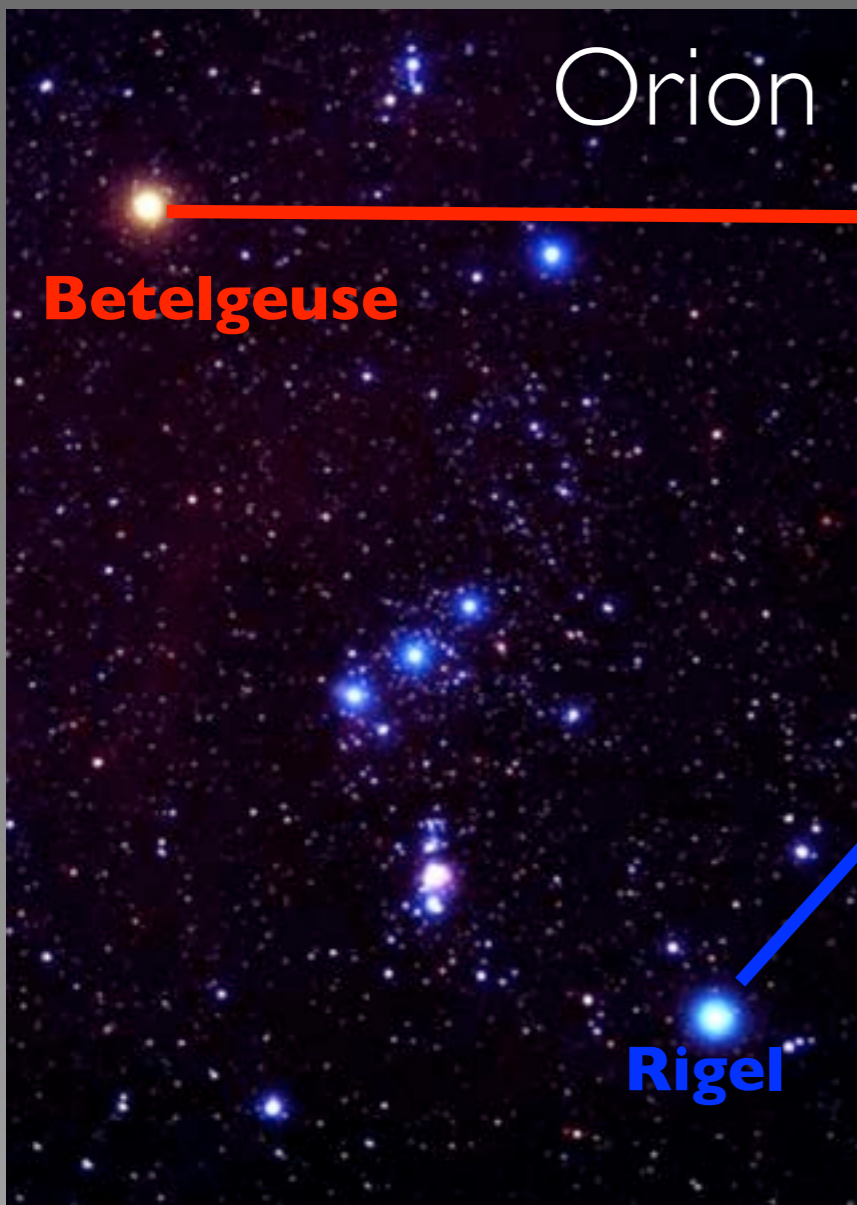
# All “solid” objects emit light



# All "solid" objects emit light



# All "solid" objects emit light

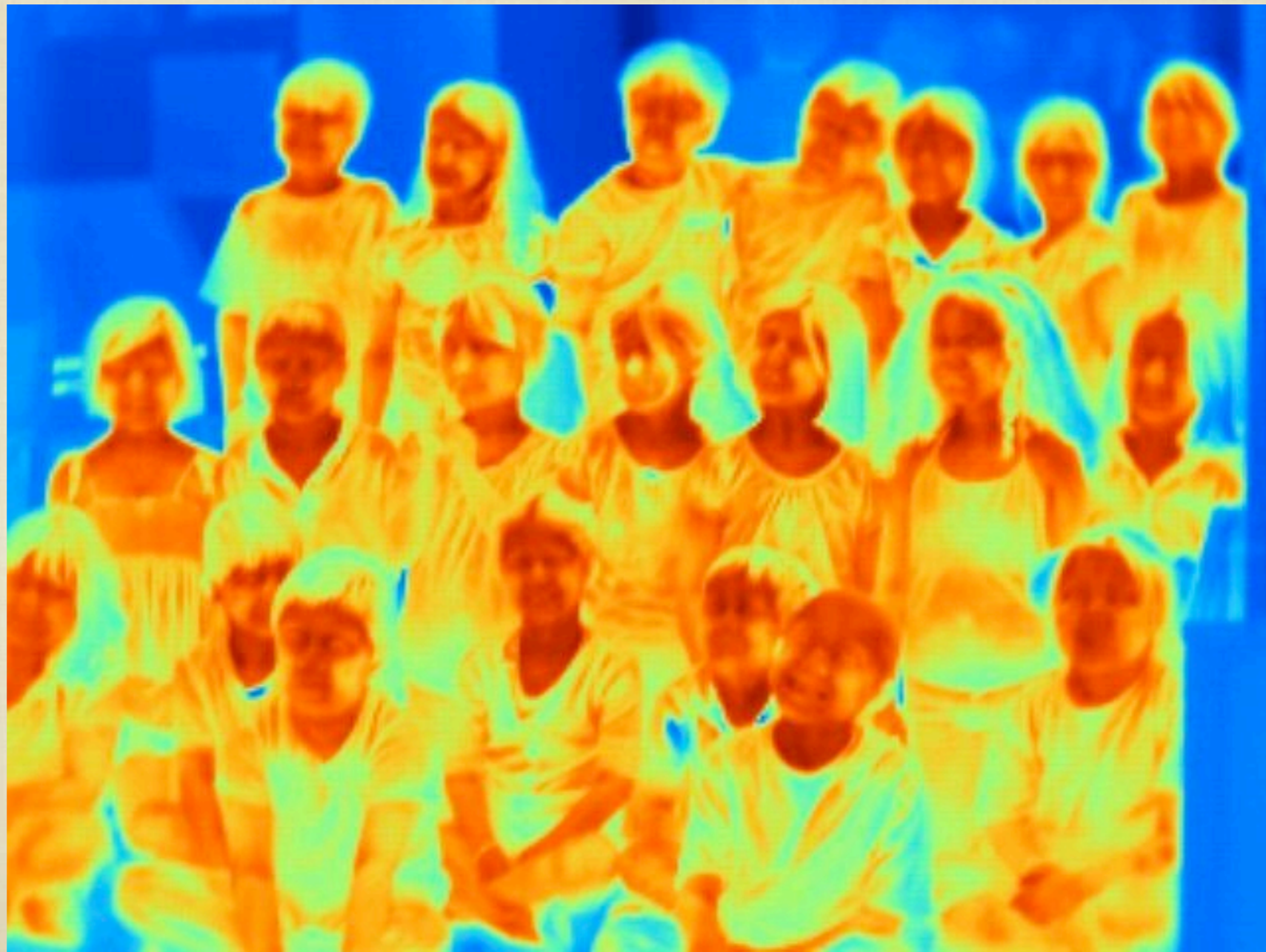


# Thermal Emission from Pahoehoe Lava

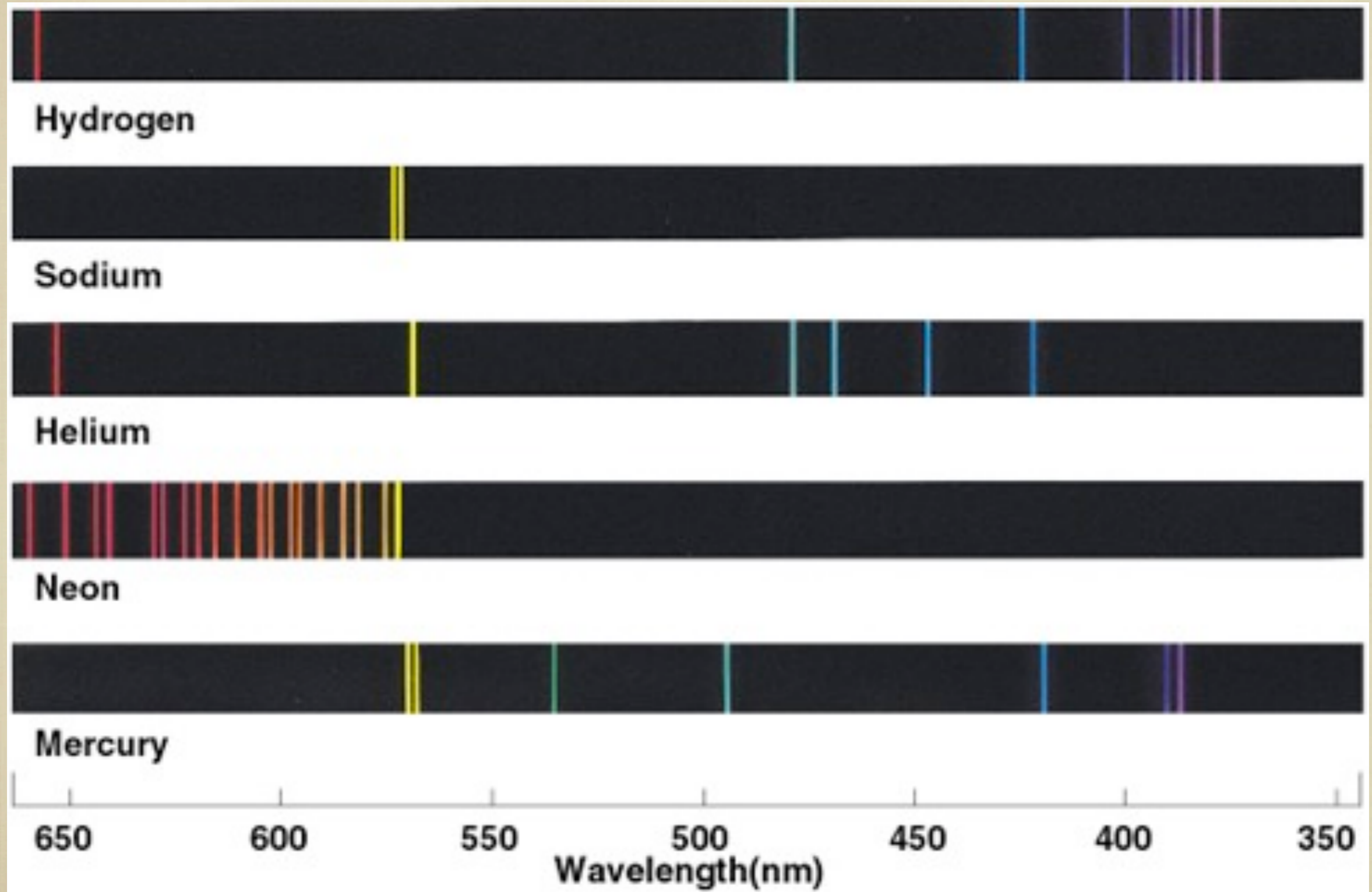


As a hot object radiates, it cools (conservation of energy)

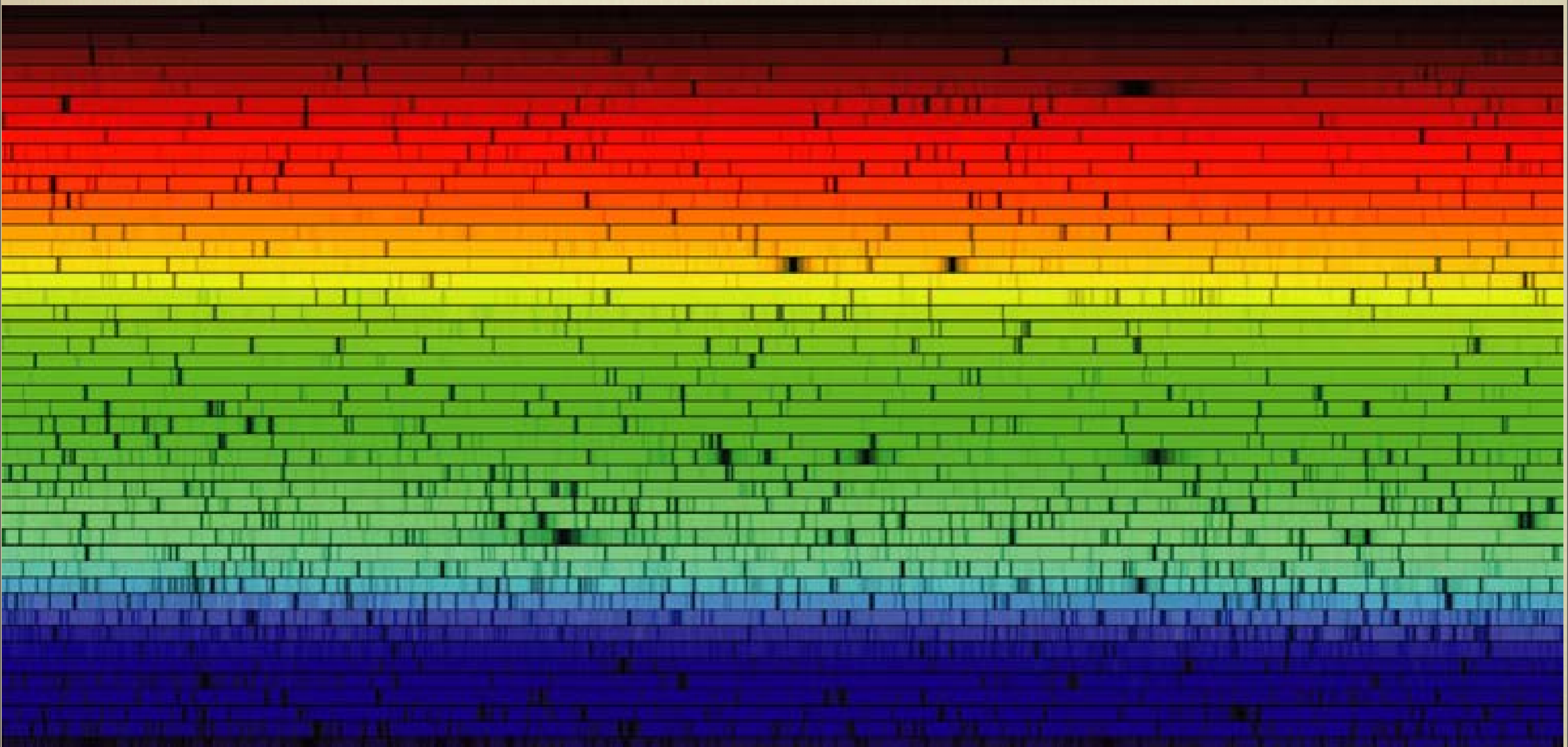
# THERMAL (10MICRON) EMISSION FROM AREA 2ND GRADERS



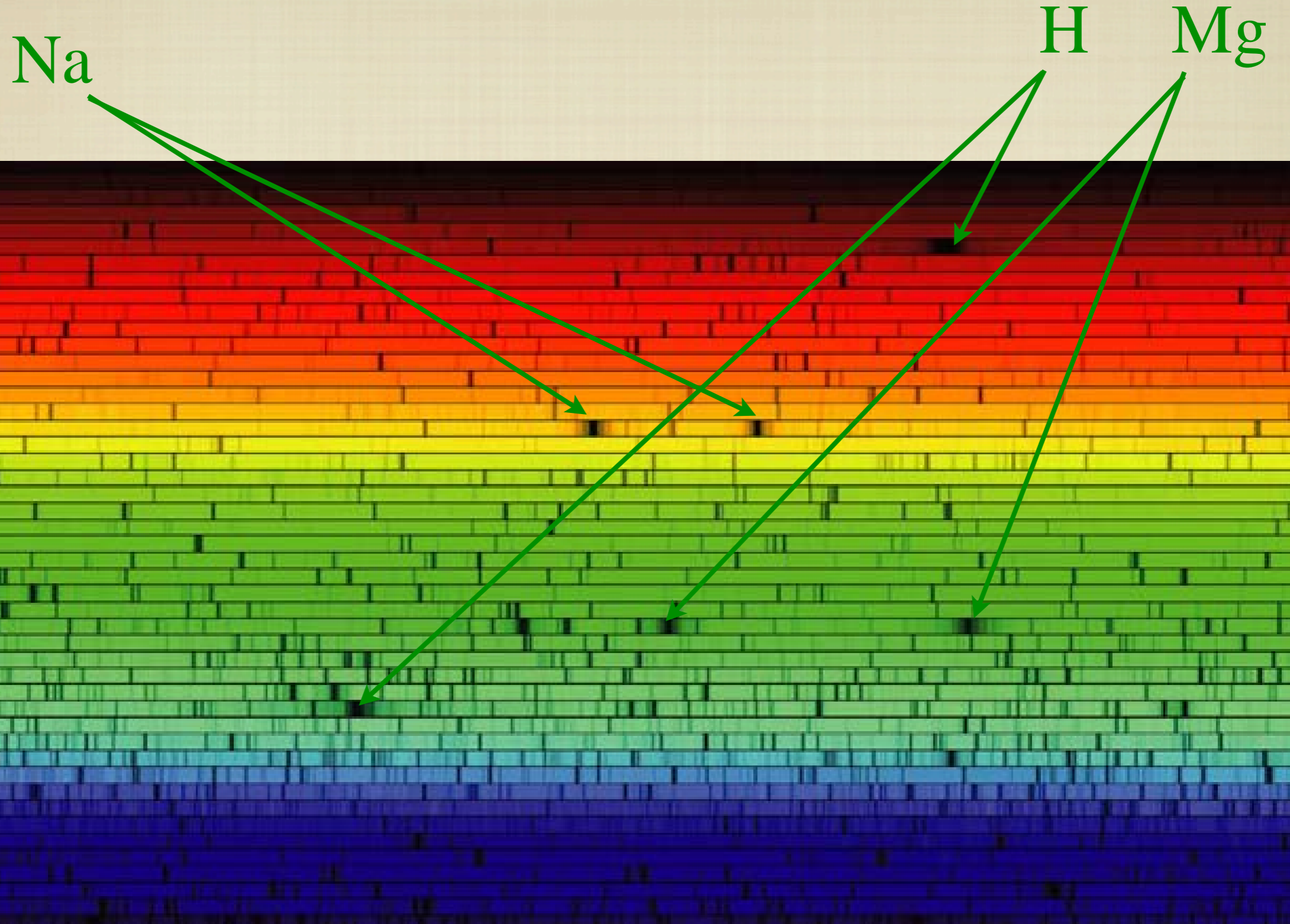
# SPECTRA



# THE SOLAR SPECTRUM



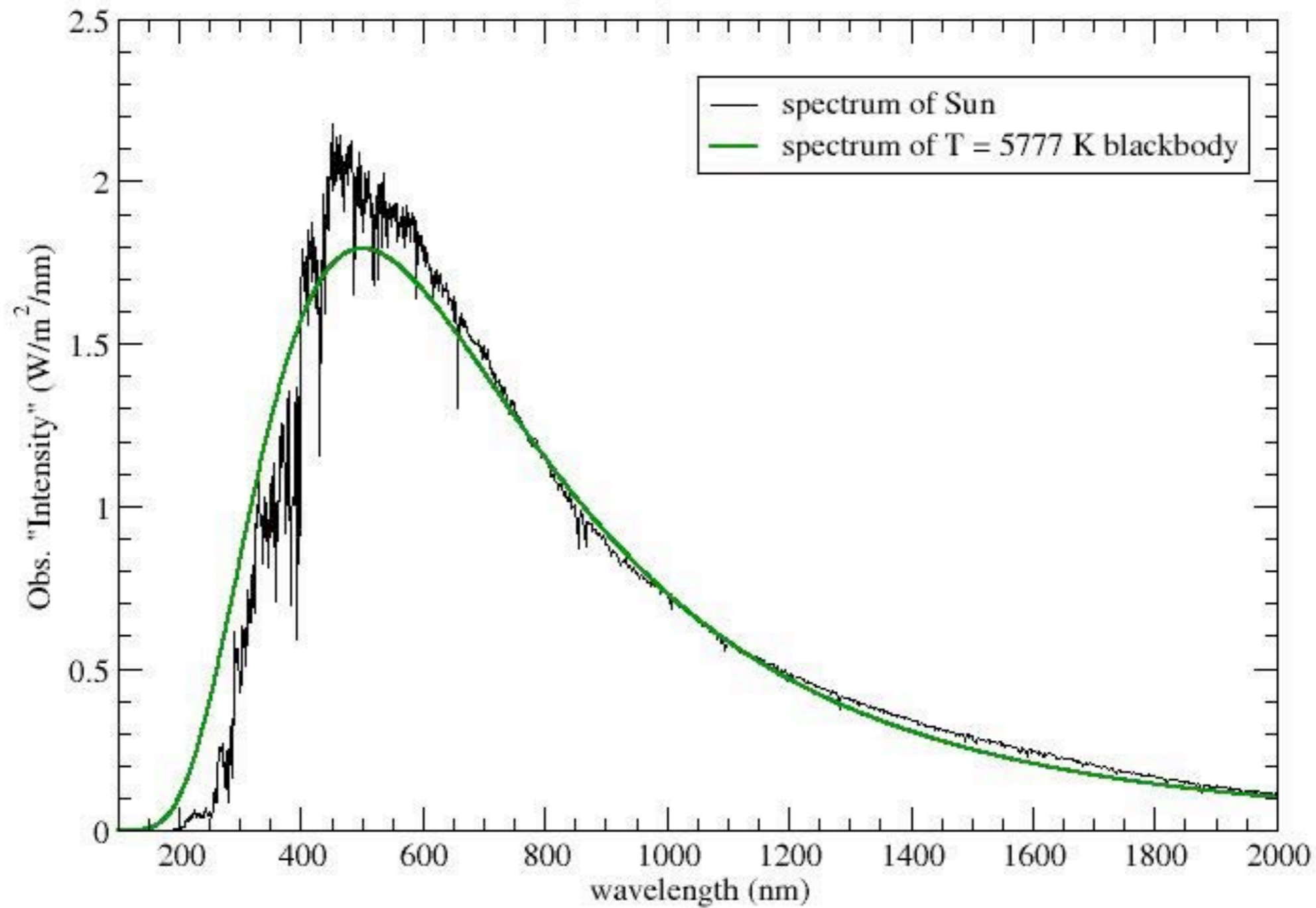
# THE SOLAR SPECTRUM





# Sun's Spectrum vs. Thermal Radiator

of a single temperature  $T = 5777\text{ K}$



# INTEGRATED POWER

$$P = A\sigma T^4 \quad \sigma = 5.67 \times 10^{-8} \text{ kg/K}^4\text{s}^3$$

■ **SUN:**

$$A = 4\pi R_{\odot}^2 = 6.1 \times 10^{12} \text{ km}^2$$
$$P = A\sigma T^4 = 3.84 \times 10^{26} \text{ W}$$

■ **YOU:**

$$A = 1.8\text{m}^2$$
$$T = 98.6\text{F} = 310\text{K}$$
$$P = A\sigma T^4 = 943 \text{ W} = 19450 \frac{\text{Calories}}{\text{day}} = 130 \frac{\text{BigMacs}}{\text{day}}$$

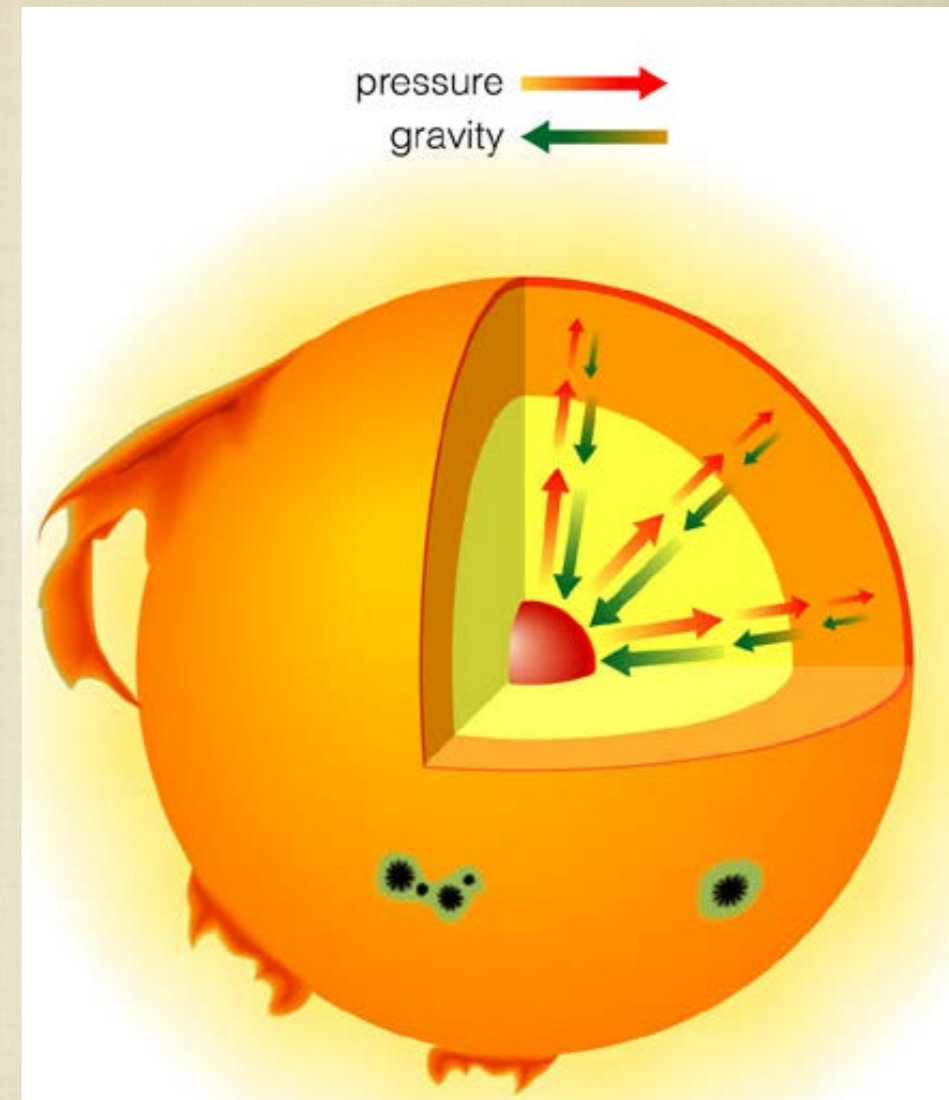
# WHAT KEEPS IT SHINING?

- 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 ...  $4 \times 10^{26}$  WATTS).



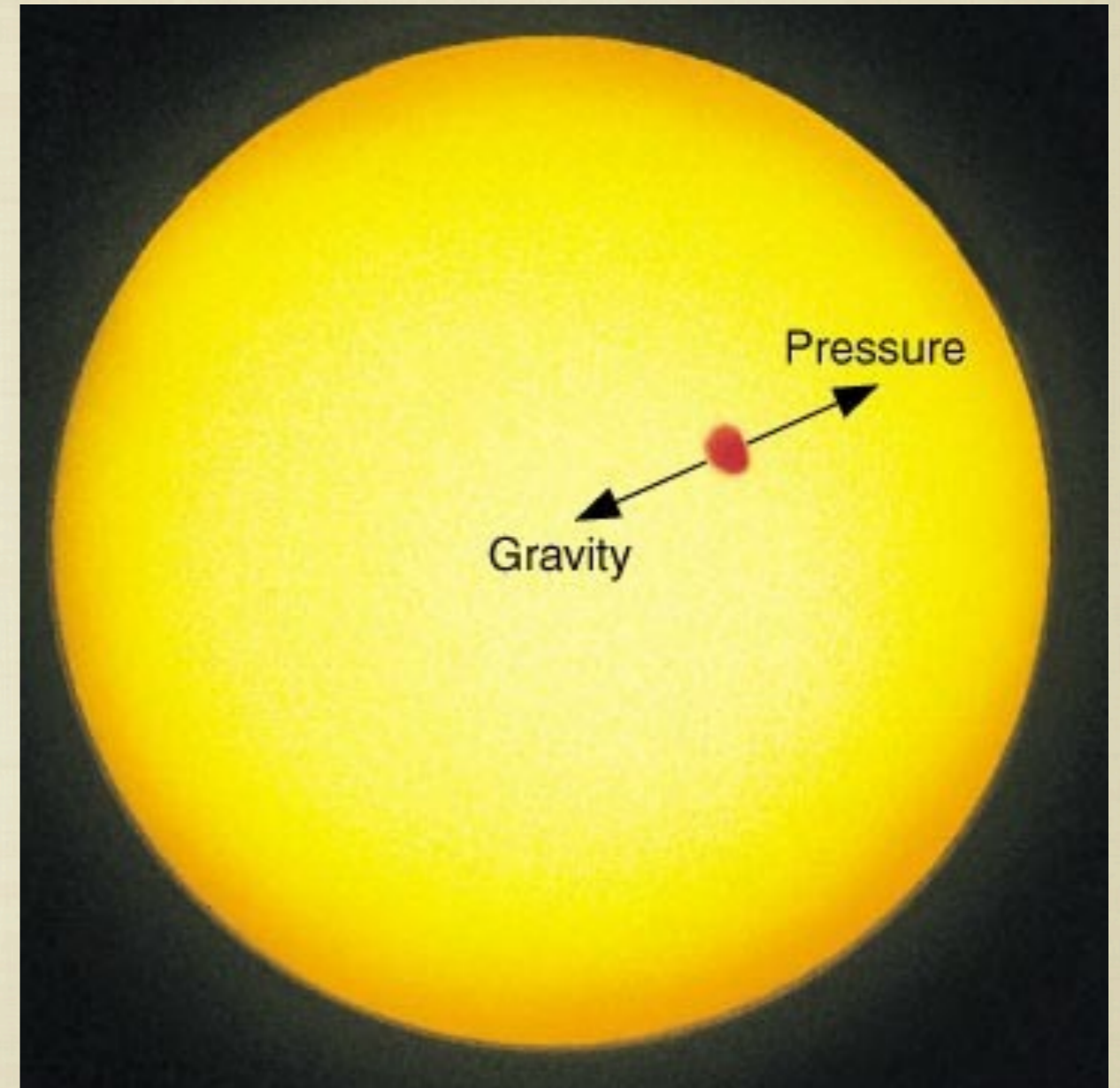
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# GRAVITY VS. PRESSURE

- **IT'S A BATTLE:  
GRAVITY FIGHTING  
AGAINST  
PRESSURE.**
- **PRESSURE  
CREATED BY THE  
HEAT, HEAT  
PRODUCED BY THE  
NUCLEAR  
REACTIONS!**



# THE SOLAR THERMOSTAT

Temperature  
Decreases

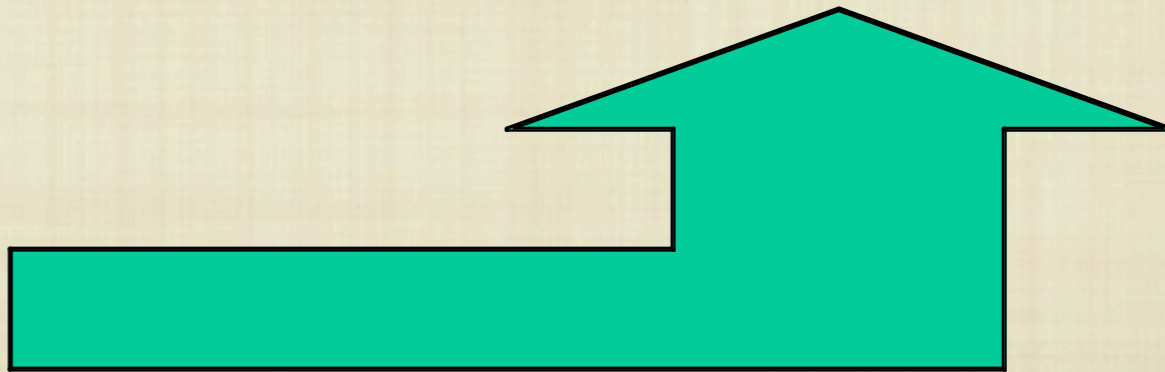


Fusion Rate Decreases



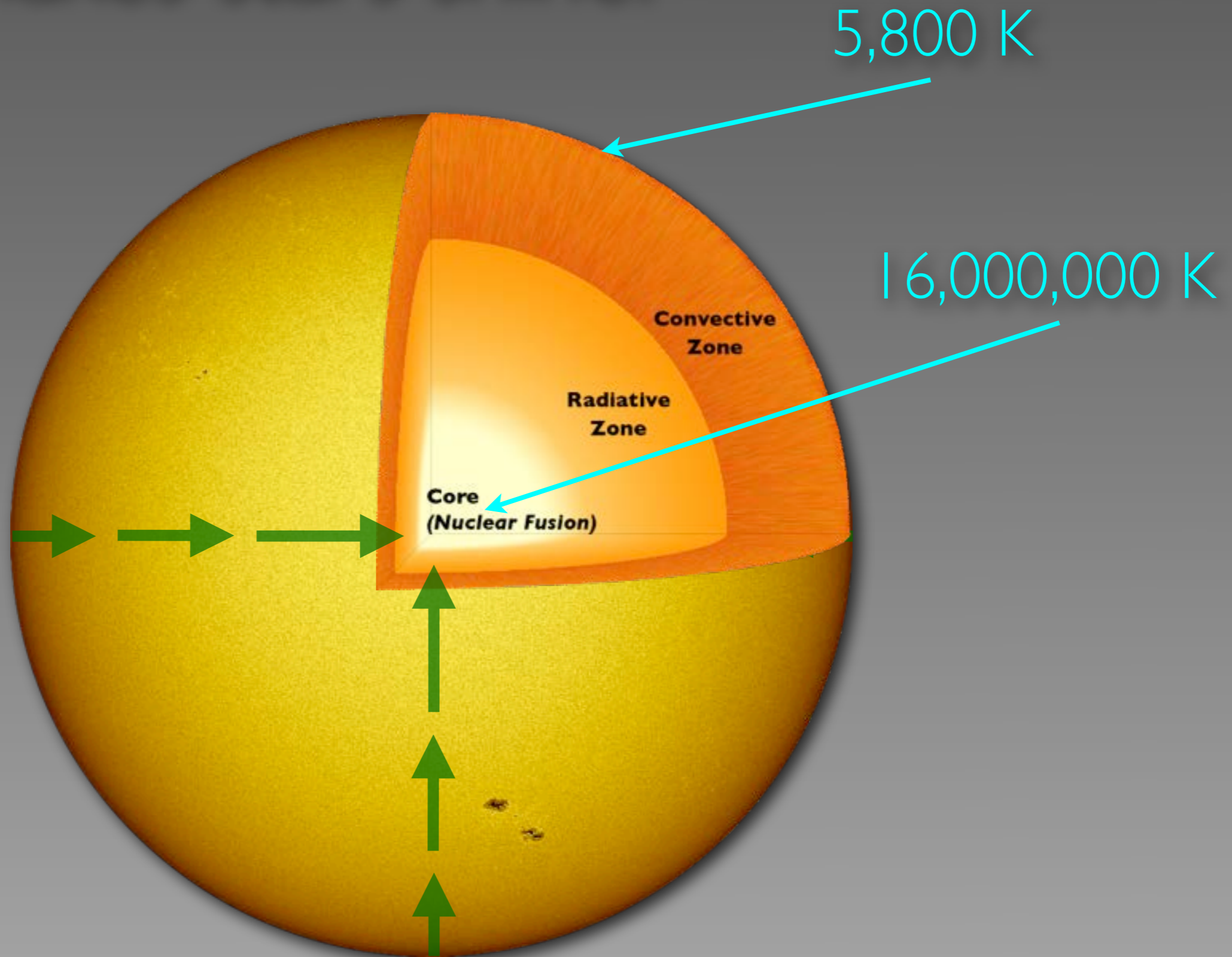
Core  
compresses

Temperature  
Restored



# What makes stars shine?

gravity



1200 K

# WHAT STARTED THE SUN SHINING?

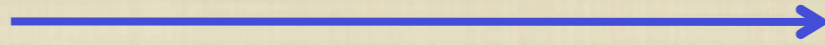
- **GRAVITATIONAL CONTRACTION!**
- **(EVEN THOUGH IT DOESN'T EXPLAIN WHY IT SHINES NOW).**
- **CONTRACTING MATERIAL HEATED UP, UNTIL HOT ENOUGH FOR NUCLEAR “FUSION” TO OCCUR.**





# NUCLEAR REACTIONS

- **FUSION:**



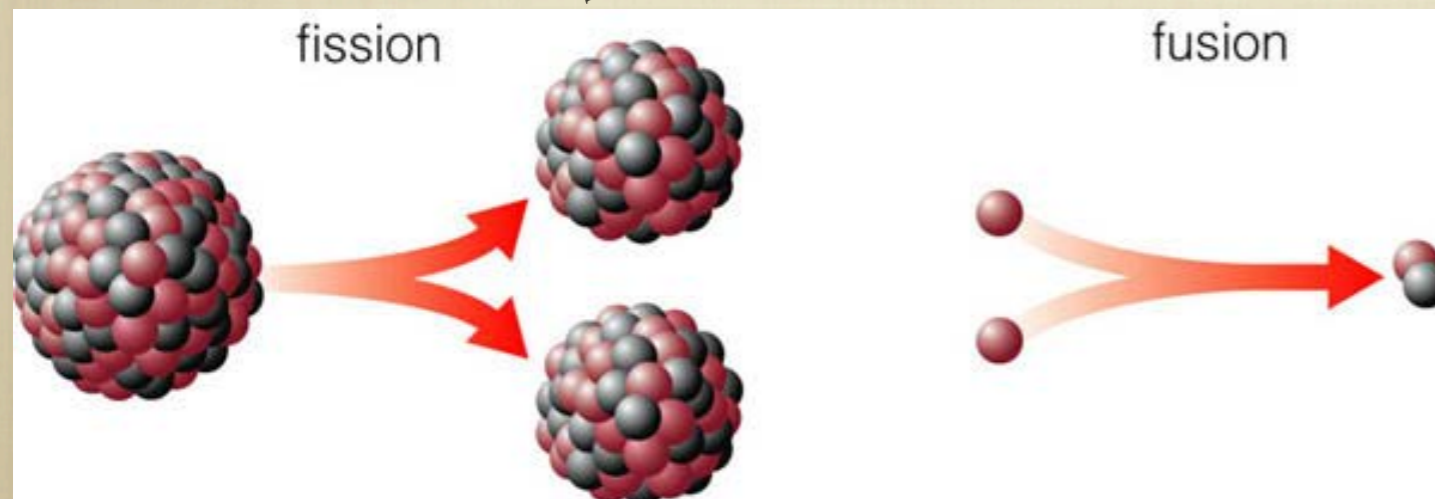
- TWO LIGHT NUCLEI JOINED INTO ONE NUCLEUS

- POWERS THE SUN

- **FISSION:**

- MASSIVE NUCLEUS SPLITS IN SMALLER NUCLEI

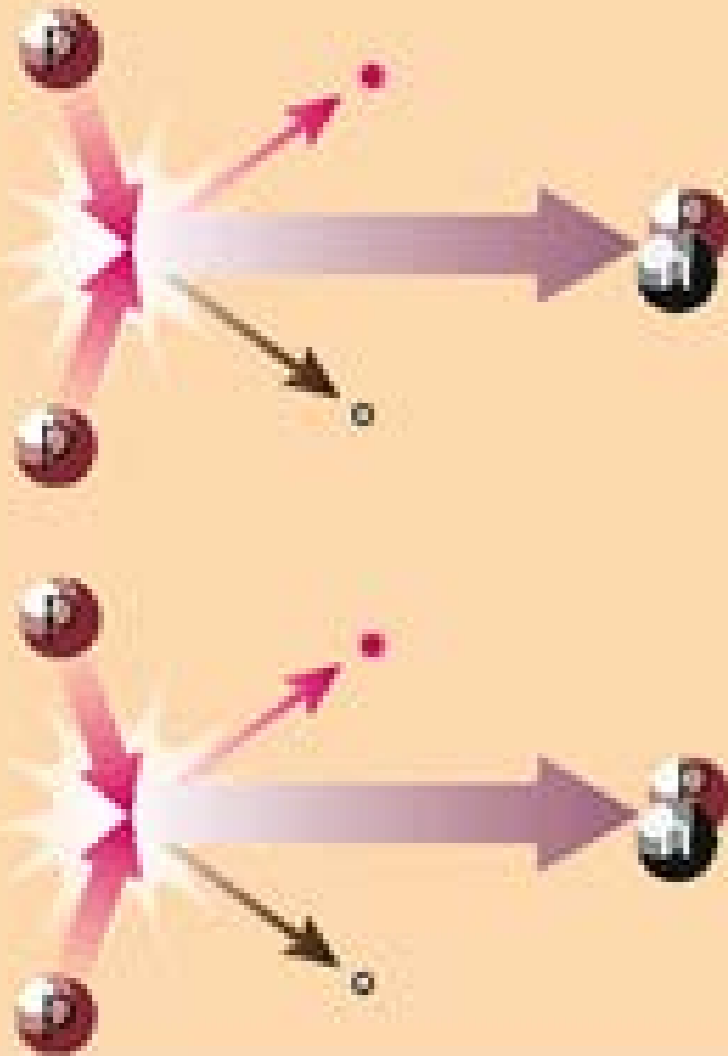
- POWERS NUCLEAR REACTORS (DAVIS-BESSE)



# 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.



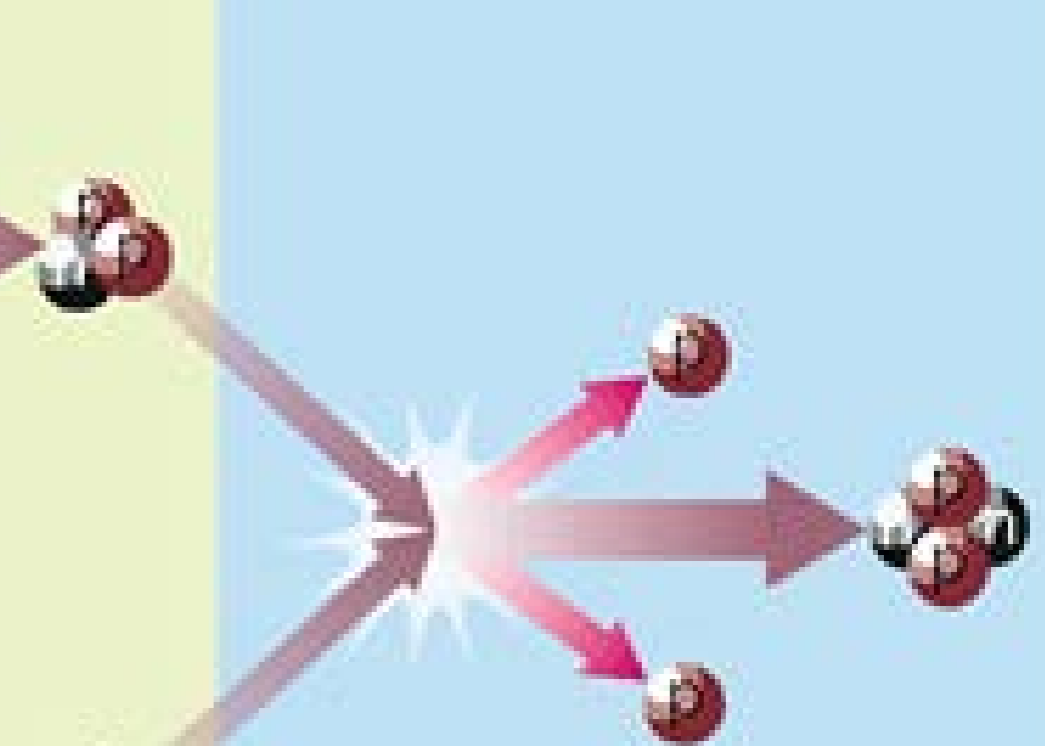
## Step 2

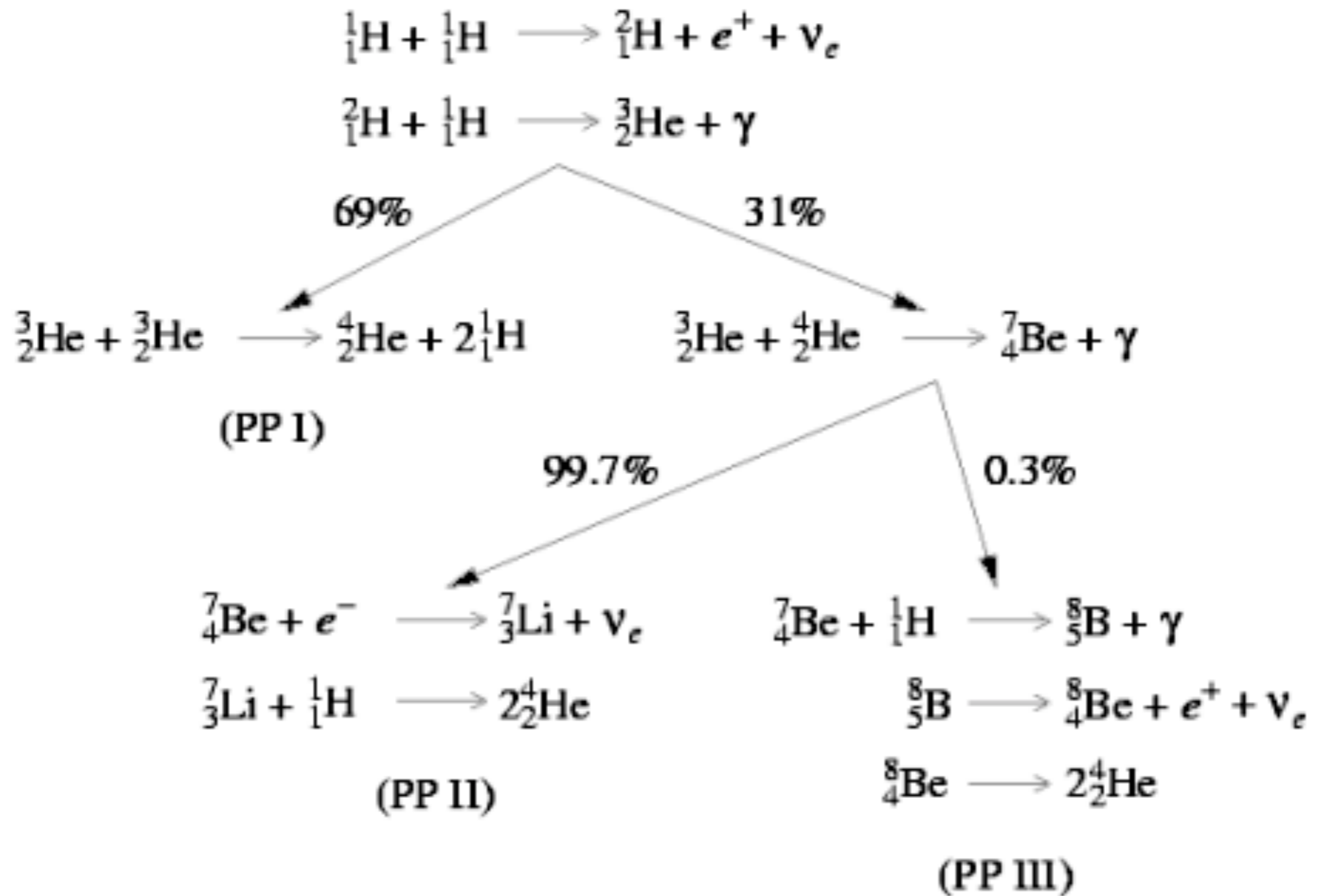
The deuterium nucleus and a proton fuse to make a nucleus of helium-3 (2 protons, 1 neutron). This step also occurs twice in the overall reaction.



## Step 3

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





# CONVERTING MASS TO ENERGY

- **NUCLEAR REACTIONS CHANGE MASS OF CONSTITUENTS**

- MASS INCREASE CONSUMES ENERGY
- MASS DECREASE RELEASES ENERGY

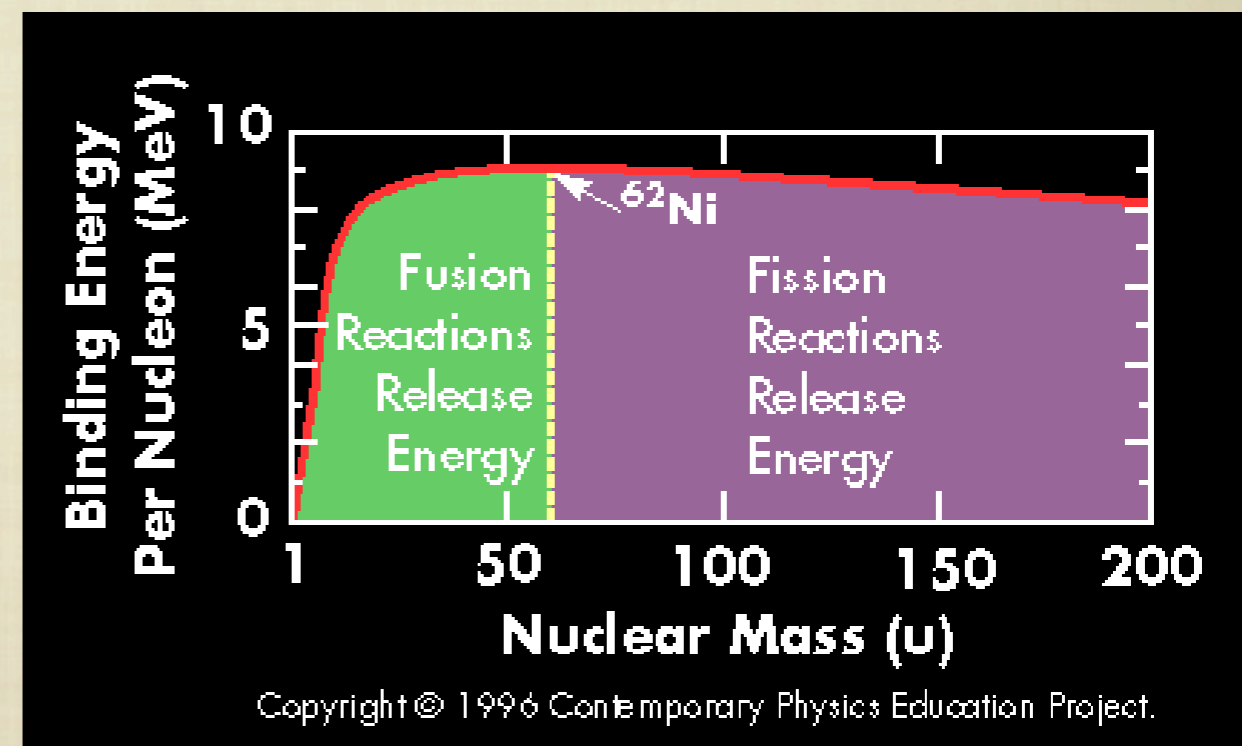
- **MASS DECREASES IN**

- **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

- ELABORATE MAGNETIC PLASMA CHAMBERS.
- HOW DOES THE SUN DO IT SO WELL?
- SUN CONVERTS 500 MILLION METRIC TONS OF HYDROGEN TO HELIUM PER SECOND.
- AND YET.... IN SOLAR CORE, POWER PRODUCTION DENSITY FROM FUSION IS JUST  $250 \text{ W/m}^3$ .
- COMPARE THIS TO YOURSELF.
- WORLD ENERGY USAGE =  $\sim 15 \text{ TW} \Rightarrow$  REQUIRES  $60 \text{ km}^3$  AT SUN'S POWER DENSITY!

# SUN: LATEST VIEW

A blue-tinted image of the Sun showing solar activity, captured by the SOHO spacecraft. The image displays the solar surface with various features, including sunspots and solar flares, set against a dark background.

YESTERDAY

FROM THE  
SOHO  
SPACECRAFT

# MORE SOHO

**SOHO**  
**10 years**  
**of operations**

**1995-2005**



# MAJOR REGIONS OF THE SUN

## ■ INTERIOR

■ CORE

■ RADIATIVE ZONE

■ CONVECTIVE ZONE

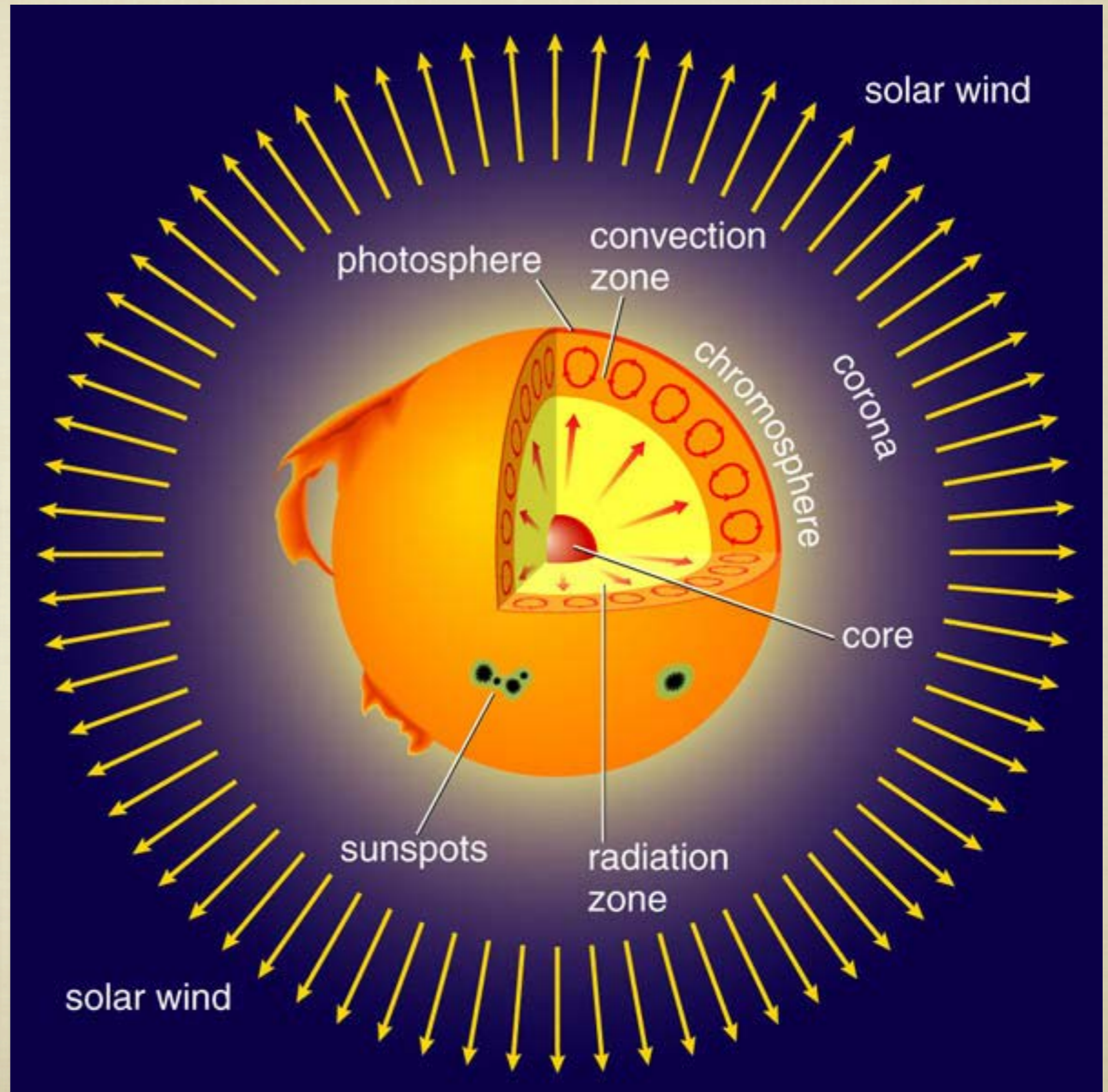
## ■ ATMOSPHERE

■ PHOTOSPHERE

■ CHROMOSPHERE

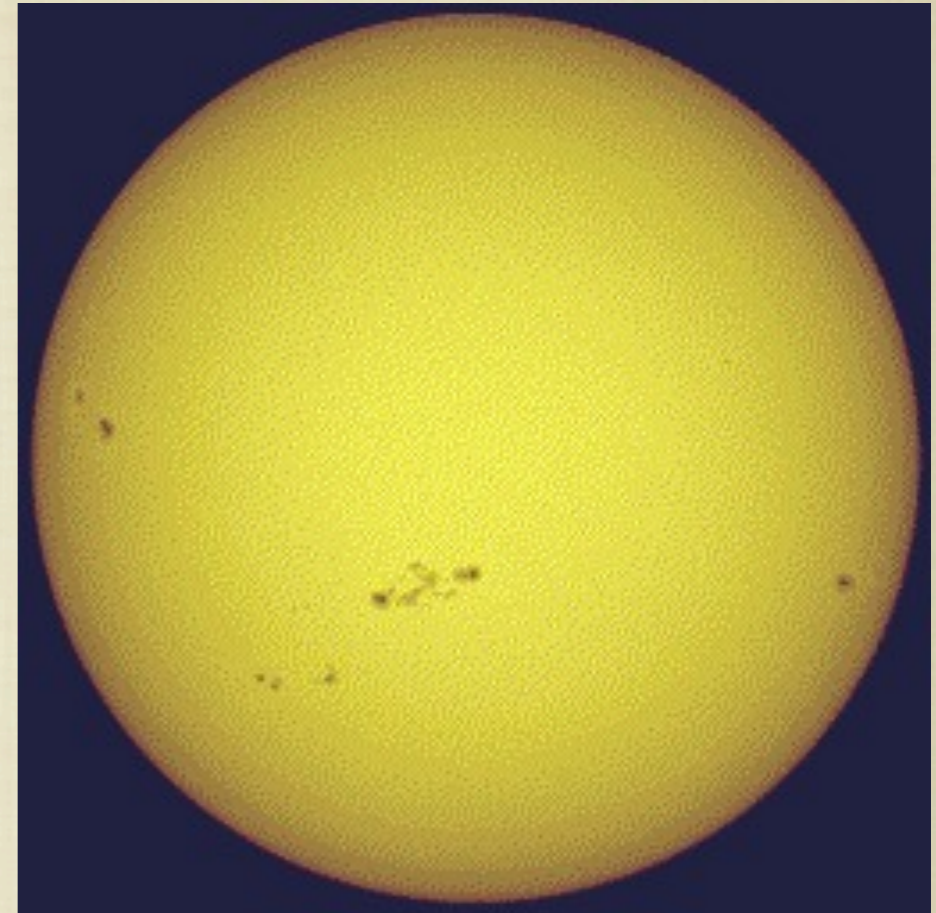
■ CORONA

■ SOLAR WIND



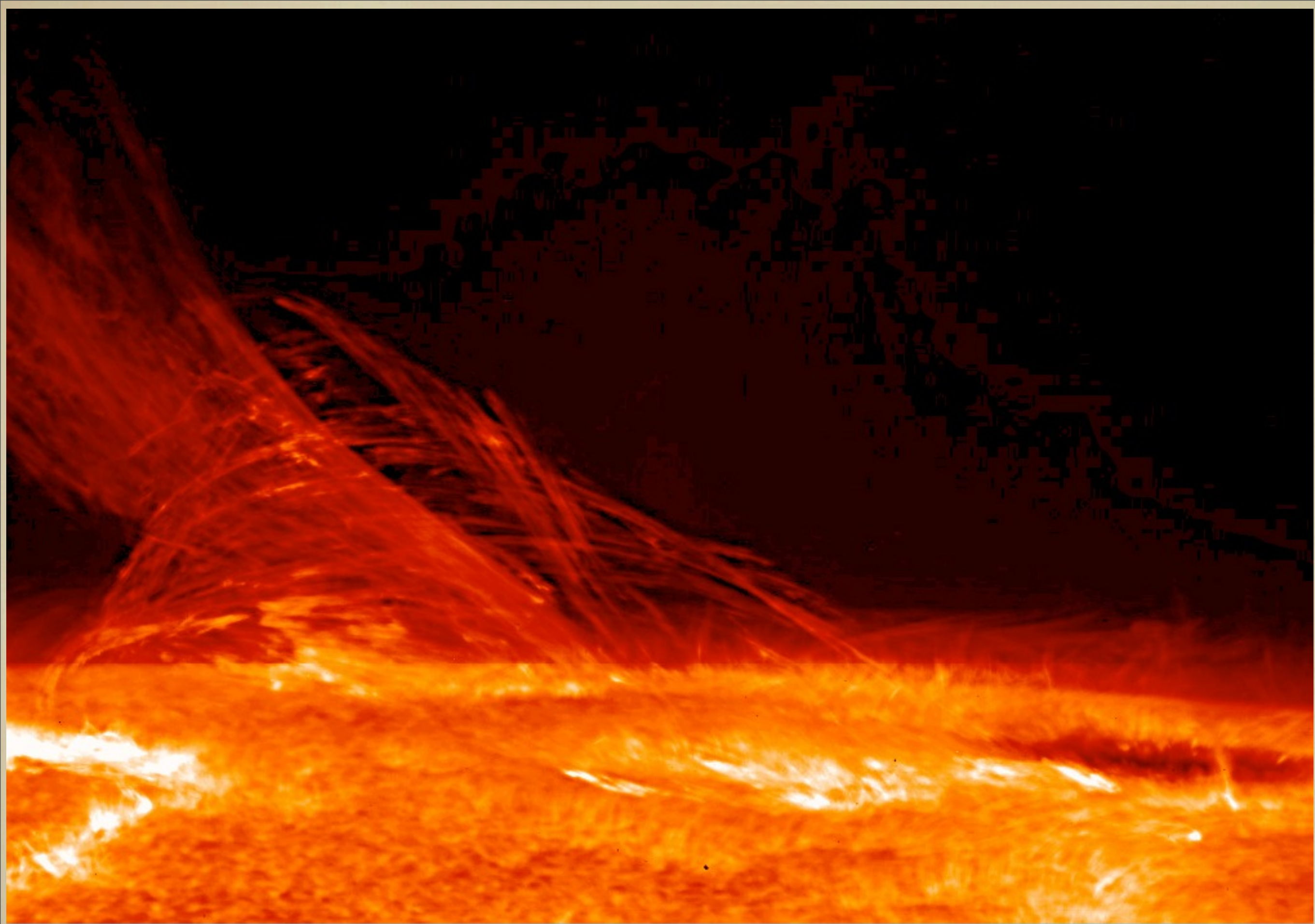
# PHOTOSPHERE

- **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!**

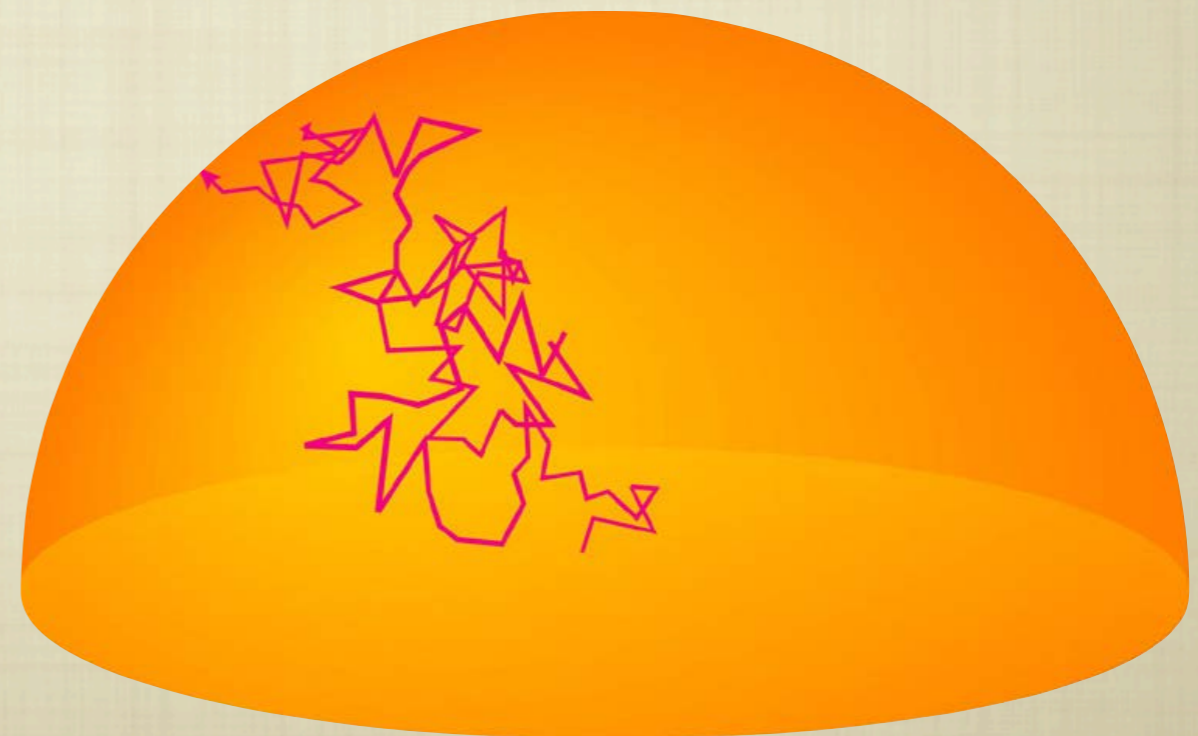


# SPACECRAFT HINODE

Thursday, January 23, 14

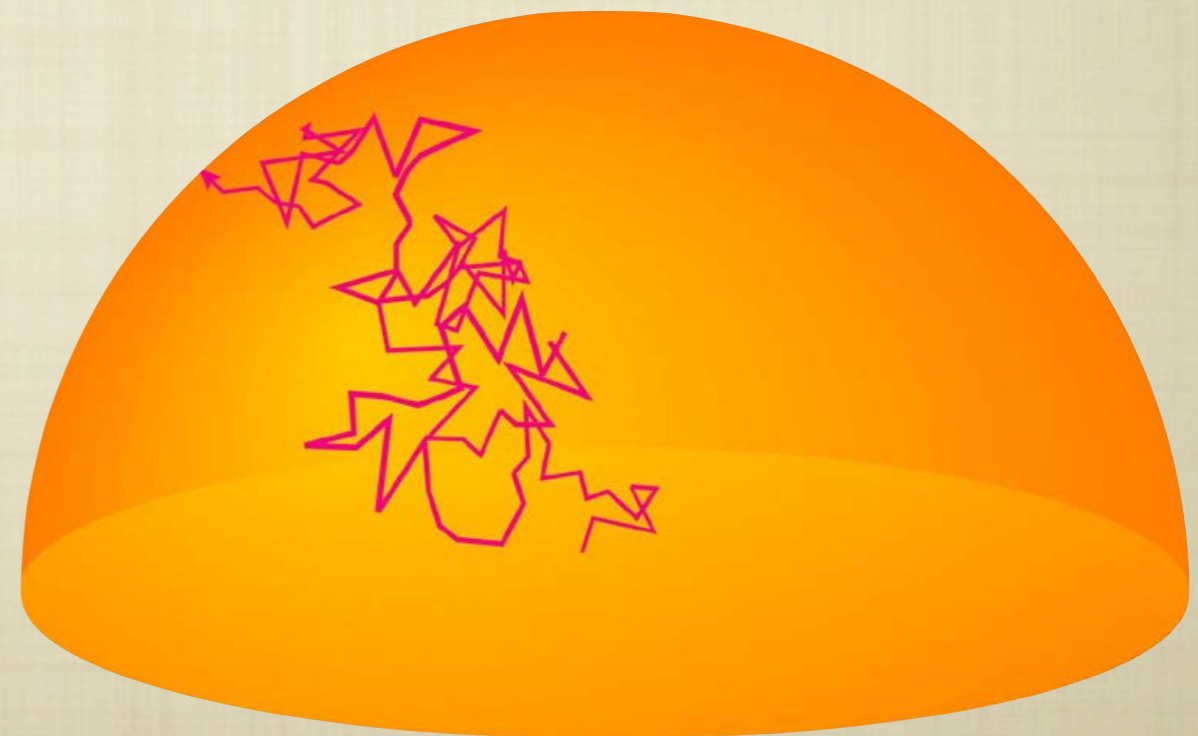
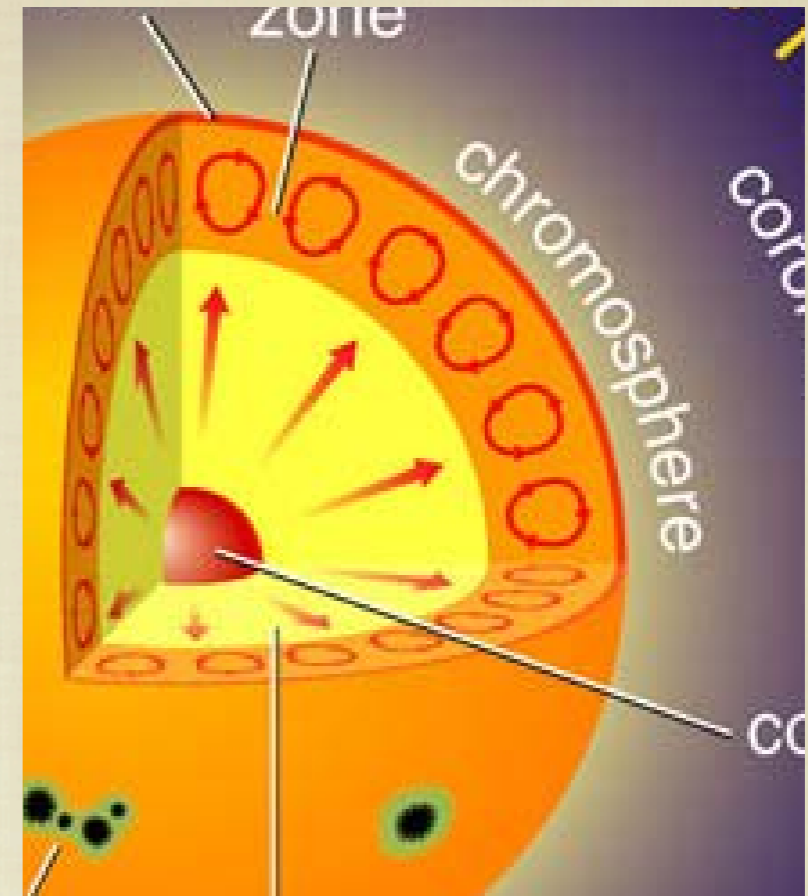
# HOW DOES ENERGY GET OUT OF THE SUN?

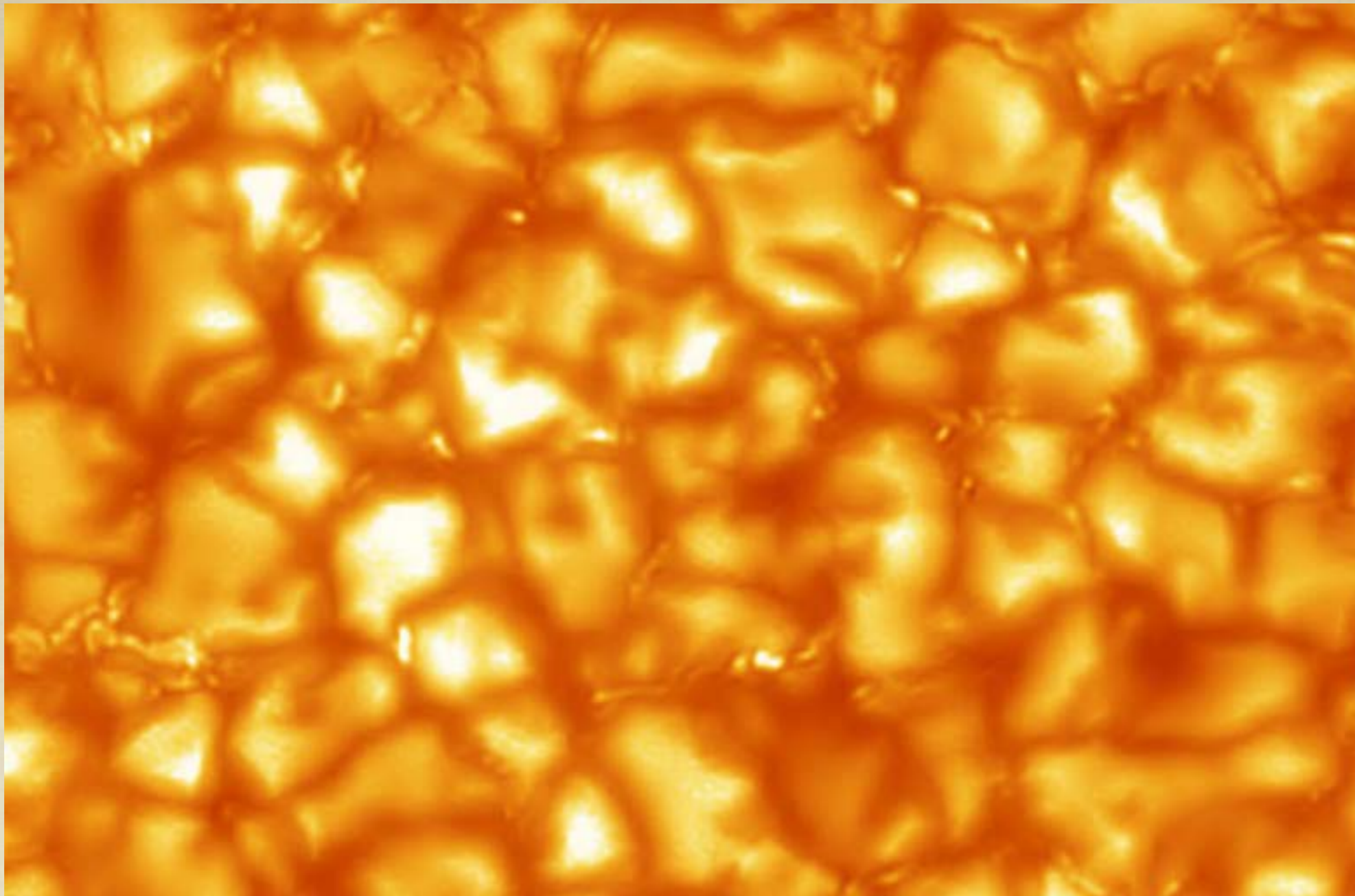
- **CONVECTION (THINK OF BOILING OATMEAL).**
- **RADIATION:  
A RANDOM WALK.**
- **TAKES A PHOTON A FEW MILLION YEARS TO REACH THE SURFACE!**



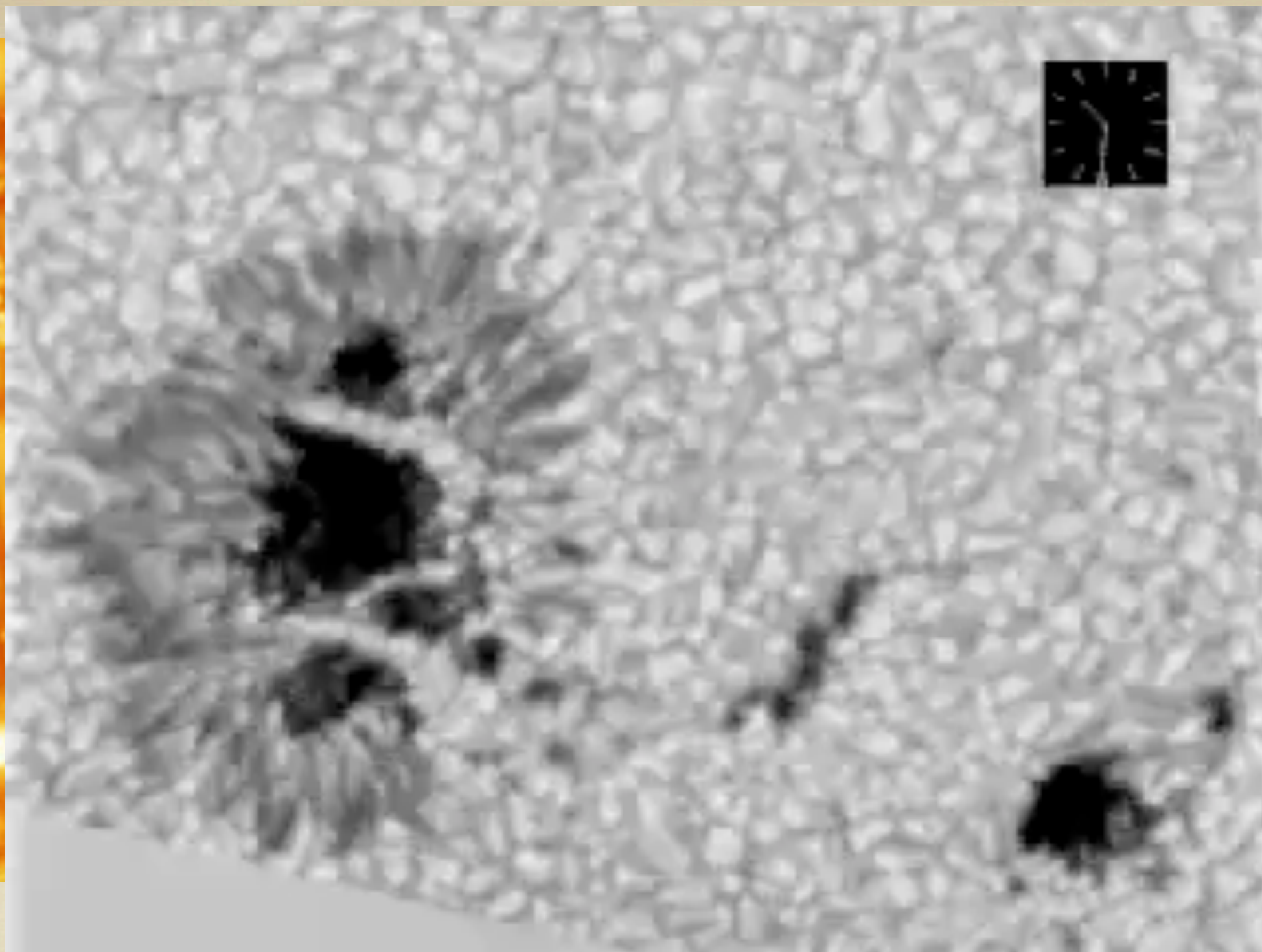
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**BRIGHT BLOBS: WHERE HOT GAS  
REACHES THE SURFACE BY CONVECTION**



**BRIGHT BLOBS: WHERE HOT GAS  
REACHES THE SURFACE BY CONVECTION**



# ATMOSPHERIC FEATURES

## ■ SUNSPOTS

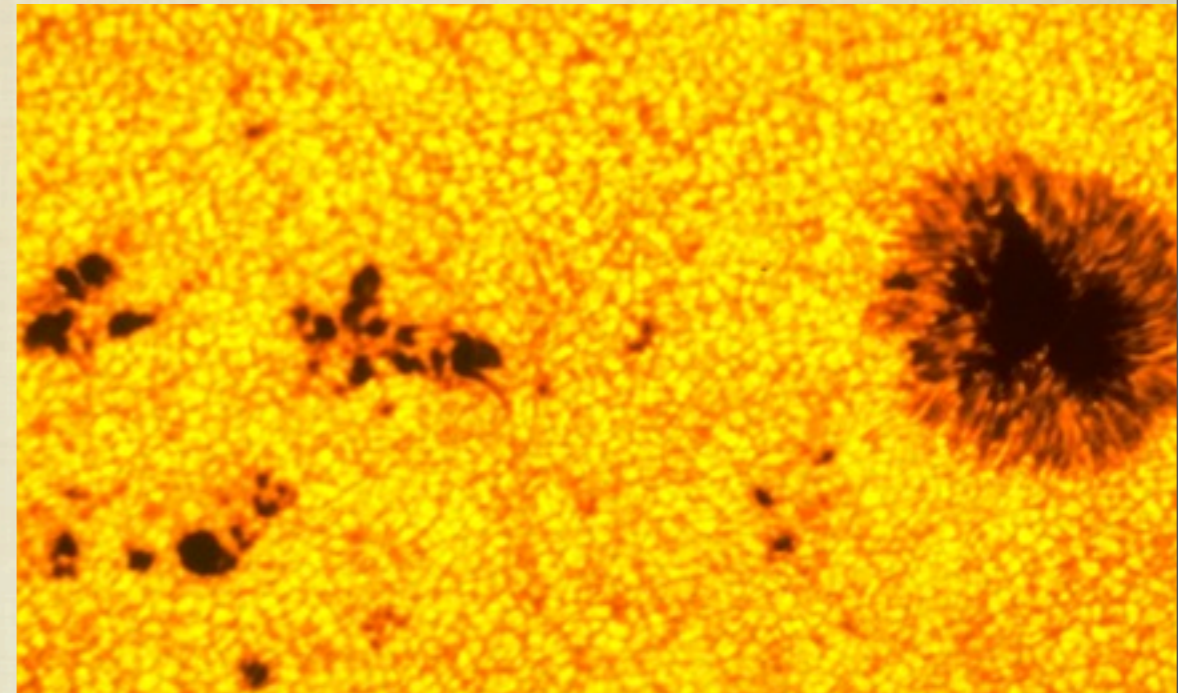
- OFTEN LARGER THAN EARTH
- OCCUR IN GROUPS
- ASSOCIATED WITH MAGNETIC FIELDS

## ■ GALILEO USED TO MEASURE SOLAR ROTATION

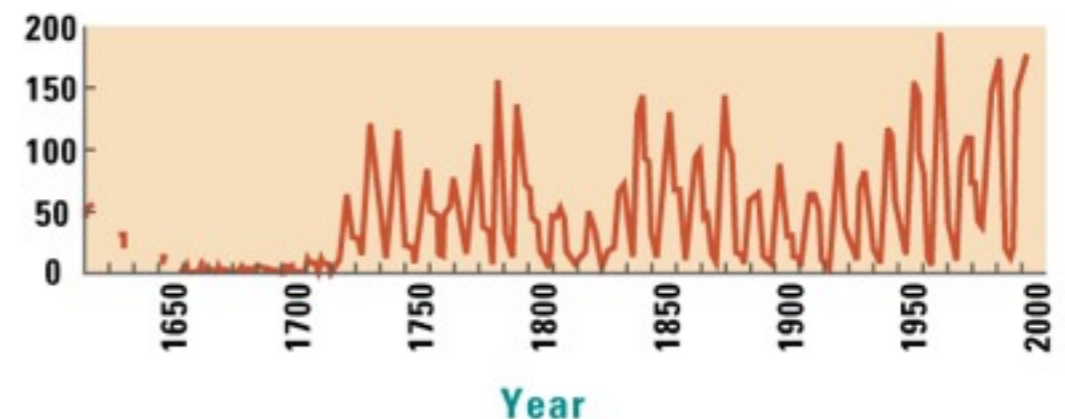
- 25 DAYS AT EQUATOR (LONGER AT POLES)

## ■ NUMBER OF SUNSPOTS IS CYCLICAL, WITH 11 YEAR PERIOD (ACTUALLY 22)

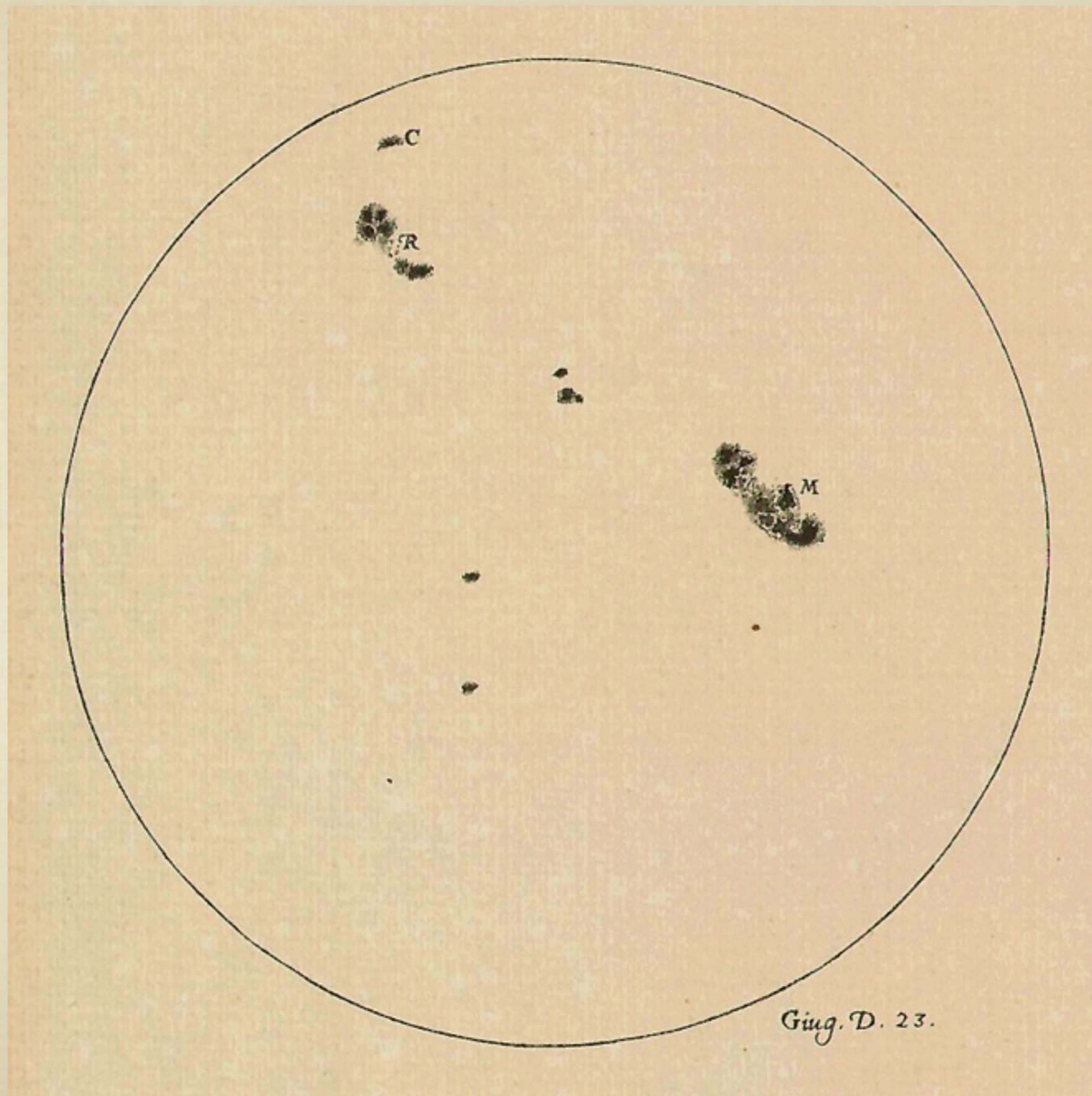
- CORRELATED WITH SOLAR ACTIVITY: GREATEST ACTIVITY AT SUNSPOT MAXIMUM, LEAST AT MINIMUM



Number of sunspots as a function of time

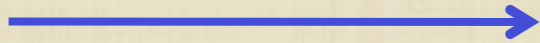


# GALILEO'S SUNSPOT DRAWINGS

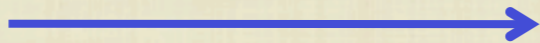


# SOLAR ROTATION

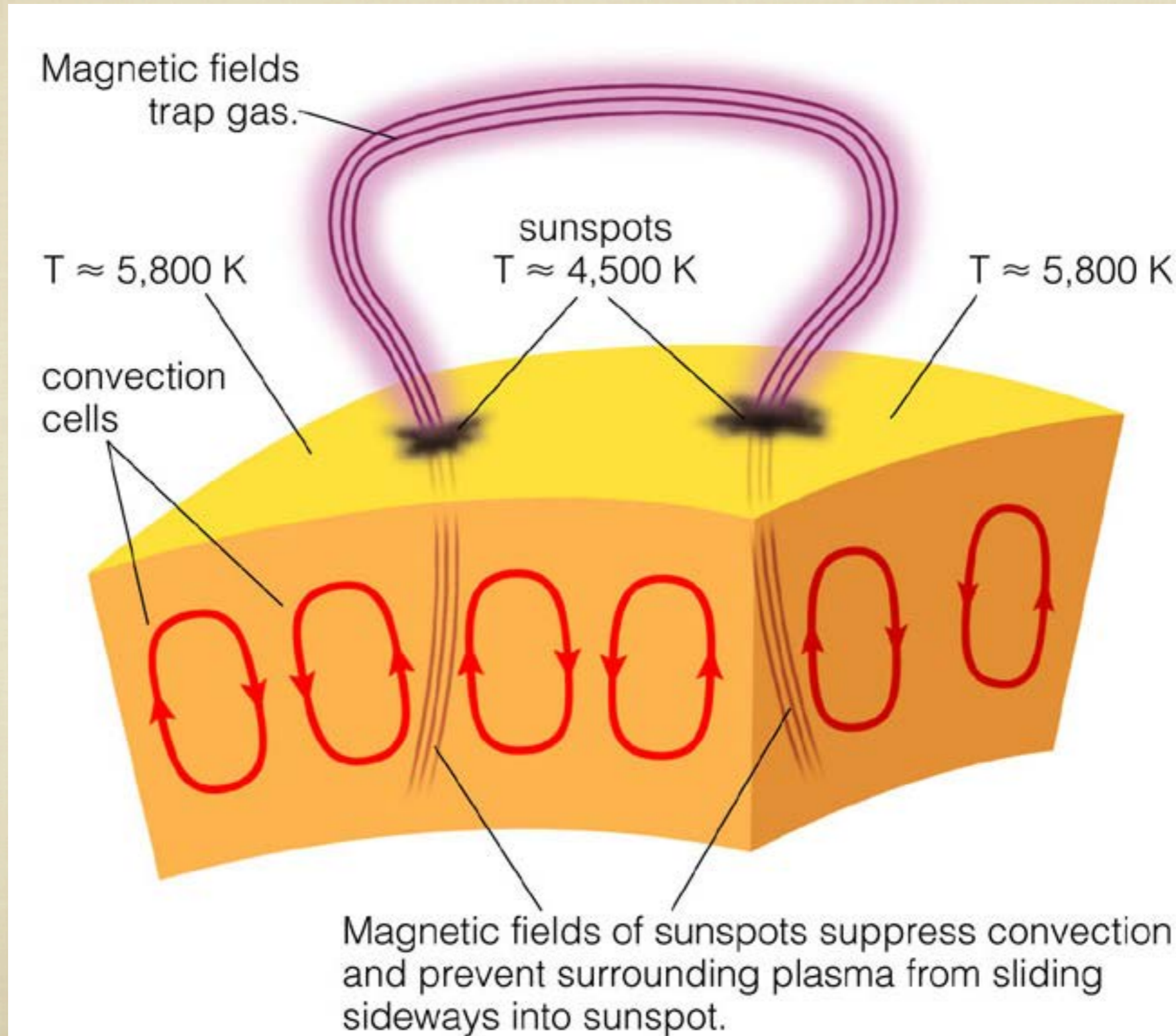
**SLOWER  
AT  
POLES**



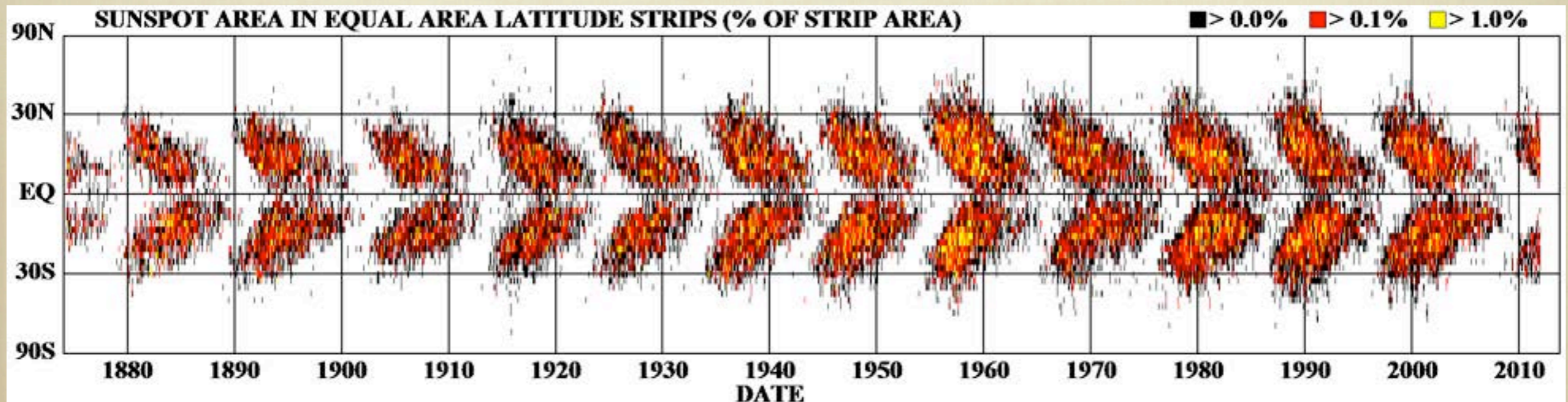
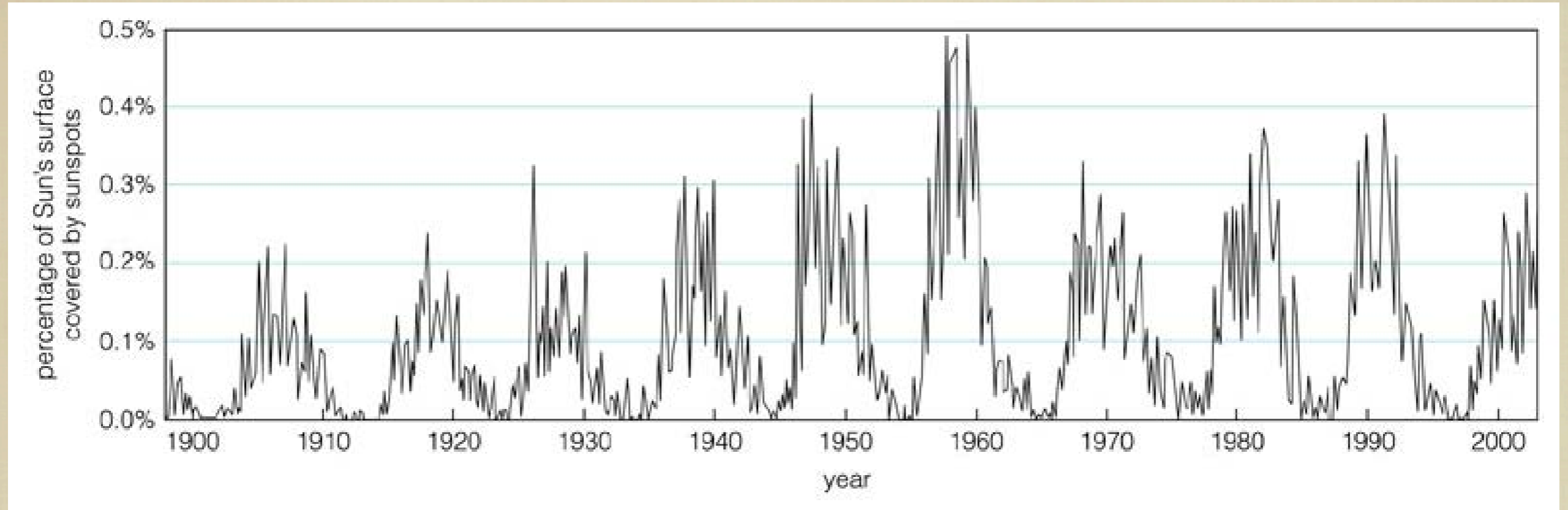
**FASTEST  
AT  
EQUATOR**



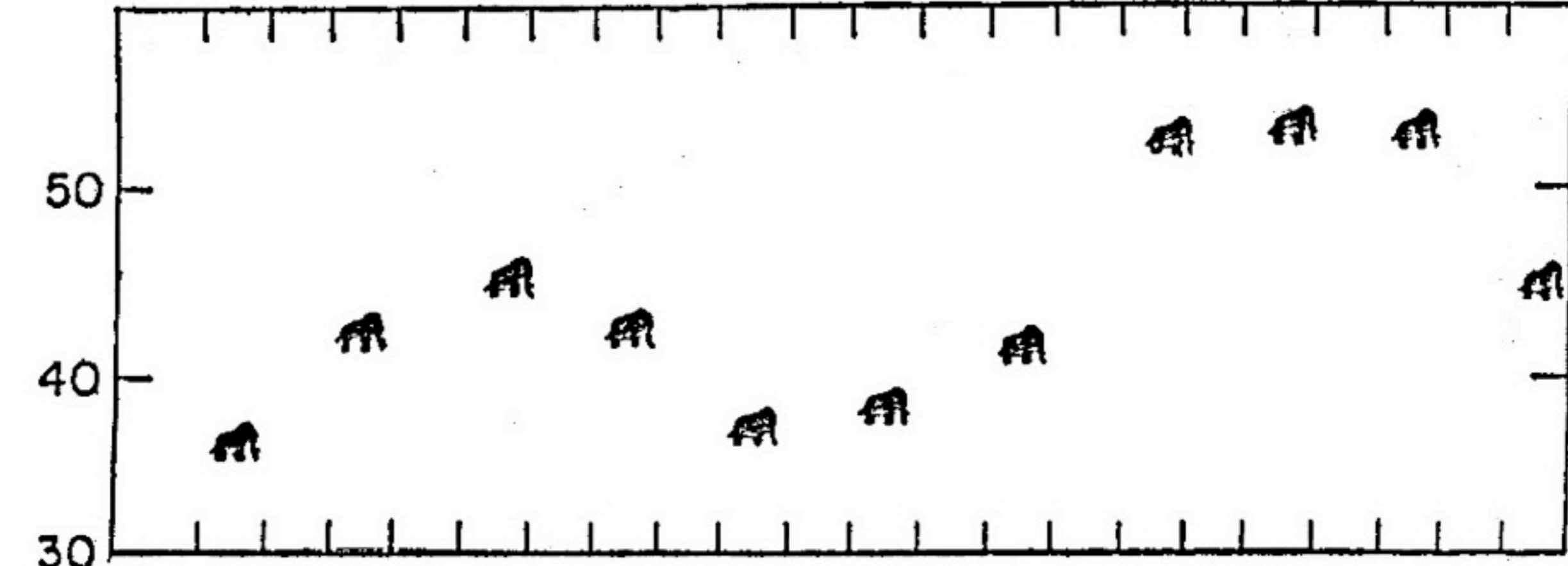
# MAGNETIC FIELDS



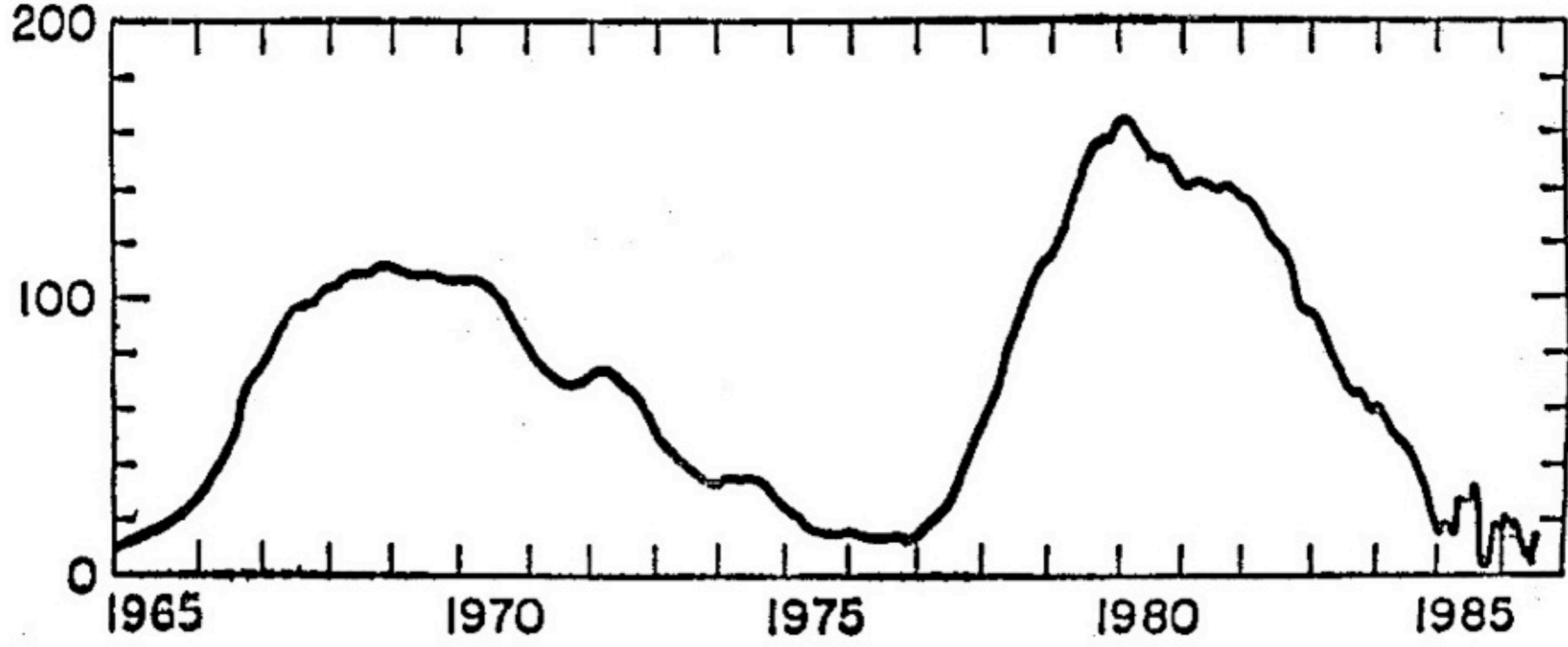
# SUNSPOT CYCLE



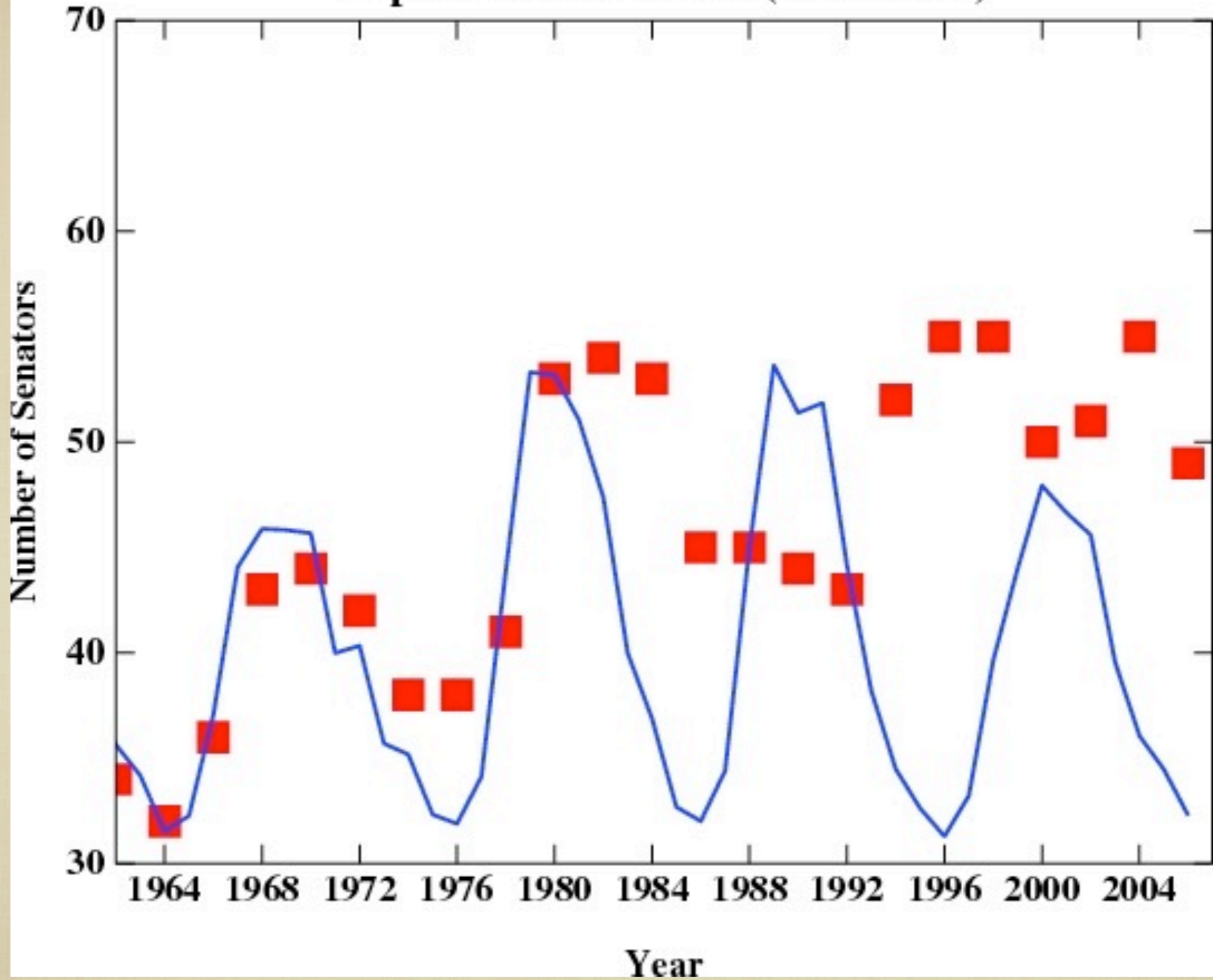
NUMBER OF REPUBLICANS  
IN U.S. SENATE



SUNSPOT NUMBER



# Republicans in Senate (Since 1959)



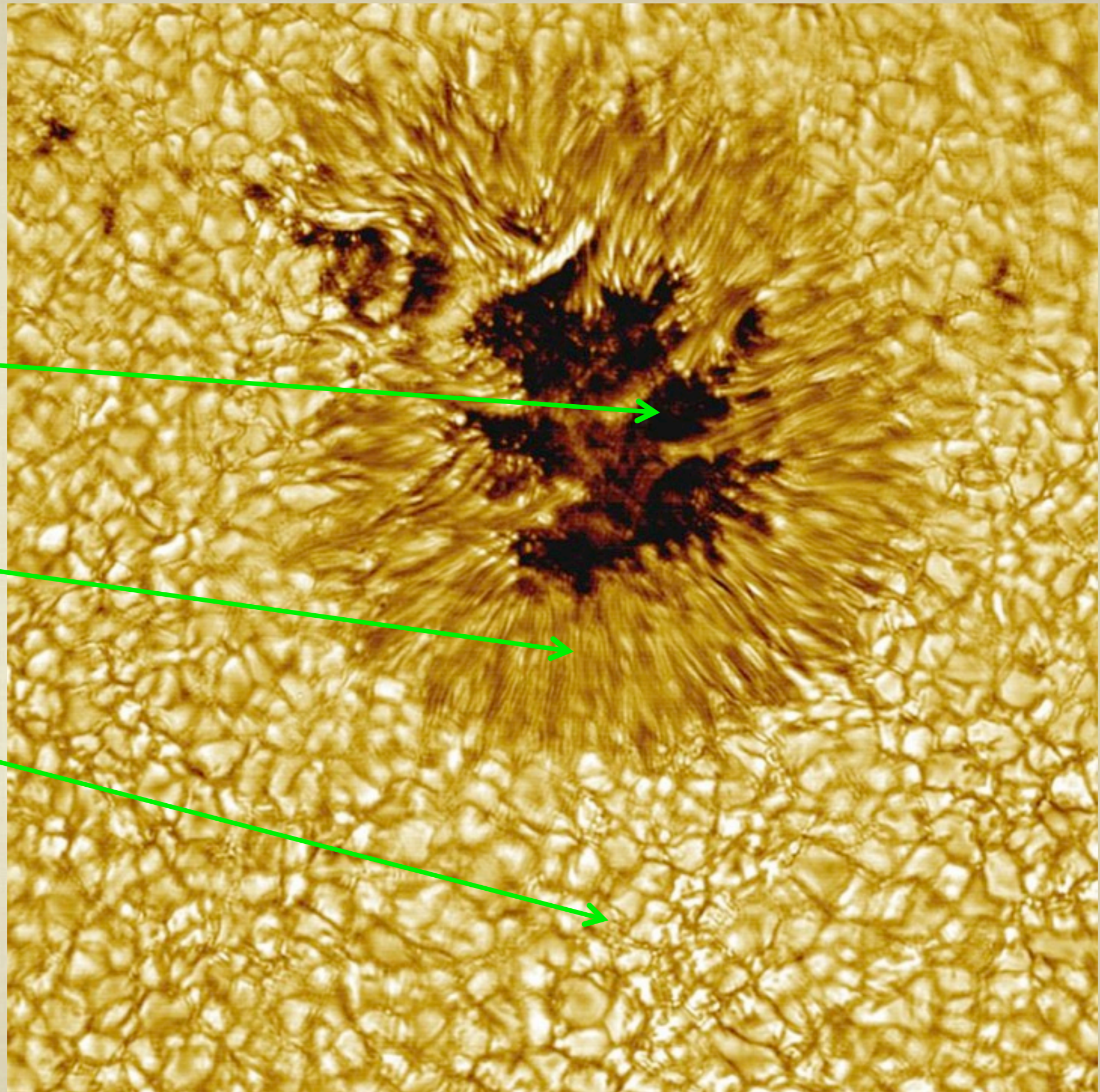
**SUNSPOT +  
GRANULATION**

**UMBRA  
(T ~ 3900K)**

**PENUMBRA**

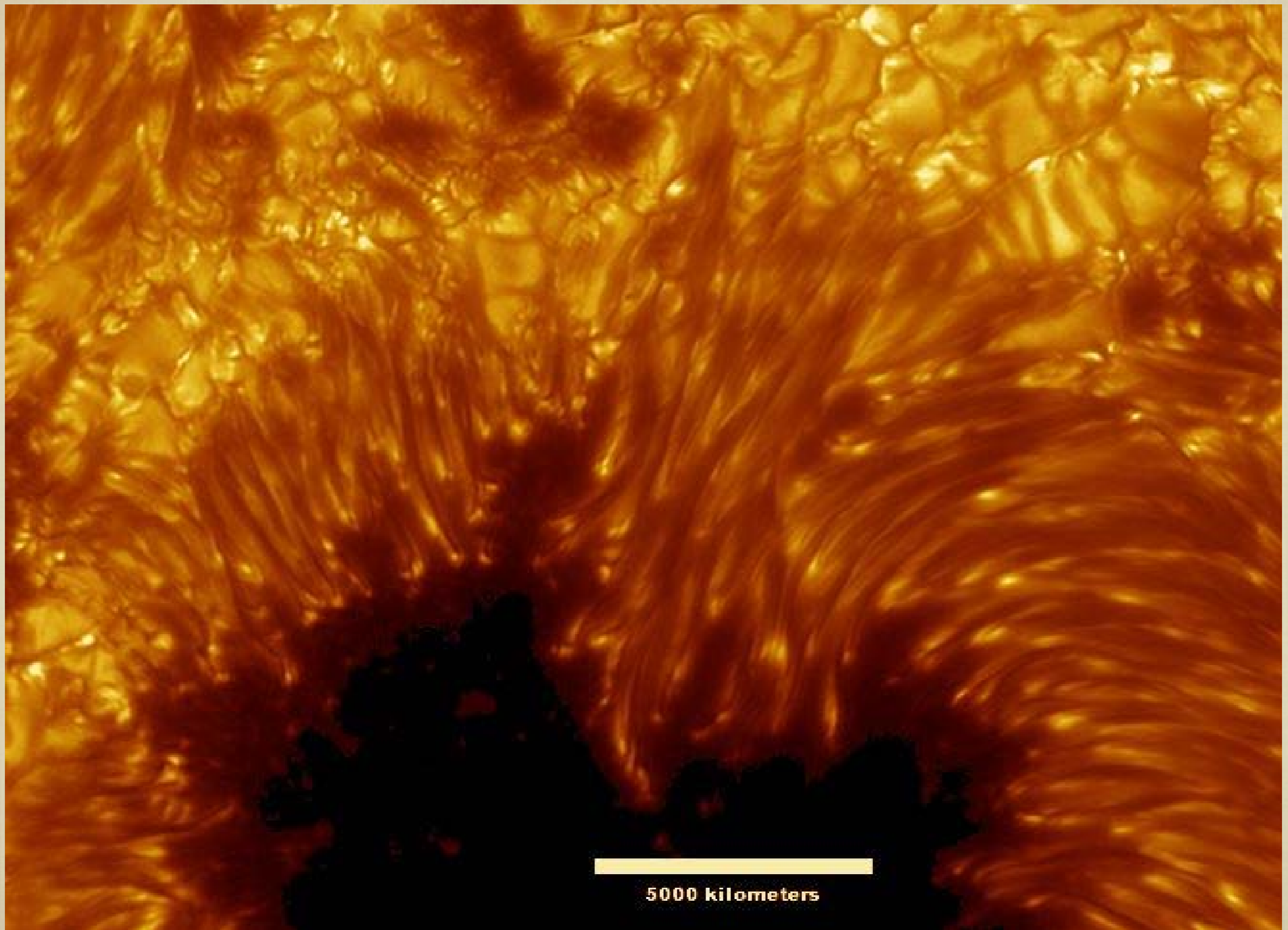
**PHOTOSPHERE  
(T ~ 5770K)**

**NOAO/NSO**





# MOST DETAILED SUNSPOT IMAGE EVER!



SWEDISH VACUUM TELESCOPE

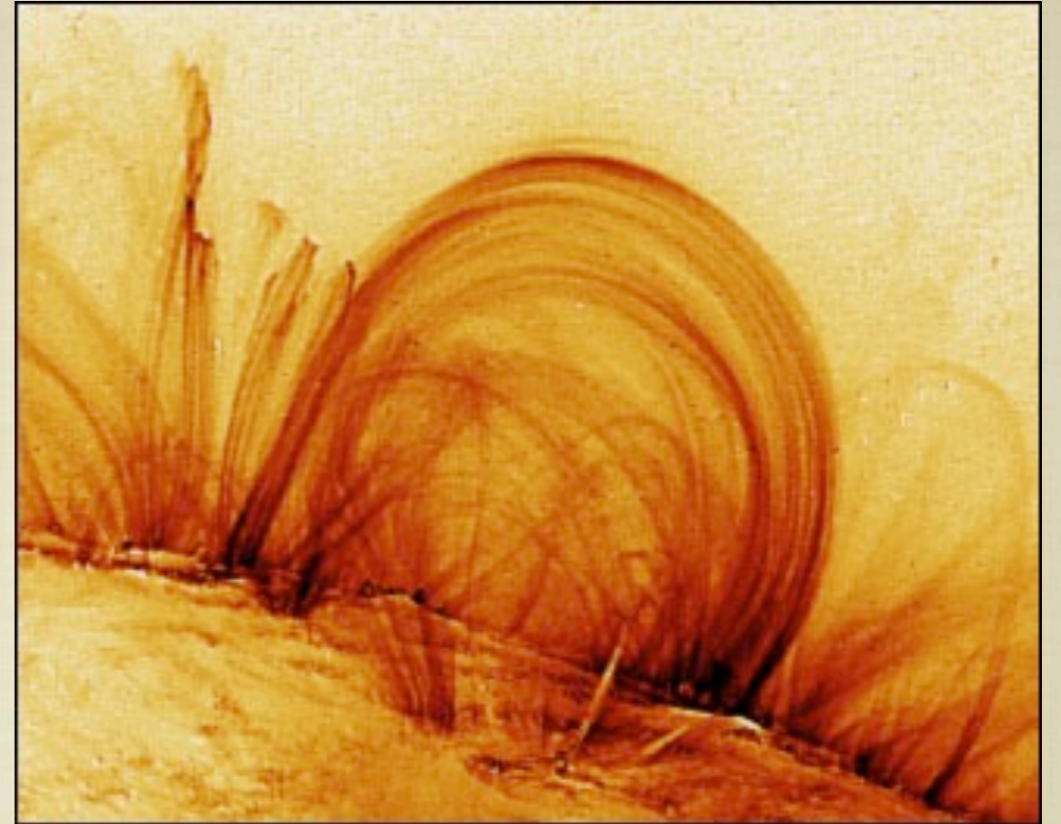
# ATMOSPHERIC FEATURES

- **PROMINENCES**

- **LOOPS OF HOT GAS**

- **BASE NEAR  
SUNSPOTS**

- **TRACE MAGNETIC  
FIELDS**



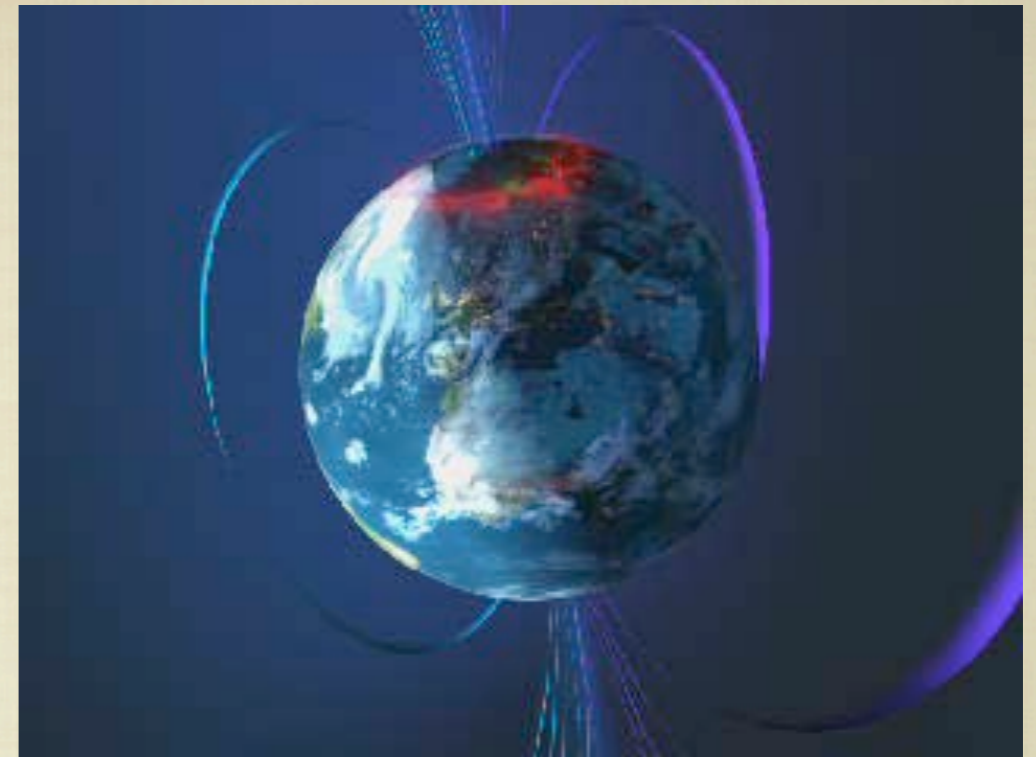
Earth shown  
for size comparison



**IMAGE CREDIT:  
NASA/SOHO**

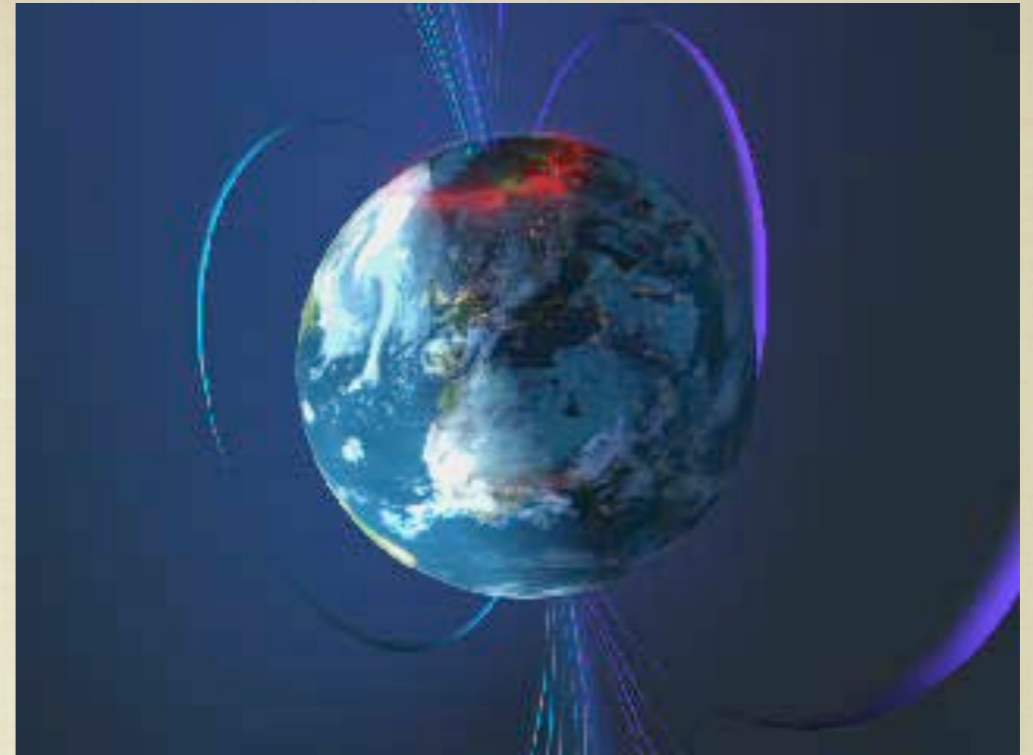
# SOLAR WIND

- 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



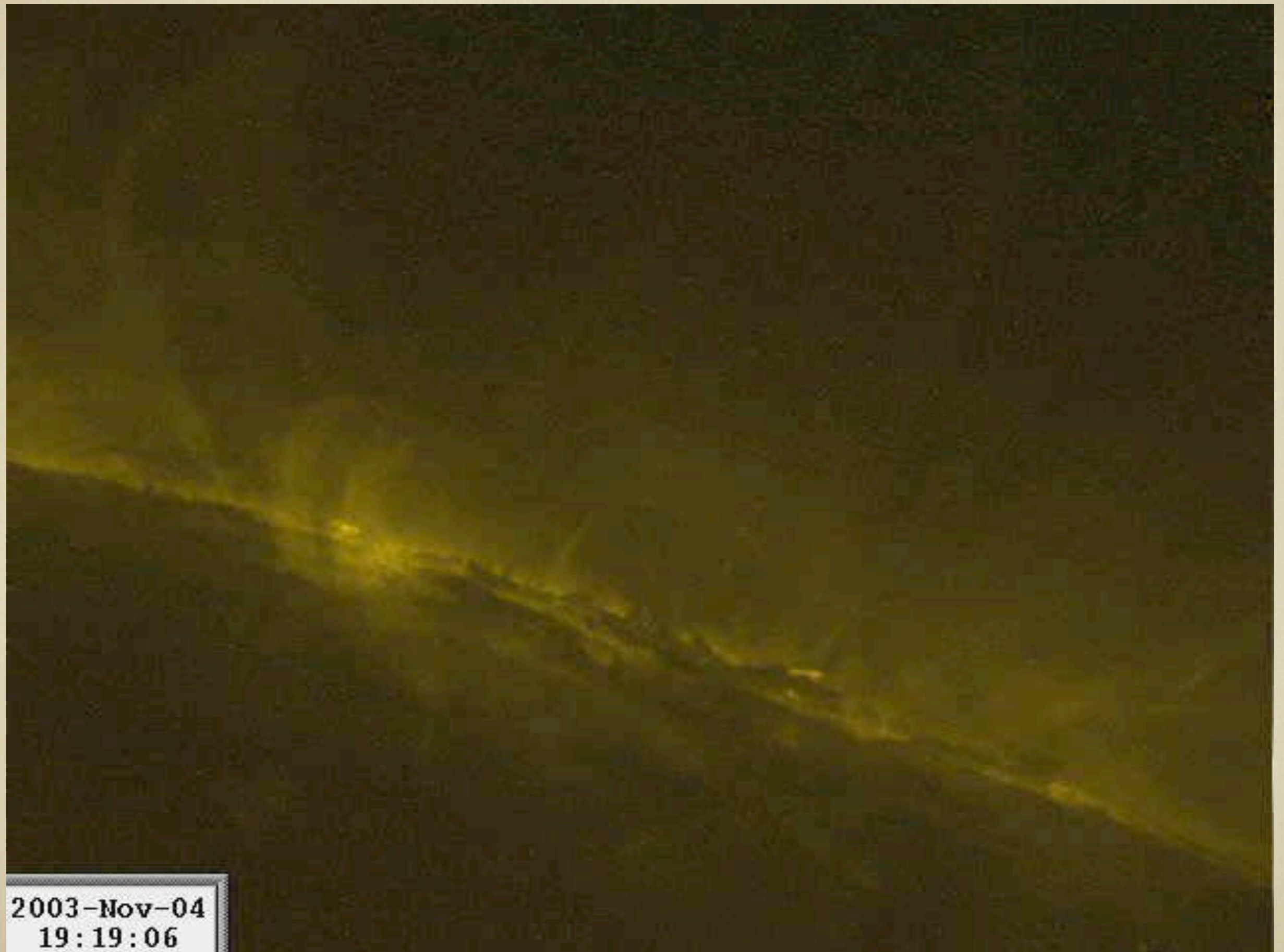
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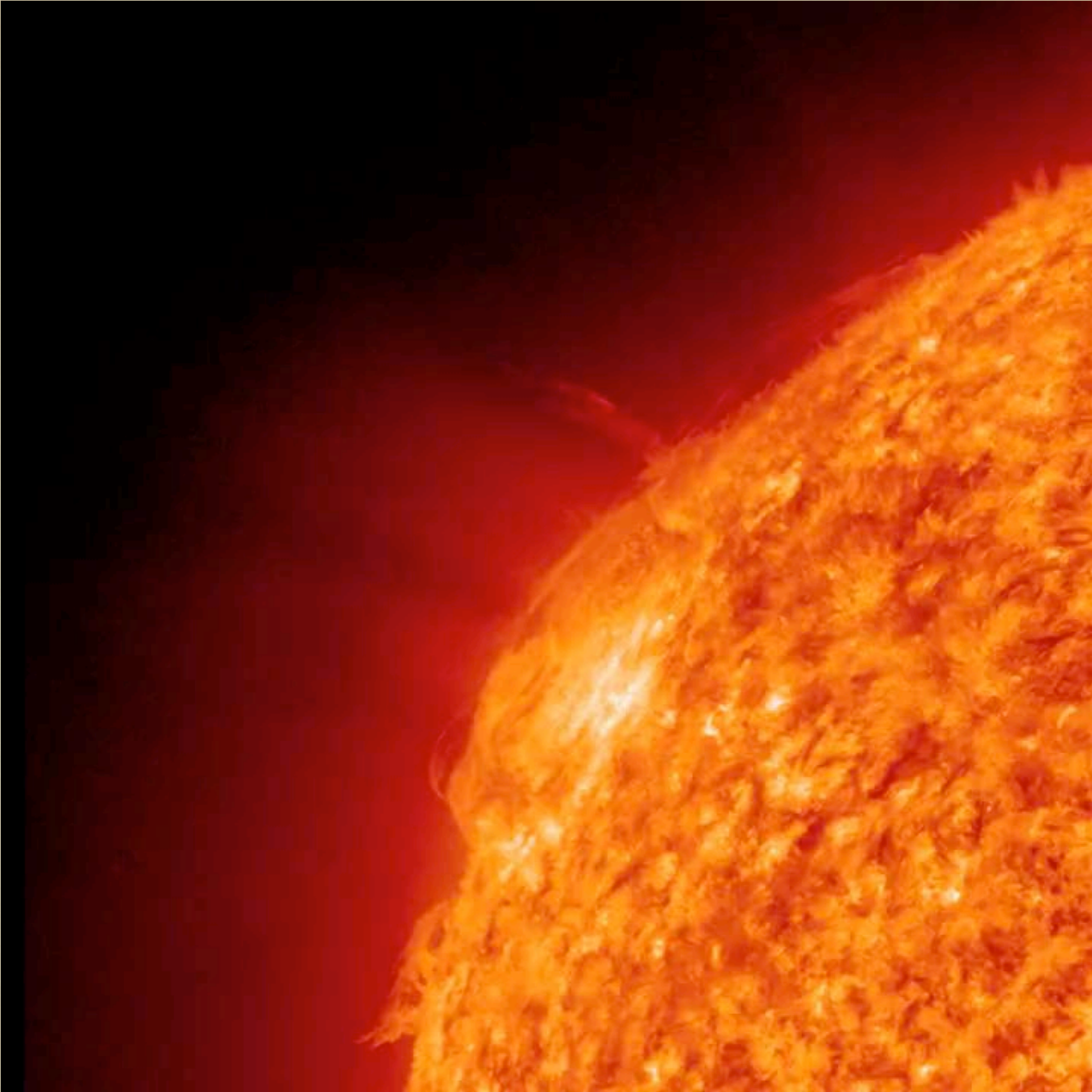


# SOLAR FLARE

IMAGE CREDIT:  
NASA/TRACE

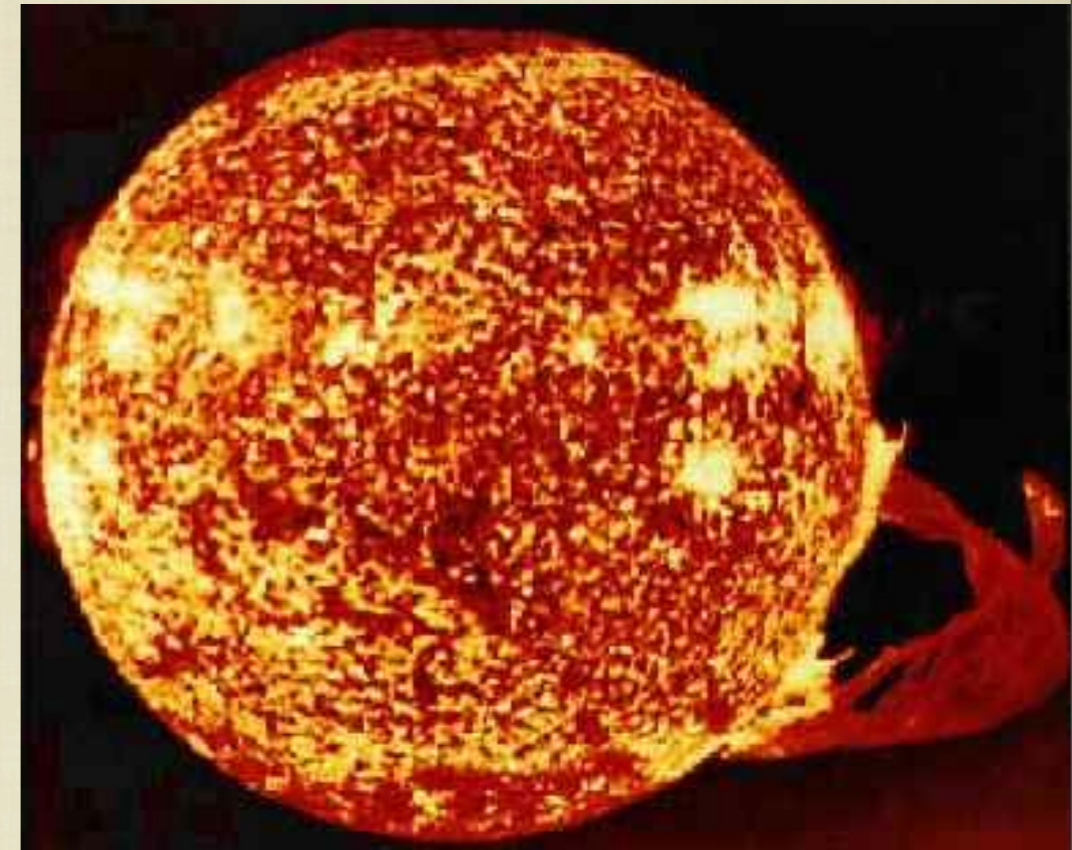


2003-Nov-04  
19:19:06

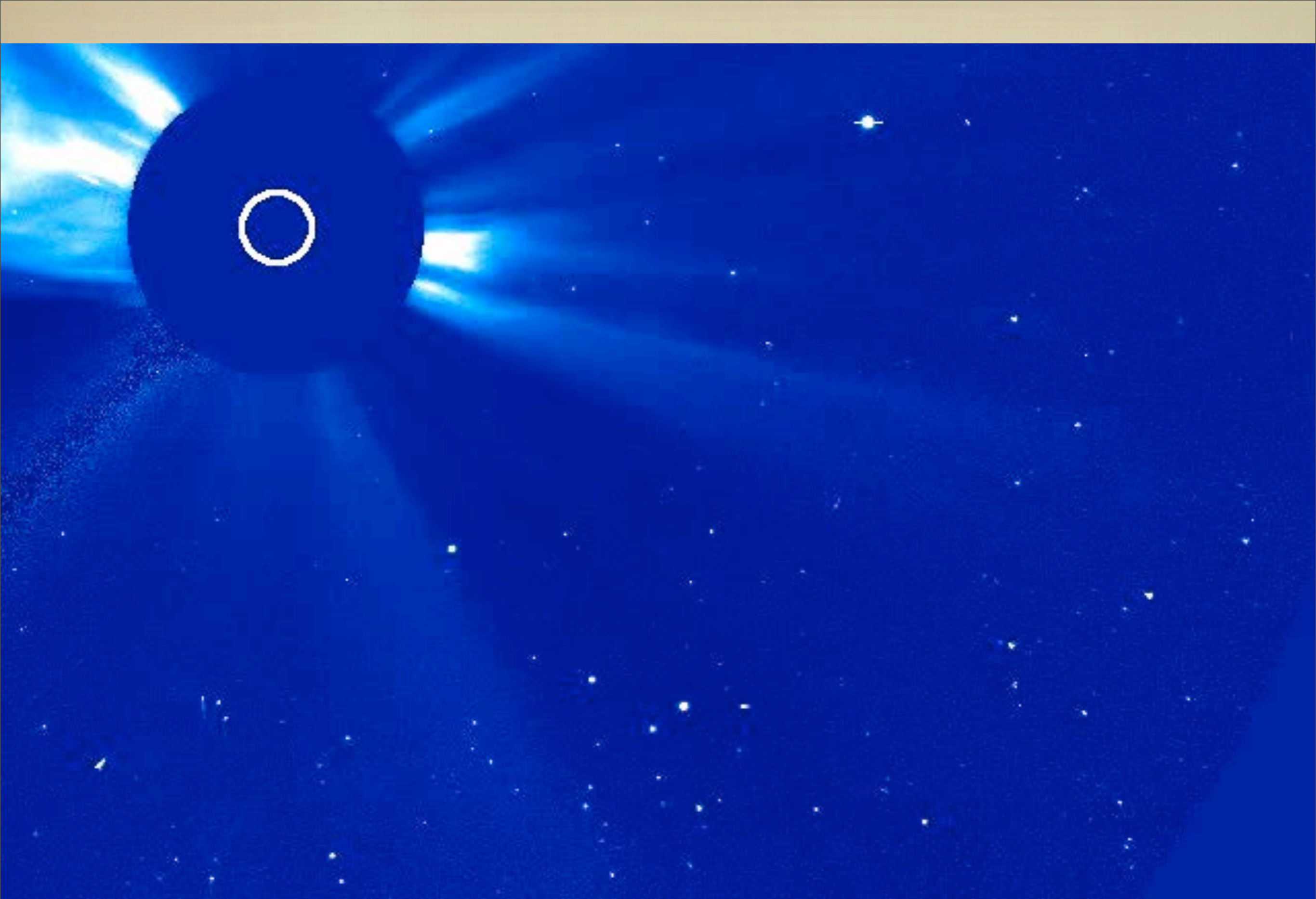


# SOLAR FLARES

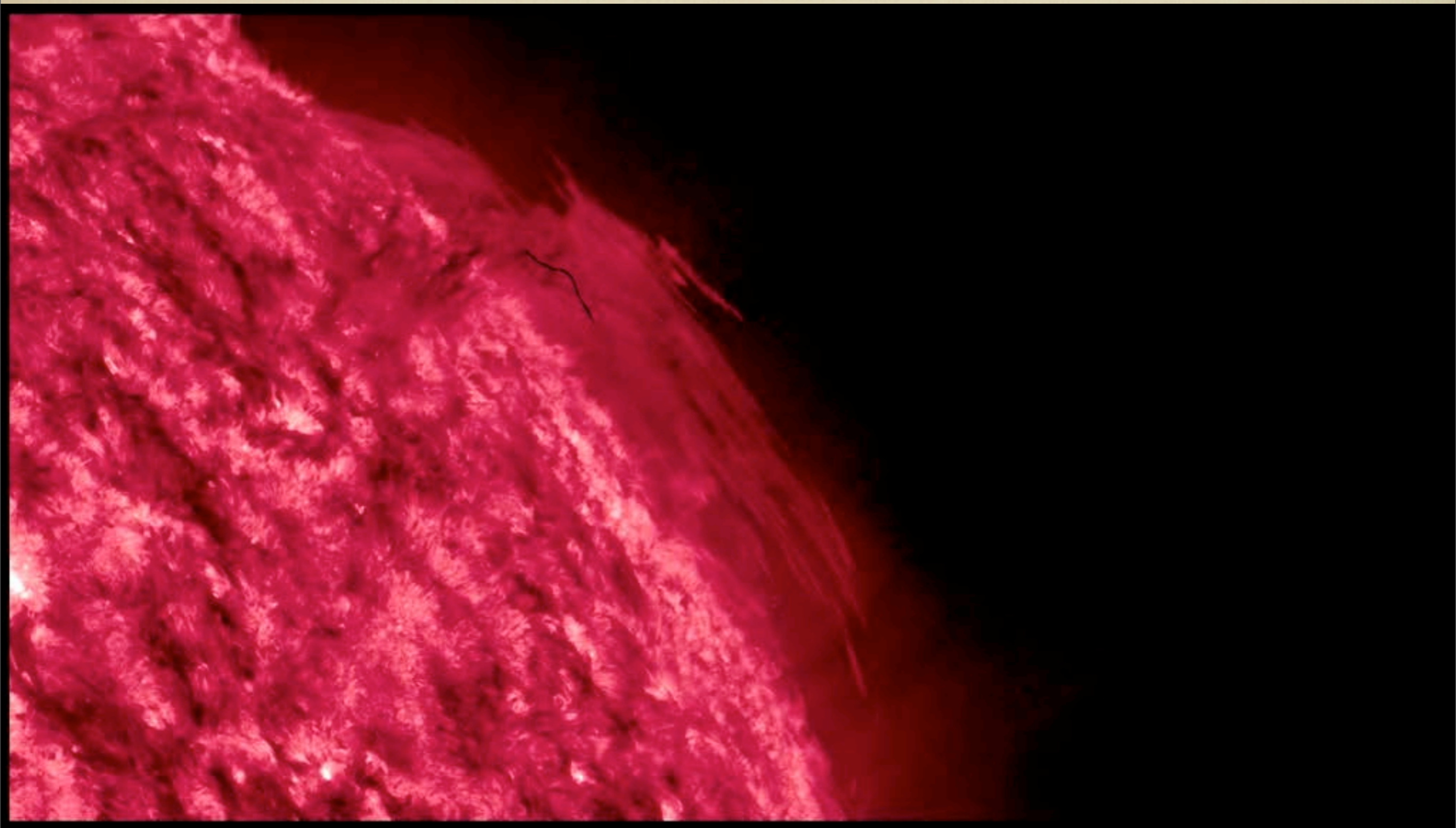
- **ERUPTIONS CAUSED BY MAGNETIC FIELDS**
  - MAY LAST 5-10 MIN
  - RELEASE HUGE AMOUNTS OF ENERGY
    - GAS HEATED TO  $10^7$  K, PRODUCES X-RAYS AND UV RADIATION
- **CORONAL MASS EJECTIONS**
  - VERY LARGE FLARES
  - LARGE MASS OF GAS EJECTED FROM CORONA







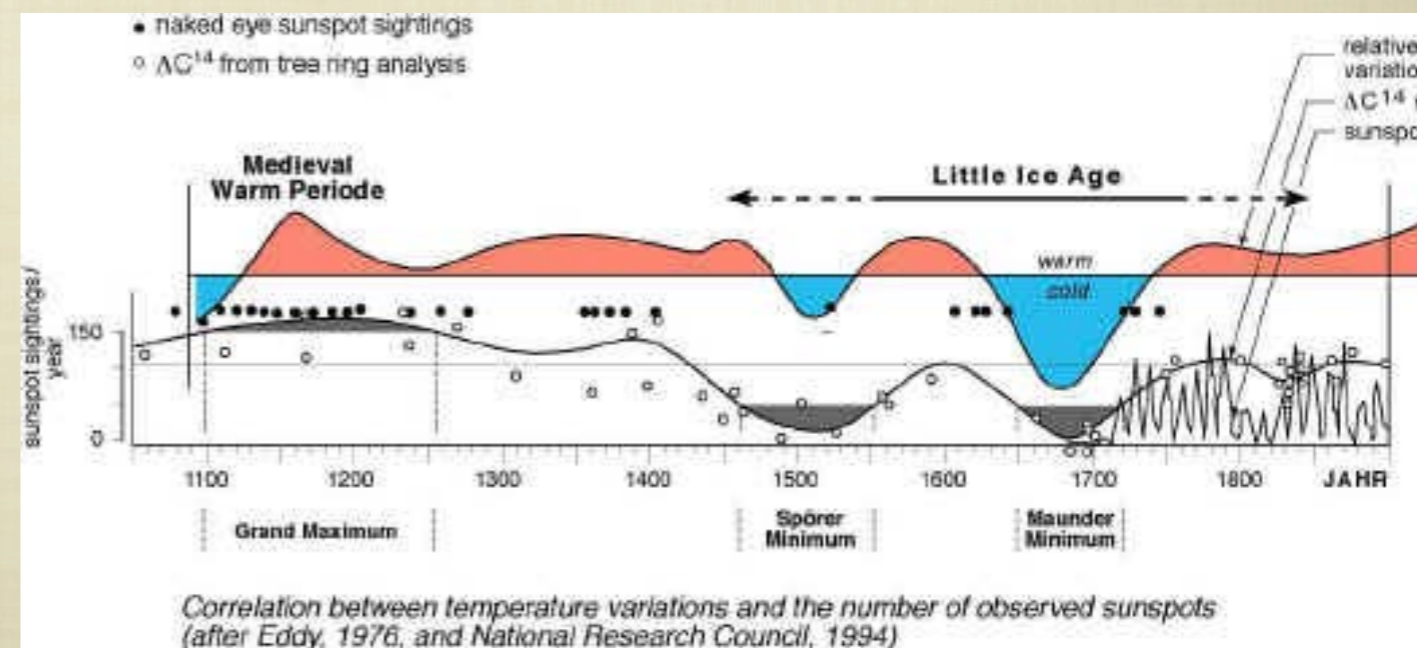
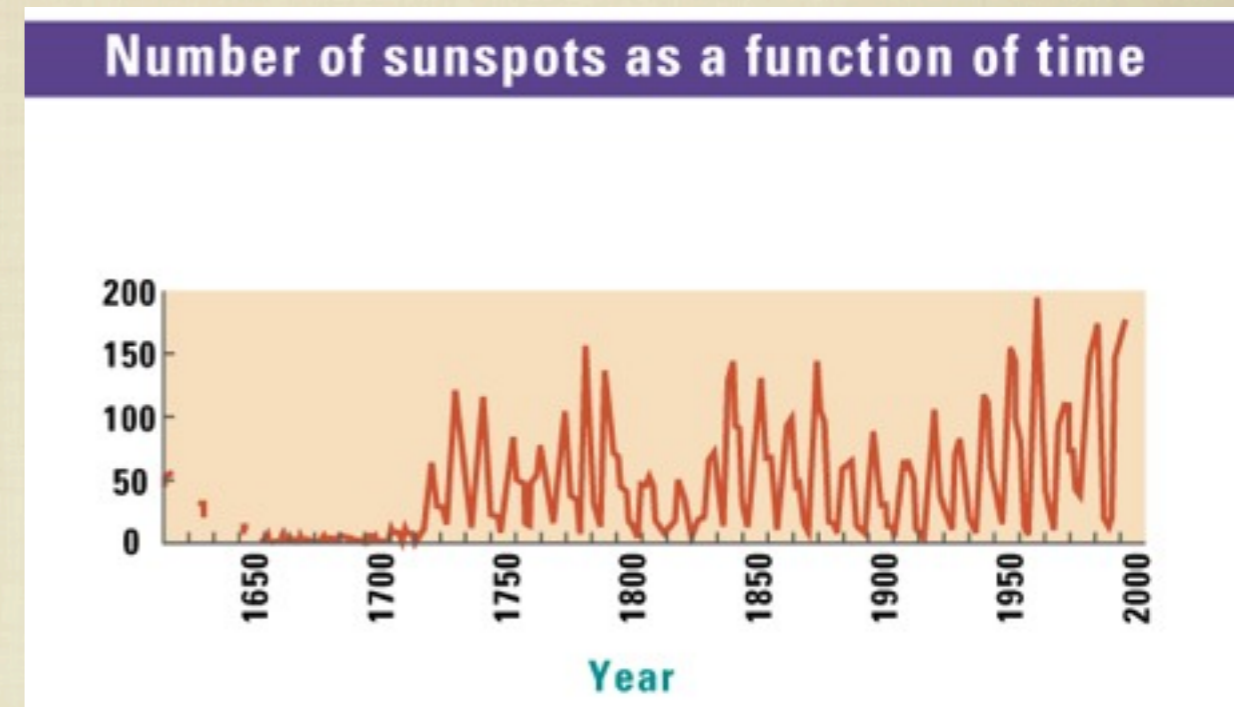
**IMAGE CREDIT:  
NASA/SOHO**

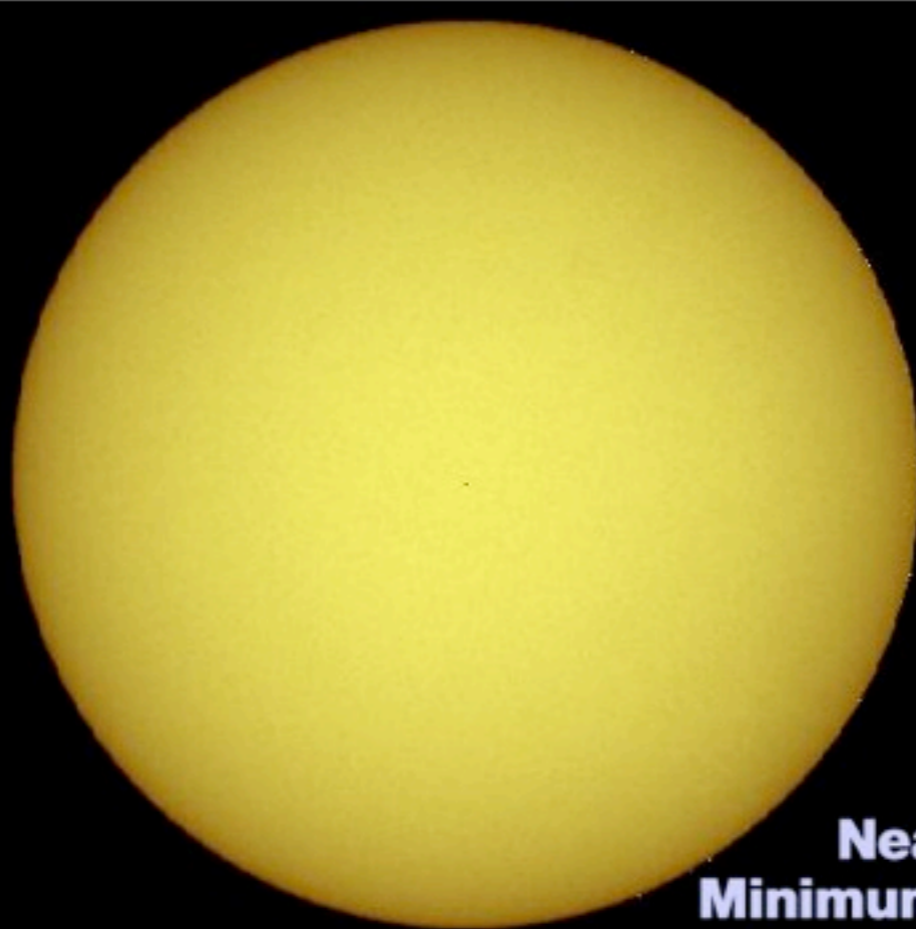


SOLAR DYNAMICS OBSERVATORY

# 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

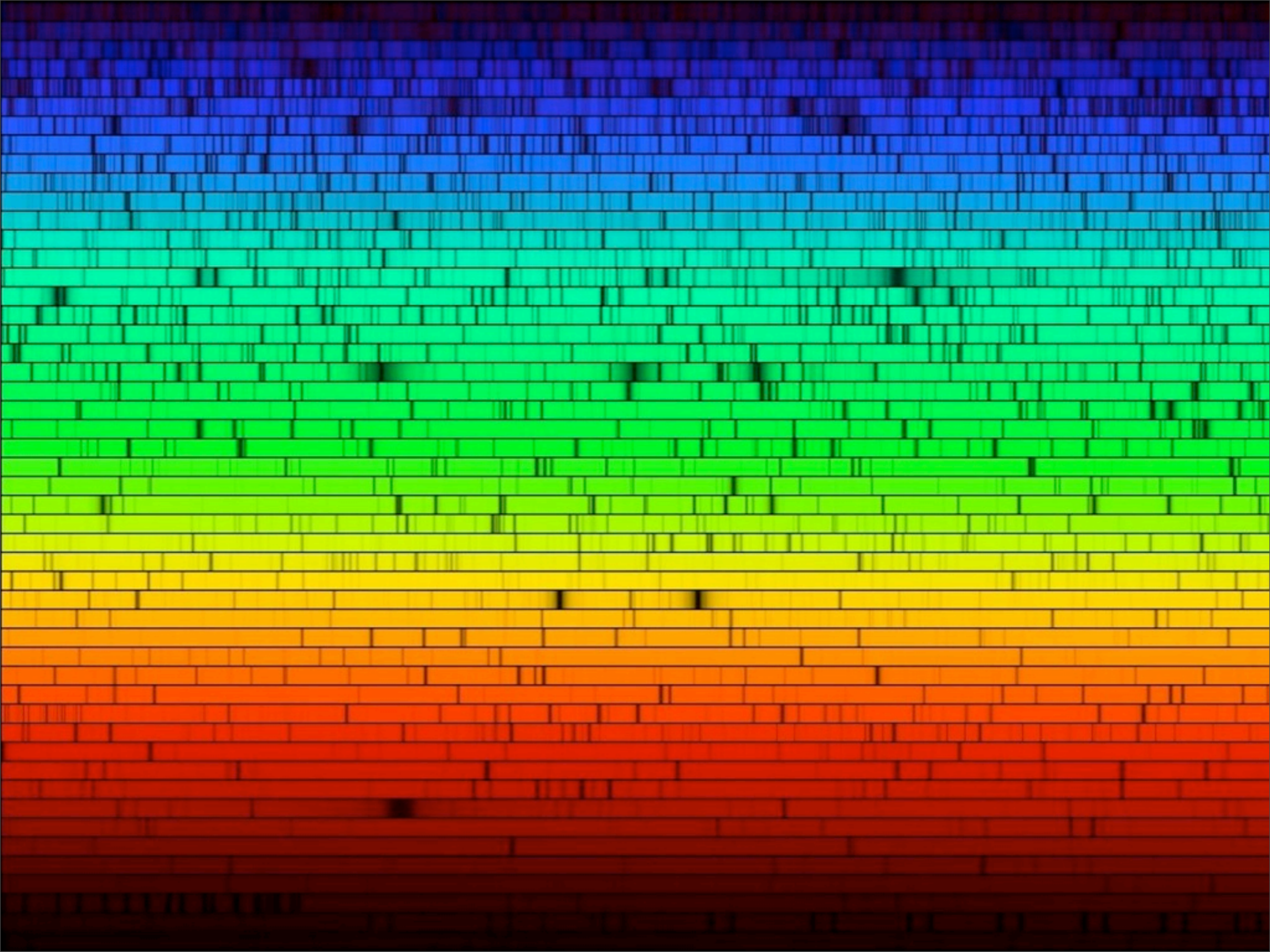




**Near  
Minimum,  
Sept. 30, 1996**

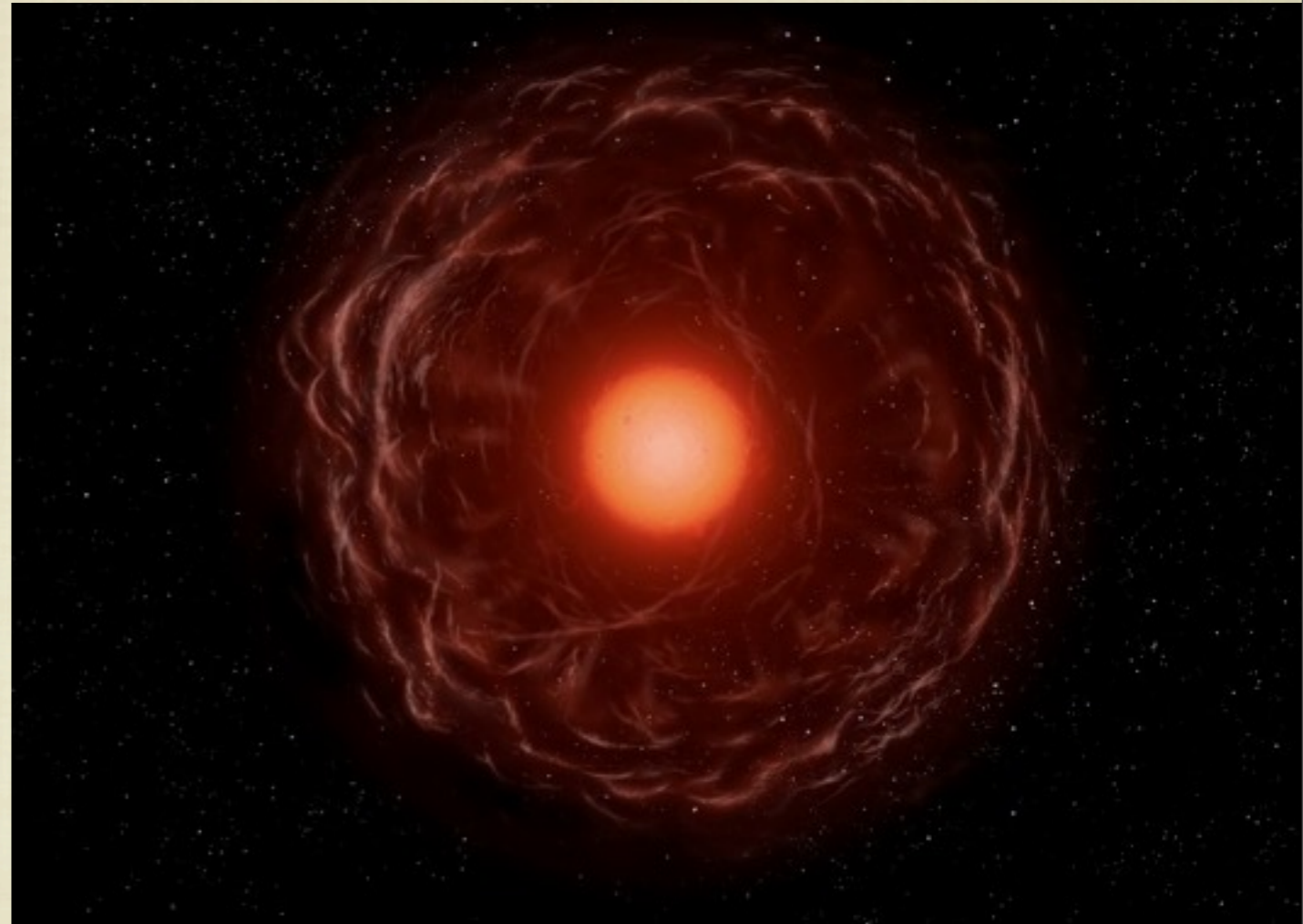


**Near  
Maximum,  
Nov. 11, 1999**



# 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

