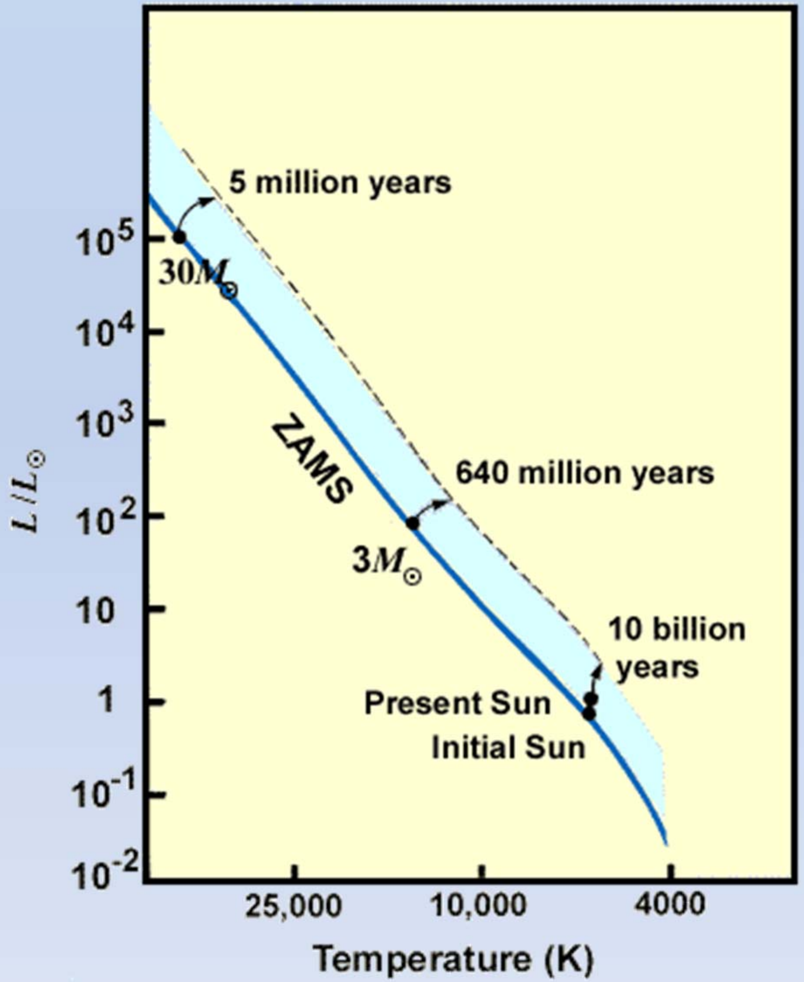
Chapter 8

Structure of stars

Structure of stars

8.1 The main sequence

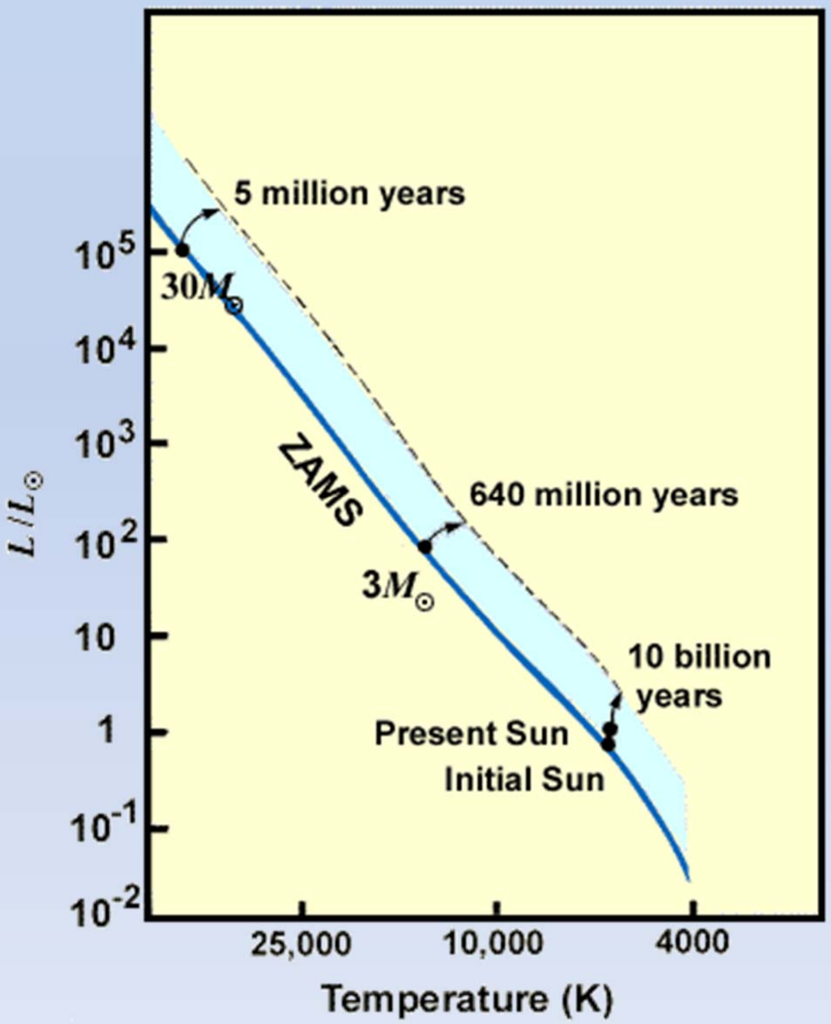
- ✓ Nuclear fusion ignites at core, radiation and gas pressures balance gravity, hence stop contraction.
- ✓ Now settle on the Zero Age Main Sequence (ZAMS)
- ✓ Stars spend ~ 90% of their lifetimes on the main sequence



8.1 The main sequence

- ✓ Nuclear fusion at the core, e.g., $4\,{}^{1}H \rightarrow He$. No. of particles drops → core pressure decreases → the stellar core shrinks.
- ✓ Core contraction → the core is heated up and hence nuclear fusion rate ↑ and release more energy. As a result, the stars becomes more **luminous**.
- ✓ Higher pushing-out radiation pressure causes the star's outer layers to expand, hence star's radius ↑ and star's outer layers become **cooler**.

8.1 The main sequence



In conclusion,

- ✓ as a main-sequence star ages and evolves, it moves to the upper-right direction across the main sequence.
- ✓ Star's core shrinks and becomes hotter; outer layers expand and becomes cooler.

8.2 Physics of stars

The Virial Theorem

Time average

$$\boxed{2\langle K\rangle = -\langle U\rangle}$$

An equilibrium condition for a gravitationally bound or periodic system. Apply to a wide ranges of system, e.g., ideal gas, a static star, a cluster of galaxies.

8.2 Physics of stars

- ✓ Application: Suppose a gas cloud is contracting so slowly that the virial theorem $2K + U = 0$ is still valid.
- ✓ While contracting, some potential energy is converted to kinetic energy. Mathematically, U takes more negative (i.e. its magnitude increases), so $K = -U/2$ increases and hence the gas heats up.
- ✓ But the total energy, $E = K + U = U/2$, decreases, therefore energy is lost.
- ✓ Conclusion: The cloud radiates EM radiations and heat up when it is contracted.

Given that the gravitational potential energy of a uniform sphere is $U = -\frac{3}{5}\frac{GM^2}{R}$. Applying the virial theorem, the total energy is $E = -\frac{3}{10}\frac{GM^2}{R}$.

Suppose that the Sun was formed by a contracting spherical nebula and that the radius of the nebula is much larger than that of the Sun and hence the gravitational potential energy. Then, the energy radiated away during the collapse of the nebula would be $\Delta E = E_i - E_f \approx -E_f = \frac{3}{10}\frac{GM^2}{R} = 1.1 \times 10^{41}$ J
Further assume that the solar luminosity is constant, $L = 3.8\times10^{26}$ W. it could emit at that rate for approximately $t_{KH} = \frac{\Delta E}{L} \sim 10^7$ years.

the Kelvin-Helmholtz timescale

According to radiative dating techniques, Moon's rock ~ 4×10^9 years.

That means, $\underbrace{\text{age of Moon > age of Sun.}}_{\text{unlikely}}$

所以，根据以上的分析，单单用重力势能不能解释星体的年龄。

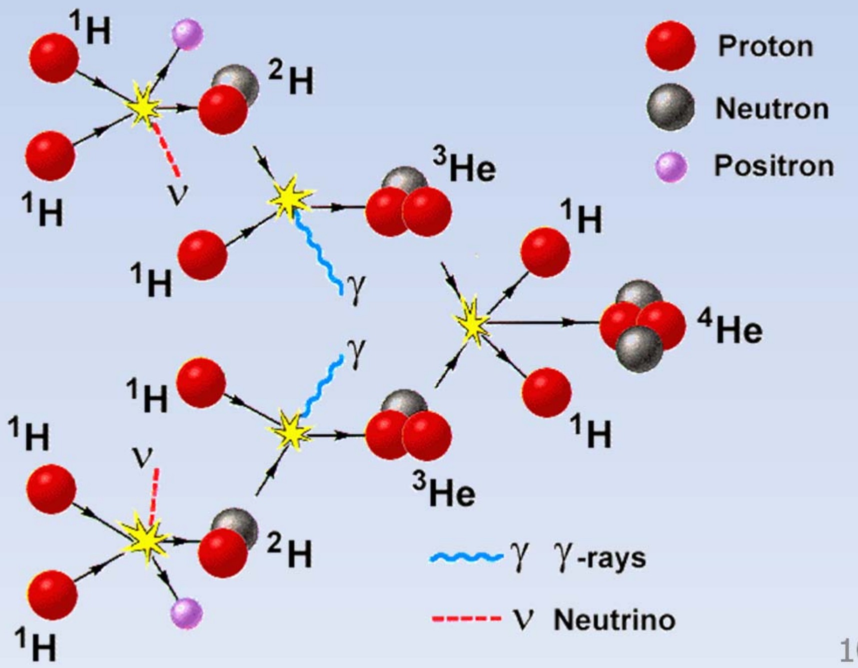
gravitational potential energy alone cannot account for the Sun's luminosity throughout its entire lifetime. Calling for another energy source.

8.2 Physics of stars

Nuclear fusion

Proton-proton chain (pp chain):

$$4\ {}^{1}\mathrm{H} \rightarrow {}^{2}\mathrm{He} + 2\, e^{+} + 2\, \nu_{e} + 2\, \gamma$$



The three branches of the pp chain, along with the branching ratios appropriate for conditions in the core of the Sun. (Adopt from Bradley, p.310)

$${}^{1}_{1}\mathrm{H} + {}^{1}_{1}\mathrm{H} \rightarrow {}^{2}_{1}\mathrm{H} + e^{+} + \nu_e$$

$${}^{2}_{1}\mathrm{H} + {}^{1}_{1}\mathrm{H} \rightarrow {}^{3}_{2}\mathrm{He} + \gamma$$

69%

$${}^{3}_{2}\mathrm{He} + {}^{3}_{2}\mathrm{He} \rightarrow {}^{4}_{2}\mathrm{He} + 2\,{}^{1}_{1}\mathrm{H}$$

(PP I)

31%

$${}^{3}_{2}\mathrm{He} + {}^{4}_{2}\mathrm{He} \rightarrow {}^{7}_{4}\mathrm{Be} + \gamma$$

99.7%

$${}^{7}_{4}\mathrm{Be} + e^{-} \rightarrow {}^{7}_{3}\mathrm{Li} + \nu_e$$

$${}^{7}_{3}\mathrm{Li} + {}^{1}_{1}\mathrm{H} \rightarrow 2\,{}^{4}_{2}\mathrm{He}$$

(PP II)

0.3%

$${}^{7}_{4}\mathrm{Be} + {}^{1}_{1}\mathrm{H} \rightarrow {}^{8}_{5}\mathrm{B} + \gamma$$

$${}^{8}_{5}\mathrm{B} \rightarrow {}^{8}_{4}\mathrm{Be} + e^{+} + \nu_e$$

$${}^{8}_{4}\mathrm{Be} \rightarrow 2\,{}^{4}_{2}\mathrm{He}$$

(PP III)

8.2 Physics of stars

Proton-proton chain (pp chain):

- ✓ mass of 4 ^{1}H nuclei $= 6.693\times10^{-27}$ kg;
  mass of 1 ^{4}He nucleus $= 6.645\times10^{-27}$ kg
- ✓ $\Delta m = 0.048\times10^{-27}$ kg ; 0.7% of mass missing
- ✓ $E = \Delta mc^2 = 0.43\times10^{-11}$ J

Is nuclear energy sufficient to power the Sun?

8.2 Physics of stars

- ✓ Assume that the Sun was originally 100% hydrogen and that only the inner 10% of the Sun's mass become hot enough to convert hydrogen into helium.
- ✓ The amount of energy available in the Sun would be $E_{nuclear} = 0.1 \times 0.007 \times M_0 \times c^2 = 1.26 \times 10^{44}$ J, where the solar mass $M_0 = 2 \times 10^{30}$ kg. The Sun could emit with solar luminosity for approximately $t_{nuclear} = \frac{E_{nuclear}}{L} \sim 10^{10}$ years, more than enough time to account for the age of the Moon rocks.

8.2 Physics of stars

- ✓ In fact, ~90% of solar energy is generated in this way.
- ✓ In the Sun, there are $m = \frac{L}{c^2} = 4.2 \times 10^9$ kg, equal to 4.2 million tons, of matter converted into energy per second
- ✓ Rate of pp chain $\propto T^4$ for temperature near 1.5×10^7 K. 10 % increase in temperature will bring about a more vigorous rate by about 50 %.

8.2 Physics of stars

Carbon-Nitrogen-Oxygen cycle (CNO cycle):

- ✓ Alternative process: fusing 4 H into a He
- ✓ Rate of CNO cycle $\propto T^{19.9}$ for temp near 1.5×10^{7} K. For example, 10 % increase in temperature will bring about a more vigorous rate by about 650 %.
- ✓ Stronger temp dependence than pp chain→ massive star: CNO; less massive: pp chain.

Carbon-Nitrogen-Oxygen cycle

catalyst

$$^{12}C + {}^{1}H \rightarrow {}^{13}N + \gamma$$

$$^{13}N \rightarrow {}^{13}C + e^{+} + \nu_e$$

$$^{13}C + {}^{1}H \rightarrow {}^{14}N + \gamma$$

$$^{14}N + {}^{1}H \rightarrow {}^{15}O + \gamma$$

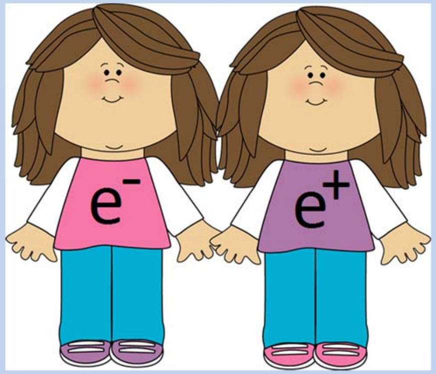
$$^{15}O \rightarrow {}^{15}N + e^{+} + \nu_e$$

$$^{15}N + {}^{1}H \rightarrow {}^{4}He + {}^{12}C$$

$$4\ {}^{1}H \rightarrow {}^{2}He + 2\ e^{+} + 2\ \nu_e + 3\ \gamma$$

8.2 Physics of stars

Background



Products (or by-products?)

- ✓ *Positron* e^+ : identical to an electron, except that it carries positive charge. Electron-positron annihilation process $e^+ + e^- \rightarrow 2\gamma$
- ✓ *Neutrino* ν : highly penetrating neutral particles, interact with matter very weakly. Our bodies encounter 10^{12} every second.

来无影，去无踪　　但是从科学上来说，必须要量出neutrino

neutrino

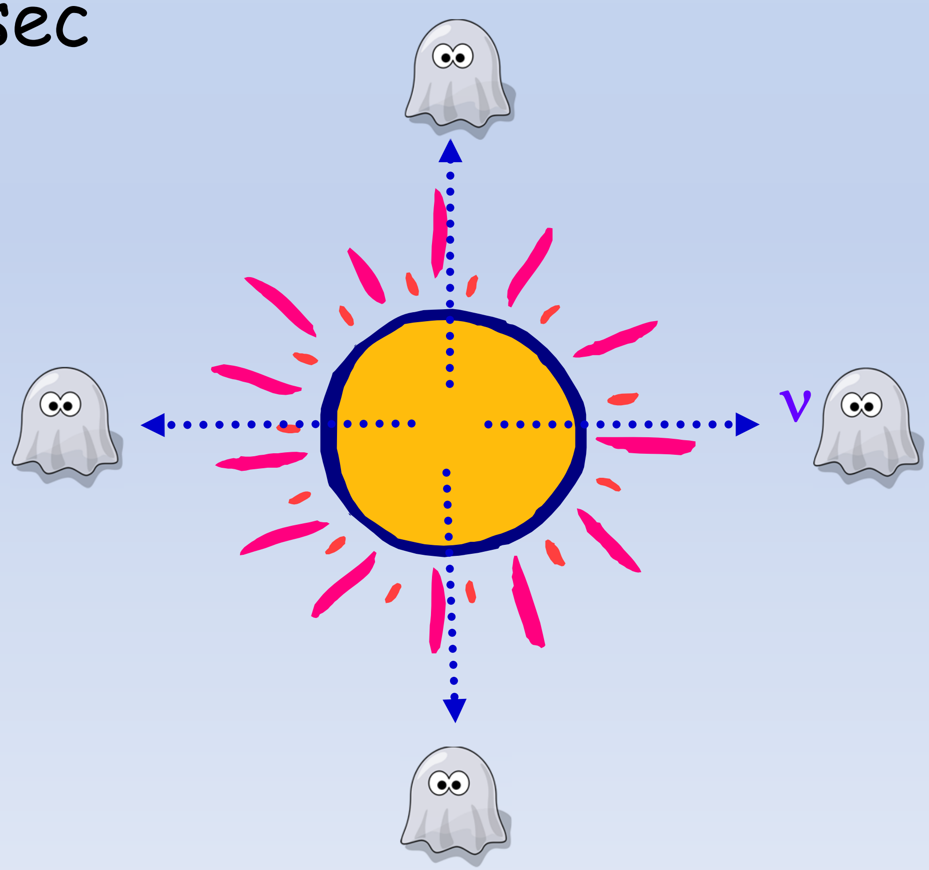
8.2 Physics of stars

Solar neutrinos problem

Just when we thought that we understood the nuclear fusion in star, …

8.2 Physics of stars

- ✓ Neutrino ν - hardly interact with matter, 10^{12} ν pass our bodies /sec
- ✓ Detection of which is an indirect evidence of nuclear reactions in the solar core.
- ✓ From the interior of Sun, they reach the Earth directly.



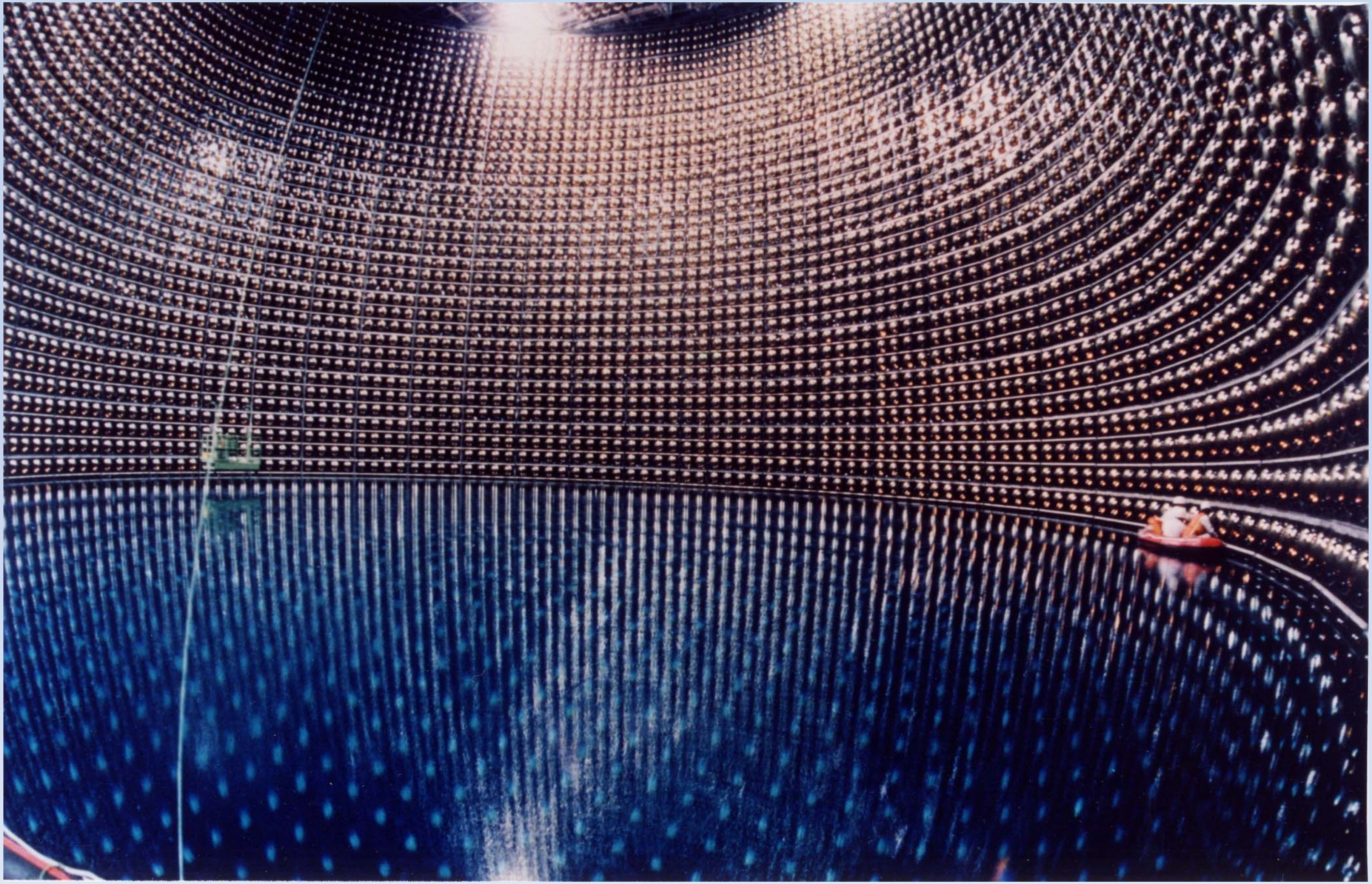
8.2 Physics of stars

- ✓ Early observation in the 1970's ~ 10^5 gallons of C_2Cl_4 underground

$$^{37}_{17}\mathrm{Cl} + \nu \rightarrow {}^{37}_{18}\mathrm{Ar} + \mathrm{e}^-$$

- ✓ Detected only 1/3 of the neutrinos from the Sun as theoretically expected.
- ✓ What's wrong? Maybe we do not understand the interior of stars as good as we think?
- ✓ Turns out we didn't understand neutrinos

the Super-Kamiokande experiment

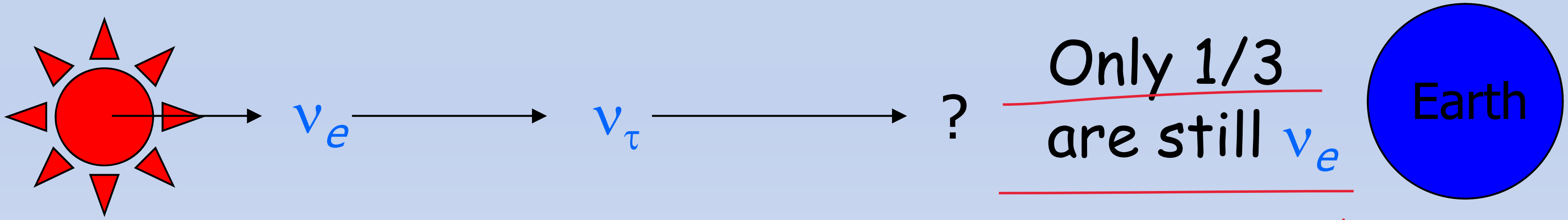


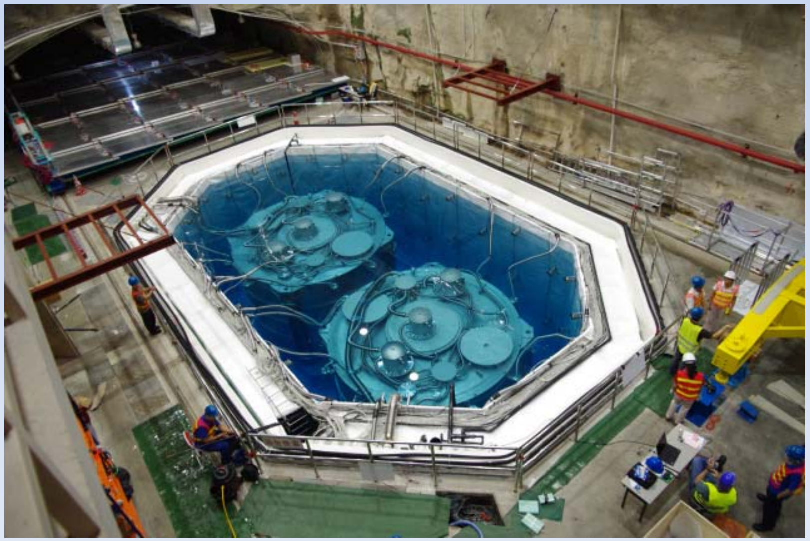
8.2 Physics of stars

✓ Neutrino oscillation

Three types of neutrinos: ν_e , ν_τ , ν_μ :

They can change from one type to another!





Daya Bay Reactor
Neutrino experiment

Revision

How does a main-sequence star move in the HR diagram when it evolves? Why?

What is the name of the timescale for which radiations are emitted only by gravitational energy?   Kelvin-Helmholtz timescale

What type of nuclear fusion happened mainly in sun-like stars? What type in massive stars?

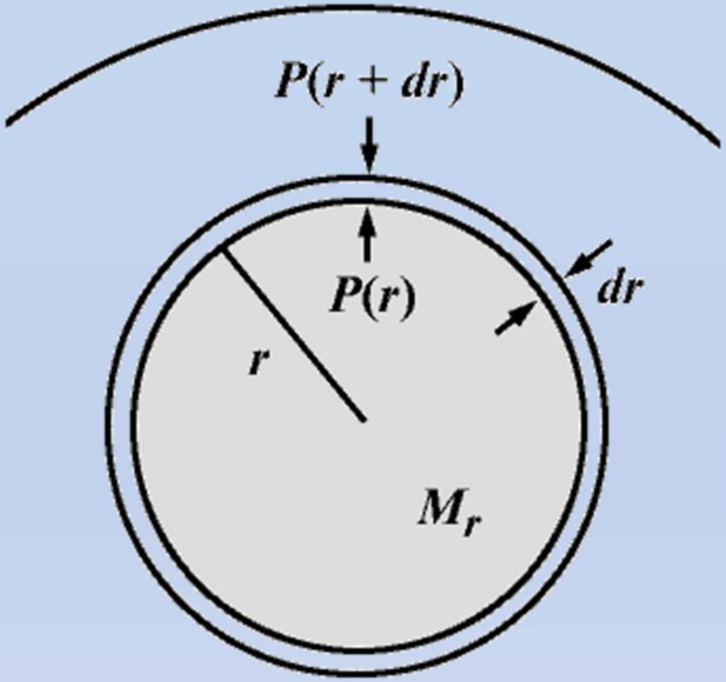
8.2 Physics of stars

Hydrostatic equilibrium

What supports a star and prevents it from collapse?

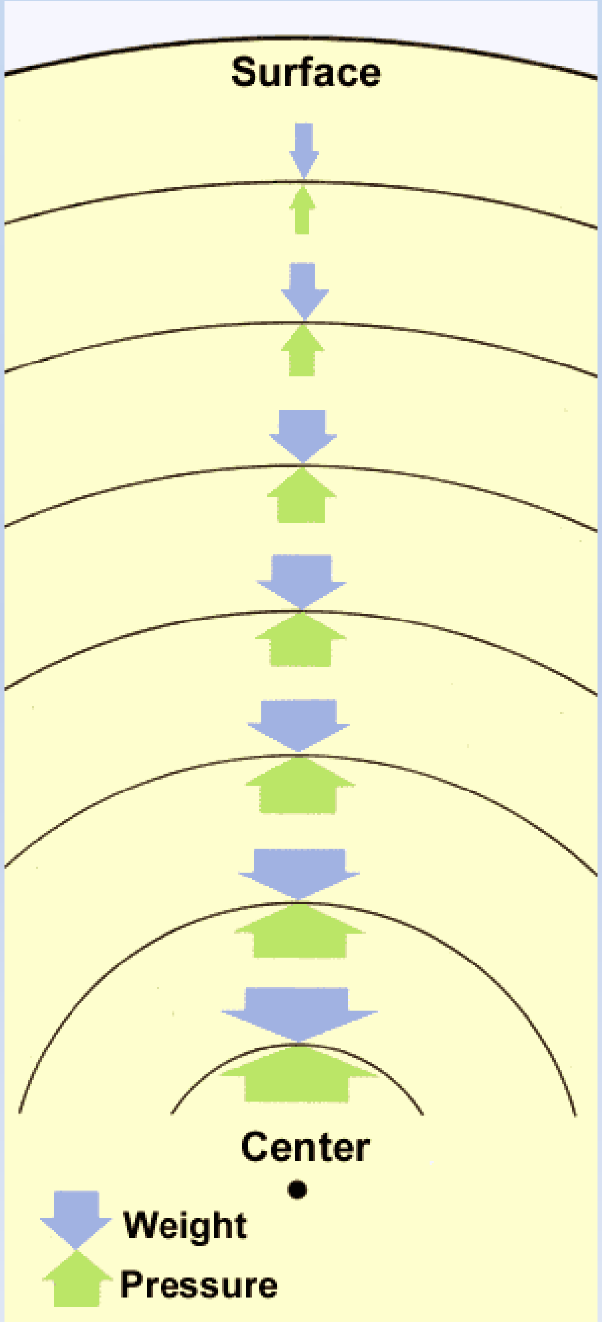
8.2 Physics of stars

- ✓ Suppose a star is spherically symmetric
- ✓ Divide a stars into concentric spherical layers
- ✓ Gravitational force on a shell: $dF = \frac{GM_r}{r^2} dm$ and $dm = 4\pi r^2 \rho dr$
- ✓ Pressure is required to counterbalance the gravitational force. We have



$$\boxed{\frac{dP}{dr} = -\frac{GM_r \rho(r)}{r^2}}$$

Condition for hydrostatic equilibrium



low-pressure surface

How high is it?

High-pressure core

Central pressure of the Sun P_c :

$$\frac{dP}{dr} \sim \frac{P_S - P_c}{R_S - 0} \sim -\frac{P_c}{R_S}$$

$$P_c \sim \frac{GM\rho}{R_S} \sim 2.7 \times 10^{14}\ \text{N m}^{-2}.$$

Crude estimate

估计了太阳的中心压力

To calculate accurate value, evaluate

$$P_c = -\int_{R_S}^{R_C} \rho \frac{GM_r}{r^2} dr.$$

$$P_c = 2.23 \times 10^{16}\ \text{N m}^{-2}.$$

Need to know r-dependence of ρ and M_r

What causes such a high pressure?

8.2 Physics of stars

Equation of state: Ideal gas law

- ✓ In the, atoms are completely ionized to become *plasma* - ions and electrons in rapid thermal motions, average K.E. >> coulomb energy
- ✓ The ideal gas law holds: $P = \frac{\rho}{\bar{m}} kT$, where ρ is mass density, and $\bar{m}$ is the average mass of particles.
- ✓ e.g., pure hydrogen plasma, i.e., H ions and electrons, $\bar{m} = \frac{m_p + m_e}{2} \approx 0.5 m_p$.

8.2 Physics of stars

For completely ionized gas, the average mass of all particles is given by

$\frac{1}{\mu} \simeq 2X + \frac{3}{4}Y + \frac{1}{2}Z$, where $\mu \equiv \frac{\bar{m}}{m_p}$, m_p is the mass of proton, X and Y are, respectively, the mass fraction of hydrogen and helium, and Z is the mass fraction of all elements heavier than helium.

e.g., the Sun at birth had 71% H, 27% He, 2% heavy elements ➔ $\bar{m} \simeq 0.62 m_p$.

1/(1.6325)

0.61255742725880551301684532924962

8.2 Physics of stars

the central temperature can be estimated by applying the ideal gas law, we have

$$T = \frac{P\bar{m}}{\rho k} = \frac{2.7\times10^{14}\times0.62m_p}{1408k} \sim 1.44\times10^7 \text{ K.}$$

This result is in reasonable agreement with more detailed calculations. One standard solar model gives a central temperature of 1.57×10^7 K

Why such a high temperature is required?

8.2 Physics of stars

Classical understanding: Fusion happens when 2 positively charged proton are as close as 10^{-15} m (Nuclear size ~ 10^{-15} m)

这里估计了温度

KE of particles = Coulomb potential barrier

$$\frac{1}{2}m\overline{v^2} = \frac{3}{2}kT_{classical} = \frac{1}{4\pi\epsilon_0}\frac{e^2}{r}$$

$$T_{classical} = \frac{e^2}{6\pi\epsilon_0 kr} \sim 10^{10}\ \mathrm{K}$$

But central temperature of the Sun is about 10^7 K only. Seemingly, it is not hot enough to start the fusion

温度不够所需发生反应，但是还是发生了。这里用量子力学中的隧道效应，穿过这个壁垒，使得这个反应发生了。

Thanks is given to tunneling effect as predicted by quantum mechanics.

Crude estimate: assume that a proton must be within approximately one de Broglie wavelength (德布羅意波波長, $\lambda = h/p$) of its target in order to tunnel through the Coulomb barrier.

KE of particles = Coulomb potential barrier

$$\frac{p^2}{2m} = \frac{(h/\lambda)^2}{2m} = \frac{1}{4\pi\epsilon_0}\frac{e^2}{\lambda}$$

m is called the reduce mass (約化質量). For 2 particles of masses x and y orbiting each other, one may consider as if a stationary particle is orbited by another particle of reduced mass m, where $\frac{1}{m} = \frac{1}{x} + \frac{1}{y}$.

8.2 Physics of stars

$$\frac{p^2}{2m} = \frac{(h/\lambda)^2}{2m} = \frac{1}{4\pi\epsilon_0}\frac{e^2}{\lambda}$$

solve for λ

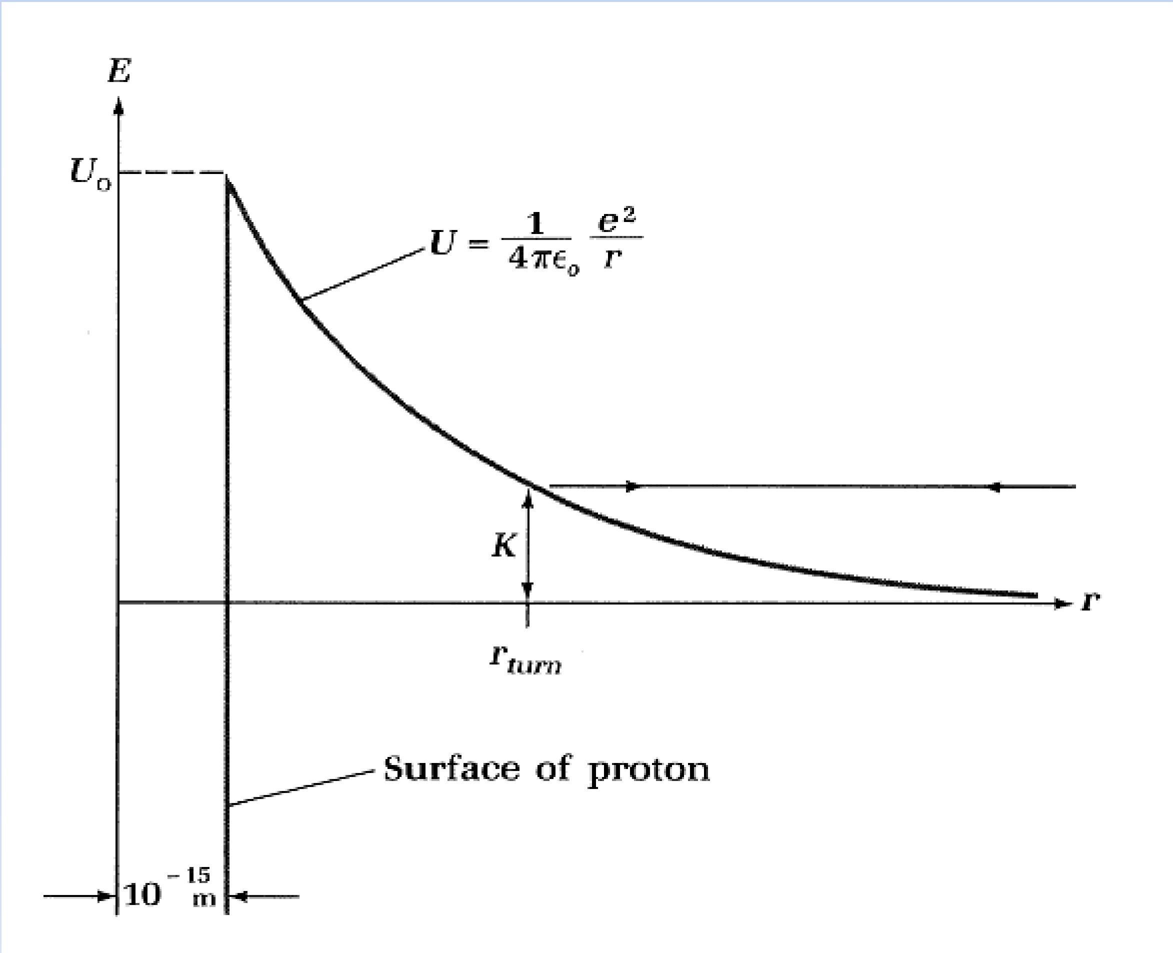
$$T_{quantum} = \frac{e^2}{6\pi\epsilon_0 k\lambda}$$

$$\frac{3}{2}kT_{quantum} = \frac{1}{4\pi\epsilon_0}\frac{e^2}{\lambda}$$

Ideal Gas

$\sim 10^7$ K

8.2 Physics of stars



8.2 Physics of stars

Thanks is given to tunneling effect as predicted by quantum mechanics.
Crude estimate: assume that a proton must be within approximately one de Broglie wavelength of its target in order to tunnel through the Coulomb barrier.

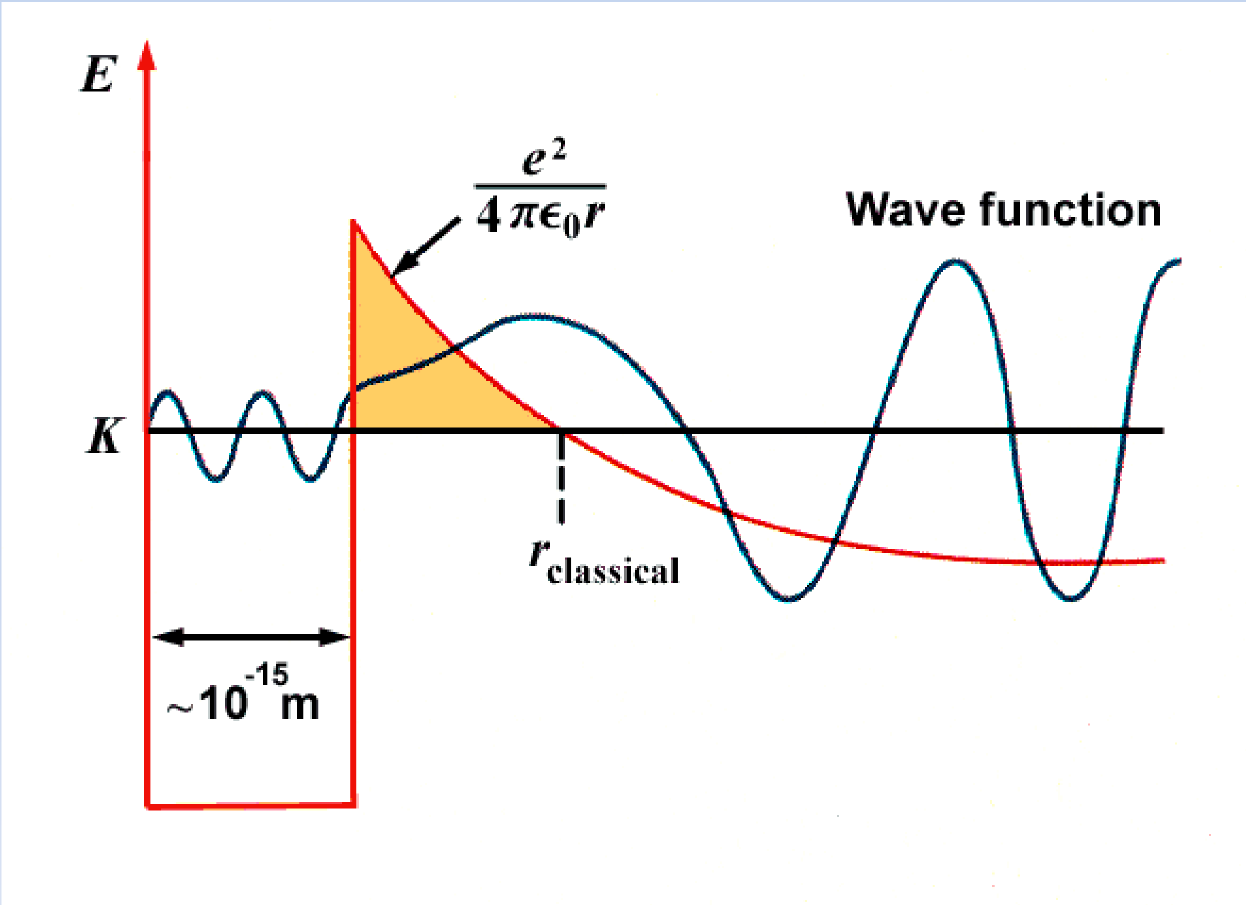
KE of particles = Coulomb potential barrier

$$\frac{p^2}{2m} = \frac{(h/\lambda)^2}{2m} = \frac{1}{4\pi\epsilon_0}\frac{e^2}{\lambda}$$

solve for λ

$$T_{quantum} = \frac{e^2}{6\pi\epsilon_0 k\lambda} \sim 10^7 \text{ K}$$

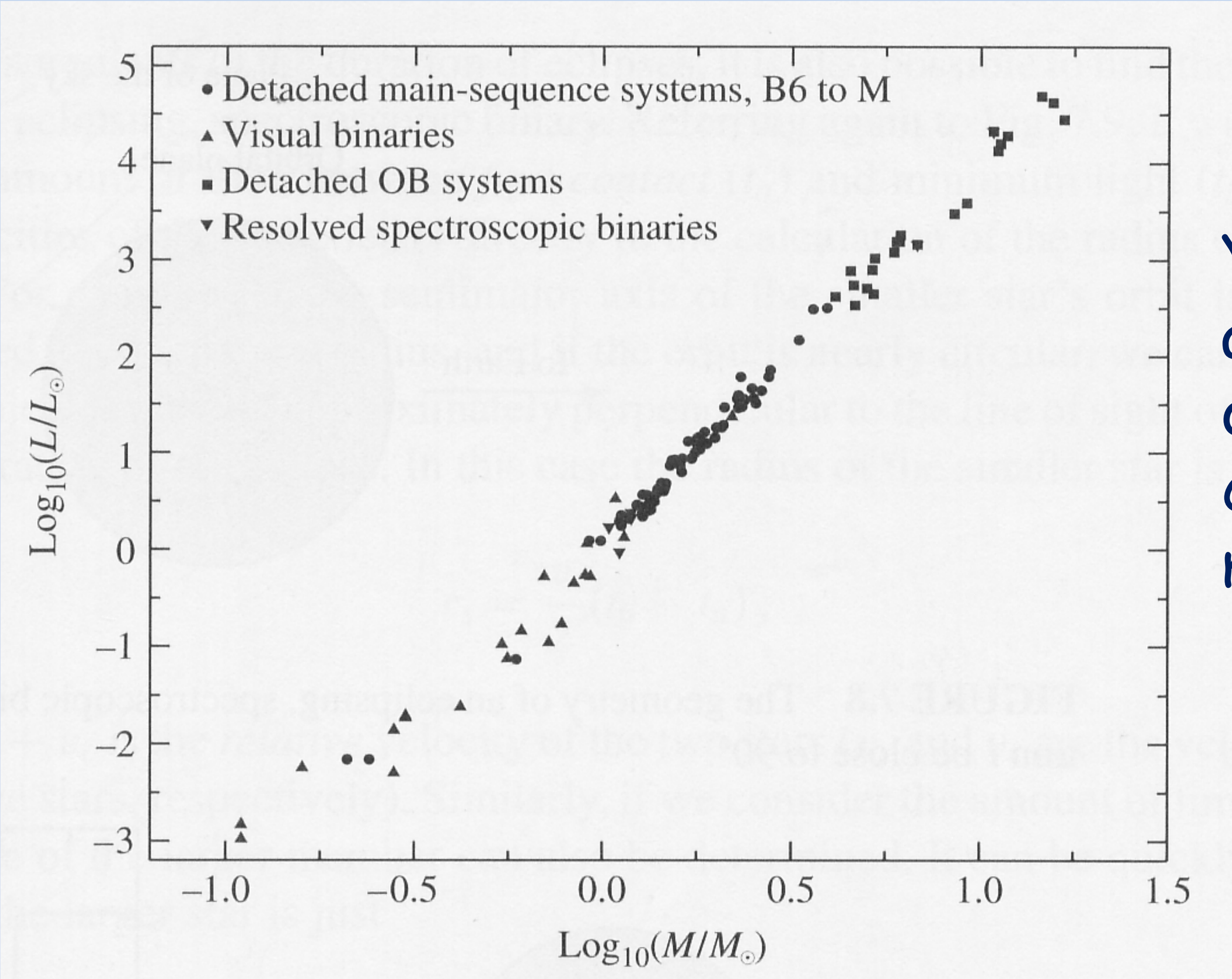
8.2 Physics of stars



✓ Quantum mechanics: tunneling of the wavefunction

8.2 Physics of stars

Mass-luminosity relation



Years of astronomical observations: direct correlation between mass and luminosity

Data from Popper, Annu. Rev. Astron. Astrophys., 18, 115, 1980

8.2 Physics of stars

- ✓ Massive stars need higher thermal pressure to counter-balances the larger force of gravity.
- ✓ Nuclear reactions much faster (e.g., a $15\ M_\odot$ star fuses H over $3000\times$ faster than the Sun!) to achieve equilibrium, so more luminous.

How are mass M and luminosity L related?

If a power law is assumed: $L \propto M^\alpha$, what is α ?

How are mass M and lifetime τ related?

8.2 Physics of stars

The mass-luminosity relation: (applicable to a star of 0.1-50 solar masses)

$$L \propto M^{3.5}$$

Lifetime of a star: $\tau = \frac{\Delta M c^2}{L} \propto \frac{M}{M^{3.5}} = M^{-2.5}$, i.e.,

$$\tau \propto M^{-2.5}$$

Massive stars burn H rapidly, so shorter lives, and more low-mass stars in the sky.

8.2 Physics of stars

- ✓ The Sun ~ 10^{10} years
- ✓ Life span of a $10\ M_\odot$ star is about 100 million yrs

$$\tau \sim \tau_\odot \times \left(\frac{M_\odot}{M}\right)^{2.5} = 10^{10} \times \left(\frac{1}{10}\right)^{2.5} \approx 3 \times 10^{7}\text{yrs}$$

- ✓ A $20\ M_\odot$ star only lives for a few million years
- ✓ Very low mass main-sequence stars (red dwarfs) live for about 200-300 billion years

8.2 Physics of stars

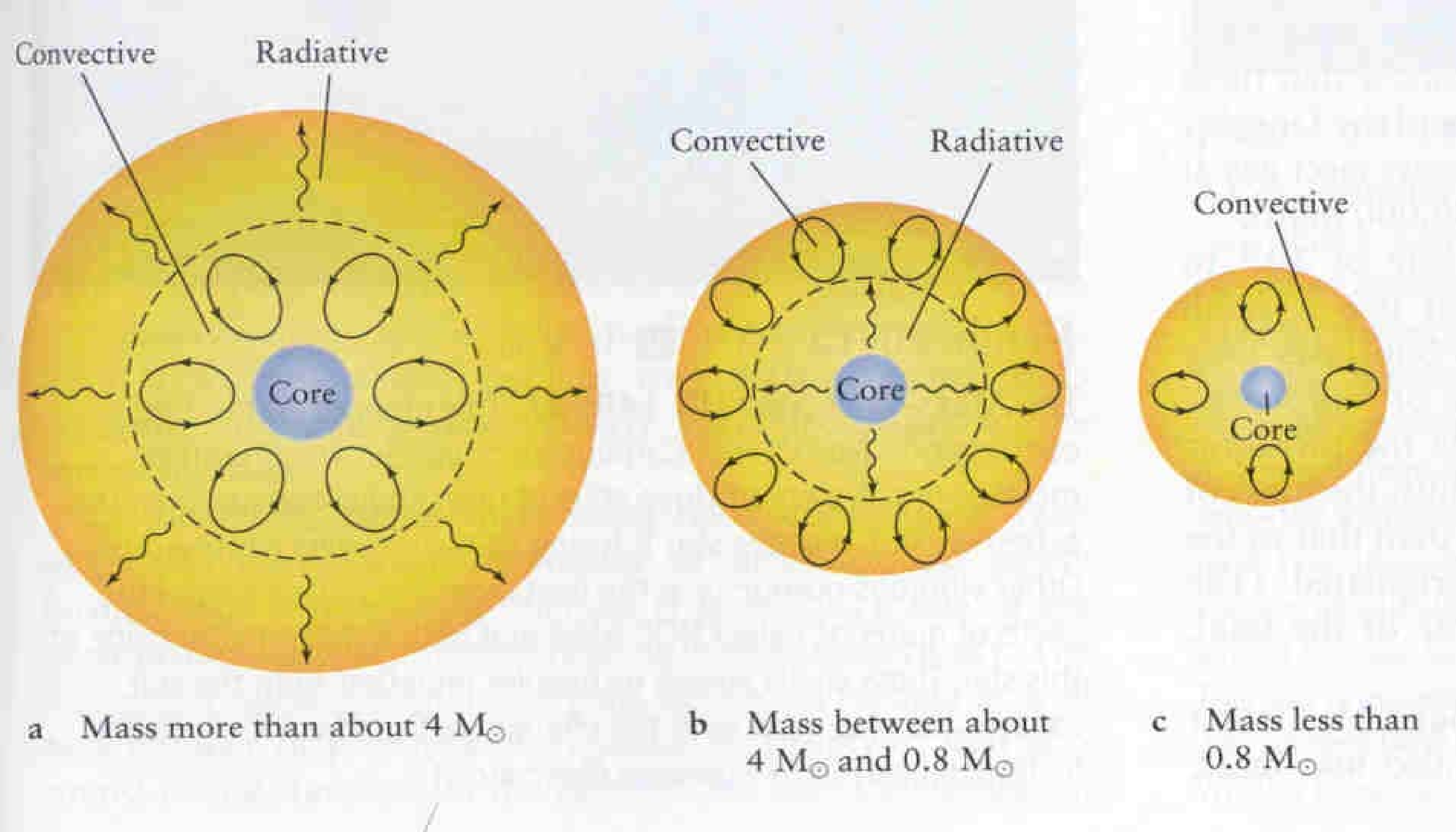
Transportation of energy

How is the energy generated at the core transported to the surface?

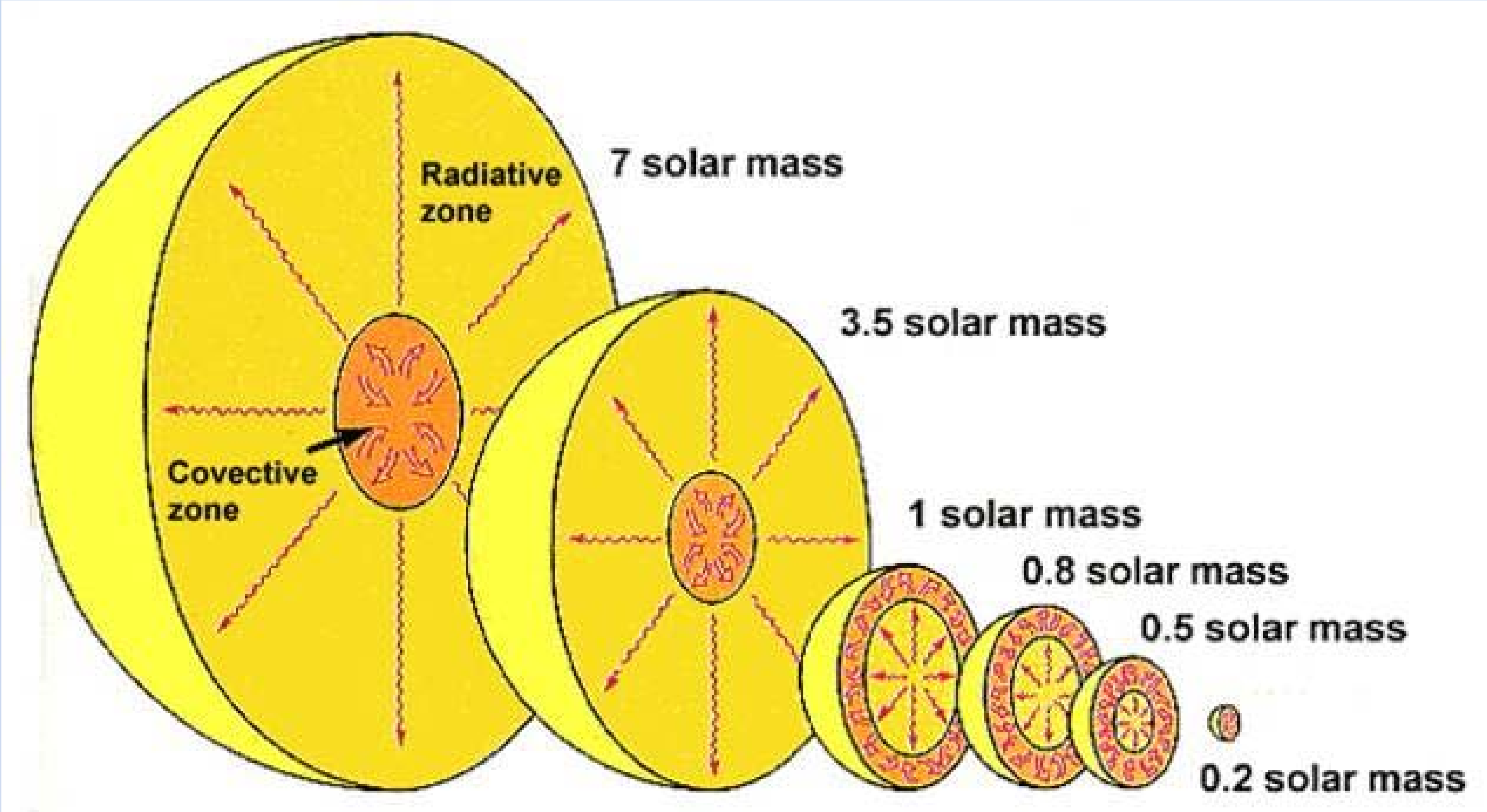
8.2 Physics of stars

Three major ways of heat transportation

- ✓ Radiation (輻射): Energy carried by electromagnetic radiation
- ✓ Convection (對流): Hot gas rises and cooler gas sinks, carrying energy outward
- ✓ Conduction



Stellar models show that the mechanism of energy transport from the inner core to the surface of the star depends on the mass of the star.



Massive stars: Convective core, radiative outer zone
Sun-like stars: Radiative core, convective outer zone
Small-mass stars: Convective throughout

8.2 Physics of stars

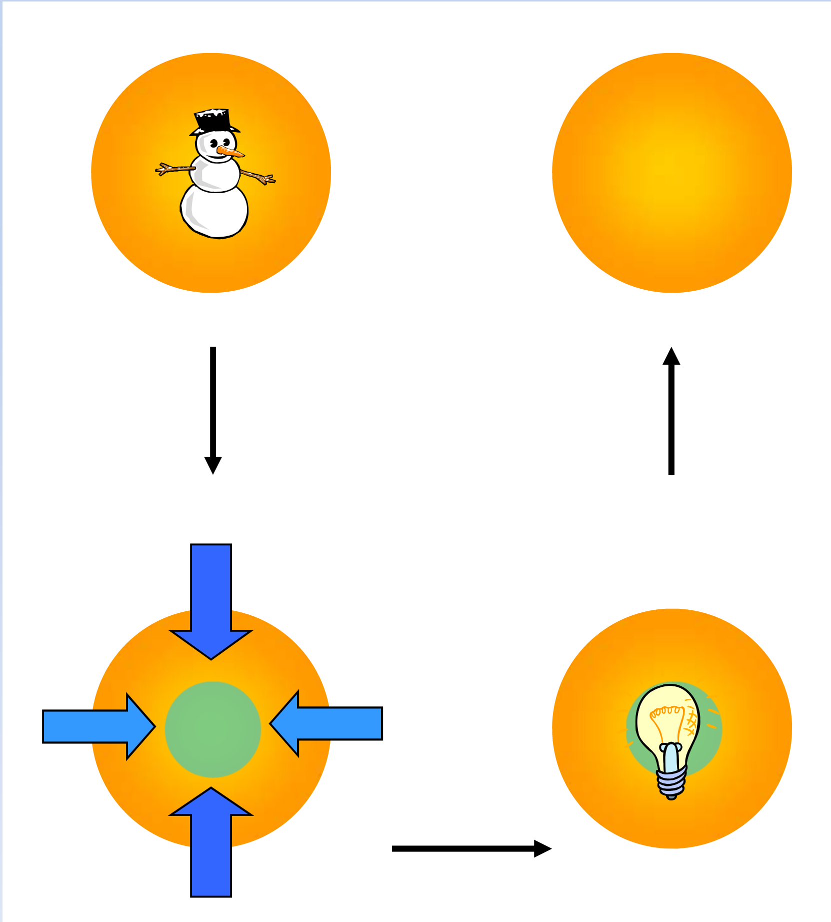
Stability of main-sequence stars

Why doesn't such a nuclear reactor get hotter and hotter and explode?

8.2 Physics of stars

Pressure-temperature thermostat:

- ✓ If nuclear reactions slow down, the temperature decreases and thermal pressure drops.
- ✓ Gravity contracts the star, compression heats the core, thus increases the nuclear energy generation.

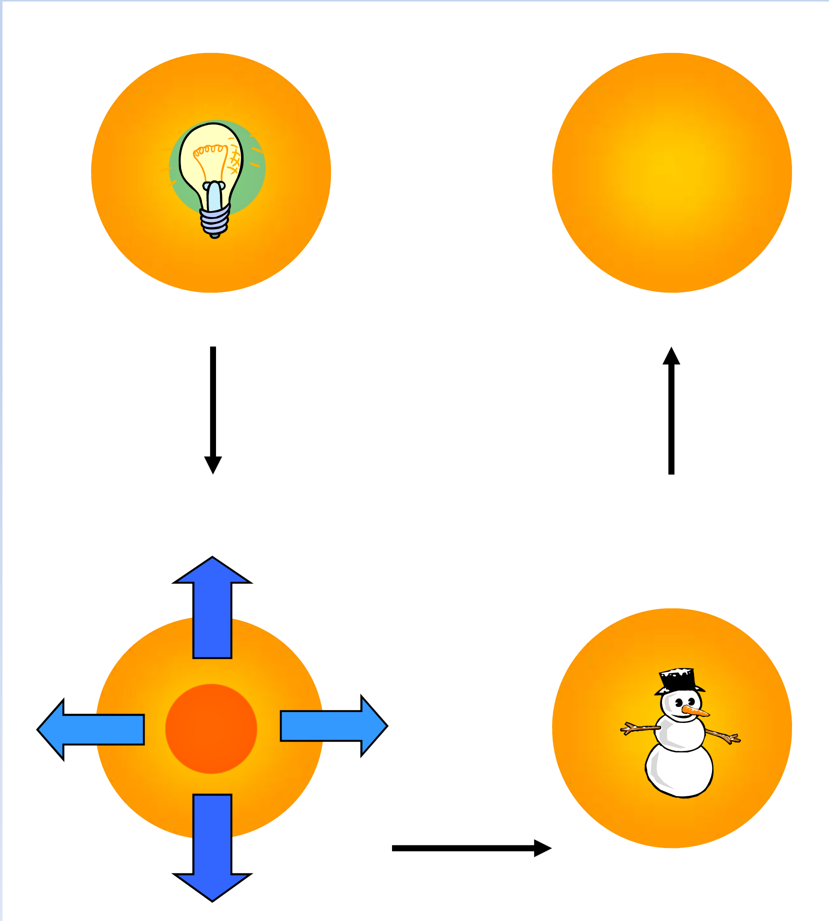


8.2 Physics of stars

Pressure-temperature thermostat:

✓ If nuclear reactions become too fast, the temperature increases and thermal pressure rises.

✓ The stellar core expands, expansion cools the core, and slows down the nuclear reactions rate.



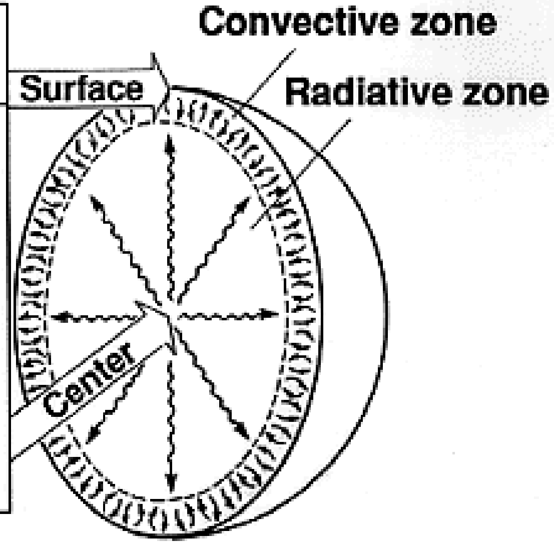
8.2 Physics of stars

A star is very stable in the main sequence, spending 90% of their lifespan in main-sequence. No wonder most observed stars in the sky are main-sequence stars

Equations governing stellar structure (for reference):

- Mass-density relation: $$\frac{dM_r}{dr} = 4\pi r^2 \rho$$
- Hydrostatic equilibrium: $$\frac{dP}{dr} = -\frac{GM_r \rho}{r^2}$$
- Equation of state: $$P = \frac{\rho}{\overline{m}} kT$$
- energy transport (Radiation): $$L = -\frac{16\pi acr^2}{3} \frac{T^3}{\overline{\kappa}\rho} \frac{dT}{dr}$$
- energy transport (Convection): $$\frac{dT}{dr} = -\left(1 - \frac{1}{\gamma}\right) \frac{\overline{m}}{k} \frac{GM_r}{r^2}$$

$r/R_\odot$	T / 10^6 K	Density / g/cm^3	$M/M_\odot$	$L/L_\odot$
1.00	0.006	0.00	1.00	1.00
.90	.60	.009	.999	1.00
.80	1.27	.035	.996	1.00
.70	1.80	.12	.990	1.00
.60	2.42	.40	.97	1.00
.50	3.42	1.3	.92	1.00
.40	4.74	4.1	.82	1.00
.30	6.65	13.	.63	.99
.20	9.35	36.	.34	.91
.10	12.65	85.	.073	.40
0.00	14.62	134.	.000	0.00



$$\frac{dM}{dr} = 4\pi r^2 \rho$$

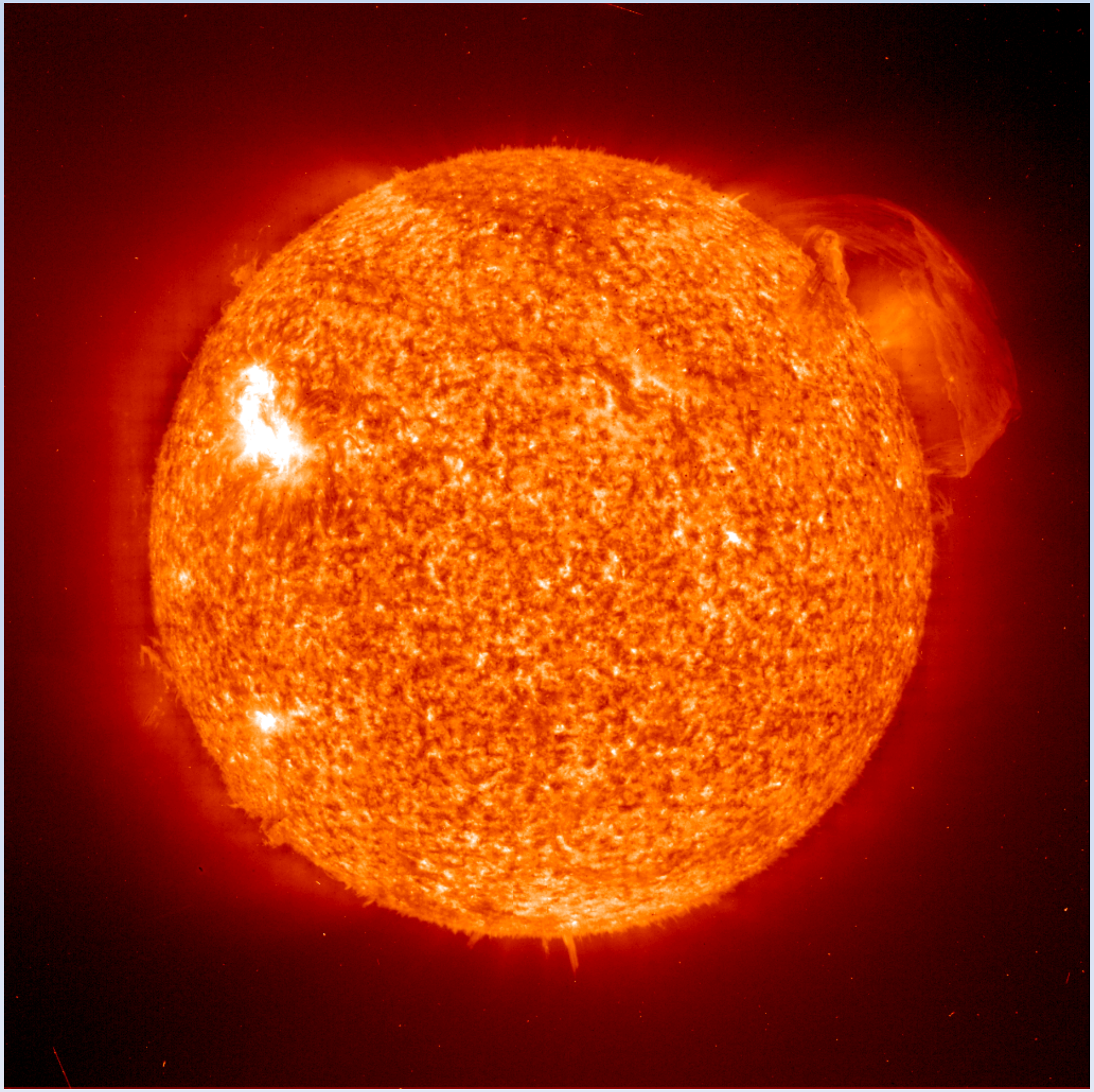
$$\frac{dL}{dr} = 4\pi r^2 \rho e$$

$$\frac{dP}{dr} = -\frac{GM}{r^2}\rho$$

$$\frac{dT}{dr} = \frac{-3}{16\pi ac}\frac{\bar{\kappa}\rho}{T^3}\frac{L}{r^2}$$

Solve them numerically in computers

8.3 The Sun - the nearest star



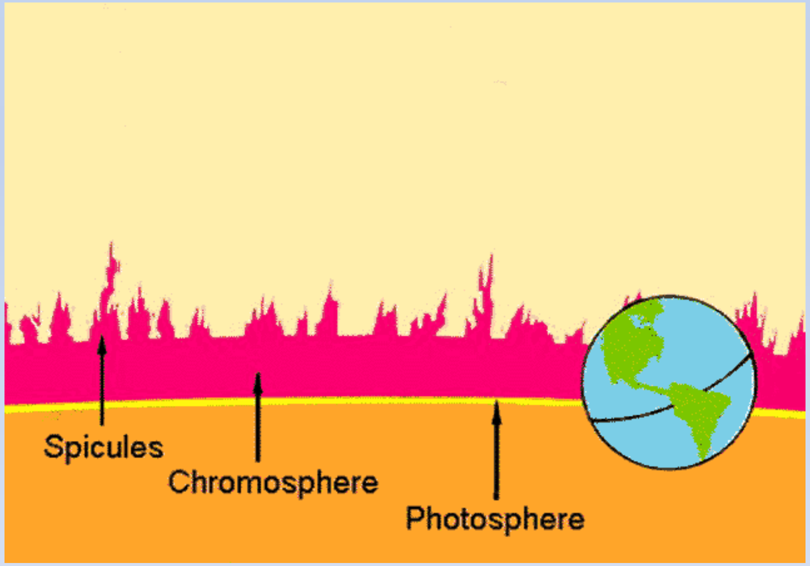
8.3 The Sun – the nearest star

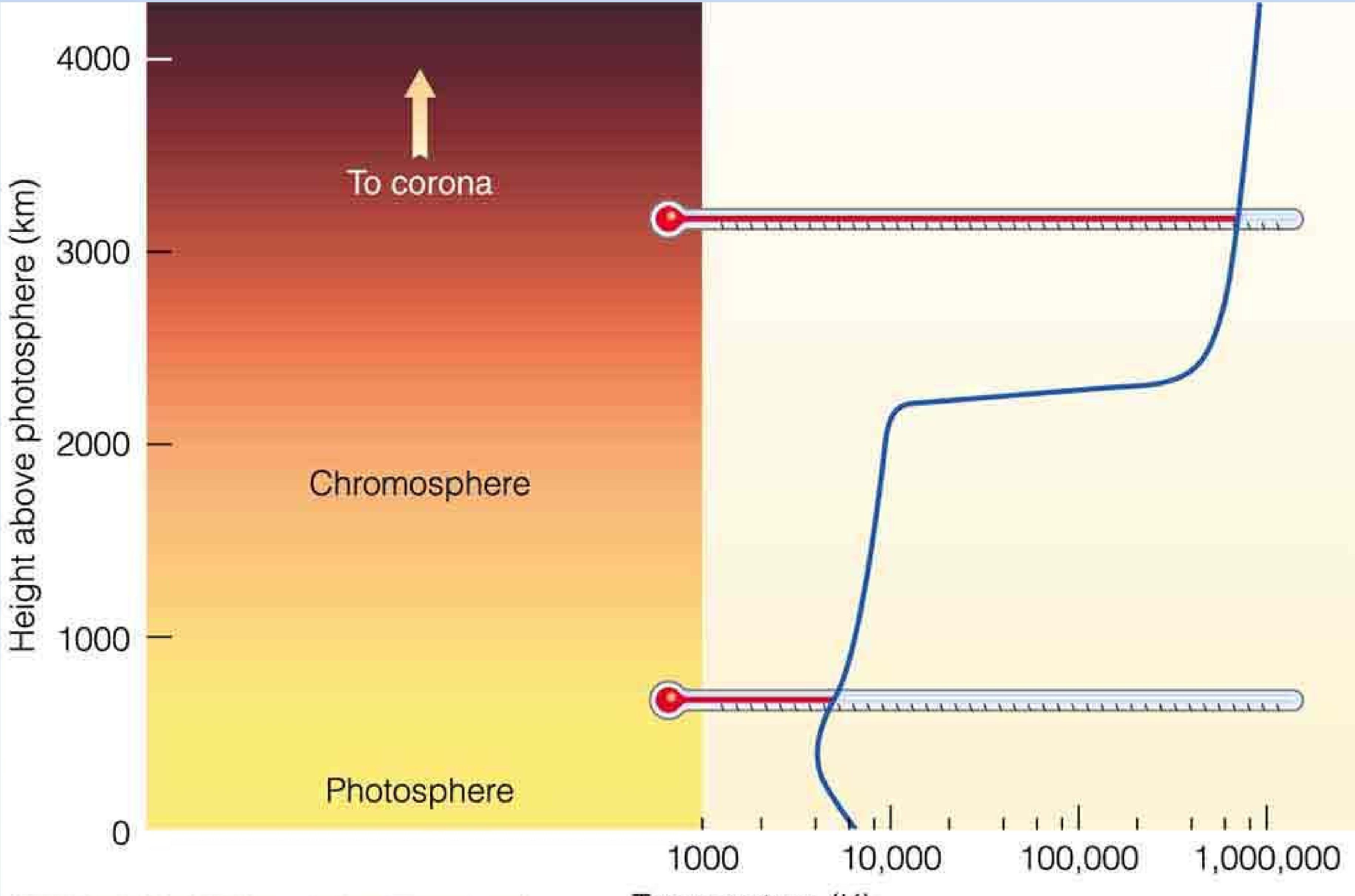
There could be a lot to talk about. We will however focus on

- ✓ The solar atmosphere
  - ➢ The photosphere
  - ➢ The chromosphere
  - ➢ The corona
- ✓ The solar interior and structure
- ✓ Solar activities

The Solar atmosphere

- ✓ The Sun is made of gas (plasma). The top layers are transparent.
- ✓ Atmosphere: roughly 3 layers.
  - ➢ Photosphere (光球層): the bottom layer, about 6,000 K.
  - ➢ Chromosphere (色球層): middle layer, T as high as 1,000,000 K.
  - ➢ Corona (日冕): the outermost layer.



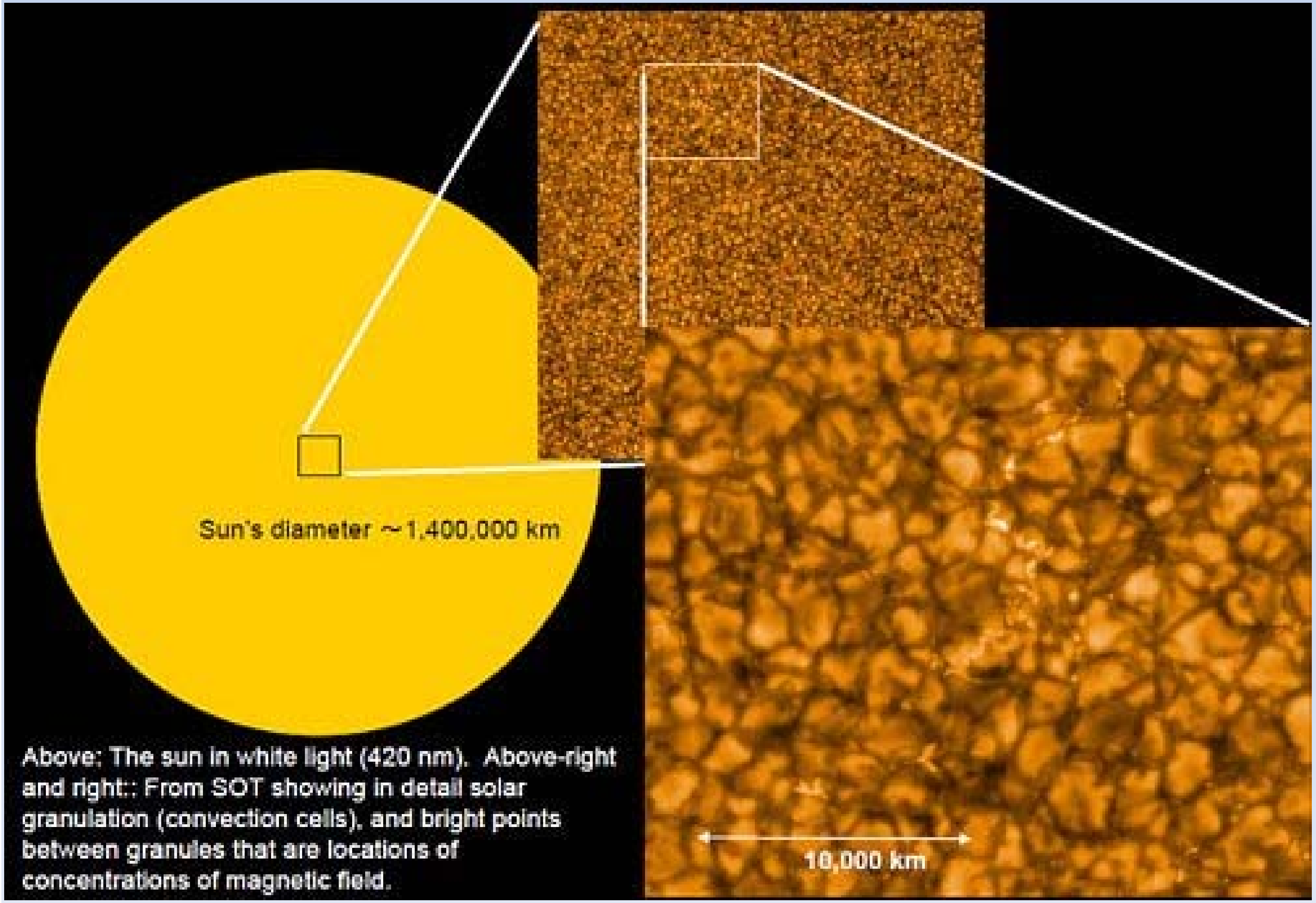

4000
3000
2000
1000
0
Height above photosphere (km)
To corona
Chromosphere
Photosphere
1000
10,000
100,000
1,000,000
Temperature (K)

The Solar atmosphere - The photosphere (光球層)

- ✓ emits visible light, the photosphere is the visible surface of the Sun.
- ✓ A gaseous layer of about 500 km in depth.
- ✓ Generates most of sunlight we see.
- ✓ The temperature ~ 6,000 K.
- ✓ Low dense, only 0.1% of atmospheric density at the sea level.

The Solar atmosphere - The photosphere

Feature I: Granulation (米粒組織)



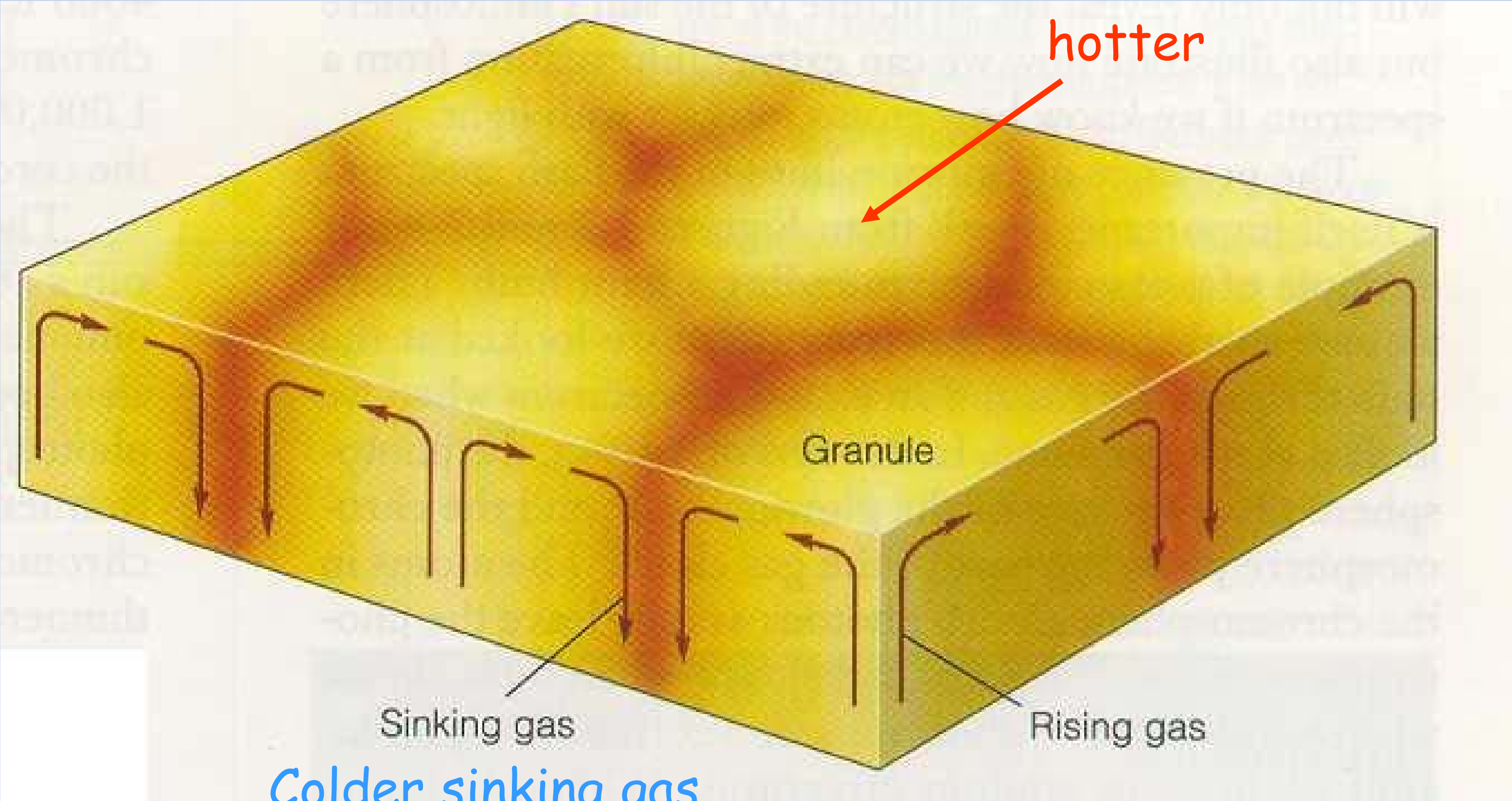
Above: The sun in white light (420 nm). Above-right and right:: From SOT showing in detail solar granulation (convection cells), and bright points between granules that are locations of concentrations of magnetic field.

- ✓ due to the convection of gas
- ✓ ~1,000 km in diameter
- ✓ lasts for 20 minutes

Image: NASA

The Solar atmosphere - The photosphere

Feature I: Granulation (米粒組織)

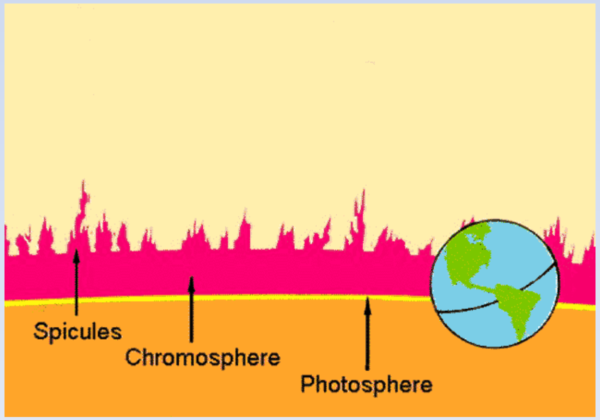


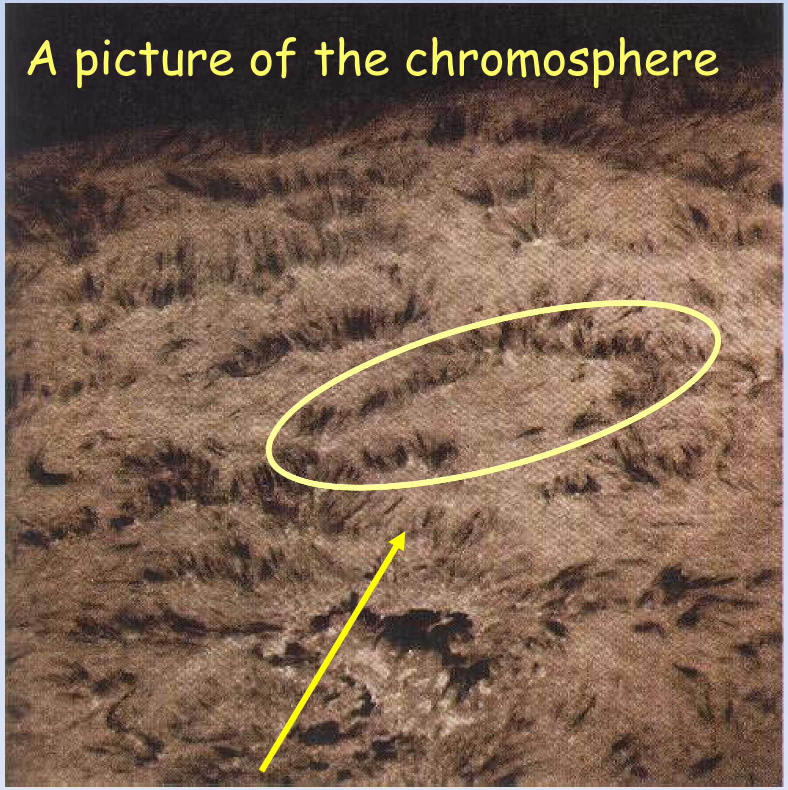
Colder sinking gas

The Solar atmosphere - The photosphere

Feature II: Supergranules

- ✓ Groups of about 300 granules (see also later in chromosphere).
- ✓ ~30,000 km in diameter.
- ✓ Each lasts for a day or two.
- ✓ Very slowly rising hot gases.



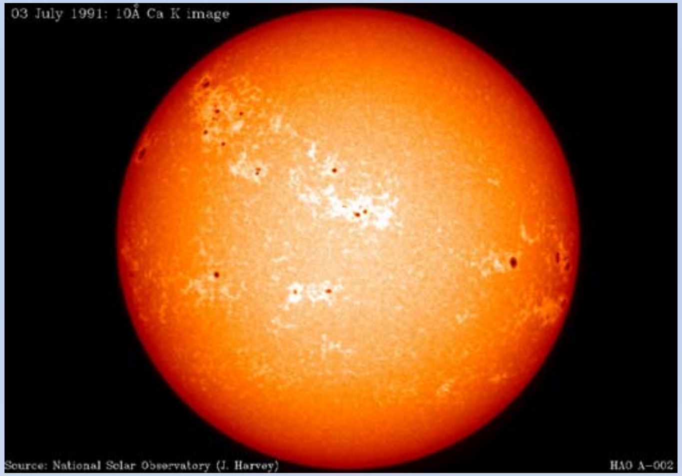


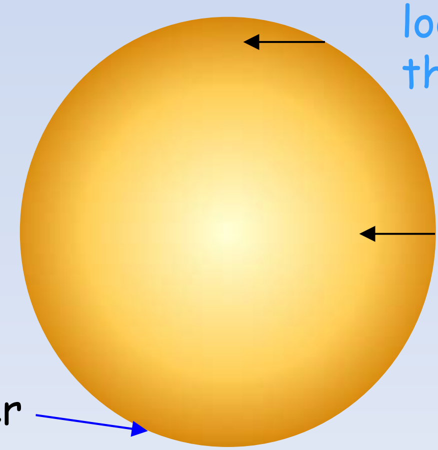
At the edge of a supergranule

The Solar atmosphere - The photosphere

Feature III: Limb darkening (臨邊昏暗)

- ✓ Looking at a steep angle when look at the limb…
- ✓ Evidence of slight temperature decrease with height in the photosphere.

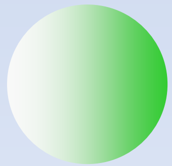




looking at cooler gas along this line of sight

looking at hotter gas along this line of sight

The surface is cooler



Earth

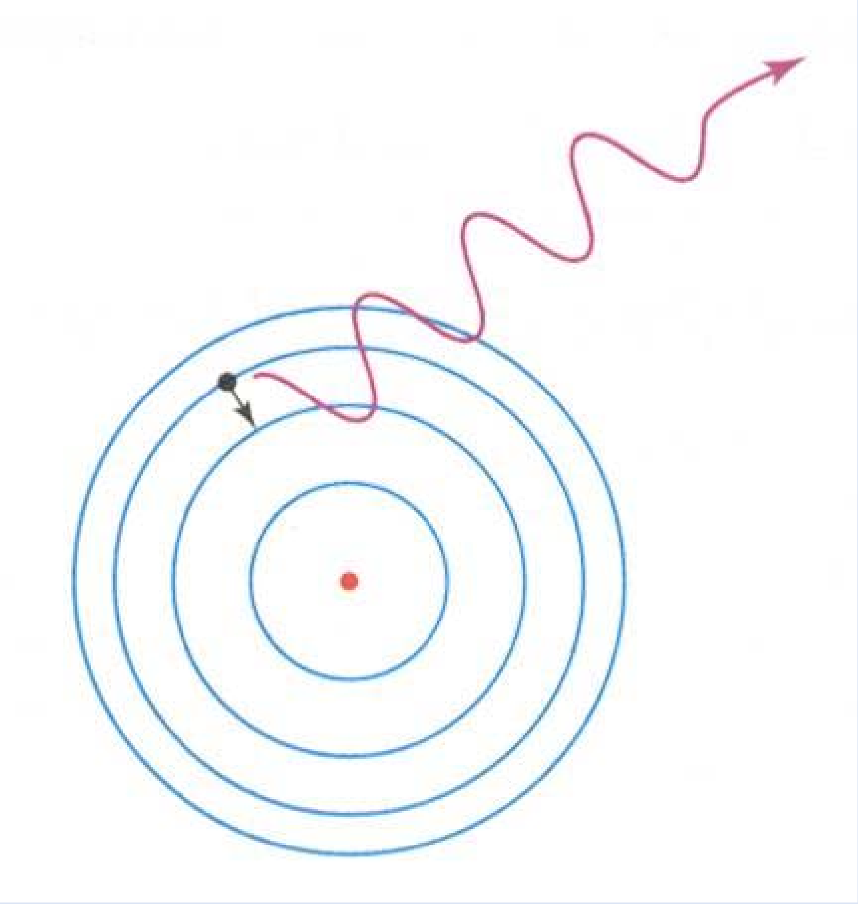
The Solar atmosphere - The chromosphere (色球層)

- ✓ A layer of gas of about 10,000 km thick
- ✓ Very low density, only 0.01% of photosphere, so you couldn't see it normally. Can be seen during solar eclipse.
- ✓ at the top of chromosphere, extremely low density (about 10^{-13} of that of the air we breathe !).

The Solar atmosphere - The chromosphere

✓Emission spectrum: mainly H_α Balmer n = 3 level to the n = 2 level, which has wavelength ~ 656.3 nm, and reddish-pink colour

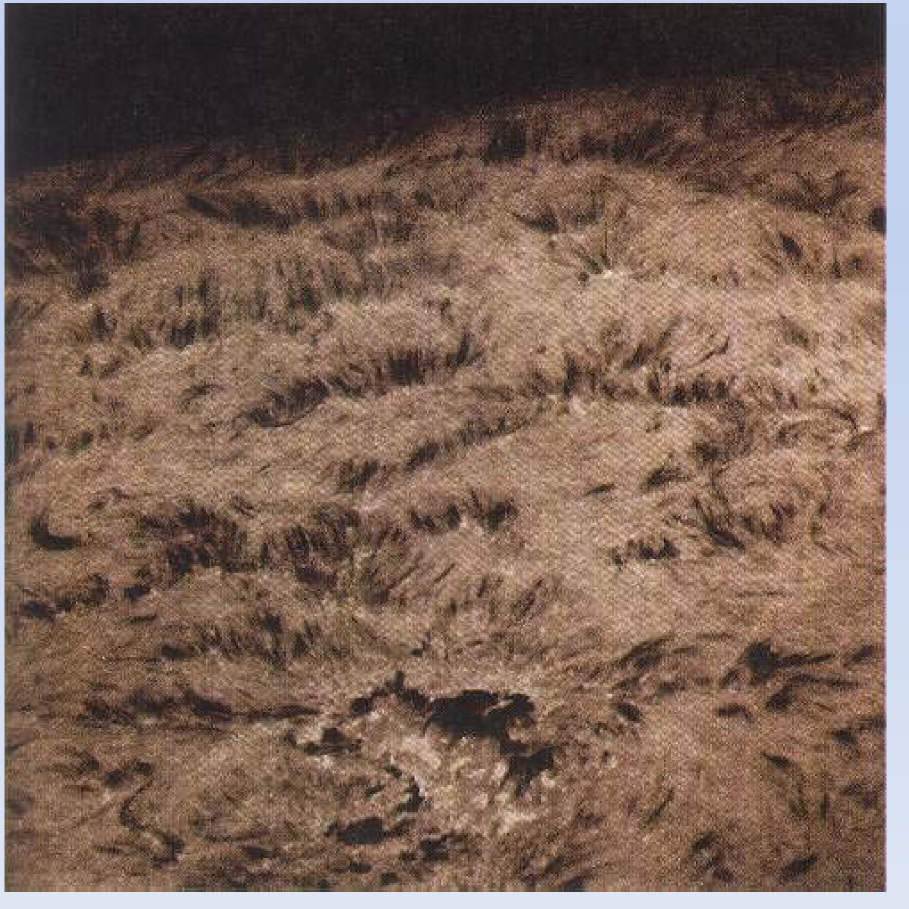
✓also lines of ionized helium, calcium, ..



The Solar atmosphere - The chromosphere

Feature I: Spicules (針狀體)

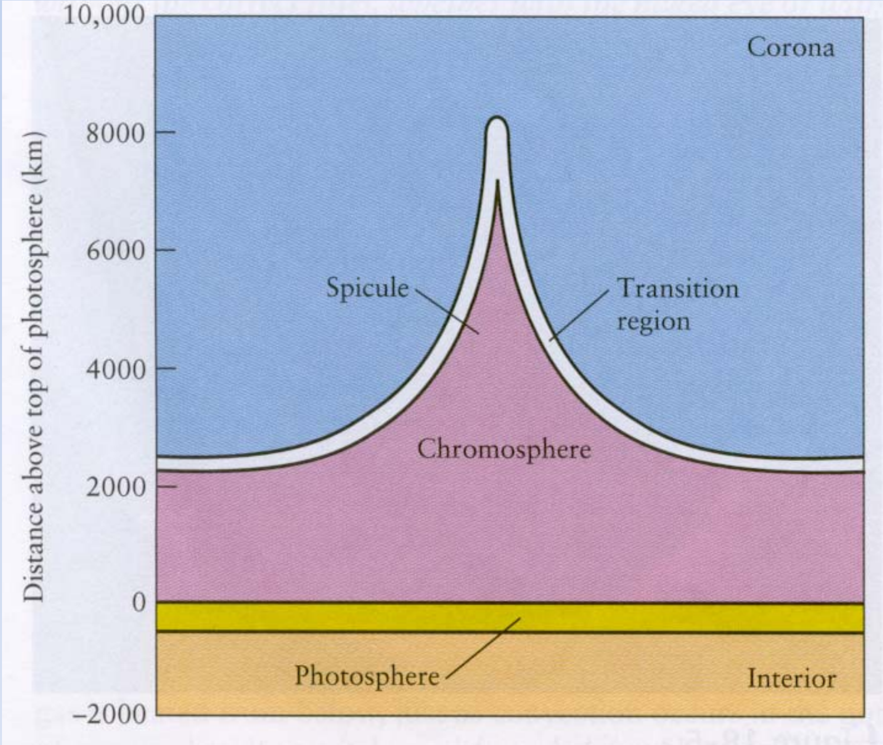
- ✓ By H_α filter, grass-like spicules mark the edges of supergranules (enormous convective cells in the photosphere) underneath.



The Solar atmosphere - The chromosphere

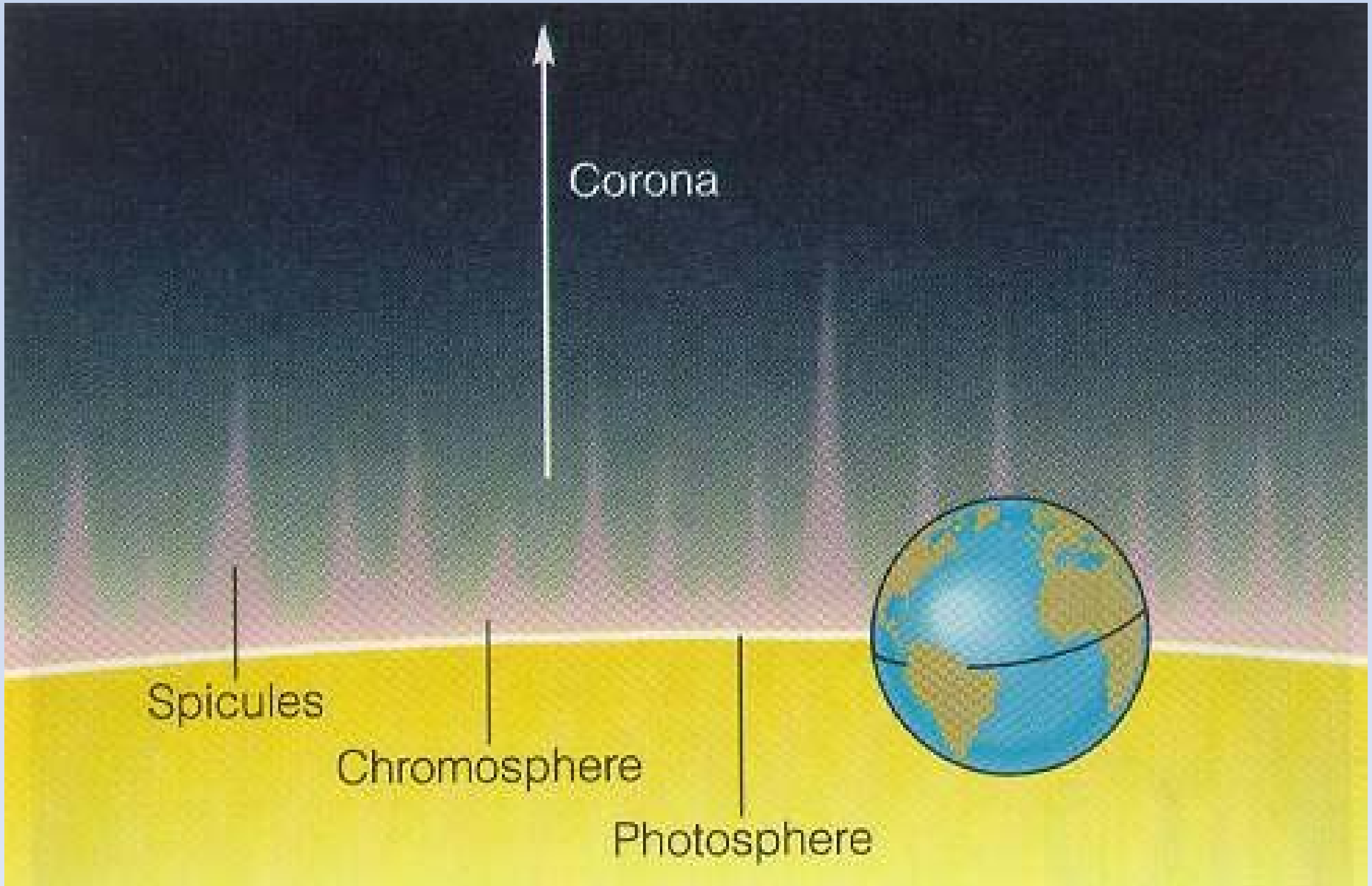
Feature I: Spicules

- ✓ Flame-like structures extending up to 12,000 km above the photosphere.
- ✓ Can last for about 5 to 15 minutes.
- ✓ Appear to be cooler regions, about 10,000 K in temperature, extending up into the corona.



The Solar atmosphere - The chromosphere

Feature I: Spicules



The Solar atmosphere - The chromosphere

Feature I: Spicules

An H_α filtergram showing the entire solar disk reveals the structure of the chromosphere.

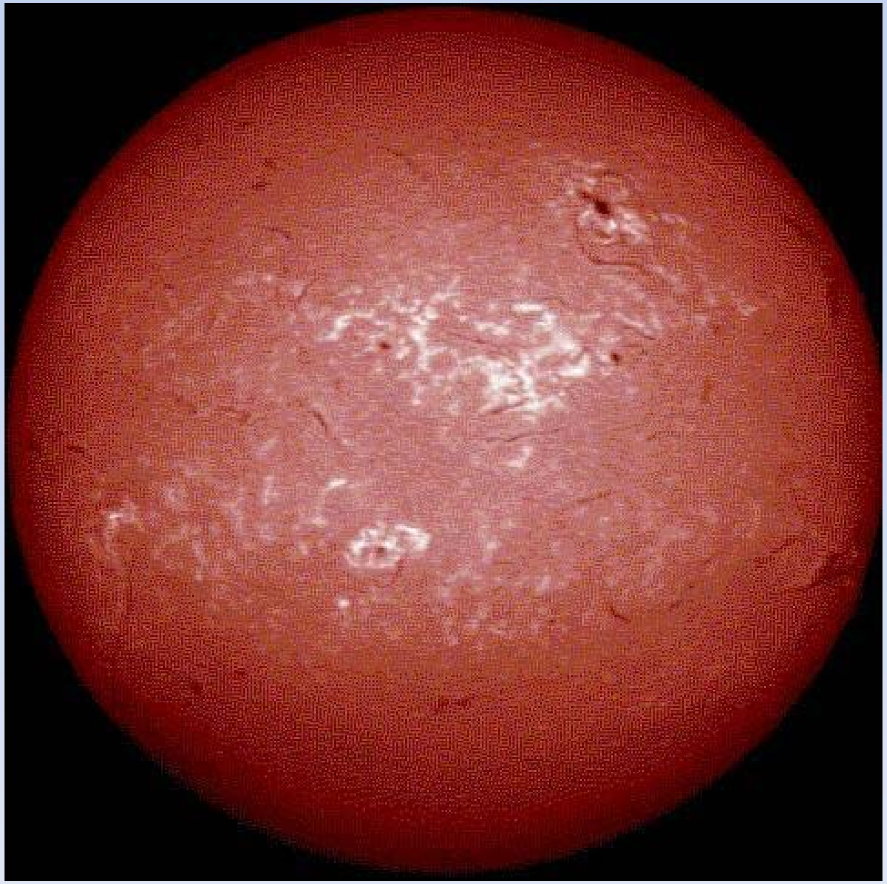


Image: NASA

The Solar atmosphere - The chromosphere

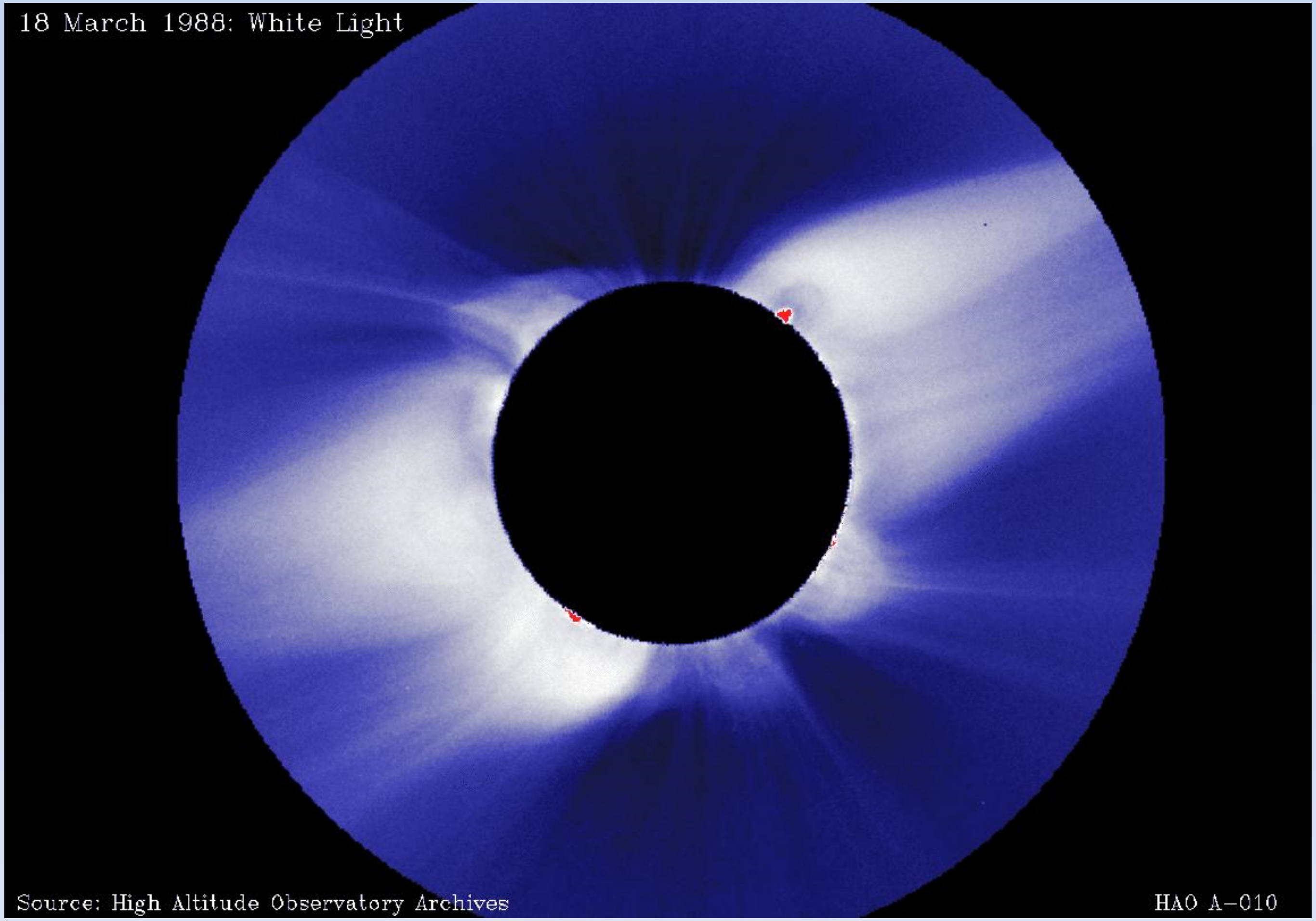
Feature II: Solar wind

- ✓ Hot gases blowing outward.
- ✓ Consists mainly of high-speed (about 400 km/s) ionized hydrogen.
- ✓ Low density, only a few particles per cubic centimetre.
- ✓ Causes a mass loss of about 10^7 tons/year, a minor loss in the solar mass.

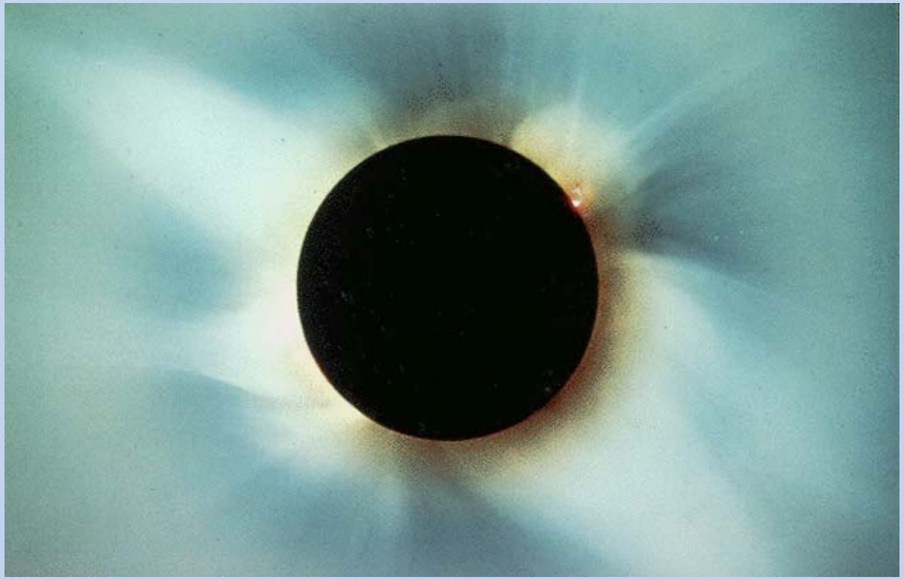
The Solar atmosphere - The corona (日冕)

- ✓ The outermost layer.
- ✓ Extend out to many (even 39) solar radii.
- ✓ Visible only during total solar eclipses.
- ✓ 500,000 K to 3,500,000 K (not fully understood why so hot and so strong magnetic field)
- ✓ The density is very low, about a few atoms per cubic centimetre.

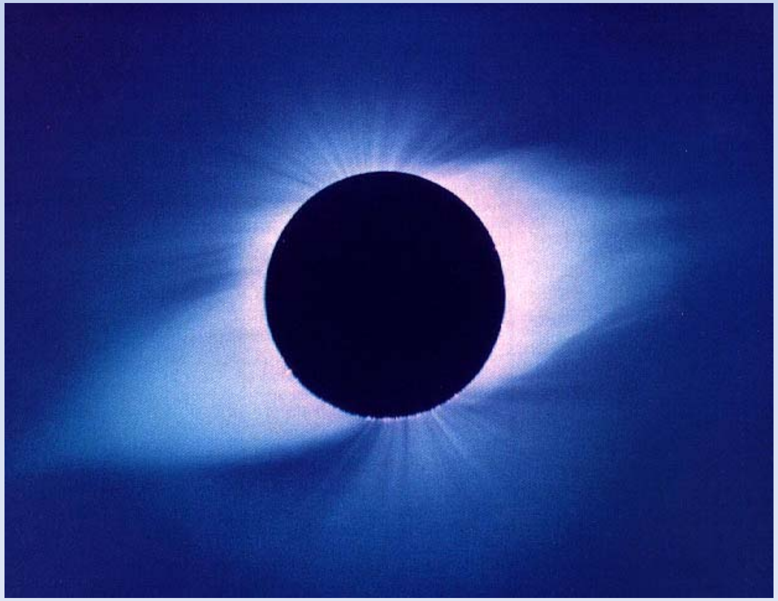
The Solar atmosphere - The corona

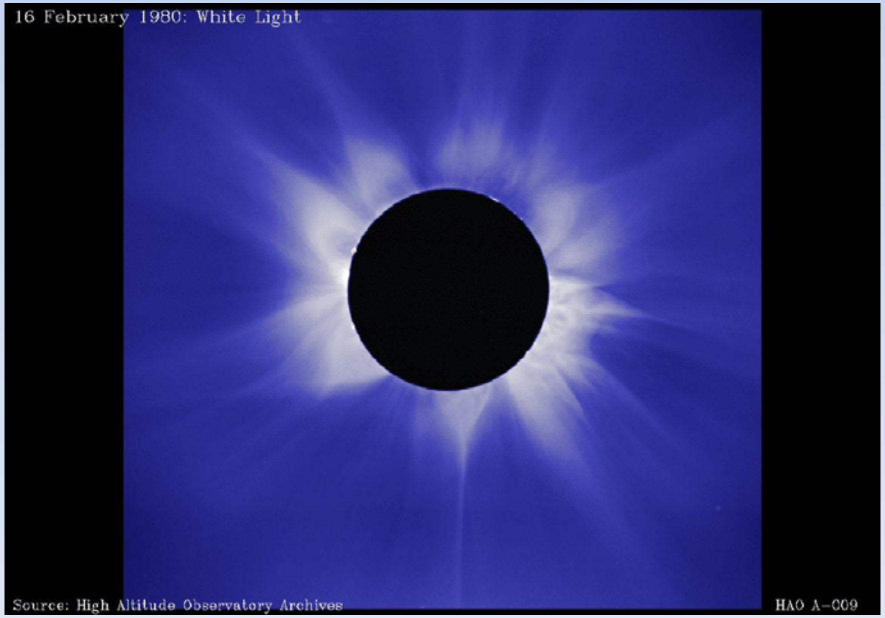


Visible only during total solar eclipses



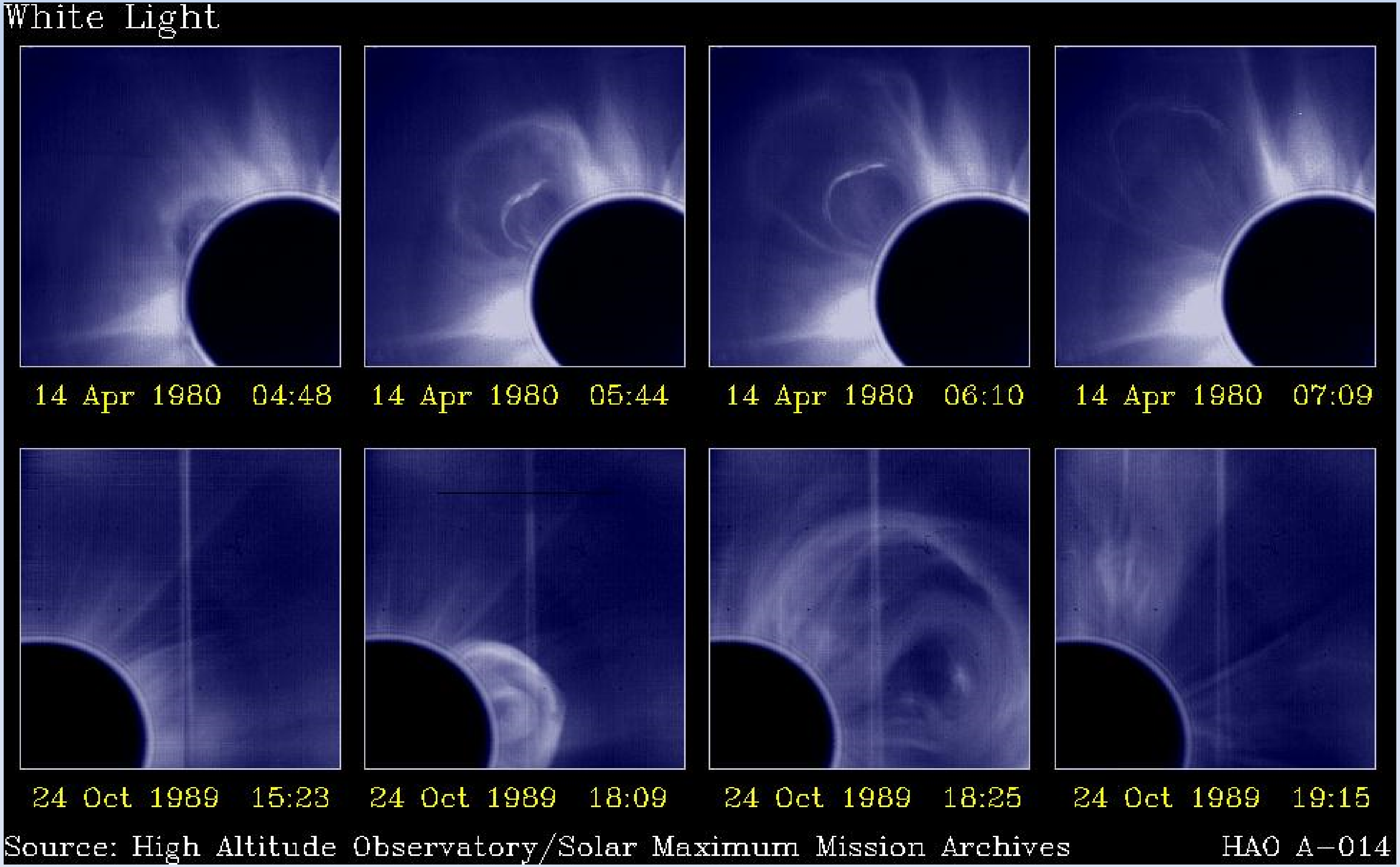

Solar Corona at Eclipse, 3 Nov 1994, Putre, Chile.
High Altitude Observatory, NCAR, Boulder, Colorado, USA.



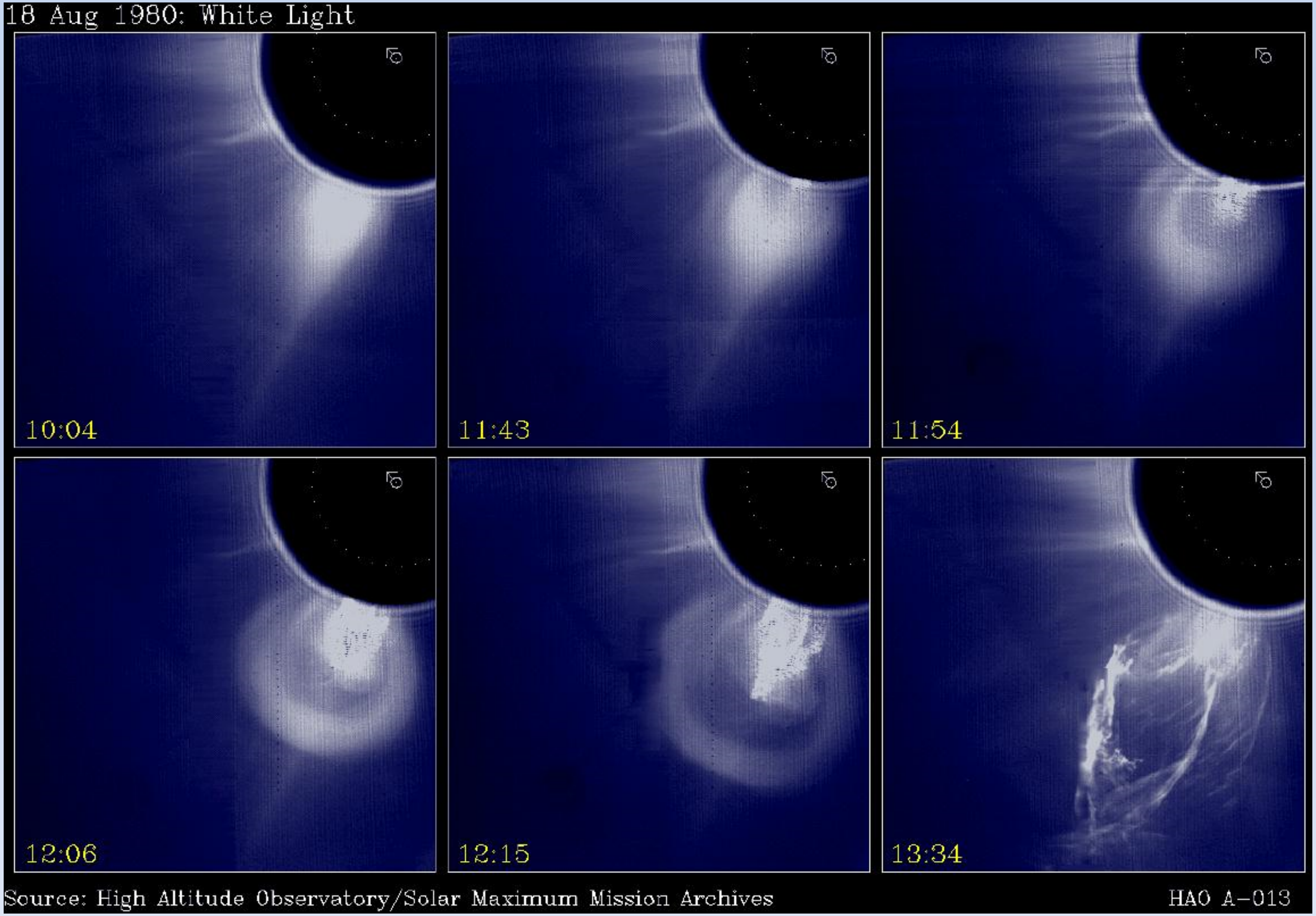

16 February 1980: White Light
Source: High Altitude Observatory Archives
HAO A-009


MK3 Coronameter
MLSO
Jan 1, 1995
DOY 1
North is straight up

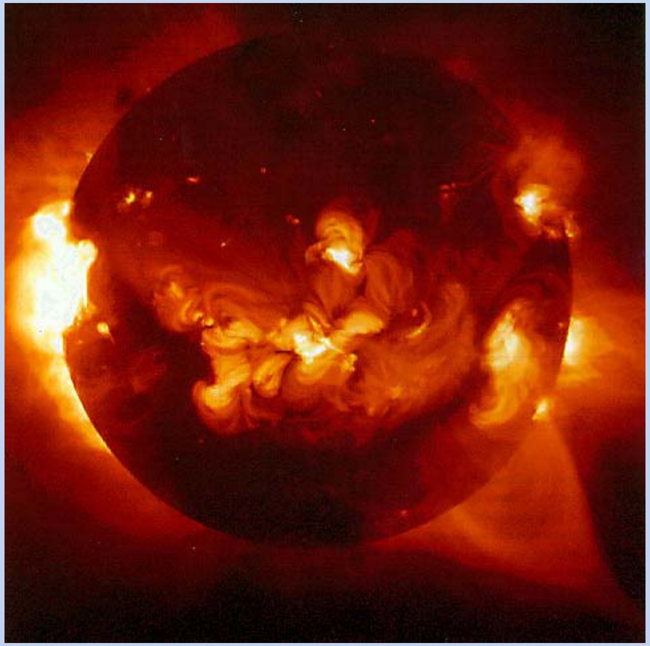
The Solar atmosphere - The corona

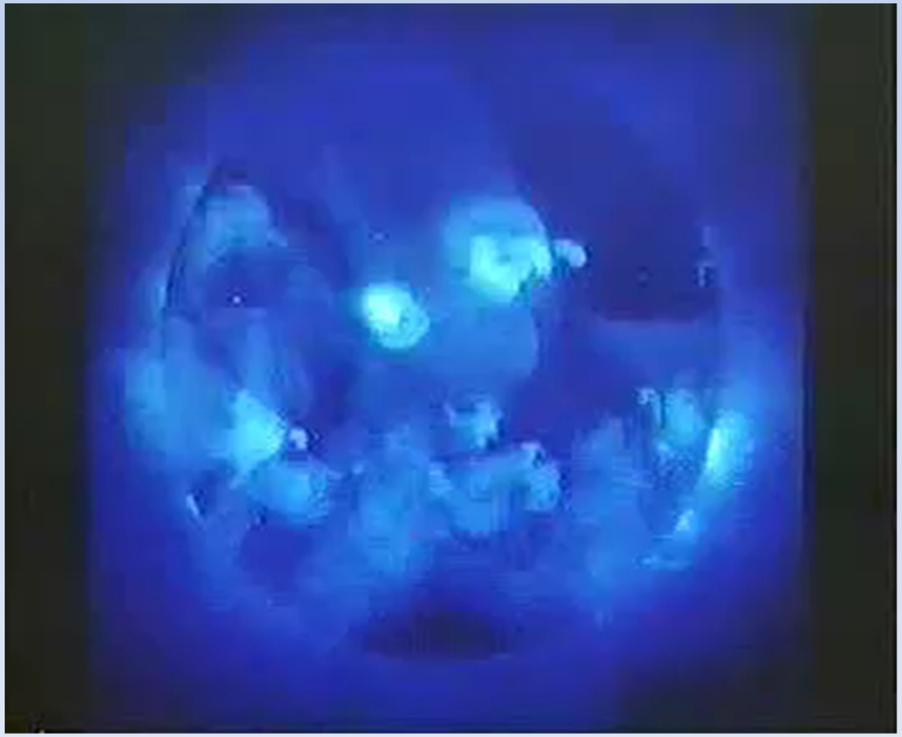


Coronal mass ejection


18 Aug 1980: White Light
10:04
11:43
11:54
12:06
12:15
13:34
Source: High Altitude Observatory/Solar Maximum Mission Archives
HAO A-013

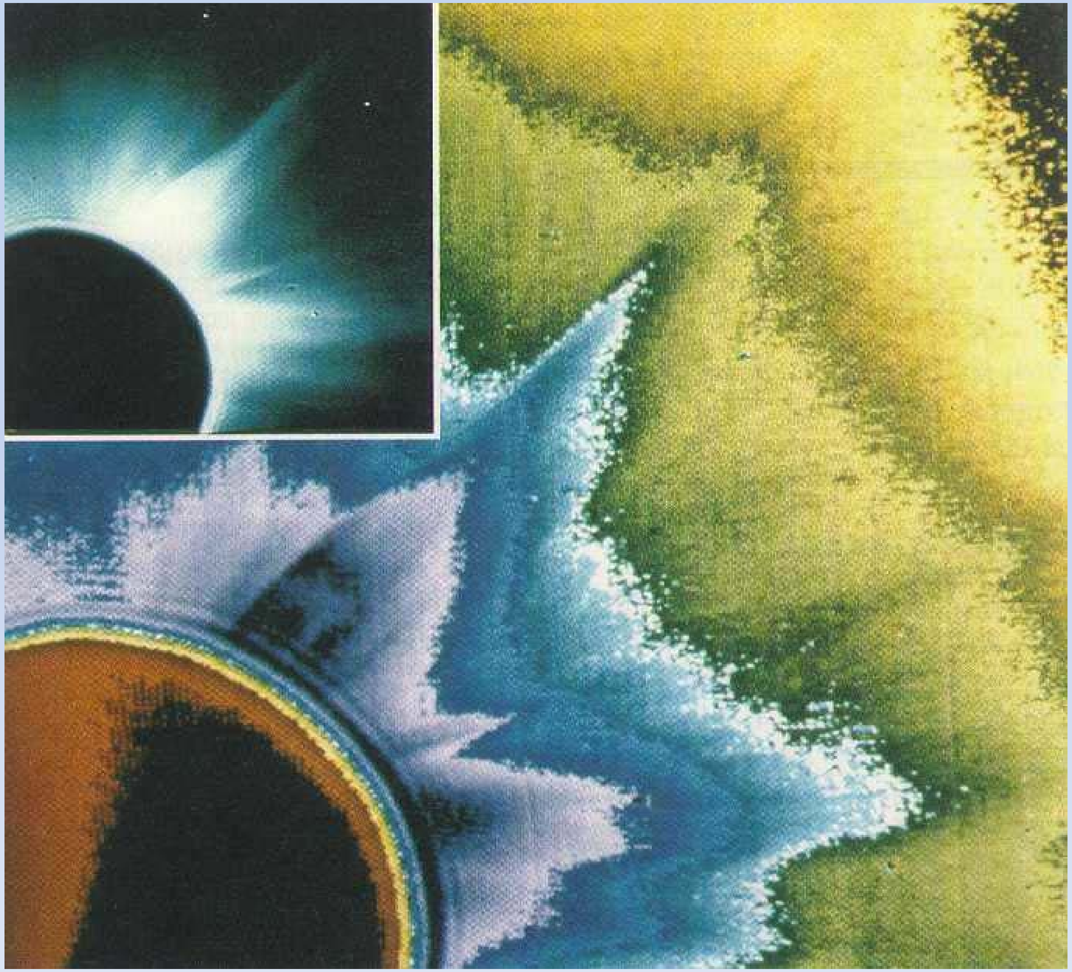
X-ray picture of the corona





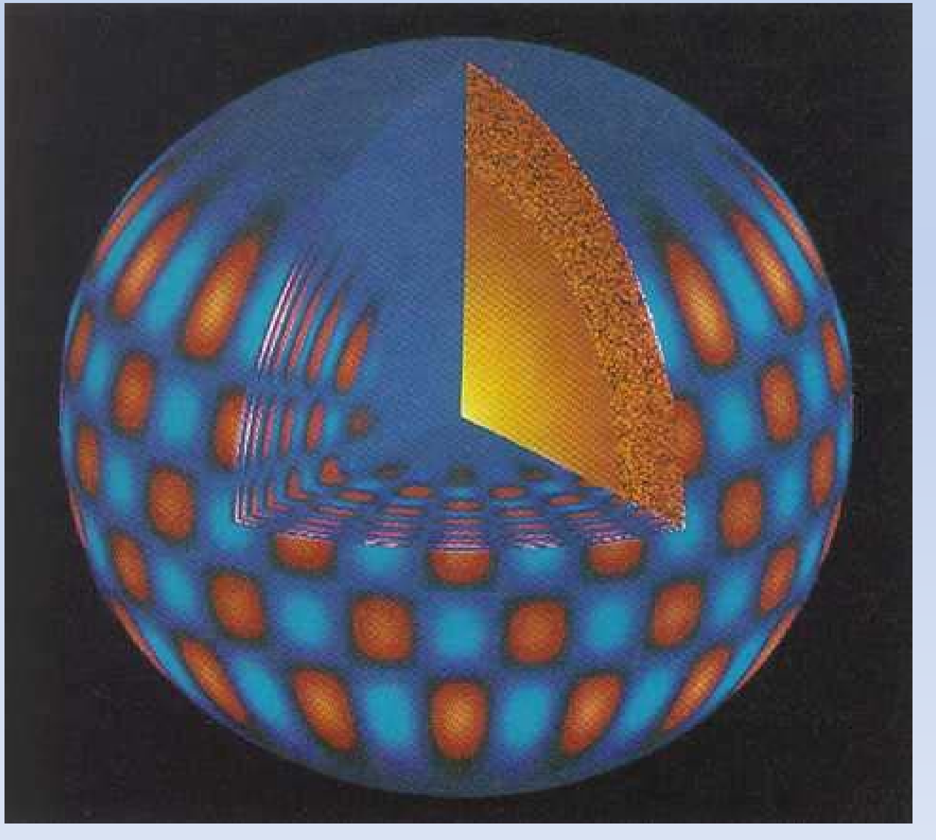
The Solar atmosphere - The corona

- ✓ Streamers in the solar corona.
- ✓ Computer-enhanced to produce a false-colour image.



The solar interior

- ✓ Helioseismology: a study of solar vibrations
- ✓ There are many possible modes of oscillation of the Sun. Here's one in the figure.
- ✓ Red regions are receding, while blue regions are approaching.



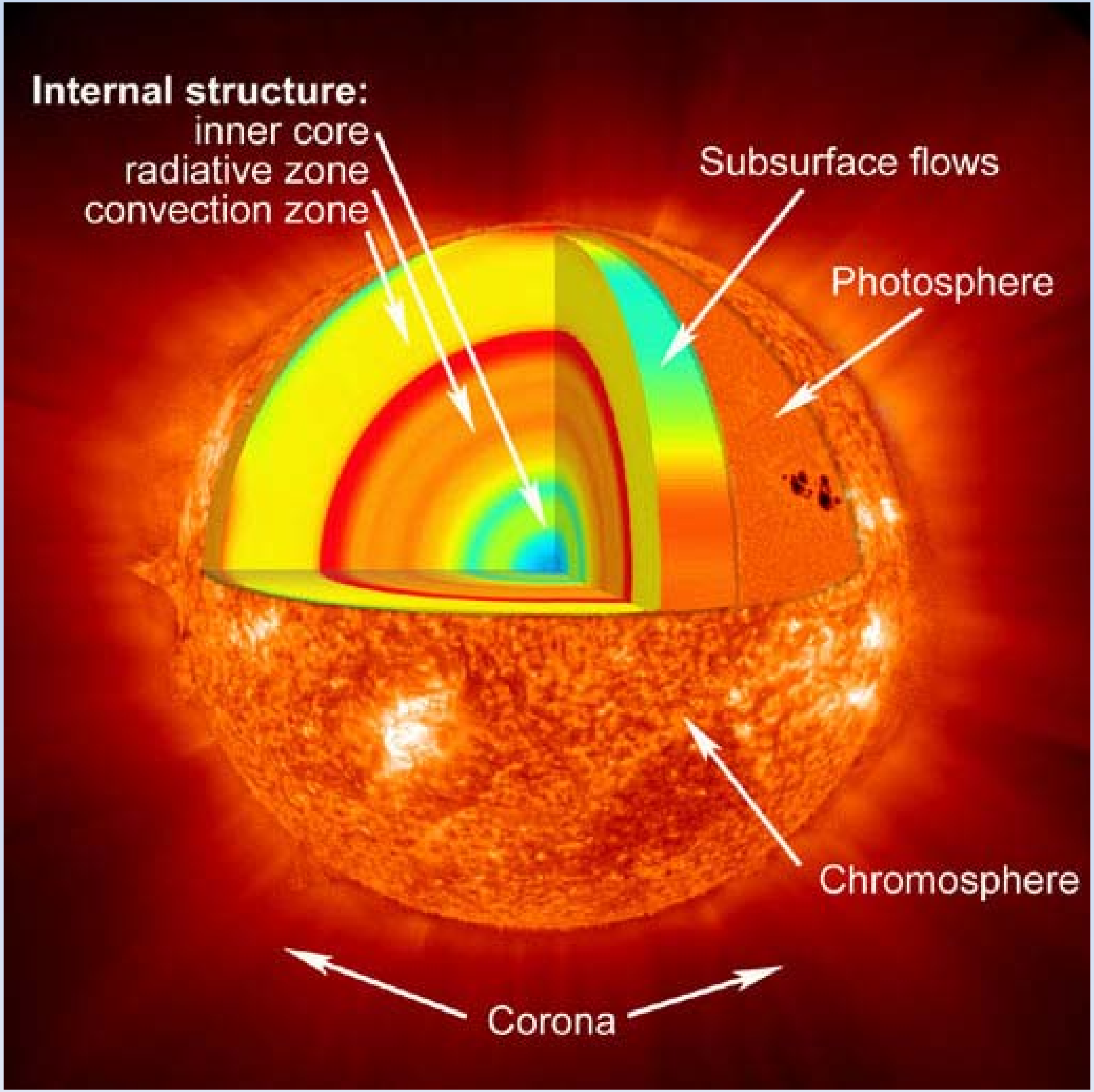

Internal structure:
inner core
radiative zone
convection zone
Subsurface flows
Photosphere
Chromosphere
Corona

Image: NASA

Solar activities

- ✓ There are many violent solar activities.
- ✓ We shall discuss sunspots (太陽黑子), prominences (日珥), and flares (耀斑).
- ✓ We shall also discuss the effects of solar activities on the Earth.

Solar activities – Sunspots (太陽黑子)

- ✓ Umbra: the central region, ~ 4,000 K.
- ✓ Penumbra: a bit hotter than the umbra region but is still cooler than the photospheric average.

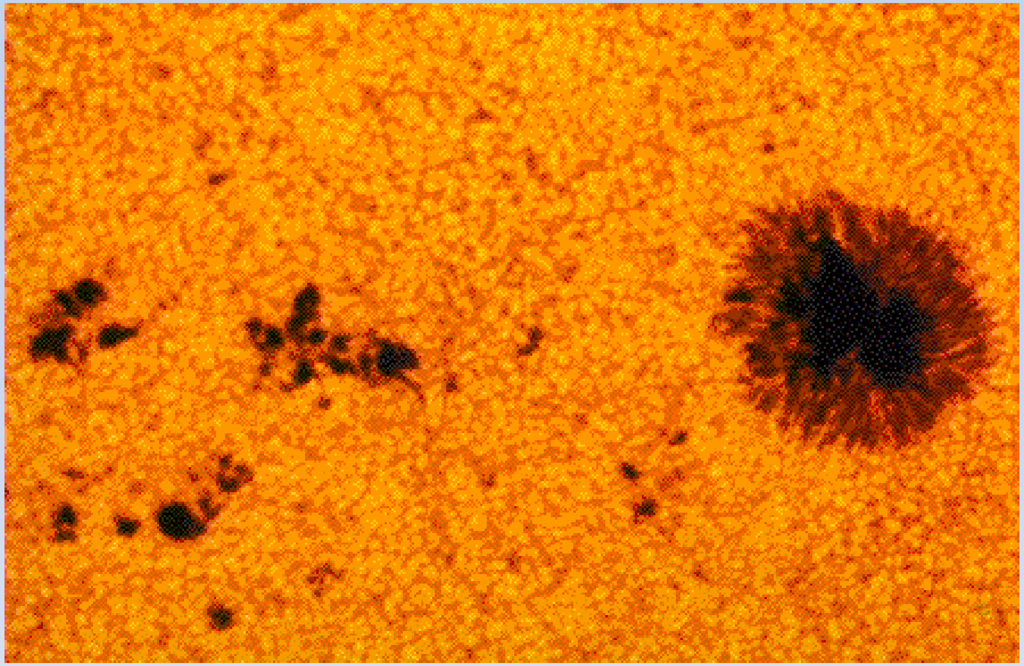
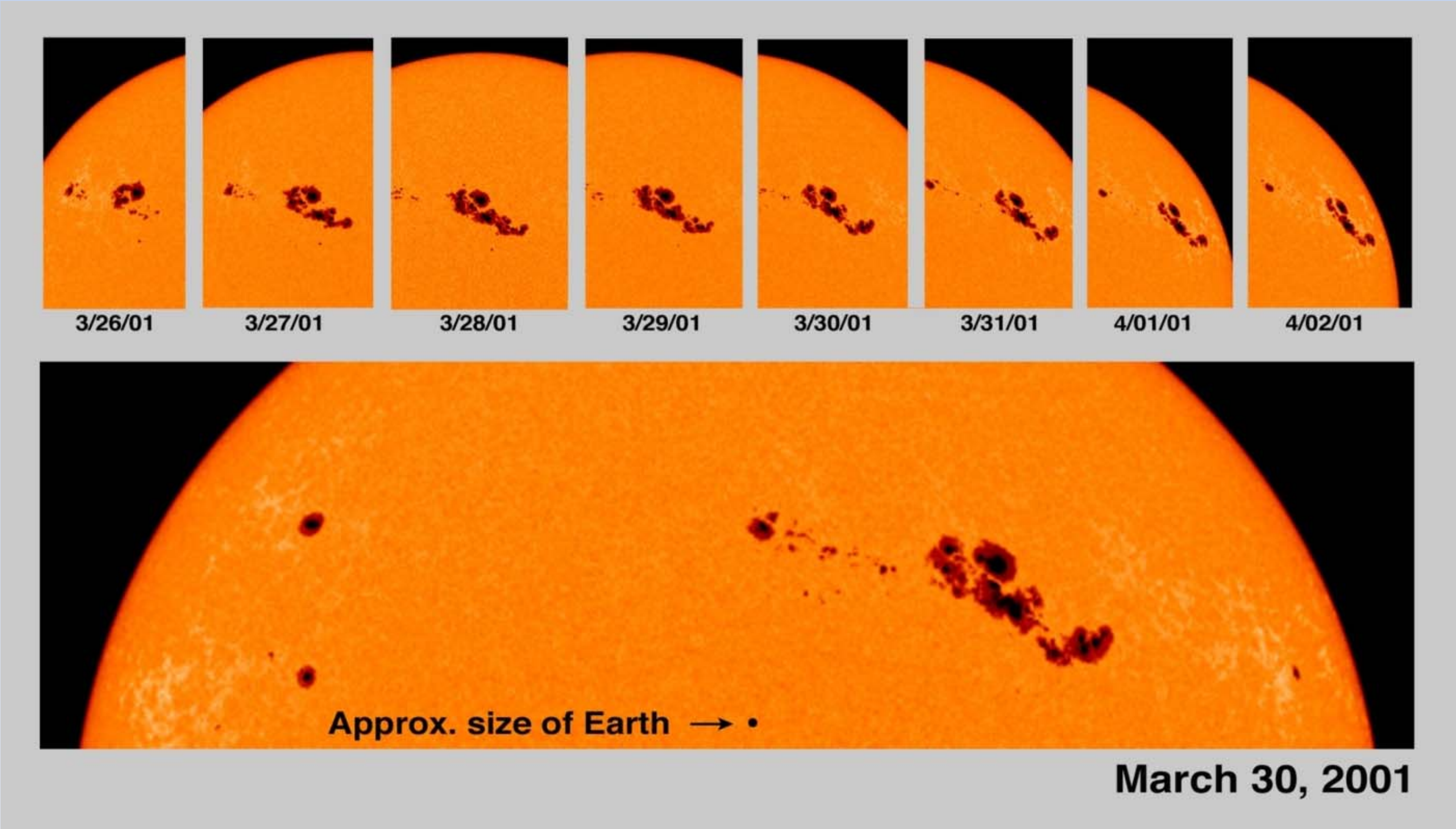


Image: NSO/AURA/NSF

Solar activities - Sunspots

Organization and motion:

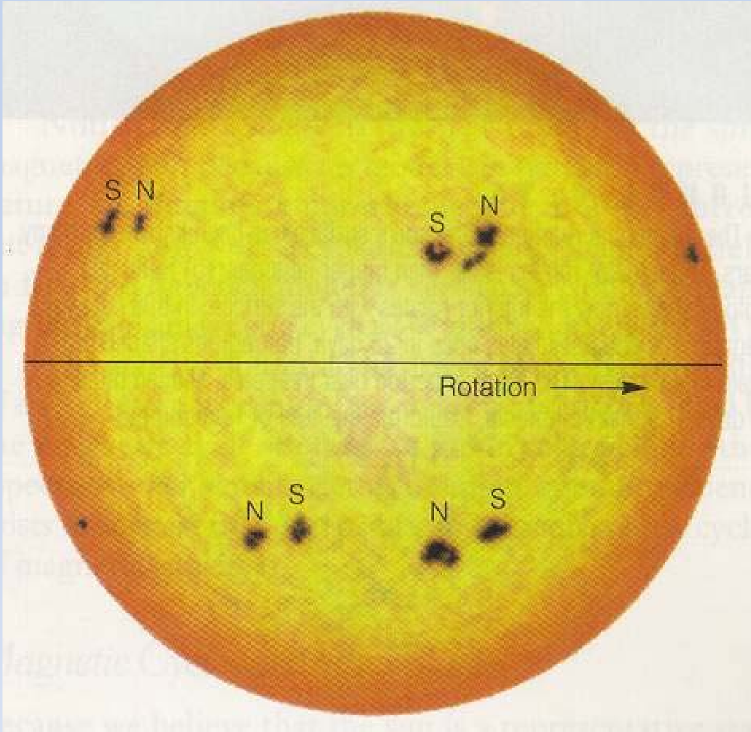
- ✓ Move in groups.
- ✓ Move from higher latitudes to near the equator.

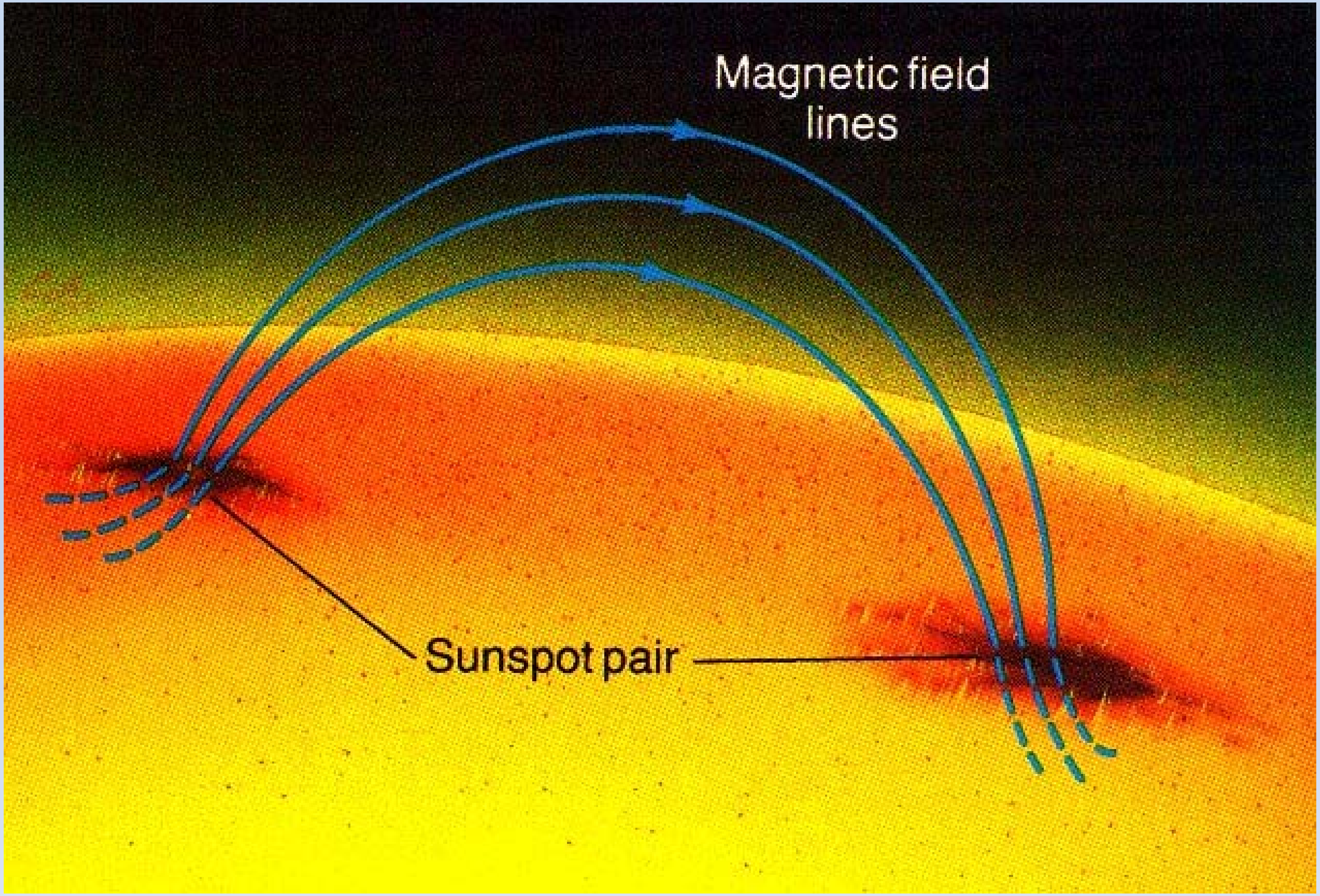


Solar activities - Sunspots

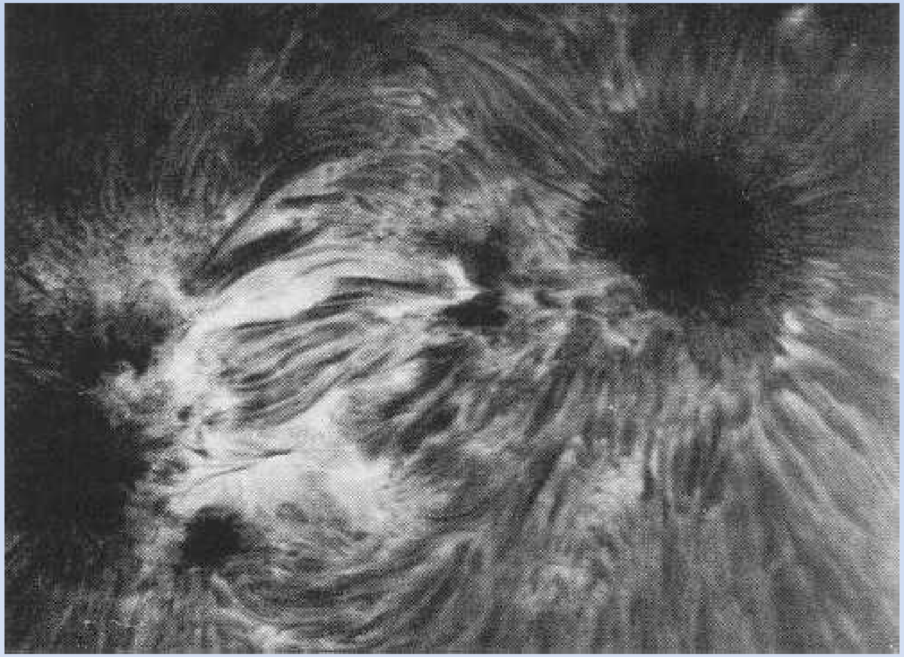
Physical properties and spot cycle:

- ✓ Regions of strong magnetic fields, about 1000 times stronger than the solar average.
- ✓ Appear in pairs.
- ✓ The sunspots in a pair are of opposite magnetic polarities.
- ✓ Across the equator, polarity reverses.

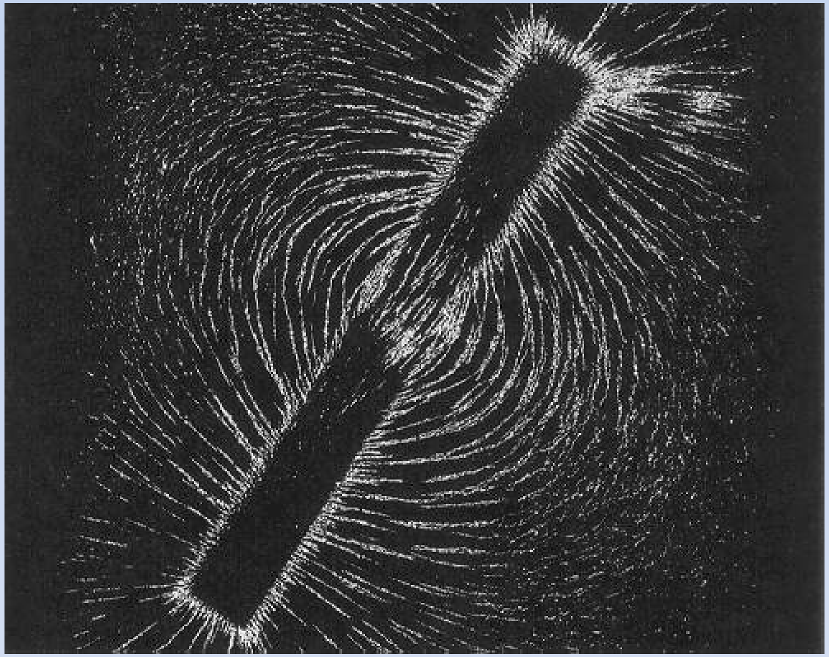



Magnetic field lines
Sunspot pair

Solar activities - Sunspots



An H-alpha filtergram
of a sunspot group

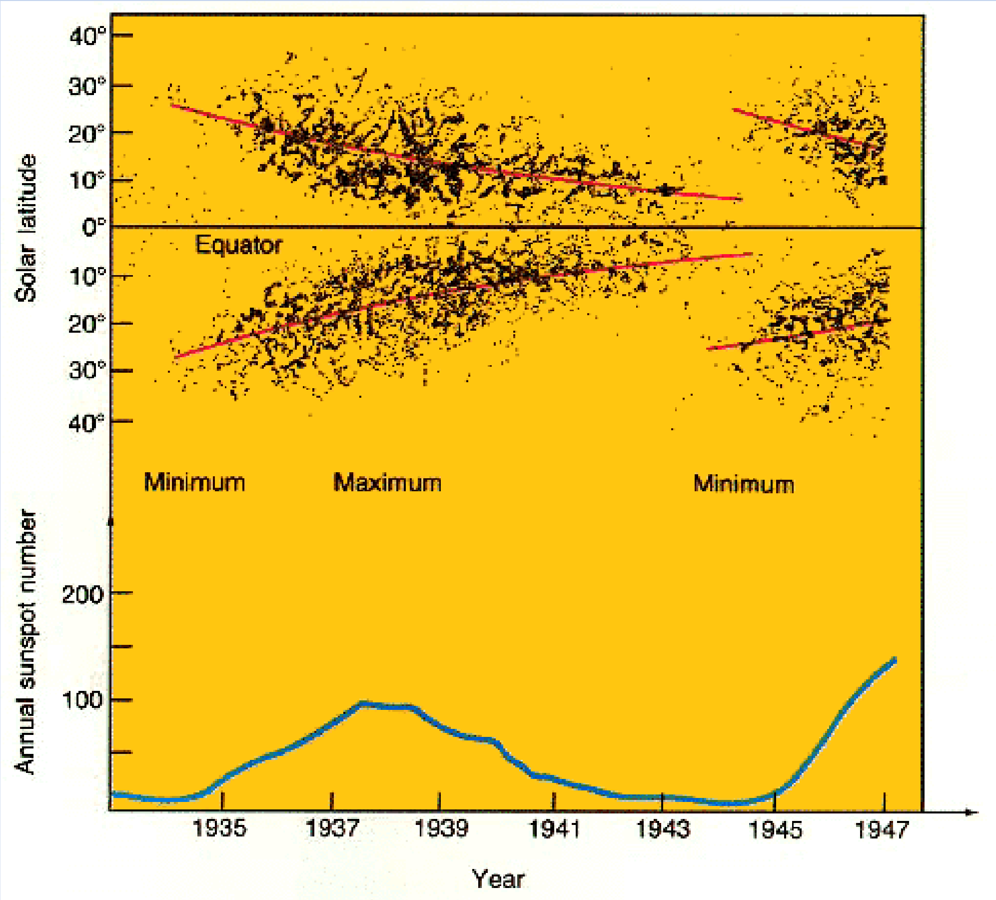


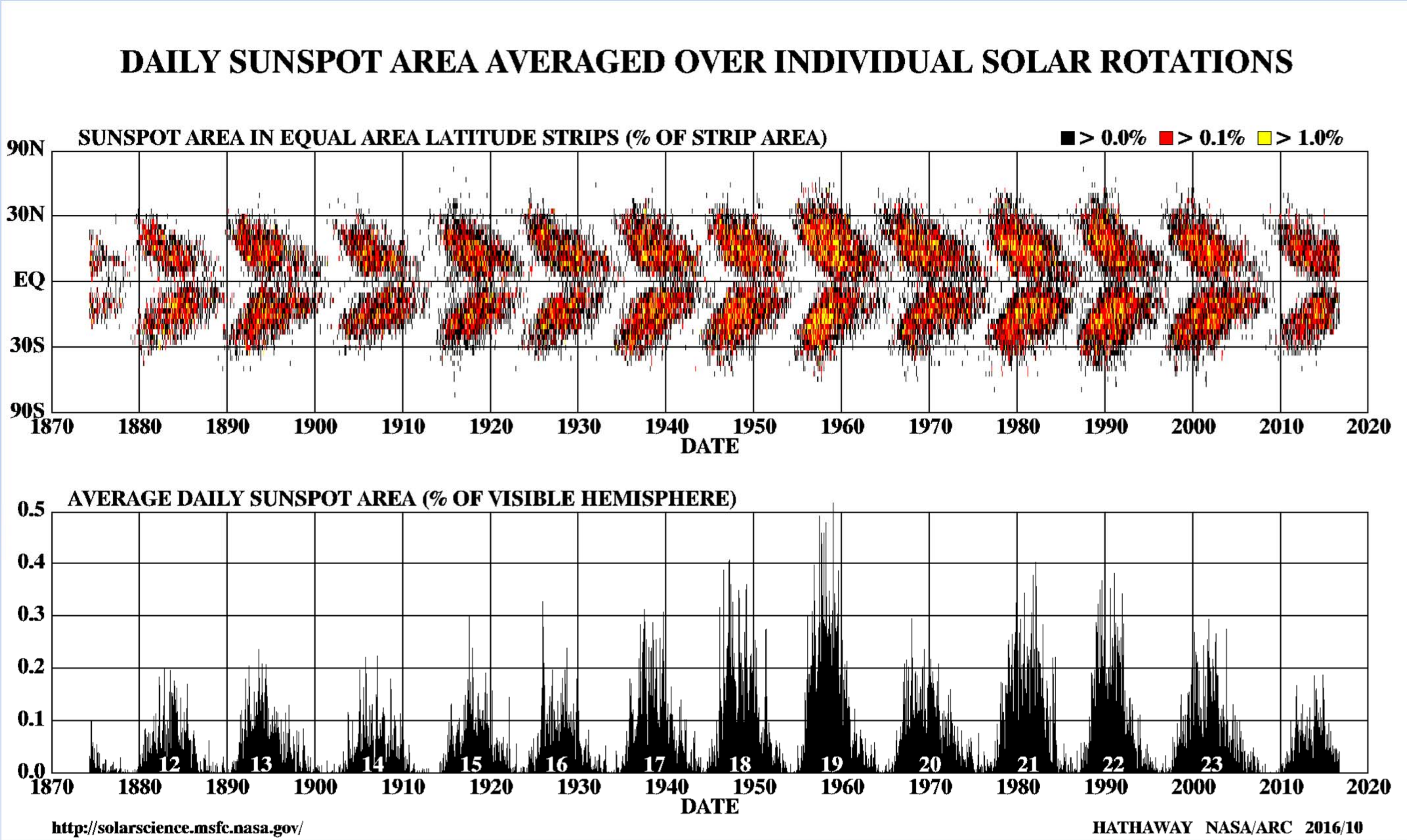
Iron filings sprinkled
over a bar magnet

Solar activities - Sunspots

Physical properties and spot cycle:

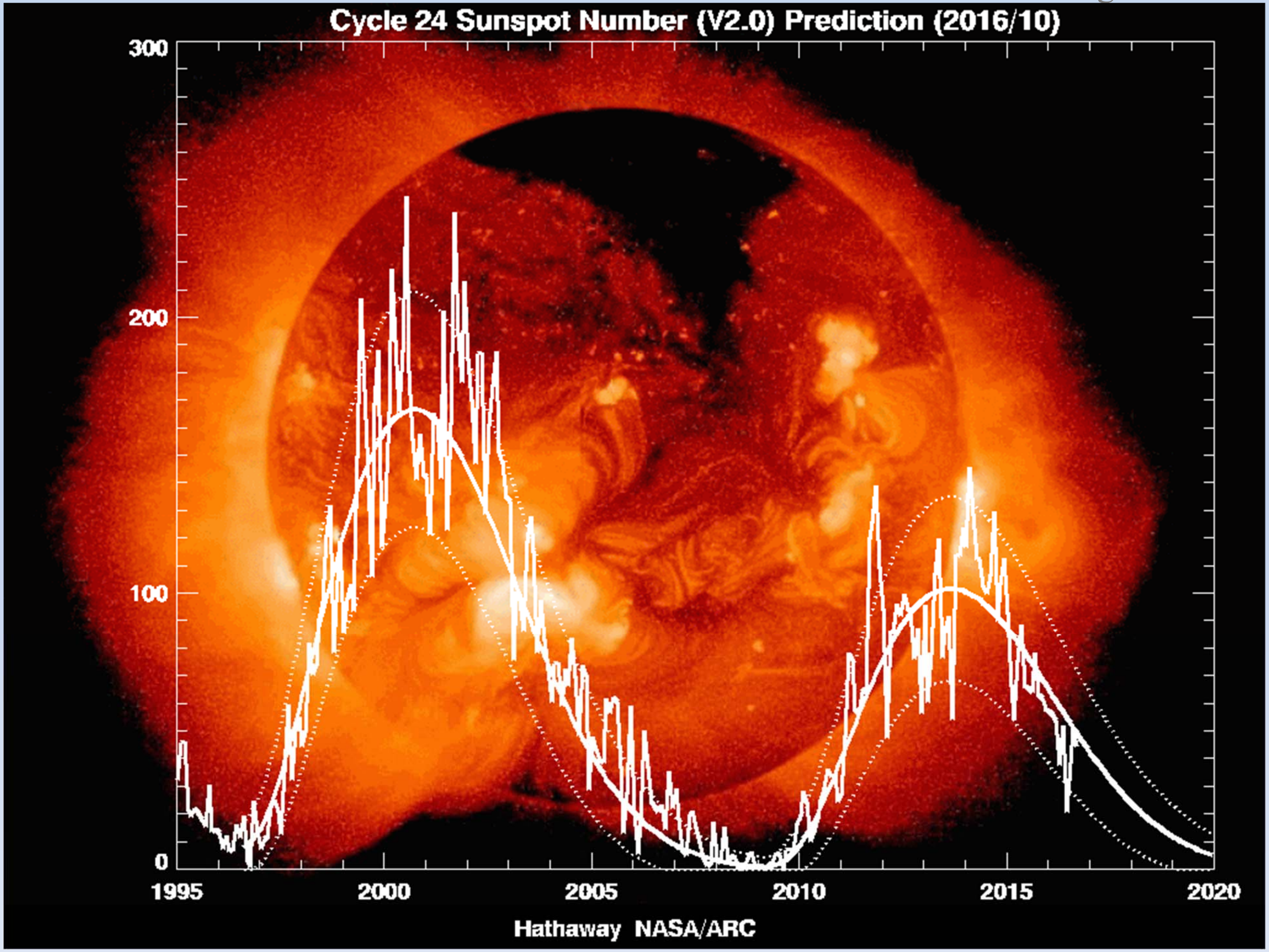
- ✓ The number of sunspots varies with a period of about 11 years (*just past a solar maximum*)
- ✓ a **sunspot cycle**.
- ✓ Again, move from higher latitudes to near the equator.





Butterfly diagram (positions of sunspots)
and the sunspot area in the last 140 years.

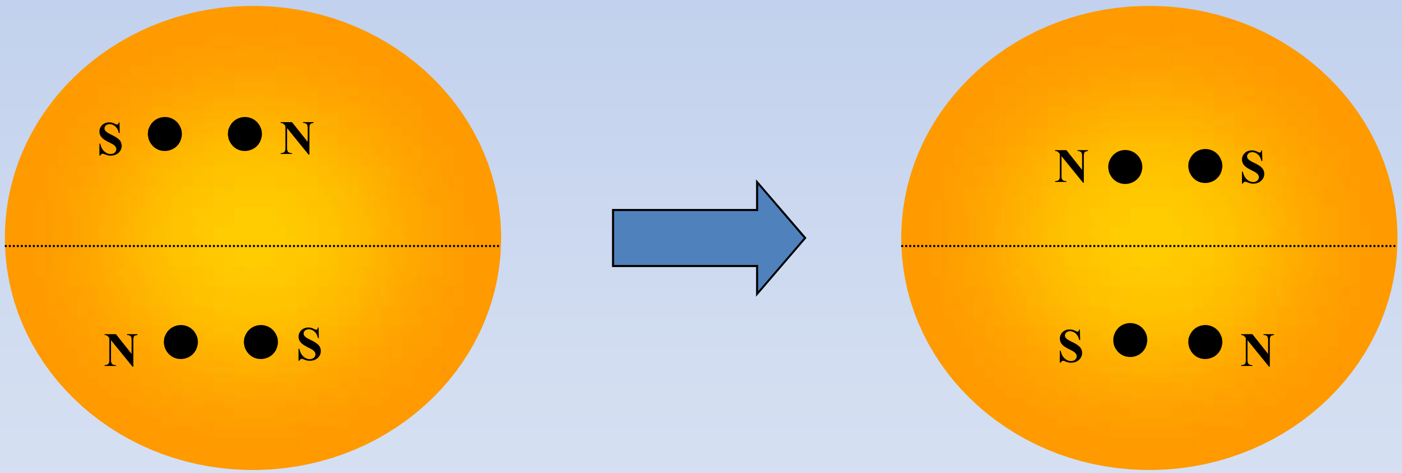
Image: NASA



The current solar cycle

Solar activities - Sunspots

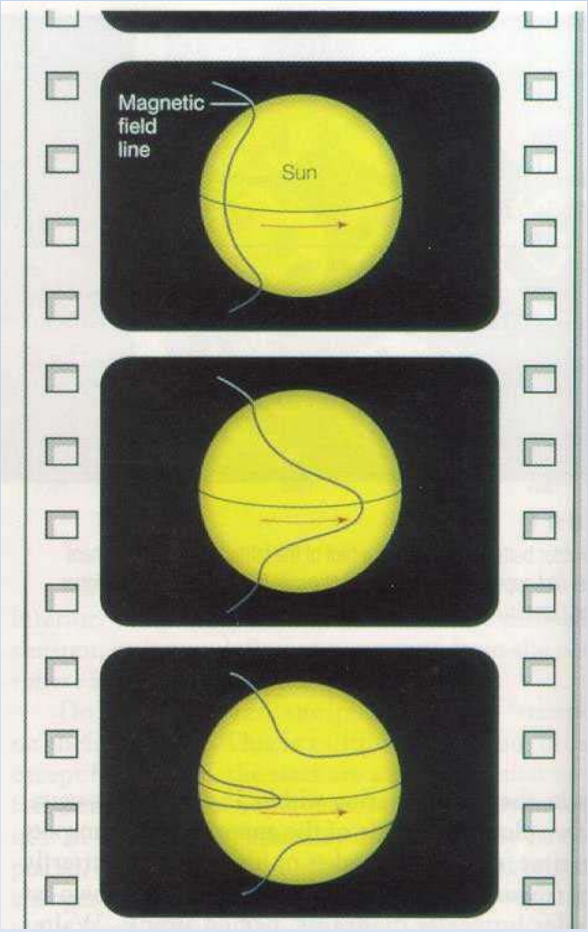
✓ The overall polarity reverses from cycle to cycle.

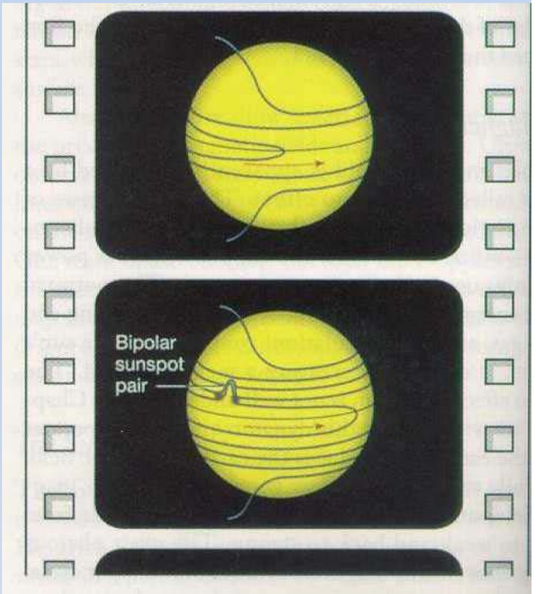


Solar activities - Sunspots

Formation:

- ✓ Differential rotation of the Sun leads to twisting of magnetic fields.
- ✓ Magnetic buoyancy instability of the tangled field leads to the rising of magnetic flux tube.

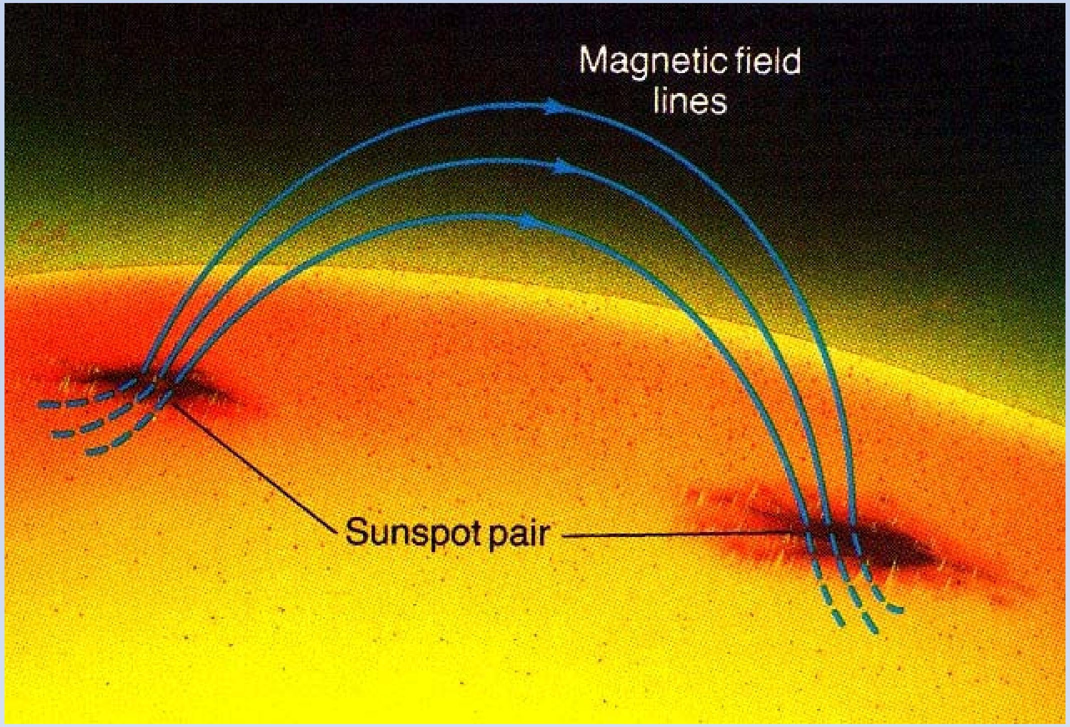




Solar activities - Sunspots

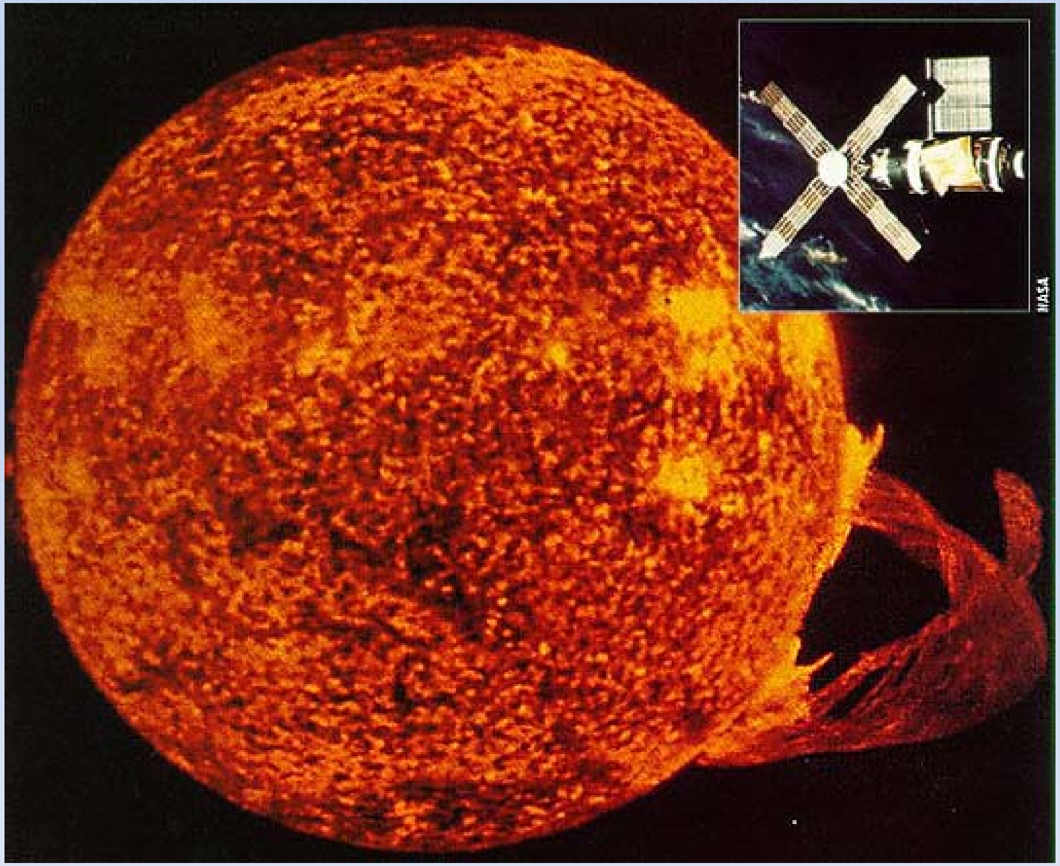
Formation:

- ✓ When the field bursts through the surface, sunspot pairs form.
- ✓ Magnetic fields inhabit circulation by slowing rising hot gas.
- ✓ The sunspots become cooler.



Solar activities – Prominences (日珥)

- ✓ Red filaments shooting upward from magnetic regions (sunspots).
- ✓ Ionized gases trapped in magnetic fields.
- ✓ Some last for hours, some for months.



Prominence
(日珥)

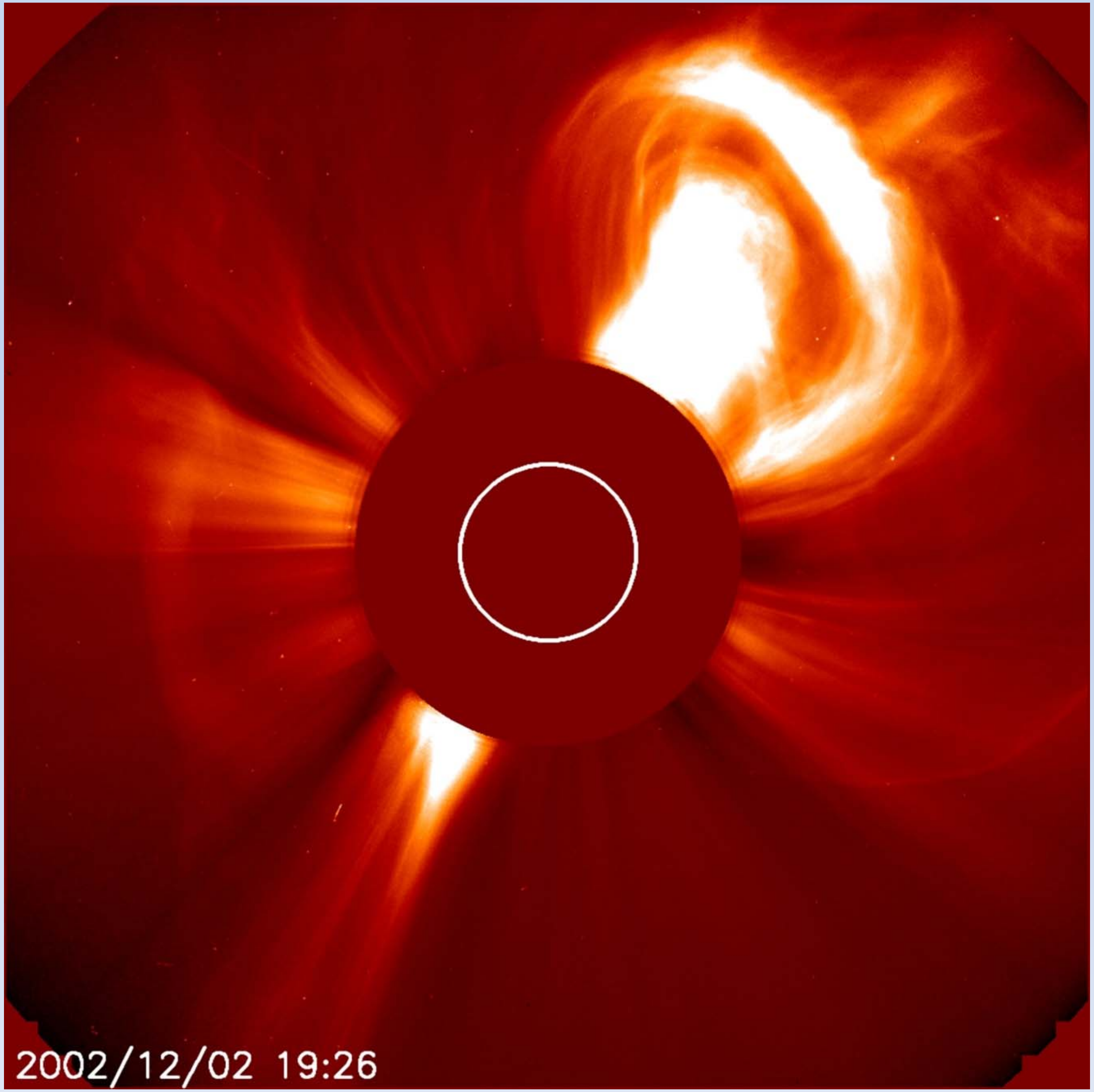


Image: SOHO
(ESA & NASA)

Coronal loops

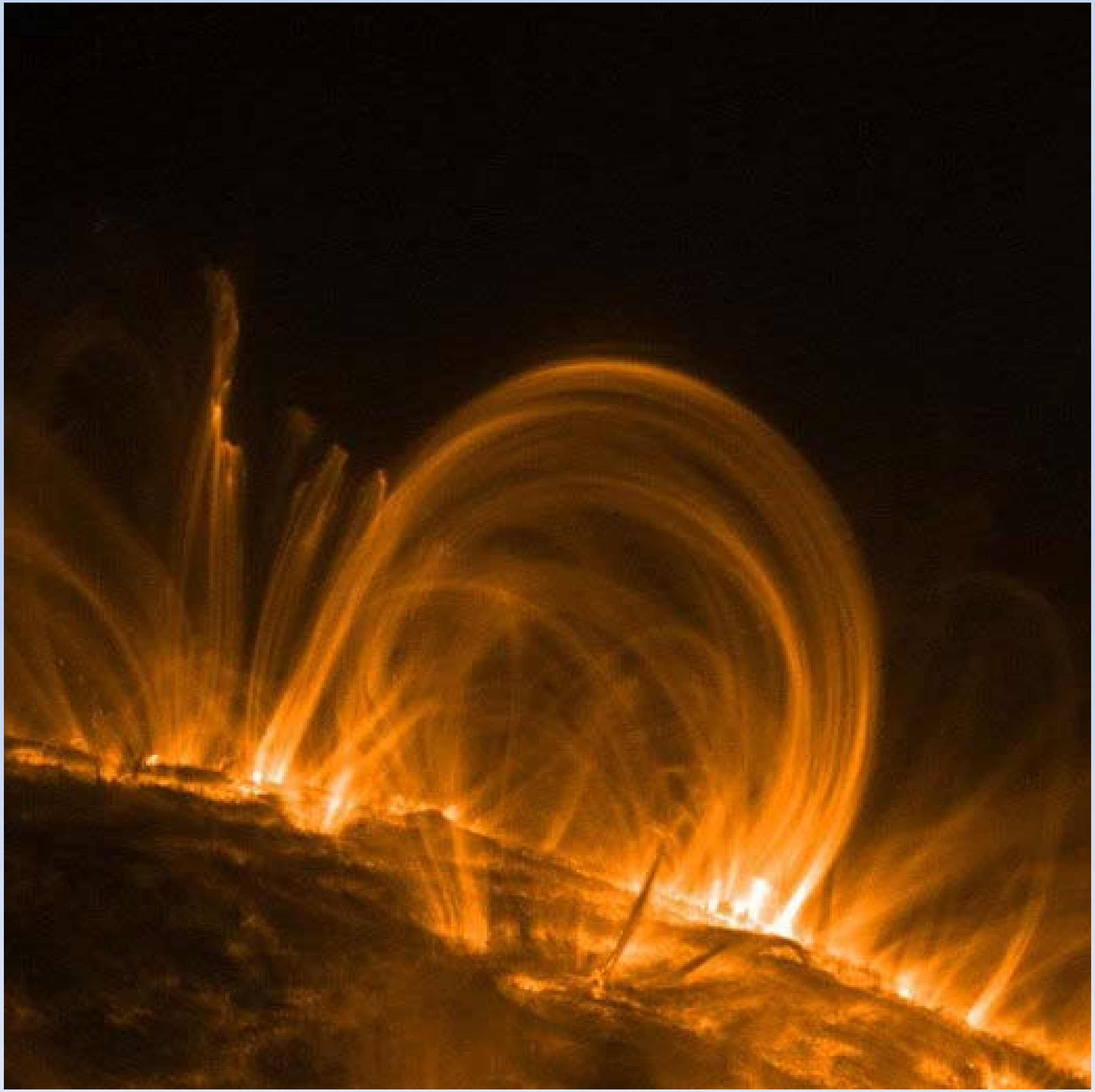
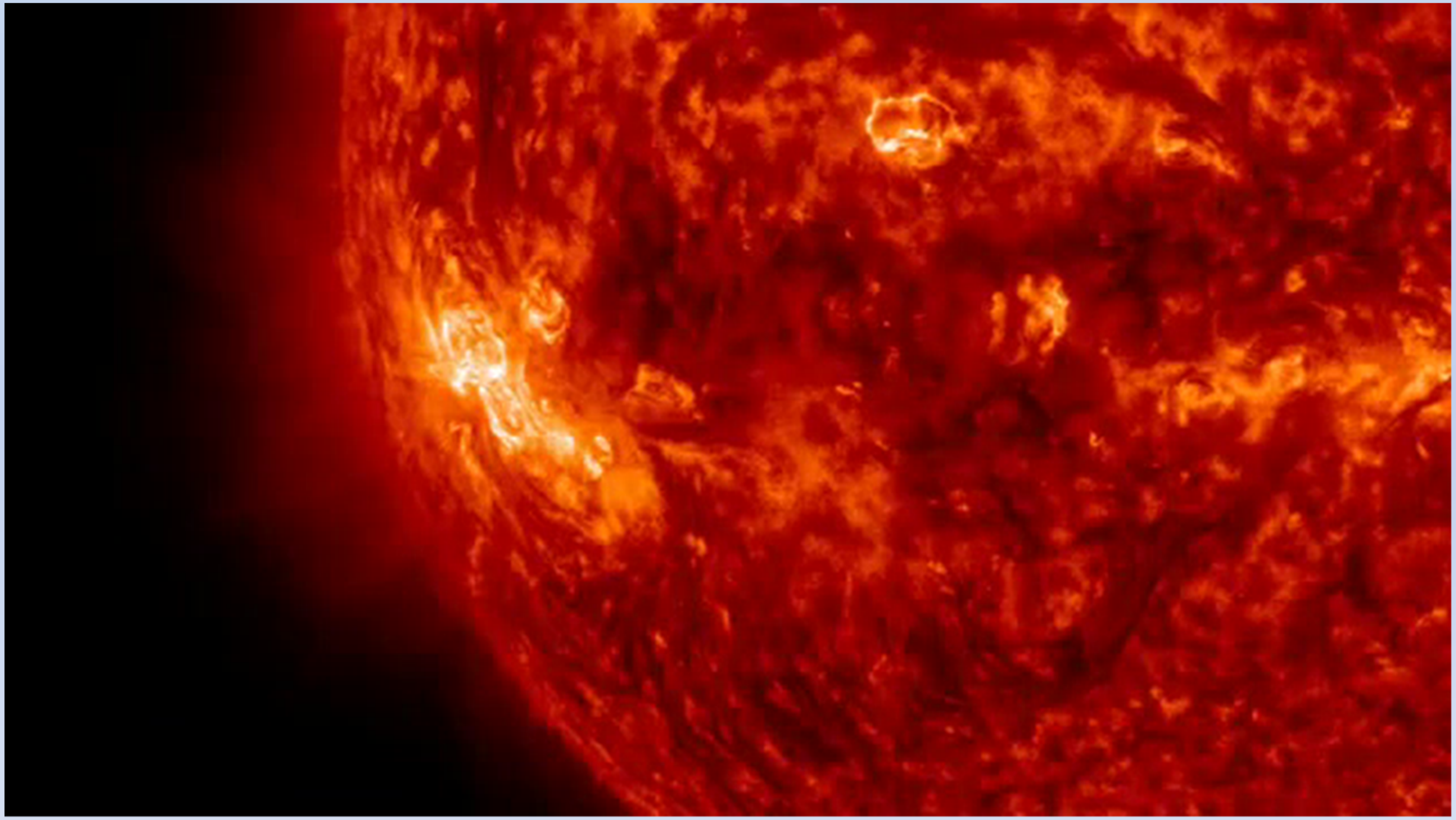


Image: NASA

Solar activities – Flares (耀斑)

- ✓ More violent eruption rising to maximum in minutes.
- ✓ Emit X-ray, ultraviolet, visible light, and high-energy particles.
- ✓ The emitted radiations and particles can interrupt communications on the Earth and cause auroras near poles.
- ✓ Always occur near sunspot groups.



A strong flare in Oct 2014,
without significant CME.

Solar activities – Effects on Earth

Charged particles in the solar wind interact with the Earth's magnetosphere.

The electrons dissipate their energy into the upper atmosphere. The process results in **aurora** (northern light, 極光).

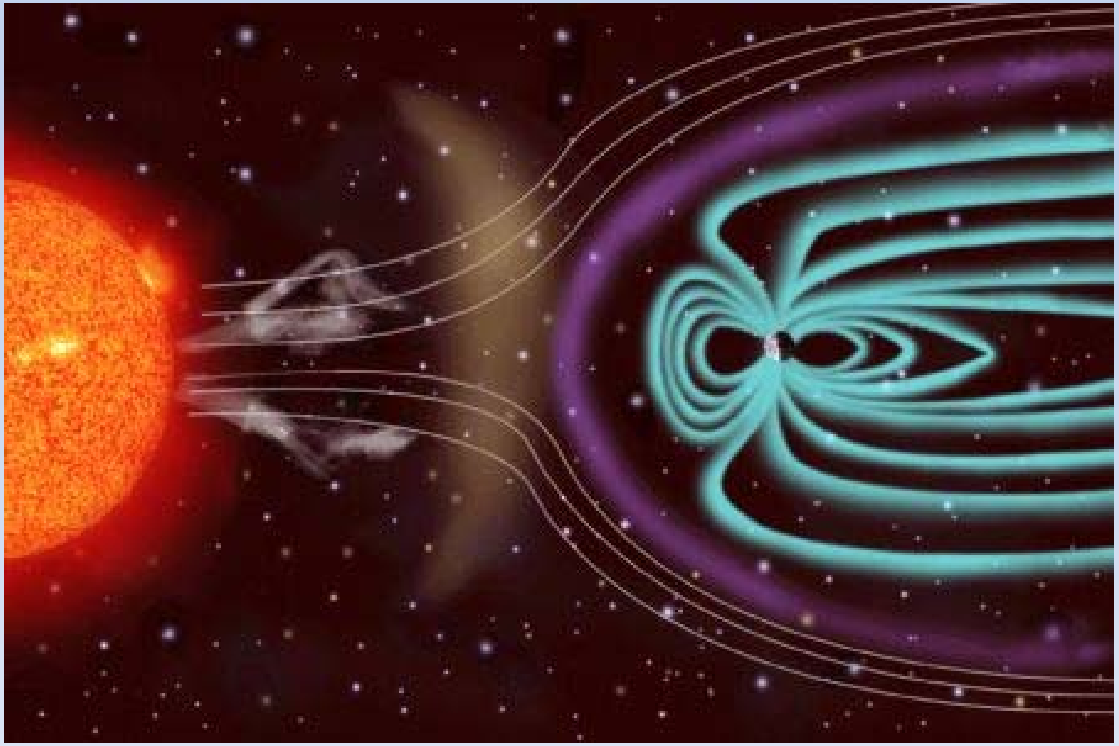
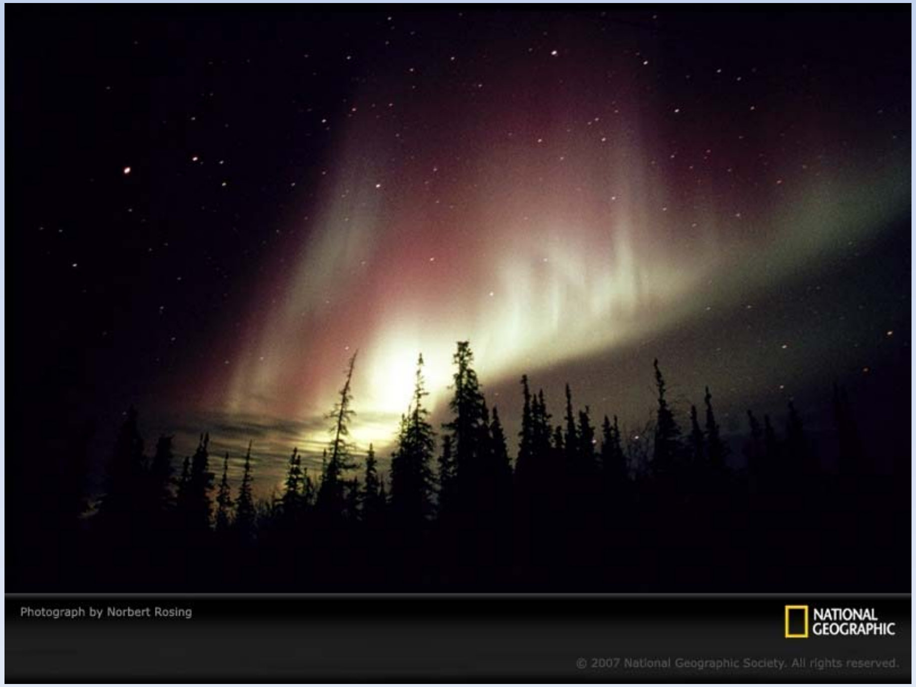


Image: HKO

Aurora


Photograph by Norbert Rosing
NATIONAL GEOGRAPHIC
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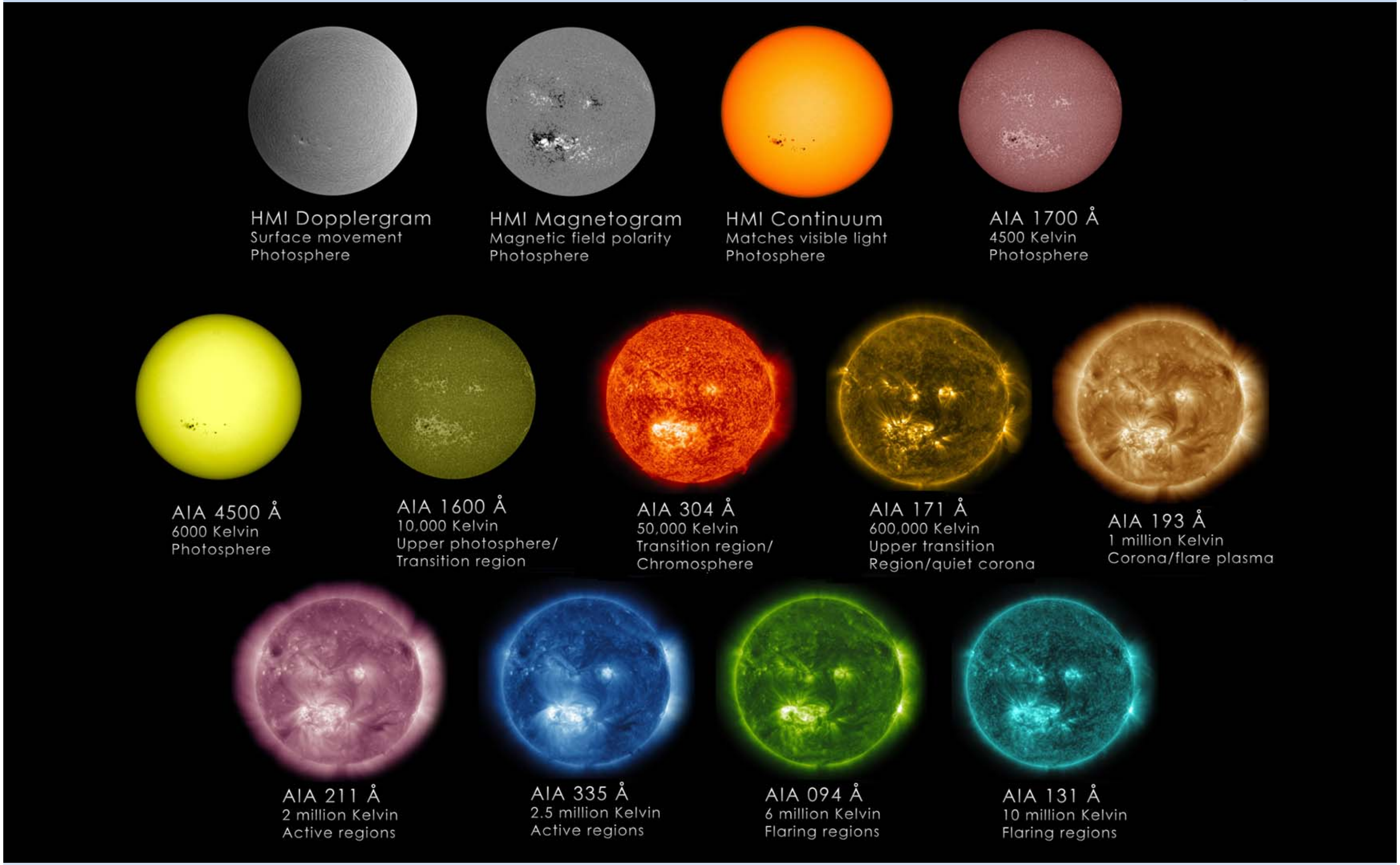
Solar activities – Effects on Earth

The Solar constant:

- ✓ The total solar energy reaching the surface of the Earth, ~ 1360 W/m^2.
- ✓ In fact not constant.
- ✓ If there is a 1% change in the solar constant, there will be 1 - 2°C change in the Earth's temperature.
- ✓ Observation: a long-term decrease of 0.018% per year in solar constant.
- ✓ It is believed that variations in the solar constant can cause long-term changes in the Earth's climate, for example, ice ages.

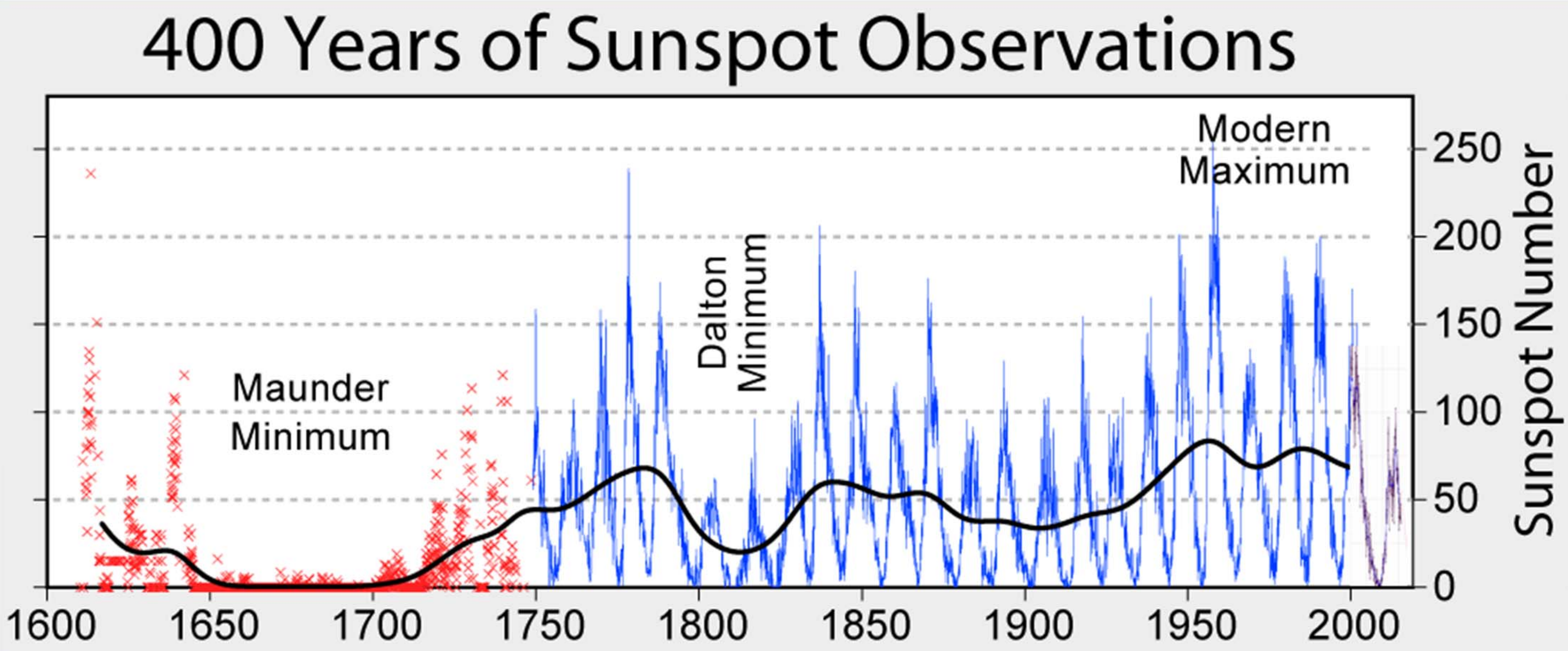
Image: NASA



Continuous and multi-wavelength observation of the Sun by NASA's Solar Dynamics Observatory spacecraft (SDO)

Wouldn't it be great if stars last forever? All good things must come to an end at some point. We are both interested in the process and the destination. Now we shall resume our discussion on how stars evolve...

Image: Wikimedia Commons, Robert A. Rohde, Global Warming Art



A long period of very low number of sunspot coincided with an extended low-temperature period several hundred years ago.