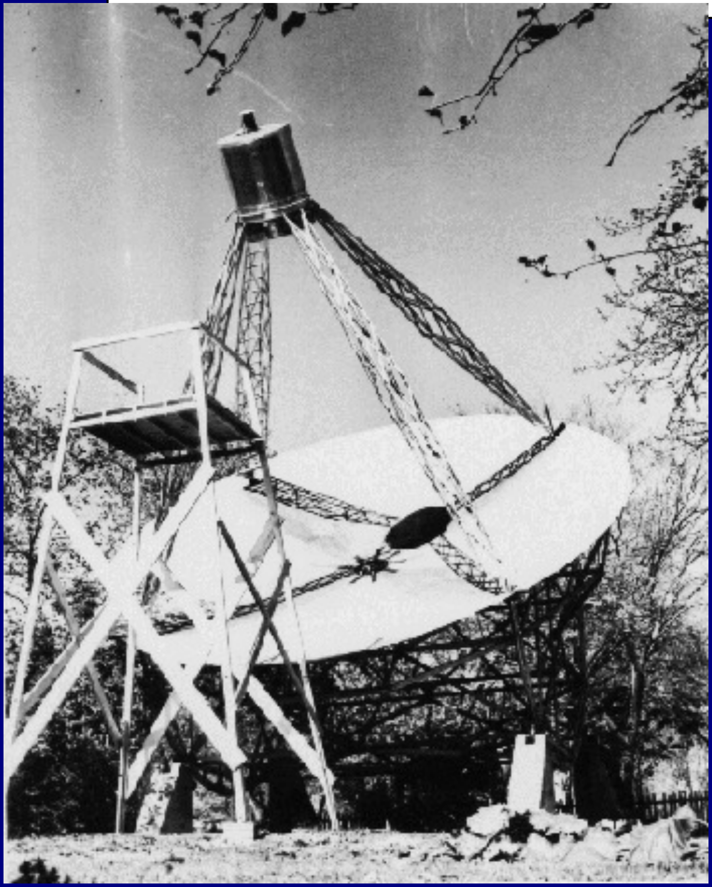
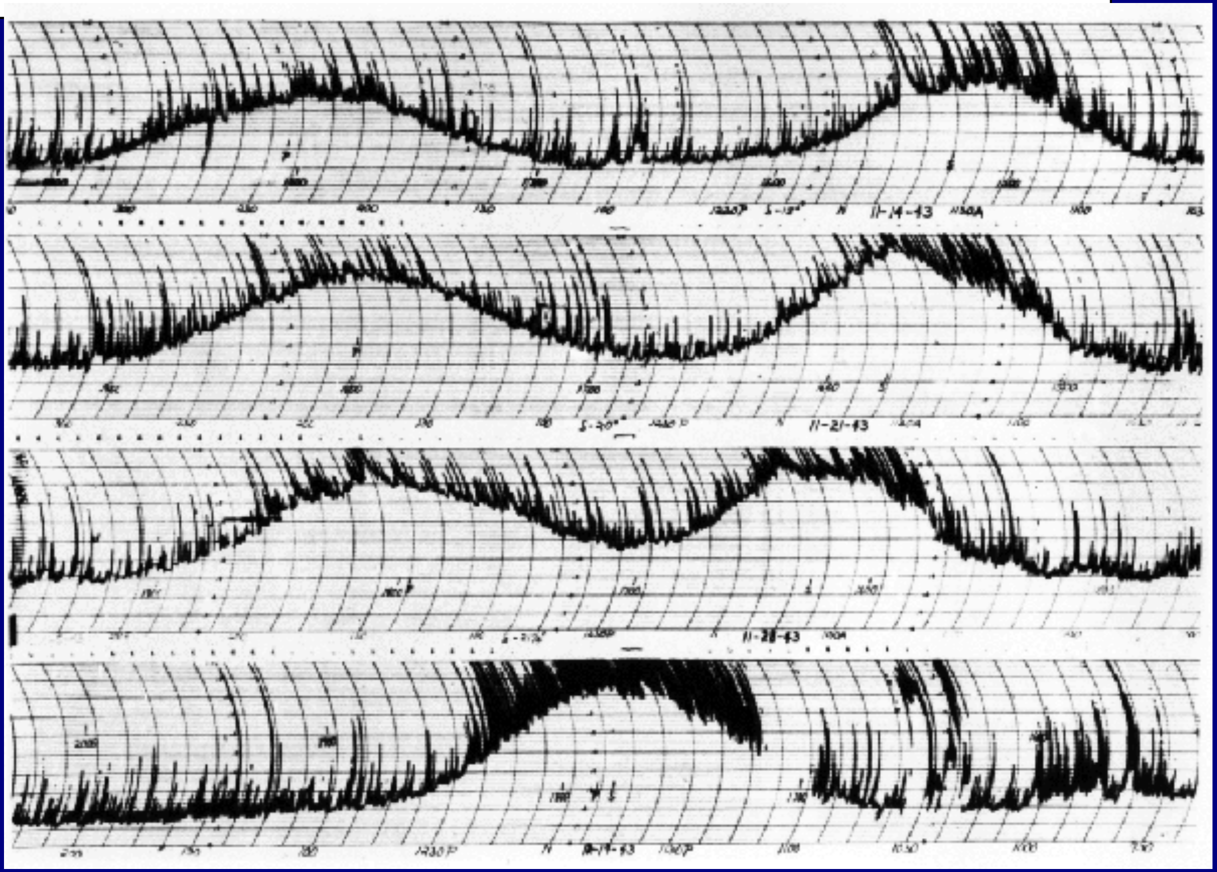
Radio Frequency Interference





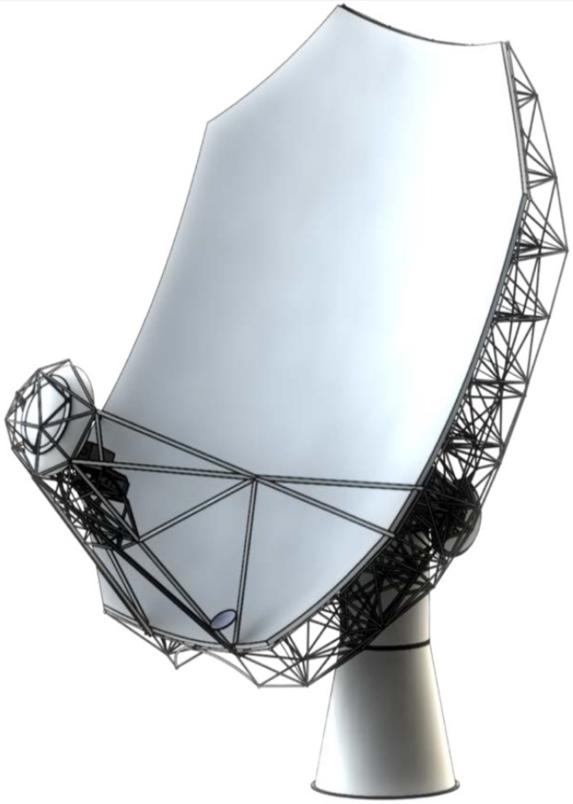
Grote Reber's telescope and Radio Frequency Interference in 1938

Eric J. Murphy – ngVLA Project Scientist

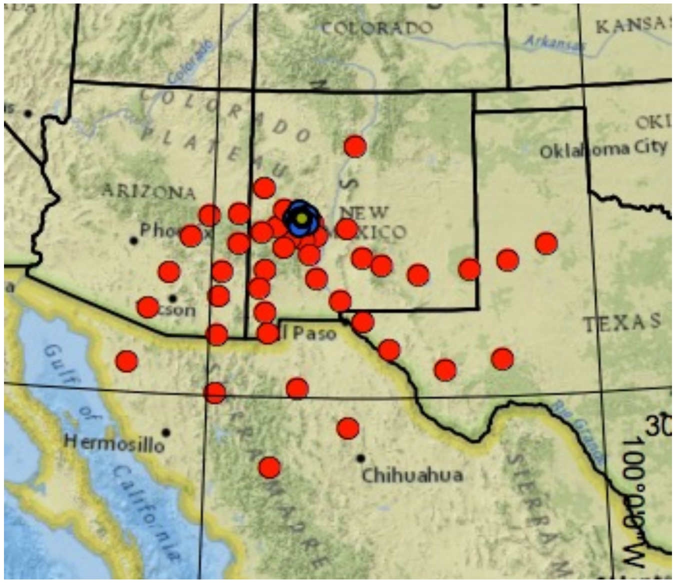
ngVLA.nrao.edu

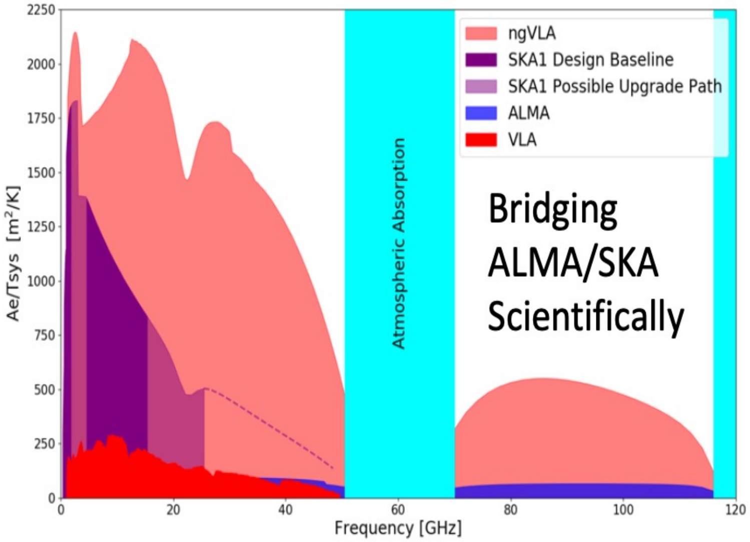
ngvla
Next Generation Very Large Array

A next-generation Very Large Array (ngVLA)



- Scientific Frontier: ***Thermal imaging at milli-arcsec resolution***
- Sensitivity/Resolution Goal: ***10x sensitivity & resolution of JVLA/ALMA***
- Frequency range: ***1.2 –116 GHz***
- Located in Southwest U.S. (NM, TX, AZ) & MX, centered on VLA
- Low technical risk (reasonable step beyond state of the art)





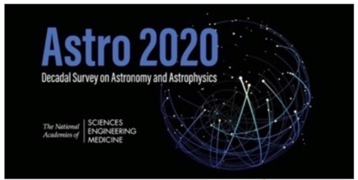
Bridging
ALMA/SKA
Scientifically

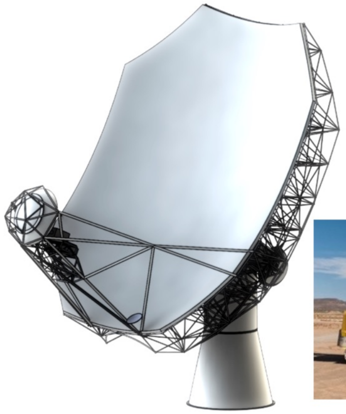
Complementary suite of meter-to-submm arrays for the mid-21st century

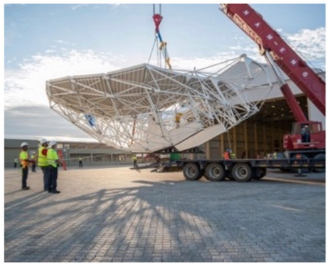
- **< 0.3 cm:** ALMA 2030
- **0.3 to 3 cm: ngVLA**
- **> 3 cm:** SKA

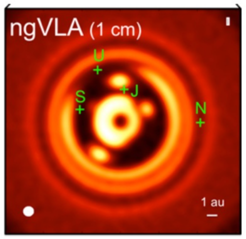
http://ngvla.nrao.edu

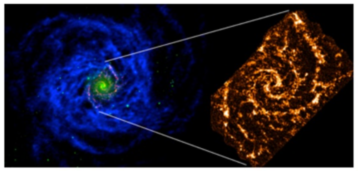
next generation Very Large Array

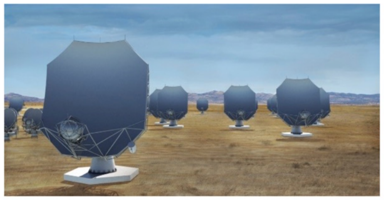












2019 2021 2023 2025 2026 2029 2035

ngVLA Submission to Astro2020

Astro2020 Recommendation Published

Submit ngVLA Proposal to NSF/MREFC

Prototype Delivered to VLA Site

Complete NSF/MREFC FDR

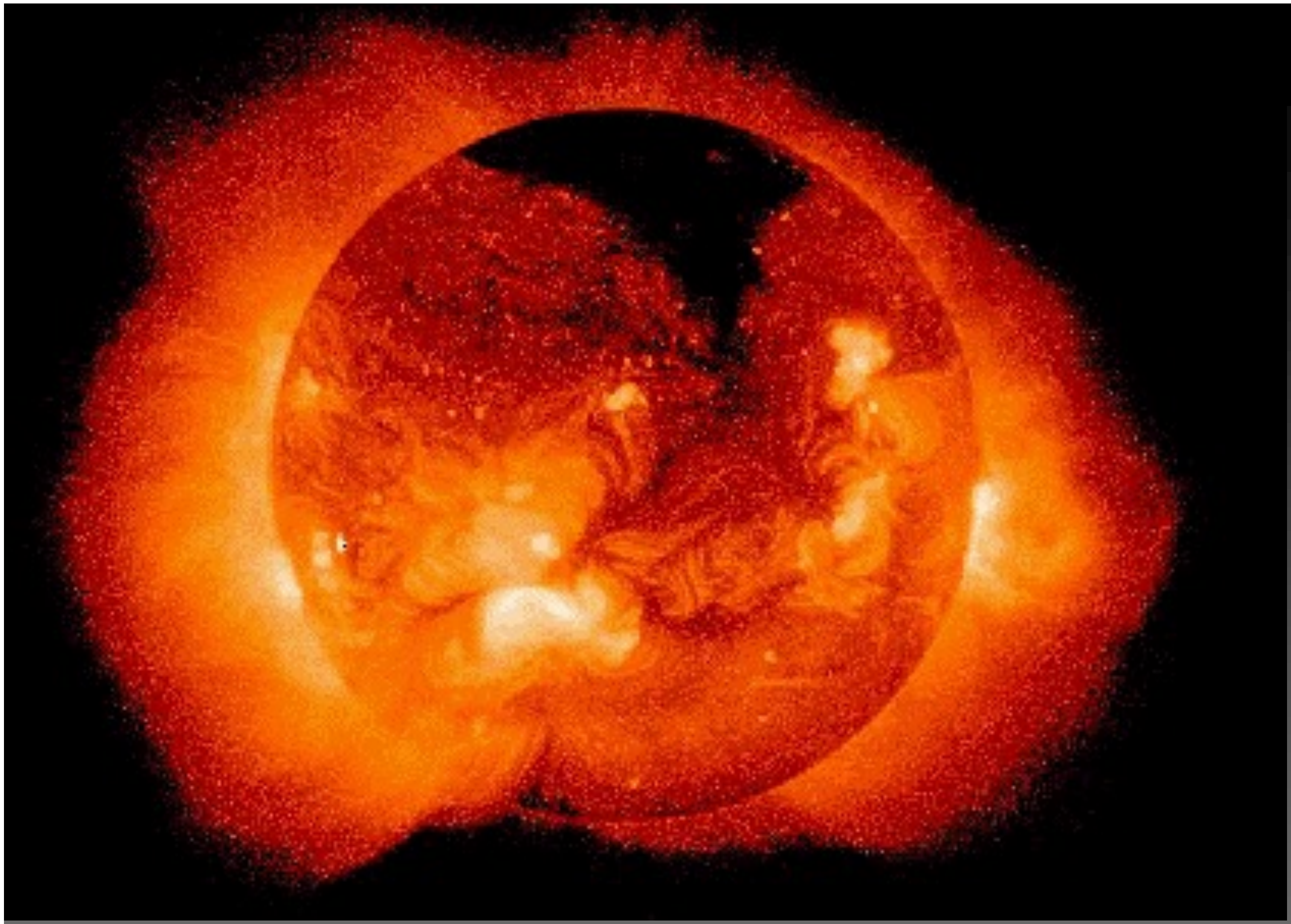
ngVLA Construction →

Initiate ngVLA Early Science (> VLA capabilities)

Achieve Full Science Operations

Announcements

- Office Hours Tu/Th 9-10 am or by appointment
- Homework #2 is due next Thursday



The Sun

Key concepts:

- Energy production
- Stability
- Solar cycle

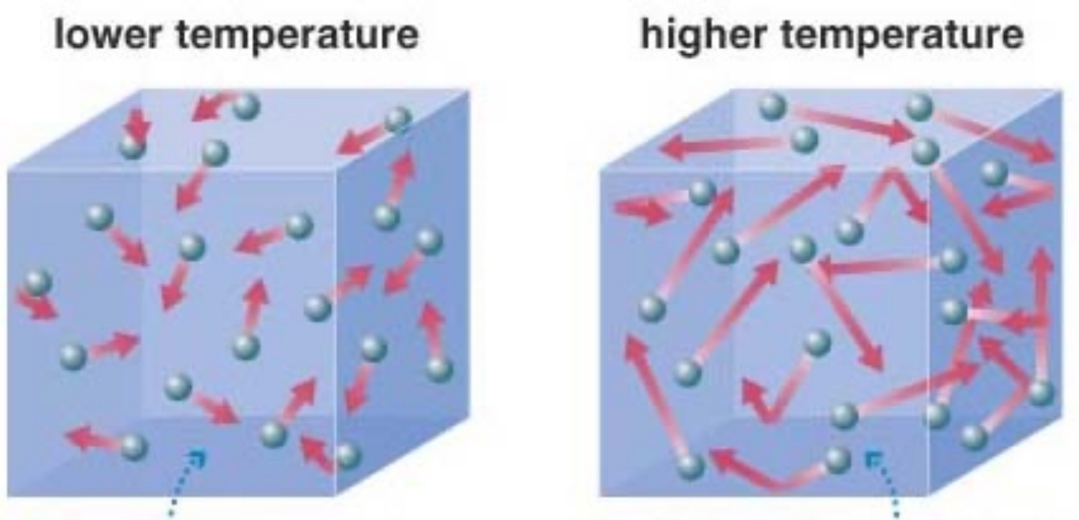
Basic data

Diameter	1.4×10^6 km	$= 109\ D_{earth}$
Mass	2×10^{30} kg	$= 333{,}000\ M_{earth}$
Composition (by mass)	74% H, 25% He	
Density	$1.4\ g/cm^3$	
Light travel time to Earth	8.32 min	
Orbital period (MW)	220×10^6 years	
Temperature	5800 K to 1.55×10^7 K	
Luminosity	3.86×10^{26} W	

Recall: the ideal gas law

- Particles in hot gas move faster, and collide with more force than those in a cooler gas

  => hot gas exerts higher pressure on any neighboring surface (P=F/A)



- However, gas pressure also depends on the number of particles that are colliding with the surface area per sec (number density n [cm^{-3}])

- This is expressed in the ideal gas law:

$$P = nkT$$

where P is the gas pressure [J/cm^3], n the number density [cm^{-3}], and k is Boltzmann's constant.

Thus, to determine pressure we need both T and n.

Luminosity - intrinsic property

- Total energy radiated per second.
- How does this relate to flux? Recall flux (flux density) is energy radiated per area per second.
- For the Sun (a sphere):

$$L_\odot = \text{Area x Flux} = (4\pi R_\odot{}^2)(\sigma T_\odot{}^4)$$
$$= 3.85 \times 10^{26}\ \text{W}$$

- How long can the Sun shine?

  Lifetime = internal heat (J)/luminosity (J/s)

- Sources of energy known in the 1800s:
  - Chemical energy
  - Gravitational energy

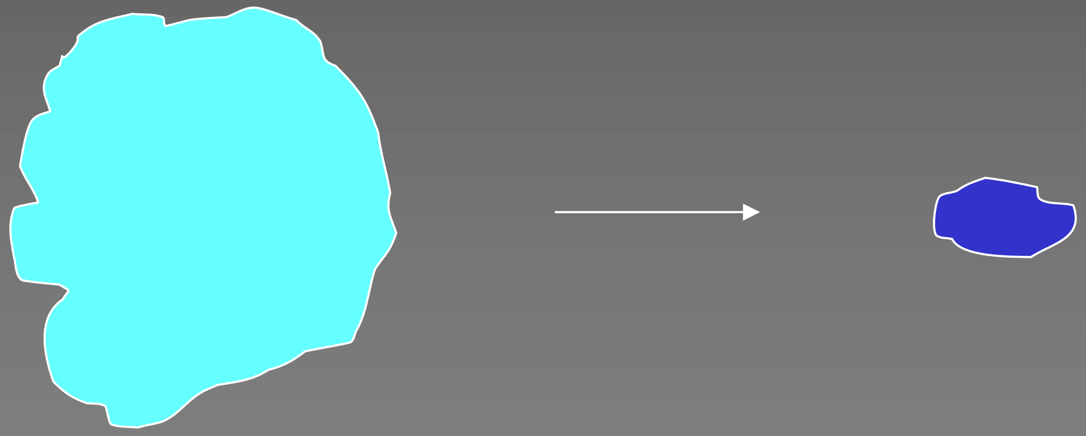
Burning of fuel by oxidation

Waterfalls, meteorite impacts

- But chemical reactions can only keep the Sun active for ~10,000 years… so how can the Earth (estimated at 4.5 Gyr) be older than the Sun?

The energy source

- First try: Kelvin-Helmholtz contraction
  - A contracting gas cloud heats up because of the gravitational potential energy of particles at large radii being converted into thermal energy
  - Some energy escapes as radiation (luminosity)

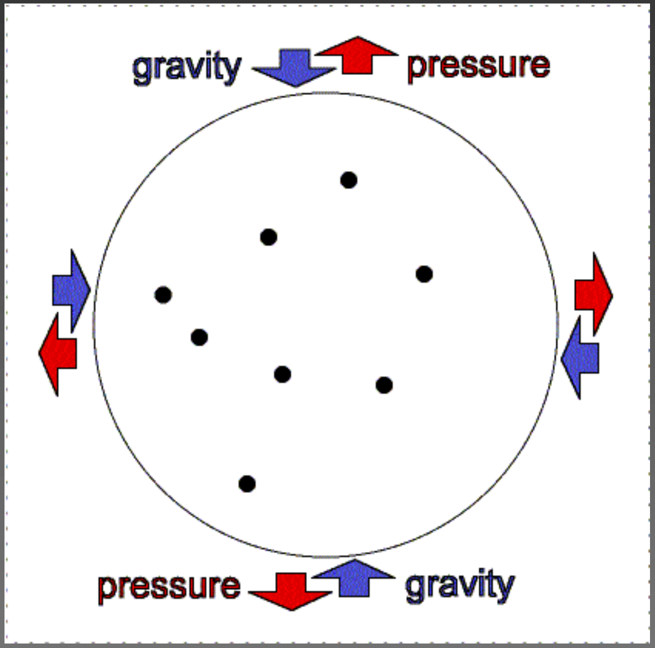


More gravitational energy

More thermal energy

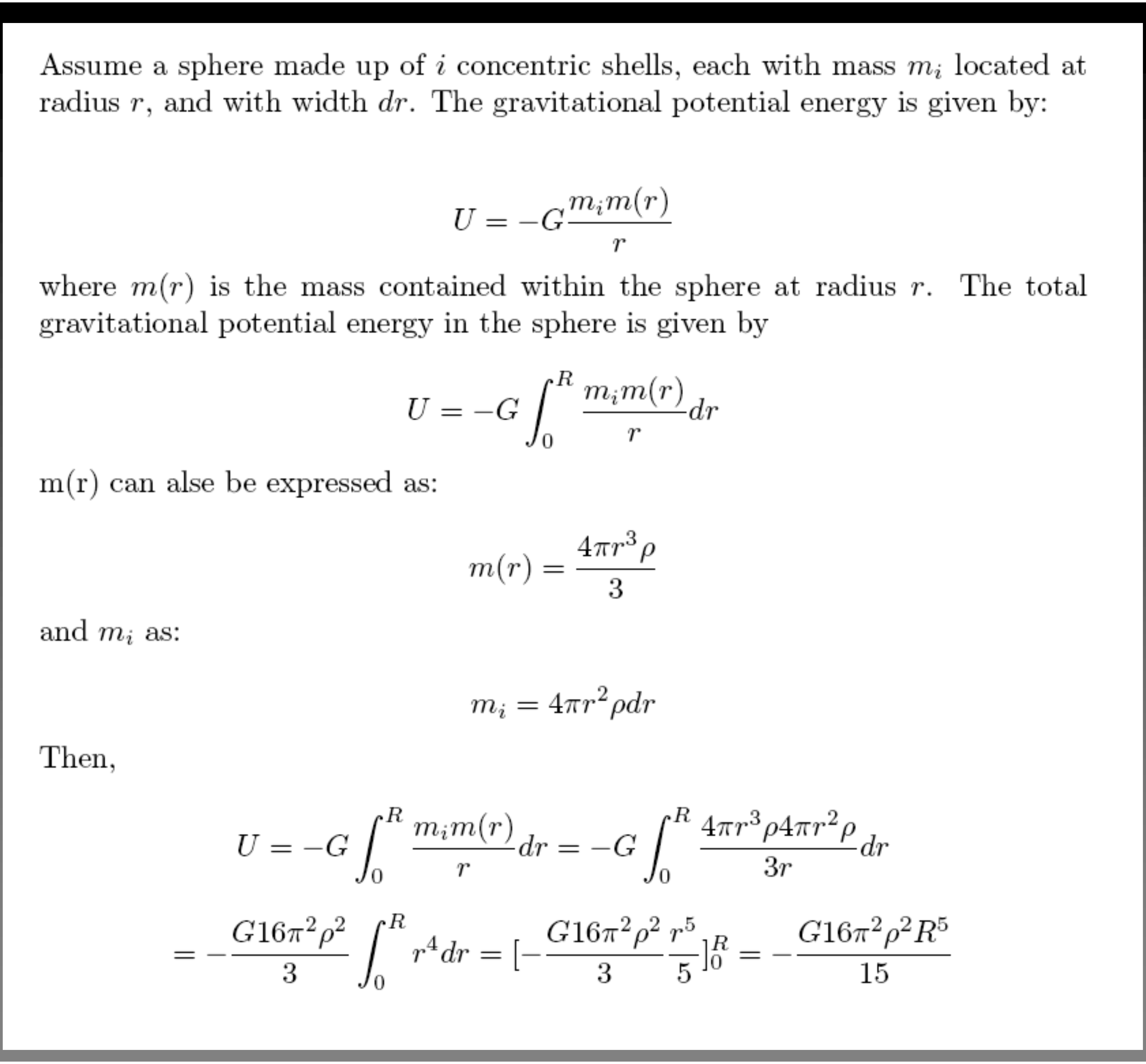
Kelvin-Helmholtz mechanism

- Gravity pulls inward
- Pressure pushes outwards
- When there is exact balance, we have *hydrostatic equilibrium.* This is where we start.



- Luminosity => heat radiates away, cools off the Sun
- Lower internal pressure => gravity compresses the Sun
- Pressure and internal heat increases => hydrostatic equilibrium restored
- … and over again, but now the Sun is slightly smaller!

Problem: the generated power seems insufficient =>



Assume a sphere made up of i concentric shells, each with mass m_i located at radius r, and with width dr. The gravitational potential energy is given by:

$$U = -G\frac{m_i m(r)}{r}$$

where $m(r)$ is the mass contained within the sphere at radius r. The total gravitational potential energy in the sphere is given by

$$U = -G\int_0^R \frac{m_i m(r)}{r}dr$$

m(r) can alse be expressed as:

$$m(r) = \frac{4\pi r^3\rho}{3}$$

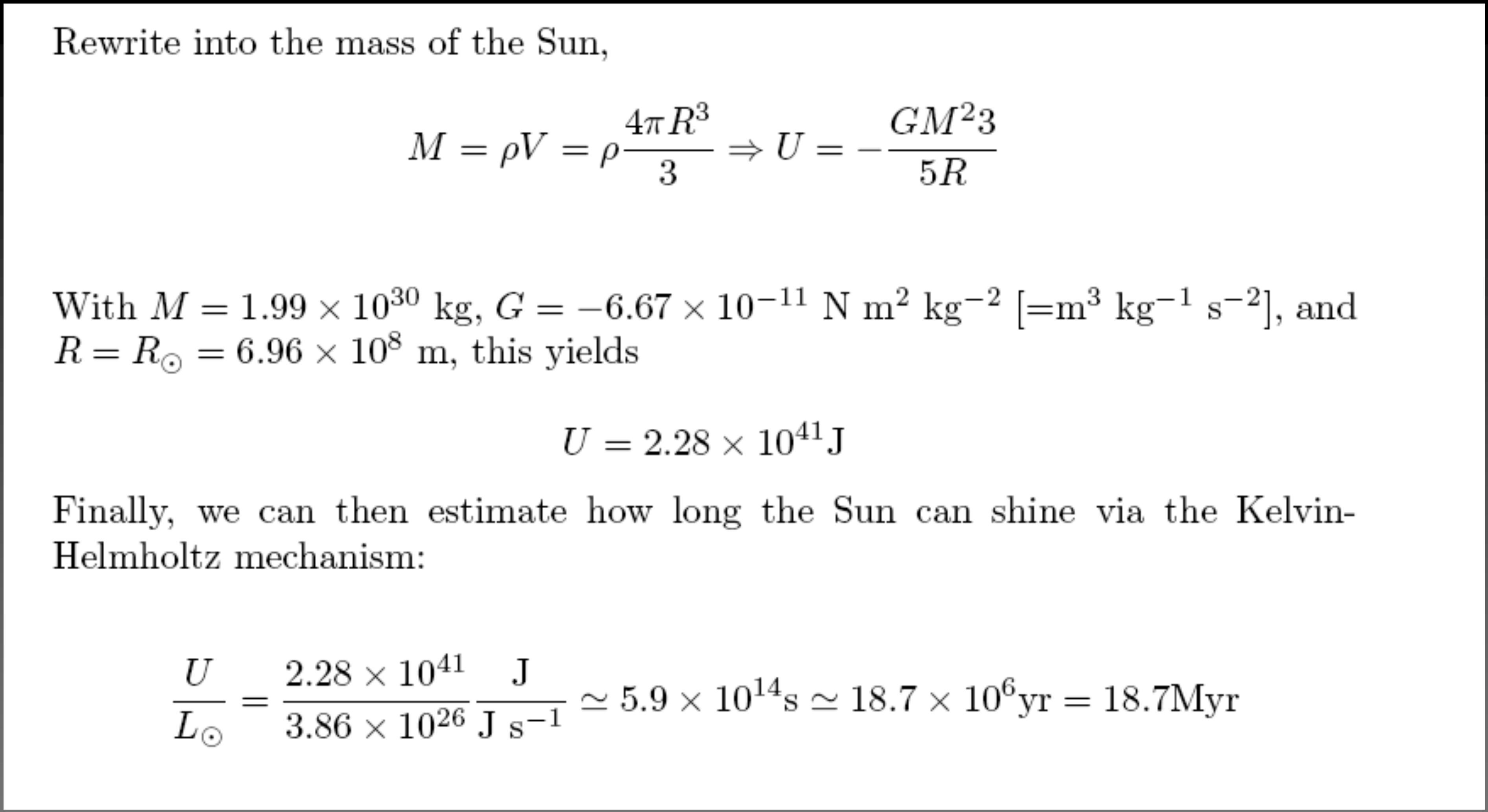
and m_i as:

$$m_i = 4\pi r^2\rho dr$$

Then,

$$U = -G\int_0^R \frac{m_i m(r)}{r}dr = -G\int_0^R \frac{4\pi r^3\rho 4\pi r^2\rho}{3r}dr$$

$$= -\frac{G16\pi^2\rho^2}{3}\int_0^R r^4 dr = [-\frac{G16\pi^2\rho^2}{3}\frac{r^5}{5}]_0^R = -\frac{G16\pi^2\rho^2 R^5}{15}$$



Rewrite into the mass of the Sun,

$$M = \rho V = \rho \frac{4\pi R^3}{3} \Rightarrow U = -\frac{GM^2 3}{5R}$$

With $M = 1.99 \times 10^{30}$ kg, $G = -6.67 \times 10^{-11}$ N m^2 kg^{-2} [=m^3 kg^{-1} s^{-2}], and $R = R_\odot = 6.96 \times 10^8$ m, this yields

$$U = 2.28 \times 10^{41}\text{J}$$

Finally, we can then estimate how long the Sun can shine via the Kelvin-Helmholtz mechanism:

$$\frac{U}{L_\odot} = \frac{2.28 \times 10^{41}}{3.86 \times 10^{26}} \frac{\text{J}}{\text{J s}^{-1}} \simeq 5.9 \times 10^{14}\text{s} \simeq 18.7 \times 10^6\text{yr} = 18.7\text{Myr}$$

- But geologists estimated the age of Earth is ~ 4.5 Gyrs!

Nuclear physics: early 1900s

- Röntgen and Becquerel discovered radio activity

- Einstein discovered that $E=mc^2$

- Eddington discovered that 4 protons have 0.7% more mass than 2p+2n (1 He) nucleus.

- Fusion: build up large nuclei from small ones
- Fission: break down large nuclei into small ones

- Given that 99% of the Universe is H and He, the two simplest nuclei, fusion is far more common than fission.

Fundamental forces of nature

Interactions in nature are governed by four fundamental forces:

- Gravitational force
- Weak nuclear force
- Electromagnetic force
- Strong nuclear force

- Gravity dominates on largest scales: binds massive objects together, and mediates orbital motions

- Electromagnetism dominates on atomic scale: binds electrons to protons, atoms to atoms

- Strong and weak forces dominates on nuclear scales: binds protons to neutrons, mediates nuclear reactions

Nuclear reactions come about because of the strong and weak nuclear forces.

The strong one holds nuclei together.

The weak one causes certain particles to change into others through radioactive decay.

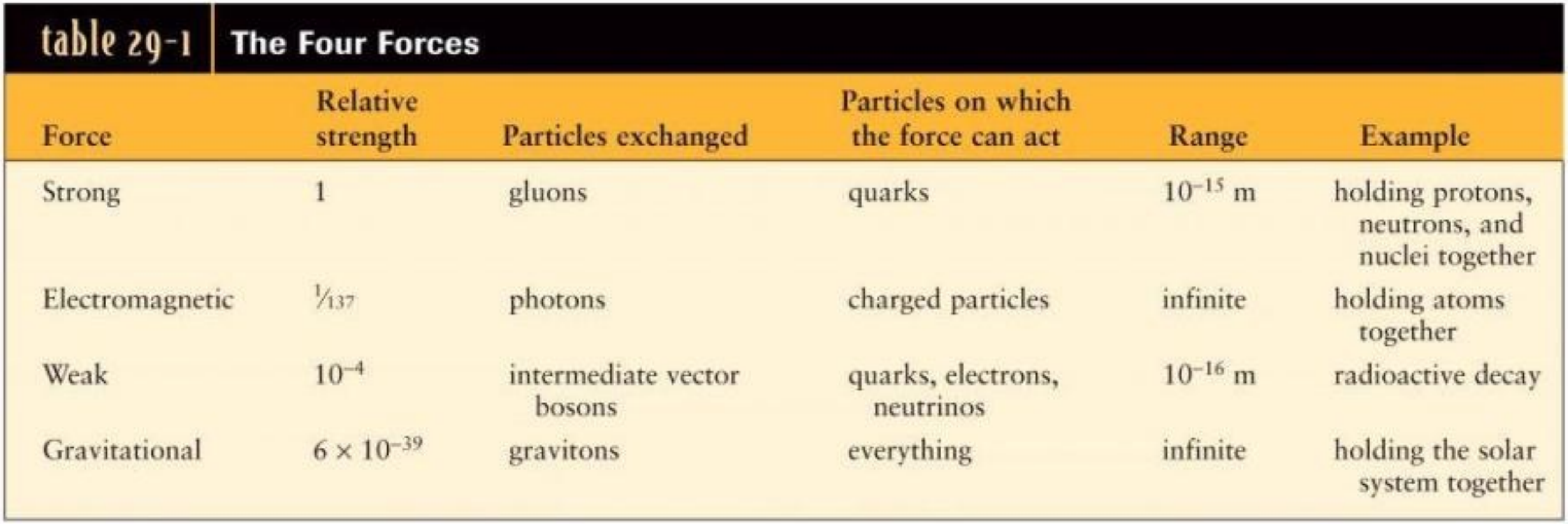


table 29-1 **The Four Forces**

Force	Relative strength	Particles exchanged	Particles on which the force can act	Range	Example
Strong	1	gluons	quarks	10^{-15} m	holding protons, neutrons, and nuclei together
Electromagnetic	$1/137$	photons	charged particles	infinite	holding atoms together
Weak	10^{-4}	intermediate vector bosons	quarks, electrons, neutrinos	10^{-16} m	radioactive decay
Gravitational	6×10^{-39}	gravitons	everything	infinite	holding the solar system together

Antimatter, annihilation and neutrinos

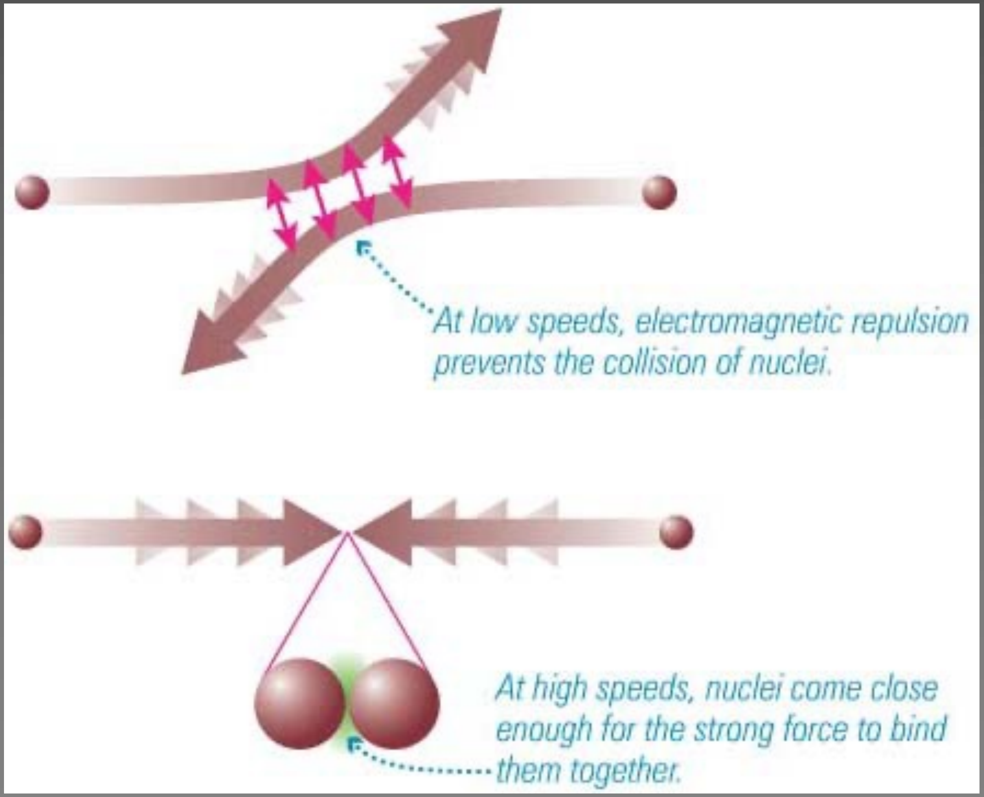
- Antimatter: for every charged particle there is an antiparticle that differs in charge
  - Example: positron (e^+) is like the electron except positive charge

- Annihilation: if a particle and its antiparticle touch they completely disappear (explosively) as mass and liberate energy (again $E=mc^2$)

- Neutrinos (ν):
  - Exotic particles that have no charge and little mass.
  - Interact with other particles only via the weak nuclear force. Thus, they interact only very weakly with material in the Sun.

Hydrogen fusion

- How to fuse 4 ^{1}H (p) into a ^{4}He (2p+2n)?
  - Unlikely 4 protons are colliding at once
  - Must turn 2 protons into 2 neutrons
  - Must be > 10^{7} K to get protons close enough for fusion

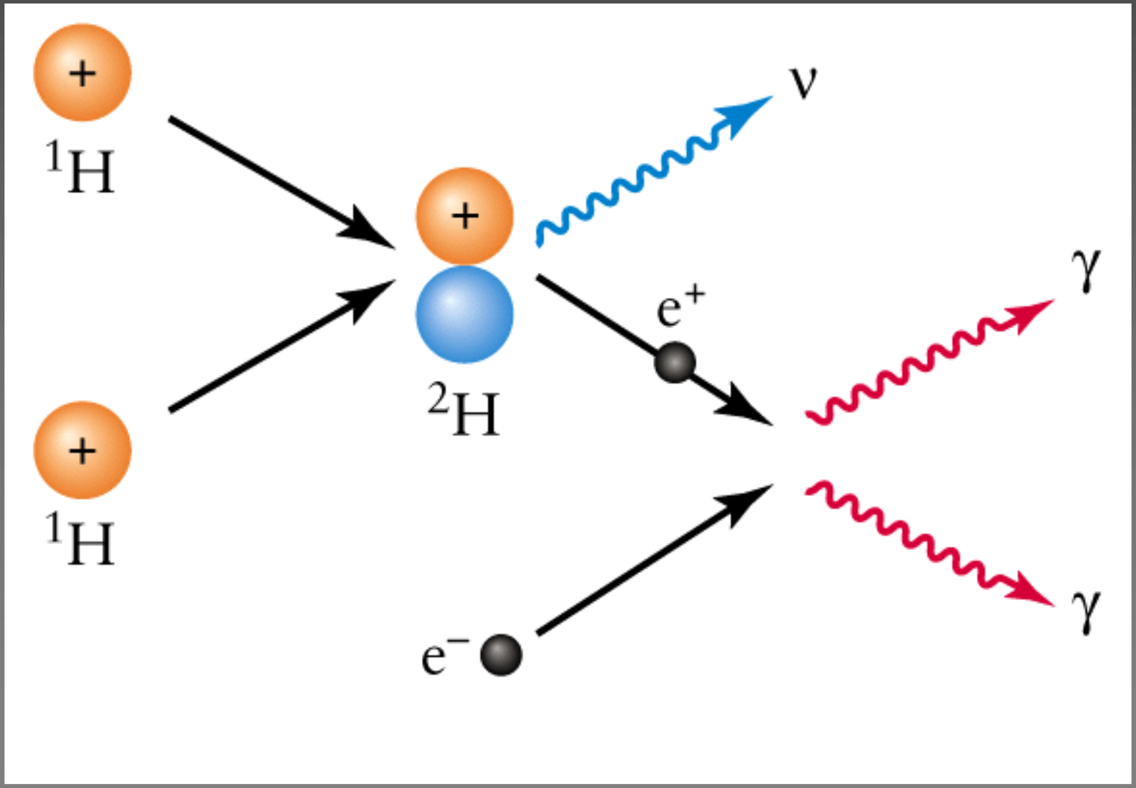


Key: bring nuclei sufficiently close for the strong force to dominate over the electromagnetic force.

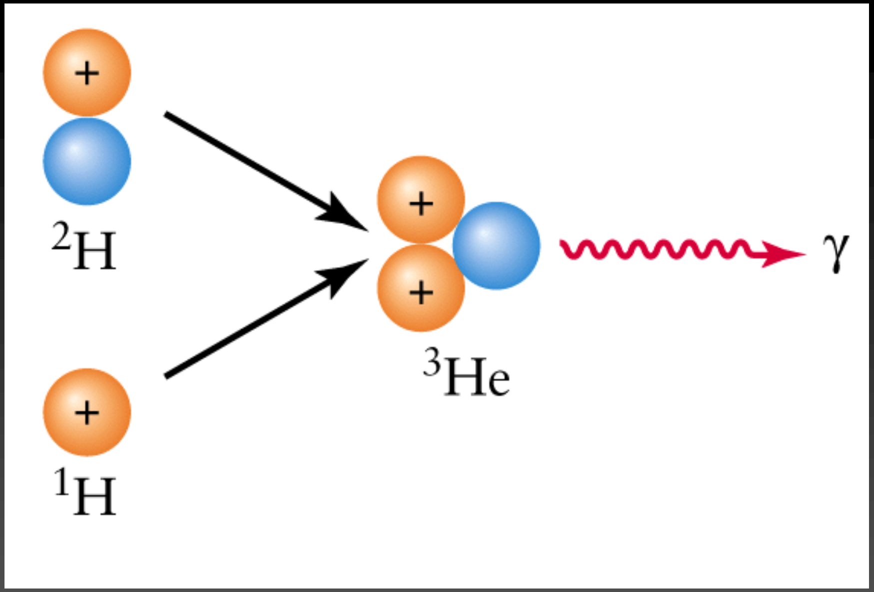
The proton-proton chain in pictures

- Starting point: at 1.5x10^7 K, hydrogen in the core of the Sun is completely ionized, thus a mixture of free electrons and protons (plasma)

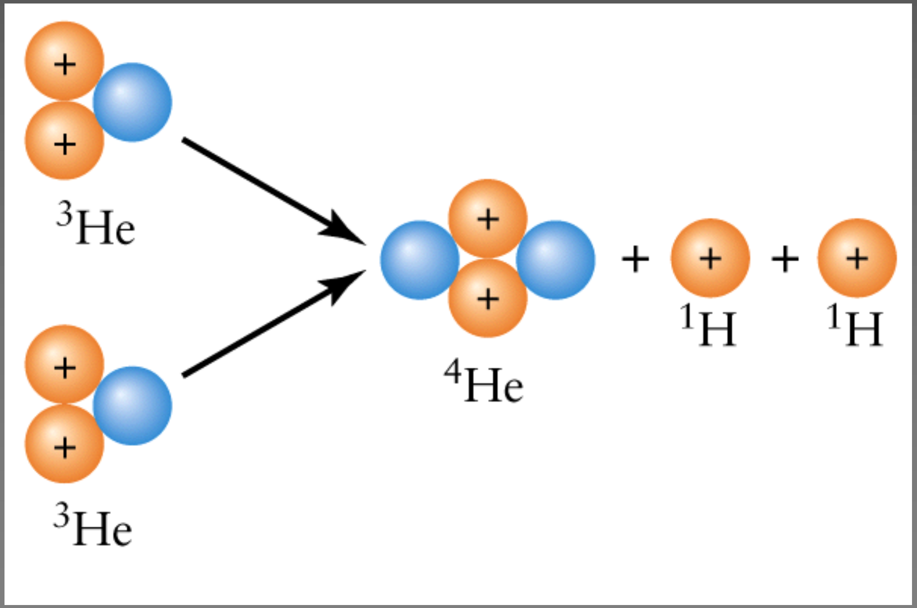
- Step 1:



Once the deuterium has been created, step 2 happens:



In step 3 common helium is formed:



Proton-proton chain

$p + p \rightarrow {}^{2}H + e^{+} + \nu_e$ (twice)

$p + {}^{2}H \rightarrow {}^{3}He + \gamma$ (twice)

$${}^{3}He + {}^{3}He \rightarrow {}^{4}He + p + p$$

Note the six important byproducts: 2e+, 2 neutrino, 2 photons

Calorimetry

- The 4 protons have 4.8×10^{-29} kg more mass than the He nucleus (0.7% of the total mass has gone into en).
- $E=mc^2$ => 4.3×10^{-12} J is released by the formation of a single He nucleus.
- $L_\odot = 3.9 \times 10^{26}$ J/s => 6×10^{11} kg of H is converted to He every second.

100 Burj Khalifas
Every second

Worksheet

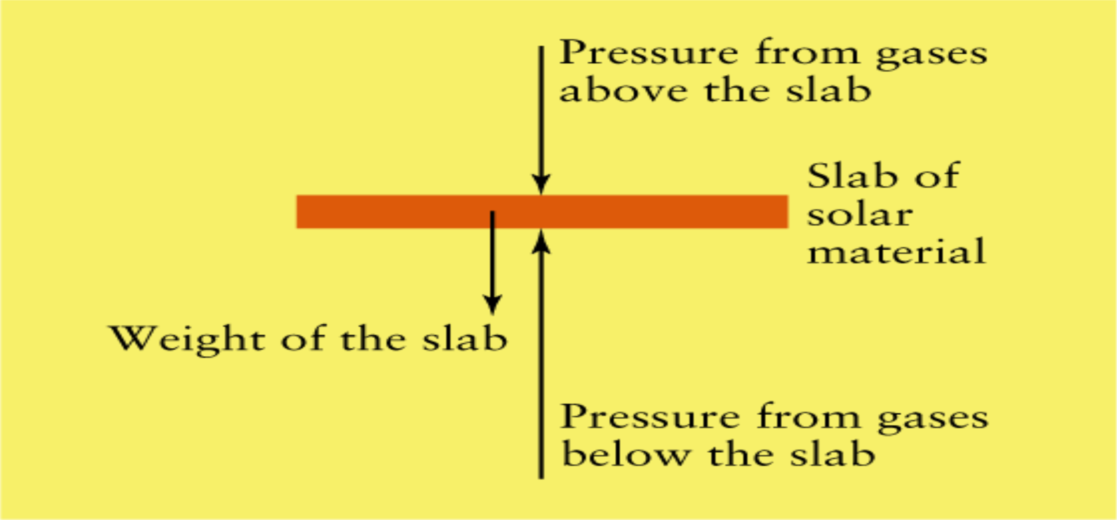
- About 4×10^9 kg converted to energy per second
- Sun contains 21×10^{24} kg H (but only the inner 10% of the Sun is hot enough for fusion to take place)
- => fusion lifetime about 10 Gyrs.

Radioactive dating of oldest rocks gives age of Earth to 4.5 Gyrs - no age crisis!

- The fusing together of nuclei is also called thermonuclear fusion, because it can only happen at very high temperatures
- Sun must be different at core than at the surface!

Models of the Sun's interior

- The Sun's interior is a gas (actually, a plasma = ionized gas)
- Hydrostatic equilibrium keeps it stable



(a) **In hydrostatic equilibrium, forces balance**

- Upward pressure is caused by the nuclear reactions and upward flow of energy

- Using ideas of hydrostatic equilibrium and thermal equilibrium (all energy generated by thermonuclear reactions in the Sun’s core must be transported to the surface and radiated into space) we can create models of the Sun’s interior.

- Models are created by solving equations, such as for hydrostatic equilibrium:

$$\frac{dP}{dr} = -\rho g$$

where g is local gravitational acceleration at radius r, and ρ is the density at r.

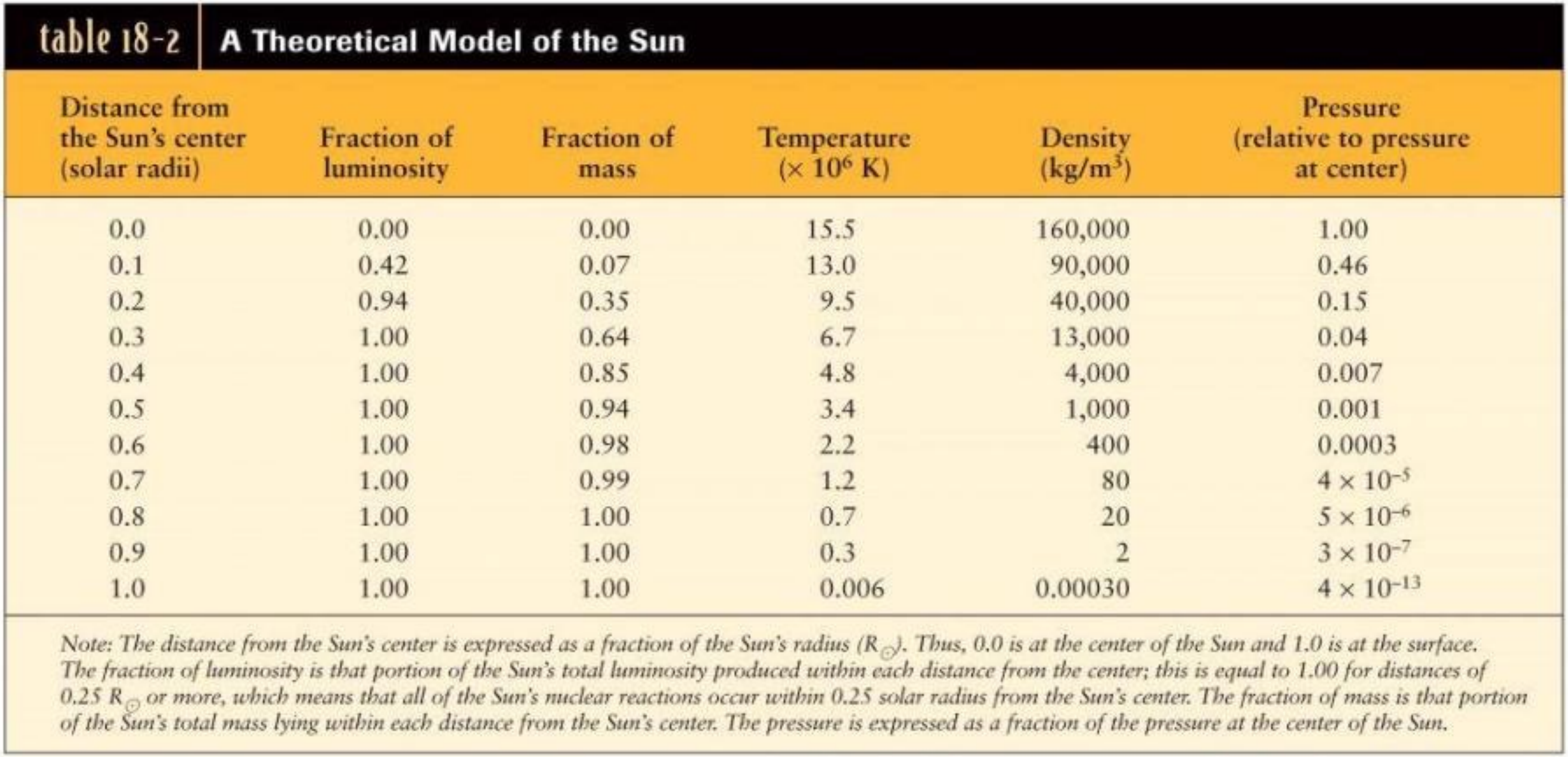
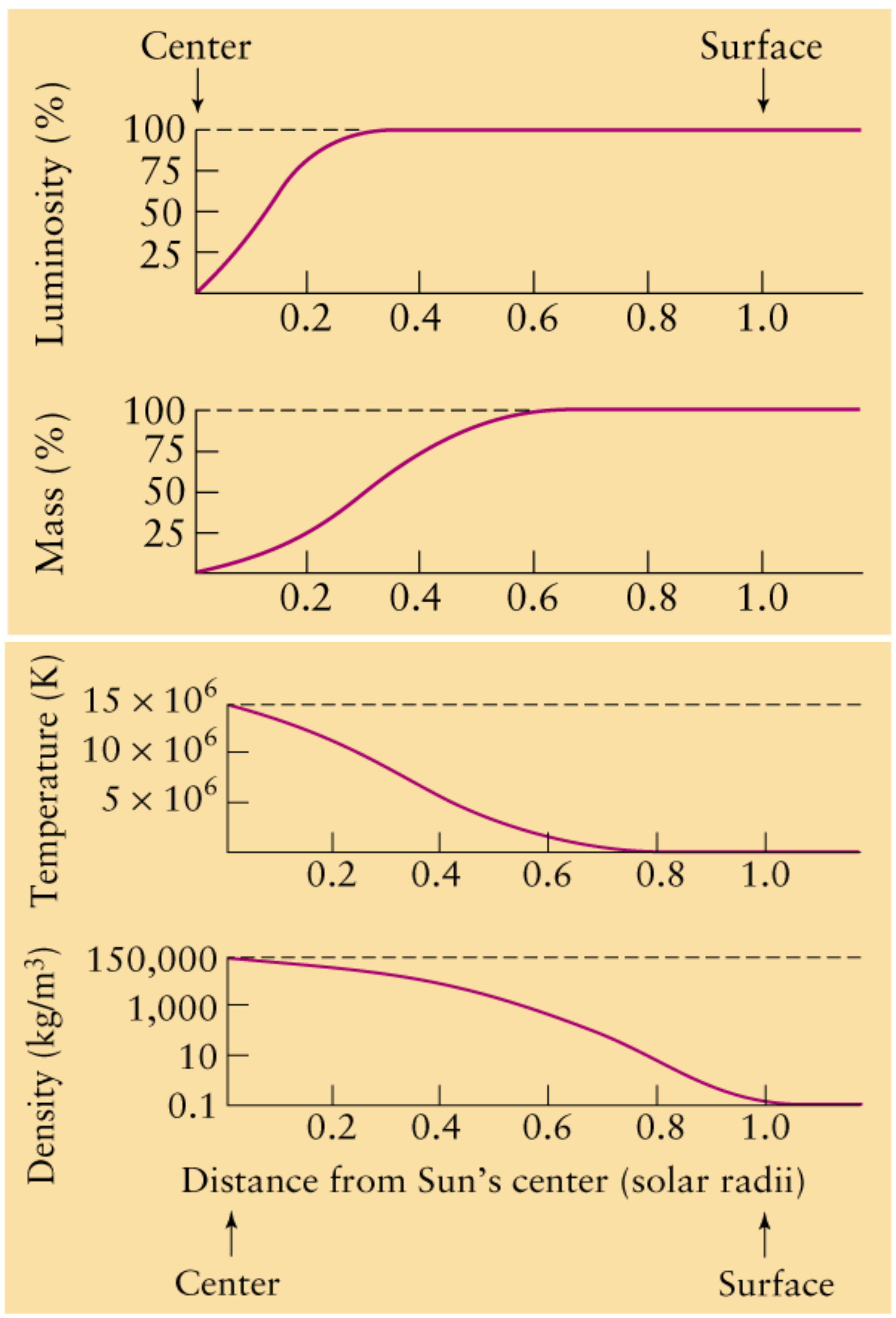


table 18-2 A Theoretical Model of the Sun

Distance from the Sun's center (solar radii)	Fraction of luminosity	Fraction of mass	Temperature ($\times 10^6$ K)	Density (kg/m^3)	Pressure (relative to pressure at center)
0.0	0.00	0.00	15.5	160,000	1.00
0.1	0.42	0.07	13.0	90,000	0.46
0.2	0.94	0.35	9.5	40,000	0.15
0.3	1.00	0.64	6.7	13,000	0.04
0.4	1.00	0.85	4.8	4,000	0.007
0.5	1.00	0.94	3.4	1,000	0.001
0.6	1.00	0.98	2.2	400	0.0003
0.7	1.00	0.99	1.2	80	4×10^{-5}
0.8	1.00	1.00	0.7	20	5×10^{-6}
0.9	1.00	1.00	0.3	2	3×10^{-7}
1.0	1.00	1.00	0.006	0.00030	4×10^{-13}

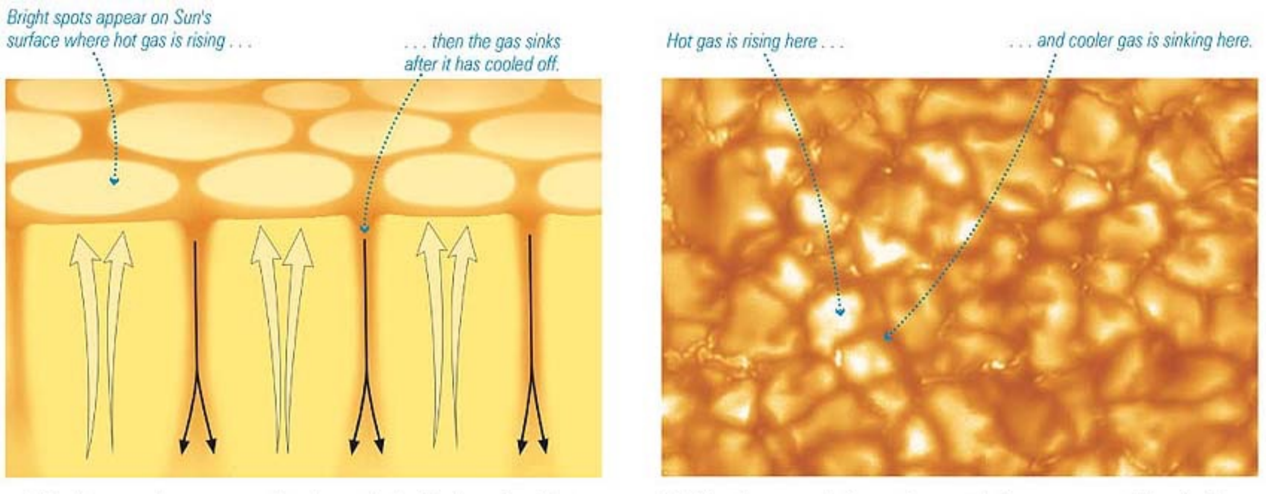
Note: The distance from the Sun's center is expressed as a fraction of the Sun's radius ($R_\odot$). Thus, 0.0 is at the center of the Sun and 1.0 is at the surface. The fraction of luminosity is that portion of the Sun's total luminosity produced within each distance from the center; this is equal to 1.00 for distances of 0.25 $R_\odot$ or more, which means that all of the Sun's nuclear reactions occur within 0.25 solar radius from the Sun's center. The fraction of mass is that portion of the Sun's total mass lying within each distance from the Sun's center. The pressure is expressed as a fraction of the pressure at the center of the Sun.


Center
Surface
Luminosity (%)
100
75
50
25
0.2
0.4
0.6
0.8
1.0
Mass (%)
100
75
50
25
0.2
0.4
0.6
0.8
1.0
Temperature (K)
15×10^6
10×10^6
5×10^6
0.2
0.4
0.6
0.8
1.0
Density (kg/m^3)
150,000
1,000
10
0.1
0.2
0.4
0.6
0.8
1.0
Distance from Sun's center (solar radii)
Center
Surface

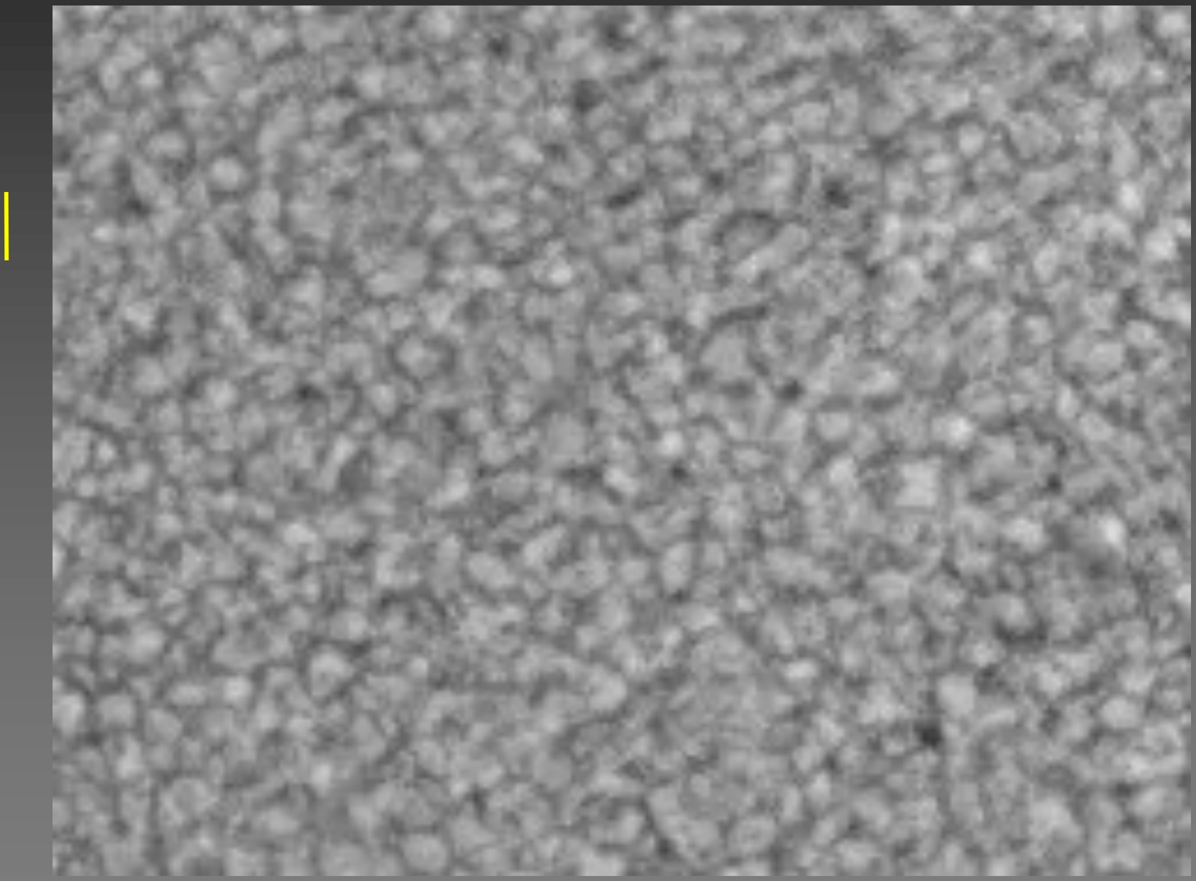
How does energy get to the surface?

- Radiation, or "radiative diffusion"
  - Photons created in core diffuse outward toward surface. Individual photons are quickly absorbed and reemitted by atoms and electrons in the Sun.

- Convection
  - Mass motion of gas, takes over where the Sun is too opaque for radiation to work well.



Can see rising and falling convection cells => granulation. Bright granules hotter and rising, dark ones cooler and falling. (Remember convection in Earth's atmosphere, interior and Jupiter).



Why are cooler granules dark? Stefan's Law: brightness α T^4

Image from the Swedish 1-m Solar Telescope, ~90 km resolution

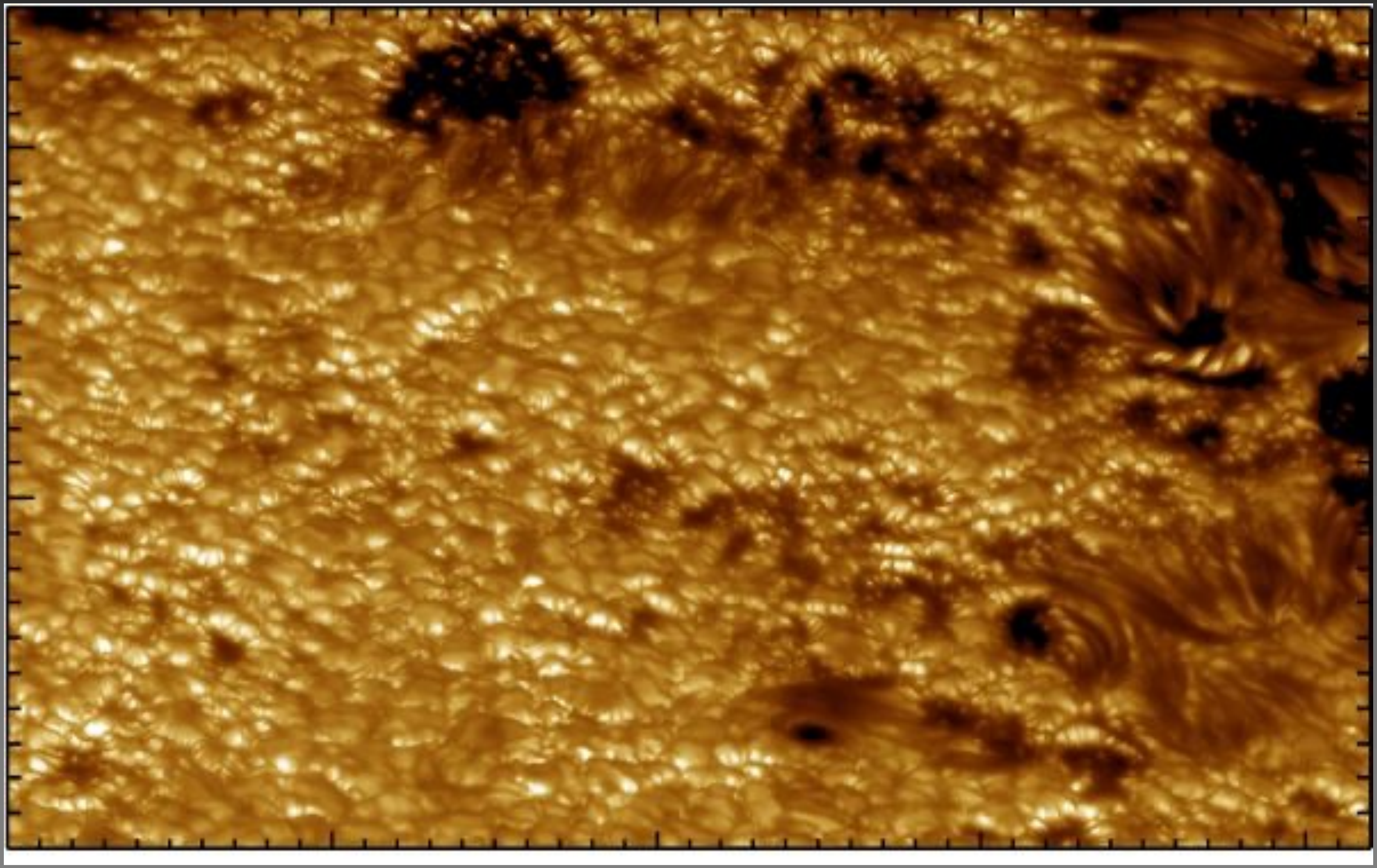
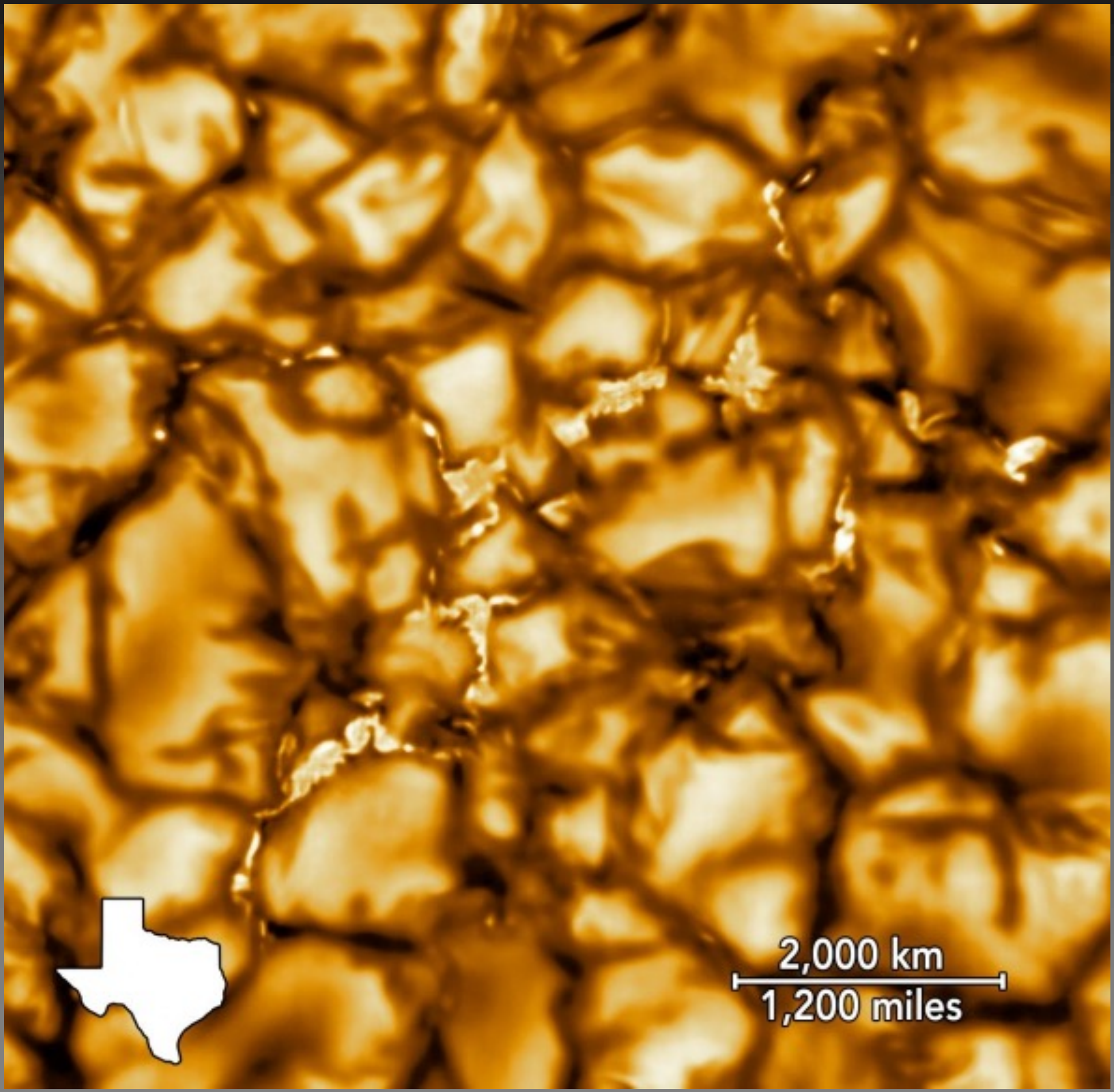
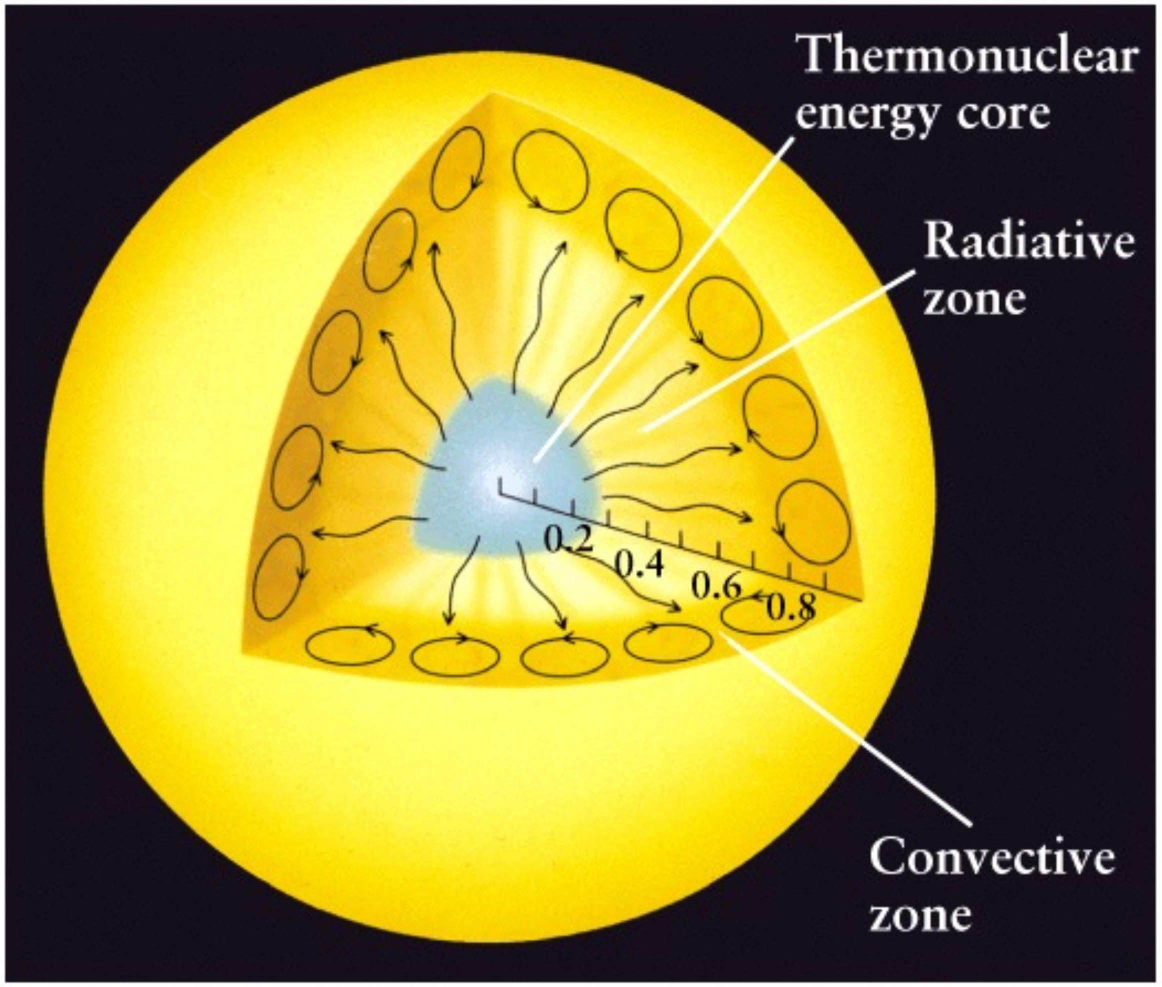


Image from DKIST (4m) on Maui, ~30 km resolution





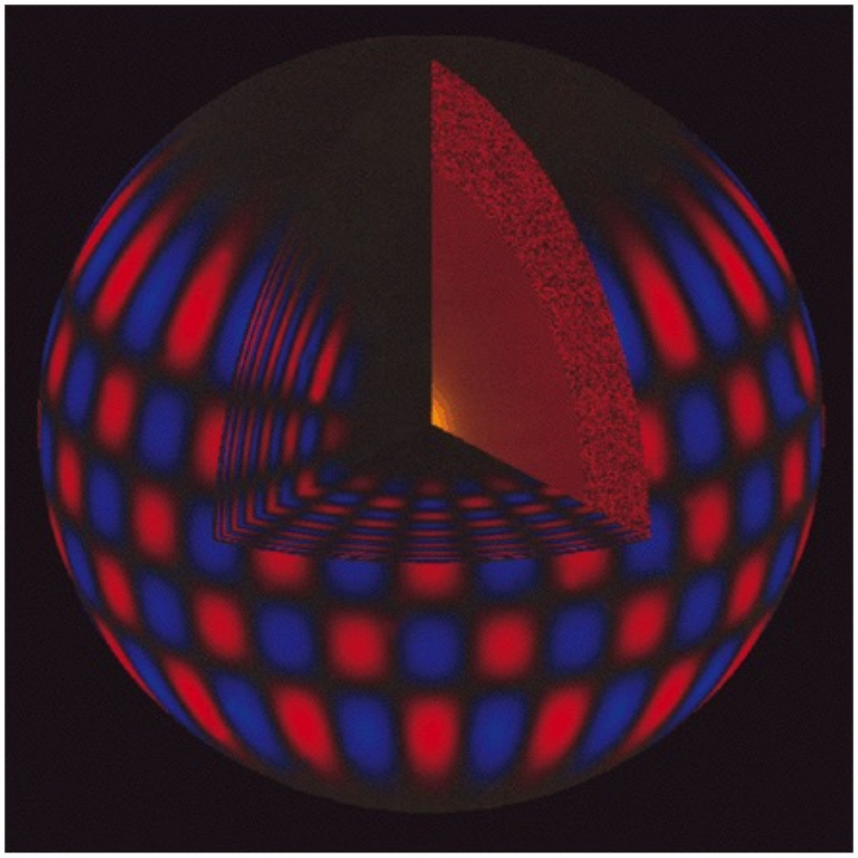
Gas is transparent

Gas is opaque (atoms and molecules can form here)

It takes about 170,000 years for energy created in the Sun’s core to get out, but it takes only about 8 minutes for light to travel from the photosphere to us.

Helioseismology

- A check on our models - sound waves probe the interior of the Sun, and generally confirm our theoretical understanding.



>10^7 modes seen by Doppler shifting at surface.

Periods depend on depth of resonant cavities and propagation speeds => probes temperature, composition and motions down to the core.

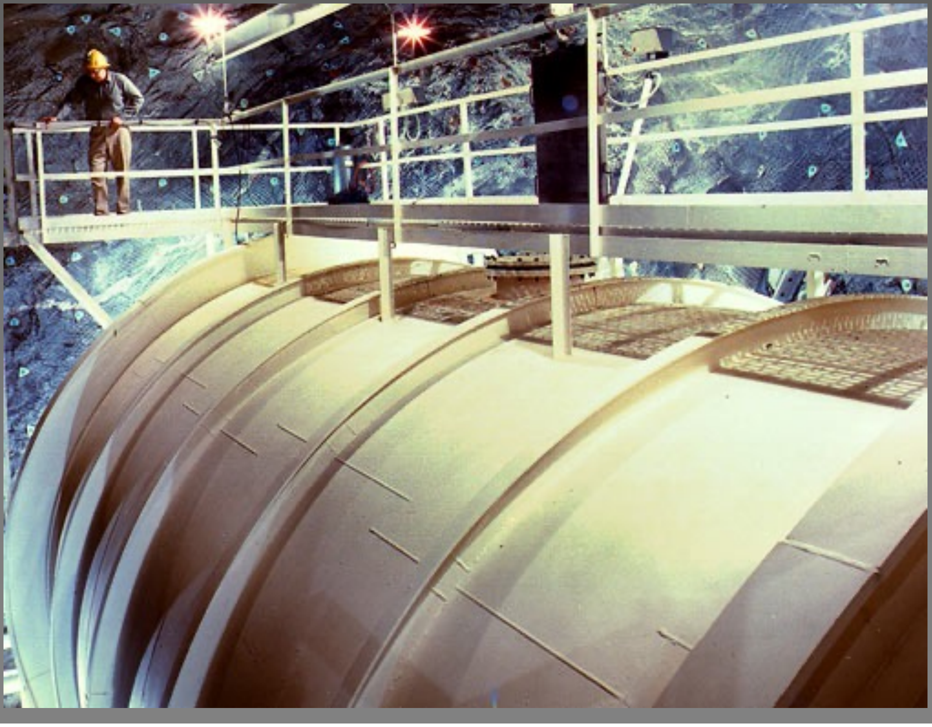
Does nuclear fusion really occur?

- Test: look for the neutrinos produced in the proton-proton chain.
- Neutrinos are weakly interacting subatomic particles
  - Nearly mass less, traveling near *c*
  - Interact with matter via the weak nuclear force
  - Can pass undisturbed through a slab of lead of thickness 1 pc
- Detected via Cherenkov radiation: when a particle is moving at speeds larger than the speed of light in a medium.

Solar neutrino problem

In 1960s Ray Davis and John Bahcall measured the neutrino flux from the Sun and found it to be lower than expected (by 30-50%)

Confirmed in subsequent experiments
Theory of p-p fusion well understood
Solar interior well understood



Answer to the Solar neutrino problem

Theoriticians like Bruno Pontecorvo realized
There was more than one type of neutrino
Neutrinos could change from one type to another

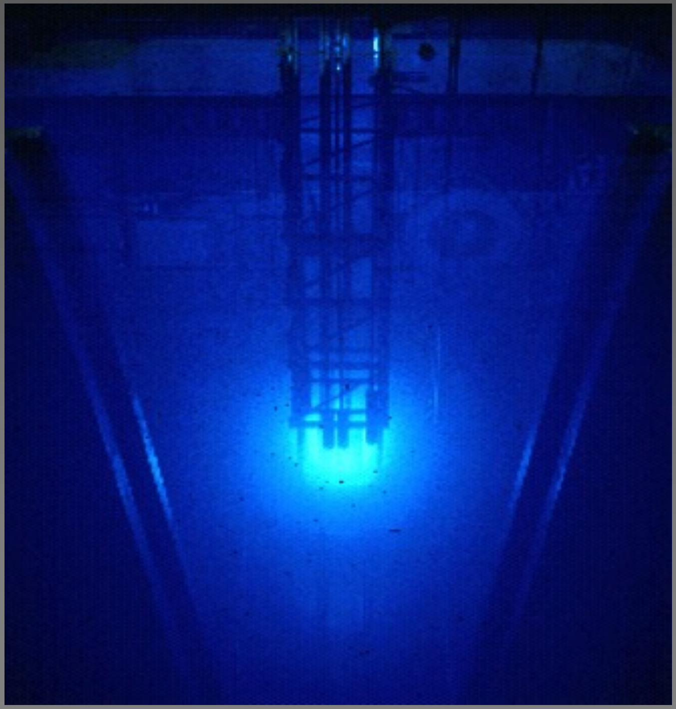
Confirmed by Super-Kamiokande experiment in Japan in 1998

50,000 gallon tank

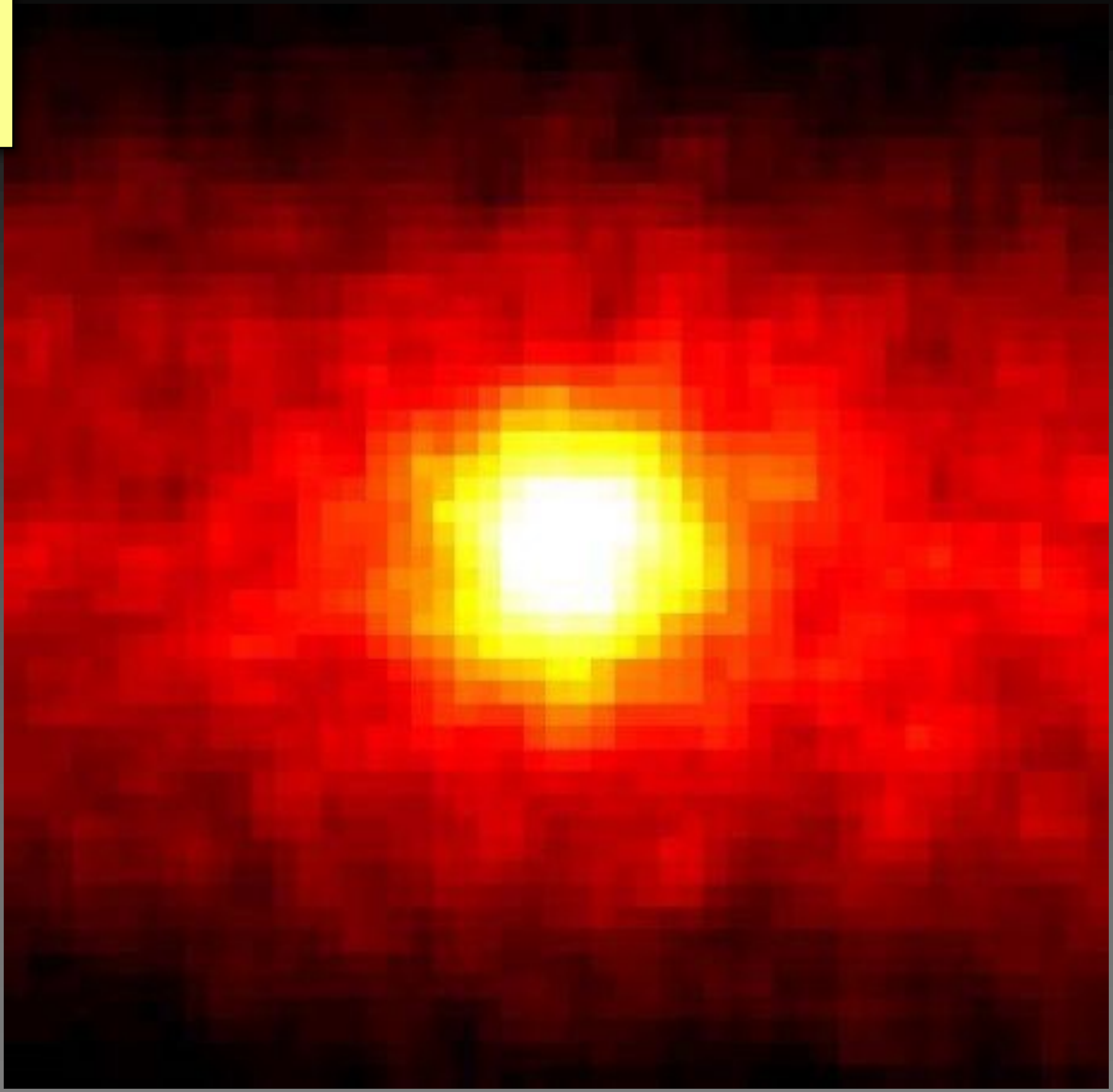
Total number of neutrinos agrees with predictions

- Detection hard, since enormous amount of detector material needed (heavy water, gallium), and must be underground to be shielded from other cosmic radiation

- Examples of neutrino detectors: Kamiokande and Super-Kamiokande (Japan), Sudbury Neutrino Observatory (Canada), AMANDA/IceCube (South pole), GALLEX (Italy)

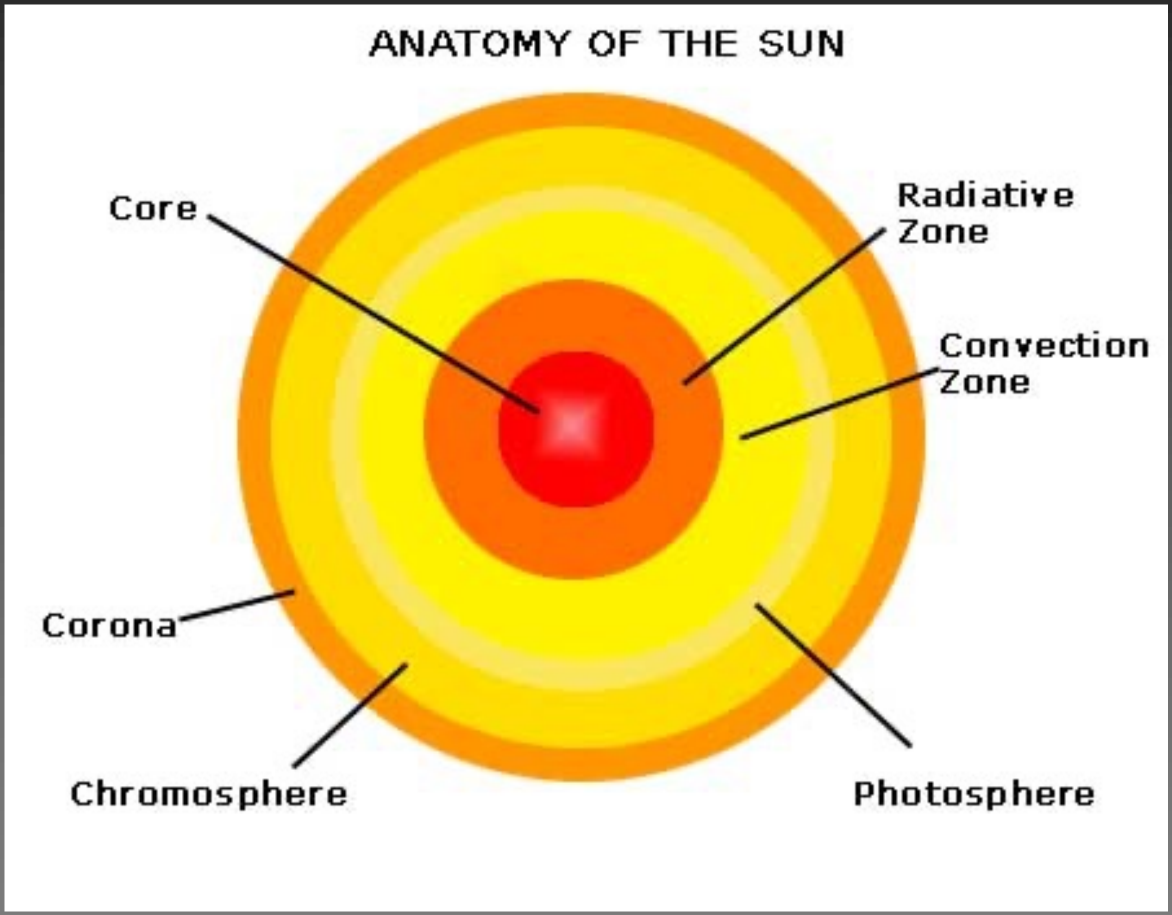


90 x 90 degree neutrino image in direction of Sun



Neutrinos detected at expected energies confirm that the energy source in stars is nuclear fusion.

Overall structure



The Sun's atmosphere

- Photosphere: yellowish color. The part we see, T=5800 K.
- The Sun is a giant sphere or gas - so it doesn't have a well defined surface
- Talking about the surface: we mean the photosphere
- The point where atmosphere becomes completely opaque is the photosphere (defines diameter of the Sun)

Solar photosphere as a function of depth

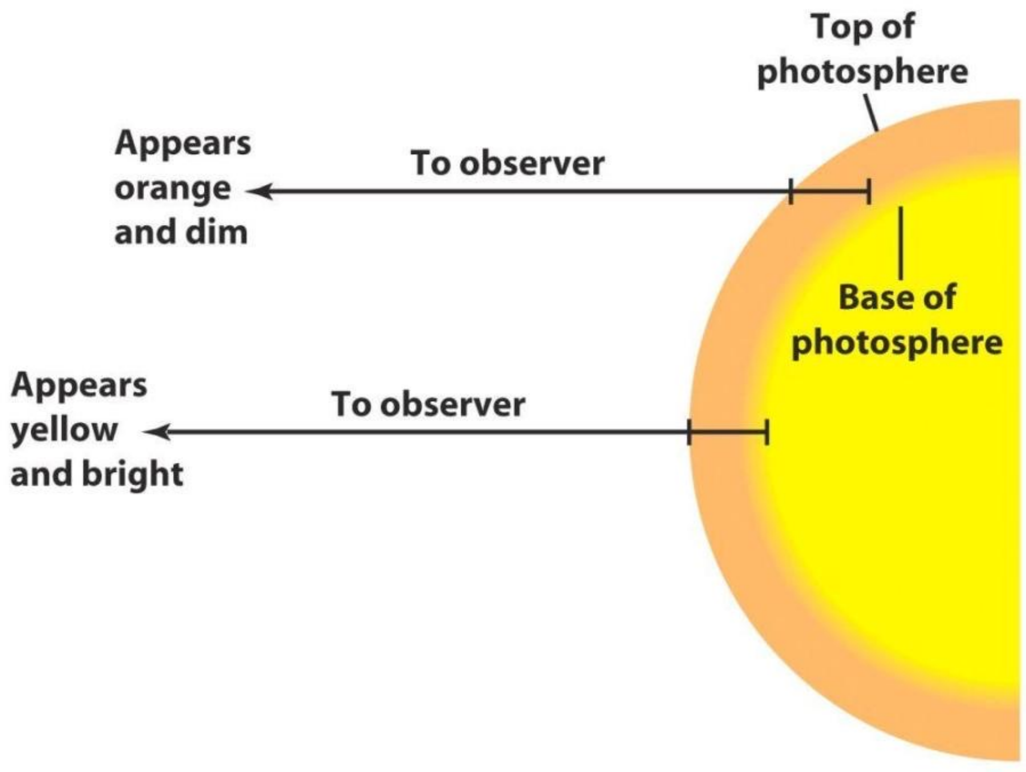
Depth (km)	% Light	Temp (K)	Pressure(bars)
0	99.5	4465	6.8×10^{-3}
100	97	4780	1.7×10^{-2}
200	89	5180	3.9×10^{-2}
250	80	5455	5.8×10^{-2}
300	64	5840	8.3×10^{-2}
350	37	6420	1.2×10^{-1}
375	18	6910	1.4×10^{-1}
400	4	7610	1.6×10^{-1}

Limb darkening

- Outer portions of photosphere being cooler
- Photons travel about the same path length

Dimmer light comes from higher, relatively cool layer within the photosphere

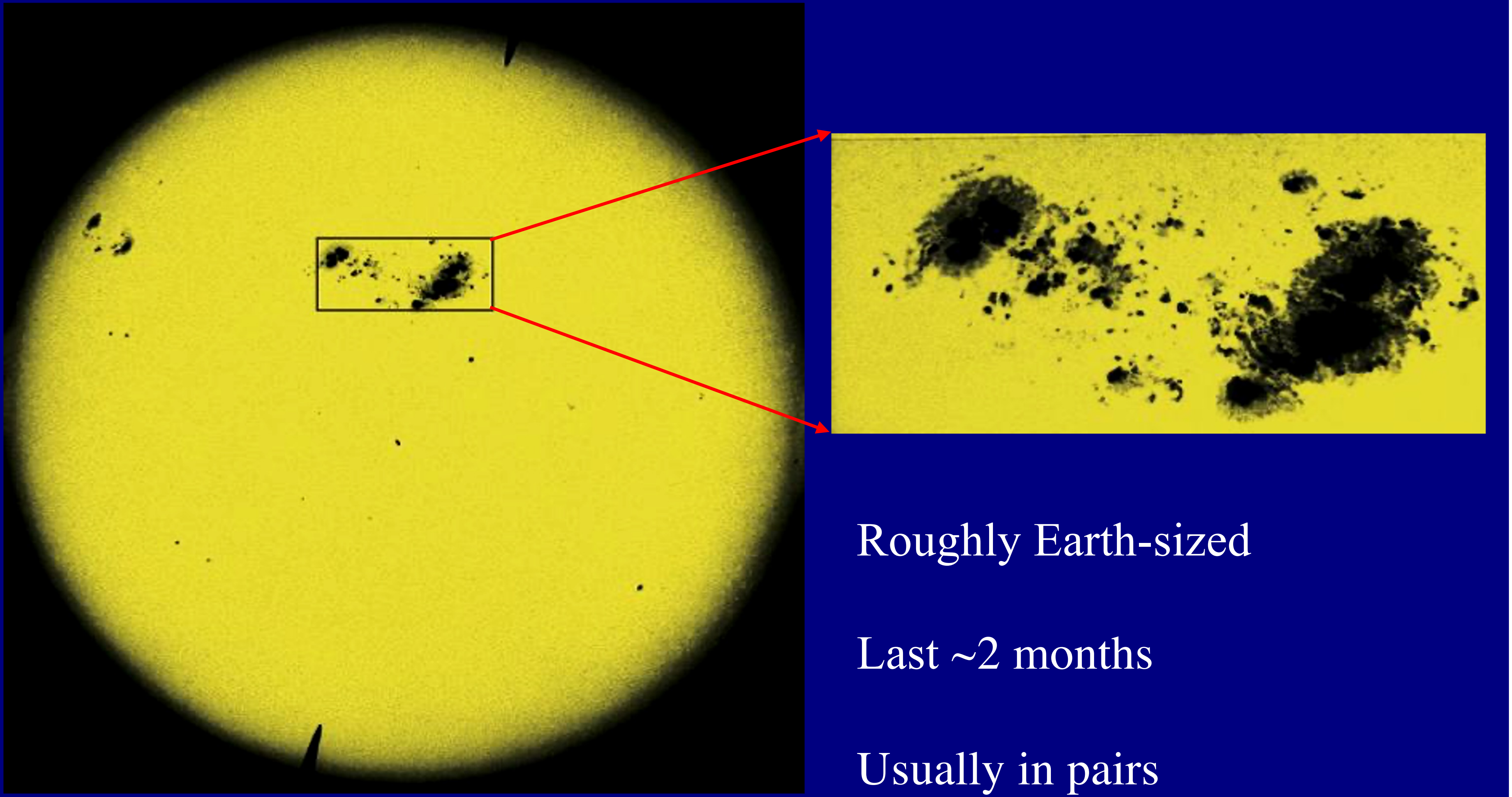
Bright light comes from low-lying, hot layer within the photosphere



- For something not having a well defined surface, it doesn't look very fuzzy, it looks well defined?

- We see about 400 km into photosphere - a tiny distance (0.06%) compared to radius (696,000 km) so looks sharp ("unresolved" to eyes).

Sunspots

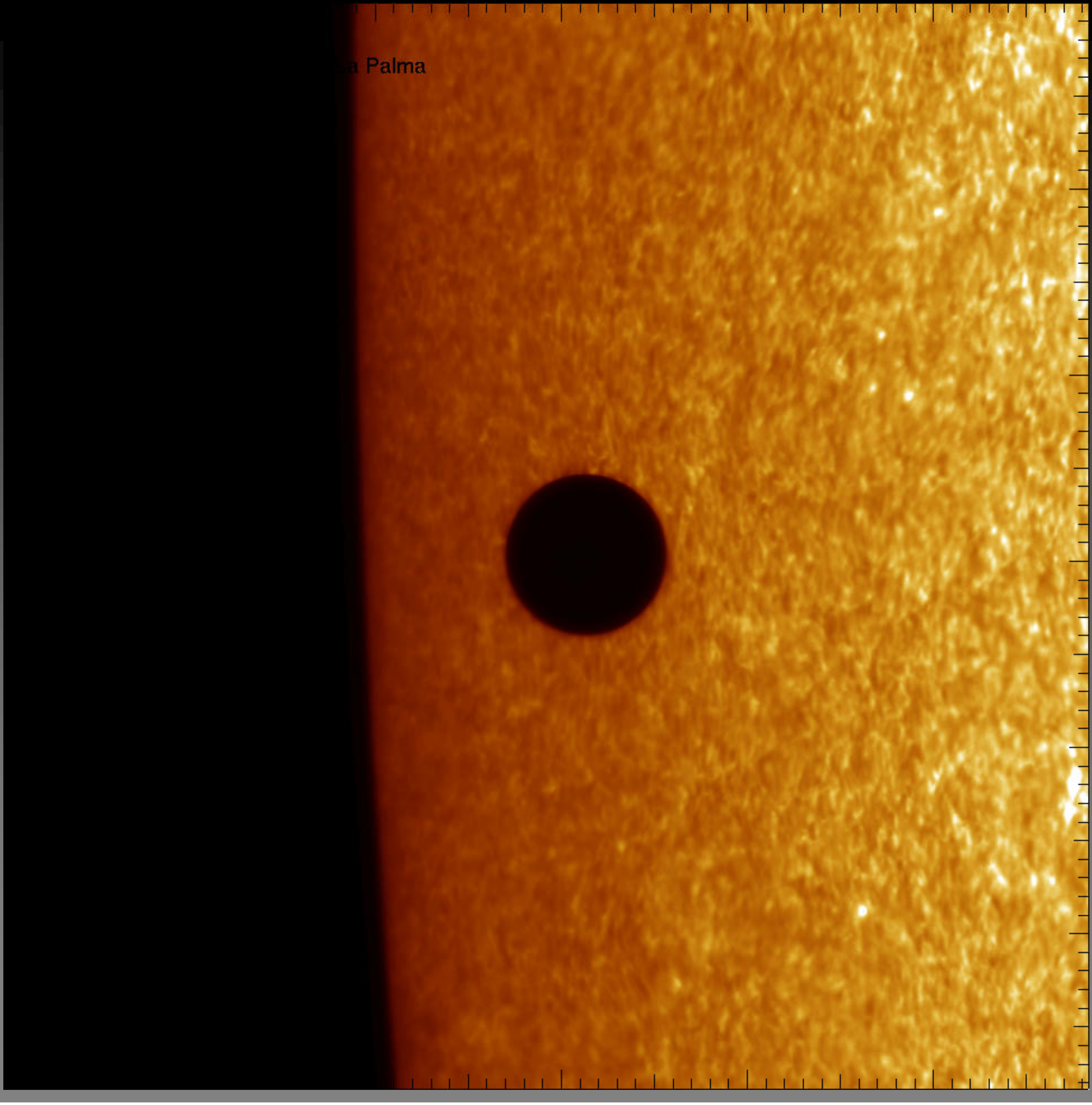


Roughly Earth-sized

Last ~2 months

Usually in pairs

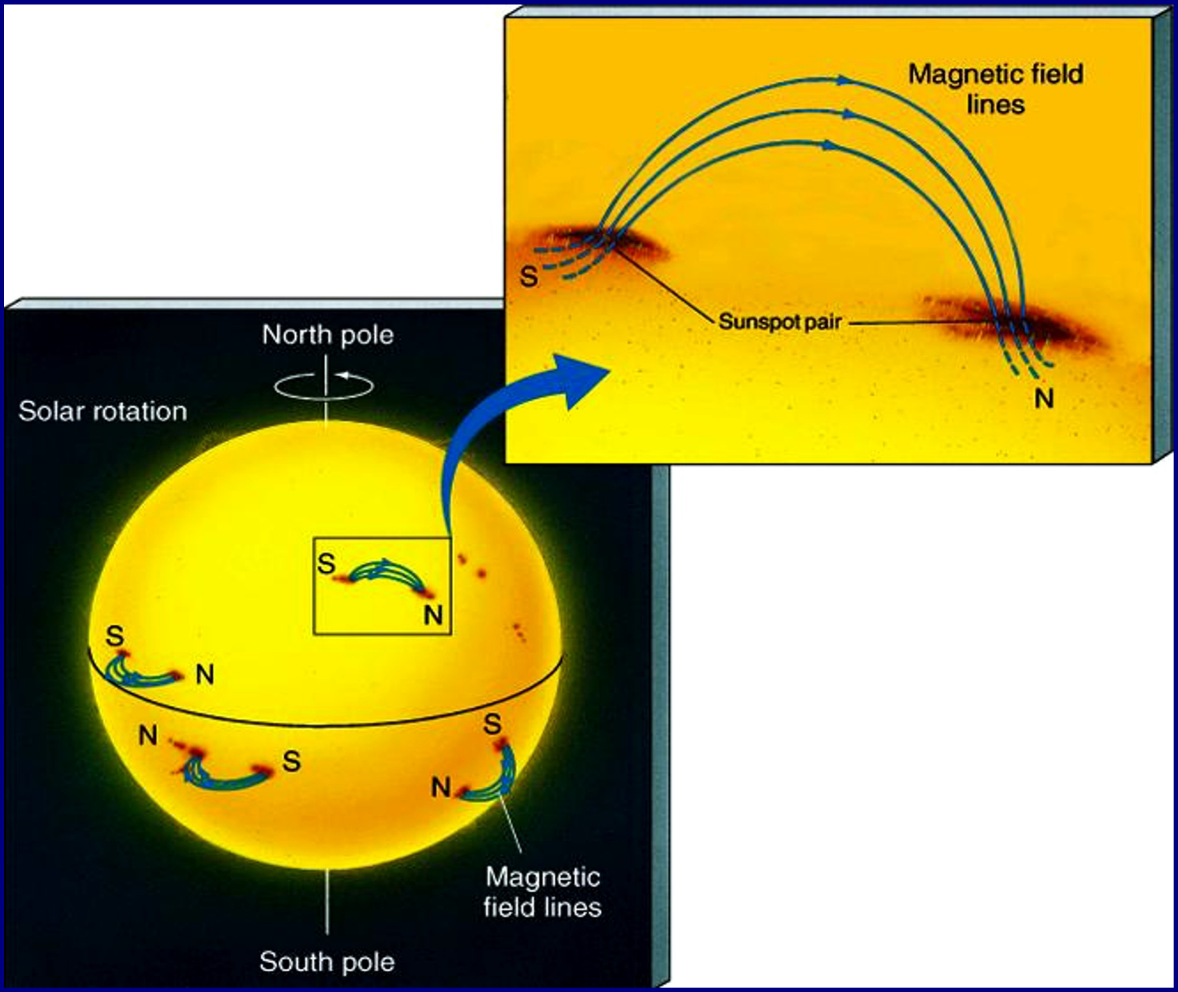
Follow solar rotation


a Palma

Sunspots

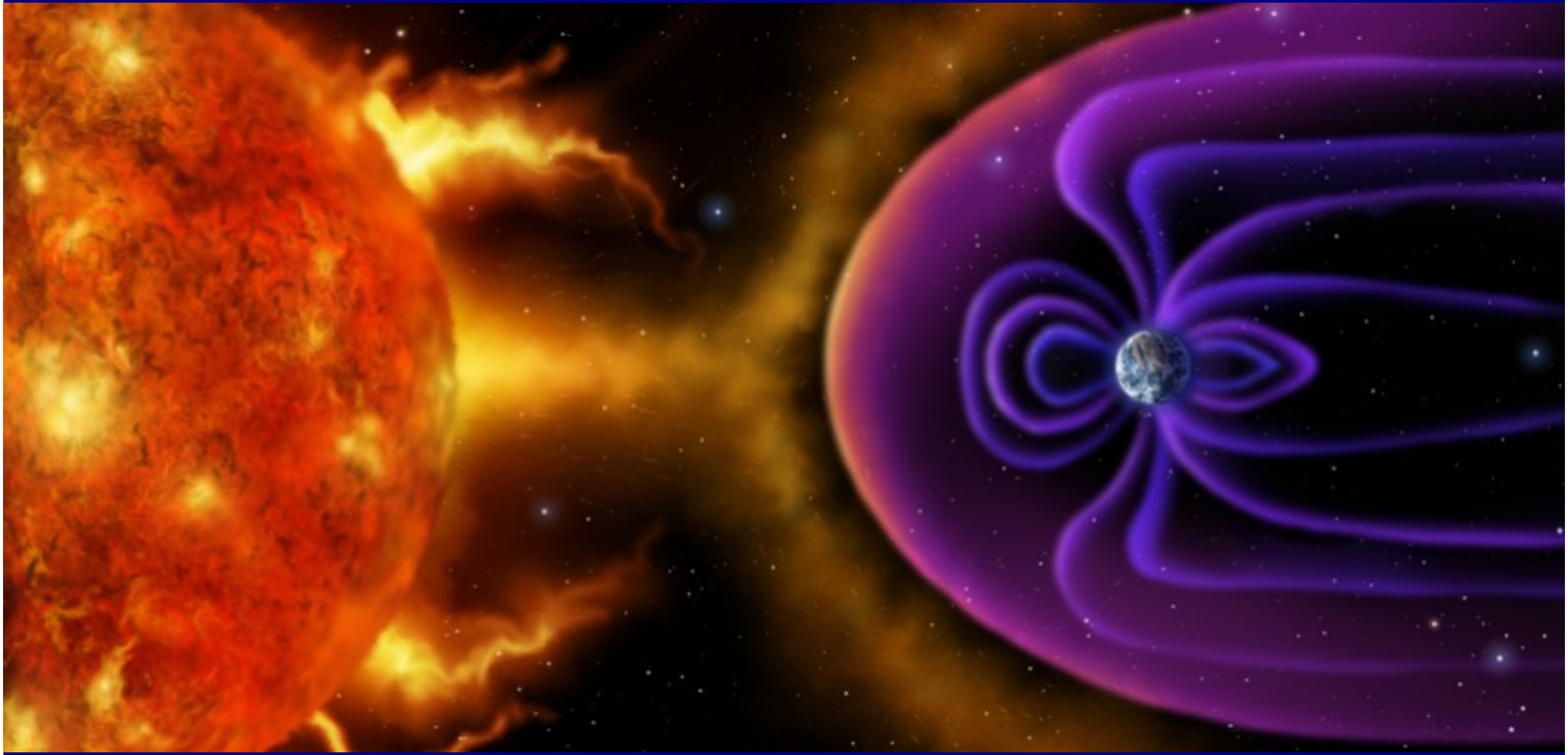
They are darker because they are cooler (4500 K vs. 5800 K).

Related to loops of the Sun's magnetic field.

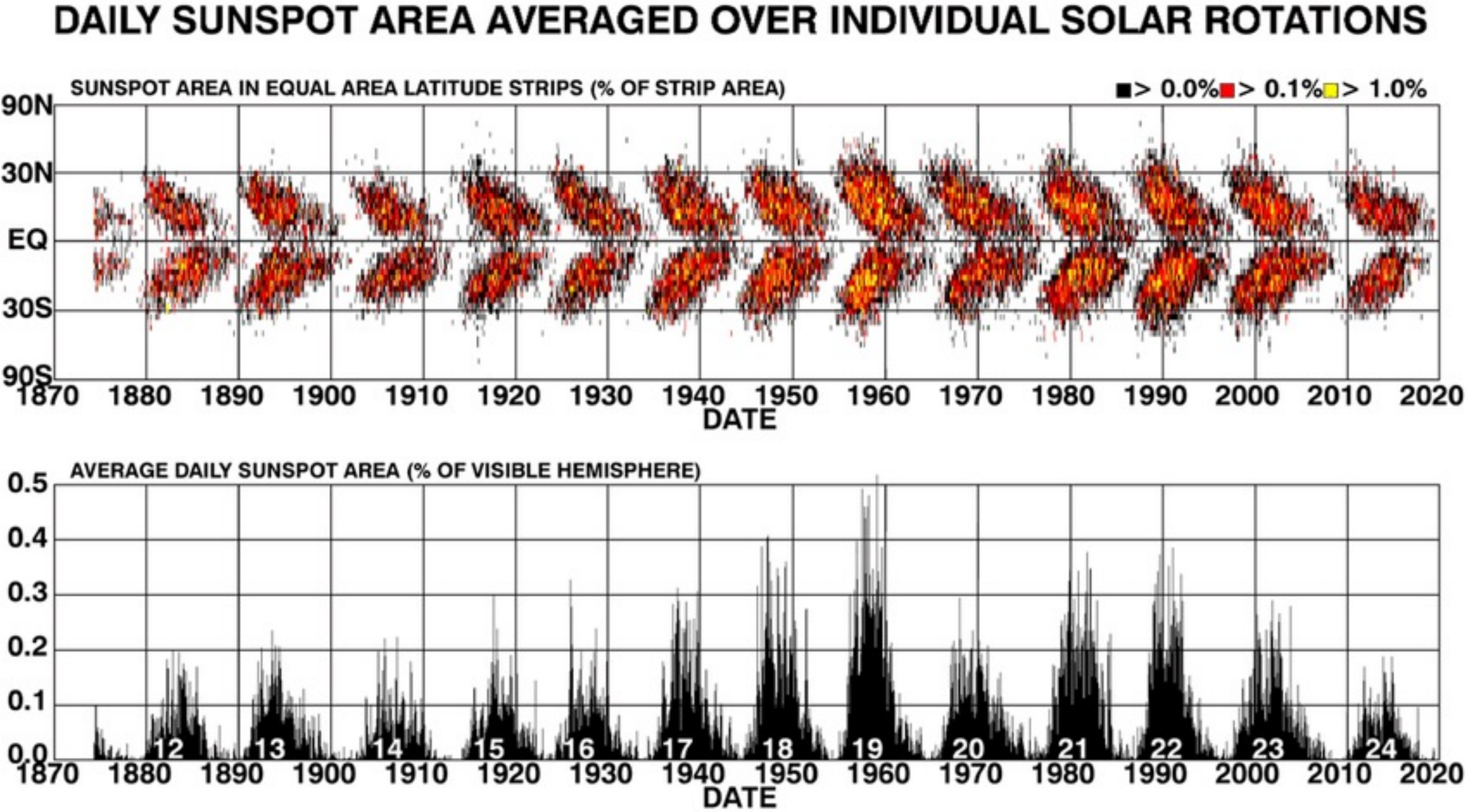


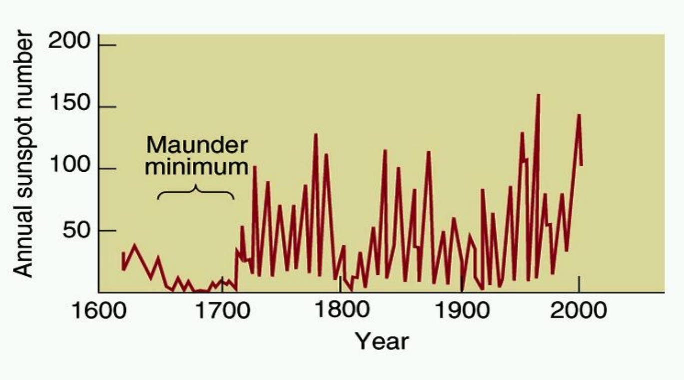
radiation from hot gas flowing along magnetic field loop at limb of Sun.

Solar Storms!

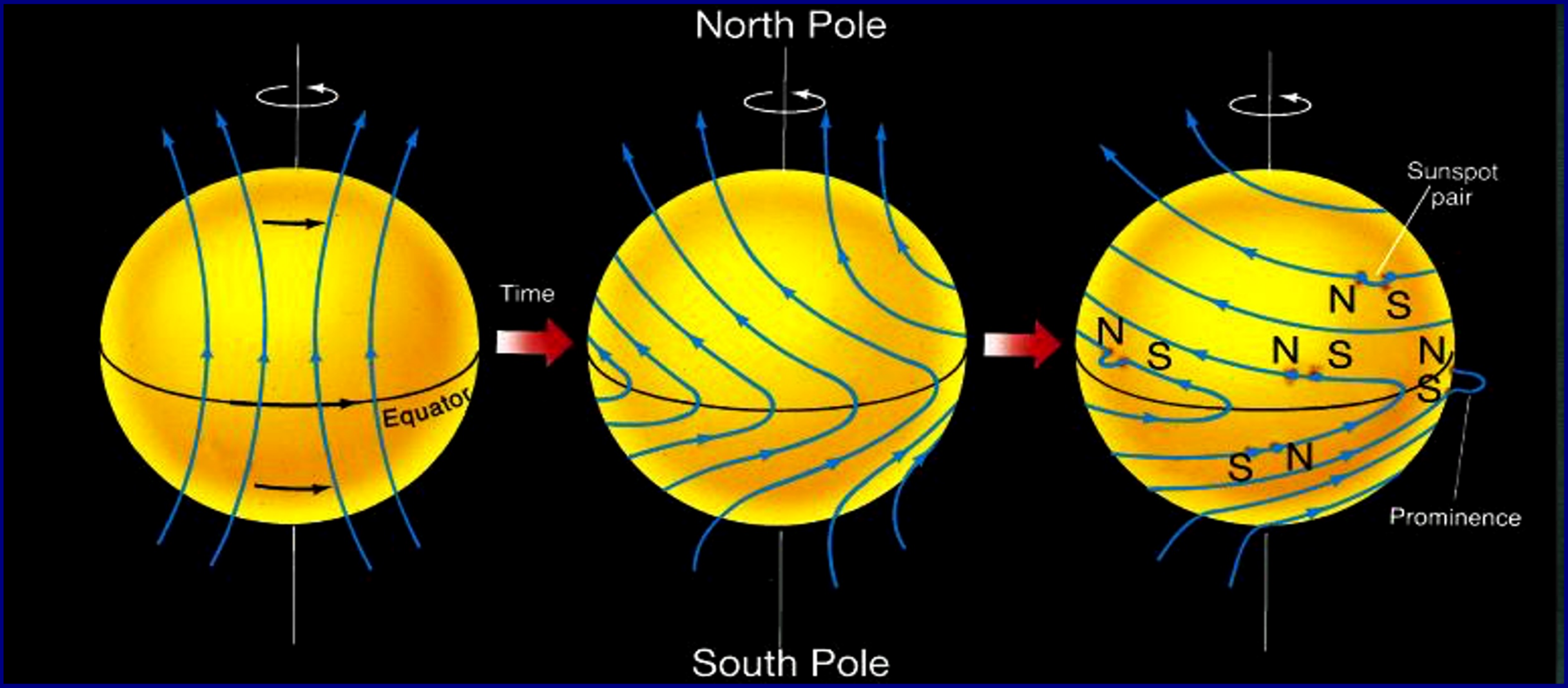


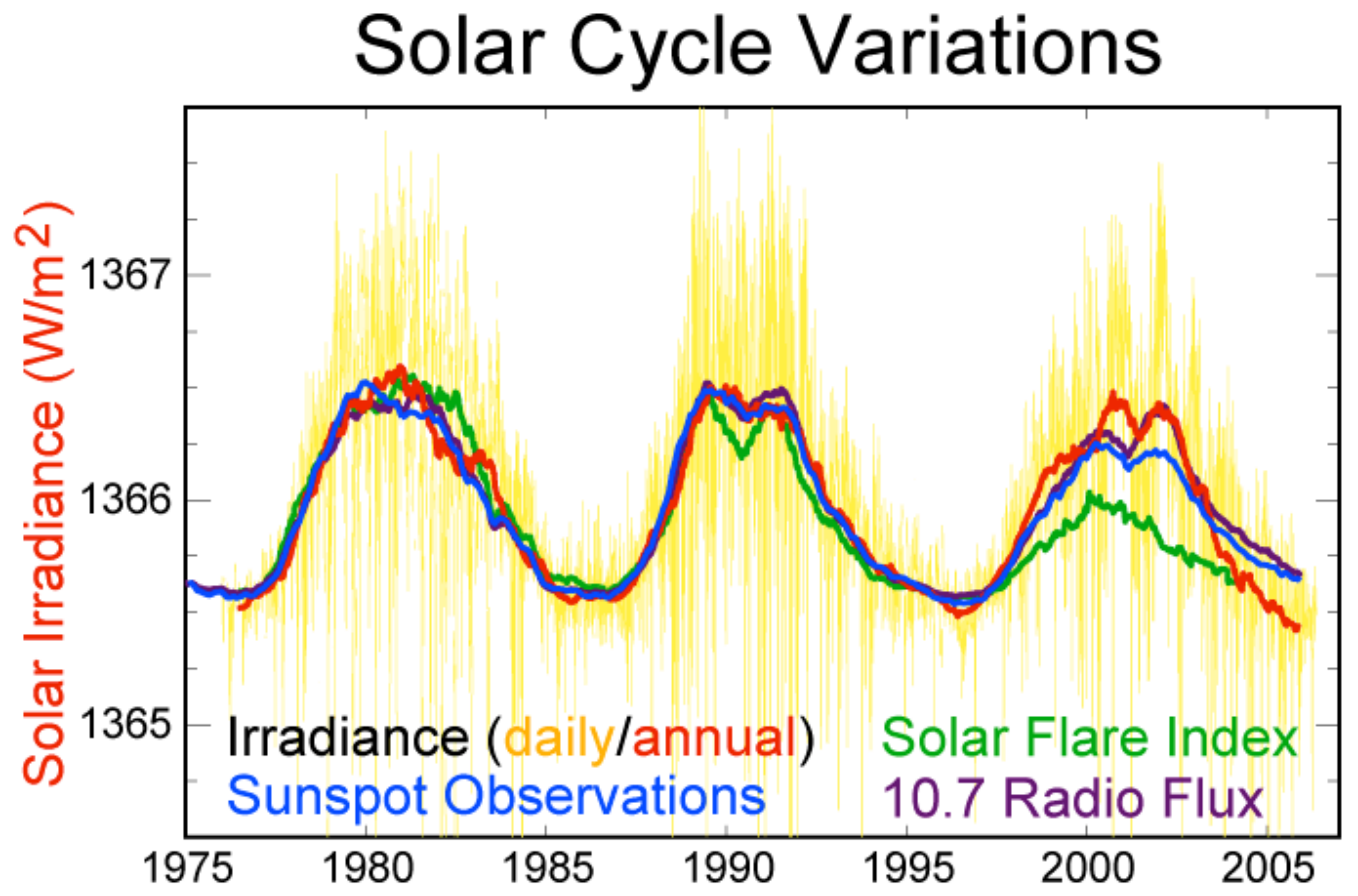
Sunspot numbers vary on a 11 year cycle.





Sun's magnetic field changes direction every 11 years. Maximum sunspot activity occurs about halfway between reversals.

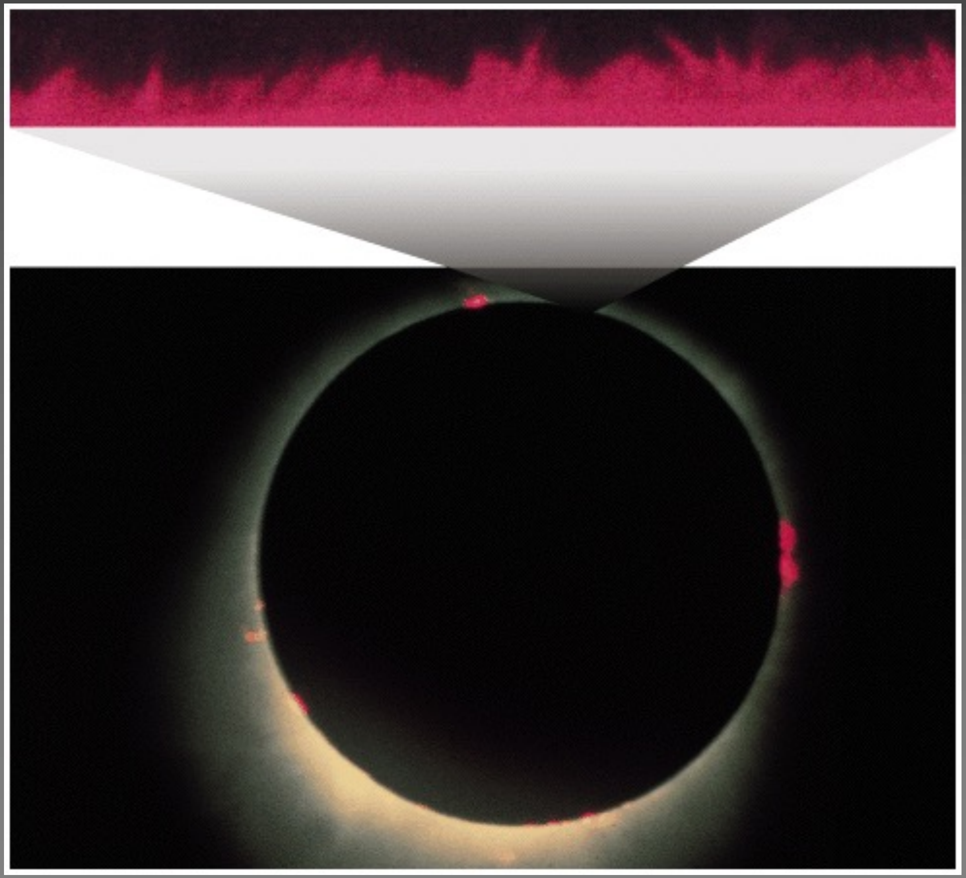




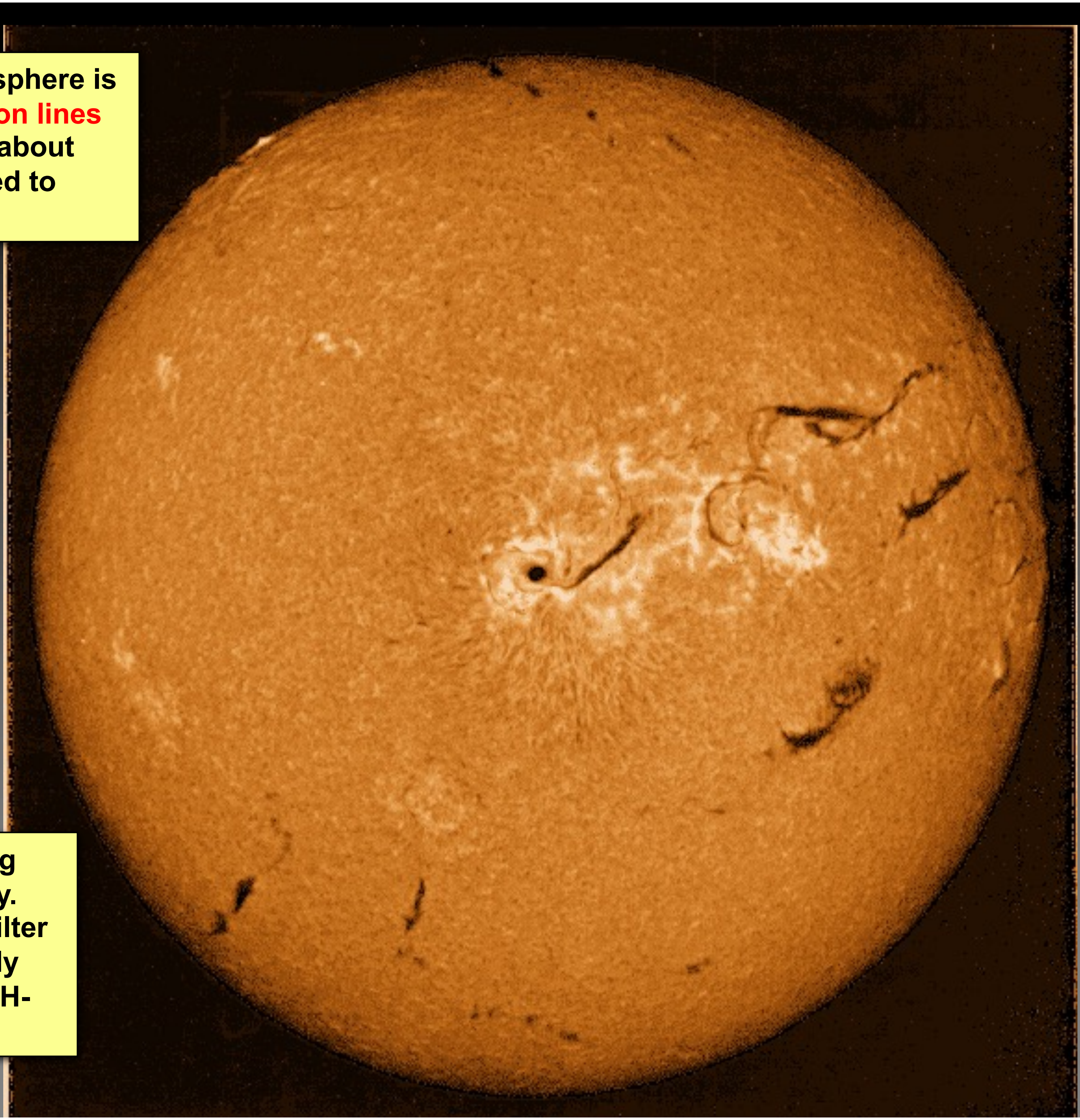
0.1% variation from maximum to minimum

Chromosphere

- Middle layer, characterized by Hα emission: red color.
- The gas is very rarefied (10^{-4} density of photosphere).
- Also featured are gas plumes jutting upward.



Spectrum of chromosphere is dominated by emission lines – what does this say about temperature compared to photosphere?



H alpha image showing chromospheric activity. Photo taken through filter which lets through only light of wavelength of H-alpha (656 nm).