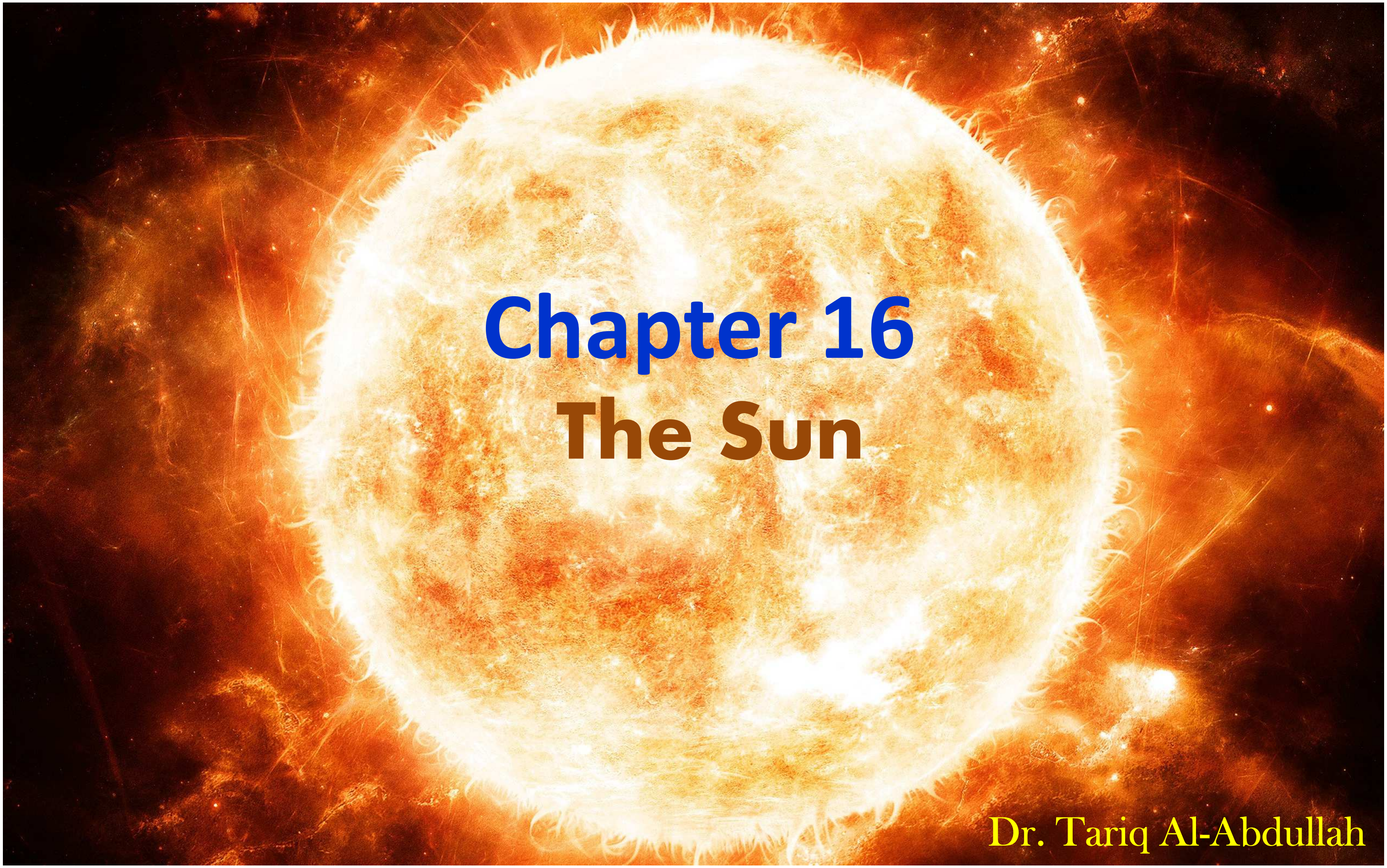

Chapter 16
The Sun
Dr. Tariq Al-Abdullah

Learning Goals:

16.1 Physical Properties of the Sun

16.2 The Solar Interior

16.3 The Sun's Atmosphere

16.4 Solar Magnetism

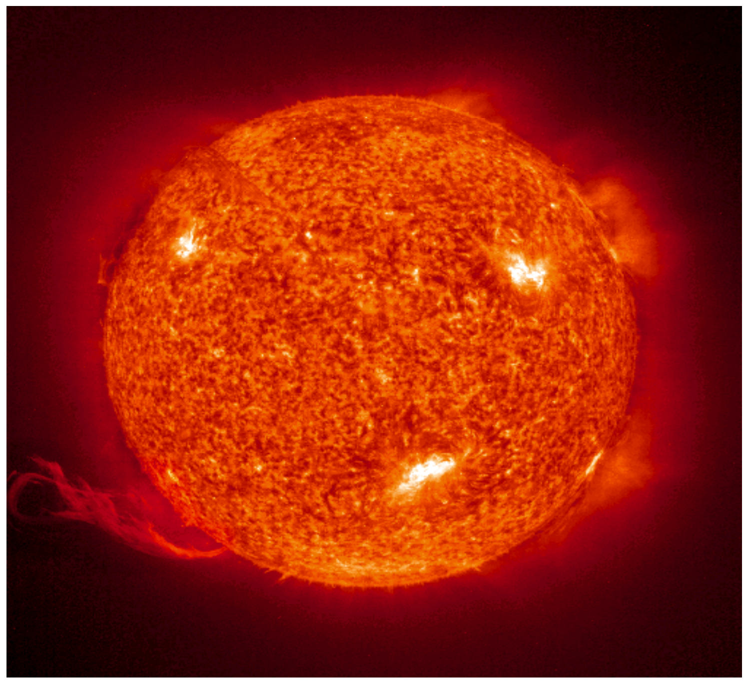
16.5 The Active Sun

16.6 The Heart of the Sun

16.7 Observations of Solar Neutrinos

16.1 Physical Properties of the Sun

- ✓ **The Sun:** a star – glowing ball of gas held together by its gravity.
- ✓ Sole source of light and heat powered by nuclear fusion.
- ✓ Typical star, average star, knowledge of solar phenomena
- ✓ Understand other stars in the universe.

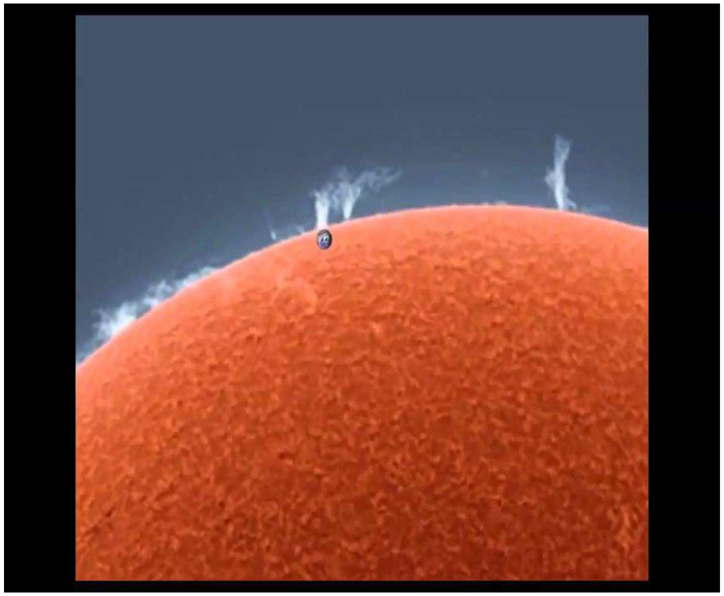


16.1 Physical Properties of the Sun

- The Sun radius 696,000 km.
- Its angular size 0.5° ≈ 32.5’. (ch1)
- Distance from Earth: 150,000,000 km (1AU)

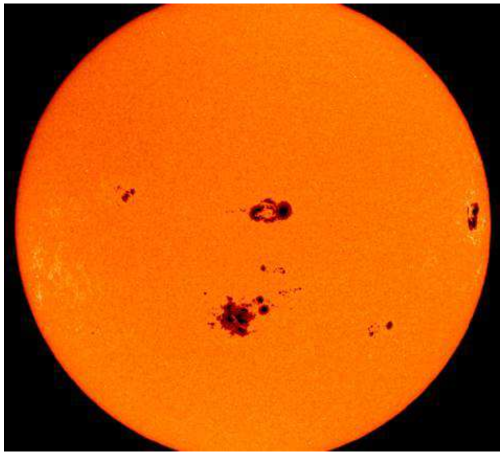
Mass $1.99*10^{30}$ kg ≈ 332,000 Earth’s mass. (ch2)

- Mean density 1410 kg/m^3, 0.255 Earth
- Surface Gravity 274 m/s^2, 28 Earth.
- Escape Velocity 618 km/s. 11km/s Earth
- Central temperature: 15,000,000 K
- Surface temperature: 5800 K.



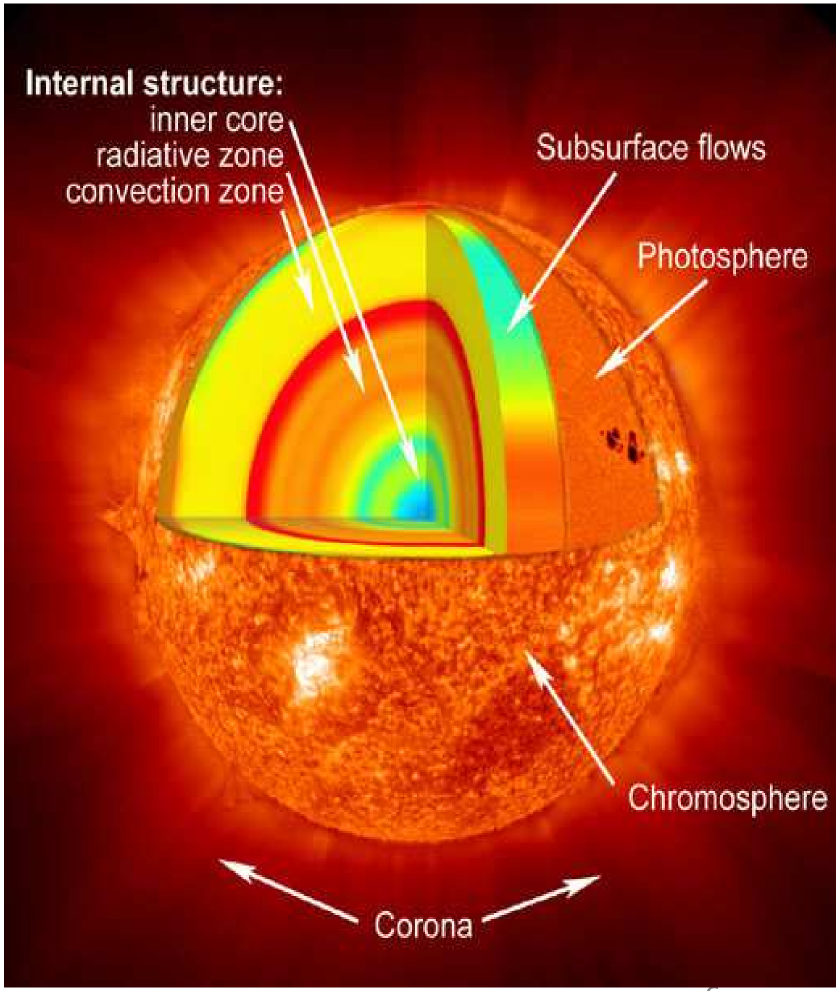
16.1 Physical Properties of the Sun

- **Sidereal rotation period:**
  - 25.1 solar days (equators)
  - 30.8 solar days (60^o) latitude.
  - 36 solar days (poles)
  - 26.9 solar days (interior)



16.1 Physical Properties of the Sun

- **Core**
  - radius = 0 to 200,000 km
  - Temperature (inner radius) =15,000,000 K
  - Energy generated by nuclear fusion
- **Radiation Zone**
  - radius = 200,000 to 496,000 km
  - Temperature (inner radius) = 7° MK
  - Energy transported by EM radiation
- **Convection Zone**
  - radius = 496,000 to 696,000 km
  - Temperature (inner radius) = 2° MK
  - Energy transported by convection
- **Photosphere**
  - radius = 696,000 to 696,500 km
  - Temperature(inner radius) = 5800 K
  - EM radiation escapes - visible surface



16.1 Physical Properties of the Sun

- Chromosphere
  - radius = 696,500 to 698,000 km
  - Temperature (inner radius) = 4500 K
  - Cool lower atmosphere
- Transition Zone
  - radius = 698,000 to 706,000 km
  - Temperature (inner radius) = 8000 K
  - Temperature rising rapidly
- Corona
  - radius = 706,000 km out
  - Temperature (inner radius) = 3,000,000 K
  - Hot, low-density upper atmosphere
- Solar Wind
  - radius = 10,000,000 km out
  - Temperature (inner radius) = >1,000,000 K
  - Material escaping and flowing through the solar system

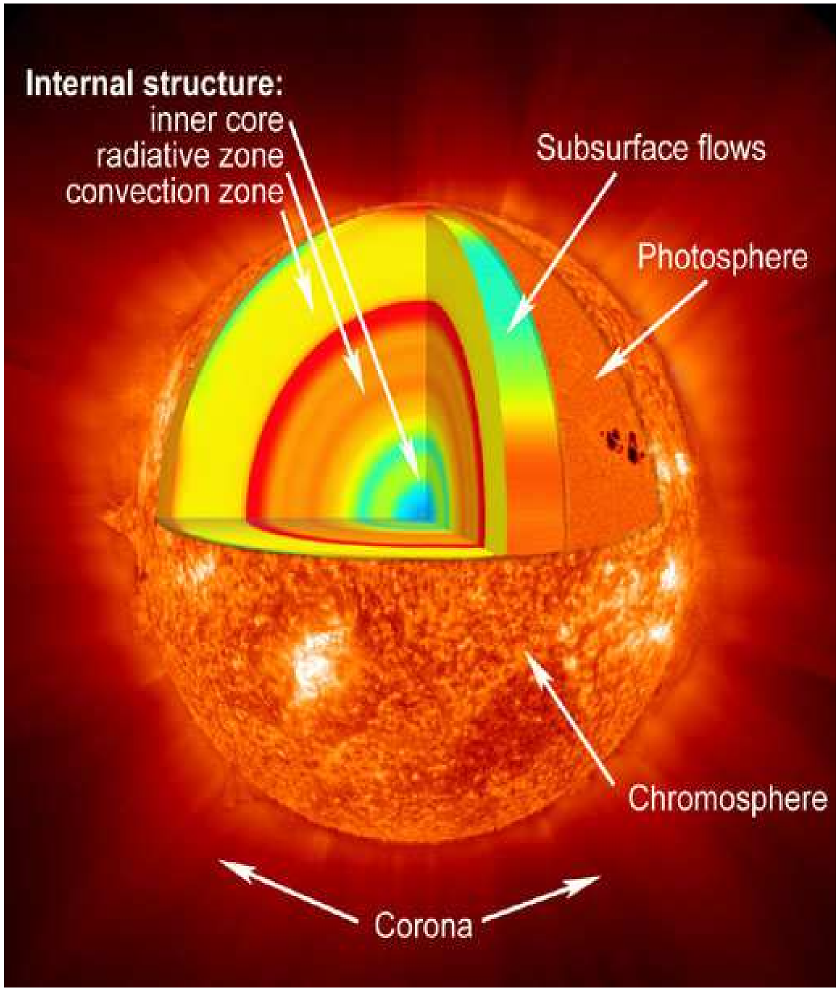


TABLE 16.1 The Standard Solar Model

Region	Inner Radius (km)	Temperature (K)	Density (kg/m^3)	Defining Properties
Core	0	15,000,000	150,000	Energy generated by nuclear fusion
Radiation zone	200,000	7,000,000	15,000	Energy transported by electromagnetic radiation
Convection zone	496,000*	2,000,000	150	Energy carried by convection
Photosphere	696,000*	5800	2×10^{-4}	Electromagnetic radiation can escape—the part of the Sun we see
Chromosphere	696,500*	4500	5×10^{-6}	Cool lower atmosphere
Transition zone	698,000*	8000	2×10^{-10}	Rapid increase in temperature
Corona	706,000*	3,000,000	10^{-12}	Hot, low-density upper atmosphere
Solar wind	10,000,000	>1,000,000	10^{-23}	Solar material escapes into space and flows outward through the solar system

* *These radii are based on the accurately determined radius of the photosphere. The other radii quoted are approximate, round numbers.*

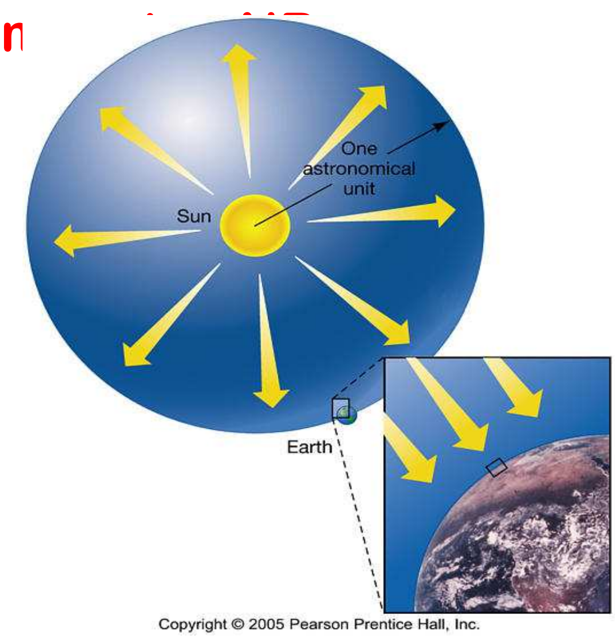
16.1 Physical Properties of the Sun

* **Total Luminosity of the Sun:** equivalent to the energy flow through a sphere surrounding the Sun.

  - The surface area of this sphere is $2.8 \times 10^{23}\ m^2$
  - Solar constant $1400\ W/m^2$; energy reaching the Earth each second
  - So, the total luminosity is: $1400\ Watts/m^2 \times 2.8 \times 10^{23}\ m^2$

$$= 4 \times 10^{26}\ Watts$$

- Each second: the Sun produces 100 billion one-m
- 6 sec would evaporate the oceans.
- 3 min would melt the Earth's crust.

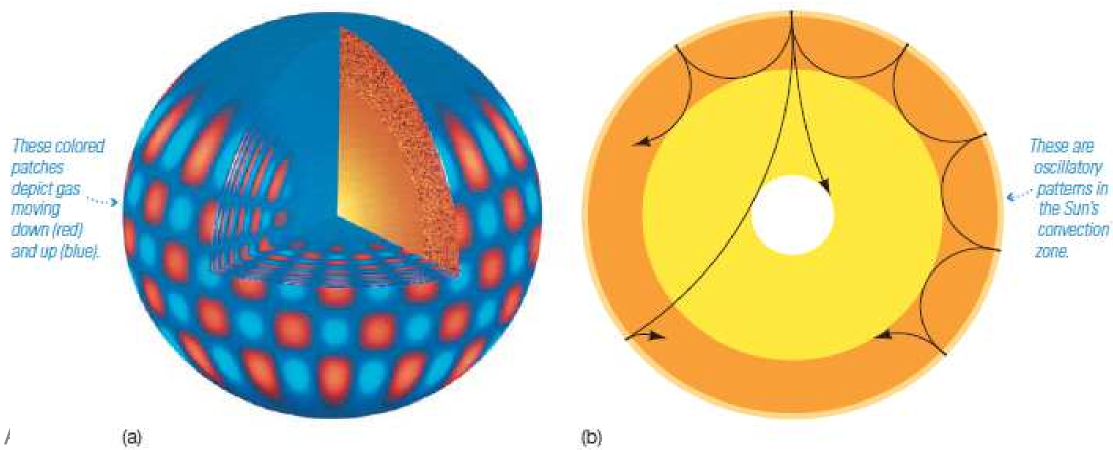


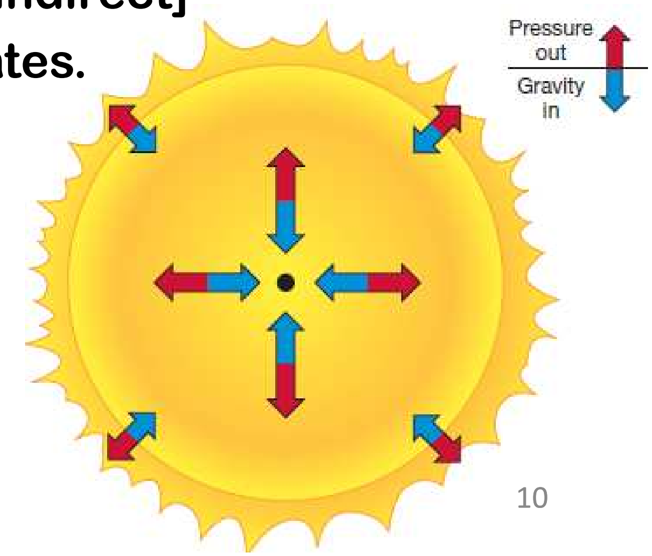
16.2 The Solar Interior

- **Lacking direct measurements , researchers looking for mathematical models**
- **Combining all available data with theoretical insight➔ Standard Solar Model**

Model Structure of the Sun:

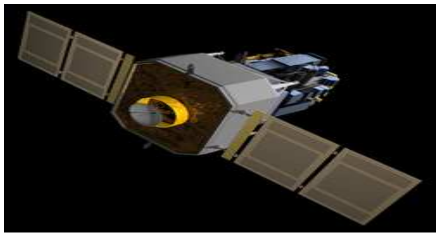
- **Sun’s mass, radius, temperature and luminosity are almost stable.**
- **Theoretical models begin with the assumption: It’s in hydrostatic equilibrium**
- **Pressure’s outward push balances the gravity’s inward pull.**
- **This assumption allow theorists to predict Sun’s Properties.**
- **Information about the Sun’s interior are required! [indirect]**
- **Doppler shifts of solar spectral lines ➔ Sun Oscillates.**





16.2 The Solar Interior

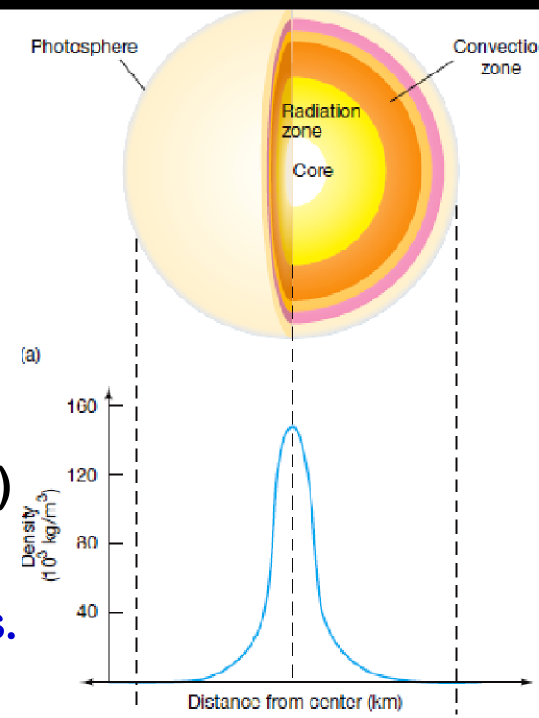
- **Helioseismology: vibrating waves in the Sun → earthquakes**
- **P-wave & S-wave**



Continuous Observation by SOHO

1.5 million km between Earth & Sun

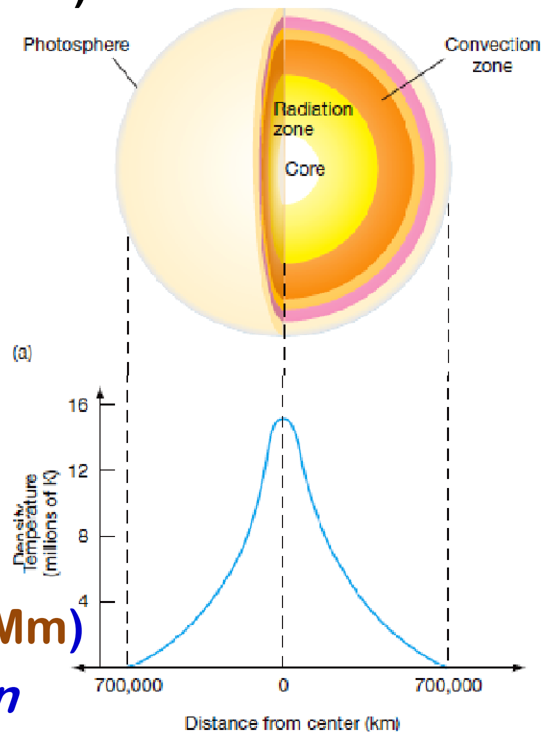
- **Data → Temp., rotation, density**
- **Theoretical models (SSM) Predicts:**
- **Variation in density is large:**
  - **core 150,000 kg/m^3 (20 times density of iron)**
  - **at 350,000 km ➔ 1000 kg/m^3 (water)**
  - **Photosphere ➔ 2x10^{-4} kg/m^3 (10^{-4} Earth's surface)**
  - **Far Corona ➔ 10^{-23} kg/m^3**
- **90% of Sun's mass is within the inner half of its radius.**



16.2 The Solar Interior

- **Theoretical models (SSM) Predicts:**
- **Variation in temperature is also large (not as rapid as density):**
  - **15 MK at the core (10 MK to enthuse nuclear reactions)**
  - **5800 K at the surface**

- **Helioseismology indicates Sun's rotation speed varies with the depth (No clear explanation)**



- **Energy Transport**
- **very hot interior ➔ Atoms are fully ionized ➔ transparent to radiations → no absorption of energy**
- **Moving outward ➔ electrons remain bounded in atoms ➔ Absorption outgoing radiation ➔ Totally opaque (500 Mm)**

*** The escaping energy reaches the surface by *convection***

16.2 The Solar Interior

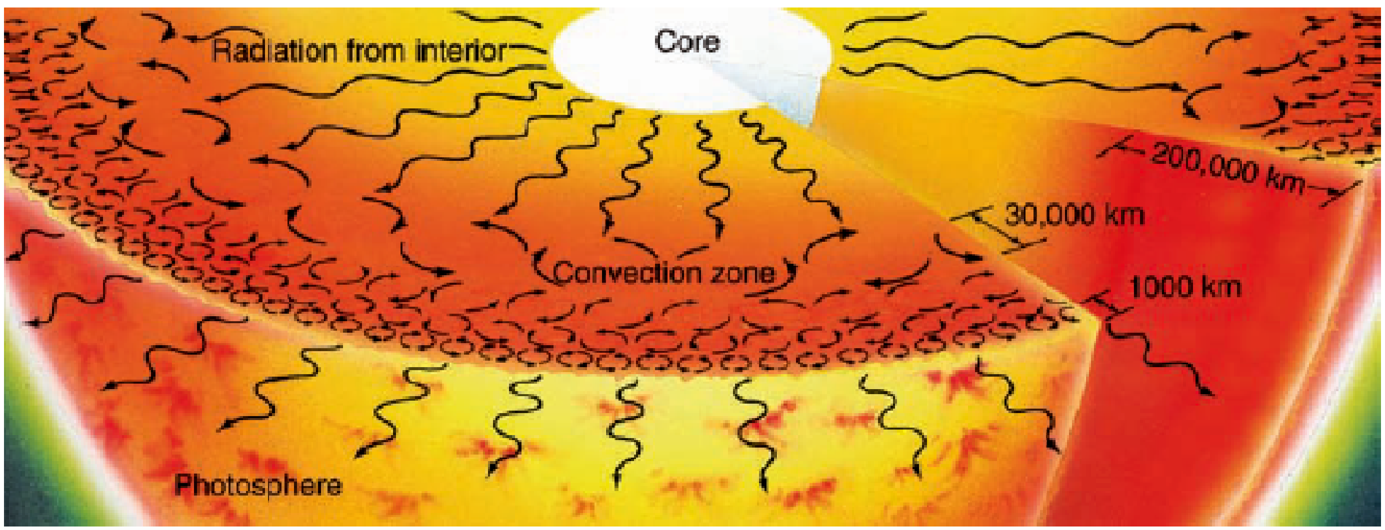
- Energy Transport
- Convection cells organized of different sizes at different depths (200,000 km)

➔ Astronomers see the cells attached to the photosphere.

- Above the photosphere, the gas become thin ➔ transparent

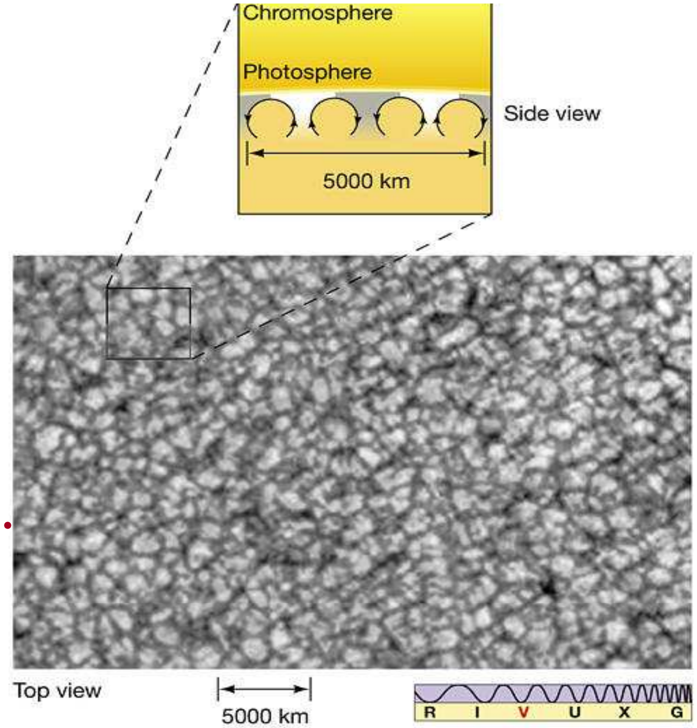
➔ Transition from opacity to complete transparency is very rapid

➔ Thin outer layer (photosphere)



Granulation

- Above the Convection Zone and below the Photosphere:
- regions of bright (blue shifted) and dark (red shifted) gas.
- Each bright granule 1000 km
- life-time 5-10 min.
- Direct evidence of upward motion of gas; boiling.
- Supergranules = 30,000 km.



General overview of atmosphere

*Photosphere

*Chromosphere

*corona

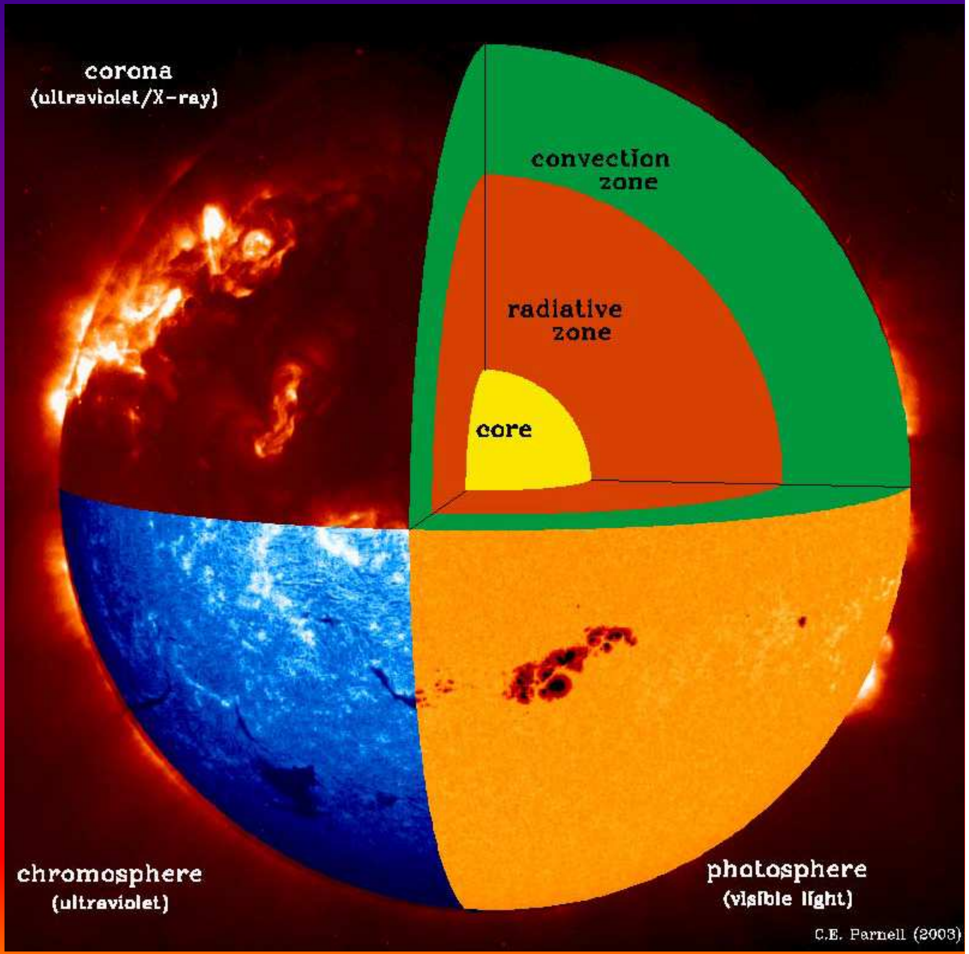
*Solar wind

Solar Atmosphere

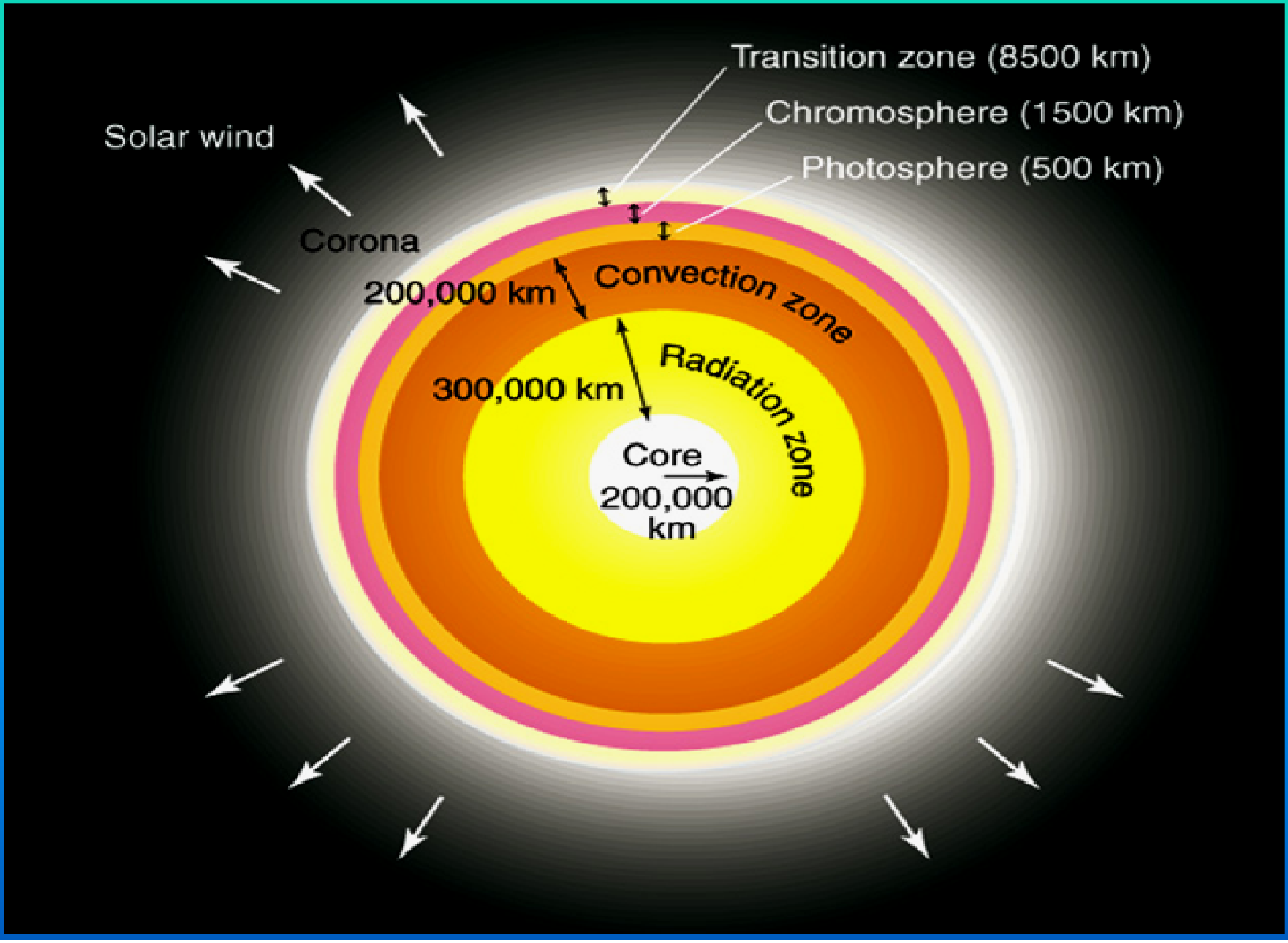
Photosphere

Chromosphere

Corona

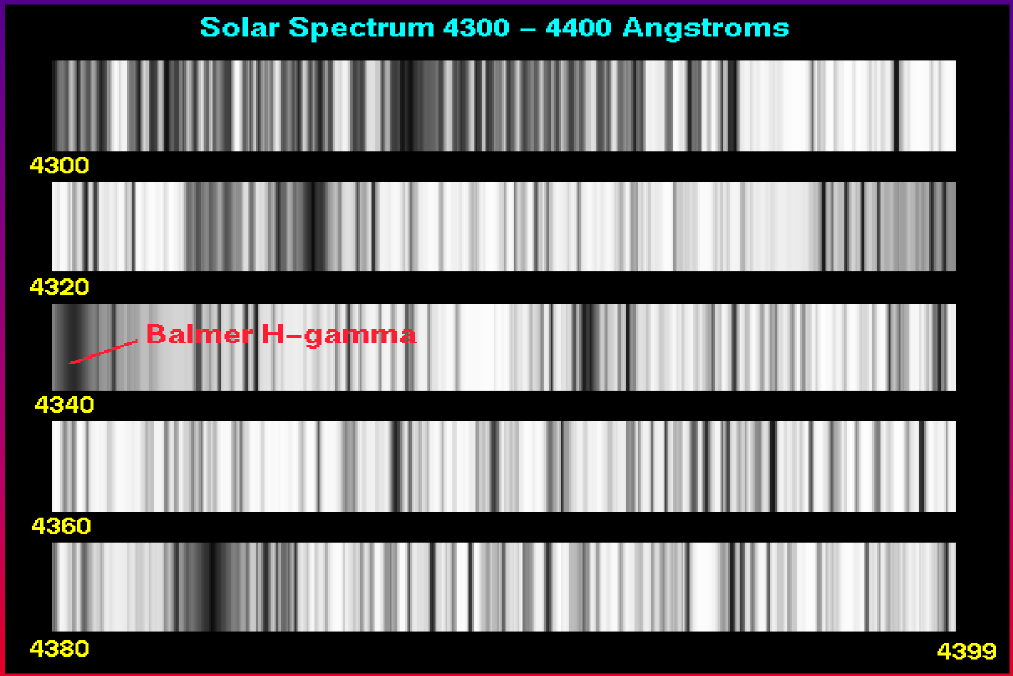


Main Regions of the Sun



The Solar Atmosphere

- The solar spectrum has *thousands* of absorption lines
- More than 67 different elements are present!
- *Hydrogen* is the most abundant element followed by *Helium* (1st discovered in the Sun!)



Spectral lines are formed when light is absorbed before escaping from the Sun; this happens when its energy is close to an atomic transition, so it is absorbed

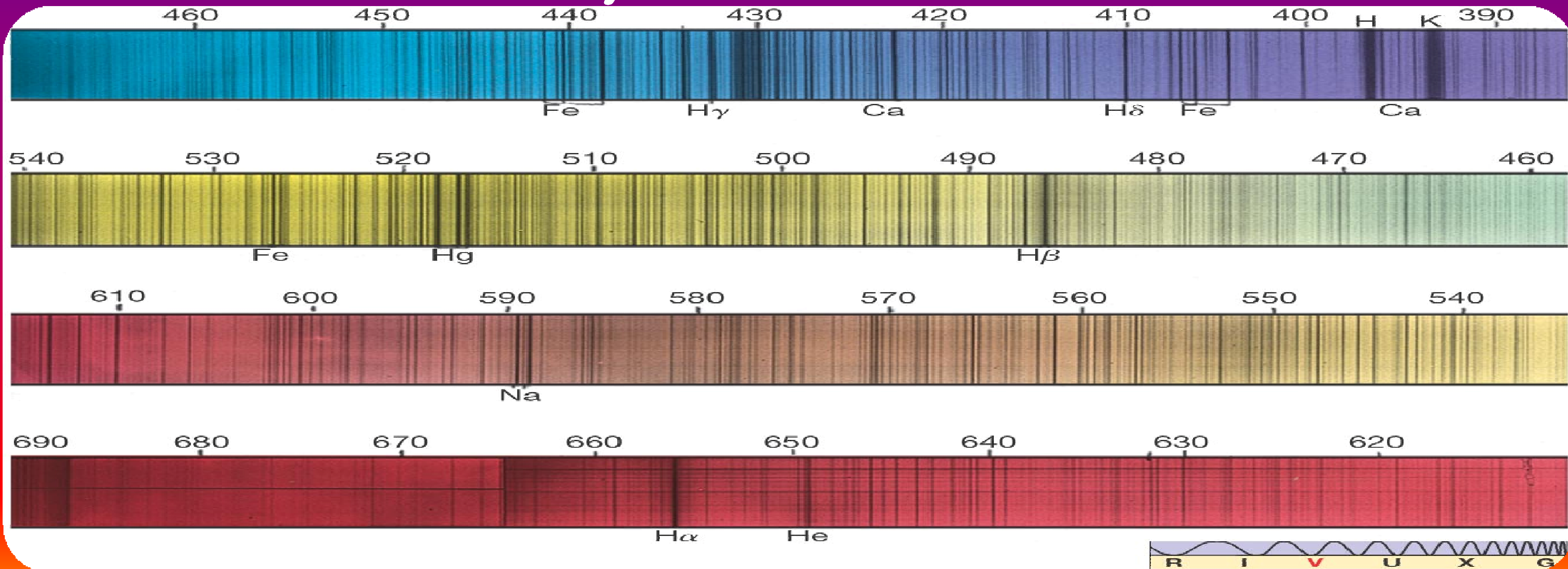
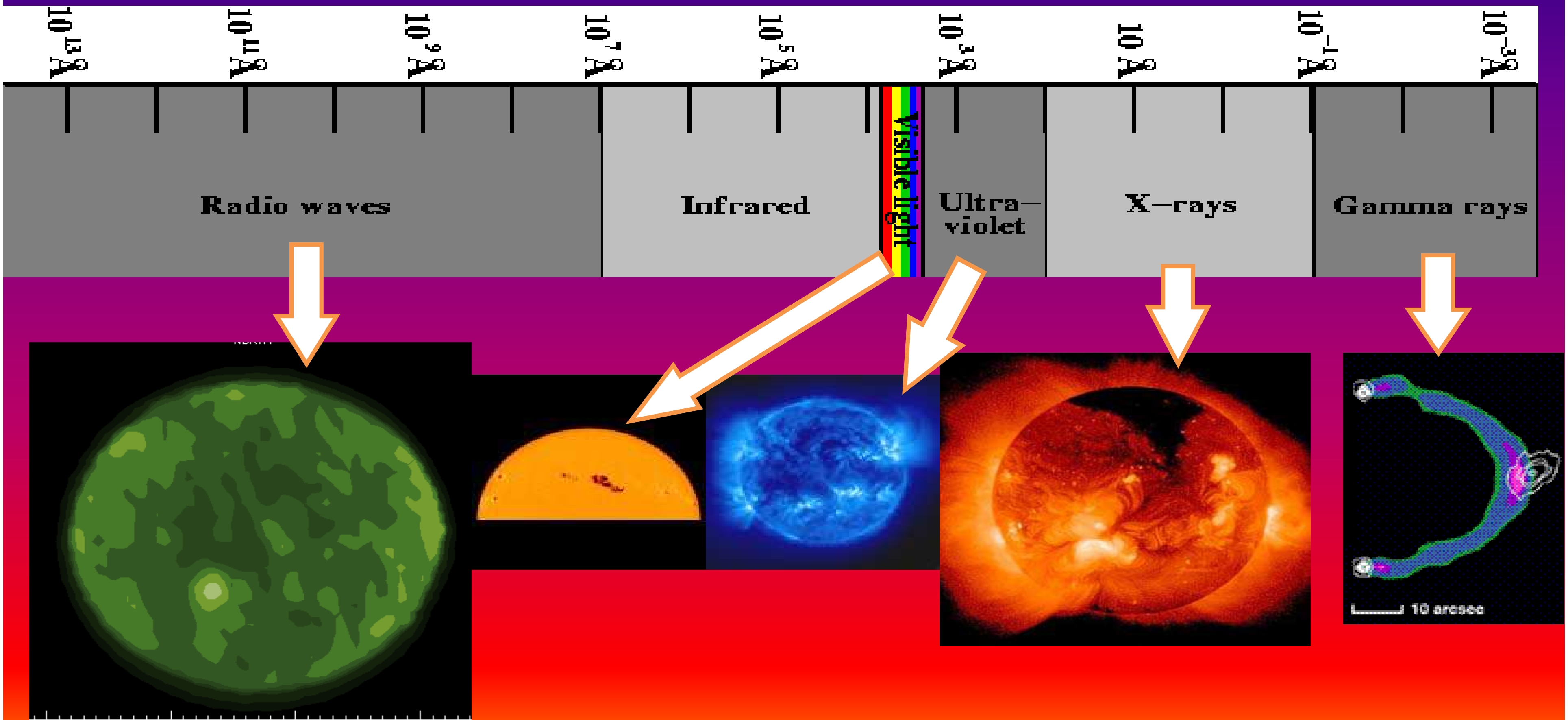


TABLE 16.2 The Composition of the Sun

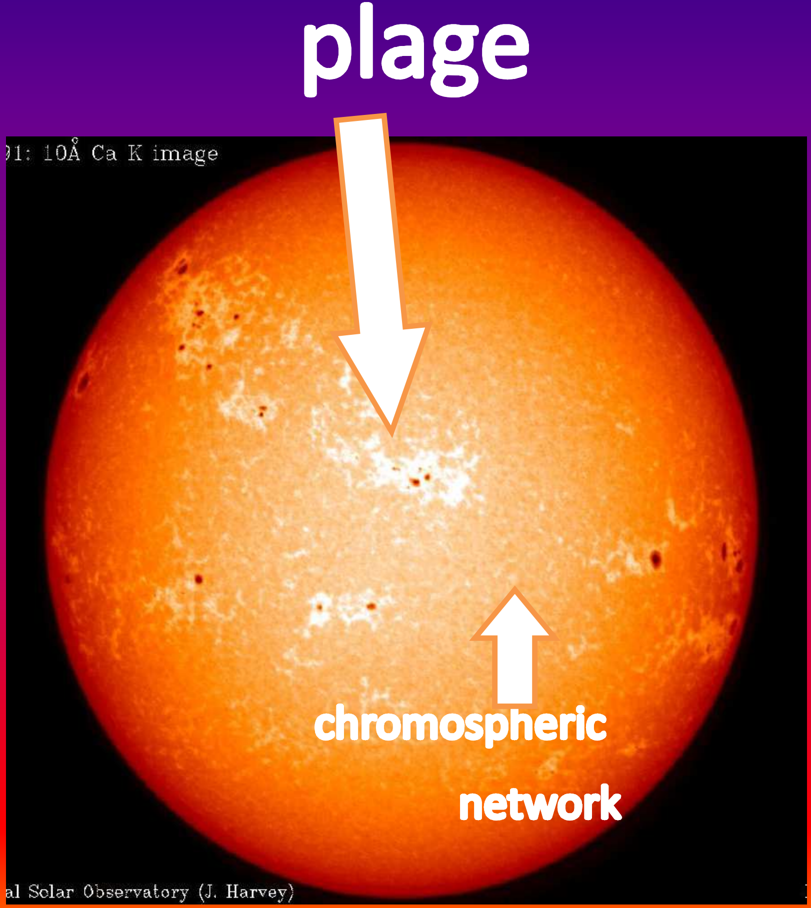
Element	Percentage of Total Number of Atoms	Percentage of Total Mass
Hydrogen	91.2	71.0
Helium	8.7	27.1
Oxygen	0.078	0.97
Carbon	0.043	0.40
Nitrogen	0.0088	0.096
Silicon	0.0045	0.099
Magnesium	0.0038	0.076
Neon	0.0035	0.058
Iron	0.0030	0.14
Sulfur	0.0015	0.040

Observing Sun’s Atmosphere

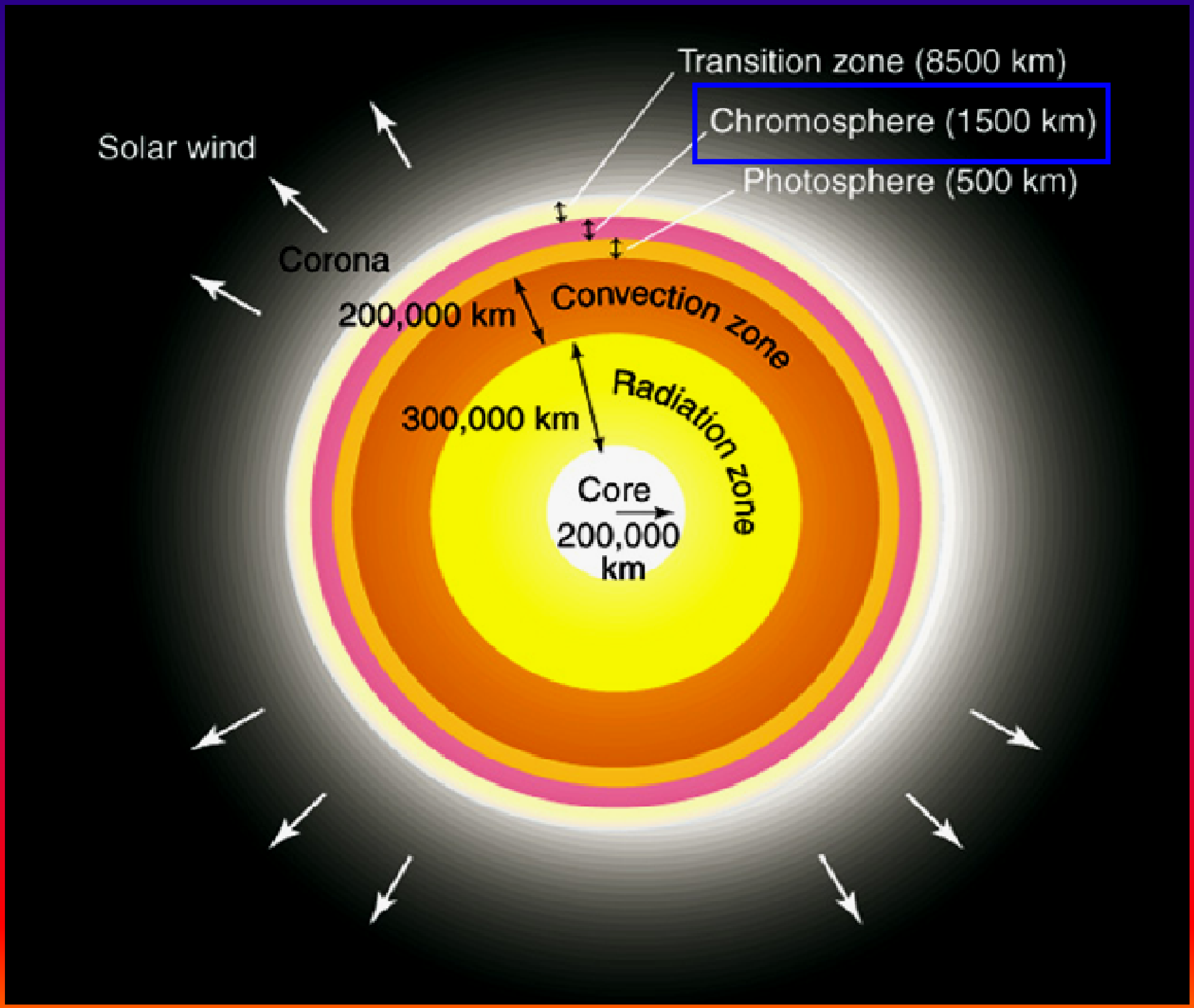


Chromosphere

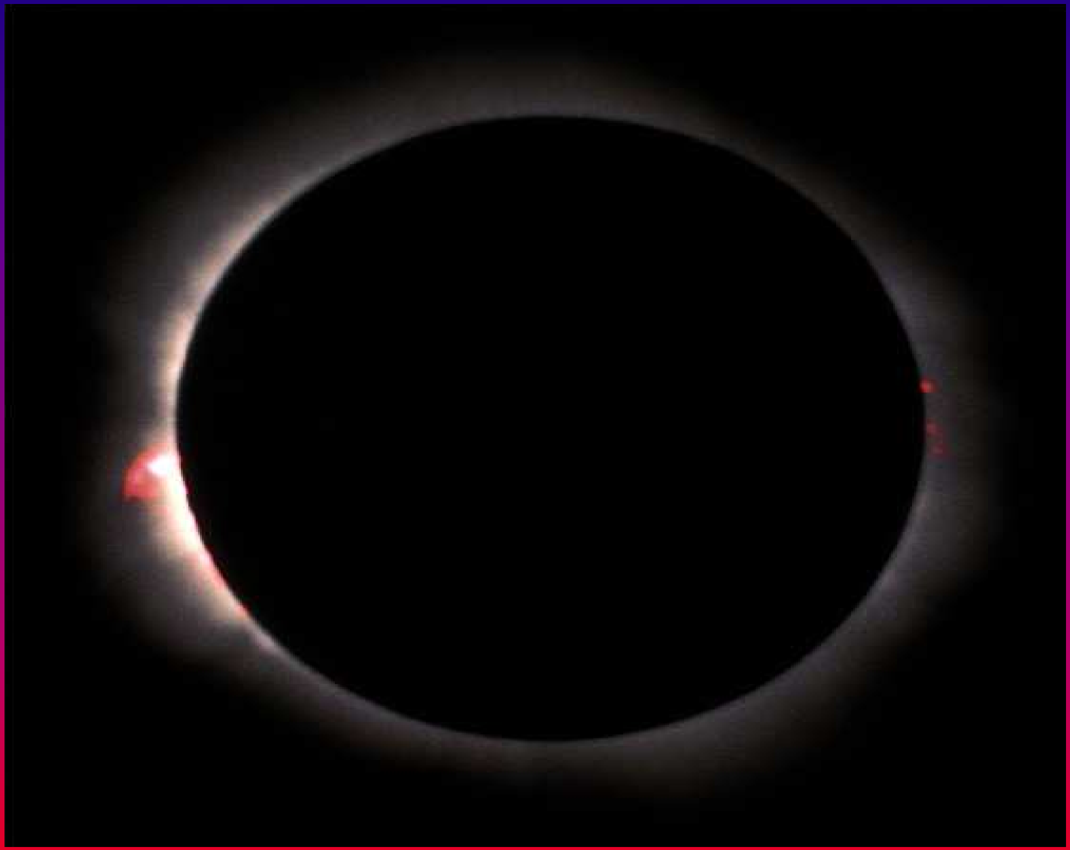
- Highly non-uniform
- 4300 K < T < 10^6 K
- n decreases to ~ 10^{15} m^{-3} in transition region
- Observed in many wavelengths, e.g.,
- Ca II K (393.3 nm)
- H alpha (656.3 nm),... •



Chromosphere



Chromosphere (seen during full Solar eclipse)



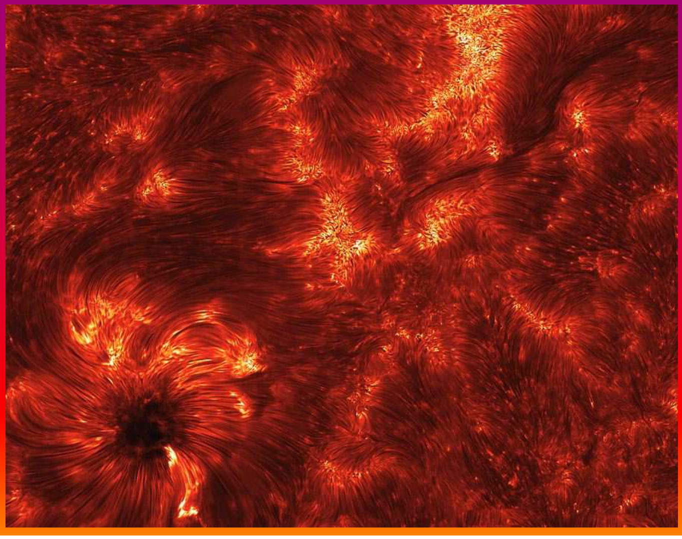
- Chromosphere emits very little light because it is of low density
- Reddish hue due to (656.3 nm) line emission from Hydrogen

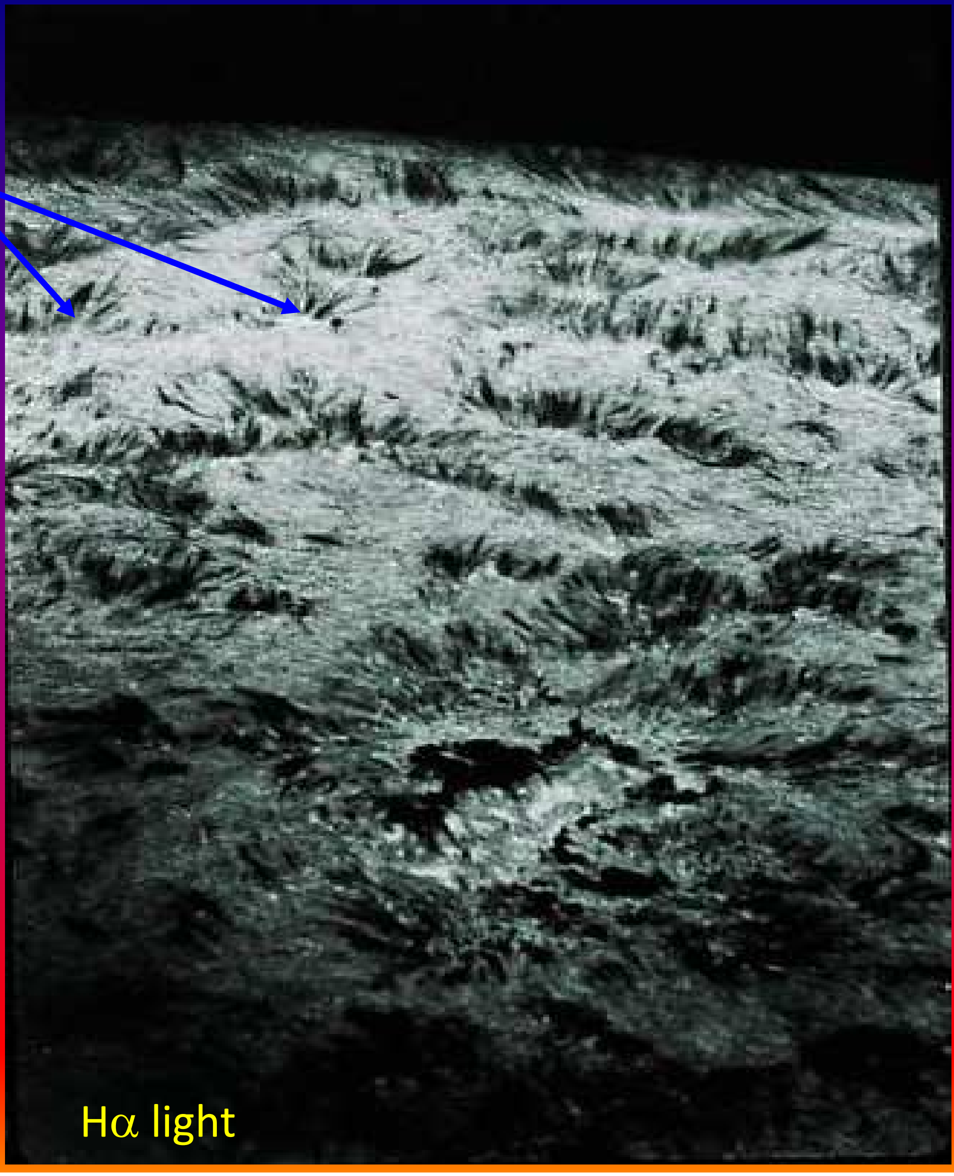
Chromospheric Spicules:

warm jets of matter shooting out at ~100 km/s last only minutes

Reach several thousands km above the photosphere

Spicules **are thought to be the result of magnetic disturbances**





Chromospheric Spicules:

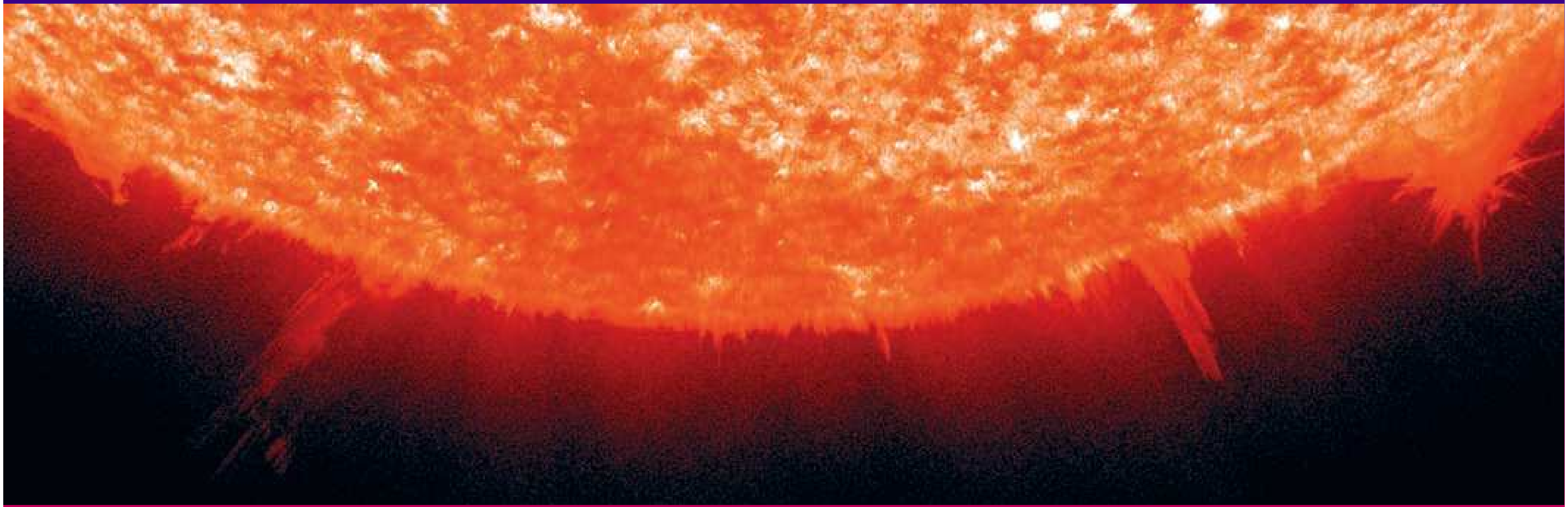
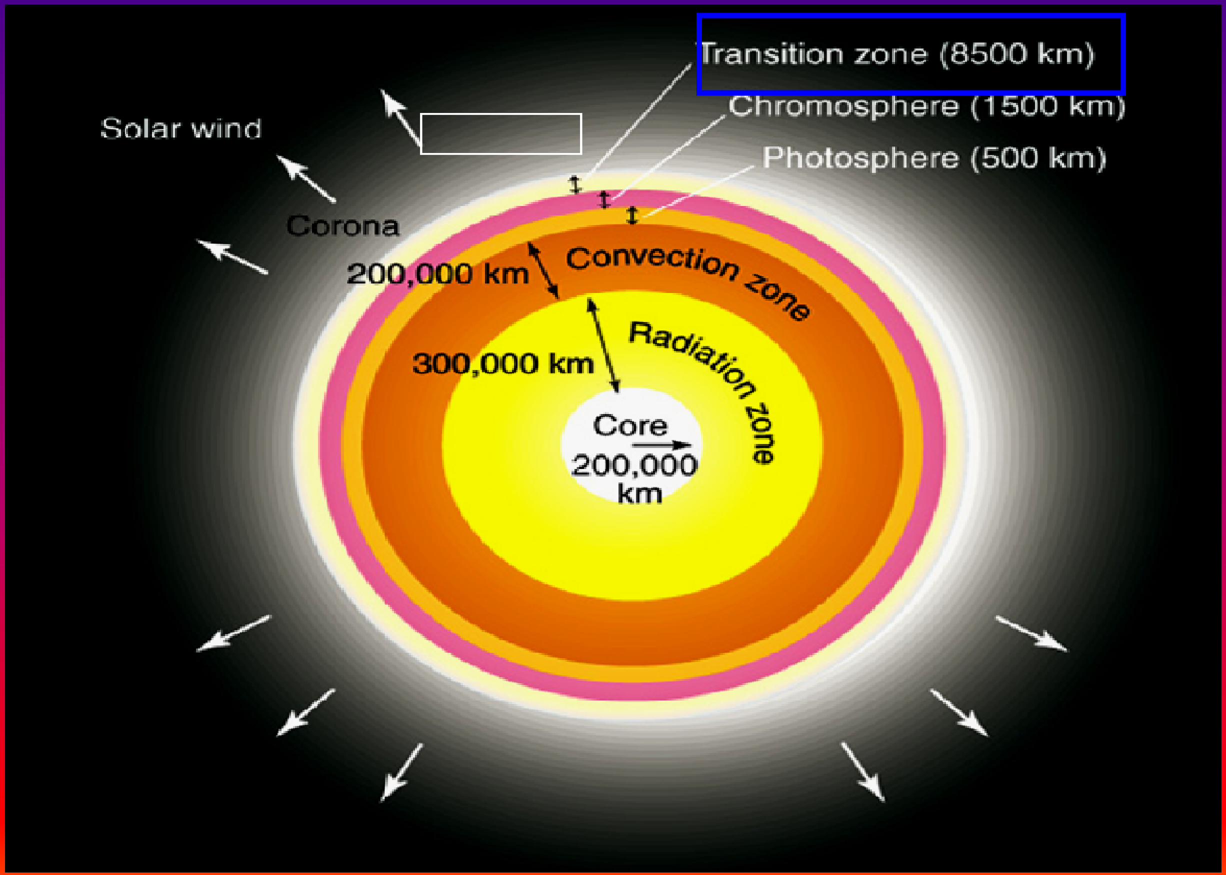


Figure 16.11 Solar Spicules Short-lived, narrow jets of gas that typically last few minutes can be seen sprouting up from the solar chromosphere in this ultraviolet image of the Sun. These so-called spicules are the thin spikelike regions whose gas escapes from the Sun at speeds of about 100 km/s

Transition Zone and Corona

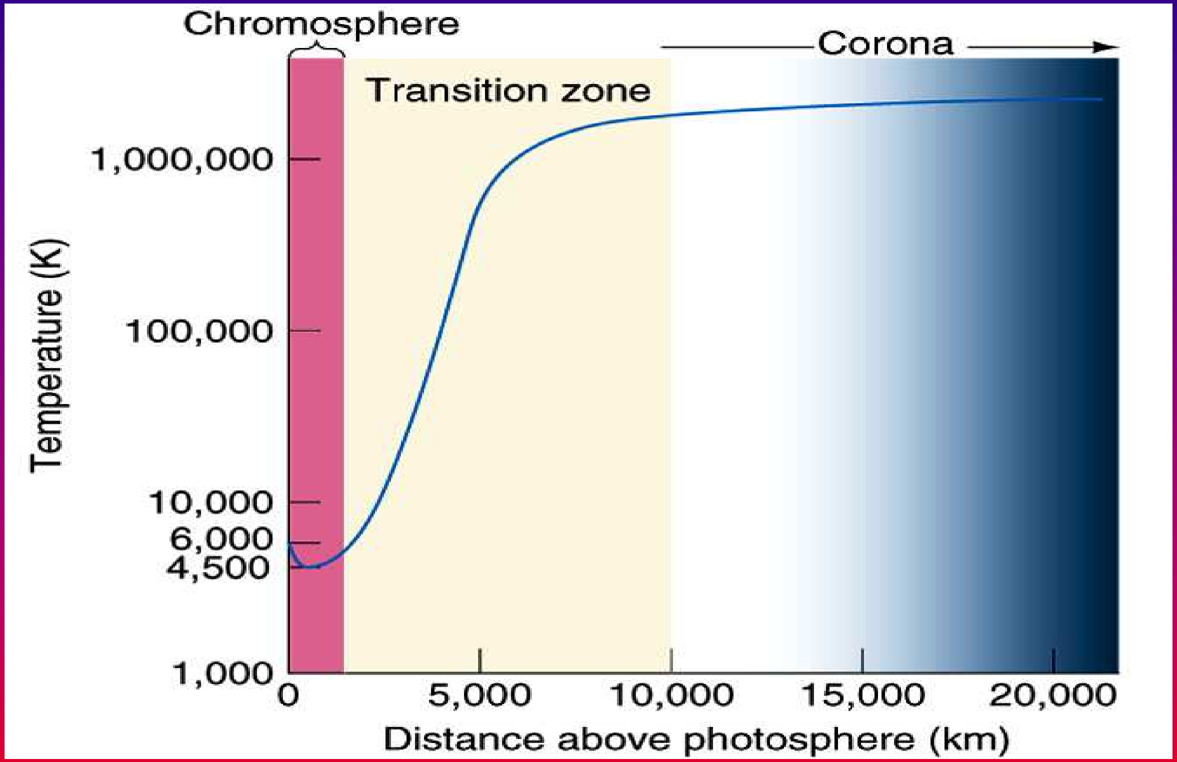


Transition Zone & Corona

Very low density,

T ~ 10^6 K

We see emission lines from highly ionized elements (Fe^{+5} – Fe^{+13}) which indicates that the temperature here is very *HOT*

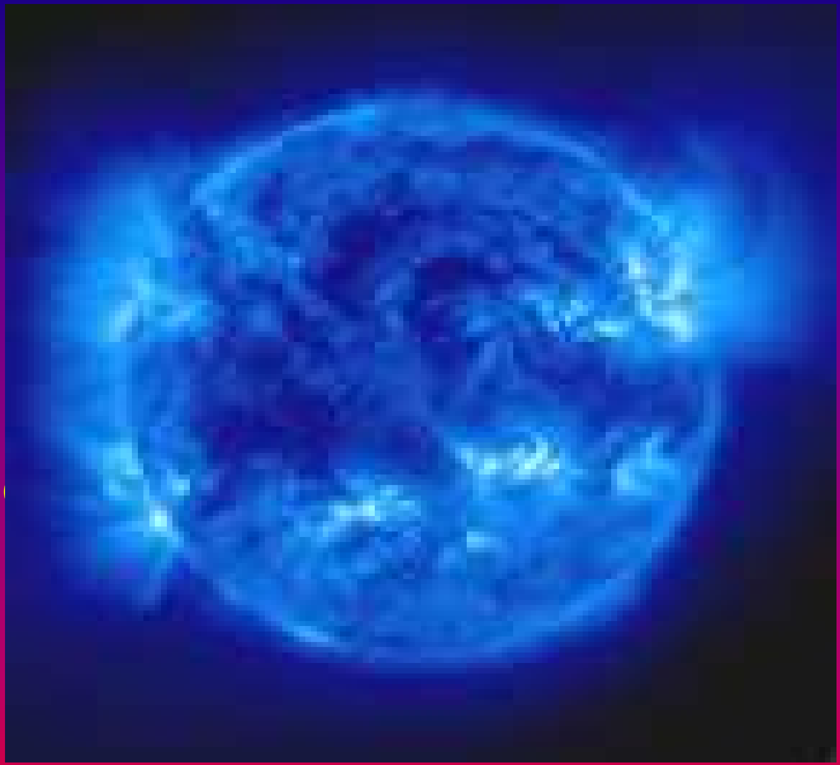


- Why does the Temperature rise *further* from the hot light source?
  → magnetic "activity" -spicules and other more energetic phenomena (more about this later…)

Corona

- $T > 10^6$ K @ 10,000 km
- $n < 10^{15}$ m^{-3}
- extends to Earth & beyond!
- Observed in EUV ($T \sim 10^6$ K)
- Soft X-ray (T > 2 MK)

<> The cause of rapid temperature ris
ids not fully understood.

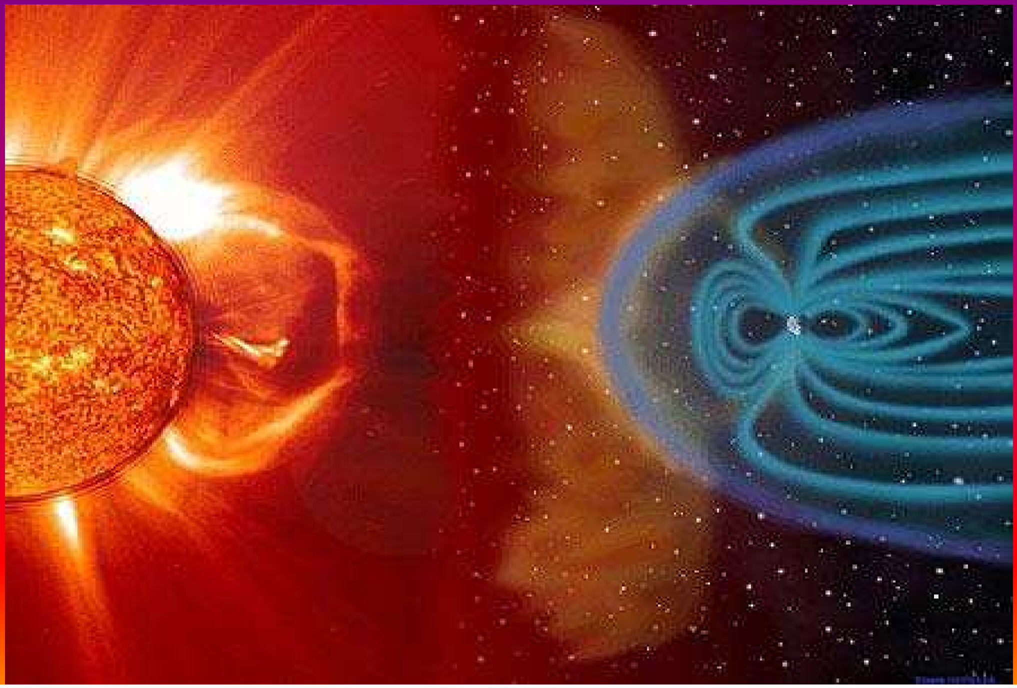


Corona

Hot coronal gas escapes the Sun
→ Solar wind

Solar Wind

- Coronal gas has enough heat (kinetic) energy to escape the Sun's gravity.
- The Sun is evaporating via this "wind".
- Solar wind travels at ~500 km/s, reaching Earth in ~3 days
- The Sun loses about 2 million tons of matter each second!
- However, over the Sun's lifetime, 4.6 billion year, it has lost only ~0.1% of its total mass.



16.4 Solar Magnetism

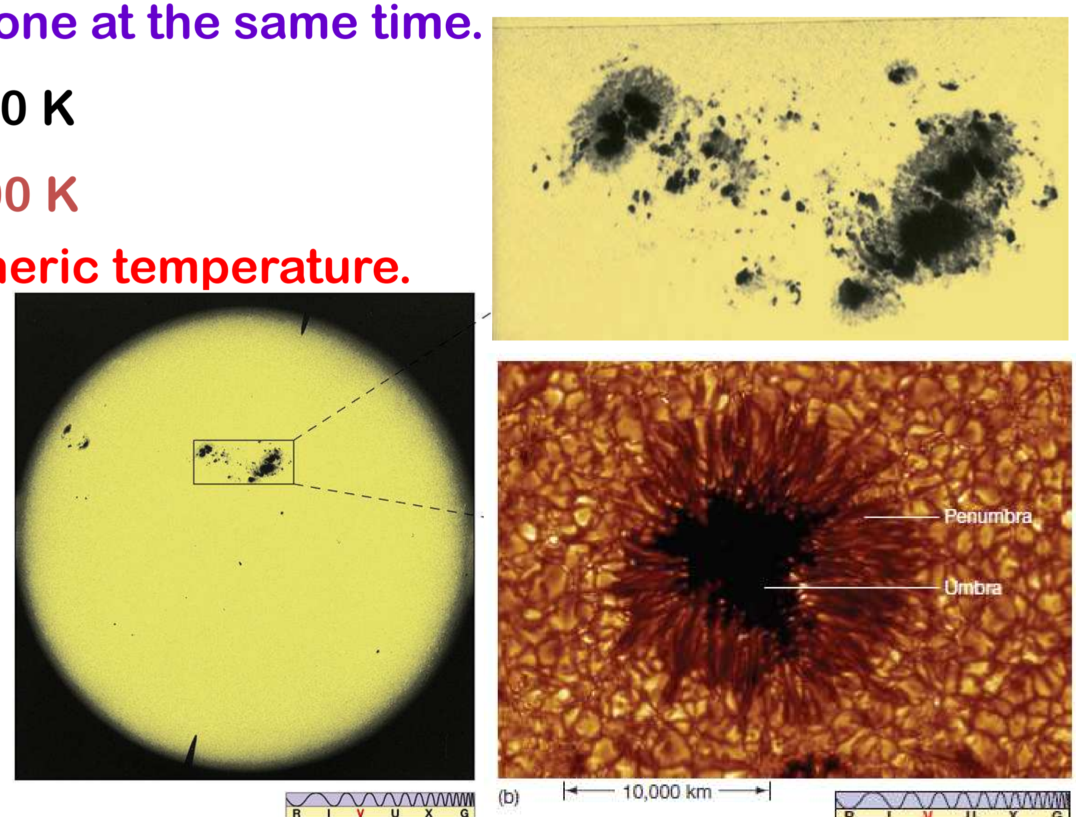
*** The sun has a powerful and complex magnetic field (Hale 1908)**

- **Sun Spots**
- **Irregularly shaped dark spots on the Photosphere ; discovered by Galilio.**
- **10,000 km across, hundreds or none at the same time.**
- **umbra (dark spots): cooler ~ 4500 K**
- **penumbra (grayish): hotter ~ 5500 K**

o **Degree of darkness → Photospheric temperature.**

o **Dark w.r.t bright Sun**

o **Last 1-100 days**



16.4 Solar Magnetism

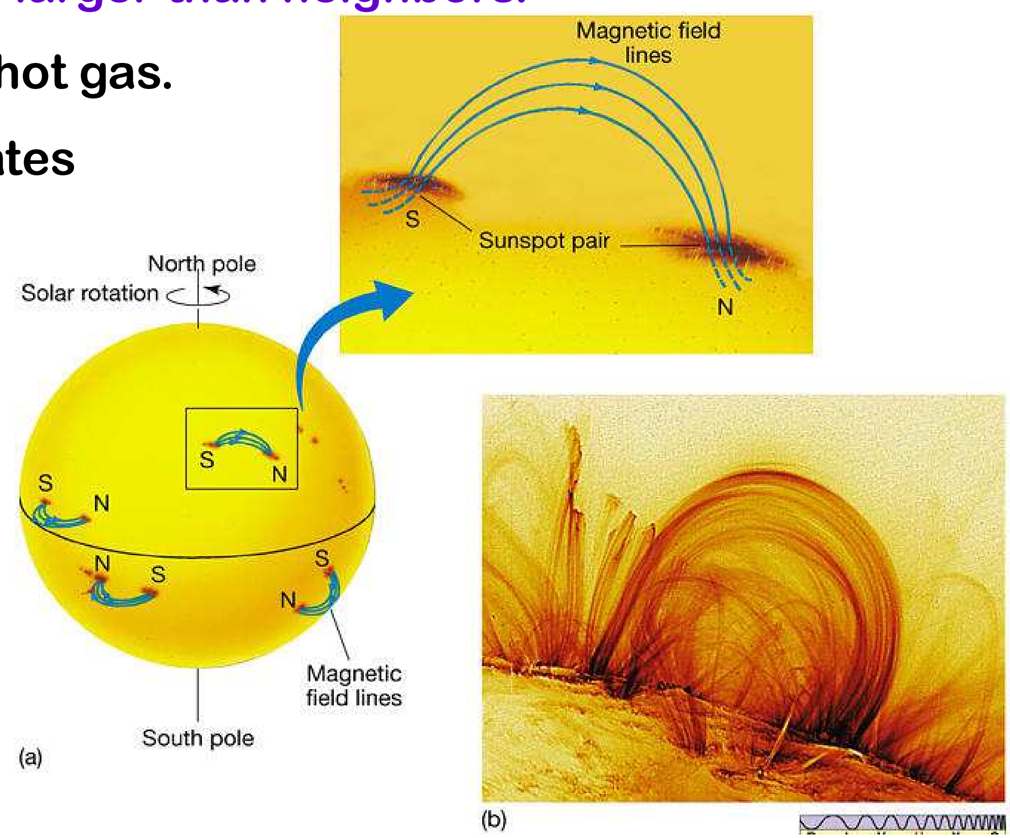
- What causes Sunspots
- Analysis of spectral lines can yield information about the origin of the magnetic field.
- In sunspots the B-field is 1000 times larger than neighbors.
- B-field block the convective flow of hot gas.
- Polarity of grouping sunspots indicates the direction of B

o S= emerge from the interior.

o N= dive below photosphere

o S----->N

o Sunspots pairs in the same hemisphere have the same magnetic configuration.



* Direction of the B-field reverses itself every 11 years.

16.4 Solar Magnetism

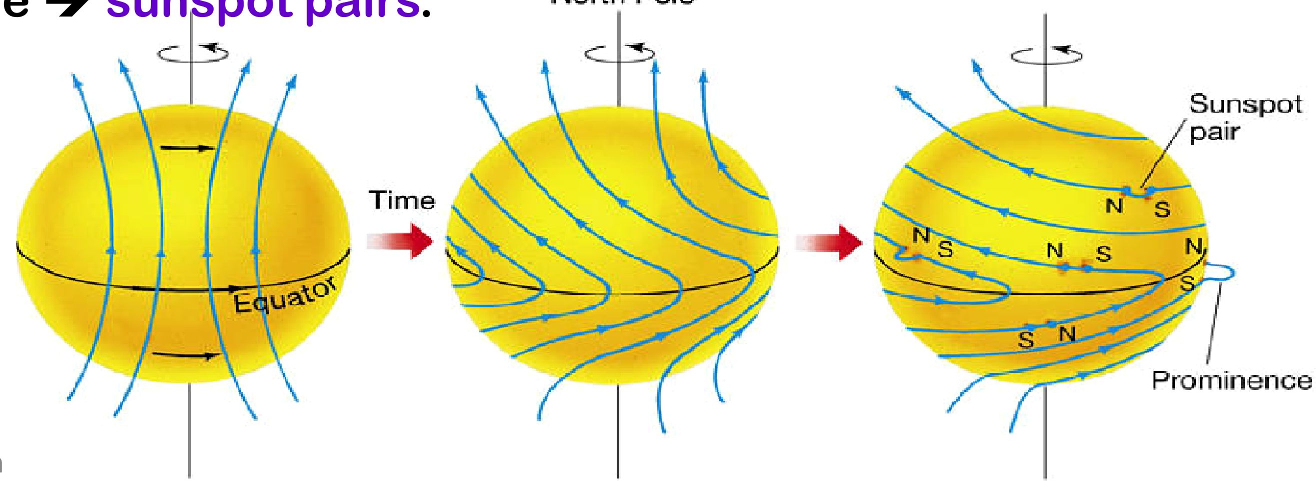
• Sun's differential rotation: 25-36 days; distorts the B-field.

• wrapping it around the equator ➔ north-south field reoriented in an east-west direction.

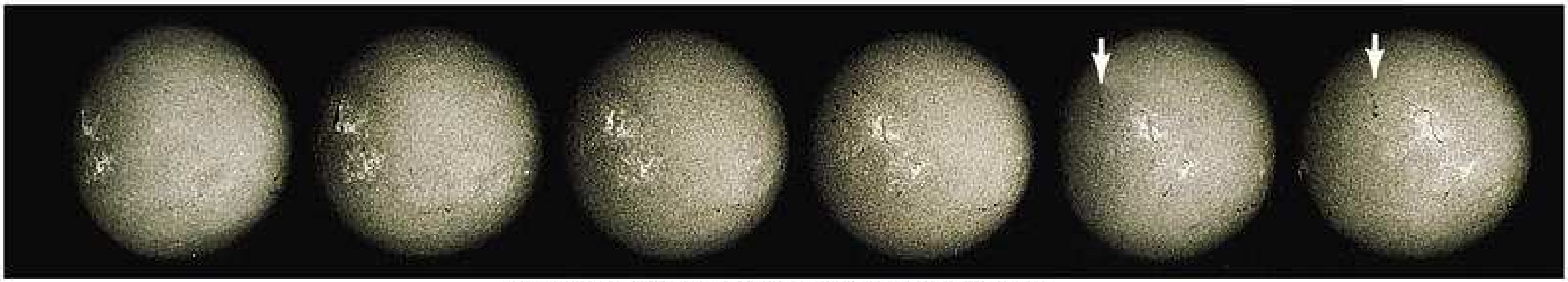
• Convection causes hot magnetized gases to upwell toward the surface and tangle the field pattern.

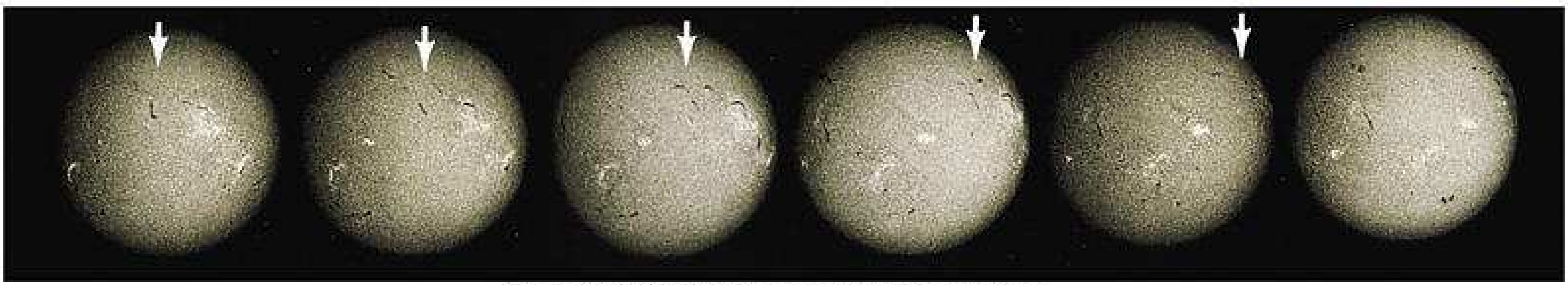
• B-field is strong > Sun's gravity.

• A tube of field lines bursts out of the surface and loops through the lower atmosphere ➔ sunspot pairs.



Sun Spots

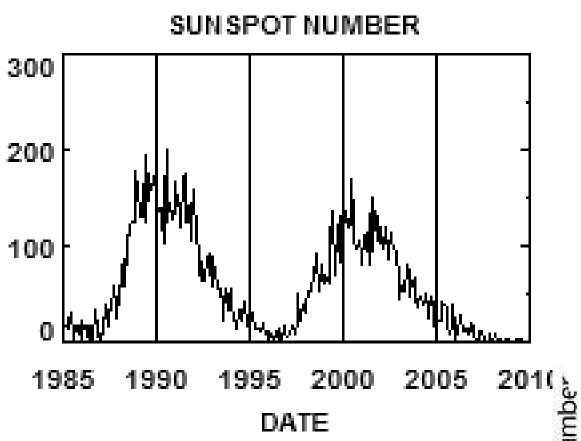


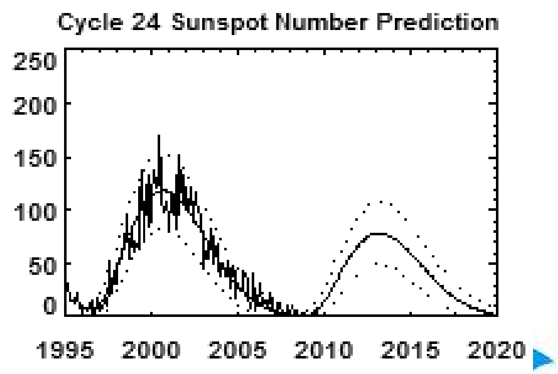


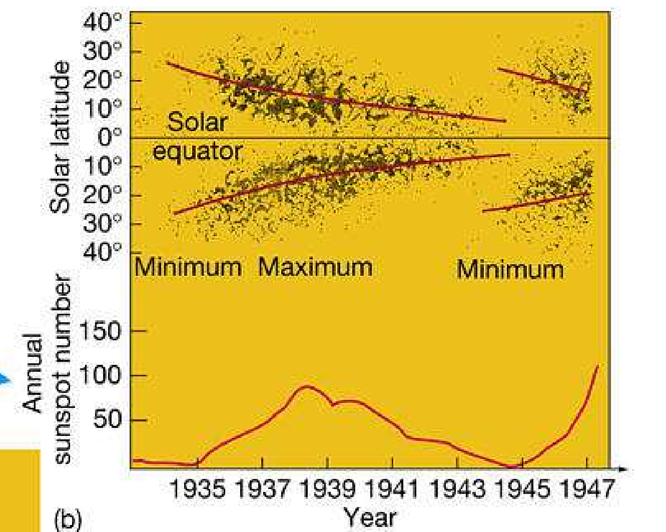
* Reveal the differential rotation of Photosphere

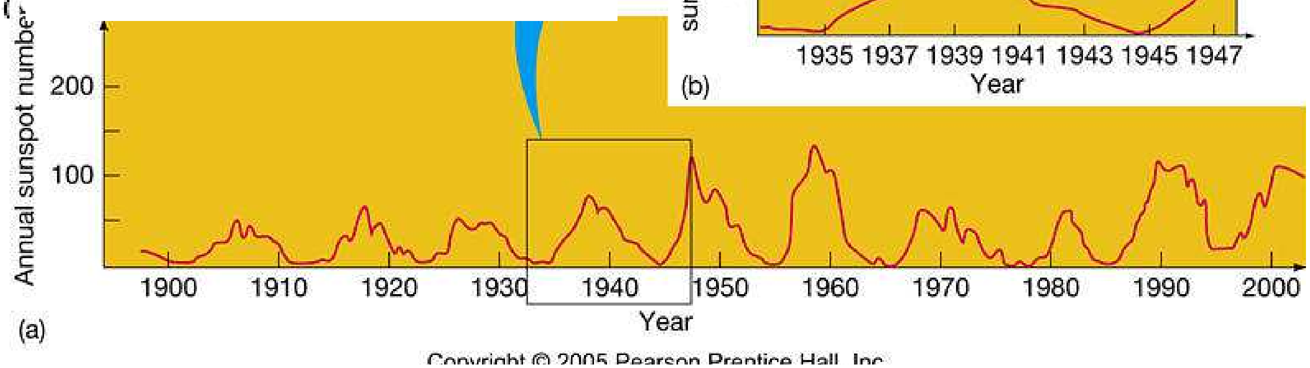
16.4 Solar Magnetism

- The average # of sunspots reaches maximum each 11 years (sunspot cycle).
- At maximum 100-200 spots may occur each year.
- Solar cycle (22 years).
- 2008-2009 no spots were observed.

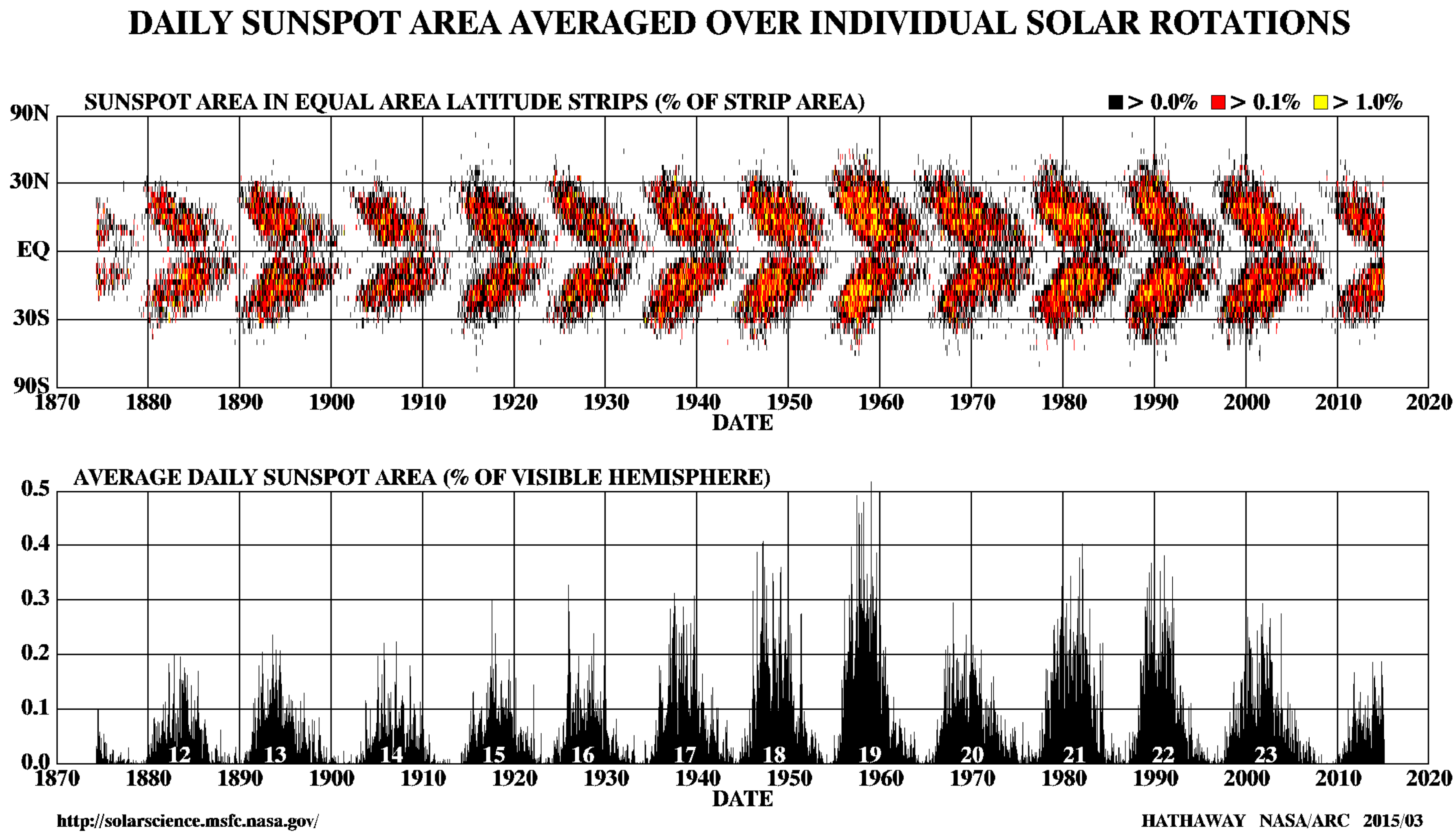




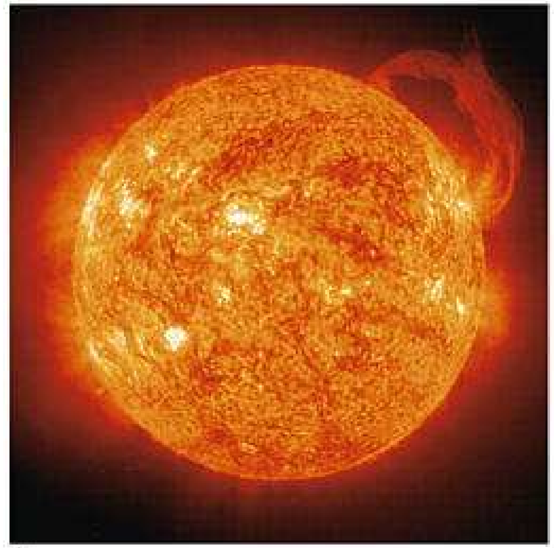




16.4 Solar Magnetism



16.5 The Active Sun



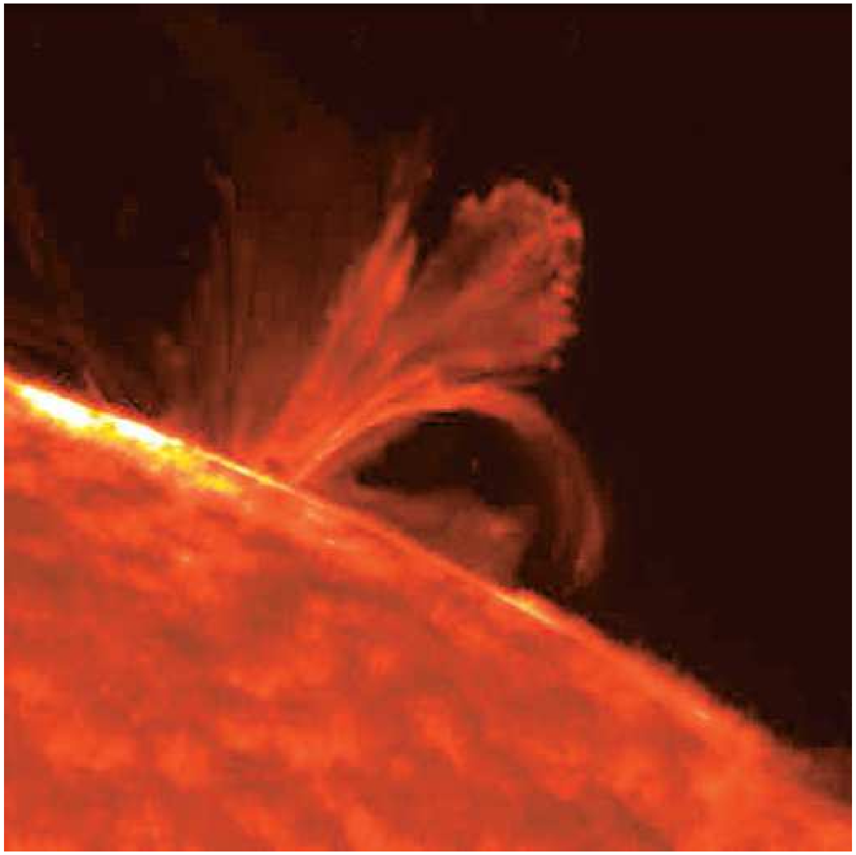
- The photosphere surrounding a pair or group of sunspots can be a violent place: active regions.

•Prominence: a loop of glowing gas ejected from an active region on the solar surface.

- Quiescent prominence → days or weeks, high above the atm.
- Active prominence → hours.
- 100,000 km radius. Length0.5 M km
- brightness → 1 MK.
- Released Energy: 10^{25} Joule

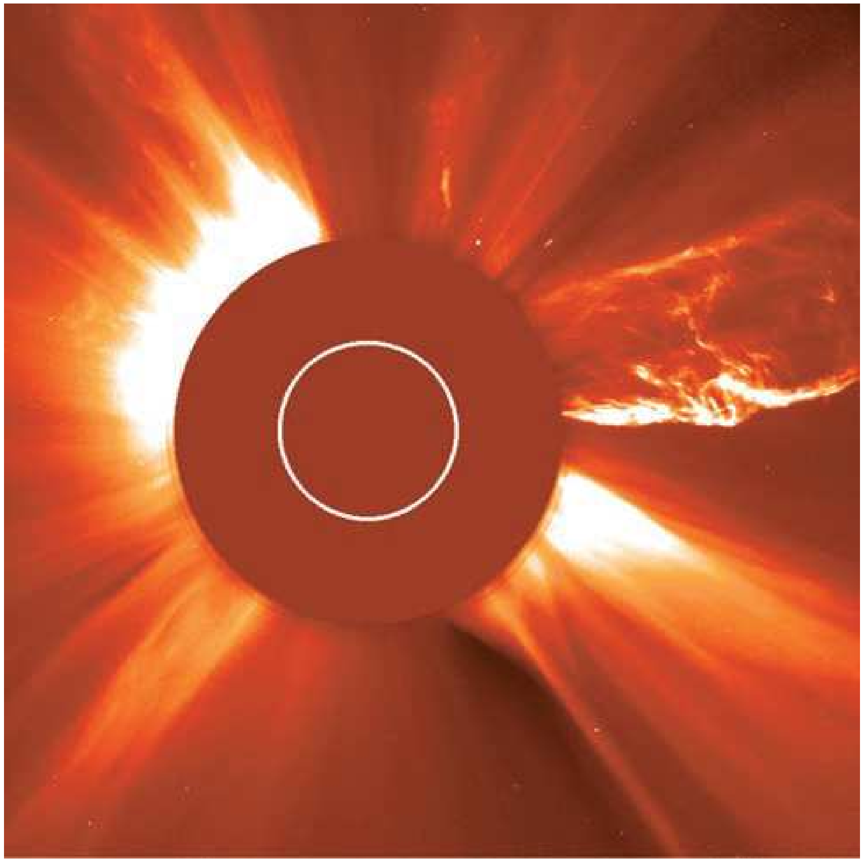
16.5 The Active Sun

- Flares: flashes occur across a region of the Sun in a minute.
- X-rays and UV emissions are ejected.
- Temp → 100 MK.
- Bombs exploding in the lower region of the Sun.
- Are believed to be responsible for most of the internal pressure waves
➔ Solar Oscillations



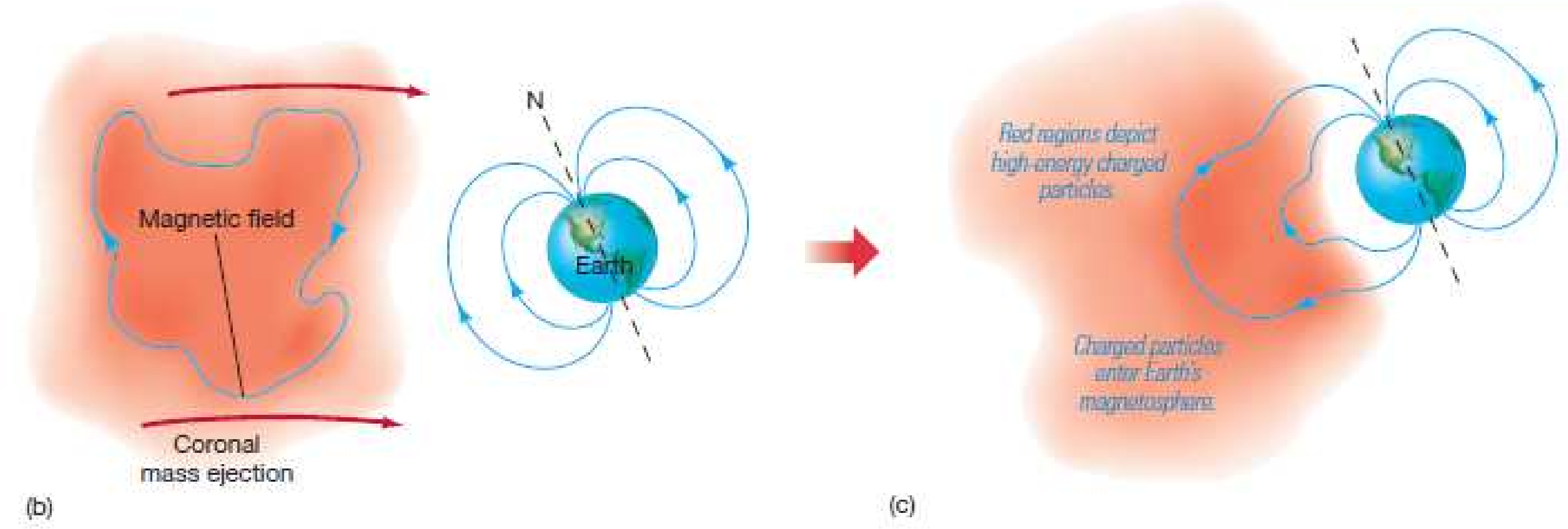
16.5 The Active Sun

- Coronal mass ejection: associated with flares and prominences, giant magnetic bubbles of ionized gas separated from the atm and escape into space.
- Occurs once/week when sunspots are minimum.
- Occurs 2-3 times/day when sunspots are maximum.



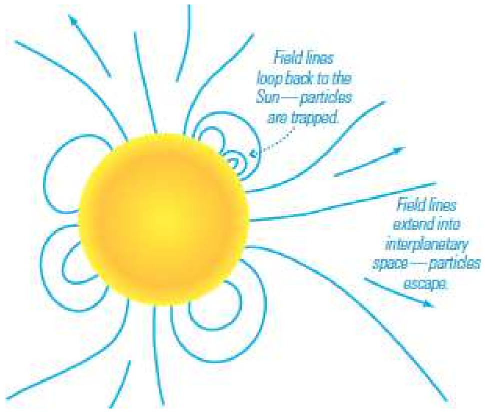
16.5 The Active Sun

- Coronal mass ejection merge with the Earth's magnetic field
- Dumping some of its energy into the magnetosphere.
- Causing communications and power disruptions.



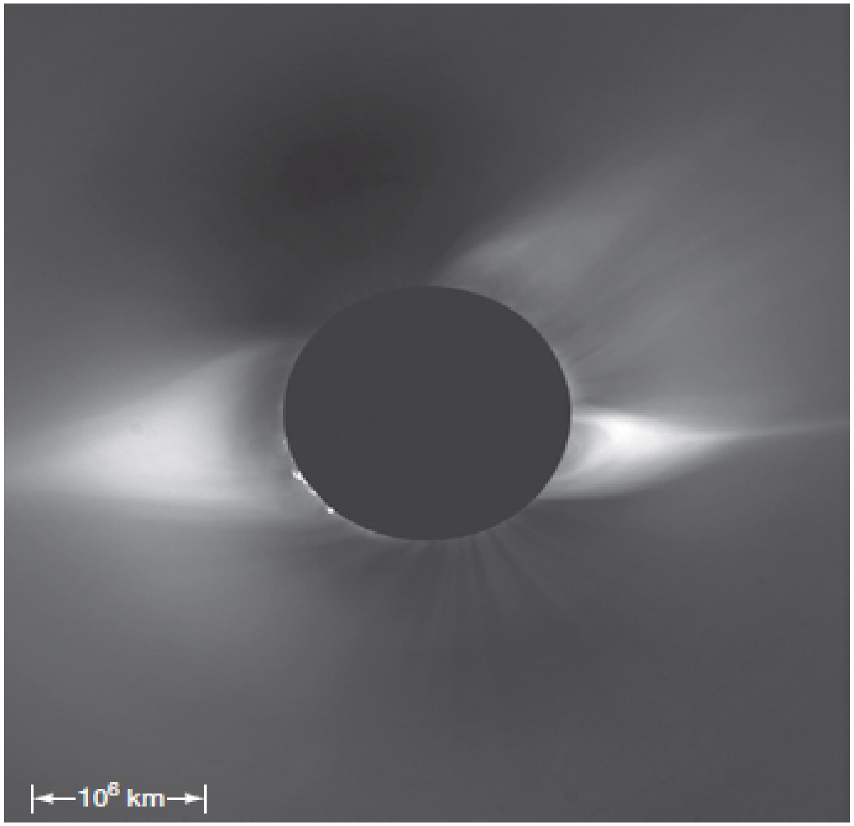
16.5 The Active Sun

- Changing Solar Corona
- High temperatures → emitting X-rays → X-ray telescopes.
- Solar Winds escapes through solar windows: coronal holes.
- X-ray observations, 3 MK.
- lack of matter, less density.
- dark V-shaped



16.5 The Active Sun

- Solar corona varies with the sunspot cycle.
- It is much larger and more irregular during the sunspot maximum



Questions?!?

- For about 5 billion years, the Sun has been emitting :
  4×10^{26} Watts

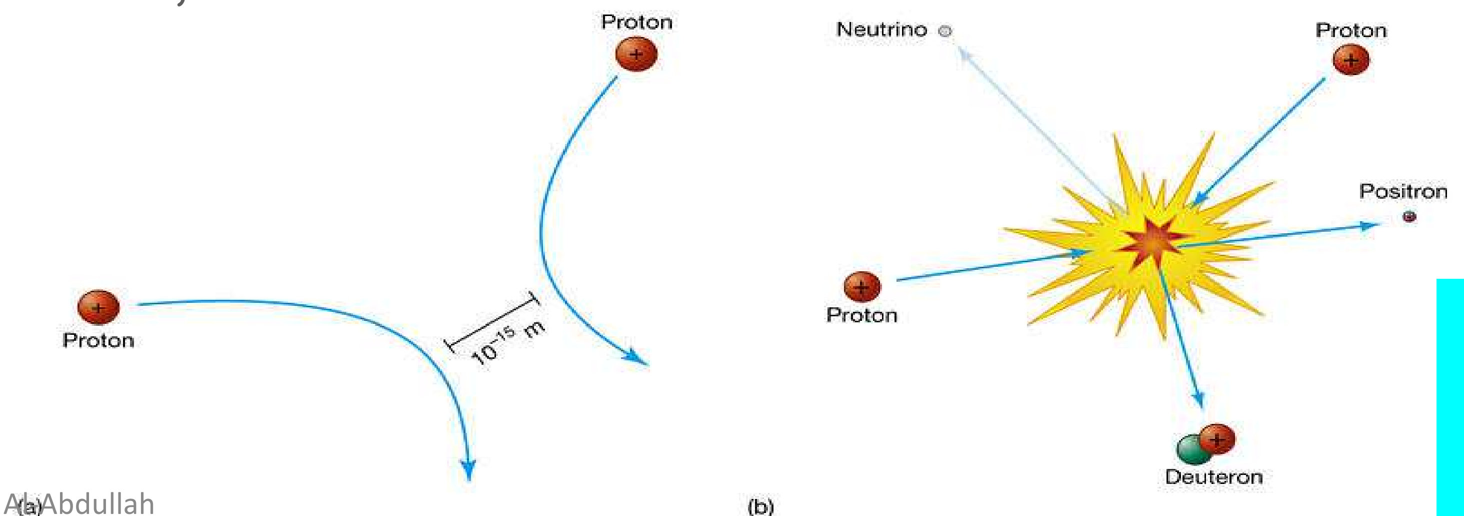
- This is about 3×10^{13} Joules per kilogram

- What can possibly be the source of so much energy?

16.6 The Heart of the Sun

Thermonuclear Fusion

- nucleus 1 + nucleus 2 → nucleus 3 + energy.
- The total mass decreases.
- Conservation of mass and energy ➔ $E=mc^2$.
- Strong nuclear force > Coulomb force.
- The temperature is the trigger of the fusion, Thermonuclear.
- Neutrinos , weak nuclear force.



H and ^{2}H are isotopes

What is a neutrino?

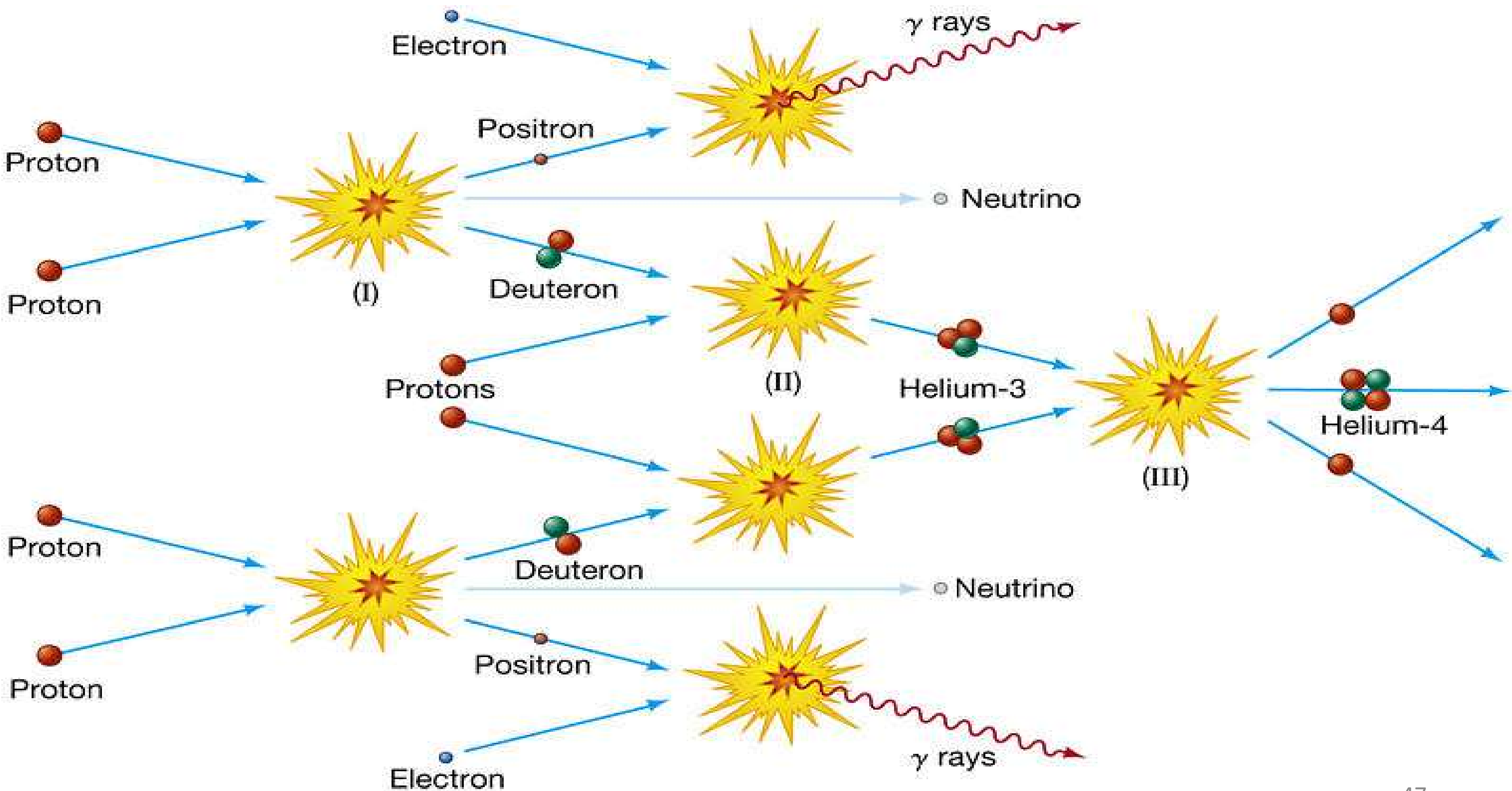
Neutrinos have
* no charge
* very small mass (10^{-5} m_e)
* spin
* energy $E = hf$
* Speed of light

They are produced only by weak interactions, e.g. decay of the neutron:

$$p \rightarrow n + e^{+} + \nu \qquad n \rightarrow p + e^{-} + \bar{\nu}$$

where $\bar{\nu}$ is an anti-neutrino (all particles have an anti-matter partner, and this is the neutrino's one; the electron's anti-particle is the positron, with a positive charge). All neutrinos are associated with a lepton – this one, from neutron decay, is an electron neutrino.

Thermonuclear Fusion: pp-chain



16.6 The Heart of the Sun

PP chain

$$^{1}H + {}^{1}H \rightarrow {}^{2}H + e^{+} + \nu_e + 0.42\ MeV$$

$$e^{+} + e^{-} \rightarrow 2\,\gamma + 1.02\ MeV$$

$$^{2}H + {}^{1}H \rightarrow {}^{3}He + \gamma + 5.49\ MeV$$

$$^{3}He + {}^{3}He \rightarrow {}^{4}He + {}^{1}H + {}^{1}H + 12.86\ MeV$$

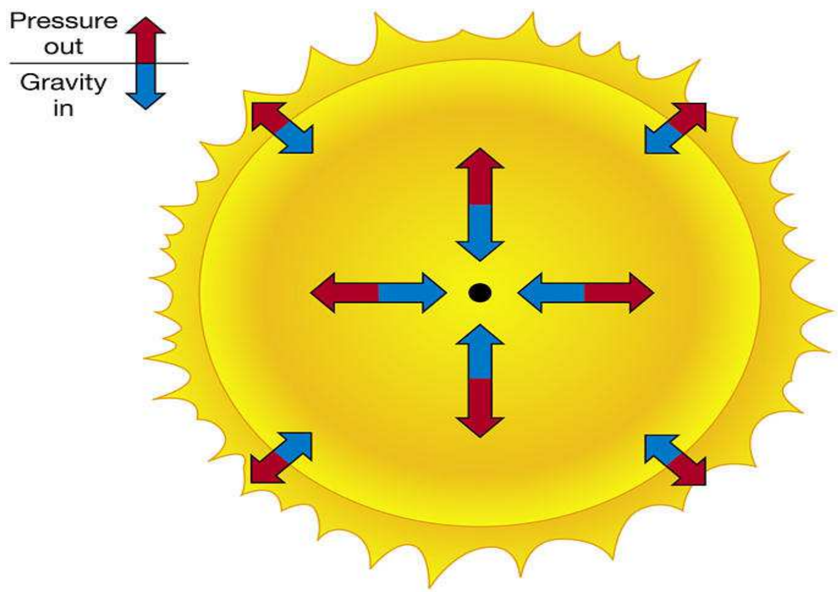
- The complete PP1 chain releases a net energy of 26.7 MeV.
- PP1 chain is dominant in temperatures of 10-14 MK.
- Below 10 MK, the PP-chain does not produce much ^{4}He.

16.6 The Heart of the Sun

- Tremendous weight of the mass of the Sun presses inward under the force of gravity.

- Enormous pressure (generated by Thermonuclear fusion) inside the Sun pushes back.

- <u>**HYDROSTATIC EQUILIBRIUM**</u> occurs when these two forces are balanced throughout the Sun.



16.7 Observations of Solar Neutrinos

The solar neutrino problem was a major discrepancy between measurements of the numbers of neutrinos flowing through the Earth and theoretical models of the Solar interior

A look at the numbers

- 2 x 10^{38} solar neutrinos produced every second
- Almost all make it out of the sun
- Traveling very near the speed of light (8 min travel time to earth)
- 70 billion neutrinos per second in each 1 cm square patch on earth
- Idea: catch the neutrinos and see if they tell us anything about the solar interior

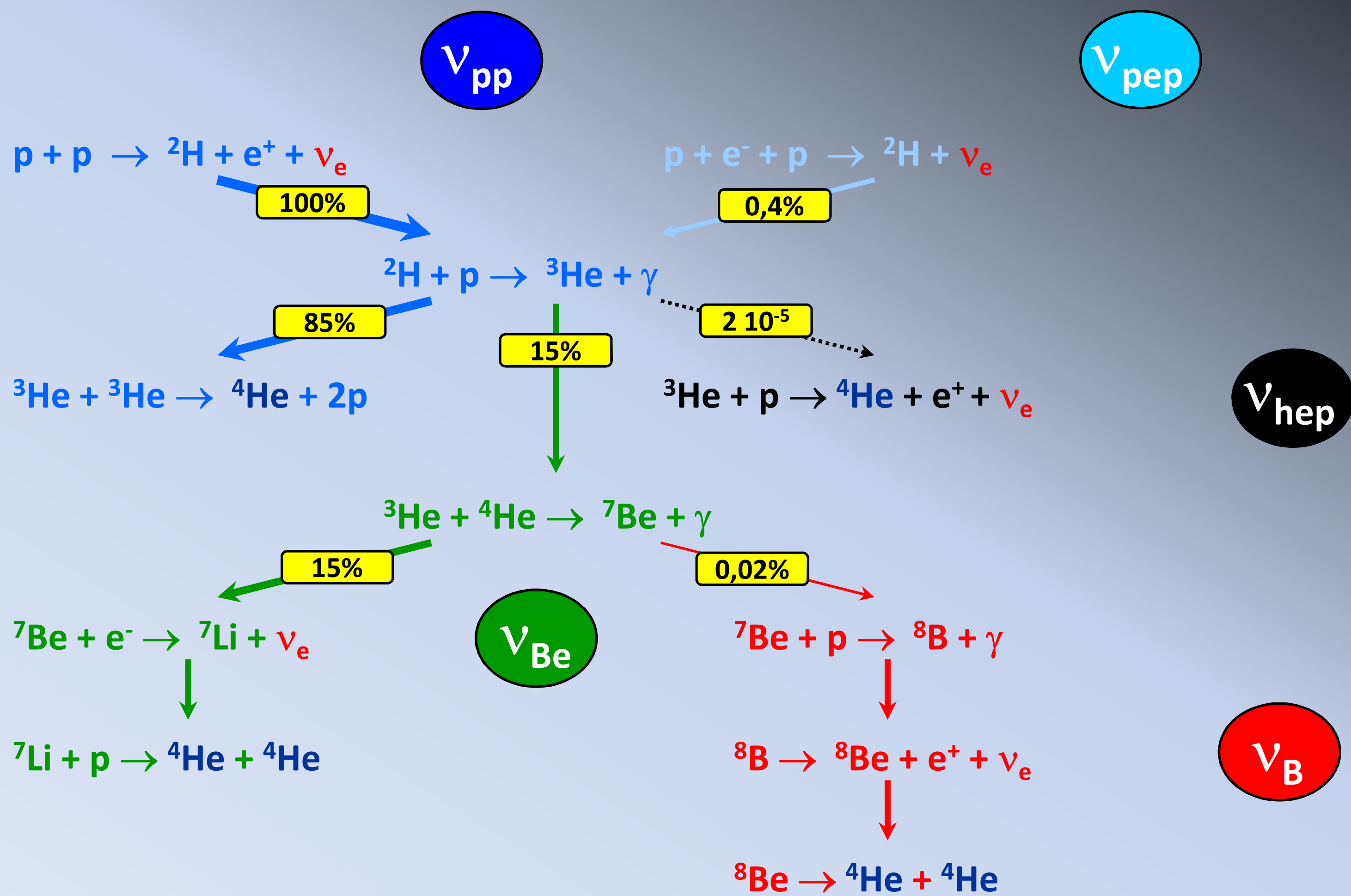
Solar Neutrinos – what is a neutrino?

There are three types of neutrino, each associated with a different lepton:

Neutrino	Associated lepton
ν_e	electron ($m_e c^2$ ~ 0.5 MeV)
ν_μ	muon (~200 electron masses)
ν_τ	tau (~4000 electron masses,~ 2 proton masses)

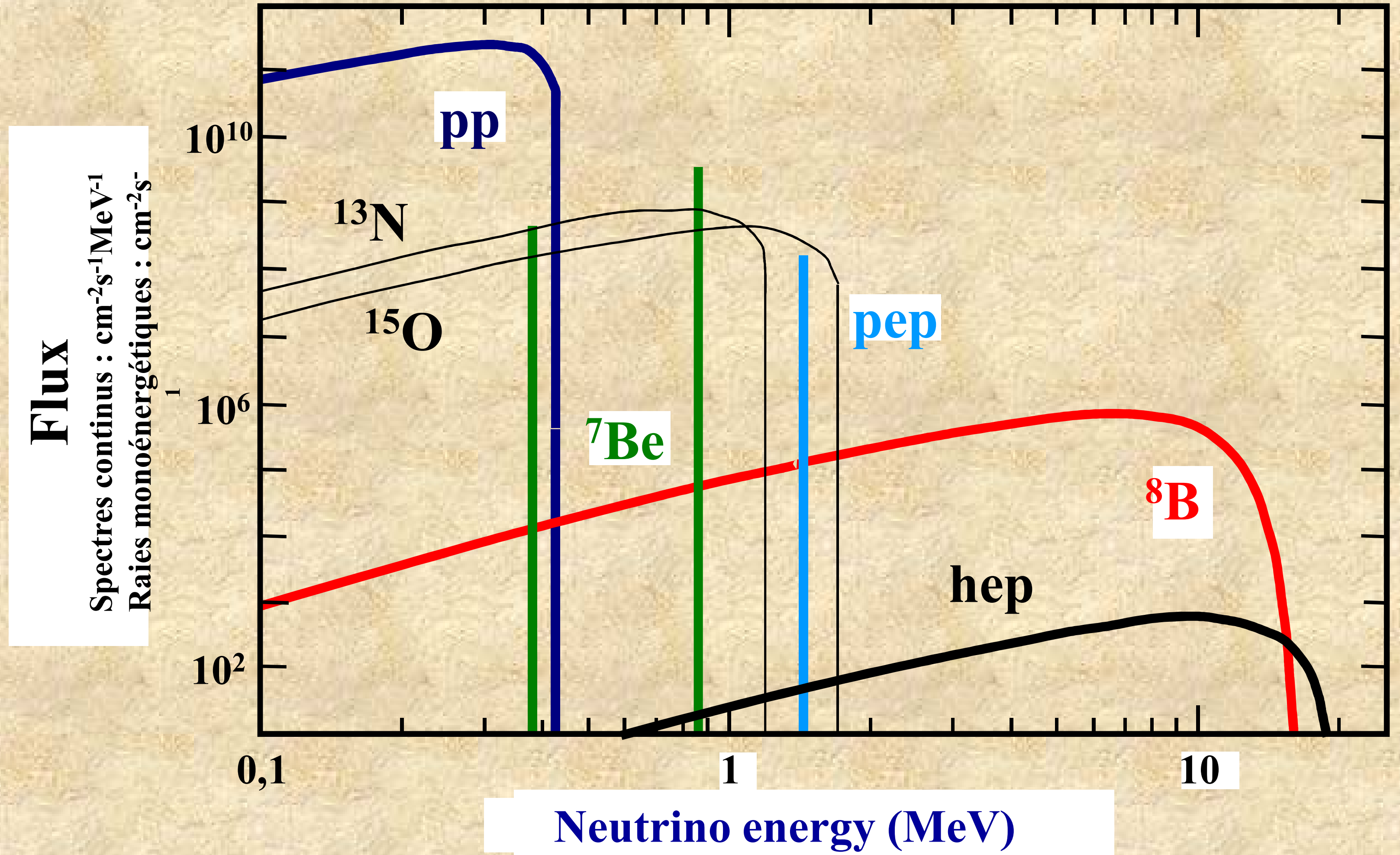
- Neutrinos have a very weak interaction with ordinary matter
- (typical mean free path ~ 1 light year of water! – depends on energy).
- Any neutrinos produced at the centre of the Sun escape freely
- they are a direct probe of conditions at the centre of the Sun.

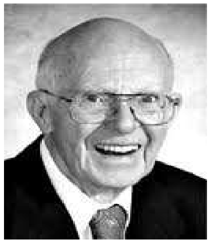
Nuclear reactions in the Sun



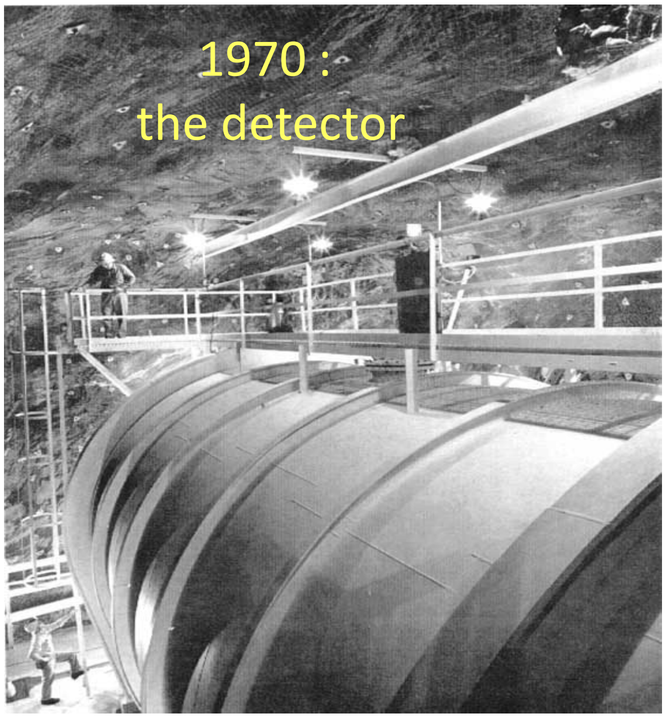
Solar Neutrinos – flux from Standard Model

Most neutrinos are low energy
Only a few have high energy

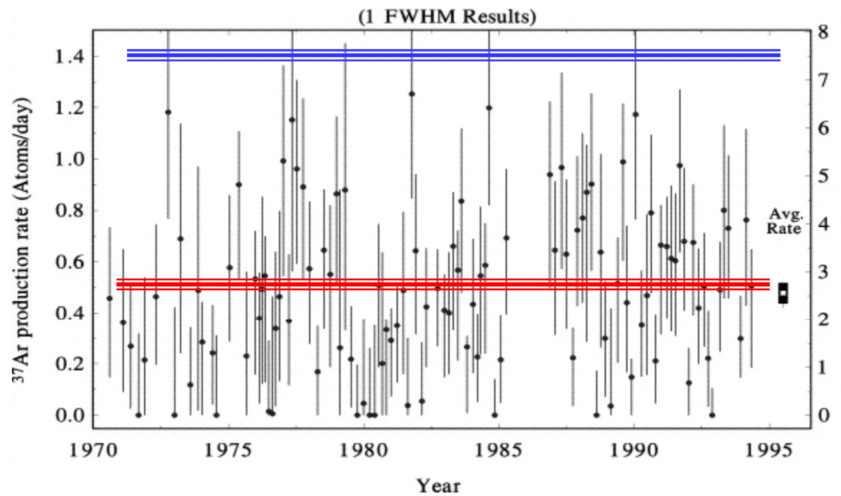




The « pionneering » chlorine experiment



- Radiochemical
- Sensitive to ^{7}Be and ^{8}B



Homestake mine (South Dakota)

600 tons of C_2Cl_4

$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$

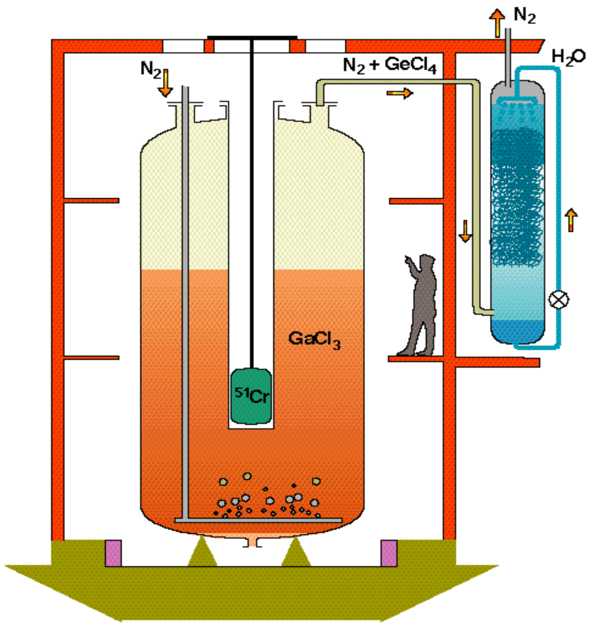
$\hookrightarrow {}^{37}Cl \ (T_{1/2}=35\ d)$

Result :
2.56 ± 0.20 SNU

1/3 of solar models
(6.9-7.5 SNU)

GALLEX / GNO :

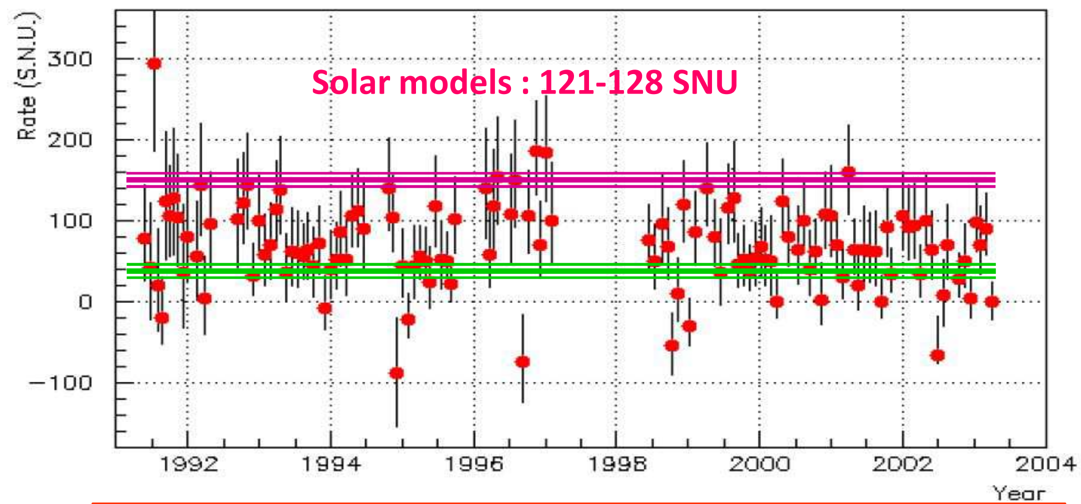
radiochemical detection of primordial solar ν



30.3 tons of gallium
in aqueous solution (GaCl$_3$ + HCl)

$$\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$$

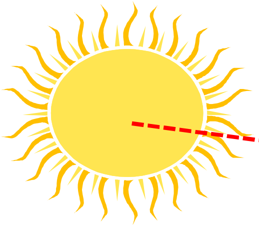
threshold = 233 keV
sensitive to all ν

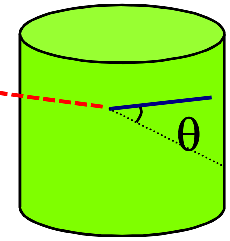


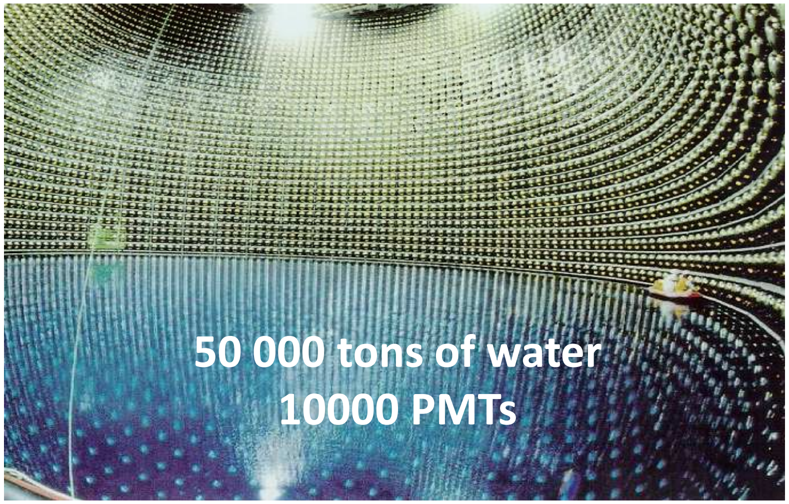
GALLEX : 77.5 ± 7.8 SNU (73.4 ± 7.2 SNU)
GNO : 62.9 ± 6.0 SNU
GALLEX/GNO : 69.3 ± 5.5 SNU (67.6 ± 5.1 SNU)

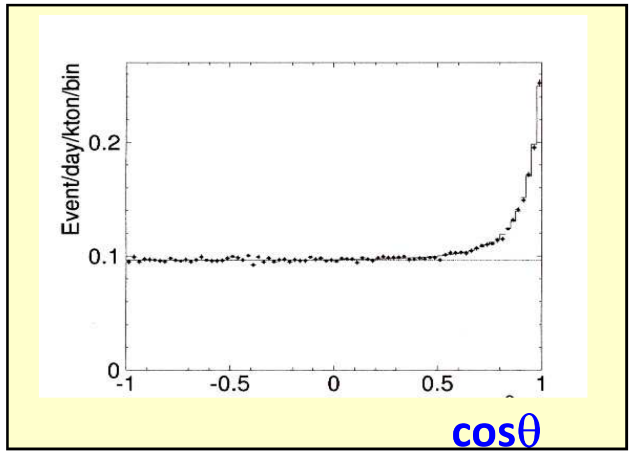
~60% of solar models

SuperKamiokande









$\nu_e + e^- \rightarrow \nu_e + e^-$

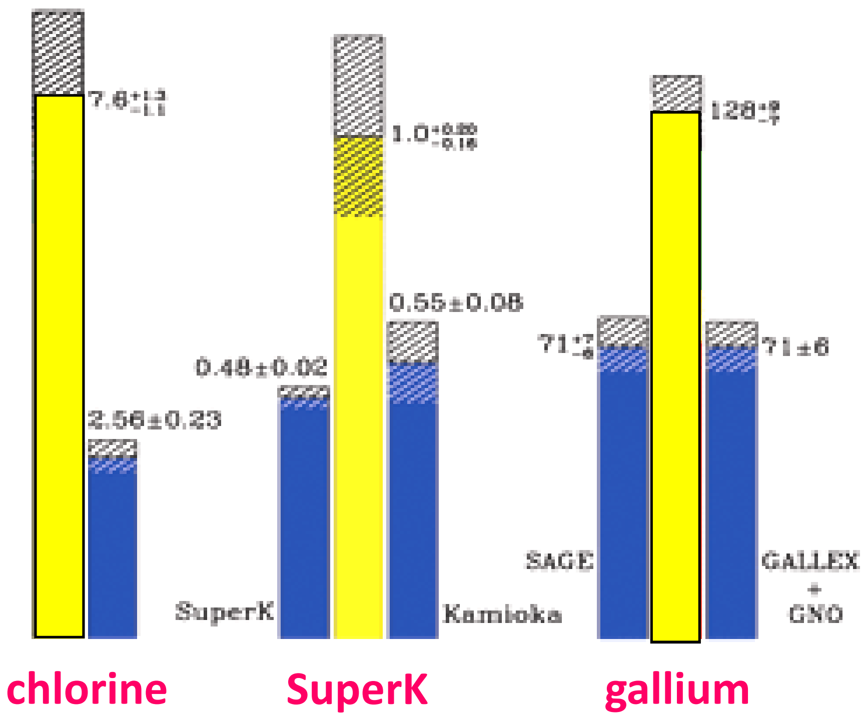
E > 5 MeV
sensitive to ^8B ν

Flux measured for ^8B ν :
(2.32 ± 0.03 (stat.) ± 0.08 (syst.)) 10^6 cm^{-2} s^{-1}

45% of solar models
(5 ±1) 10^6 cm^{-2} s^{-1}

S. Fukuda et al. : hep-ex/0103032

Solar neutrinos:
results and predictions



Spring 2001

Sudbury Neutrino Observatory (SNO)

- 1000 tons D_2O (target)
- 7000 tons H_20 (shield)
- 9600 8" PM for Cerenkov light
- Canada-USA-GB Collaboration

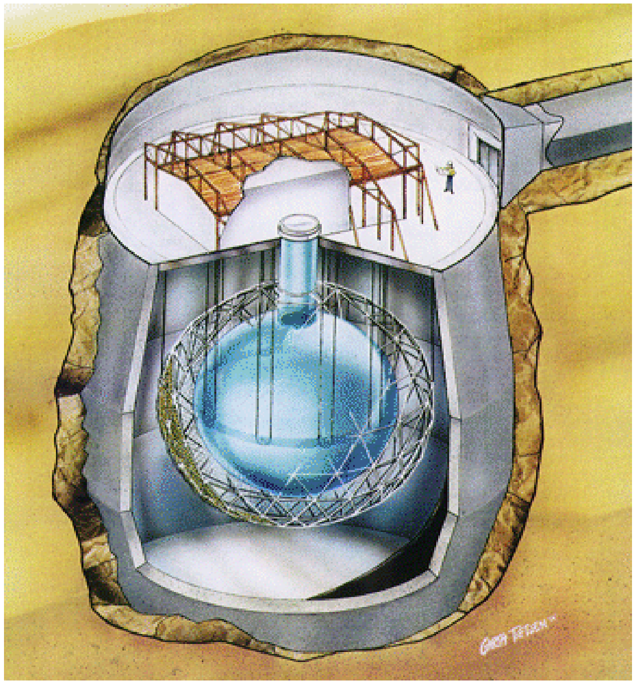
$\nu_e + d \rightarrow p + p + e^-$ (CC)

$\nu_x + d \rightarrow p + n + \nu_x$ (NC)

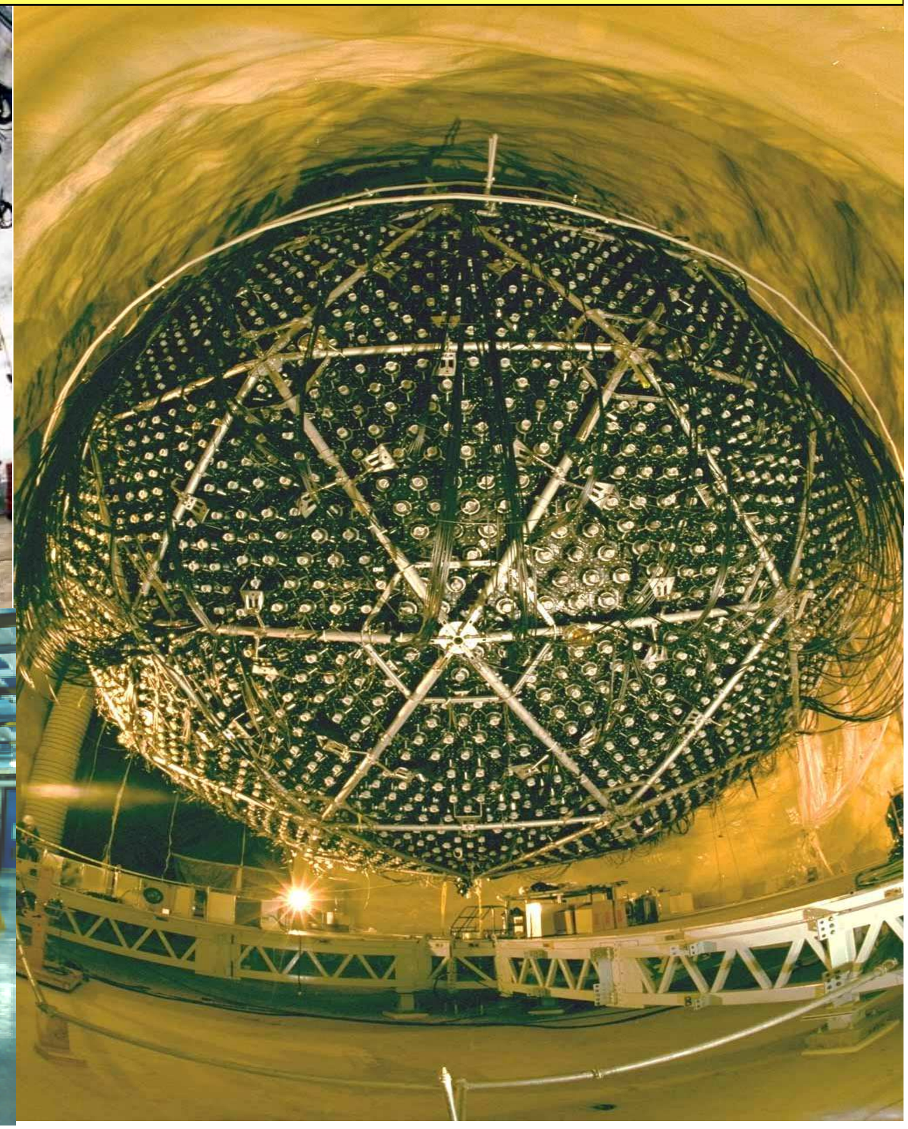
n detection:
$n + d \rightarrow t + \gamma$
$n + Cl \rightarrow Cl + \gamma$
$n + {}^3He \rightarrow t + p$

$\nu_e + e^- \rightarrow \nu_e + e^-$ (elastic sc.)

E > 4-5 MeV
sensitive to ^8B ν

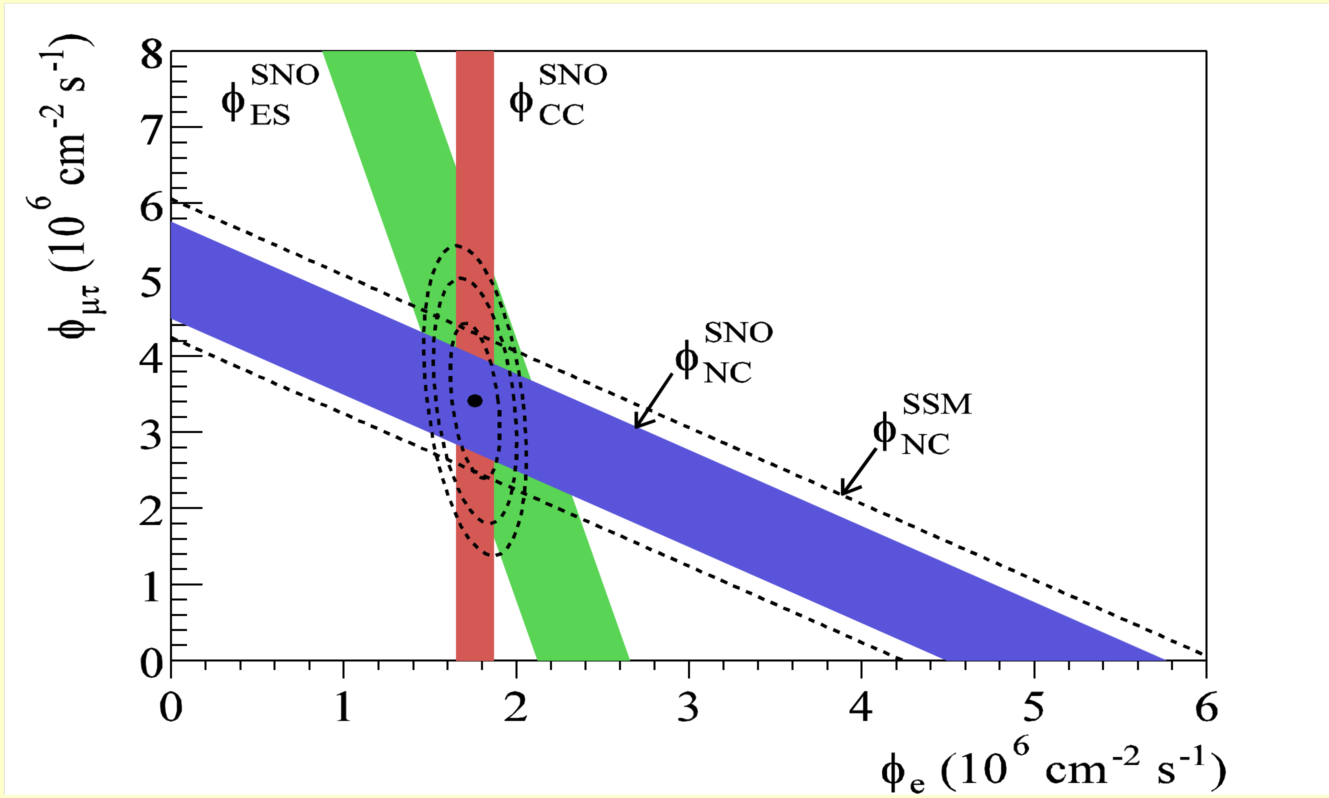


One million pieces transported and assembled under ultra-clean conditions.



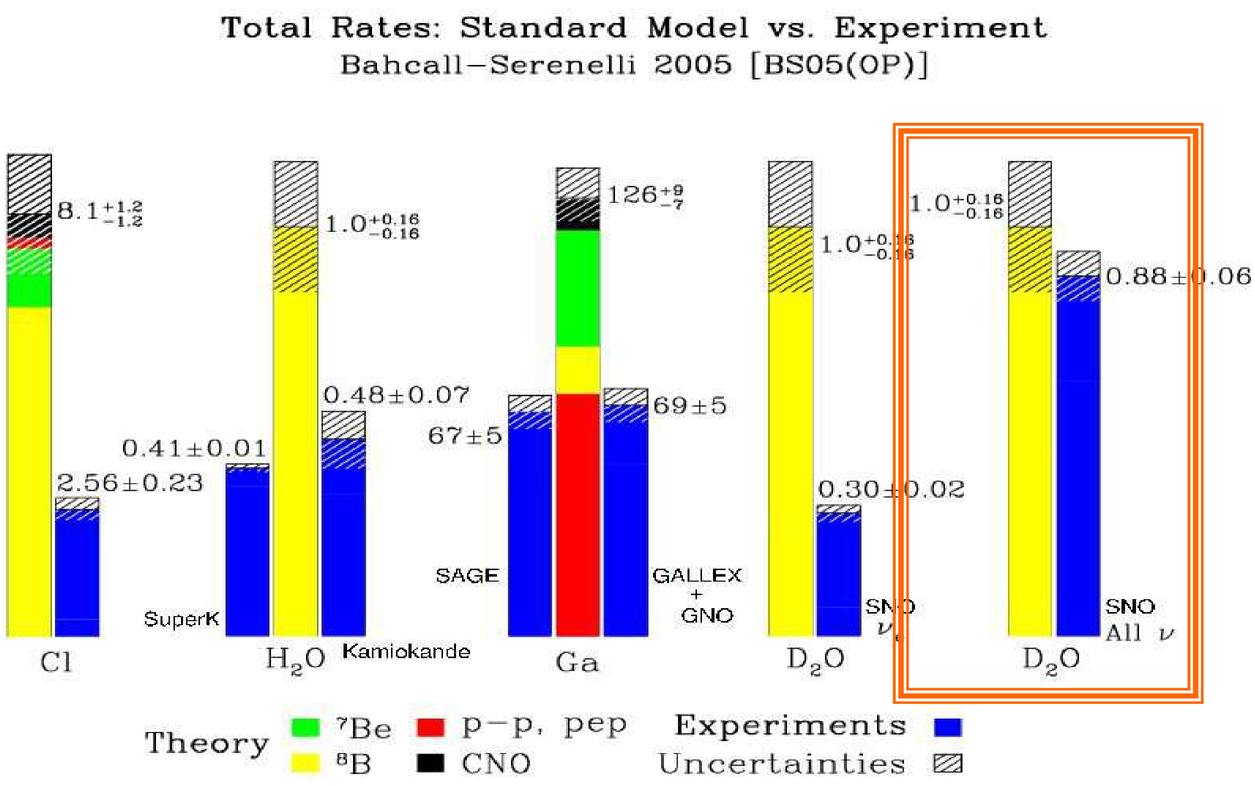
Physics Implication: Flavor Content

$\Phi_{ssm} = 5.05\,^{+1.01}_{-0.81}$ $\Phi_{sno} = 5.09\,^{+0.44}_{-0.43}\,^{+0.46}_{-0.43}$



Clear evidence of flavor change

Experimental results after SNO



☺ The problem is solved

❶ Nuclear reactions in the Sun produce only ν_e

❷ Until SNO, solar neutrino detectors were sensitive only (mainly) to ν_e

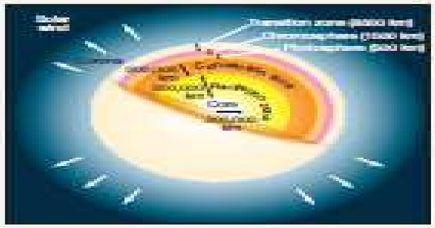
SNO has shown that :

a) solar ν_e have been (partially) transformed into ν_μ or ν_τ and the oscillation mechanism explains the observed deficit

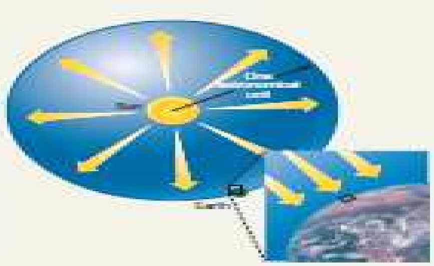
b) the SSM is (at first order) right !

SUMMARY

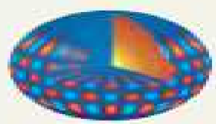
1 Our Sun is a **star (p. 390)**, a glowing ball of gas held together by its own gravity and powered by nuclear fusion at its center. The **photosphere (p. 390)** is the region at the Sun's surface from which virtually all the visible light is emitted. The main interior regions of the Sun are the **core (p. 390)**, where nuclear reactions generate energy; the **radiation zone (p. 390)**, where the energy travels outward in the form of electromagnetic radiation; and the **convection zone (p. 390)**, where the Sun's matter is in constant convective motion.



2 The amount of solar energy reaching a 1 m^2 at the top of Earth's atmosphere each second is a quantity known as the **solar constant (p. 390)**. The Sun's **luminosity (p. 391)** is the total amount of energy radiated from the solar surface per second. It is determined by multiplying the solar constant by the area of an imaginary sphere of radius 1 AU.



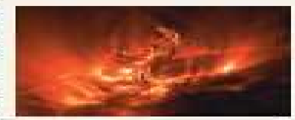
3 Much of our knowledge of the solar interior comes from mathematical models. The model that best fits the observed properties of the Sun is the **standard solar model (p. 392)**. **Helioseismology (p. 393)**—the study of vibrations of the solar surface caused by pressure waves in the interior—provides further insight into the Sun's structure. The effect of the solar convection zone can be seen on the surface in the form of **granulation (p. 396)** of the photosphere. Lower levels in the convection zone also leave their mark on the photosphere in the form of larger transient patterns called **supergranulation (p. 397)**.



4 Above the photosphere lies the **chromosphere (p. 390)**, the Sun's lower atmosphere. Most of the absorption lines seen in the solar spectrum are produced in the upper photosphere and the chromosphere. In the **transition zone (p. 390)** above the chromosphere, the temperature increases from a few thousand to around a million kelvins. Above the transition zone is the Sun's thin, hot upper atmosphere, the solar **corona (p. 390)**. At a distance of about 15 solar radii, the gas in the corona is hot enough to escape the Sun's gravity, and the corona begins to flow outward as the **solar wind (p. 390)**.

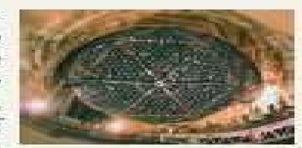
5 **Sunspots (p. 401)** are Earth-sized regions on the solar surface that are a little cooler than the surrounding photosphere. They are regions of intense magnetism. Both the numbers and locations of sun spots vary in a roughly 11-year **sunspot cycle (p. 404)** as the Sun's magnetic field rises and falls. The overall direction of the field reverses from one sunspot cycle to the next. The 22-year cycle that results when the direction of the field is taken into account is called the **solar cycle (p. 404)**.

6 Solar activity tends to be concentrated in **active regions (p. 405)** associated with groups of sunspots. **Prominences (p. 405)** are looplike or sheetlike structures produced when hot gas ejected by activity on the solar surface interacts with the Sun's magnetic field. The more intense **flares (p. 406)** are violent surface explosions that blast particles and radiation into interplanetary space. **Coronal mass ejections (p. 406)** are huge blobs of magnetized gas escaping into interplanetary space. Most of the solar wind flows outward from low-density regions of the corona called **coronal holes (p. 407)**.



7 The Sun generates energy by converting hydrogen to helium in its core by the process of **nuclear fusion (p. 410)**. Nuclei are held together by the **strong nuclear force (p. 411)**. When four protons are converted to a helium nucleus in the **proton–proton chain (p. 412)**, some mass is lost. The **law of conservation of mass and energy (p. 411)** requires that this mass appear as energy, eventually resulting in the light we see. Very high temperatures are needed for fusion to occur.

8 **Neutrinos (p. 411)** are nearly massless particles that are produced in the proton–proton chain and escape from the Sun. They interact via the **weak nuclear force (p. 412)**. Despite their elusiveness, it is possible to detect a small fraction of the neutrinos streaming from the Sun. Observations over several decades led to the **solar neutrino problem (p. 414)**—substantially fewer neutrinos are observed than are predicted by theory. The accepted explanation, supported by recent observational evidence, is that **neutrino oscillations (p. 415)** convert some neutrinos to other (undetected) particles en route from the Sun to Earth.




END CHAPTER 16