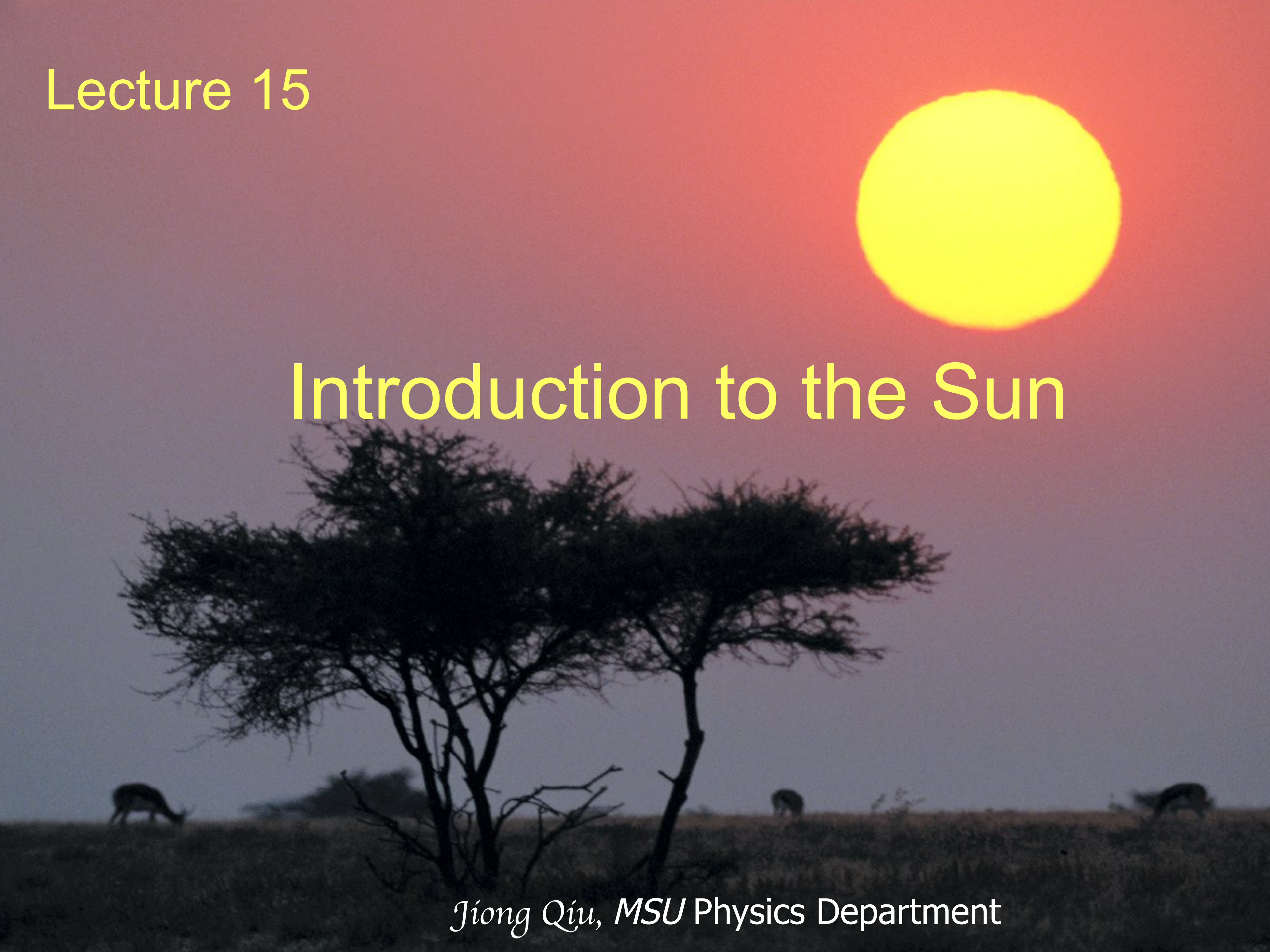
Lecture 15

Introduction to the Sun



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Open Q: what physics do we learn about the Sun?

1. Energy
   - nuclear energy
   - magnetic energy
2. Radiation
   - continuum and line emissions;
   - particle radiation
   - other effects;
3. Magnetism:
   - origin
   - energy build-up
   - energy release
4. Observing techniques:
   - optical and infrared observation: adaptive optics
   - radio and X-ray technology

Guiding Questions

1. What is the source of the Sun's energy?
2. What is the internal structure of the Sun?
3. How can astronomers measure the properties of the Sun's interior?
4. How can we be sure that thermonuclear reactions are happening in the Sun's core?
5. What is the standard solar model? How is it built? What are the observational tests it has survived?

14.1 Introduction

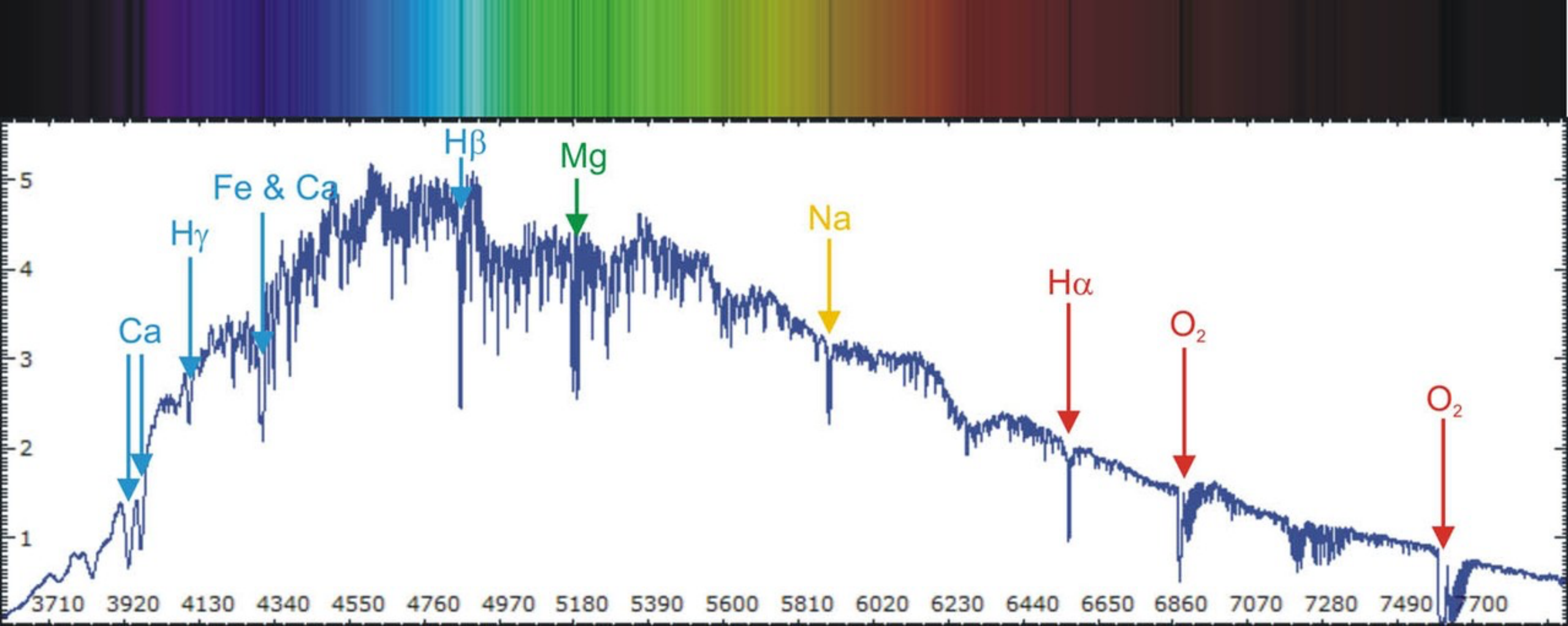
Our star, the Sun, is a hot **plasma** ball. It is an average star in terms of its mass, size, temperature, composition, and evolution.

Sun Data

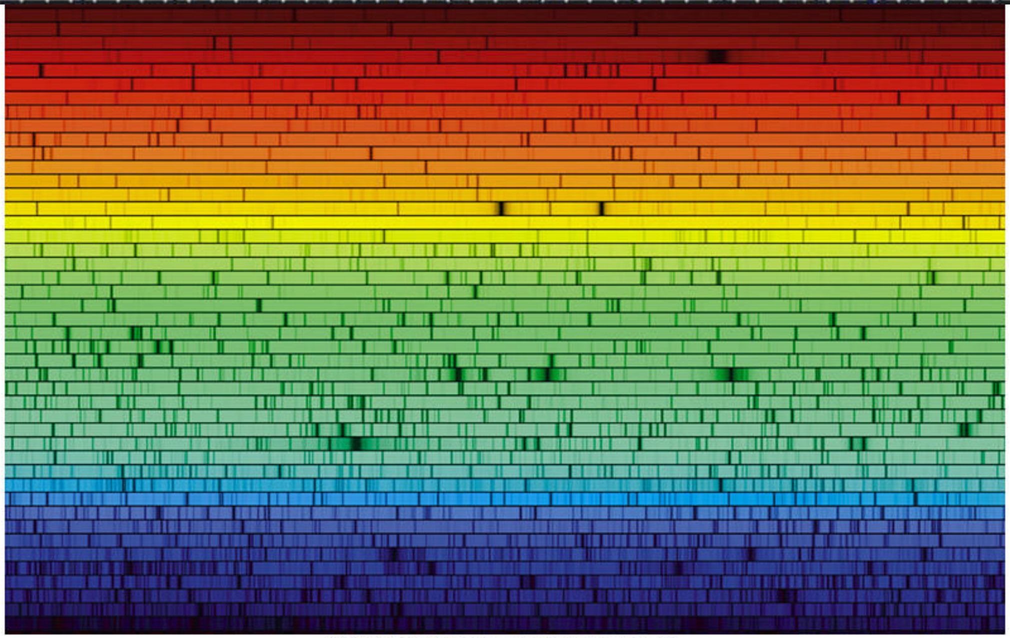
Distance from the Earth:	Mean: 1 AU = 149,598,000 km
	Maximum: 152,000,000 km
	Minimum: 147,000,000 km
Light travel time to the Earth:	8.32 min
Mean angular diameter:	32 arcmin
Radius:	696,000 km = 109 Earth radii
Mass:	1.9891×10^{30} kg = 3.33×10^{5} Earth masses
Composition (by mass):	74% hydrogen, 25% helium, 1% other elements
Composition (by number of atoms):	92.1% hydrogen, 7.8% helium, 0.1% other elements
Mean density:	1410 kg/m^3
Mean temperatures:	Surface: 5800 K; Center: 1.55×10^{7} K
Luminosity:	3.86×10^{26} W
Distance from center of Galaxy:	8000 pc = 26,000 ly
Orbital period around center of Galaxy:	220 million years
Orbital speed around center of Galaxy:	220 km/s

Similar to Jupiter

Q: L = ??



Q: what produces the continuum? How to find the surface temperature of the Sun? What produces the absorption lines?



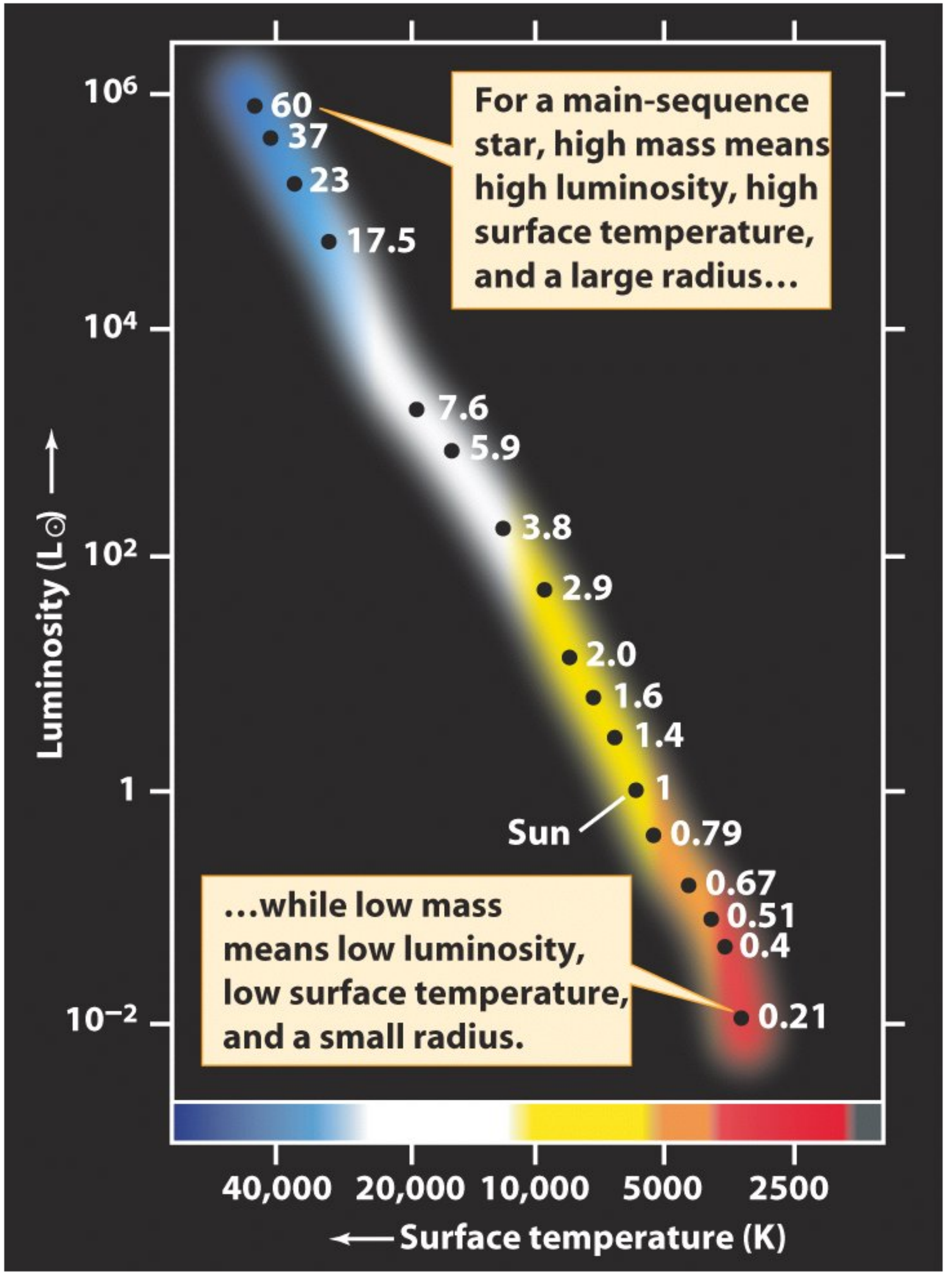
Ex.2: the Sun's position in the H-R diagram as an average main sequence star.

H-R diagram: a star's luminosity (brightness) versus its temperature (color)

$$L = 4\pi R^2 \sigma T^4$$

A main sequence star:
- Same chemical composition: 75% hydrogen and 25% helium);
- Fueled by thermonuclear reaction;
- Lie in the H-R diagram

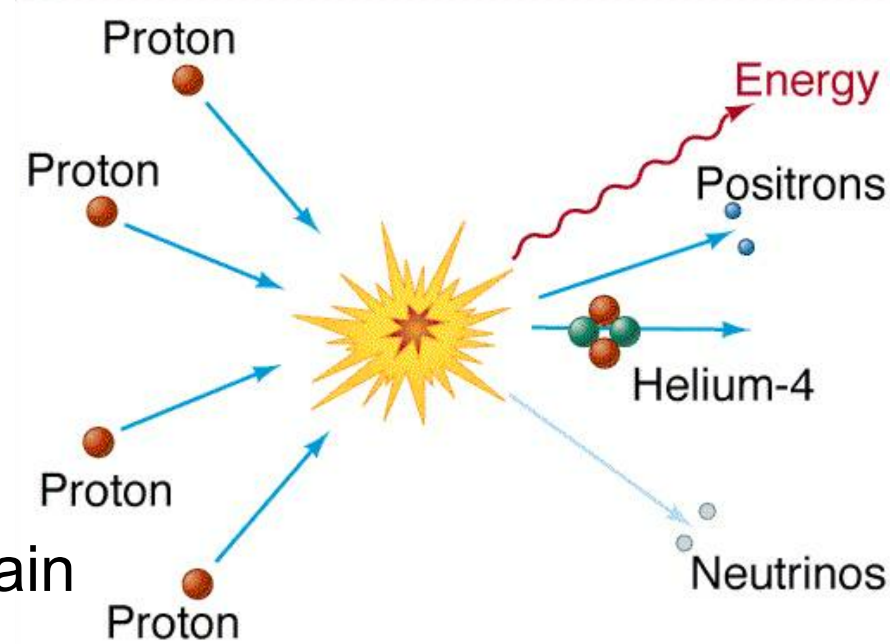
Mass determines all.



14.2 Source of Energy

- Like all stars, the Sun's energy is generated by **thermonuclear reactions** in its core, where temperature, density and pressure are tremendously high to push light atoms to fuse into heavy ones, e.g., hydrogen **fusion**.

Q: why only in the core?



Energy release by mass loss:

$$E = \Delta mc^2$$

- Neither Kelvin-Helmholtz contraction nor chemical reaction provides enough energy to maintain its brightness for billions of years.

Q: what is different between a chemical reaction and a nuclear reaction?

Ex.3: the mass of a hydrogen atom is 1.67353×10^{-27} kg, and the mass of a helium atom is 6.64648×10^{-27} kg. How much energy is liberated when 1g of hydrogen is converted to helium?

Step I: every 4 hydrogen atoms fuse into 1 helium atom, the mass loss is:

$$\Delta m = 4m_H - m_{He}$$
$$= 4 \times 1.67353 \times 10^{-27} kg - 6.64648 \times 10^{-27} kg$$
$$= 4.76578 \times 10^{-29} kg = 0.7\%(4m_H)$$

and the released nuclear energy is therefore:

$$E = \Delta mc^2 = 4.76578 \times 10^{-29} kg \times (3.00 \times 10^8 m/s)^2 = 4.29 \times 10^{-12} J$$

(i.e, every second, 10^{38} times hydrogen fusion would be taking place to provide the luminosity of the Sun.)

Step II: Every 1g of hydrogen contains this many times 4-hydrogens:

$$0.001kg / 4m_H = 0.001kg /(4 \times 1.67353 \times 10^{-27} kg) = 1.49 \times 10^{23}$$

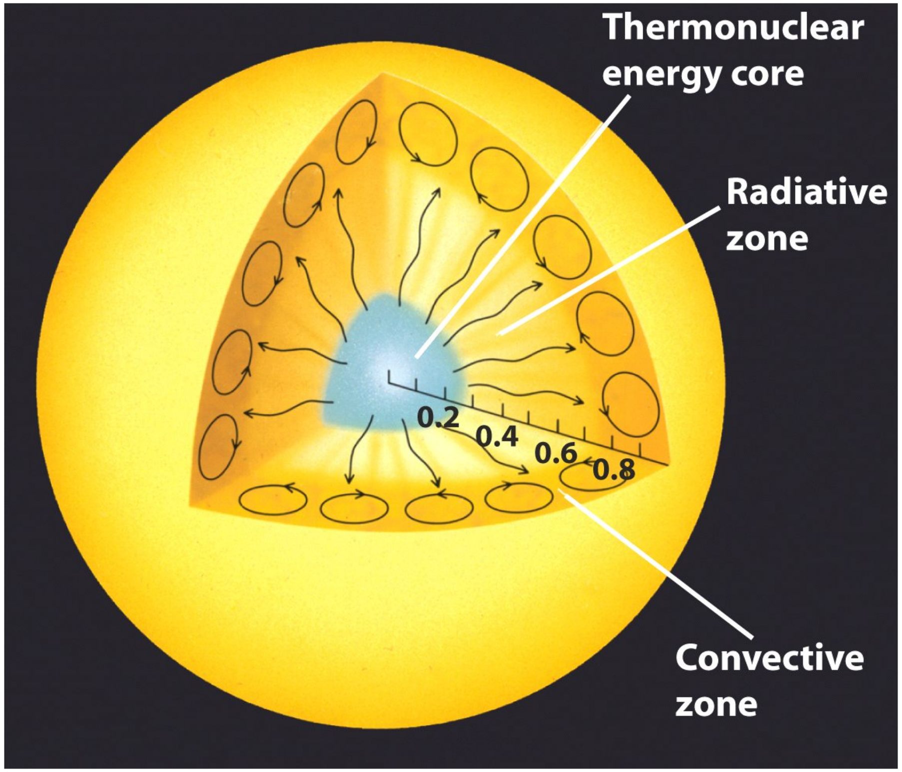
the energy release by 1g hydrogen through fusion is, therefore:

4.29×10^{-12}J x 1.49×10^{23} = 6.39×10^{11} J.

(In 2005, total worldwide energy consumption was 5×10^{20} J)

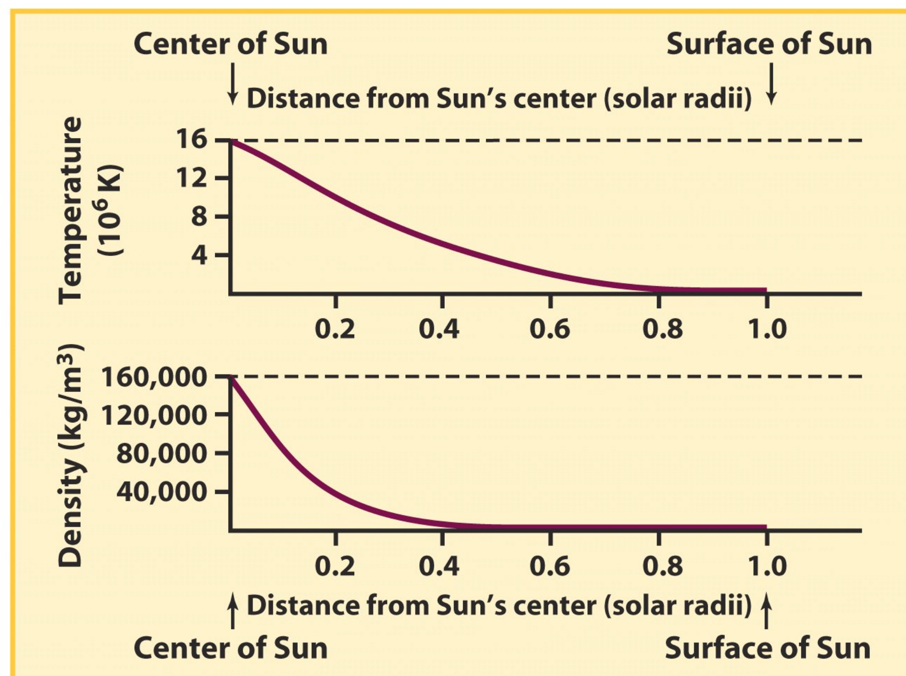
Net energy input: nuclear fusion energy
Net energy output: radiation

14.3 Interior of the Sun



The Sun's energy is transported from the 15 MK center outward by radiation in the **radiative zone** and then convection in the **convective zone.**

Ex.4: A Gamma-ray photon from the Sun's center zigzags out to be degraded to optical photons !



Standard solar model is built using all the fundamental physical principles and solving **equilibrium equations**. It has survived observational tests.

Treating the solar (stellar) interior in **equilibrium**

- **Hydrostatic equilibrium is a force balance:** gas pressure and radiation pressure work against gravity

  Ex.5: force balance in light and heavy stars.

- **Thermal equilibrium is an energy balance:** the same amount of energy enters and leaves a layer

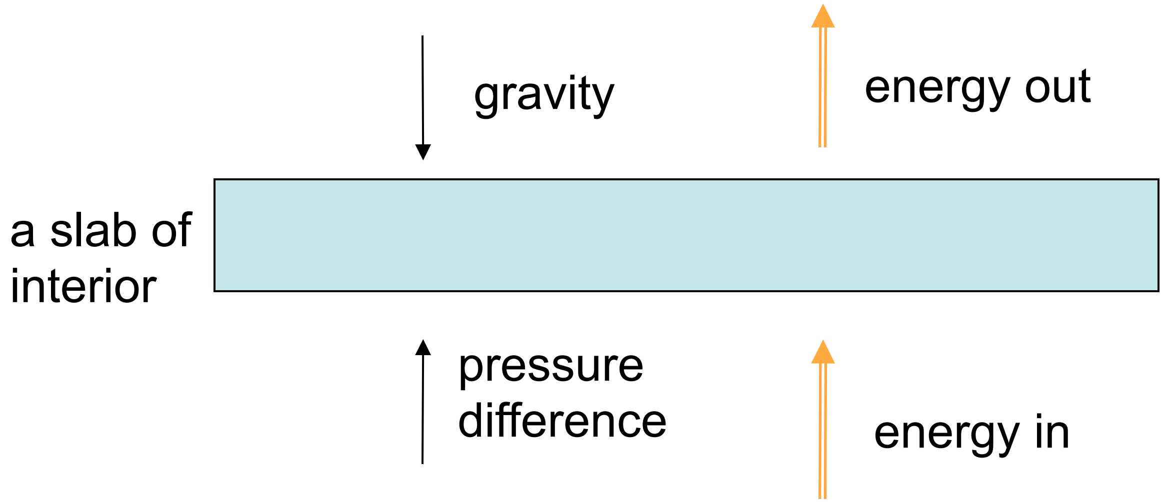
  Q: the form of incoming and outgoing energy.

- **Energy transfer inside the Sun (stars) by radiation and convection:**

  by radiation, energy is carried away in **photons** with **temperature gradient;** by convection, energy is transported by gas flows.

  Ex.6: the radiative energy flux and radiative pressure are both proportional to T^4.

The solar/stellar interior structure is modeled by **numerical simulations** with observational constraints.



A layer in equilibrium should maintain a force balance and energy balance.

(optional) Ex.7: equations describing the stellar structure

$$\frac{\partial P(r)}{\partial r} = -G\frac{m(r)\rho(r)}{r^2} - \cancel{\rho(r)\frac{d^2r}{dt^2}}$$ momentum equation

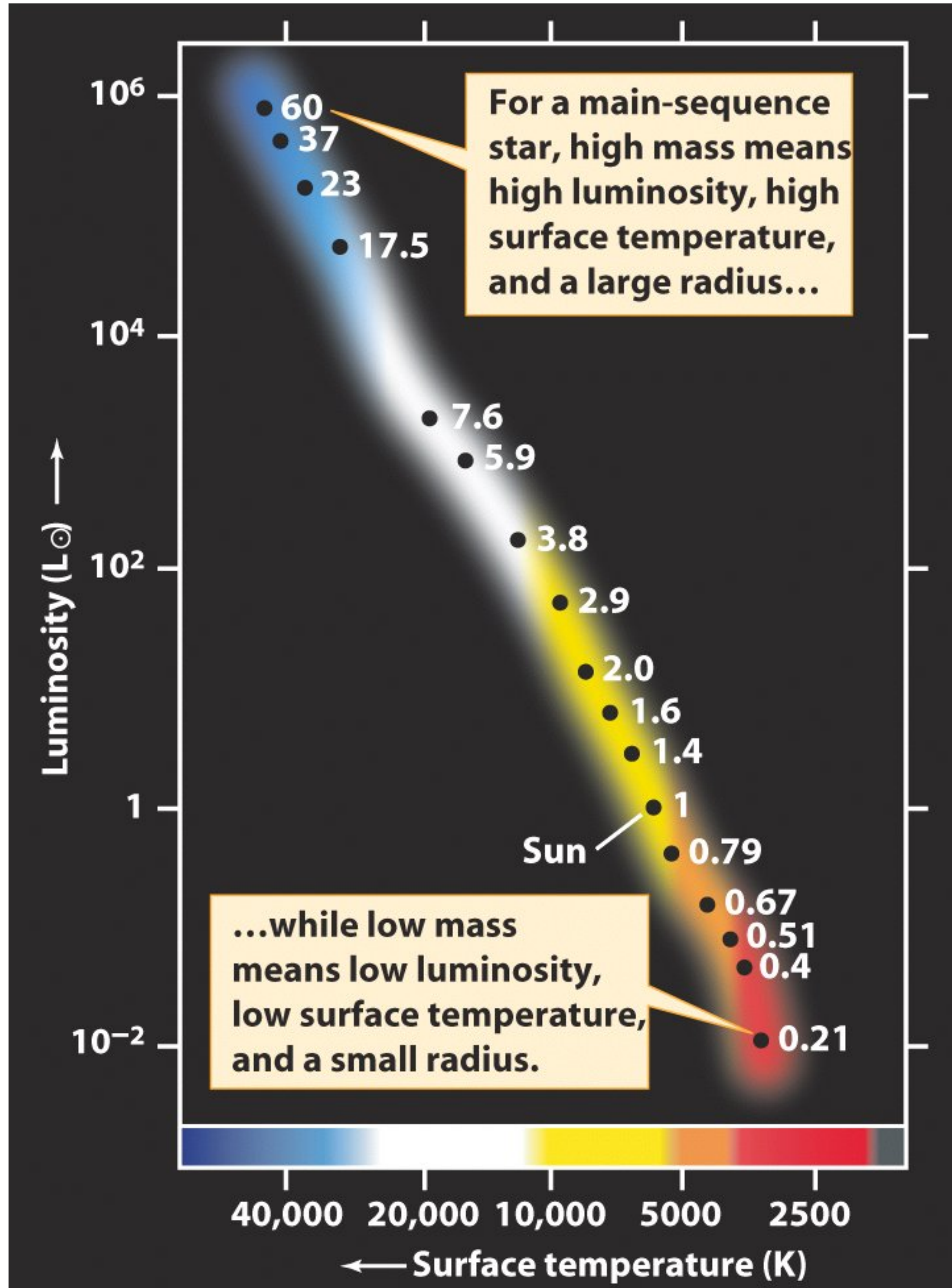
$$\frac{\partial m(r)}{\partial r} = 4\pi r^2\rho(r)$$ mass conservation

$$\frac{\partial T(r)}{\partial r} = -\frac{3\kappa\rho(r)}{16\pi ac}\frac{L(r)}{r^2T(r)^3}$$ energy transfer

$$\frac{\partial L(r)}{\partial r} = 4\pi r^2\rho(r)\left[\varepsilon(r) - \cancel{T\frac{ds}{dt}}\right]$$ energy equation

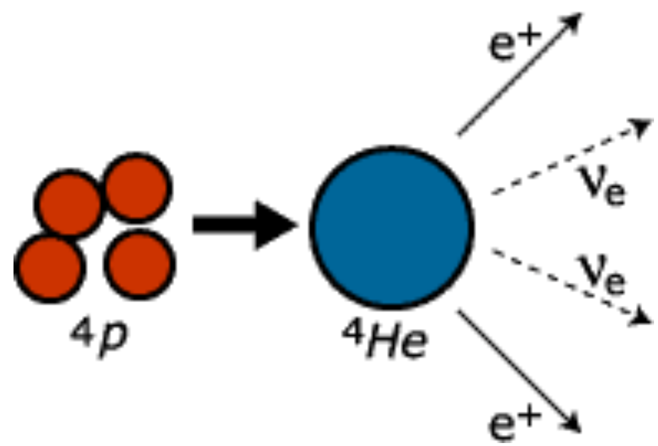
Observed mass, radius, surface temperature, and luminosity provide constraints.

the standard stellar model successfully produced the theoretical H-R diagram.



14.4 Solar Neutrinos and Standard Solar Model - reading assignment

The standard solar model survives the tests by solar neutrino experiments and helioseismology.

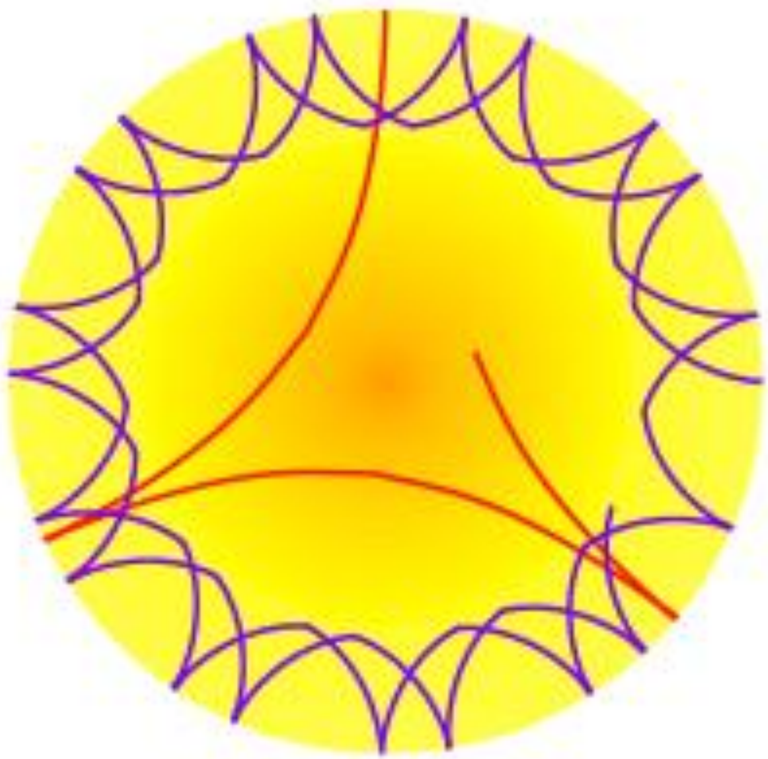


Solving the mystery of the missing neutrinos
(http://nobelprize.org/nobel_prizes/physics/articles/bahcall/)

14.5 Solar Oscillations and Helioseismology

The interior of the Sun can be "observed" by its oscillations in brightness, size, and velocity on surface.

Trapped acoustic waves

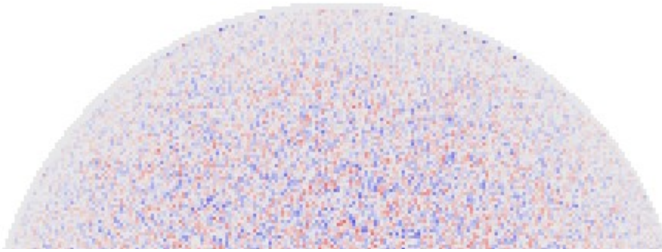


5-minute oscillation: a quasi-sinusoidal radial variation in the velocity field with an amplitude of a few hundred m/s and period of 5 min, produced by trapped acoustic waves, or pressure **P mode wave -** refracted in the interior by increased temperature and reflected below the surface by low density. Long wavelength waves travel deeper into the sun. Oscillations are thought to be produced by turbulence in the convective zone.

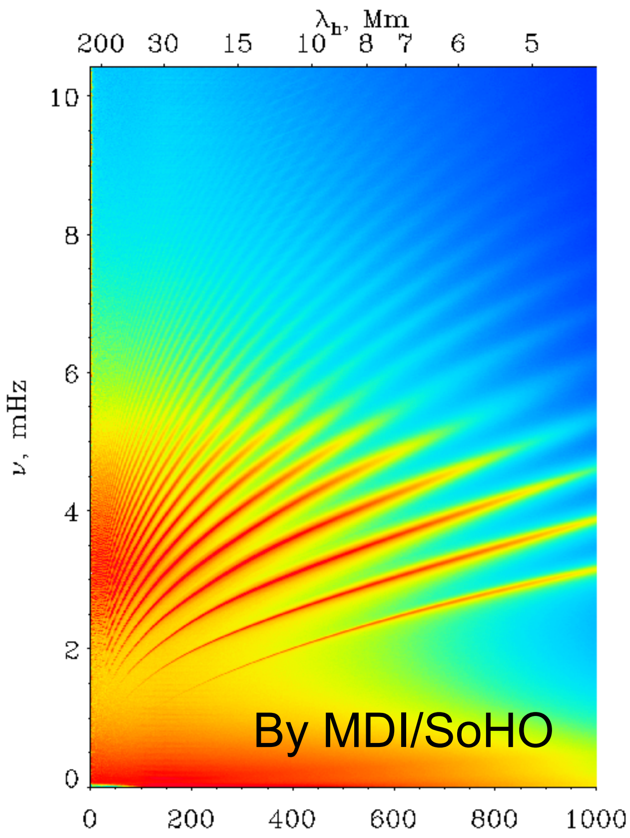
Just like sound echoing all around in a room or a concert hall, sound is bouncing all around and echoing inside the sun.

Q: what do you think is the best method to observe the Sun's oscillation?

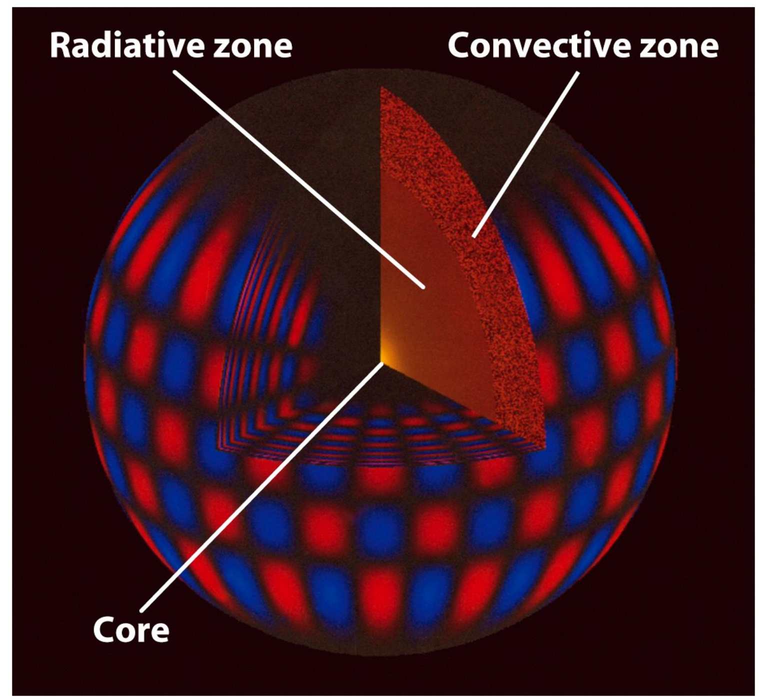
Observed Dopplergram of the Sun



The sun is like a huge musical instrument. It rings like a bell, and vibrates like an organ pipe. Just like a piano has 88 keys or musical notes, the sun has 10 million keys or notes.

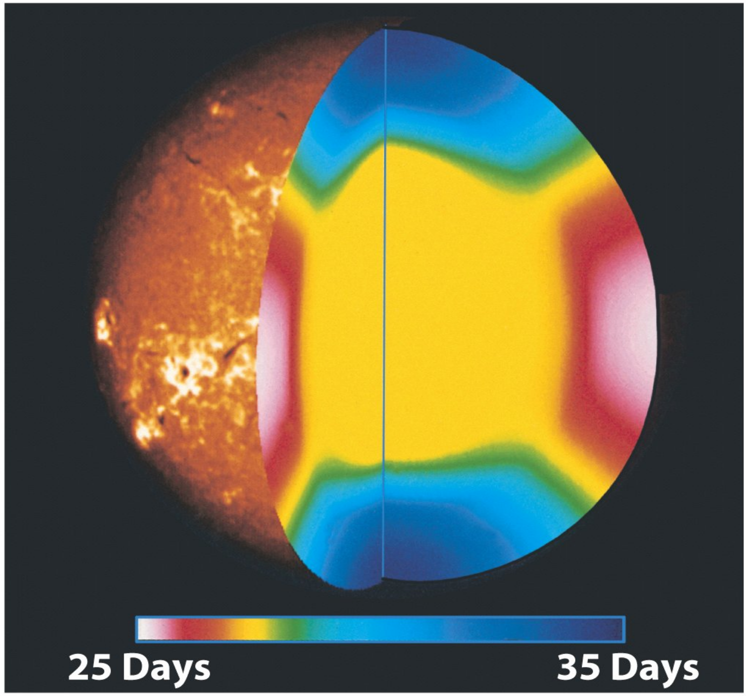


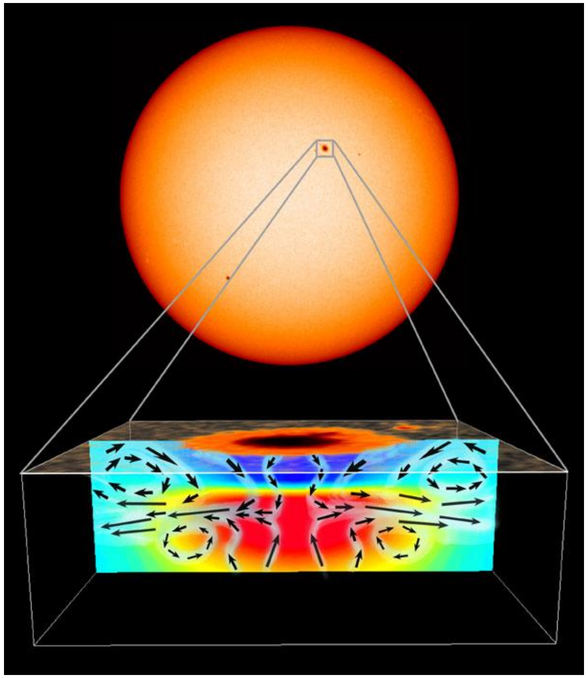
Spatial-temporal spectrum, showing that only waves with specific combination of period and wavelength resonate within the sun.



Simulated interior of the Sun.

Helioseismology techniques are used to probe the Sun's internal structure by studying the Sun's oscillations, i.e., measuring the time taken by a sound wave to travel down to the bottom and back and the distance between reflection points.





Achievements:

- standard model survives helioseismology tests with refined convection zone depth and opacity.
- determination of the Sun's **internal differential rotation**.
- flow and temperature beneath sun spots

Key Words

- convective zone
- differential rotation
- fusion
- gas pressure
- helioseismology
- hydrostatic equilibrium
- Kelvin-Helmholtz contraction
- plasma
- radiative pressure
- radiative zone
- solar neutrino
- standard solar model
- thermal equilibrium
- thermonuclear reaction

Summary

- The Sun is a hot plasma ball. Solar energy comes from **thermonuclear fusion** in its high temperature core.
- The Sun's interior includes a hot dense core, **radiative zone,** and **convection zone.**
- The Sun's internal structure is studied through **helioseismology.** The Sun has a differential rotation.
- **The standard solar model** is built by numerically solving equilibrium equations. It has survived observational tests by helioseismology and **solar neutrino** experiments.