#1. The mass of one hydrogen atom is $1.673 \times 10^{-24}$ gm. The mass of one helium atom is $6.645 \times 10^{-24}$ gm.

a) Using $E=mc^2$ calculate the amount of energy generated from converting four hydrogen atoms into one helium atom.

The nuclear fusion process is: $4 \text{ H atom} \rightarrow 1 \text{ He atom}$

The energy created per one nuclear fusion event is:

$$\Delta E = [4m_{\text{H}}c^2] - [m_{\text{He}}c^2]$$

$$\Delta E = [(4 \times 1.673 \times 10^{-24} \text{ gm}) \times (3.0 \times 10^{10} \text{ cm/s})^2] - [(6.645 \times 10^{-24} \text{ gm}) \times (3.0 \times 10^{10} \text{ cm/s})^2]$$

$$\Delta E = 4.23 \times 10^5 \text{ ergs}$$

b) Assuming the Sun converts 600 million metric tons of Hydrogen to Helium each second, calculate the Sun's luminosity. (1 metric ton = $10^6$ gm)

The key here is to calculate the amount of energy that the conversion of 600 million metric tons of Hydrogen to Helium generates.

600 million metric tons of Hydrogen = $6.0 \times 10^{14}$ gm

= $6.0 \times 10^{14}$ gm * [1 atom / (1.673 x 10^{-24} gm)] = $3.586 \times 10^{38}$ H atoms

From (a), every 4 H atoms generate $4.23 \times 10^5$ ergs of energy when converted to Helium by fusion.

Thus, [(3.586 x 10^{38} H atoms) / 4 atoms] * (4.23 x 10^5 ergs) = $3.8 \times 10^{33}$ ergs

This amount of energy is generated each second. So, the luminosity is $3.8 \times 10^{33}$ ergs/second.

c) The Sun has a radius of $7 \times 10^{10}$ cm. What is the Sun’s Flux?

The Sun’s Flux (at the surface) is simply the amount of energy emitted from each piece of the solar surface per time. Thus, we expect units of ergs per squared-centimeter per second.

Solar Flux at Surface = Solar Luminosity / Solar Surface Area

= $(3.8 \times 10^{33} \text{ ergs/second}) / (4 \pi (7 \times 10^{10} \text{ cm})^2)$

= $6.2 \times 10^{10}$ ergs/second/cm^2

#2. Describe the three regions of the solar interior.

**The Core:**
Innermost region of the Sun where nuclear fusion is converting hydrogen to helium and thus creating energy.

**The Radiation Zone:**
The region between the core and the convection zone. In this region the energy generated in the core travels outward in the form of photons through a diffusion process.

**The Convection Zone:**
The outermost region of the solar interior. Here energy is transported primarily through a convective process much like a pot of boiling water.

#3. Describe the three regions of the solar atmosphere.
**Photosphere**: This is the lowest layer of the solar atmosphere and is the “visible” surface of the Sun. It is here that we see sunspots and the granulation pattern due to the convection below.

**Chromosphere**: A layer directly above the photosphere that is less dense and higher in temperature than the photosphere. Many features can be seen here such as filaments and spicules.

**Corona**: The outermost part of the Sun’s atmosphere. It has extremely low density but an extremely high temperature. The source of this heat remains a puzzle.

#4. How do astronomers detect magnetic fields in the photosphere of the Sun?

**The Zeeman Effect**: The magnetic fields in the photosphere can be measured by measuring the splitting of specific spectral lines. This splitting is due to the Zeeman effect.

#5. Give some every day examples of heat transfer by convection and radiative transport.

Examples of convection: boiling water, Earth’s atmosphere has large convection cells that transport heat, a ‘Lava Lamp’

Examples of radiative transport: microwave oven, the heating of Earth’s atmosphere by radiation, UV light of the sun ‘burning’ your skin (i.e. sunburn), heat lamps at a cafeteria and/or restaurant

#6. Why do thermonuclear reactions in the Sun only take place in its core?

Thermonuclear reactions only take place in the core since the process requires very high temperatures and pressures to occur.

#7. Describe the basics of hydrogen fusion.

Hydrogen fusion requires high temperatures and high pressures to occur. In the process, four hydrogen atoms are transformed into one helium atom. The result of this process is not only a helium atom, but considerable energy.

#8. Using the mass and size of the Sun, calculate the Sun’s average density. Compare to the average density of Earth and the outer planets. The volume of a sphere is \((4/3)\pi r^3\).

Mass of the Sun: \(2.0 \times 10^{33}\) gm
Radius of the Sun: \(7 \times 10^{10}\) cm

Average density of the sun = \(\frac{\text{mass of the Sun}}{\text{volume of the Sun}}\)
= \(\frac{M_{\text{sun}}}{(4/3)\pi r_{\text{sun}}^3}\)
= \(\frac{2.0 \times 10^{33}\text{gm}}{(4/3) \pi (7 \times 10^{10}\text{cm})^3}\)
= \(1.392\) gm / cm\(^3\)

Average density of other planets:

- Earth = \(5.515\) gm / cm\(^3\)
- Jupiter = \(1.326\) gm / cm\(^3\)
- Saturn = \(0.687\) gm / cm\(^3\)
  (Less than water! Saturn would float in a huge glass of water!)
- Uranus = \(1.27\) gm / cm\(^3\)
- Neptune = \(1.638\) gm / cm\(^3\)
#9. Assuming that the current rate of hydrogen fusion in the Sun remains constant, what fraction of the Sun’s mass will be converted into helium over the next five billion years. How will this affect the chemical composition of the Sun. Use some of the numbers given in #1.

From #1 part (b), we know that 6.0 \times 10^{14} \text{ grams of Hydrogen is converted into Helium every second. Thus, over five billion year, we can calculate how much Hydrogen is converted into Helium in total by:}

- 1^{st} convert years to seconds: \(5 \text{ billion years} \times (3.14 \times 10^7 \text{ seconds/year}) = 1.57 \times 10^{17} \text{ seconds}\)
- Thus, \((6.0 \times 10^{14} \text{ gm/sec}) \times (1.57 \times 10^{17} \text{ sec}) = 9.42 \times 10^{31} \text{ grams. This means that 9.42 \times 10^{31} grams of Hydrogen will be converted to Helium over 5 billion years.}\)
- What percentage of the Sun’s mass is this? \(
\frac{9.42 \times 10^{31} \text{ grams}}{(2.0 \times 10^{33} \text{ grams})} \times 100 = 4.71\%
\)

A small percentage of the Sun’s hydrogen is converted to Helium, and thus the chemical composition of the Sun changes slightly. In general the percentage of Hydrogen will decrease and the percentage of Helium will increase.

#10. Calculate the wavelengths at which the photosphere, chromosphere and corona emit the most radiation. Explain how the results of your calculations suggest the best way to observe these regions of the solar atmosphere. (Hint: Use Wien’s law and assume that the average temperatures of the photosphere, chromosphere and corona are 5800 K, 50000 K and \(1.5 \times 10^6\) K respectively).

Wien's Law: 
\[
\lambda_{\text{max}} = \frac{2.9 \times 10^{-1}}{T} \quad \text{where the wavelength is in centimeters and temperature is in Kelvin.}
\]

So, for the three regions, the peak blackbody wavelength is:
- Photosphere: \(\lambda_{\text{max}} = \frac{(2.9 \times 10^{-1})}{(5800 \text{ K})} = 5.0 \times 10^{-5} \text{ cm (Visible Light)}\)
- Chromosphere: \(\lambda_{\text{max}} = \frac{(2.9 \times 10^{-1})}{(50000 \text{ K})} = 5.8 \times 10^{-6} \text{ cm (Ultraviolet Light)}\)
- Corona: \(\lambda_{\text{max}} = \frac{(2.9 \times 10^{-1})}{(1.5 \times 10^6 \text{ K})} = 1.9 \times 10^{-7} \text{ cm (X-rays & Gamma rays)}\)

#11. Describe the rotation of the Sun.

At the surface (i.e. the photosphere) and in the convection zone, the Sun rotates faster at the equator than at its pole. This is called differential rotation. In the radiation zone, the rotation is uniform (i.e. like a solid body such as the Earth). The transition between the differential rotation and the uniform rotation is called the tachocline.