Chapter 10: The Sun: Our Extraordinary Ordinary Star

Radius: 6.96×10^5 km (109 $D_\oplus$)

Mass: 1.99×10^{30} kg (333,000 $M_\oplus$)

Density: 1410 kg/m^3 (similar to Jovian planets)

Temperature: 5800 K (from Wien's law)

Rotation Rate: 25 days at the equator, 35 days near the poles.

A. Luminosity: Total energy radiated by the Sun each second.

1. Solar constant: energy reaching the Earth per square meter.
How do astronomers measure the Sun's luminosity. First, we start by measuring how much solar radiation strikes the Earth's surface, after correcting for the absorption by the Earth's atmosphere. The value that we get is:

$$\text{solar constant} = 1400 \text{ watts/m}^2$$

2. Luminosity is determined by multiplying the solar constant by the area of the sphere that surrounds the Sun which has a radius of one astronomical unit (1.5×10^8 km).

$$\begin{aligned}\text{Luminosity} &= (1400 \text{ watts/m}^2) \times (2.8 \times 10^{23} \text{ m}^2) \\ &= 3.9 \times 10^{26} \text{ watts}\end{aligned}$$

B. Interior: Internal structure is deduced from mathematical models that match the observed properties of the surface and from analysis of vibrations of pressure waves (helioseismology) that bounce through the solar interior.

Concept Test

The light from the east limb (edge) of the Sun is blueshifted and the light from the west limb is redshifted. This is because

a) different kinds of atoms emit light at the opposite edges.
b) the Sun is rotating.
c) the distance from the Sun to the Earth changes.
d) the two sides of the Sun are at different temperatures.

Standard Solar Model:

1. Core: Region where energy is generated by the fusion of hydrogen into helium. Gamma rays are formed as a by-product of the fusion process.

a. Density = 150,000 kg/m^3.
b. Temperature ~ 15 million Kelvins.

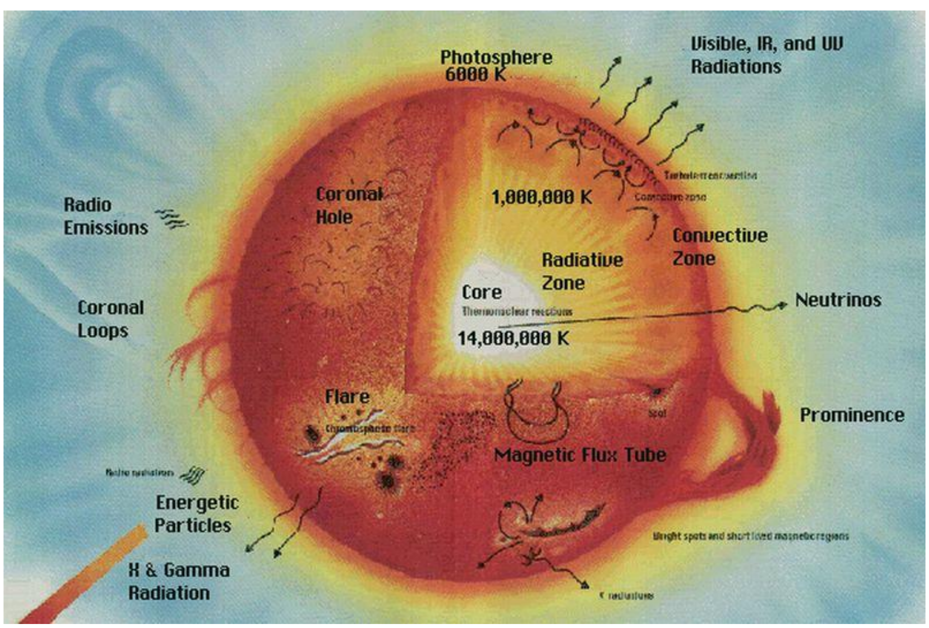
2. Radiative Zone: Energy is transported by radiation. Photons traveling out from the core travel only a short distance before encounter slightly cooler material, which absorbs the photons. The slightly cooler gas re-emits photons having a slightly longer wavelength in random directions. It can take several hundred thousands years for the photons to reach the Sun's surface. By the time the photons emerge from the Sun they have been gradually degraded from gamma rays to visible light

a. Density = 15,000 kg/m^3.
b. Temperature = 7 million Kelvins.

3. Convective Zone: Energy transported by convection. Photons are totally absorbed at boundary between radiative and convective zones.

a. Density = 150 kg/m^3.
b. Temperature = 2 million Kelvins.

c. Convective cells carry energy to the surface. Cells are seen at the surface (photosphere) as granulation.



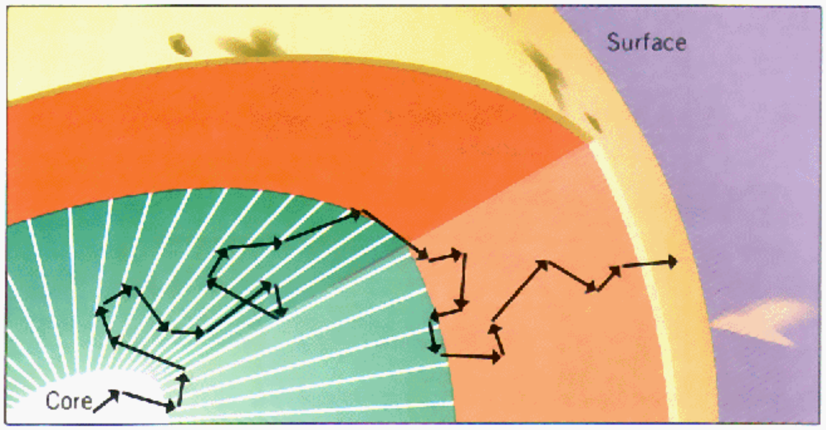


FIGURE 16-13. The path followed by photons from production in the solar interior until they reach the surface. The original gamma ray photon is not the one that is emitted from the surface; different photons are constantly absorbed and reemitted.

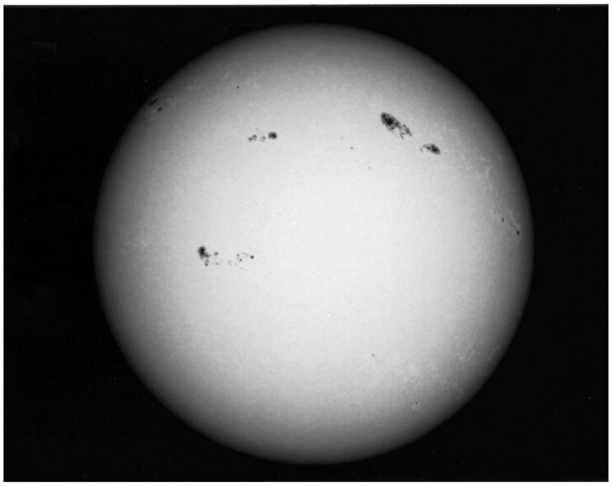
C. Visible Surface: Photosphere (400 km thick)

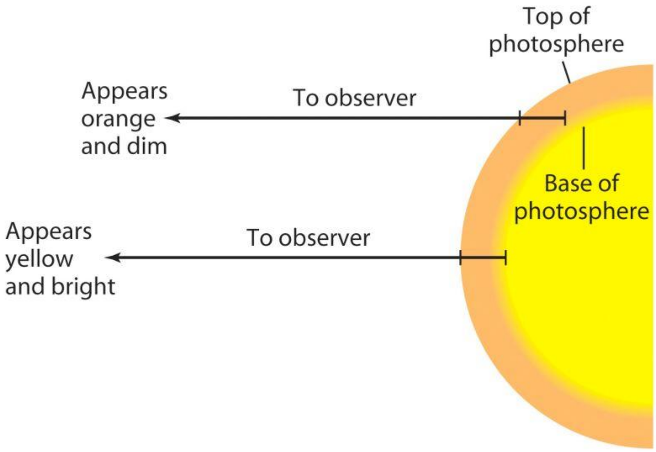
1. Temperature: 5800 Kelvins.
2. Density: 2 x 10^{-4} kg/m^3

3. **Granules**: 1000 km wide. Lifetime of 5 to 10 minutes.

   a. **Supergranules** (~30,000 km wide) result from larger convection cells deeper in the convective layer.

4. Most visible photons arise from within the photosphere, which gives it a very sharp appearance.





5. **Limb darkening**: edge is darker than at the center.

a. Photons coming from edge originate from a shallower depth (cooler) while those from the center come from deeper regions (hotter) where more radiation is emitted.

Concept Test

The photosphere (the visible surface) of the Sun is like
a) the surface of the Earth; you could stand on it, if you could survive the heat.
b) the surface of the ocean; you couldn't stand on it, but you would clearly be able to detect differences above and below it.
c) an apparent surface; you would notice very little change as you go through it, as when you fly through a cloud.
d) the surface of a trampoline; you could land on it, but the intense pressure would push you away again.

D. Atmosphere:

1. Chromosphere:

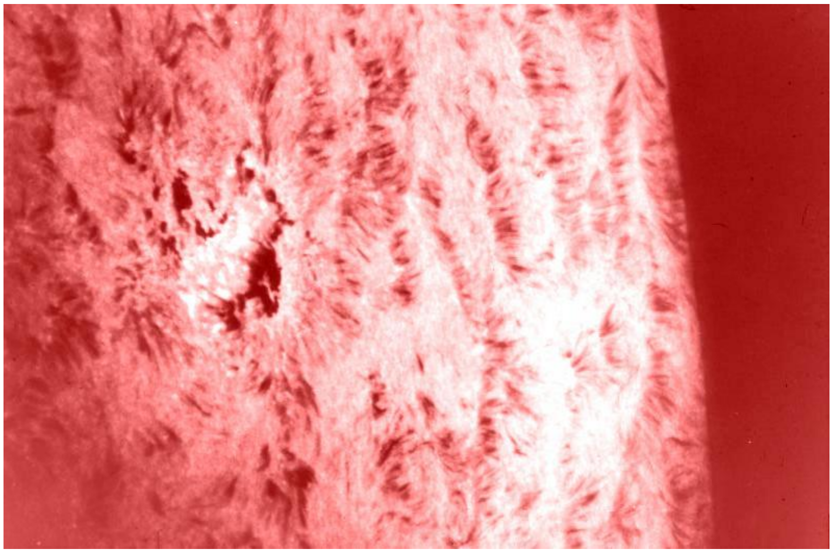
a. Low density: 5×10^{-6} kg/m^3

b. Temperature: 4500 Kelvins

c. Seen only during total solar eclipses.

d. Pink color due to Hydrogen alpha emission.

e. **Spicules**: jets of hot gas resulting from magnetic disturbances at edges of supergranules.



2. Corona: Spectrum is dominated by emission lines. Kirchhoff's 2nd law applies.

a. Temperature: 1 million Kelvins. The high temperature is thought to be due to waves in the Sun's magnetic field.

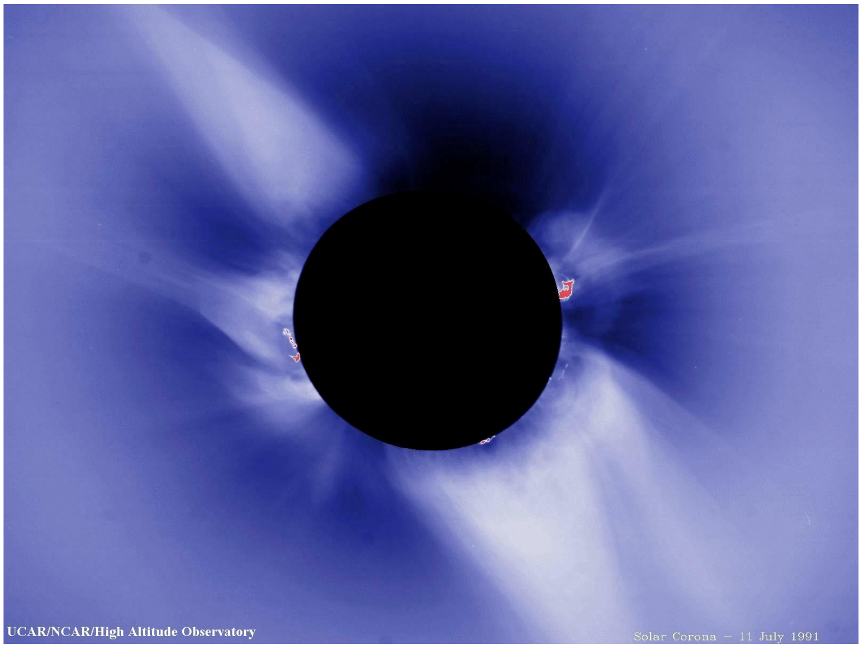
b. Density: 1 x 10^{-12} kg/m^3

c. Seen during eclipses or with special instruments that can block out the photosphere (coronagraphs).

i. Numerous coronal streamers seen during eclipses which are related to the Sun's magnetic field.

d. Most atoms are highly ionized due to the high temperature.

e. Emits radiation primarily as X-rays.



3. Solar Wind: Escaping protons and electrons traveling at ~400 km/sec.

a. High temperature of solar corona causes coronal gases to reach escape velocity (10 million km above photosphere).

b. Solar wind is a means that the Sun looses its mass (~ 0.1 % so far).

c. Solar wind escapes primarily through coronal holes (areas with very little matter). Over coronal holes the solar wind can reach 800 km/s.

E. Solar Activity:

1. Quiet Sun: steady radiation from photosphere. Simple, symmetrical corona, and very few sunspots.

2. Active Sun: unpredictable explosive outbursts. Complex coronal structure and many sunspots.

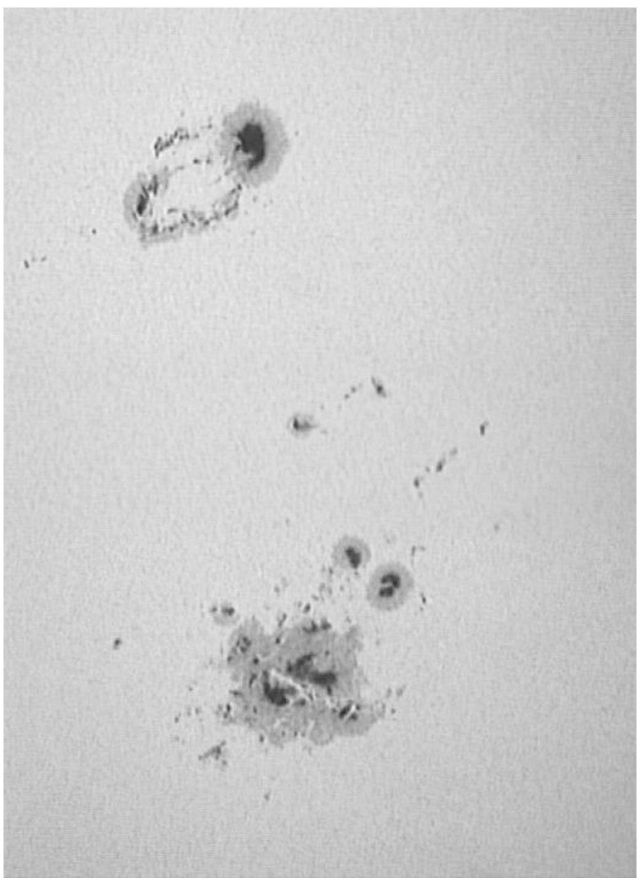
a. **Sunspots**: dark areas in the photosphere representing cooler regions (4500 K). Appear dark only because they are cooler.

i. Umbra - dark center.

ii. Penumbra - grayish outer region.

iii. Spots rotate with the Sun and reveal that it rotates differentially.

iv. Usually found in pairs.



b. Solar Magnetism

i. Sunspots are regions of very strong magnetic fields as revealed by the splitting of absorption lines (Zeeman effect).

ii. Sunspot pairs are like the north and south poles of a magnet connected by a magnetic field.

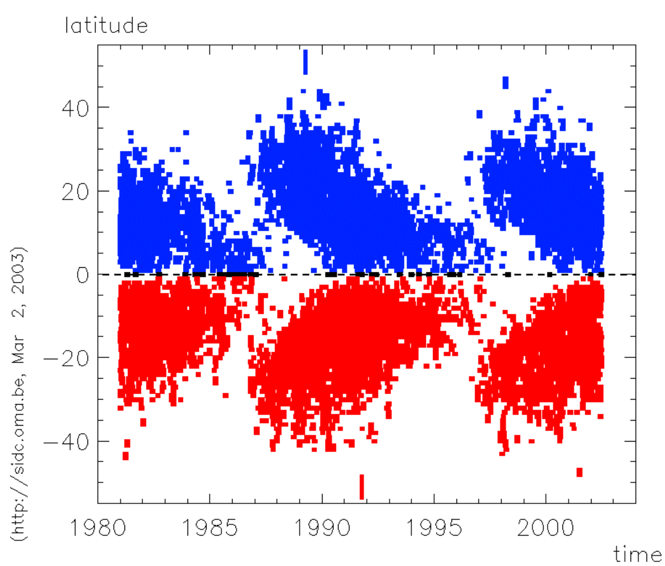
iii. Sunspot numbers occur in an **eleven year cycle**.

a. Solar minimum: beginning of each cycle when few spots are visible.

b. Sunspots confined to narrow regions 25^o to 30^o north and south of the equator and move to within 15^o to 20^o of the equator at solar maximum.

c. Magnetic cycle occurs on a **22 year cycle** where the polarity of the leading spots change.

iv. Sunspots caused by twisting of the Sun's magnetic field as the differential rotation winds up the magnetic field lines.



v. **Maunder Minimum**
From 1645 to 1715 there wasn't a sunspot maximum. During this period Europe experienced what we refer to as the Little Ice Age and Western North America experienced a severe drought. During periods of heightened solar activity during the 11th and 12th centuries the Earth experienced warmer than usual temperatures.

Therefore, we can conclude that there is a complex link between solar activity and Terrestrial weather patterns.

Summer in the Netherlands, c. 1615

c. Active regions: sites of explosive eruptions resulting from magnetic instabilities. Generally, they surround sunspots.

i. **Prominences** - loops and sheets of gas ejected from active regions.

Quiescent: last several days to several weeks.

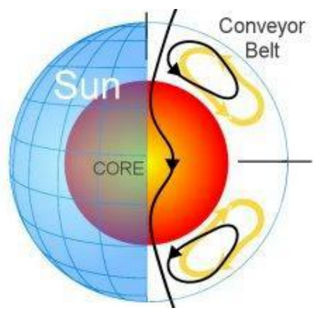
Active: short lived (hours) and erratic.

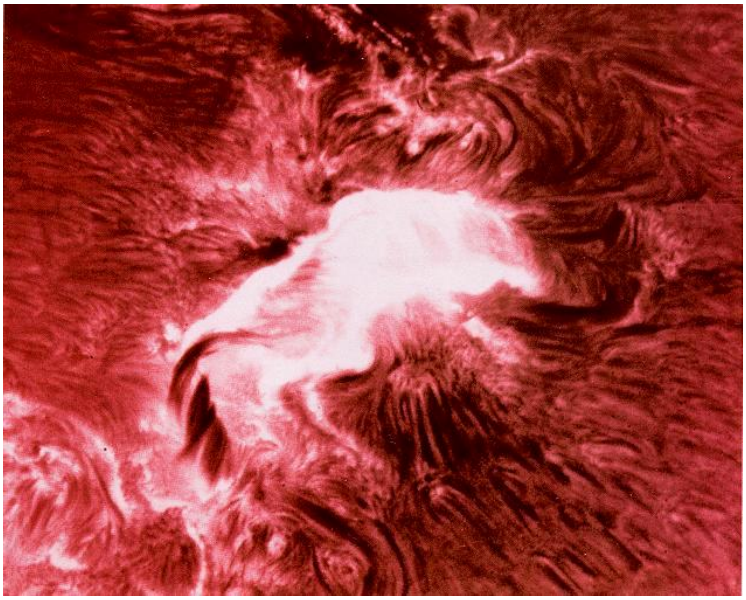
ii. **Flares** - most violent eruptions. Very short lived (minutes). Disrupt communications on Earth.

Temperatures within a flare can reach 100 million Kelvins.

Gases within a flare have enough energy to escape the Sun's magnetic field.

d. Predicting Solar Activity: In March 2006 astronomers with the National Center for Atmospheric Research announced that they have a model that can predict future solar activity. Their model called the conveyor belt explains the strength of sunspot cycles.





Solar Flare

Prominence

Concept Test

The 11 year solar cycle is NOT followed by the
a) number of sunspots on the Sun.
b) typical latitude of sunspots on the Sun.
c) rate of solar flares.
d) incidence of strong aurora on the Earth.
e) None of the above.

F. Energy Production:

1. Nuclear Fusion: combination of lighter elements into heavier elements with a release of energy governed by $E=mc^2$.

a. **Proton-proton chain**: Requires a temperature of 10 million Kelvins.

Proton_1 + proton_2 ------> proton_3 + neutron + positron + neutrino

Neutron: chargeless particle of nearly the same mass as a proton.

Positron: positively charged electron. Combines with electrons to form gamma rays.

Neutrino: small (nearly massless and chargeless) particle that travels near the speed of light and does not interact easily with matter.

Neutron and proton combine to form a deuteron.

neutron + proton -----> deuteron

Step 1: formation of deuterium (^2D)

^1H + ^1H -------> ^2D + positron + neutrino

Step 2: formation of helium isotope (^3He).

^2D + ^1H -------> ^3He + energy

Step 3: formation of helium (^4He).

^3He + ^3He -------> ^4He + ^1H + ^1H + energy

In general, four hydrogen atoms combine to form one helium atom.

$4(^1H)$ -------> ^4He + energy + 2 neutrinos

The mass of the resulting helium atom is slightly less than the mass of the four protons that were combined to form the helium atom. This mass difference accounts for the energy released according to Einstein's famous formula $E = mc^2$.

An Astronomer's Toolbox 10-1

The energy released in the formation of a single helium atom is 4.3×10^{-12} J.

How many helium atoms need to be formed in order to light a 60 Watt light bulb for 12 hours?

Answer:

The number of atoms is the total energy required to light the bulb divided by the amount of energy released per helium atom. The Watt is defined as energy per unit time (J/sec).

$$\text{Number of atoms} = \frac{60 \text{ J/sec} * 12 \text{ hours} * 3600 \text{ sec/hr}}{4.3 \times 10^{-12} \text{ J}}$$

$$= 6.0\text{x}10^{17} \text{ helium atoms.}$$

Since each helium atom has a mass of $6.647\text{x}10^{-24}$ grams the total mass of these helium atoms is

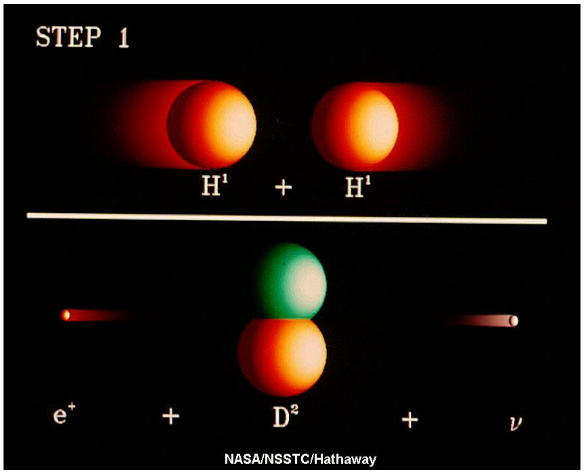
$$\text{Mass} = 6.0\text{x}10^{17} \text{ atoms} * 6.647\text{x}10^{-24} \text{ grams/atom}$$

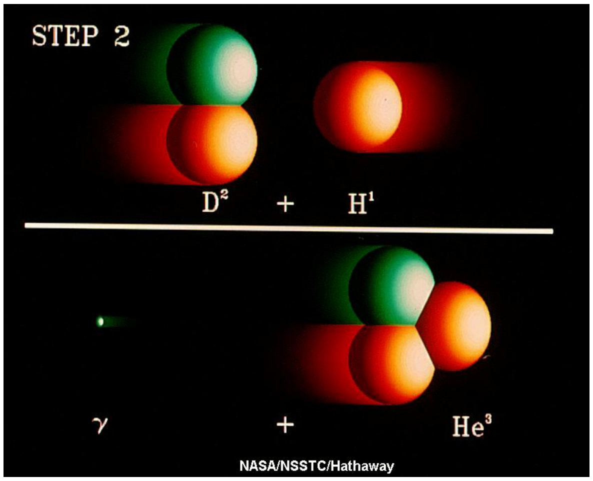
$$= 4.0\text{x}10^{-6} \text{ grams}$$

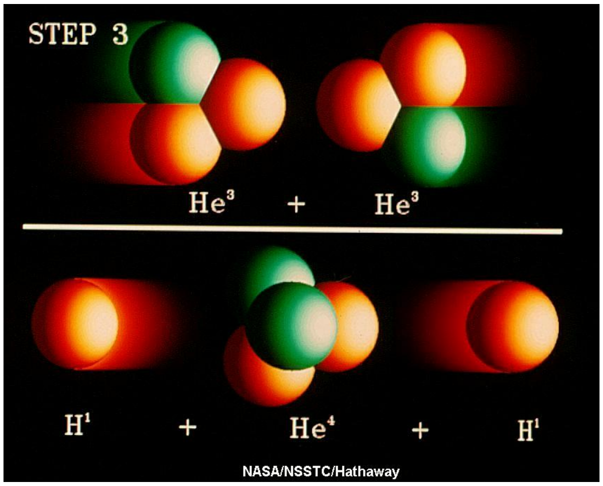
Concept Test

The chemical composition of the Sun 3 billion years ago was different from what it is now in that it had

a) more hydrogen.
b) more helium.
c) more nitrogen.
d) molecular hydrogen.


STEP 1
H¹ + H¹
e⁺ + D² + ν
NASA/NSSTC/Hathaway


STEP 2
D² + H¹
γ + He³
NASA/NSSTC/Hathaway


STEP 3
He³ + He³
H¹ + He⁴ + H¹
NASA/NSSTC/Hathaway

b. CNO cycle: secondary process. Requires a higher temperature. Accounts for 10% of Sun's energy. This becomes important late in the Sun's life.

1. $^{12}C + ^{1}H$ -------> ^{13}N + energy

2. ^{13}N -------> ^{13}C + positron + neutrino

3. $^{13}C + ^{1}H$ -------> ^{14}N + energy

4. $^{14}N + ^{1}H$ -------> ^{15}O + energy

5. ^{15}O -------> ^{15}N + positron + neutrino

6. $^{15}N + ^{1}H$ -------> $^{12}C + ^{4}He$

In general, one carbon plus four hydrogen atoms produce one carbon atom plus one helium atom.

$^{12}C + 4(^{1}H)$ -------> $^{12}C + ^{4}He$

G. Neutrino Problem:

1. Expected number of neutrinos in the past didn't match the observed number.

Expected: one per day.

Detected: two or three per week.

2. All experiments agreed upon a neutrino deficit. Experiments were not at fault.

3. Neutrino deficit was real.

4. Proposed Solutions to the Problem:

a. Temperature in core is lower than thought. However, that would lower the Sun's luminosity below what is observed.

b. Sun is pulsating. Nuclear reactions turning on and off.

c. Internal structure influenced by presence of matter not included in the Standard Model. (Weakly Interacting Massive Particles).

d. Neutrinos oscillate - turn into something else after leaving the Sun (if they have mass).

5. In June 2001 the Sudbury Neutrino Observatory (Ontario, Canada) detected solar neutrino oscillations. The problem now appears to be solved.