Sun

- The sun appears as a disk whereas other stars are point sources of light.
- Basic Properties

  Distance = 1.50 x 10^{13} cm (150 million km) = 1.496×10^{11} m

  Mass = 1.99 x 10^{33} gm = 1.989×10^{30} kg

  Radius = 6.96 x 10^{10} cm = 109 $R_\oplus$ = 6.96×10^{5} km

  Density = 1.41 gm / cm^3 = 1410 kg/m^3

  Luminosity = 3.83 x 10^{33} erg / sec = 3.83×10^{26} Joules/s

  Surface Temperature = 5770°k = 5778 K

  Rotation Period = 25 days at equator / 35 days at the poles

  Composition : 70% H; 27% He; 3% heavier elements
- Measurement of the sun's temperature
  - Plot energy E versus wavelength λ
  - Find λ_{max} the wavelength at which energy E is a maximum
  - Use Wien's law to obtain temperature
  - $T°k = 3x10^7 / \lambda_{max}$ Å
- Appearance of the sun's spectrum : Continuous spectrum superimposed by a set of dark absorption lines.
- Measurement of the sun's distance

  Measure synodic period (S) of Venus or Mars

  Obtain sidereal period (P) from

  $1 / P = 1 + 1 / S$ Inferior planet

  $1 / P = 1 - 1 / S$ Superior planet

  Use Kepler's 3rd law $P^2 = a^3$ to obtain distance of the planet from the sun in A.U.

  Use trigonometry to find the relative distance of Venus or Mars from earth in A.U.

  Bounce radar waves off the surface of Venus or Mars and obtain distance in centimeters.

  Convert A.U. to cm.

- Sun's Composition
- Fraunhoffer observed dark lines in the solar spectrum. He named the prominent lines A, B, ...from red to blue.
- Later researchers found - H and K lines are emitted by ionized calcium CaII; D line is emitted by neutral sodium NaI; and so on. Kirchhoff realized that if any atom emits a set of lines at certain wavelengths it will also absorb at those wavelengths.
- To find the composition measure wavelength of spectral line and identify the element. From the temperature and the strength of the spectral line obtain the number of absorbing atoms and hence the composition.

- Sun's Mass
- Use Kepler's 3rd law as modified by Newton

$(M_1 + M_2)\, P^2 = (4\pi^2 / G)\, a^3$

M_1 = Mass of the sun ($M_\odot$) in grams

M_2 = Mass of the earth ($M_\oplus$) in grams which we neglect because it is so small compared to the mass of the sun.

P = earth's orbital period in seconds

a = astronomical unit in centimeters

$G = 6.67 \times 10^{-8}$ c.g.s.unit

- Hence mass of the sun : $M_\odot = (4\pi^2 / G)\,(a^3 / P^2)$

[Note : we had to determine the distance to the sun before we could get its mass.]

- Sun's Diameter
- Use small angle equation

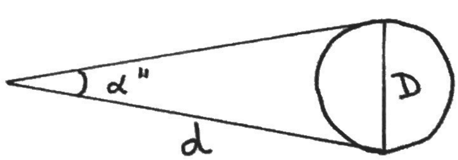
Angular diameter of the sun = α'' = 1/2° = 1800" of arc

Linear diameter = D cm

Distance = d cm

$\alpha'' / 206265 = D / d$

Linear diameter $D = (\alpha'' / 206265)\, d$



[Note : Once again we had to know distance to obtain diameter.]

- Sun's Density
- We know the sun's mass and radius (= diameter / 2). Then

$$\text{Density} = \text{Mass / Volume} = M / (4/3\ \pi R^3) = \rho\ (\text{rho})$$

- Sun's Absolute Luminosity
- The amount of energy received on the earth from the sun is the apparent luminosity of the sun l in erg / sec / cm^2. This is related to the actual amount of energy released by the sun or its absolute luminosity L in erg / sec

$$l = L / (4\ \pi\ d^2)$$

where d is the distance to the sun. Hence by measuring l, and knowing d we can obtain L.

Solar constant = 1388 Watts / meter^2

- Sun's Energy Source
- The sun is at least 4.5 billion years old. [From oldest rocks on earth and moon.]
- The sun's energy output has been fairly constant. [From fossil evidence.]
- What is the source of the sun's energy?
  - Chemical? [energy from combustion; e.g. burning natural gas] The sun would last only a few thousand years.
  - Gravitational Potential Energy? Kelvin-Helmholtz Contraction ("hypothesis") : The sun could be slowly contracting. It will lose potential energy which would be converted to heat. The sun would last 10^7 years.
  - Nuclear Energy? Yes, by nuclear fusion of hydrogen into helium.
- Proton - Proton Chain

$${}^1H_1 + {}^1H_1 \rightarrow {}^2H_1 + e^+(\text{positron}) + \upsilon(\text{neutrino})$$

$${}^2H_1 + {}^1H_1 \rightarrow {}^3He_2 + \gamma\ \text{ray}$$

$${}^3He_2 + {}^3He_2 \rightarrow {}^4He_2 + {}^1H_1 + {}^1H_1$$

Net result $4\ ({}^1H_1) \rightarrow {}^4He_2$

But the mass of $4(^1H_1)$ > mass of $^4He_2$. Some mass is lost in the fusion process. This lost mass is converted to energy by the formula $E = mc^2$. For every 1 gram of Hydrogen fused to Helium 0.007 gram is converted to energy.

- Structure of the Sun's Interior
- Energy is produced only in the core where $T_c = 1.5x10^7$°k and $P_c = 2.5x10^{11}$atmos.
- Energy transport
    - Radiation [up to 0.86R]
    - Convection [from 0.86R to surface]
- It takes energy produced in the core 10^6 years to reach the surface because of innumerable absorptions and emissions. High energy [high frequency] photons are degraded to low energy [long wavelength] photons.

- Solar Neutrino Puzzle
- The p-p chain predicts a certain number of neutrinos. The sun is emitting only 1/3 as much. There are two explanations :
    1) Weakly interacting massive particles (WIMP's) carry energy from the core, thereby cooling it and lowering the thermonuclear rate.
    2) Neutrinos transmute to a different species that are not detected by the experiments.

- Solar Atmosphere

photosphere	4000 to 6500 °k
chromosphere	6000 to 10,000 °k
corona	0^6 °k

- Photosphere
    - granules - convection cells - 1000 to 2000 km in diameter
    - wave motion on the surface, wavelength ~5000 km, period ~ 5 min
    - limb darkening - the edge of the sun appears darker than the center.

    You see deeper (hotter) layers when you are looking at the center of the sun's disk.

- Chromosphere
    - hot, low density gas - shows emission lines
    - best studied with spectroheliographs made in Hα = 6563Å
    - shows cell structure - supergranulation - diameter of cells ~30,000 km
    - spicules - hot, columns of gas 10,000 km long

- Corona
    - hot ($2x10^6$°k) and very low density (10^9 particles/cm^3) gas
    - x-ray pictures reveal that the corona is patchy and vary with time
    - regions of very low density called coronal holes

- Sun Spots

Regions that appear dark because they are cooler [T ~ 4000 to 4500 °k]. Magnetic field in a sunspot x1000 times stronger than the rest of the sun's magnetic field. Magnetic field affects the plasma which is a gas with many charged particles. It inhibits convection.

- Sun Spot Cycle
    - Sunspots occur in pairs or groups. In a pair there is a leading and trailing member (in the sense of rotation). The leading and trailing members have opposite polarity.

- At the beginning of a cycle sunspots form at high latitudes (~30°). In the northern hemisphere if the leading sunspot has a north polarity then in the southern hemisphere the leading spot will have a south polarity.
- A sunspot group will last a couple of solar rotation and then disappear.
- When fresh spots appear they are formed at slightly lower latitudes.
- They finally disappear when they reach close to the equator. It takes about 11 years for this sub-cycle.
- When new spots form at high latitudes the leading spots have reversed polarities.
- The sub-cycle takes another 11 years to complete.
- If the magnetic polarity is taken into account the sunspot cycle is 22 years.

- Disturbed Sun
- prominences : jets of hot gas ejected from the surface of the sun, usually linked with sunspots
- flares : more energetic solar activity; outburst of charged particles, visible, ultraviolet, and x-ray emissions
- solar wind : a stream of charged particles (electrons + protons), temp = 200,00°k, and speeds ~600km/s at the earth's distance
    - wind appears to stream out from the coronal holes
    - density of charged particles increases during a solar flare
    - solar wind interacts with the earth's magnetic field - produces aurora and affects radio transmission