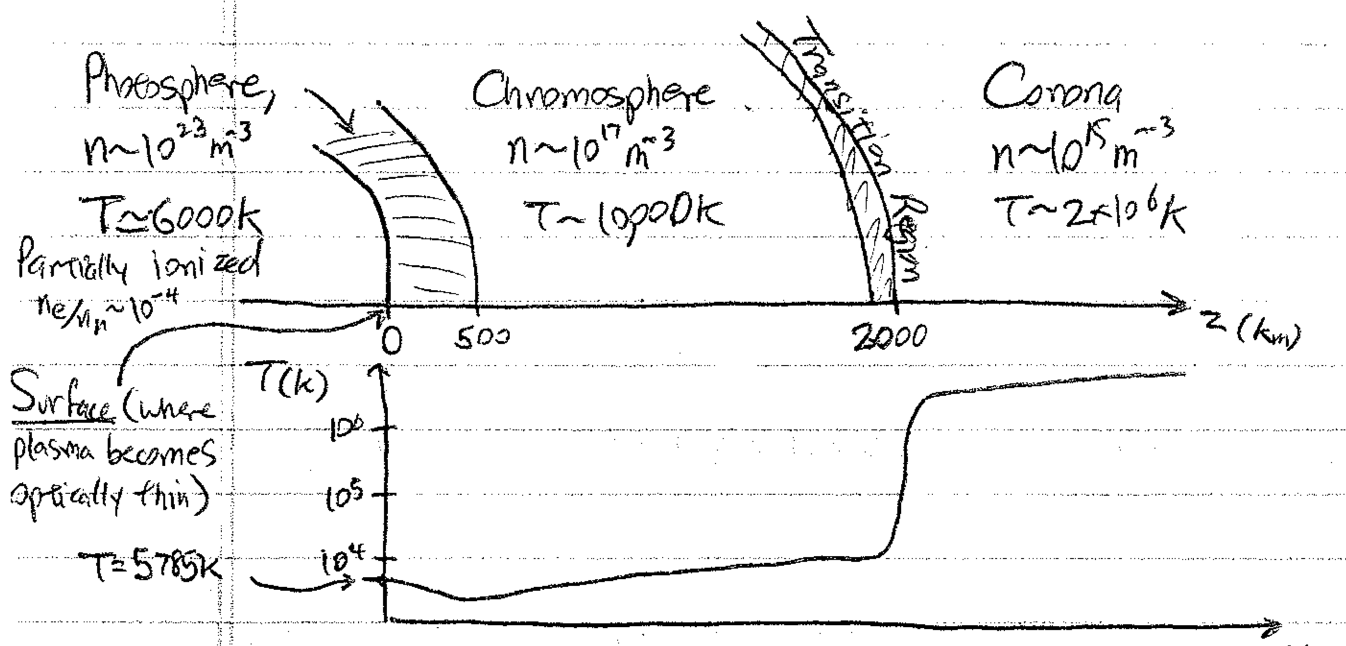
# Lecture #6: The Sun

## I. The Basic Properties of the Sun

### A. Basic Characteristics:

1. Astronomy: Spectral Type: G2V
   Magnitude 4.8
2. Mass: $M_\odot = 1.99 \times 10^{30}$ kg
3. Radius: $R_\odot = 6.96 \times 10^8$ m
4. Equatorial Period: $T_{eq} = 26$ days
5. Surface Temperature: $T = 5785K$
6. Inclination to earth's orbit: $7°$
7. Composition: 90 % H
   10 % He
   0.1 % C, N, O, others
8. At R=1AU, radiated power = 1 kW/m²

### B. The Atmosphere of the Sun




MHD

1. Energy Density $E = \frac{1}{2}\rho U^2 + \frac{P}{\gamma - 1} + \frac{B^2}{2\mu}$ where $P = nT$, $\gamma = \frac{5}{3}$
(Lect #6)

Lecture #16 (Continued) Howes (2)

I. B.1. (Continued)

a. Energy density due to thermal pressure, $E = \frac{P}{\gamma-1} = \frac{nT}{\gamma-1}$

| Region | Temperature (K) | Density ($m^{-3}$) | Thermal Energy Density ($J/m^3$) |
|---|---|---|---|
| photosphere | $6.0 \times 10^3$ | $10^{23}$ | $1.2 \times 10^4$ |
| chromosphere | $10^4$ | $10^{17}$ | $2 \times 10^{-2}$ |
| corona | $2 \times 10^6$ | $10^{15}$ | $4 \times 10^{-2}$ |

b. Even though corona is at a very high temperature, the density is very low, so the energy density is relatively small.

c. At $R \simeq 1$ AU, $n \simeq 10^7 m^{-3}$ and $T \simeq 10^5 K$

C. Energy Source: The p-p cycle

1. The dominant nuclear reaction in the sun's core is the proton-proton (p-p) cycle:

$$p + p \longrightarrow D + e^+ + \nu_e \quad (1.44 \text{ MeV})$$
$$D + p \longrightarrow {}^3_2He + \gamma \quad (5.49 \text{ MeV})$$
$${}^3_2He + {}^3_2He \longrightarrow {}^4_2He + 2p \quad (12.86 \text{ MeV})$$

2. The conditions in the core: $n \simeq 10^{32} m^{-3}$
$T = 1.5 \times 10^7 K$

a. At this relatively "low" temperature, but high density, the p-p cycle dominates. Nuclear Fusion in the laboratory is based on D-T reactions:

$$D + T \longrightarrow {}^4_2He + {}^1_0n \quad (17.6 \text{ MeV})$$

but requires temperatures of $T \sim 10 keV \rightarrow T = 10^8 K$

D. Radiation Spectrum.

1. Stefan-Boltzman Law:

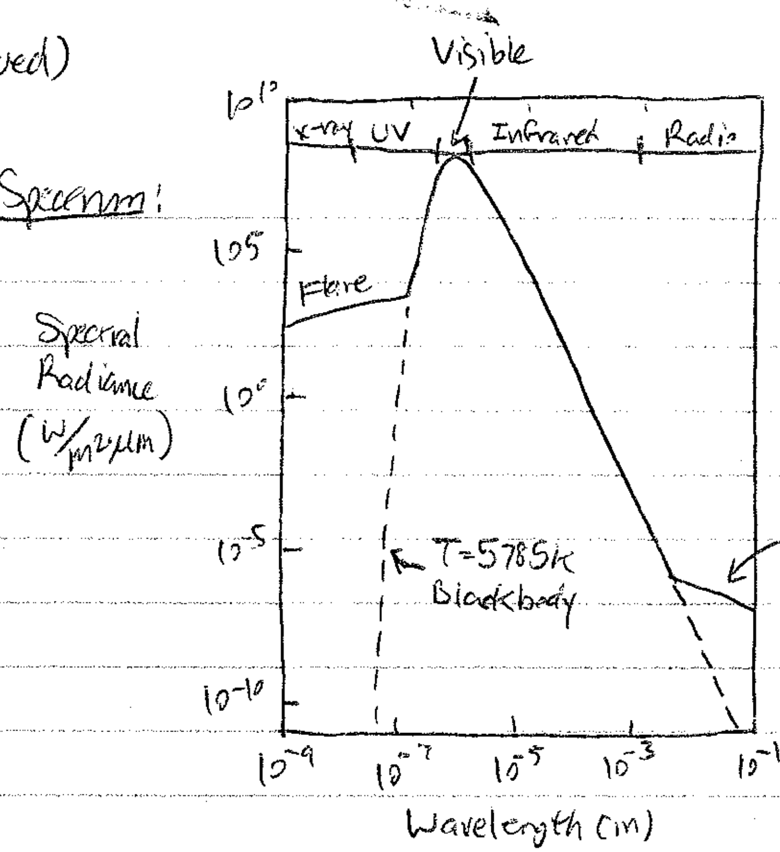
a. Radiated power per unit area,

$$R = \sigma T^4 \quad \sigma = 5.67 \times 10^{-8} \frac{W}{m^2 K^4}, \quad T_{eff} = 5.785 \times 10^3 K$$

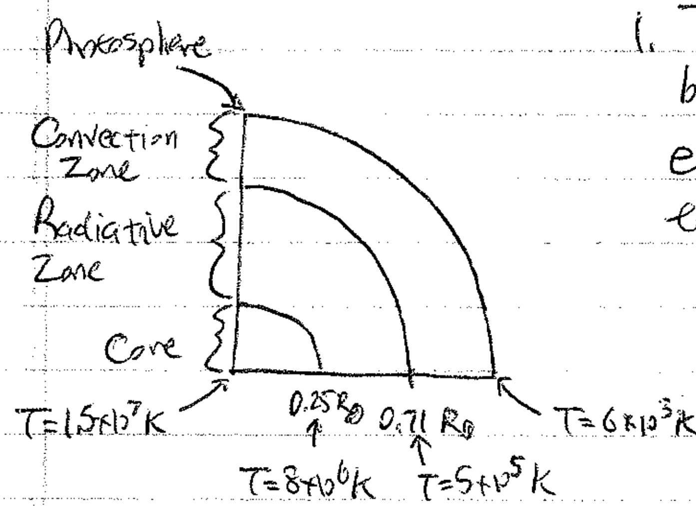
Lecture #16 (Continued)

I. D. (Continued)

2. Blackbody Spectrum:




E. Interior Structure of the Sun:




1. The structure of the sun is determined by the dominant mechanisms for energy (heat) transport from the core to the surface.

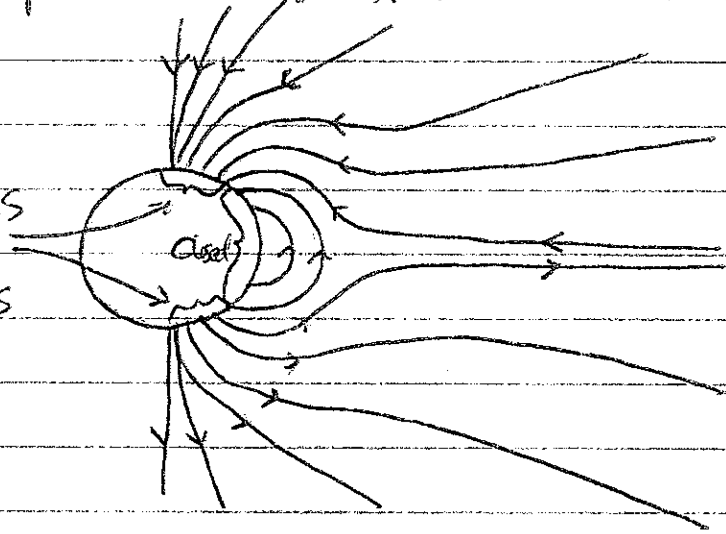
2. Radiative Zone: Energy transfer in approximately the inner 3/4 of the sun ($< 0.71 R_\odot$) is dominated by radiative in the very optically thick plasma.
   a. Radiation is scattered many, many times.
      i) Direct flight to surface: 2s
      ii) Diffusive path: $10^7$ years
3. Convection Zone: Due to the rapid decrease of temperature with radius, at $0.71 R_\odot$ the plasma becomes convectively unstable ⇒ magnetoconvection.

I. E. (Continued)

4. Photosphere: The surface of the sun is the photosphere, where the sun's plasma becomes optically thin and emitted radiation can propagate directly out ⇒ the "surface" observed at Earth.
   a. The photosphere is also the top of the "boiling", bubbling shell of the convection zone.
   b. Granular and supergranular patterns of convection are observed at the photosphere.

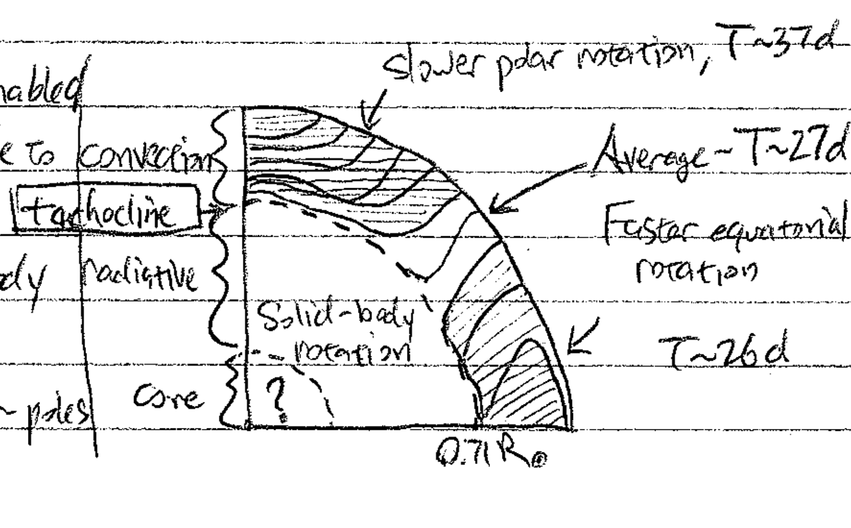
## F. Solar Magnetic Field:

1. The sun has a dipole magnetic field generated internally, but its structure above the surface is strongly modified by the spherical outflow of the solar wind.




## G. Differential Rotation

1. Helioseismology has enabled the internal rotation profile to be determined.
2. Radiative Zone: Solid-body
3. Convection Zone: Differential rotation, faster equator, slower poles

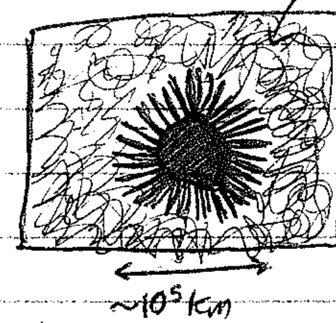


Lecture #16 (Continued) Howes (5)

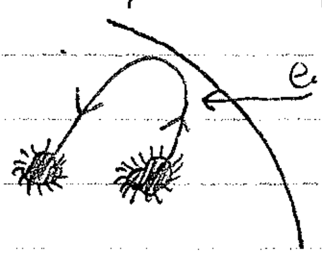
I. G. (Continued)

4. The layer of strong radial shear at $\sim 0.71 R_\odot$ is called the tachocline, and is coincident with the base of the solar convection zone.

## H. Solar Activity:




1. Sunspots: Dark spots on the sun
   a. Central umbra surrounded by filamentary penumbra
   b. Cold plasma $T \sim 4000$ K, strong fields $B \sim 0.3T = 30$ kG
   c. Pressure balance ($p + \frac{B^2}{2\mu_0} =$ const) implies they have low density.
   → low density, cooler temperature explains their dark appearance.
   d. Sunspots have a single sign of magnetic polarity, but appear accompanied by another sunspot of opposite polarity



   e. Sunspots can be modeled as points where a magnetic flux rope passes through solar surface.

2. Active Regions: a. Areas with groups of sunspots are known as active regions because they are locations of vigorous solar activity.

3. Solar Flares: a. Explosive release of energy in the chromosphere that releases a large amount of high energy radiation (EUV & x-rays) as well as energetic particles.
   b. Total energy released is typically $10^{21}$ to $10^{25}$ J.

4. Solar Prominences: a. Sheets of cool plasma that erupts and extend into the much hotter, less dense solar corona.

I. H.4. (Continued)

b. Prominences are likely to be supported against gravity by magnetic field structures (twisted flux ropes).

5. Coronal Mass Ejections (CME): a. Large amounts of mass ($10^{12}$ to $10^{13}$ kg) are sporadically ejected from the sun into the interplanetary medium

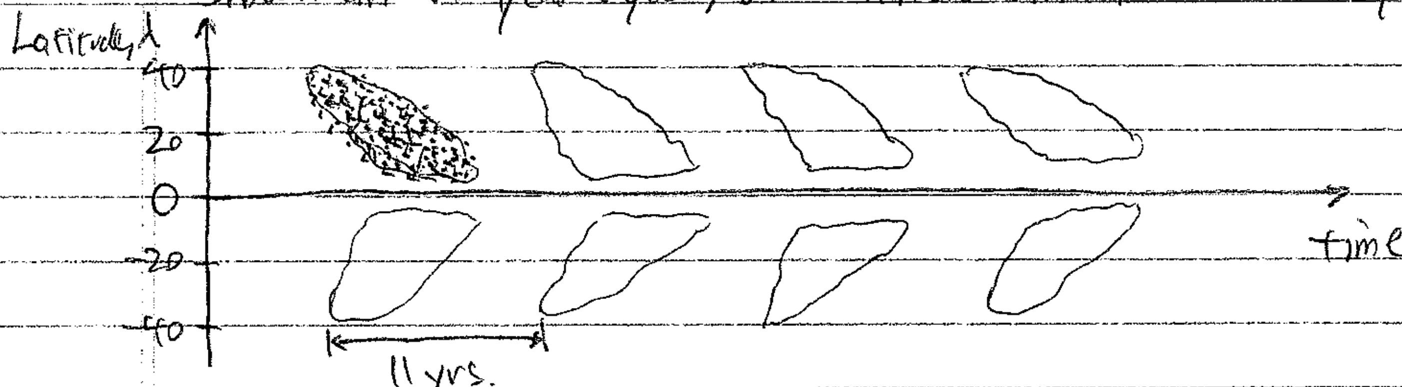
b. Ejection speeds range from 50 km/s to 2000 km/s

c. Originate from closed field regions

d. CME-driven shocks are very effective at producing energetic particles

I. The Solar Cycle

1. Since the 1600's, observations of the sunspot number have shown an 11-year cycle, with latitude variation within the cycle




2. In fact, the solar magnetic field reverses polarity each 11 yrs, resulting in a 22-year magnetic solar cycle

3. This cyclical behavior of the Sun's magnetic field is evidence of a solar dynamo that acts to generate the Sun's magnetic field.