Reading

Finish Sec. 11.1 C&O

Skip Ch. 12

Read Ch. 13 Stellar Evolution (all)

Croswell: Chapter 11
The solar model describes (as a function of radius) the Sun’s:

\[ T(r) = \text{Temperature} \]
\[ M(r) = \text{Mass} \]
\[ \varepsilon(r) = \text{Energy Generation} \]
\[ \rho(r) = \text{Density} \]
\[ X(r), Y(r), Z(r) = \text{Composition} \]

Conservation laws give 4 coupled differential equations. (If some simplifying assumptions are made, these transform into the Lane-Endem Equation.)

But usually numerical simulation (computers) is required. A complete solar model will also incorporate time.
While on the Main Sequence, the Sun’s T & L change very slowly.

{Off-topics: Faint Early Sun Problem, Snowball Earth}
Solar Model: Different physical conditions cause different phenomena: Three regions: Core, Radiative Zone, Convective Zone,
Results of one Solar Model

...but how did they come up with this?
Testing Solar Models

To test a model, we need observations. Eg., boundary conditions. A few are easy. Just set \( r = R_{\text{SUN}} \) Then:

\[
T(R_{\text{SUN}}) = T_{\text{eff}}
\]
\[
L(R_{\text{SUN}}) = L_{\text{Sun}}
\]
\[
M(R_{\text{SUN}}) = M_{\text{Sun}}
\]

But another set of boundary conditions: \( r = 0 \) The core.
Core conditions constrain models...but how do we measure them?
Proton Proton Chain

The net reaction is:

$$4 \, ^1_1\text{H} \rightarrow ^4_2\text{He} + 2e^+ + 2\nu_e + 2\gamma$$

The He’s remain.
The e⁺’s annihilate
The x-ray photons bounce off atoms and degrade to longer wavelengths
(It takes them about 300,000 years to exit the Sun)

The neutrinos provide our only way to probe the core of the Sun...if we could only detect them.
The PP Chain has several branches

\begin{align*}
\text{PP I:} & \quad ^{1}\text{H} + ^{1}\text{H} \rightarrow ^{2}\text{H} + e^+ + \nu_e \\
& \quad ^{2}\text{H} + ^{1}\text{H} \rightarrow ^{3}\text{He} + \gamma \\
& \quad ^{2}\text{He} + ^{3}\text{He} \rightarrow ^{4}\text{He} + 2^{1}\text{H} \\
& \quad ^{3}\text{He} + ^{4}\text{He} \rightarrow ^{7}\text{Be} + \gamma \\
\text{PP II:} & \quad ^{7}\text{Be} + e^- \rightarrow ^{7}\text{Li} + \nu_e \\
& \quad ^{7}\text{Li} + ^{1}\text{H} \rightarrow 2^{4}\text{He} \\
\text{PP III:} & \quad ^{8}\text{B} \rightarrow ^{8}\text{Be} + e^+ + \nu_e \\
& \quad ^{8}\text{Be} \rightarrow 2^{4}\text{He} \\
\end{align*}

E_{\nu} \sim 15 \text{ MeV}
Neutrinos react very rarely. Their signal is swamped by other reactions, eg. cosmic rays....unless these contaminants are blocked. So place your detector underground.... in an abandoned mine.

A neutrino from this PP reaction:

$$^{8}_{5}\text{B} \rightarrow ^{8}_{4}\text{Be} + e^+ + \nu_e.$$  

Might collide w/ a 
$^{37}_{17}\text{Cl} + \nu_e \rightleftharpoons ^{37}_{18}\text{Ar} + e^-.$

You’ll need a lot of Cl! 100,000 gallons!
Results from Homestake Mine in normalized “Solar Neutrino Units”
MSW Effect

The Homestake Experiment disagreed with the best solar models. So...
- The experiment could have systematic errors
- There could be something wrong with the solar model
- There could be something wrong with Physics!!

The Standard Model of Particle Physics has two types of Fermion (spin 1/2 particle):

**Quarks**, which make up the proton & neutron
**Leptons**: including electrons & neutrinos.
Neutrinos react very rarely. Their signal is swamped by other reactions, e.g., cosmic rays. Unless these contaminants are shielded out. So place your detector underground.

A neutrino from this PP reaction:

\[ p + n \rightarrow n + p \]

Might collide with a Chlorine atom:

You'll need a lot of Cl!}

### FUNDAMENTAL PARTICLES AND INTERACTIONS

#### Fermions

- **Leptons**: spin = 1/2, 3/2, 5/2, ...
  - \( e^- \), \( \mu^- \), \( \tau^- \)
  - \( e^+ \), \( \mu^+ \), \( \tau^+ \)
  - Neutrinos

- **Quarks**: spin = 1/2
  - \( u \), \( d \), \( c \), \( s \), \( t \), \( b \)

**Mass**:
- \( u \), \( d \), \( e^- \), \( \mu^- \), \( \tau^- \): \(< 10^{-8} \) GeV/c^2
- \( \mu \), \( \tau \): \( 0.00511 \) GeV/c^2

**Electric Charge**:
- \( u \), \( d \): 0
- \( e^- \), \( \mu^- \), \( \tau^- \): -1

**Bosons**

- **Photon** (\( \gamma \))
- **W^-**, **W^+**, **Z^0**

**Color Charge**

Each quark carries one of three types of strong charge, also called color charge. These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons, but as electrically charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and W and Z bosons have no strong interactions and hence no color charge.

**Mesons and Baryons**

One cannot isolate quarks and gluons, they are confined in color-neutral particles called hadrons. This confinement results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see the figure). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: mesons and baryons.

#### Properties of the Interactions

**Gravitational**

- Acts on: All
- Mass, Energy

**Weak (Electroweak)**

- Acts on: Particles experiencing: Quarks, Leptons
- Electromagnetically charged

**Fundamental**

- Acts on: Quarks, Gluons
- Electrostatically charged

**Strong**

- Acts on: Hadrons
- Color Charge

**Residual**

- Acts on: Not applicable to quarks

- Hadrons

#### Masses

- **Mesons (q\(\bar{q}\))**
  - \( \pi^- \)
  - \( K^- \)
  - \( B^- \)
  - \( \eta_c \)

**Matter and Antimatter**

For every particle type, there is a corresponding antiparticle type, denoted by a bar over the particle symbol (e.g., \( \bar{p} \) is the antiproton). Particle and antiparticle have identical mass and spin but opposite charge. Some electrically neutral bosons (e.g., \( Z^0 \), \( W^+ \), \( W^- \), \( \gamma \), and quarks, but not \( \pi^0 \) are their own antiparticles.

#### Figures

These diagrams are an artist's conception of physical processes. They are not exact and have no meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.
FUNDAMENTAL PARTICLES

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the

FERMIONS

<table>
<thead>
<tr>
<th>Flavor</th>
<th>Mass GeV/c^2</th>
<th>Electric charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_e$</td>
<td>$&lt;1 \times 10^{-8}$</td>
<td>0</td>
</tr>
<tr>
<td>$e$</td>
<td>0.000511</td>
<td>-1</td>
</tr>
<tr>
<td>$\mu_e$</td>
<td>$&lt;0.0002$</td>
<td>0</td>
</tr>
<tr>
<td>$\mu$</td>
<td>0.106</td>
<td>-1</td>
</tr>
<tr>
<td>$\nu_\tau$</td>
<td>$&lt;0.02$</td>
<td>0</td>
</tr>
<tr>
<td>$\tau$</td>
<td>1.7771</td>
<td>-1</td>
</tr>
</tbody>
</table>

**Leptons**

**Quarks**

<table>
<thead>
<tr>
<th>Flavor</th>
<th>Approx. Mass GeV/c^2</th>
<th>Electric charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u$</td>
<td>0.003</td>
<td>2/3</td>
</tr>
<tr>
<td>$d$</td>
<td>0.006</td>
<td>-1/3</td>
</tr>
<tr>
<td>$c$</td>
<td>1.3</td>
<td>2/3</td>
</tr>
<tr>
<td>$s$</td>
<td>0.1</td>
<td>-1/3</td>
</tr>
<tr>
<td>$t$</td>
<td>175</td>
<td>2/3</td>
</tr>
<tr>
<td>$b$</td>
<td>4.3</td>
<td>-1/3</td>
</tr>
</tbody>
</table>

**Spin** is the intrinsic angular momentum of particles. Spin is given in units of $\hbar$, which is the quantum unit of angular momentum, where $\hbar = h/(2\pi) = 6.58 \times 10^{-34}$ GeV s $= 1.05 \times 10^{-34}$ J s.

**Electric charges** are given in units of the proton's charge. In SI units the electric charge of the proton is $1.60 \times 10^{-19}$ coulombs.

The **energy** unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c^2 (remember $E = mc^2$, where 1 GeV = $10^9$ eV = $1.60 \times 10^{-19}$ joule. The mass of the proton is 0.938 GeV/c^2 = $1.67 \times 10^{-27}$ kg.

Structure within the Atom

Quark

Size: $< 10^{-19}$ m

Nucleus

Size: $10^{-14}$ m

Atom

Size: $10^{-10}$ m

If the protons and neutrons in this picture were 10 cm, then the quarks and electrons would be less than 0.1 mm. The size and the entire atom would be about 10 km across.
Neutrino Oscillations

Under the Standard model, the 6 types of quark (up/down, strange/charmed & top/bottom) could “oscillate” from one type to another.

Mikheyev Smirnov & Wolfenstein (MSW) proposed that neutrinos could do this as well.

The Sun produces only electron neutrinos. The detector is only sensitive to electron neutrinos.

If some of the $\nu_e$’s oscillated into $\nu_\mu$’s $\nu_\tau$’s then they wouldn’t be detected.

“Neutrino problem solved!”

Final confirmation occurred after $\nu_\mu$’s $\nu_\tau$’s were detected directly.