Class Reference: K&R Chapter 3.1 and links given in these slides
Solar Physics

• Solar Energy Generation
  – p - p chain, CNO cycle

• Observables
  • Luminocity, dynamics, spectrum, mass, Neutrinos, etc

• Composition

• Standard Solar Model
Energy Production

\[
\begin{align*}
pp & \rightarrow ^2H + e^+ + \nu_e \\
^2H + p & \rightarrow ^3He + \gamma \\
^3He + ^3He & \rightarrow ^4He + 2p \quad 85\% \\
^3He + ^4He & \rightarrow ^7Be + \gamma \quad 15\% \\
e^- + ^7Be & \rightarrow ^7Li + \nu_e \\
^7Li + p & \rightarrow ^{14}He \\
p + ^7Be & \rightarrow ^8B + \gamma \quad 0.02\% \\
^8B & \rightarrow ^8Be^* + e^+ + \nu_e \\
^8Be^* & \rightarrow ^{14}He
\end{align*}
\]
**HOMESTAKE**

- **Site**: Homestake golden mine, in South Dakota, USA.
- **Detector**: built in 1967 at Brookhaven laboratory, it contains about 615 tons of tetrachloroethylene. Under neutrino interaction, the Chlorine 37 becomes Argon 37, which is radioactive with a half-life of 35 days. As in Gallex experiment, Argon 37 is isolated and its radioactivity is measured. The number of Argon 37 atoms detected gives the number of neutrino
  - interactions in the chlorine vat, thus
  - the solar neutrino flux.
- **Results**: data taken from 1969 until 1993 (24 years!!) gives a mean of
  - 2.5+-0.2 SNU while theory predicts
  - 8 SNU (1 SNU = 1 neutrino interaction per second for 10E+36 target atoms).
This is a neutrino deficit of 69%. Depending on the solar neutrinos experiments, the detected solar neutrinos are not in the same energy domain. Nothing forbids Homestake experiment and Gallex experiment to have compatible results.
More history and explanation about neutrinos at http://lappweb.in2p3.fr/neutrinos/

• Why do we believe these detectors work – when they see only one detection for 10E+36 target atoms per second (1 SNU)?
• Because of Supernova 1987a (see https://en.wikipedia.org/wiki/SN_1987A)

<table>
<thead>
<tr>
<th>Neutrino Source</th>
<th>Homestake</th>
<th>Gallium</th>
</tr>
</thead>
<tbody>
<tr>
<td>pp</td>
<td>0.0</td>
<td>70.8</td>
</tr>
<tr>
<td>pep</td>
<td>0.2</td>
<td>3.1</td>
</tr>
<tr>
<td>$^7$Be</td>
<td>1.2</td>
<td>35.8</td>
</tr>
<tr>
<td>$^8$B</td>
<td>6.2</td>
<td>13.8</td>
</tr>
<tr>
<td>$^{13}$N</td>
<td>0.1</td>
<td>3.0</td>
</tr>
<tr>
<td>$^{15}$O</td>
<td>0.3</td>
<td>1.9</td>
</tr>
<tr>
<td>Total</td>
<td>8.0 ± 3.0</td>
<td>131.5$^{+21}_{-17}$</td>
</tr>
</tbody>
</table>

Table 2: Predicted rates in SNU ($10^{-36}$ atom$^{-1}$ s$^{-1}$) from the various flux components for the chlorine and gallium experiments, from [26]. The uncertainties are the total theoretical range, $\sim 3\sigma$. 

More history and explanation about neutrinos at http://lappweb.in2p3.fr/neutrinos/
Sudbury Neutrino Observatory (SNO)

\[ ne + d \rightarrow p + p + e^- \]

e- has \( v > c \) (medium) thus emits Cherenkov radiation
CNO Cycle for Burning Hydrogen
(less important for Sun)
Cosmic Abundance

In the universe as a whole, hydrogen is by far the commonest element followed by helium and more distantly by heavier elements such as oxygen and carbon. Locally, the proportion of heavy elements varies from one star system to another and is an influential factor in the formation of planets.

<table>
<thead>
<tr>
<th>Element</th>
<th>Number of Atoms per 10,000,000 of Hydrogen</th>
</tr>
</thead>
<tbody>
<tr>
<td>hydrogen</td>
<td>10,000,000</td>
</tr>
<tr>
<td>helium</td>
<td>1,400,000</td>
</tr>
<tr>
<td>oxygen</td>
<td>6,800</td>
</tr>
<tr>
<td>carbon</td>
<td>3,000</td>
</tr>
<tr>
<td>neon</td>
<td>2,800</td>
</tr>
<tr>
<td>nitrogen</td>
<td>910</td>
</tr>
<tr>
<td>magnesium</td>
<td>290</td>
</tr>
<tr>
<td>silicon</td>
<td>250</td>
</tr>
<tr>
<td>sulfur</td>
<td>95</td>
</tr>
<tr>
<td>iron</td>
<td>80</td>
</tr>
<tr>
<td>argon</td>
<td>42</td>
</tr>
<tr>
<td>aluminum</td>
<td>19</td>
</tr>
<tr>
<td>sodium</td>
<td>17</td>
</tr>
<tr>
<td>calcium</td>
<td>17</td>
</tr>
<tr>
<td>all other elements</td>
<td>50</td>
</tr>
</tbody>
</table>

Number of atoms per 10,000,000 of hydrogen
Standard Solar Model

• 4 basic assumptions:
  ▪ Hydrostatic Equilibrium
  ▪ Energy transport: radiation, conduction, convection
  ▪ Nuclear reactions the only source of energy
  ▪ Composition at start was homogeneous and primordial
4 equations, 4 unknowns

\[ \frac{dP}{dr} = -\frac{Gm\rho}{r^2} \quad \quad \quad P = \frac{\rho T \mathcal{R}}{\mu} \]

\[ \frac{dT}{dr} = -\frac{3\kappa \rho L}{16\pi acr^2 T^3} \]

\[ \frac{dL}{dr} = 4\pi r^2 \rho \varepsilon \]

or

\[ \frac{dT}{dr} = \left(1 - \frac{1}{\gamma}\right) \left(\frac{T}{P}\right) \frac{dP}{dr} \]

\[ \varepsilon = \varepsilon_\gamma - \varepsilon_\nu \]

nuclear energy generation rate per unit mass minus the luminosity of neutrinos

— Most stellar energy production occurs in the core.
Density as a function of Radius

Density (g/cm³)

Radius (r/R)
Convection becomes important when the star cannot transport all of its energy via radiation.
Fig. 1. Structure of two model convection zones with depth. Figure adapted from Gough and Weiss (1976), who computed models based on formulation of Böhm-Vitense (1958), solid lines, and on that of Öpik (1950), dashed lines. Curves from these two formulations coincide except within $10^{-3}$ km of outer boundary of convection zone. Arrows labelled H, He I, He II denote 10–9% ionization zones for hydrogen and helium.