Reading

Start Chapter 11: Only Sec. 11.1 required
Focus on:

- nuclear reactions
- neutrinos.
- results of solar models

Croswell: Chapter 9 & 10
The Sun Now:

- On the Main Sequence
- Core is:
  - 70 % H
  - 30 % He

In 5 billion years, all the Hydrogen in the Sun’s core will be gone!!

Plan A: Fuse H into He

In the Core
The Sun in 5 billion years:

- Leaving the Main Sequence
  -- Core is:
  0 % H
  100 % He

Shell fusion deposits heat in the star, causing it to expand.... Becoming a Red Giant

Plan B: Fuse H into He

In a Shell around the core
The Sun as a main-sequence star
(diameter = $1.4 \times 10^6$ km $\approx \frac{1}{100}$ AU)

The Sun as a red giant
(diameter $\approx 1$ AU)

Sun Today

Sun 5 Billion Years From now

- The Sun will become so large it will swallow up Mercury and Venus!
Triple Alpha Process

When the Sun’s H is exhausted, fusion will stop. Lacking a source of heat, gravity will compress & heat the core.

Until...

\[
\begin{align*}
\frac{4}{2}\text{He} + \frac{4}{2}\text{He} & \rightleftharpoons \frac{8}{4}\text{Be} \\
\frac{8}{4}\text{Be} + \frac{4}{2}\text{He} & \rightarrow \frac{12}{6}\text{C} + \gamma.
\end{align*}
\]
Triple Alpha Process

(He nucleus = “Alpha Particle”)

1. $^4\text{He}$

2. $^4\text{He}$

3. $^8\text{Be}$ $^4\text{He}$

Three Helium nuclei fuse into Carbon
But this reaction shouldn’t happen! The $^8$Be is unstable and almost immediately decays back to He.

He + Be are unlikely to react into C because of a large energy difference. So....Carbon shouldn’t exist in the universe.... Unless.... There is an excited state of Carbon that matches the energy of:

$^8$Be + $^4$He

The “Hoyle State”

{Slightly off-topic: Anthropic Principle}
Massive Star Fusion

If Helium is depleted, fusion of heavier elements can produce energy...up to $^{56}\text{Fe}$

$^{16}_{8}\text{O} + ^{16}_{8}\text{O} \rightarrow \begin{cases} ^{24}_{12}\text{Mg} + 2^4\text{He} \text{ ***} \\ ^{28}_{14}\text{Si} + ^4\text{He} \\ ^{31}_{15}\text{P} + p^+ \\ ^{31}_{16}\text{S} + n \\ ^{32}_{16}\text{S} + \gamma \end{cases}$

$^{12}_{6}\text{C} + ^{12}_{6}\text{C} \rightarrow \begin{cases} ^{16}_{8}\text{O} + 2^4\text{He} \text{ ***} \\ ^{20}_{10}\text{Ne} + ^4\text{He} \\ ^{23}_{11}\text{Na} + p^+ \\ ^{23}_{12}\text{Mg} + n \text{ ***} \\ ^{24}_{12}\text{Mg} + \gamma \end{cases}$

(Note: the Sun will not get hot enough to do these reactions.)

*** = endothermic
Making Heavy Elements

Starting with H, He, C, O, N fusion can create many other elements:
Mg, Na, Al, Si, etc.

These elements make up rocks and the Earth.
They were all formed in stars!
Casual Quiz

\[ ^{13}\text{C} + ^{1}\text{H} \rightarrow \quad \quad + \gamma \]

\[ ^{15}\text{O} \rightarrow \quad + \quad \text{e}^+ \quad + \quad \quad \]
Stellar Recycling

The atoms in us were created in stars, which later died. They ejected their outer layers into the ISM. These atoms were then incorporated into Earth. Someday they may be returned to the ISM.
Chart of Nuclides

<table>
<thead>
<tr>
<th>Z</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>H</td>
<td>1.0079</td>
<td>HYDROGEN</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>H</td>
<td>99.985</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>He</td>
<td>4.002602</td>
<td>HELIUM</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Li</td>
<td>6.941</td>
<td>LITHIUM</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Be</td>
<td>9.012182</td>
<td>BERYLLIUM</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>B</td>
<td>10.811</td>
<td>BORON</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>C</td>
<td>12.011</td>
<td>CARBON</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>B7</td>
<td>4E-22 s</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>B8</td>
<td>770 ms</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>B9</td>
<td>8E-19 s</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>C8</td>
<td>2.0E-21s</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>C9</td>
<td>177 ms</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>C10</td>
<td>19.3 s</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>C11</td>
<td>20.3 m</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>C12</td>
<td>98.90</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>C13</td>
<td>1.10</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>C14</td>
<td>5730 a</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>C15</td>
<td>2.45 s</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>C16</td>
<td>0.75 s</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>B10</td>
<td>19.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>B11</td>
<td>80.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>B12</td>
<td>20.20 ms</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>B13</td>
<td>17.4 ms</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>B14</td>
<td>14 ms</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>B15</td>
<td>9 ms</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>Be6</td>
<td>5.0E-21 s</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>26</td>
<td>Be7</td>
<td>55.28 d</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>27</td>
<td>Be8</td>
<td>8E-17 s</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>28</td>
<td>Be9</td>
<td>100</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>29</td>
<td>Be10</td>
<td>1.6E6 a</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>Be11</td>
<td>13.8 s</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>31</td>
<td>Be12</td>
<td>24 ms</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>32</td>
<td>Be14</td>
<td>4 ms</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>33</td>
<td>Li5</td>
<td>3E-22 s</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>34</td>
<td>Li6</td>
<td>7.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>35</td>
<td>Li7</td>
<td>92.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>36</td>
<td>Li8</td>
<td>0.84 s</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>37</td>
<td>Li9</td>
<td>177 ms</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>38</td>
<td>Li11</td>
<td>8.7 ms</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>39</td>
<td>He3</td>
<td>0.000138</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>He4</td>
<td>9.999867</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>41</td>
<td>He5</td>
<td>7.6E-22 s</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>42</td>
<td>He6</td>
<td>80/ ms</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>43</td>
<td>He7</td>
<td>3E-21 s</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>44</td>
<td>He8</td>
<td>119 ms</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>45</td>
<td>He9</td>
<td>VERY SHORT</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Why more N than Z?
The Solar Interior (Sec. 11.1)

Sun’s Composition (in astro-speak):

\[
\begin{align*}
X &= 0.74 \\
Y &= 0.24 \\
Z &= 0.02
\end{align*}
\]

74% Hydrogen,  
24% Helium,  
2% Other (“metals”)

These are mass fractions, which are not the same as number of atoms.

Example: You have 5 atoms of Helium, 5 atoms of Hydrogen, what are \(X\&Y\)? (what % of the mass is H or He)?
Solar Models

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

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

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*. 