Hydrogen Burning in More Massive Stars

http://apod.nasa.gov/apod/astropix.html

For temperatures above 18 million K, the "CNO cycle" dominates energy production.

\[
\begin{align*}
{^{12}\text{C}} + p &\rightarrow {^{13}\text{N}} + \gamma + 1.94\text{ MeV} \\
{^{13}\text{N}} &\rightarrow {^{13}\text{C}} + e^+ + \nu_e + 1.20\text{ MeV} \\
{^{13}\text{C}} + p &\rightarrow {^{14}\text{N}} + \gamma + 7.55\text{ MeV} \\
{^{14}\text{N}} + p &\rightarrow {^{15}\text{O}} + \gamma + 7.29\text{ MeV} \\
{^{15}\text{O}} &\rightarrow {^{15}\text{N}} + e^+ + \nu_e + 1.74\text{ MeV} \\
{^{15}\text{N}} + p &\rightarrow {^{12}\text{C}} + {^4}\text{He} + 4.97\text{ MeV}
\end{align*}
\]

Putting it all together, subtracting off the 1.71 MeV carried away by the neutrinos and adding the 2.64 MeV from positron annihilation

\[
4p + {^{12}\text{C}} \rightarrow {^4}\text{He} + {^{12}\text{C}} + 25.02\text{ MeV} \\
(\text{\#atom} \sim 6 \times 10^{18}\text{ erg/s/m})
\]

The $^{12}\text{C}$ is a catalyst. It is not used up but makes the series of reactions possible. Note however, nucleosynthetic aspects.

CNO $\rightarrow {^{14}\text{N}}$

For temperatures above 18 million K, the "CNO cycle" dominates energy production.

CNO CYCLE (Shorthand)

\[
{^{12}\text{C}}(p,\gamma){^{13}\text{N}}(e^+\nu){^{13}\text{C}}(p,\gamma){^{14}\text{N}}(p,\gamma){^{15}\text{O}}(e^+\nu){^{15}\text{N}}(p,\alpha){^{12}\text{C}}
\]

nb. $\alpha \equiv {^4}\text{He}$
CNO CYCLE vs PP 1

\[ \epsilon_{\text{CNO}} \approx 3.4 \times 10^{-4} \rho X_{\text{CNO}} X_H (T/10^7)^{-20} \text{erg s}^{-1} \]

where \( X_{\text{CNO}} \) is the mass fraction of carbon, nitrogen, and oxygen combined. This is based on the slowest reaction, \(^{14}\text{N}(p,\gamma)^{15}\text{O})\).

\[
\frac{\epsilon_{\text{CNO}}}{\epsilon_{\text{pp}}} = \frac{3.4 \times 10^{-4}}{0.076} \left( \frac{X_{\text{CNO}}}{X_H} \right) (T/10^7)^{-20} \\
= (4.5 \times 10^{-3})(0.01/0.70)(T/10^7)^{-16} \\
= 6.4 \times 10^{-5}(T/10^7)^{-16}
\]

which is greater than unity for \( T \) greater than 18 million K.

This turns out to mean that the CNO cycle dominates in (Population I) stars of over 2 \( M_\odot \).

### More Massive Main Sequence Stars

<table>
<thead>
<tr>
<th></th>
<th>10 ( M_\odot )</th>
<th>25 ( M_\odot )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( X_H )</td>
<td>0.32</td>
<td>0.35</td>
</tr>
<tr>
<td>( L )</td>
<td>( 3.74 \times 10^{38} ) erg s (^{-1} )</td>
<td>( 4.8 \times 10^{38} ) erg s (^{-1} )</td>
</tr>
<tr>
<td>( T_{\text{eff}} )</td>
<td>24,800 (B)</td>
<td>36,400 (O)</td>
</tr>
<tr>
<td>Age</td>
<td>16 My</td>
<td>4.7 My</td>
</tr>
<tr>
<td>( T_{\text{center}} )</td>
<td>33.3 ( \times 10^6 ) K</td>
<td>38.2 ( \times 10^6 ) K</td>
</tr>
<tr>
<td>( \rho_{\text{center}} )</td>
<td>8.81 g cm (^{-3} )</td>
<td>3.67 g cm (^{-3} )</td>
</tr>
<tr>
<td>( \tau_{\text{MS}} )</td>
<td>23 My</td>
<td>7.4 My</td>
</tr>
<tr>
<td>( R )</td>
<td>( 2.73 \times 10^{11} ) cm</td>
<td>( 6.19 \times 10^{11} ) cm</td>
</tr>
<tr>
<td>( P_{\text{center}} )</td>
<td>( 3.13 \times 10^{16} ) dyne cm (^{-2} )</td>
<td>( 1.92 \times 10^{16} ) dyne cm (^{-2} )</td>
</tr>
<tr>
<td>% ( P_{\text{radiation}} )</td>
<td>10%</td>
<td>33%</td>
</tr>
</tbody>
</table>

Surfaces stable (radiative, not convective); inner roughly 1/3 of mass is convective.

Convective history 15 \( M_\odot \) and 25 \( M_\odot \) stars

The 15 solar mass star is bigger than the 25 solar mass star when it dies.
The Sun

Matter rises in the centers of the granules, cools then falls down. Typical granule size is 1300 km. Lifetimes are 8-15 minutes. Horizontal velocities are 1 – 2 km s⁻¹. The movie is 35 minutes in the life of the sun.

http://www3.kis.uni-freiburg.de/~pnb/granmovtext1.html

June 5, 1993

Andrea Malagoli
35 minutes  4680 ± 50 A filter

size of granules 250 - 2000 km

smallest size set by transmission through the earth’s atmosphere

Looking more towards edge of the sun to see 3D structure

http://www.boston.com/bigpicture/2008/10/the_sun.html
http://www.uwgb.edu/dutchs/planets/sun.htm

A moderately large sunspot. The Earth would just cover the darkest area. The darkest area is called the “umbra”. The surrounding radial darkness the “penumbra”.

The umbra is cooler by about 1000 K than the surrounding star (note granulation). The magnetic field in the sunspot is typically 1000 - 4000 Gauss. (The Earth’s magnetic field is about 1 Gauss; the sun, on the average < 100 Gauss).
Breaks “degeneracy” in energy of states with different "spins".

Strength of the field can be measured by the degree of splitting.

Zeeman Effect

outside sunspot

inside sunspot

1.1 hours

about 25,000 km across

11 year cycle
Variability in solar irradiance was undetectable prior to satellite observations starting in 1978.

The sun actually changes its luminosity ...

Sunspot activity as a function of latitude:
Spots start to happen at high and low latitude and then migrate towards the equator.

Radial magnetic field:
Complete cycle takes 22 years and the sun's magnetic field reverses every 11 years.
The exact cause of the solar cycle is not well understood, but it is known that the magnetic field of the sun (or at least its surface field) goes through reversals every ~11 years. The whole cycle takes 22 years.

In the “Babcock model”, the cycle is caused by the differential rotation of the sun. In three years the equatorial regions go round 5 additional revolutions compared with the polar ones. This winds up the field and creates stress that is released in part by surface activity (flares, sunspots, etc).
convection

convection

radiation

convection
The smallest loop is 3 times the size of the Earth

Energy stored in magnetic field

\[ E = \frac{B^2}{8\pi} \text{ erg cm}^{-3} \]

Can be released by "reconnection"

Coronal Mass Ejection

http://sprg.ssl.berkeley.edu/~tohban/nuggets/?page=article\&article_id=14
Chromosphere

- 2000 km
- \( H_z \)

Corona

Coronal Loop

Picture at 141 Angstroms

Temperature
About 10^9 K
Mass loss rate $\sim 10^{-13}$ solar masses/yr

**Temperature**
- Center: 15.7 million K
- Photosphere: 5800 K
- Sunspot (umbra): 4240 K
- Penumbra: 5680 K
- Chromosphere: 5000 – 20000 K
- Corona: 0.5 to 3 million K

**Density**
- Mean density entire sun: 1.41 g cm$^{-3}$
- Central density: 150 g cm$^{-3}$
- Photosphere: $10^{-9}$ g cm$^{-3}$
- Chromosphere: $10^{-12}$ g cm$^{-3}$
- Corona: $10^{-16}$ g cm$^{-3}$
- Air (earth): $10^{-3}$ g cm$^{-3}$

**Effects on earth of solar cycle**
- Radio communications and satellite health
- Ozone production and hence uv flux at earth
- Cosmic ray flux
- Aurorae

The current magnetic field strength at the Earth's surface of 0.6 Gauss. But long term observations show that it is DECREASING at a rate of about 0.07 percent PER YEAR. This means that in 1500 years from now, it will only be about 35 percent as strong as it is today, and in 4000 years it will have a strength of practically zero.

The last reversal was 800,000 yrs ago, but the average time between reversals is 300,000 yrs.

Names are the rock strata where the field is measured.

http://www.astronomycafe.net/qadir/q816.html
Magnetic north is currently in northern Canada moving at 10 to 50 km/yr.

In a few decades it will reach Siberia

Solar flares vs solar prominences (the latter are bigger)

http://science.howstuffworks.com/sun5.htm

The Solar Neutrino “Problem”

In the sun

• pp1 85%
• pp2 15%
• pp3 0.02%

T_{central} = 15.7 Million K
Hydrogen Burning on the Main Sequence

In all cases \( 4p \rightarrow ^4\text{He} + 2 \nu_e + 2 e^+ \)

**pp1**

\[
p(p, e^+ \nu_e)^2 \text{H}(p, \gamma)^3\text{He}(3\text{He}, 2p)^4\text{He}
\]

\[
p(p, e^+ \nu_e)^2 \text{H}(p, \gamma)^3\text{He}
\]

**pp2**

\[
p(p, e^+ \nu_e)^2 \text{H}(p, \gamma)^3\text{He}(\alpha, \gamma)^7\text{Be}(e^- \nu_e)^7\text{Li}(p, \alpha)^4\text{He}
\]

**pp3**

\[
p(p, e^+ \nu_e)^2 \text{H}(p, \gamma)^3\text{He}(\alpha, \gamma)^7\text{Be}(p, \gamma)^8\text{B}(e^+ \nu_e)^8\text{Be}^*
\]

\[
^8\text{Be}^* \rightarrow ^4\text{He} + ^4\text{He}
\]

### Neutrino Energies

<table>
<thead>
<tr>
<th>Species</th>
<th>Average energy</th>
<th>Maximum energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>( p+p )</td>
<td>0.267 MeV</td>
<td>0.420 MeV</td>
</tr>
<tr>
<td>( ^7\text{Be} )</td>
<td>0.383 MeV</td>
<td>0.383 MeV 10%</td>
</tr>
<tr>
<td>( ^8\text{B} )</td>
<td>6.735 MeV</td>
<td>15 MeV</td>
</tr>
</tbody>
</table>

*In the case of \( ^8\text{B} \) and \( p+p \), the energy is shared with a positron hence there is a spread. For \( ^7\text{Be} \) the electron capture goes to a particular state in \( ^7\text{Li} \) and the neutrino has only one energy.*

Since 1965, experiements have operated to search for and study the neutrinos produced by the sun - in order to:

- Test solar models
- Determine the central temperature of the sun
- Learn new particle physics
**DETECTORS**

The chlorine experiment – Ray Davis – 1965 - ~1999

\[ ^{37}\text{Cl} + \nu_e \rightarrow ^{37}\text{Ar} + e^- - 0.814 \text{ MeV} \]


\[ ^{71}\text{Ga} + \nu_e \rightarrow ^{71}\text{Ge} + e^- - 0.233 \text{ MeV} \]

Kamiokande II - 1996 – 2001

\[ e^- + \nu_e \rightarrow e^- + \nu_e \]

Inelastic scattering of neutrinos on electrons in water. Threshold 9 MeV. Scattered electron emits characteristic radiation.

---

**GALLEX**

In Gran Sasso Tunnel – Italy

3300 m water equivalent

30.3 tons of gallium in GaCl₃ - HCl solution

\[ ^{71}\text{Ga} + \nu_e \rightarrow ^{71}\text{Ge} + e^- \]

Threshold 0.233 MeV

Sees pp, \(^7\text{Be}\), and \(^8\text{B}\).

Calibrated using radioactive \(^{51}\text{Cr}\) neutrino source

---

**Kamiokande II (in Japanese Alps) 1996 - 2001**

In Homestake Gold Mine

Lead, South Dakota

4850 feet down

tank 20 x 48 feet

615 tons (3.8 x 10⁵ liters) C₂Cl₄

Threshold 0.814 MeV

Half-life \(^{37}\text{Ar}\) = 35.0 days

Neutrino sensitivity \(^7\text{Be}\), \(^8\text{B}\)

8 x 10⁴⁰ atoms of Cl

Nobel Prize 2002

Depth 1 km
Detector H₂O
Threshold 9 MeV
Sensitive to \(^8\text{B}\)
20” photomultiplier tubes
Measure Cerenkov light
2.3 x 10³² electrons
The Sun - 1999
(First picture in neutrinos)

This “picture” was taken using data from the Kamiokande 2 neutrino observatory. It contains data from 504 nights (and days) of observation. The observatory is about a mile underground.

Each pixel is about a degree and the whole frame is $90^\circ \times 90^\circ$.
Particle physics aside:

emitted by pp-cycle

cosmology limits the sum of the neutrino masses to < 1 eV

http://www.sno.phy.queensu.ca/sno/sno2.html - interactions

Neutrino interactions with heavy water D₂O = ²H₂O

Electron neutrino

\[ \nu_e + \frac{2}{\text{H}} \to (pp) \to p + p + e^- \]

All neutrinos

\[ \nu_{e,\mu,\tau} + ^2\text{H} \to n + p + \nu_{e,\mu,\tau} \]

add salt to increase sensitivity to neutrons,

\[ \nu_{e,\mu,\tau} + e^- \to \nu_{e,\mu,\tau} + e^- \]

Results from SNO – 2002

The flux of electron flavored neutrinos above 5 MeV (i.e., only pp3 = ⁸B neutrinos) is

\[ 1.76\pm0.1 \times 10^6 \text{ cm}^{-2} \text{ s}^{-1} \]

But the flux of \( \mu \) and \( \tau \) flavored neutrinos is

\[ 3.41\pm0.64 \times 10^6 \text{ cm}^{-2} \text{ s}^{-1} \]

Nobel Prize in Physics - 2002

Standard Solar Model ⁸B neutrinos

\[ 5.05^{+1.01}_{-0.81} \times 10^6 \text{ neutrinos cm}^{-2} \text{ s}^{-1} \]
The explanation of the solar neutrino "problem" is apparently **neutrino flavor mixing**.

A flux that starts out as pure electron-"flavored" neutrinos at the middle of the sun ends up at the earth as a mixture of electron, muon, and tauon flavored neutrinos in comparable proportions.

The transformation occurs in the sun and is complete by the time the neutrinos leave the surface. The transformation affects the highest energy neutrinos the most (MSW-mixing).

Such mixing requires that the neutrino have a very small but non-zero rest mass. This is different than in the so called "standard model" where the neutrino is massless. The mass is less than about $10^{-5}$ times that of the electron.

New physics.... (plus we measure the central temperature of the sun very accurately – 15.71 million K)