Ay 190 Assignment 7

pp-Chain Nucleosynthesis

February 21, 2013

1 Modeling hydrogen burning in the Sun

Frank Timme's Fortran 90 pp-chain nuclear reaction network model (`http://cococubed.asu.edu/code_pages/burn.shtml`) was used to model hydrogen burning in the Sun. Initial mass fractions 25% and 75% ^{4}He and ^{1}H, respectively, were assumed in a hydrostatic model of the sun with a constant temperature of $1.5 \times 10^7 K$ and density of 150 g cm^{-3} that was evolved over 10^{12} years.

The H-burning model calculated using the above stellar properties overpredicts the amount of H-burning that has occured early in the Sun's life and underpredicts at later times. According to the model, the Sun, estimated to be 4.57 Gyr old, should currently be composed of 26.68% ^{1}H by mass (currently believed to be 38.5%). The current best estimate to the ^{1}H mass fraction (0.385) was reached by the model at 2.63 Gyr. The model predicts that the Sun will reach the end of the main sequence phase (approximately when when the core is 1% ^{1}H by mass) at 123.16 Gyr (should be about 10 Gyr). Initializing the model with more accurate protosolar conditions of mass fractions of 71.1% ^{1}H and 27.4% He decreases the predicted solar main-sequence lifetime to 97.1 Gyrs.

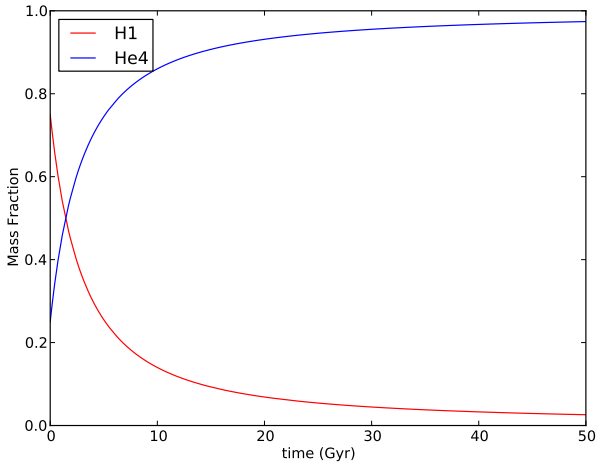

Figure 1: The evolution of the mass fraction of hydrogen and helium in a stellar model with .

2 The proton-proton (pp-)chains

Hydrogen is converted into Helium primarily through 3 proton-proton chains. The net reaction is

$$4^1_1 H \rightarrow^4_2 He + 2e^+ + 2\nu_e + 2\gamma$$

. The first proton-proton chain (PPI) involves three reactions,

$$\begin{aligned} {}^1_1\mathrm{H}+{}^1_1\mathrm{H} &\rightarrow {}^2_1\mathrm{H}+e^+ + \nu_e \\ {}^2_1\mathrm{H}+{}^1_1\mathrm{H} &\rightarrow {}^3_2\mathrm{He}+\gamma \\ {}^3_2\mathrm{He}+{}^3_2\mathrm{He} &\rightarrow {}^4_2\mathrm{He}+2{}^1_1\mathrm{H}. \end{aligned}$$

The first step is mediated by the weak force, which causes a proton to decay into a neutron, and is the slowest step of the PPI chain. The helium-3 nuclei can alternatively interact with helium-4 nuclei in the second proton-proton chain (PPII),

$$\begin{aligned} {}^3_2\mathrm{He}+{}^4_2\mathrm{He} &\rightarrow {}^7_4\mathrm{Be}+\gamma \\ {}^7_4\mathrm{Be}+e^- &\rightarrow {}^7_3\mathrm{Li}+\nu_e \\ {}^7_3\mathrm{Li}+{}^1_1\mathrm{H} &\rightarrow 2{}^4_2\mathrm{He}. \end{aligned}$$

In the solar core, this occurs with a probability of about 31%. Furthermore, about 0.3% of the time, the beryllium-7 nucleus will capture an proton and instigates the third proton-proton chain (PPIII),

$$\begin{aligned} {}^7_4\mathrm{Be}+{}^1_1\mathrm{H} &\rightarrow {}^8_5\mathrm{B}+\gamma \\ {}^8_5\mathrm{B} &\rightarrow {}^8_4\mathrm{Be}+e^+ + \nu_e \\ {}^8_4\mathrm{Be} &\rightarrow 2{}^4_2\mathrm{He}. \end{aligned}$$

The entire pp-chain sequence is diagramed below.

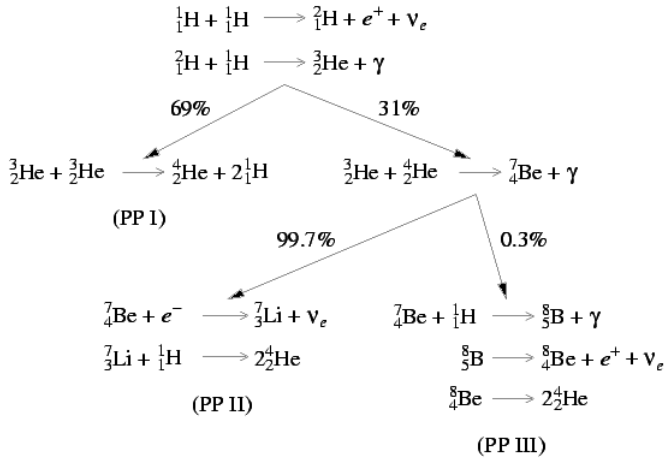

Figure 2: The three branches of the proton-proton chain. Figure from http://burro.astr.cwru.edu/Academics/Astr221/StarPhys/ppchain.gif.