Week 12, Lecture 2 – Nuclear Synthesis

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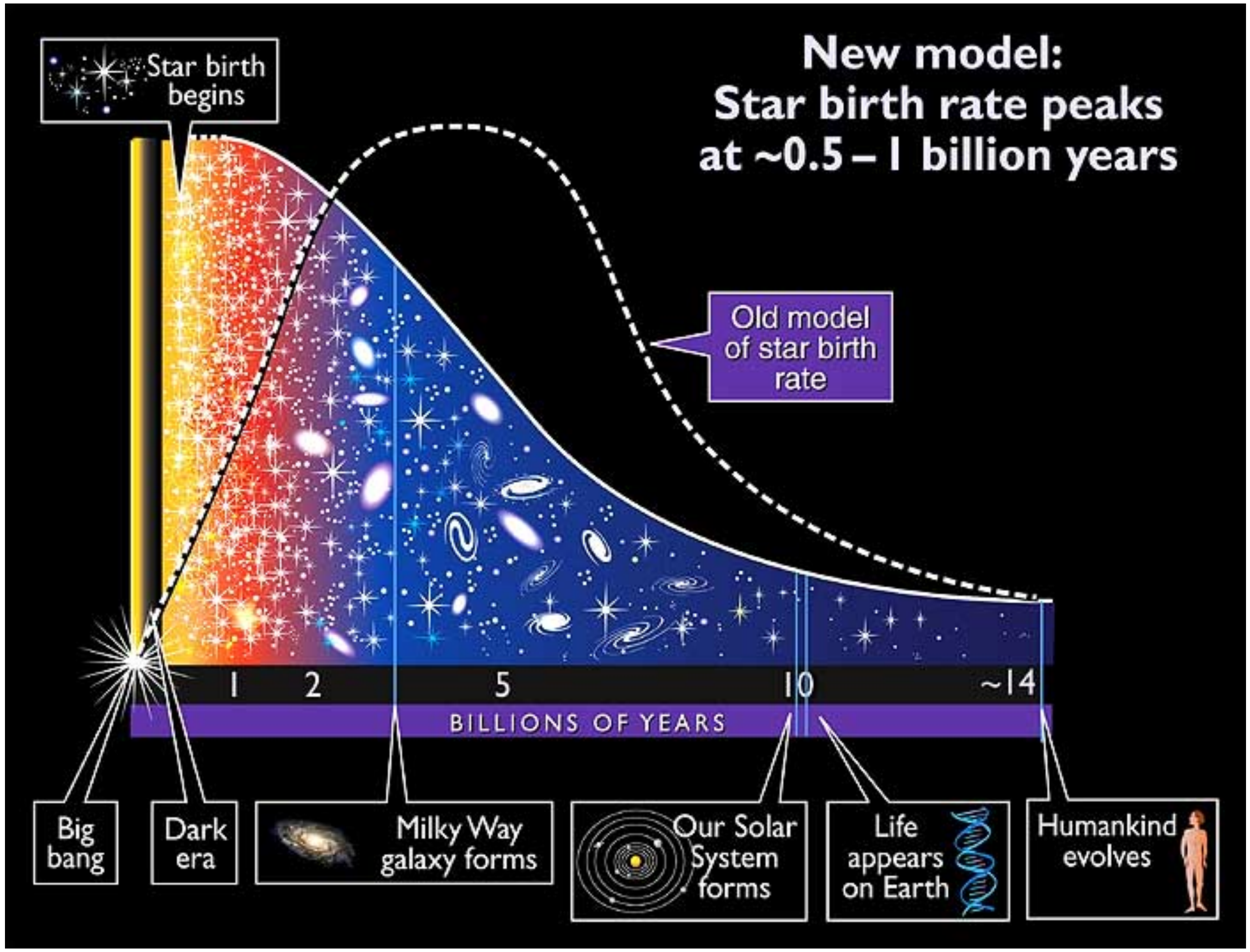
Nuclear Reactions in Space

-- Overview
-- Observational Information
--- Elemental distributions
--- EM distributions
-- Nuclear Synthesis
--- Big Bang
--- Stellar processes
---- simple proton burning
---- catalytic cycles
---- neutron capture
---- explosions

8th Homework due Monday



K.Lanzetta, et al., [arXiv:astro-ph/0111129v1]()

Big Bang Nucleosynthesis

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Recall that we have a fundamental equivalence between mass and energy, which combined with the basic assumption is that there was a singularity with all the energy/mass concentrated in one place at one time. The material is further assumed to be expanding and cooling ever since. The particles in the mix interact with one-another until the temperature drops below the interaction potential. At some point there is a mixture that is mostly electrons, protons and neutrons: Write Diff-Eqs for all reactions, solve coupled equations …

$$^{1}p^{+} + e^{-} = {}^{1}n + \nu$$

$$^{1}n + e^{+} = {}^{1}p^{+} + \bar{\nu}$$

$$^{1}p^{+} + {}^{1}n = {}^{2}d^{+} + \gamma$$

$$^{2}d^{+} + {}^{2}d^{+} = {}^{3}H^{+} + {}^{1}p^{+}$$

$$^{2}d^{+} + {}^{2}d^{+} = {}^{3}He^{2+} + {}^{1}n$$

$$^{1}p^{+} + {}^{2}d^{+} = {}^{3}He^{2+} + \gamma$$

$$^{1}p^{+} + {}^{3}H^{+} = {}^{3}He^{2+} + {}^{1}n$$

$$^{2}d^{+} + {}^{3}He^{2+} = {}^{4}He^{2+} + {}^{1}p^{+}$$

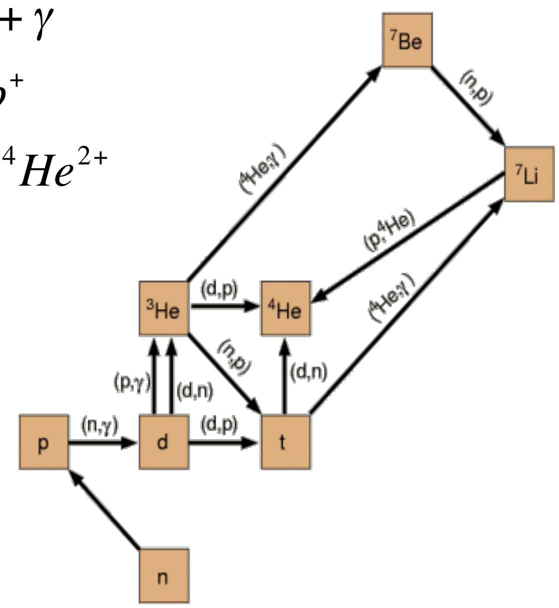
$$^{2}d^{+} + {}^{3}H^{2+} = {}^{4}He^{2+} + {}^{1}n$$

$$^{3}He^{2+} + {}^{4}He^{2+} = {}^{7}Be^{4+} + \gamma$$

$$^{3}H^{+} + {}^{4}He^{2+} = {}^{7}Li^{3+} + \gamma$$

$$^{1}n + {}^{7}Be^{4+} = {}^{7}Li^{3+} + {}^{1}p^{+}$$

$$^{1}p^{+} + {}^{7}Li^{3+} = {}^{4}He^{2+} + {}^{4}He^{2+}$$



One Example: $$\frac{d[^{7}Be]}{dt} = k_1[^{3}He][^{4}He] - k_3[^{1}n][^{7}Be] + k_{-3}[^{7}Li][^{1}n]$$

Big Bang Calculation Results

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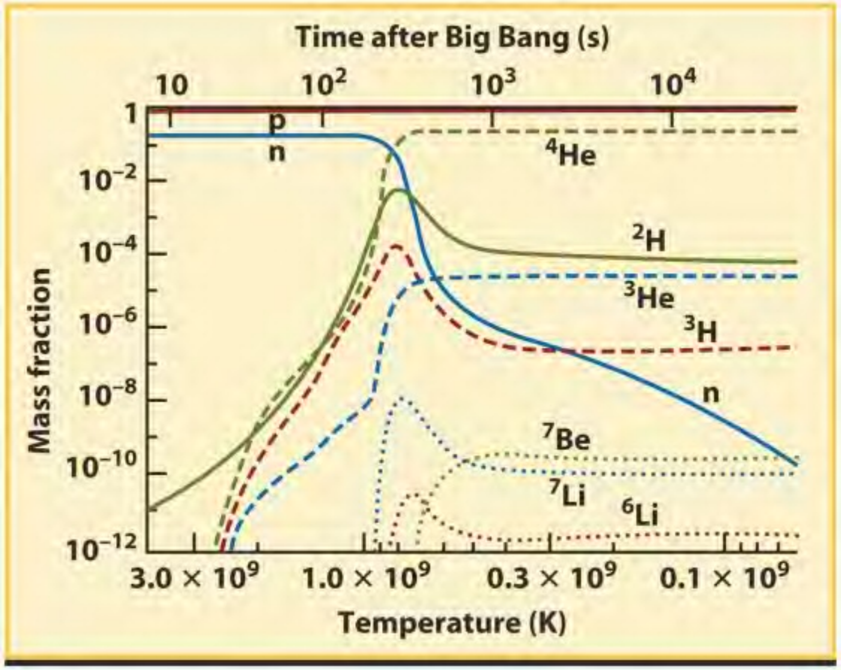
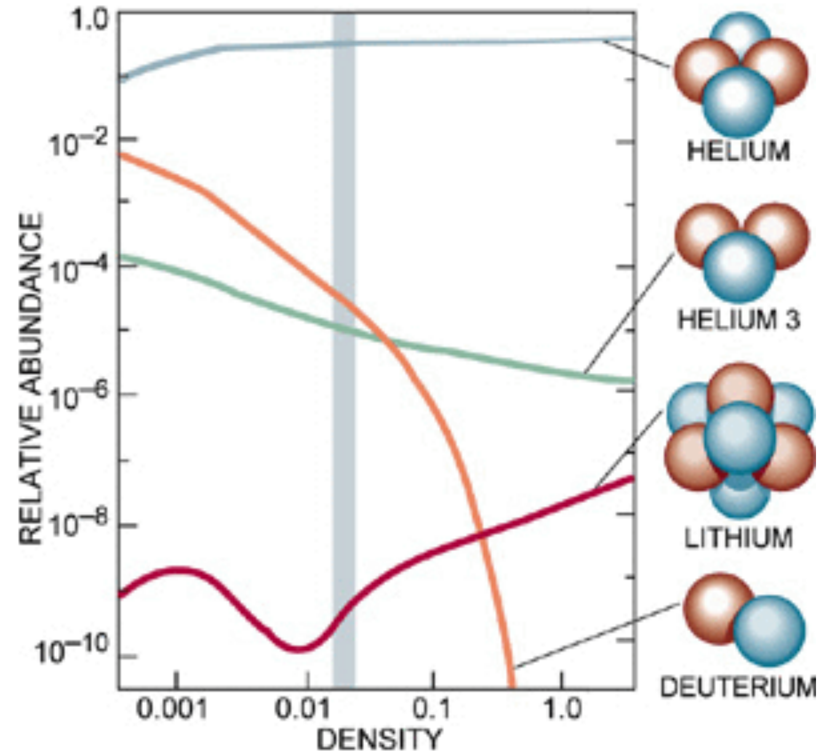


The result of solving the network equations is a time evolution of the amount of each nucleus. The time dimension is equivalent to the temperature dimension since the system is expanding and cooling. The input to these calculations are the nuclear reaction cross sections (rate constants) and the initial density.

The network calculations are run over and over with different assumptions for the (baryon) density and the results can be compared to estimates of the present amounts of the product nuclei. The present interpretation is that the density of the universe is substantially less than that necessary to stop the outward expansion (using gravity).



Fraction of the "critical density"
Similar to Fig. 12.6 in the text

Hertzsprung-Russel Sequence of Stars

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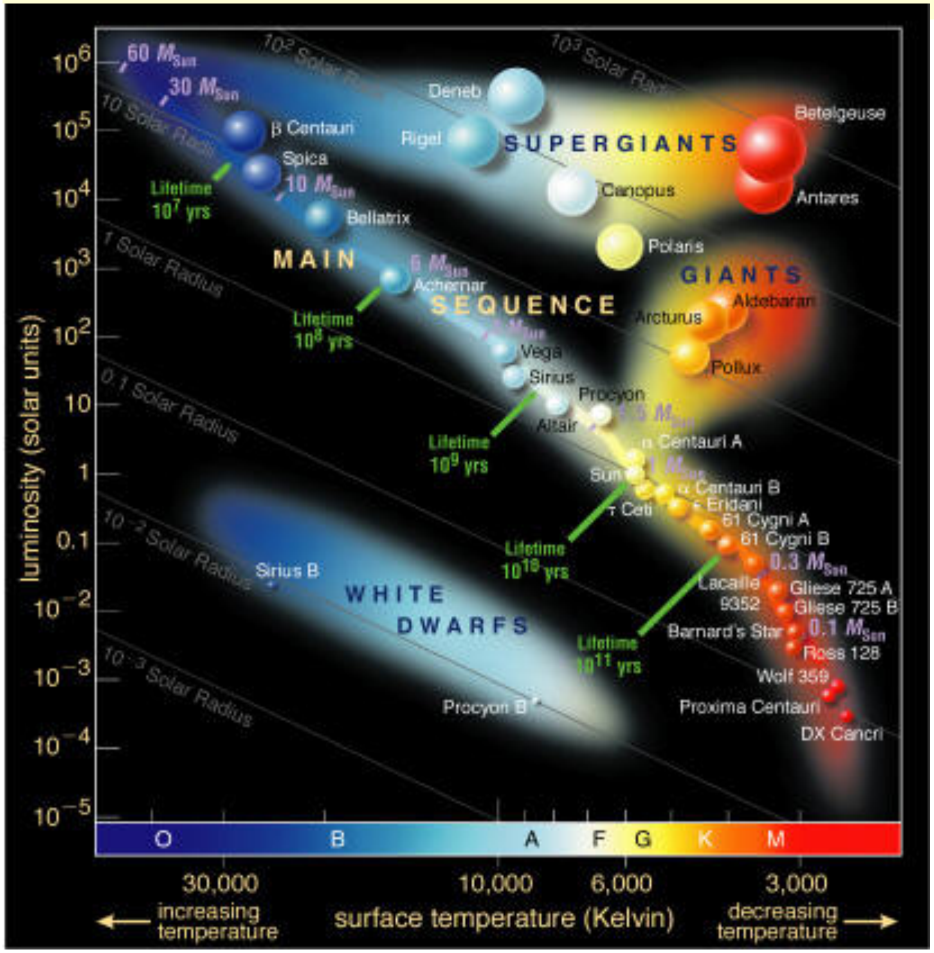
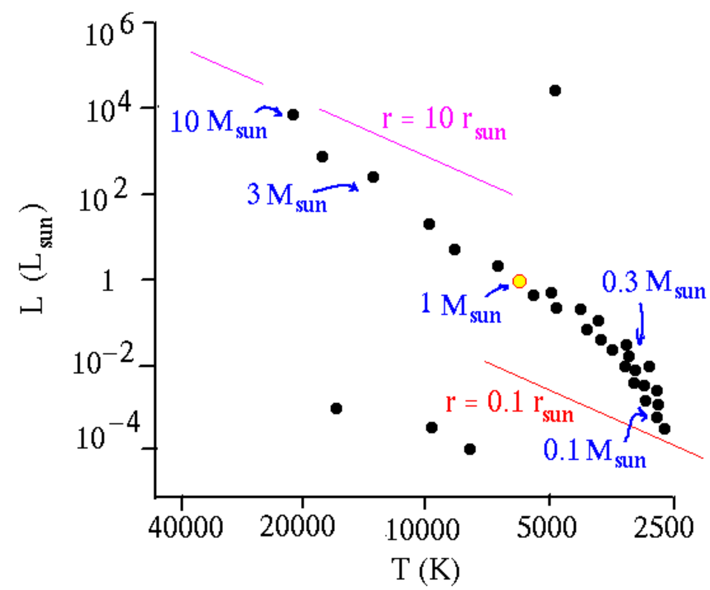


The material from the big bang has coalesced into a wide range of objects including planets, stars, galaxies, clusters of galaxies, etc. through gravitational attraction. The stars are special in this group because they are dense enough (have sufficient gravitational energy) to ignite nuclear reactions. As mentioned last time they can be characterized in terms of temperature and luminosity.

The stars fall into regions grouped by nuclear fuel !



D.E. Soper, Institute of Theoretical Science, University of Oregon

The stars fall along a sequence that is ranked by mass. The temperature (color) is an indication of the rate of nuclear reactions. A star can only make a substantial change in its mass by explosion and they make an excursion off the main sequence as the material that they burn changes…

Proton Burning in Main Sequence Stars

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The main sequence stars have two proton burning scenarios, one that runs in the oldest and simplest stars and another catalytic cycle that needs catalytic seed nuclei produced in an older star and distributed by an explosion. First the direct P+P process:

$$ {}^{1}p^{+} + {}^{1}p^{+} = {}^{2}d^{+} + e^{+} + \nu $$

$$ {}^{2}d^{+} + {}^{1}p^{+} = {}^{3}He^{2+} + \gamma $$

69%

$$ {}^{3}He^{2+} + {}^{3}He^{2+} = {}^{4}He^{2+} + {}^{1}p^{+} + {}^{1}p^{+} $$

PP-I

31%

$$ {}^{3}He^{2+} + {}^{4}He^{2+} = {}^{7}Be^{4+} + \gamma $$

99.7% of 31%

$$ e^{-} + {}^{7}Be^{4+} = {}^{7}Li^{3+} + \nu $$

$$ {}^{1}p^{+} + {}^{7}Li^{3+} = {}^{4}He^{2+} + {}^{4}He^{2+} $$

PP-II

0.3% of 31%

$$ {}^{7}Be^{4+} + {}^{1}p^{+} = {}^{8}B^{5+} + \gamma $$

$$ {}^{8}B^{5+} = {}^{8}Be^{3+} + e^{+} + \nu $$

$$ \rightarrow {}^{4}He^{2+} + {}^{4}He^{2+} $$

PP-III

Catalytic Proton Burning, CNO cycle

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If a star (again >90% hydrogen) has been able to collect or perhaps even make a small amount of ^{12}C then a catalytic process can start that has the same net reaction but avoids the slow first step of deuteron production.

$$^{1}p^{+} + ^{12}C^{6+} = ^{13}N^{7+} + \gamma$$

$$^{13}N^{7+} \rightarrow ^{13}C^{6+} + e^{+} + \nu$$

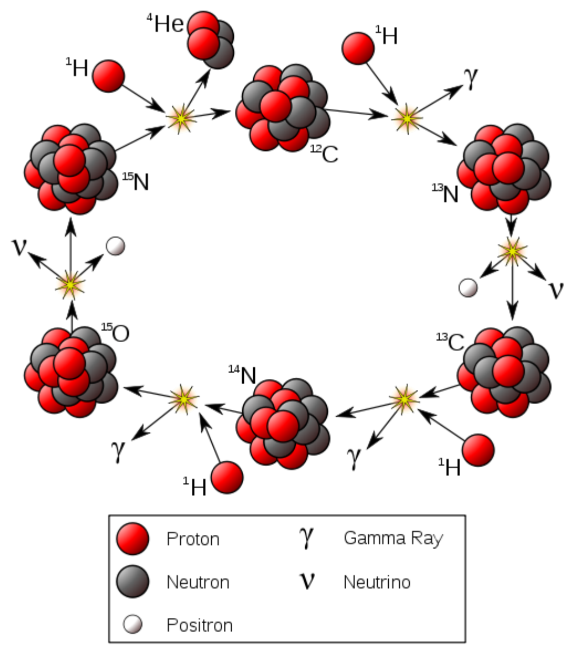
$$^{1}p^{+} + ^{13}C^{6+} = ^{14}N^{7+} + \gamma$$

$$^{1}p^{+} + ^{14}N^{7+} = ^{15}O^{8+} + \gamma$$

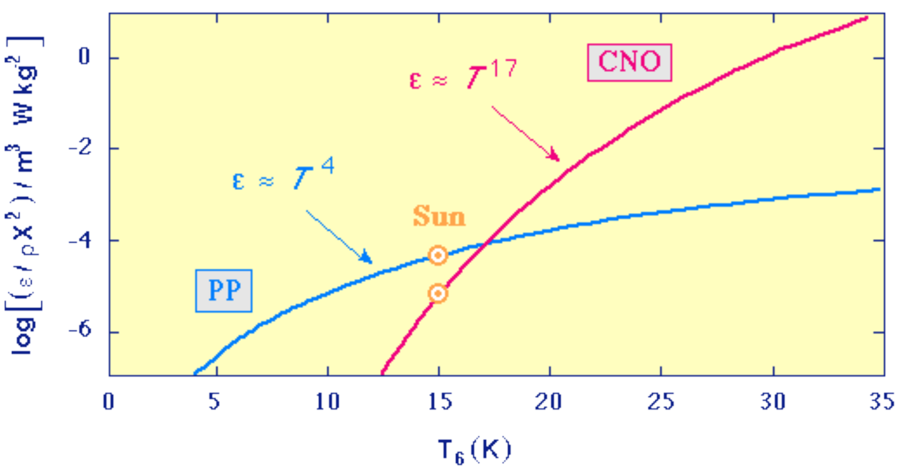
$$^{15}O^{8+} \rightarrow ^{15}N^{7+} + e^{+} + \nu$$

$$^{1}p^{+} + ^{15}N^{7+} = ^{12}C^{6+} + ^{4}He^{4+}$$

$$4\left(^{1}p^{+}\right) \rightarrow ^{4}He^{2+} + 2e^{+} + 2\nu + Q$$



The two processes have different temperature (i.e., stellar mass) dependences due to the coulomb barrier for the heavier nuclei in the CNO cycle compared to the PP process.



End Game for Stars (low mass)

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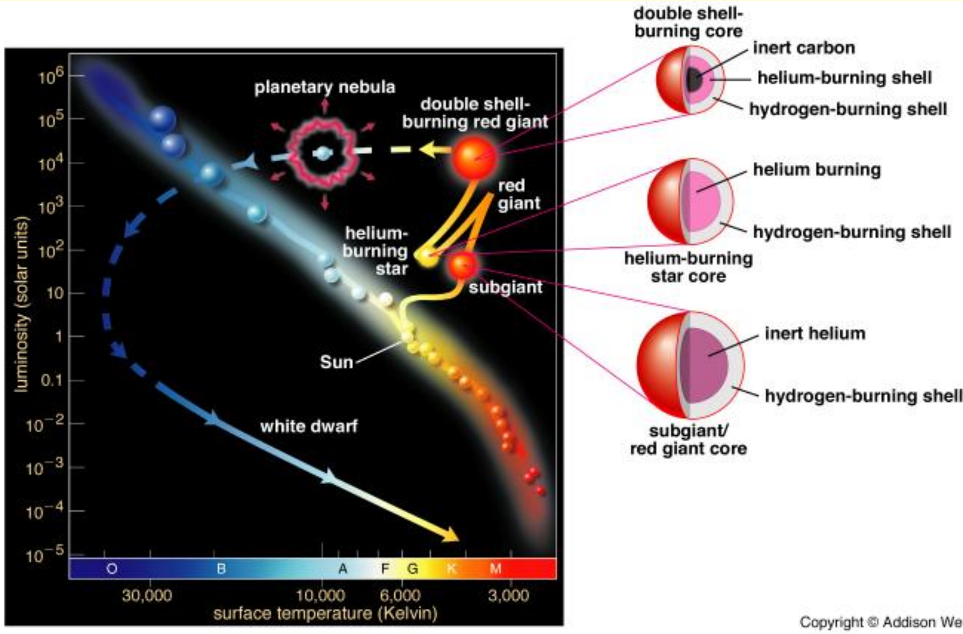
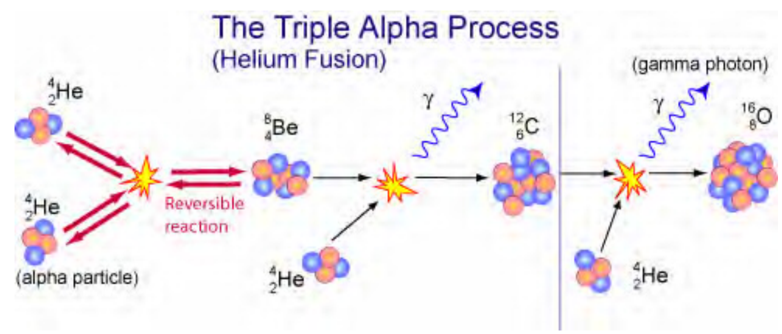


The helium (denser) collects in the center and when the star runs low on fuel (H) it cools and compresses. Eventually the core can be compressed to the point that the helium is burned in an unusual process to skip over A=8.



Net: 3 ^{4}He -> ^{12}C + Q = 7.275 MeV

a rapid equilibrium in chemical kinetics

$d[^{8}Be]/dt = k_1 [^{4}He]^2 - k_{-1} [^{8}Be] - k_2 [^{8}Be][^{4}He]$

$[^{8}Be] = k_1[^{4}He]^2 / (k_{-1} + k_2[^{4}He])$ assume derivative is zero

$d[^{12}C]/dt = k_2 [^{8}Be][^{4}He] \sim k_2 k_1 [^{4}He]^3/(k_{-1} + k_2[^{4}He])$

$d[^{4}He]/dt = -k_1 [^{4}He]^2 - k_2 [^{8}Be][^{4}He] + k_{-1} [^{8}Be]$

End Game for Stars (high mass)

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The heavy main-sequence stars continue to burn heavier and heavier nuclei in a series of fusion reactions that occur in a series of shells that are sorted by mass of the nuclei. They generally progress through the same region of the H-R diagram with one major exception. They end in a supernova.