Star Formation & Stellar Evolution

The formation of Pop III stars
The basic concepts of stellar evolution
Stellar evolutionary tracks

September 29, 2022

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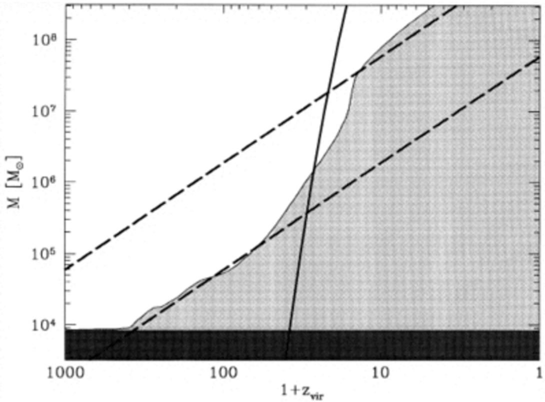
Pop III star formation

Pop III stars would have collapsed in the first dark matter halos to have successfully accumulated baryonic gas and cooled to a low enough temperature to permit H_2 formation.



The virial temperature of a CDM halo is

$$T_{\mathrm{vir}} \approx 442\Omega_{M,0}^{1/3}\left(\frac{M}{10^4 M_\odot/h}\right)^{2/3}\left(\frac{1+z_{\mathrm{vir}}}{100}\right)\ \mathrm{K}$$

Stellar evolution

Stellar evolution is driven by the change in chemical evolution due to stellar nucleosynthesis.

Assuming no bulk motion in the inner material of the star, then any changes in the chemical composition of the star due to nuclear fusion is only local, so

$$\frac{\partial X_i}{\partial t} = f_i(\rho, T, \{X_i\})$$

so that

$$X_i(t) = X_i(t_0) + f_i\left(\rho(t), T(t), \{X_i\}(t_0)\right)\delta t$$

Energy production in a star

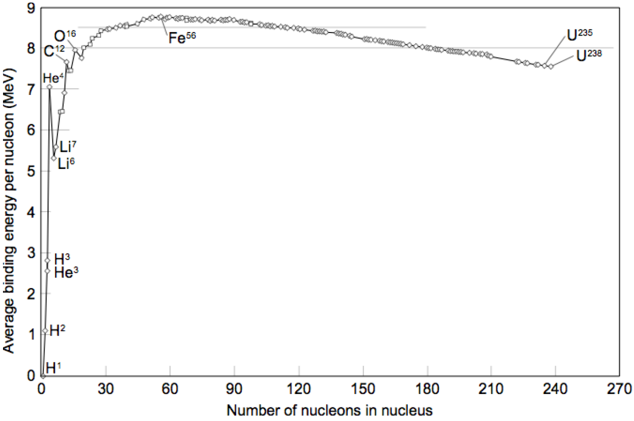
A star's luminosity is produced by the nuclear fusion reactions occurring in its core.

For the most common fusion process, $4H \rightarrow He$. The energy that this reaction releases is

$$4m_p - 3.97m_p = 0.03m_p$$

The Sun's structure and luminosity will drastically change when it uses up about 13% of its hydrogen. This results in a hydrogen-fusion lifetime of about 9×10^9 yr.

Nucleon binding energy

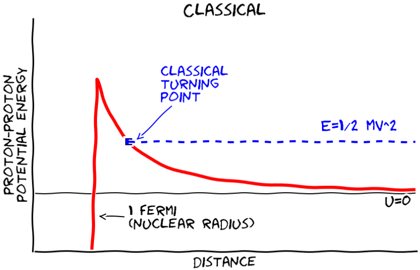


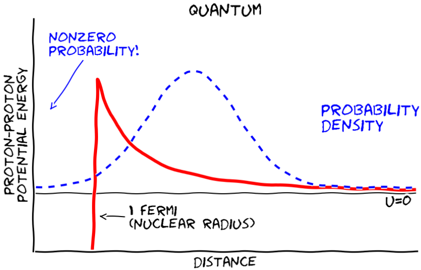
The binding energy per nucleon in a nucleus is

$$\Delta E(Q,N) = \frac{[Qm_p + Nm_n - m(Q,N)]c^2}{Q+N}$$

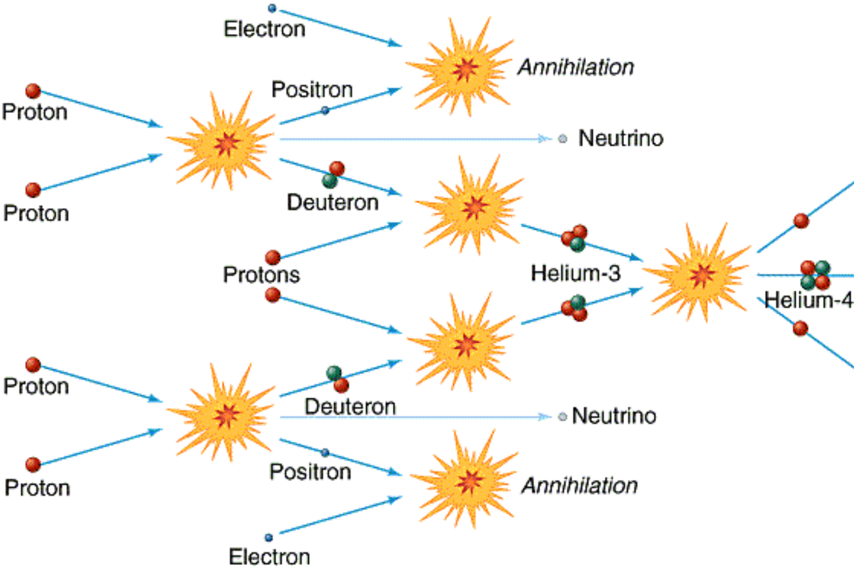
For He, $\Delta E \approx 0.007 m_p c^2$.

Overcoming the Coulomb barrier

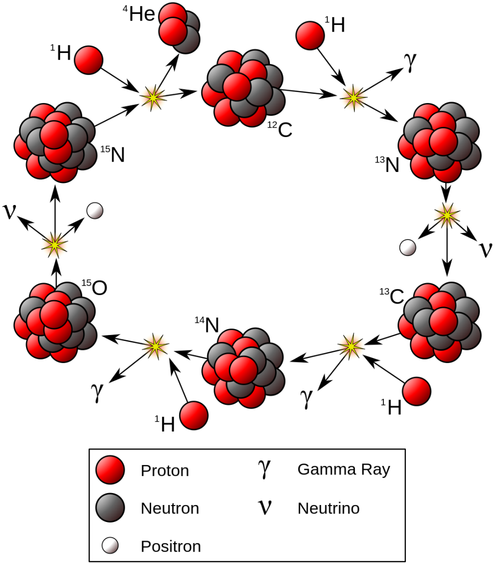




Proton-proton (pp) chain

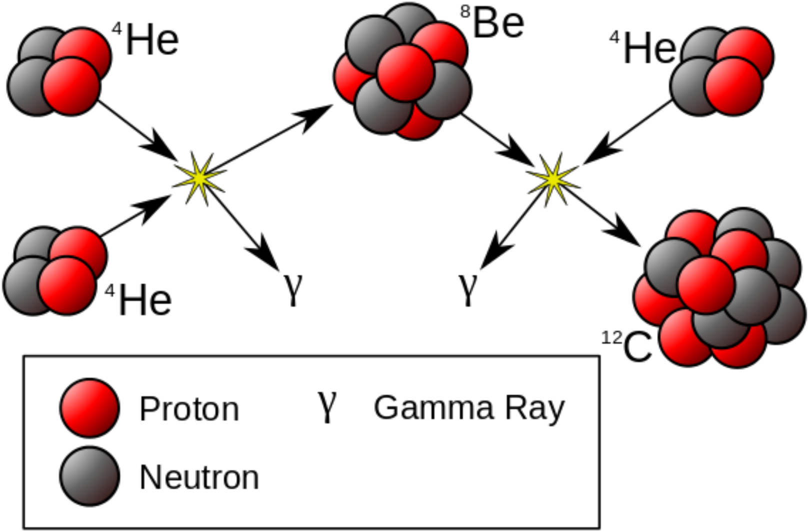


CNO cycle

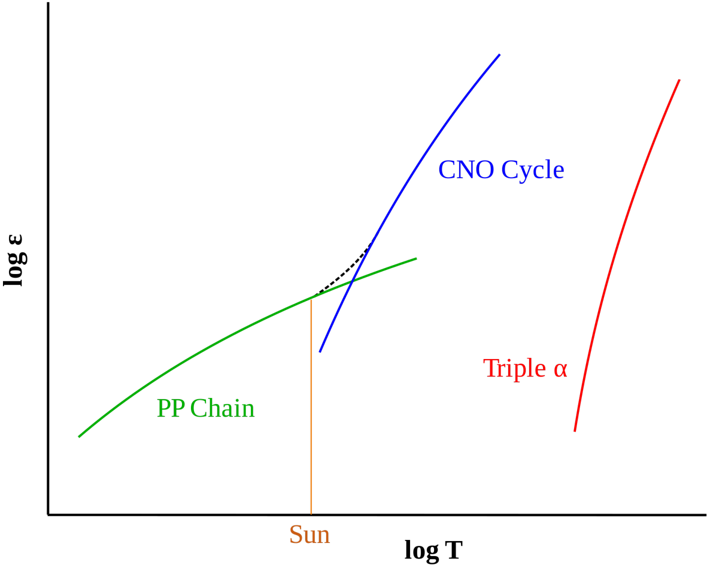


4He
1H
1H
12C
13N
15N
13C
15O
14N
1H
1H
γ
γ
γ
ν
ν
Proton
Neutron
Positron
Gamma Ray
Neutrino

Triple-α process



Comparison of these synthesis processes



Primary and secondary elements

Elements which can be synthesized in stars with zero initial metallicity (pure hydrogen and helium) are considered primary elements. These include the α elements, which form via fusion of He to O^{16}:

$$C^{12} + He^4 \rightarrow O^{16} + \gamma \qquad 2C^{12} \rightarrow Ne^{20} + He^4$$
$$Ne^{20} + He^4 \rightarrow Mg^{24} + \gamma \qquad 2O^{16} \rightarrow Si^{28} + He^4$$

Secondary elements are those which can only form in the presence of primary elements. Nitrogen is an important secondary element; it is primarily produced in the CNO cycle, which cannot occur unless a star has some initial C.

Main sequence lifetimes

Since the luminosity of a star is proportional to its mass,

$$L_* \propto M_*^4$$

the length of time a star lasts on the main sequence also scales with mass:

$$t_{\mathrm{MS}} \propto \frac{M_*}{L_*} \propto M_*^{-3}$$

Pre-MS evolution