31 Stars notes 2019/11/18 - Mon - Neutrinos and advanced burning

31.1 Evolution of $\geq 6M_\odot$ stars

The next available fuel is ^{12}C:

$$^{12} +^{12} C \rightarrow^{24} Mg$$

and the magnesium decays to several things α+^{20}Ne, p+^{23}Na, n+^{23}Mg.

The large coulomb barrier will force $T > (6-8) \times 10^8$ K before ^{12}C burning can start. Neutrino emission is importart here! So thats what we have to do next. The balance is generation balancing neutrino emission. The overview figure below shows T_c-ρ_c where we see the tracks of stars.

Note that at carbon burning the "cooling" changes from photons to neutrinos. This is a whole new kind of star, where instead of having to carry enery released in the core out the the surface, the thermal energy is just radiated directly out as neutrinos.

Also see figures 30, 31 and 33 and Table 12 in the first MESA paper.

Note also that the lifetimes of the late burning stages are quite short, years or less.

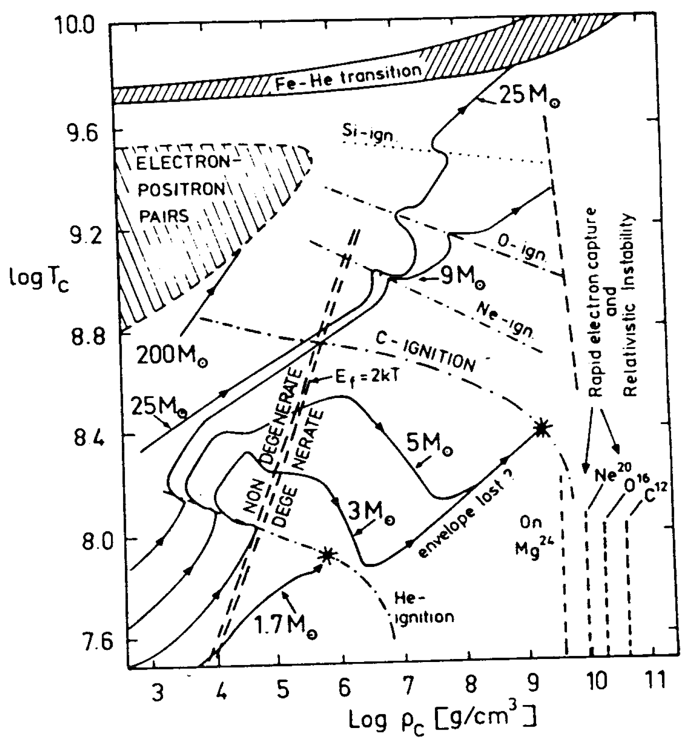


Table 9

Thermonuclear burning stages (after Arnett [16]) and timescales for a population I star with a mass of 25 $M_\odot$, after Weaver et al. [380,381]

Fuel	$T/10^9$ (K)	Ashes	E (erg/g fuel)	Cooling	Time (yr)
^{1}H	0.02	^{4}He, ^{14}N	$(5–8) \times 10^{18}$	photons	5×10^{6}
^{4}He	0.2	^{12}C, ^{16}O, ^{22}Ne	7×10^{17}	photons	5×10^{5}
^{12}C	0.8	^{20}Ne, ^{24}Mg, ^{16}O ^{23}Na, ^{25,26}Mg	5×10^{17}	neutrinos	60
	0.4	^{20}Ne, ^{23}Na	–		
^{20}Ne	1.5	^{16}O, ^{24}Mg, ^{28}Si	1.1×10^{17}	neutrinos	1
^{16}O	2	^{28}Si, ^{32}S	5×10^{17}	neutrinos	0.5
^{28}Si	3.5	^{56}Ni, $A \sim 56$ nuclei	$(0–3) \times 10^{17}$	neutrinos	0.01
^{56}Ni $A \sim 56$ nuclei	6–10	n, ^{4}He, ^{1}H (depends on photodisintegration and neutronization)	-8×10^{18}	neutrinos	10^{-6}

show massive star figures from MESA paper 1

31.2 Evolution high mass stars continued

Continuing with carbon burning phase...

Showing optically thin to ν: The typical ν cross-section is

$$\sigma_{\nu-e} \sim 10^{-44}\left(\frac{E_\nu}{MeV}\right)^2 cm^2$$

To have optical depth 1 for neutrinos need

$$\frac{M}{m_p R^2}\sigma > 1$$

for $M = M_\odot$

$$R \leq 30km\left(\frac{E_\nu}{MeV}\right)$$

will have to consider this for neutron stars, but not here, so these stars are optically thin to neutrinos.

31.3 Neutrinos and late burning

At high $T's$ ν emission ends up being the dominant mechanism for heat loss and this dramatically accelerates the stellar evolution.

$$T\frac{ds}{dt} = \epsilon_{CC} - \frac{1}{\rho}\vec{\nabla}\cdot\vec{F} - \epsilon_\nu$$

and $\epsilon_\nu \gg \frac{1}{\rho}\vec{\nabla}\cdot\vec{F}$ is the limit we'll have.

31.4 ν production at high T

Consider:

$$\gamma + \gamma \to e^+ + e^- \to \nu_e + \bar{\nu}_e$$

this is unlikely compared to the dominant process, but there

$$\frac{e^+ + e^- \to \nu_e + \bar{\nu}_e}{e^+ + e^- \to \gamma + \gamma} \simeq 10^{-19}$$

What is the equilibrium abundance of e^+ presuming that the production and anihillation are balanced. (The high energy photons in the tail can actually pair produce.)

Just using balance for $e^+ + e^- \rightleftharpoons 2\gamma$ so that $\mu_{e^+} + \mu_{e^-} = 0$ where For ideal gas

$$\mu_e = m_e c^2 - kT\ln\left(\frac{2n_{e,Q}}{n_e}\right)$$

so presuming balance we get

$$n_{e^+} = \frac{4n_{e,Q}^2}{n_e} \exp\left(\frac{-2m_ec^2}{kT}\right)$$

this is

$$n_{e^+} = 7.7 \times 10^{30} cm^{-3} \left(\frac{10^4 g/cm^3}{\rho}\right) T_9^3 \exp\left(\frac{-11.84}{T_9}\right)$$

so that at $T_9 = 1$, $\rho_4 = 1$,

$$\frac{n_{e^+}}{n_e} = 0.01$$

At higher tempratures $n_e \neq \rho/m_p$ and so we can ask where that happens $n_{e^+} = n_e$ which gives $T_9 > 1.4$. Because carbon burns at lower temperature than this about 8×10^8, we can just use the small-fraction limit just derived.

The rate of neutrino production will just be

$$\frac{ergs}{cm^3 sec} = \frac{du_\nu}{dt} = n_{e^+} n_e \langle \sigma v \rangle W$$

where W is the energy loss, just $2m_ec^2$. For this encounter:

$$\sigma = 1.4 \times 10^{-45} \frac{c}{v} (\omega^2 - 1)$$

where $\omega = E_{COM}$ including rest mass. We get

$$\langle \sigma v \rangle = 4.2 \times 10^{-45} c$$

So we have

$$\frac{du_\nu}{dt} = 5 \times 10^{18} \frac{ergs}{cm^3 sec} T_9^3 \exp\left(\frac{-11.84}{T_9}\right)$$

this is density independent which is because the product $n_e n_{e^+}$ only depends on T.

Now we can do the analog of the Kelvin-Helmholtz time. The themal energy

$$E_{th} = nkT = 7 \times 10^{19} \frac{ergs}{cm^3} T_9 \rho_4$$

so the cooling time is

$$t_{cool} \simeq \frac{E_{th}}{du_\nu/dt} = 14 sec \frac{\rho_4}{T_9^2} \exp\left(\frac{11.84}{T_9}\right)$$

for some values

T_9	t_{cool}
0.63	160 years
1	0.7 months
2	30 minutes

once ν cooling kicks in, the stellar evolution is dramatically accelerated, even though the external luminosity has basically not changed.

31.5 Nuclear lifetime of late burning

Compare to how we discussed hydrogen burning lifetime:

$$t_{nuc} = \frac{E_{nuc}/particle}{E_{th}/particle} t_{cool}$$

for sun: $t_{nuc} \simeq MS\ life = 5MeV/1keV = 5000 \times t_{cool}$

For massive star core: $E_{nuc} \simeq 1MeV/m_p$ and $E_{th} \sim 100$ keV and so

$$t_{nuc} \simeq (10-30)t_{cool}$$

Nuclear burning stages are not very long-lived. Cooling time is short, and nuclear lifetime is only 10 or so times the cooling time.

31.5.1 Plasmon Decay, another ν production process

can a free photon pair produce? no can't conserve both energy and momentum (can't boost into the rest frame of the photon). But a photon in a plasma has a dispersion relation:

$$\omega^2 = (ck)^2 + \omega_0^2$$

where

$$\omega_0^2 = \frac{4\pi n_e e^2}{m_e} = \text{plasma frequency}$$

which looks like it has a mass. So it can pair produce. (the plasma takes up the momentum slack.) At high electron densities $\hbar\omega_0 \sim kT$ and photons in the plasma become very modified. In this limit

$$E_\gamma^2 = (p_\gamma c)^2 + (\hbar\omega_0)^2$$

The "excess energy" allows the plasmon to decay into 2 ν's.

31.6 Carbon Burning

For $M \geq 8M_\odot$ ^{12}C in the C/O core ignites and burns, however the condition for an equilibrium is that

$$\epsilon_{CC} = \frac{ergs}{gr-sec} = \epsilon_\nu$$

the process is

$$^{12}C +^{12} C \rightarrow^{24} Mg^* + \gamma$$

the Mg is very unstable and decays to: $\alpha +^{20} Ne$ and $p +^{23} Na$ and $n +^{23} Mg$. So the C burning depletes all the ^{12}C and makes ^{20}Ne, ^{24}Mg and ^{23}Na. so the "ashes" are these three plus O.

The reaction rate is dominated by the coulomb barrier. The non-resonant rate is

$$\langle \sigma v \rangle = \frac{7 \times 10^{19} s}{\mu Z_1 Z_2} e^{-\tau} \tau^2$$

and $\mu = A/2$ here

$$\tau = \frac{3E_0}{kT} = \frac{84.2}{T_9^{1/3}}\left(\frac{Z}{6}\right)^{5/3}$$

and so finally

$$\langle\sigma v\rangle = \frac{690}{T_9^{2/3}} \exp\left[\frac{84.2}{T_9^{1/3}}\left(\frac{Z}{6}\right)^{5/3}\right]$$

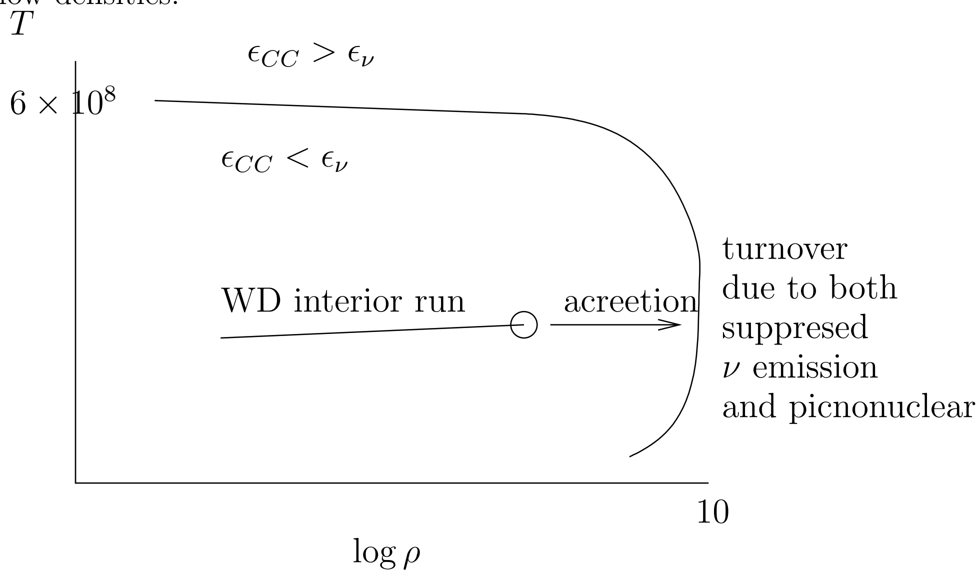
so the energy generation is

$$\epsilon_{CC} = 3 \times 10^{55} \frac{ergs}{gr - sec} \frac{\rho_6}{T_9^{2/3}} \exp\left(\frac{-84.2}{T_9^{1/3}}\right)$$

and for neutrino cooling:

$$\frac{du_\nu}{dt} = 5 \times 10^{18} T_9^3 \exp\left(\frac{-11.84}{T_9}\right) = \epsilon_\nu \rho$$

This is almost entirely temperature determined because that's in the exponent. so then the ^{12}C ignites ($\epsilon_{CC} > \epsilon_\nu$) when $T > 6 \times 10^8$. Figure above: see that carbon ignition is flat at low densities.



at high densities the ignition lines becomes colder.

At high densities the COM energy of 2 ^{12}C nuclei depends on the coulomb physics of the lattice Even at $T = 0$ there is fusion of ^{12}C due to COM energy from zero-point motion in lattice. Reaction becomes very ρ sensative. (this is real cold fusion)

There is a white dwarf drawn on the above plot, and as the center moves to the right due to accretion it eventually reaches the ignition curve. This happens at about the Chandrasekhar mass. These are what Type Ia supernova are thought to be, and this characteristic mass is why they are good standard candles.

31.7 Neon "burning" - actually photodisintegration

The star's central T is getting high enough so that

$$\gamma +^{20} Ne \rightarrow \alpha +^{16} O$$

this is called photodisintegration. These alpha particles can be captured on other things for insstance

$$\alpha +^{20} Ne \rightarrow \gamma +^{24} Mg$$

and

$$\alpha +^{24} Mg \rightarrow \gamma +^{28} Si$$

so at the end of Ne burning you are pretty much left with these O, Mg and Si. The neon ignition is also on the table with the figure above.

See plots in MESA paper 1 for massive star.