<u>**November** 19</u> . . . .

5.4.4 Futher WD properties

- It can be shown through simple Virial arguments that white dwarfs cool (approximately) according to the Mestel law
$$\Delta t \propto \left(\frac{L}{M}\right)^{-5/7} \approx \frac{4.5\times 10^7}{\mu_i}\left(\frac{LM_\odot}{L_\odot M}\right)^{-5/7} \quad \text{[year]}. \tag{5.24}$$
- The Δt represents the time for some change in luminosity.
- So higher mass WDs cool more slowly, due to more storage of energy.
- Increasing the ionic mean molecular weight decreases the evolutionary time, since there are fewer ions in that case.
- Roughly, for a WD to reach 1/1000th of the solar luminosity, it would take 1 billion years.
- A more precise cooling law would treat the ions more properly, since the steady decreae in temperature causes Coulomb interactions to become more important.
- The specific heats ratio grows and the ions form a lattice: this is *crystallization.*
- The crystallization obviously affects the EOS, and therefore the cooling times.
- The envelopes of WDs canonically predicta He layer of $\sim 10^{-2}M_{\rm tot}$ above the CO core, surrounded by a H envelope of mass $\sim 10^{-4}M_{\rm tot}$.
- Mass loss causes these notions to change.
- Metals are rarely observed due to atomic diffusion processes.
- Typically there are about 4 H WDs for every 1 non-H WD, but this varies widely with effective temperature, as evolutionary processes are still ongoing.
- The outer layers determine the opacity, and hence the cooling times.
- As WDs cool, they can develop convection zones as well.
- WDs can also be He core stars from an RGB progenitor that lost its envelope.
- There are also O-Ne WDs from higher-mass progenitors.

5.4.5 Type Ia supernovae

- Type I do not have visible hydrogen in its spectrum.
- The progenitor of these events are CO WDs that have accreted mass from a companion to exceed the critical mass .
- The companion is likely on the RGB or AGB where mass can be transferred effectively.
- In one scenario two similar stars evolve through a common envelope, and the two CO WDs merge through angular momentum loss from gravitational waves.
- The resultant object is higher than the critical mass.
- This is the *double-degenerate* channel.
- No observational evidence of these massive systems has yet to be shown.

- In the *single-degenerate* case, the events that happen depend strongly on the mass-accretion rates onto the low-mass star.
- For low rates, H burning on top of He layers produces an electron degenerate scenario, which can undergo explosive flashes.
- These are typically the classical *Novae*.
- Building up enough mass this way to reach the critical limit takes longer than a Hubble time, however.
- At moderate rates it can be shown that an explosion would occur for *sub-Chandrasekhar* mass objects.
- If enough He is accreted (either through H-burning above or from an He-rich companion), violent He-ignition can occur which can detonate the CO core.
- The explosion models must give about 10^{51}erg, as well as the production of heavy elements, such as lots of nickel.
- The explosive event is a shock wave whose speed depends on densities and abrupt thermal changes.
- Typical SNIa light curves rise rapidly and after about 20 days the light fades monotonically, with slighly different behavior in different bands.
- Almost all of them have a maximum absolute magnitude of -20 which declines linearly within 15 days after maximum.
- Thus, they are excellent standard candles.

5.5 Last stages of evolution: high-mass stars

5.5.1 Nuclear burning

- Now we consider stars greater than $15M_\odot$.
- If we only focus on the core, the processes in the late stages follow the simple causes and effects of

$$\ldots \rightarrow \text{nuclear burning} \rightarrow \text{fuel exhaustion} \rightarrow \text{core contraction} \rightarrow \text{core heating} \rightarrow \ldots \tag{5.25}$$

- At 500 million K, carbon burning can take place in the core, converting into Mg, Ne, and Na.
- Neutrinos from pair annihilation contribute a substantial amount to the luminosity (energy loss), even more than the nuclear burning.
- So the star contracts to make up the loss with gravitational energy.
- The convective C core is less massive for more massive stars, as neutrinos cause a considerable amount of mass loss.
- Eventually the burning moves to a shell of C and s-elements are produced.
- The core is now about 70% O, 25% Ne, and the rest Mg.
- Ne burning sets in .
- Oxygen burning can set in at 1.5 billion K.
- Eventually, the photons released in such reactions have such high energies that they can photo-disassociate surrounding nuclei.

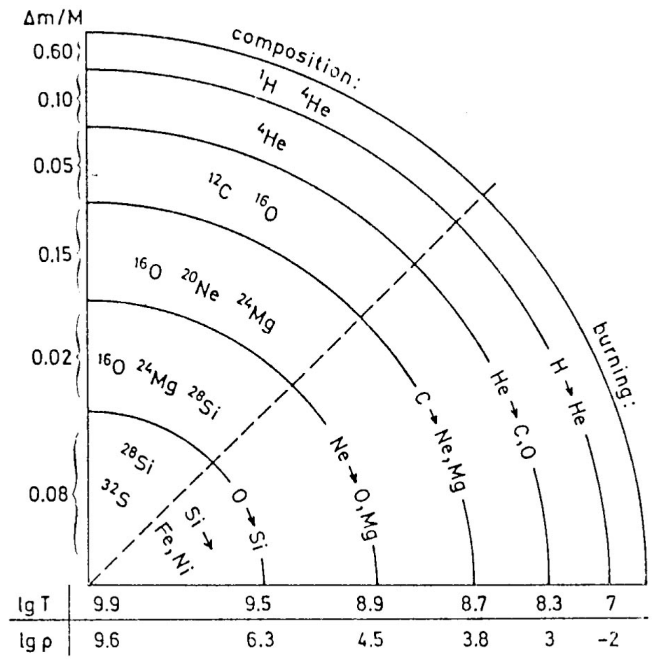

Figure 5.15: Illustration of the "onion-skin" structure in the interior of a highly evolved massive star. From Kippenhahn and Weigert [1990].

- A large number of neutrons begin to be produced.
- Silicon burning sets in through interactions with alpha particles.
- Then it moves into the shell.
- The process stops at the iron group, and the last reaction is ^{52}Fe capturing an alpha particle to make nickel.
- Further reactions would **require** energy to proceed. All reactions now are balanced by their inverse reaction.
- Figure 5.15 shows how the core builds up its layers this way.
- For a $15M_{\odot}$ star, the burning of each successive element is rapid:

$$\mathrm{H}(10^7); \mathrm{He}(10^6); \mathrm{C}(10^3); \mathrm{Ne}(10^1); \mathrm{O}(10^1); \mathrm{Si}(10^{-1}), \tag{5.26}$$

  where the times are in years.
- Since all this happens so quickly, the surface is basically "frozen in" and the star does not move from right to left until it explodes.

5.5.2 Type II supernova - core collapse

- The core of the massive star is hot, $T_9 \approx 10$, and electrons are relativistic.
- Simply, the ratio of specific heats, γ, drops below 4/3 and the star is in an unstable configuration.
- After silicon burning, electrons are captured by protons

$$p^+ + e^- \longrightarrow n + \nu_e, \tag{5.27}$$

  producing a lot of electron neutrinos and neutrons.

- Neutrinos carry away energy, cool the core, and pressure drops.
- Photo-disintegtration produces many free α particles.
- The loss of free electrons also reduces the pressure.
- The core collapses from overlying weight on the scale of a few seconds.
- This collapse halts when the neutron degeneracy pressure kicks in ($\rho \approx 10^{15}\,\mathrm{g\,cm^{-3}}$) - note that this is nuclear matter density!
- Energy release of about 10^{53}erg from change in gravitational energy $GM^2/\Delta R$.
- This is as much light as a galaxy shines at for decades.
- In one scenario, most of the light is not released however, but goes into the kinetic energy of a shock.
- This propagates outward into the outer core region that is still collapsing.
- Naively, this might blow off the outer layers, but that does not happen.
- In the more accepted scenario, the increased core density causes it to be optically thick to neutrinos.
- They begin to deposit their energy into the material.
- This causes the outward shock that blows off the star's layers.
- This is the core-collapse Type II event.
- Heavy nuclei are created through neutron capture (s and r processes)
- Just to note, the neutrino cross section is extremely small, and its mean free path is

$$\ell_\nu = \frac{1}{n\sigma_\nu} \approx \frac{1}{\mu_e A}\left(\frac{\rho}{\mu_e}\right)^{-5/3} 1.7 \times 10^{25}\,\mathrm{cm}. \tag{5.28}$$

- $\mu_e = 2$, $A = 100$, and a density of about 10^{10}, $\ell_\nu \approx 10^7$cm, which is contained withing the collapsing core
- So neutrinos do not escape without interaction.
- About 1% of the energy goes into the outward motion, and 1% of that gets released as photons
- So only about 10^{49} erg of energy gets radiated over a few months
- We observe these supernova because hydrogen lines are present.
- The collapse occured when a H-rich envelope still existed.
- If the initial star was $M \geq 25M_\odot$, the remnant is likely a neutron star.
- For higher masses, it is too much to be supported by neutron degeneracy pressure.
- The object then becomes a **black hole**.
- If the initial star was over $100M_\odot$, or a core He mass of about $40M_\odot$, a different scenario might take place.
- After He burning the thermal environment produces electron-positron pairs, reducing the specific heat so that $\gamma < 4/3$.
- The star immediately starts to collapse and subsequent burning is not enough to halt the collapse.
- The star produces a black hole in a *pair-instability* supernova.

5.5.3 Neutron star

- Masses between 1.2 and $2.5M_\odot$ and $R \approx 10$km
- The mass-radius relationship for neutron stars in each case is (derived from our polytropic equations):

$$M = \left(\frac{15.12\,\mathrm{km}}{\mathrm{R}}\right)^3 \mathrm{M}_\odot;\ \mathrm{non-relativisitic} \tag{5.29}$$

$$M = 5.73\mathrm{M}_\odot \equiv \mathrm{M}_{\mathrm{Ch}}^{\mathrm{NS}};\ \mathrm{relativisitic} \tag{5.30}$$

- However, tne maximum mass of a neutron star depends on the existence of a general-relativistic instability (interactions between nucleons)
- This likely takes place well before the M_{Ch} for a neutron star, hence the $\sim 3M_\odot$ limit
- Most neutron star observations are in a very narrow range of masses $M_{\mathrm{ns}} = 1.35 \pm 0.04M_\odot$.
- The neutron-degenerate material creates mostly an isothermal environment.
- They cool down faster than WDs.

5.5.4 Black hole

- For Type II remnant $> 2.5M_\odot$, or a progenitor $> 25M_\odot$, a black hole is produced.
- The radius, determined from the escape velocity, is:

$$R = 2\frac{GM}{c^2} = 2.95 \times 10^5 \frac{M}{M_\odot}\ [\mathrm{cm}]. \tag{5.31}$$