AST 301 Introduction to Astronomy

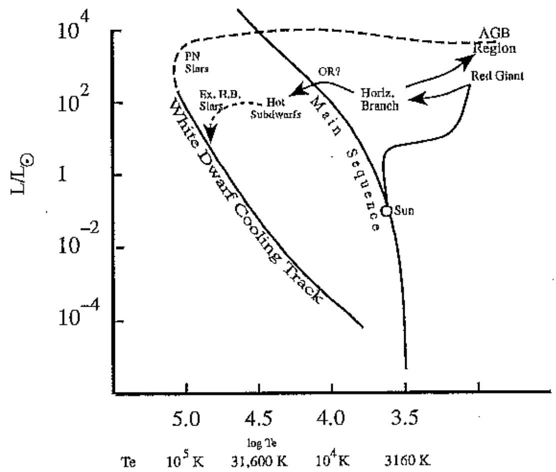
Classnotes 16

Progenitors

White dwarfs are the end product of stellar evolution for stars with main sequence masses less than about 8 $M_\odot$. We believe most stars that form white dwarfs follow the evolutionary path

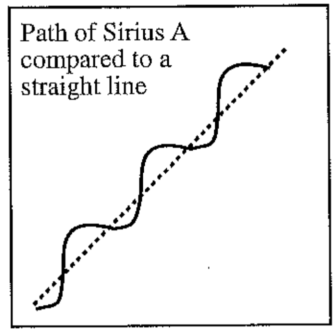
Red Giant → Horizontal Branch Star → Asymptotic Red Giant → Planetary Nebula → White Dwarf

However, there are other objects, called hot subdwarfs and extreme horizontal branch stars that appear to have gone through the horizontal branch and evolve straight towards the white dwarf region without going to the Asymptotic Giant Branch. See the H-R diagram, right, for a schematic of these evolutionary paths.



A Bit of White Dwarf History

The first white dwarf was Sirius B, called "the Pup", through the wobbles in the path of Sirius A, the "Dog Star" a Canis Majoris, as it moved through the sky. F. Bessel realized the wobbles made sense if an unseen companion orbited Sirius A. In 1861, astronomers saw the 9th magnitude Sirius B in spite of the glare from Sirius A. After determining the orbit, astronomers found that Sirius B had a mass comparable to that of the Sun ($M = 1.05 M_\odot$) but was much less luminous than the Sun ($L \sim 0.02 L_\odot$). Thus Sirius B was *not* an ordinary main sequence star. The mystery deepened when the spectra of Sirius B showed hydrogen



lines like a main sequence A star. Thus, in the early 1900's astronomers knew that Sirius B had a mass similar to the sun's, was hotter than the Sun at the photosphere, and was less luminous than the Sun. Astronomers could then calculate the radius of the Pup ($R \sim 0.01 R_\odot$), the mean density = mass/volume = 10^6 g/cm^3, and the gravitational acceleration at the surface 10^8 cm/sec^2 = surface gravity.

The density and surface gravity far exceed anything known on the Earth. The density is 1 million times greater than water and 50,000 times greater than the densest metals. Earth's surface gravity is 981 cm/sec^2, so a 180 lb. person on Earth would weigh...180 lbs $\times 10^8/10^3 = 1.8 \times 10^7$ lbs. This is the weight of a good size ship!

Only until the 1920's when physicists worked out the behavior of a degenerate electron gas, did astronomers realize the true nature of white dwarf stars. Then in the 1930's S. Chandrasekhar included relativistic effects and determined that white dwarf stars have a maximum mass, which we'll discuss later.

Physical Conditions in White Dwarfs

We've already described the extreme physical conditions in a white dwarf, but here we will describe some of the consequences of these conditions on white dwarf matter.

The density of material inside a white dwarf implies an average separation between atoms of about 10^{-10} cm, which is too small for electrons to stay bound to their atoms. Recall atoms have a size of 10^{-8} cm or so. As a result, the material in a white dwarf is completely ionized (except near the surface). Thus, we have a mixture of ions and electrons in a white dwarf that are pressure ionized.

The high densities make quantum mechanical effects of electrons important, allowing the Heisenberg Uncertainty Principle and Pauli Exclusion Principle to come into play. The Heisenberg Uncertainty Principle is:

$$\Delta X \Delta p_X \geq \hbar$$

where $\hbar$ is a very small number (Planck's Constant). In a white dwarf, the great densities severely limits the positions of the electrons, making Δx small. As a result, Δp_x shoots up, and the electrons have very large momenta (hence energies) that has nothing to do with the temperature of the gas.

The Heisenberg Uncertainty Principle also contains the seeds to setting a limit on how massive a white dwarf can be. Remember, nothing goes faster than light, so the maximum momentum of an electron is set by the speed of light and so there is a maximum pressure provided by degenerate electrons. This maximum sets the maximum mass that a white dwarf may have.

This mass is called the Chandrasekhar mass and depends slightly on the composition of the material; it is for a carbon-oxygen core.

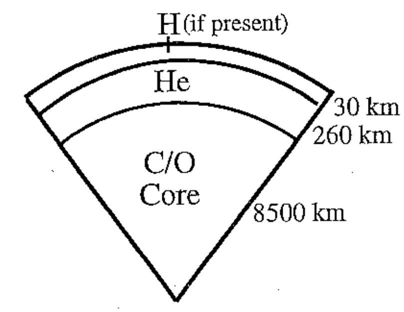
$$M_{ch} = 1.44\ M_\odot$$

White Dwarf Structure

The average white dwarf has a mass near $0.6M_\odot$ and comes in one of 2 "flavors".

~ 80% or so have pure hydrogen atmospheres.....DA
~ 20% have pure helium atmospheres..................DB
A few have other compositions.

We don't see the heavier elements because the very high gravities causes heavier material to sink to the center, leaving the lightest elements on top. This means DB white dwarfs have no hydrogen, otherwise we would see it on the surface. This gravitational sorting give white dwarfs a layered structure. The remnant hydrogen and helium layers must be quite thin to avoid fusion at the base of the layer. The maximum helium layer mass is



Cross Section of a Typical White Dwarf

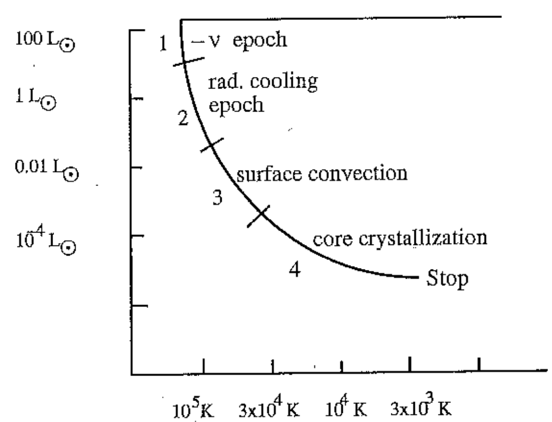
$$M_{Me} \leq 10^{-2} M_*$$

and the mass of the hydrogen layer mass is:

$$M_H \leq 10^{-4} M_*$$

thus the degenerate Carbon/Oxygen core makes up *at least* 99% of the White Dwarf's mass.

There are no internal energy sources in a white dwarf, so it radiates the immense amount of heat stored by the ions out into space. The outermost nondegenerate layers act as an insulating blanket.



White Dwarf Cooling

A good analogy for our discussion here is a very hot cannonball wrapped in a layer of asbestos. The ions are nondegenerate and hold the heat reserves of the white dwarf, while electrons have no heat stored in them, but provide pressure support. As a result, white dwarf cooling is essentially independent of white dwarf structure.

Four Major Phases

1. Pre white dwarf at $\gtrsim 100\ L_\odot$:
neutrinos are emitted and these cooling dominate the cooling process.
2. Hot white dwarf between $10L_\odot$ and $0.1L_\odot$:
heat radiated through photosphere dominates in cooling.
3. Surface convection Zone develops $0.05L_\odot - 0.005L_\odot$:
surface starts to boil, and surface composition matters now.
4. Core Crystallizes $\lesssim 0.0001L_\odot$:
The oldest white dwarfs, which are the age of our Galaxy, are in this final stage.