Cooling White Dwarfs

   White Dwarfs are some of the oldest relics in our galaxy. They come from post AGB stars that aren't big enough to do anything exciting like go supernova nor collapse to a black hole. These stars (usually ranging from 1 to 8 solar masses) merely shrug off their outer layers leaving a core of mostly ionized carbon and oxygen. The average mass of a white dwarf is .6 solar masses, but they have been known to have a radius of about 1 earth radius. These stars are very dense.

   At this point, fusion is no longer occurring in the white dwarf's core, so there is no radiation pressure keeping the star from collapsing. Instead, electron degeneracy pressure halts the collapse due to gravity. Electrons are forced to occupy the lowest energy level, but because they are fermions and must obey the Pauli-Exclusion Principle, only one may be in a single state at a time. Thus, this pressure from degeneracy builds up. This degeneracy also lends itself to high thermal conductivity. Because of this easy heat transfer through electron conduction, the white dwarf can be considered isothermal. Below, is a plot of temperature and degeneracy in the interior of a white dwarf from Carrol and Ostlie.
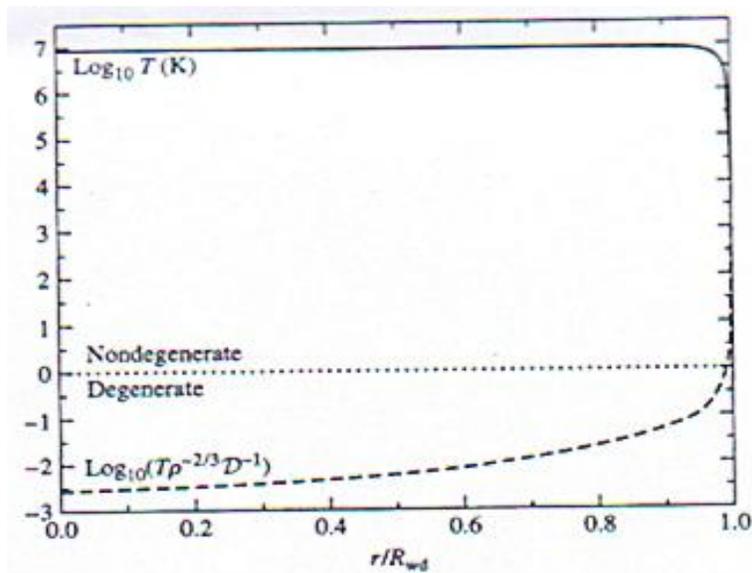

Figure 1: Temperature and Degenercy vs. Radius of a white dwarf: The top portion shows that temperature remains constant throughout the star until just before the surface. The bottom portion shows the amount of degeneracy in the white dwarf. The white dwarf remains degenerate also until right below the surface. The drop in temperature occurs at about the same radius that the white dwarf crosses into the non-degenerate area.

   Temperature remains constant through almost the entirety of the white dwarf. Near the surface there is a small convective envelope that is only partially degenerate, partially ionized, and not isothermal. This envelope may be a mixture of carbon, oxygen, and even helium or hydrogen left over from the AGB phase or accreted from the interstellar medium. Because there is no ongoing fusion, the white dwarf has nothing to do but cool off, and it

takes its time doing so. The coolest white dwarfs are the oldest stars in the galactic disk.

We can do a very basic estimation of the cooling timescale for a white dwarf. The luminosity is equal to the rate of energy loss.

$$L(t) = -\frac{dE(t)}{dt} \tag{1}$$

If we know the total energy content, then we can find the timescale. If we assume that the majority of the energy comes from the thermal energy $E_{Th}(T)$ of the white dwarf.

$$L(t) = -\frac{dE_{Th}(T)}{dT}\frac{dT)}{dt} \tag{2}$$

Thus, the cooling timescale:
$$t_{cool} \propto L^{-\frac{5}{7}} \tag{3}$$

This is a rough approximation, but it is surprisingly accurate.

In order to be more precise, there are other energies we should take into account:

A)Gravitational Energy
White dwarfs don't actually begin life as fully degenerate stars, and so contraction can still occur in places of low degeneracy. This release of gravitational energy contributes to the change in luminosity of the white dwarf - most notably during the first phases of evolution, and in the final phases.

B)Nuclear Energy Leftovers from the white dwarf's AGB phase may include residual burning of a helium or hydrogen shell. Helium burning may be a significant contribution to the luminosity function at very early times, but proton-proton burning is probably never significant.

More energies, including loss of neutrinos, thermal energy, and latent heat from crystallization are discussed in the next section.
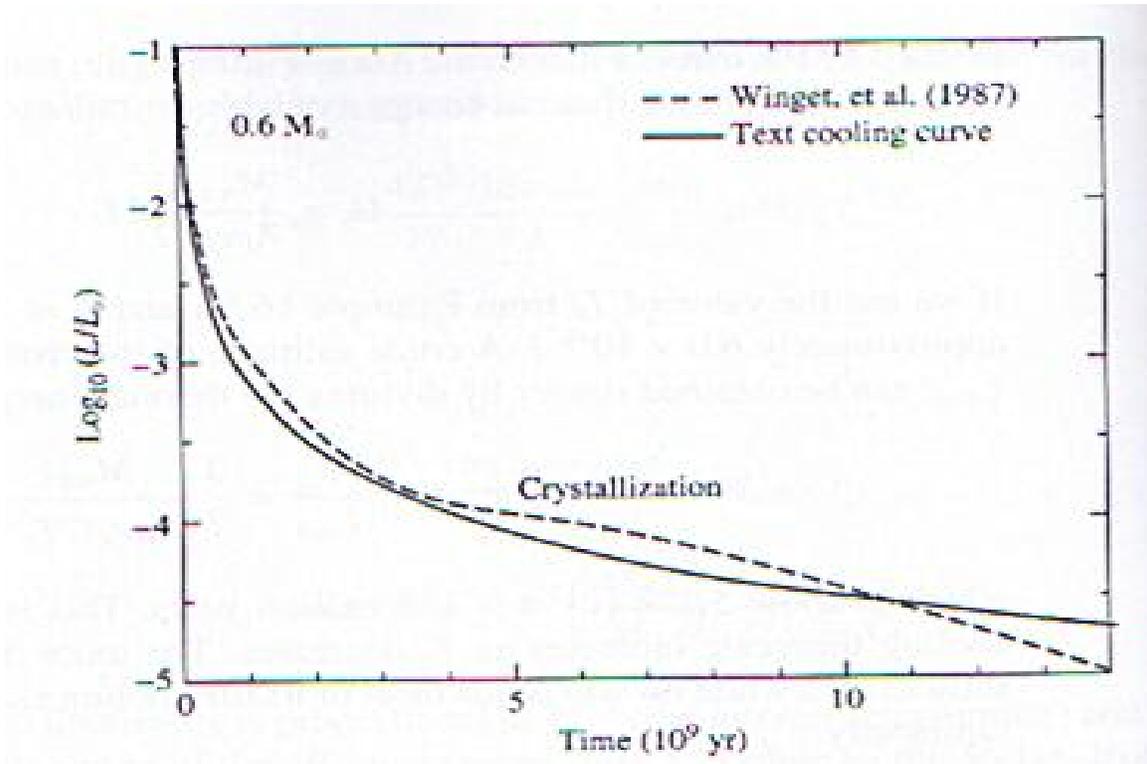
Figure 2: Cooling Curve: The log of normalized Luminosity verses time shows the slow depletion of energy is reflected in the lessening of luminosity. Specific parts of the graph are discussed below.

White Dwarf Cooling Models

For the following cooling stages, refer to Figure 2 which is the luminosity function for a .6 solar mass white dwarf.

There are four main stages in white dwarf cooling.

1)Neutrino Cooling $log\frac{L}{L_\odot} > -1.5$

At early times, the escape of neutrinos is the driving mechanism for cooling at early times. Stuff that is left over from the AGB and pre-white dwarf stages decays, and releases neutrinos.

2)Fluid Cooling $-1.5 \geq log\frac{L}{L_\odot} \geq -3$

At this time the loss in energy is mainly a thermal one. Heat is conducted through the degenerate interior and then transported through convection and radiated in the white dwarf envelope. The diffusion through this envelope which depends on the opacity plays an important role in the heat loss at this stage. In cooling models, the opacity is a major point of uncertainty, because it is not certain what the chemical make-up of the outer envelope is, nor exactly how degenerate it is. The opacity from an envelope of pure hydrogen is very different from the opacity of an envelope of helium, but it is more likely that the envelope is mixed. Unfortunately, convection depends on the chemical constitution but is also determined by it. The interplay between these parameters makes this one of the most complex parts of modeling the cooling curve.

3)Crystallization $log\frac{L}{L_\odot} > $ -3 or -4.5

At this point in the cooling time scale, we see the luminosity level off - what's referred to as a knee in the graph. This is due to the latent heat released from the crystallization of the interior of the white dwarf. The temperature has dropped enough that the thermal kinetic energy has dropped. Nuclei are settling down and moving closer together in a structure that minimizes the electrostatic interaction energy. If the white dwarf is mostly carbon, then the crystallization process essentially forms a diamond starting in the center, moving outward. The latent heat released in the changing of states delays the decrease in luminosity until most of the star has crystallized

4)Debye Cooling

After most of the star solidifies in this way, the cooling curve begins to decline again, more steeply than before. The crystal lattice causes coherent vibration, and this actually promotes energy loss. This is known as Debye cooling. The internal thermal content has been depleted and the subsequent contraction of the outer envelope contributes up to 30 percent of the luminosity output.

Observations to Check Theory

Up until now, we have been looking at the theory for the cooling process of a white dwarf. The plot from above shows us where we think white dwarfs of a certain luminosity are in their cooling process. One way to examine this theory from an observational standpoint is

to tally up the number of white dwarfs seen at each luminosity. Below is a plot of observed numbers of white dwarfs within the galactic plane verses their luminosity (Winget et al.)
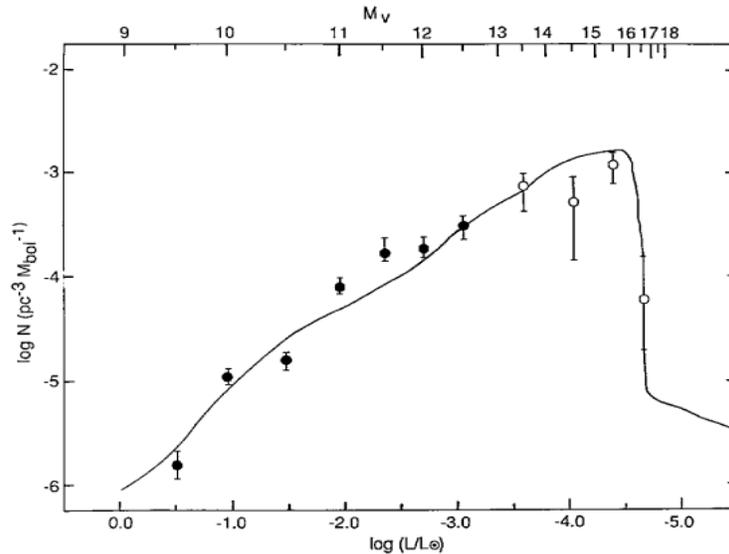

Figure 3: : White Dwarf Luminosity Distribution: log of the number of white dwarfs observed at a certain luminosity. The circles show the number observed, while the solid line represent the theoretical distribution.

The observed points in the above graph come from several sources. The hotter sources are mostly hydrogen atmosphere white dwarfs, though the statistics have taken into account the contribution from white dwarfs without hydrogen. The cooler white dwarfs were identified from the Lutyen Half Second proper motion catalogusing a method developed by Schmidt 1975. There were over 80 stars known as white dwarfs as of 1987.

The theoretical curve assumes a white dwarf of a completely carbon interior, and is a combination of models of different mass white dwarfs. From the cooling curve, it is possible to predict the number of white dwarfs at certain luminosities. Recall how quickly the luminosity dropped during the neutrino cooling phase. It makes sense to see very few white dwarfs at high luminosity, because that stage does not last very long.the number of white dwarfs rises as you reach luminosities corresponding to the fluid cooling phase because this phase is longer lasting. In the cooling curve, the knee of crystallization starts to form at luminosities of around 10^{-4}. Here, almost the same luminosity is maintained over the course of gigayears. This explains the large number of white dwarfs found at such low luminosities.

One surprise in the observed data is the lack of white dwarfs observed at low luminosities. This huge drop-off in observed number occurs well before the expected luminosity drop from Debye cooling. The idea of oservational bias against dim stars was expected and investigated. The same method from Schmidt was applied on M dwarf stars in the LHS proper motion catalog, but there were no shortage of dim stars. Something else is causing this huge dearth of dim (and therefor older) white dwarfs.

The most agreed upon idea is that these are actually the oldest white dwarfs from our galaxy. There are no stars that have yet reached the final states of cooling. In fact, the theoretical model creates the drop in the curve by assuming an epoch for the creation of the galaxy. The time for that epoch is varied until the theoretical drop-off matches the observed. This resulted in a cooling age for the oldest observed white dwarfs of 9 ± 1.8 Gyr

This has exciting implications. The age of the galaxy can be found by adding the white dwarf cooling time with the time the progenitor spent on the main sequence. The most prevalent mass of the white dwarfs at the drop in number is .8 solar masses. These most likely came from a progenitor of $2 \leq M/M_\odot \leq 4$. The average amount of time stars of these masses spent in all phases of evolution before becoming a white dwarf is $.3^{+0.8}_{-0.1}$ Gyr. This leads to an age for the galactic disk to be 9.3 ± 2.0 Gyr.

One can be ambitious and add this to the time between the big bang and the formation of the disk to get an age of the universe, but this involves deciding on a preferred cosmological model.

It is impressive how observations plus a cooling model for white dwarfs can lead to calculating the age for the galactic disk. White dwarfs are the key to a myriad of mysteries (including type Ia supernovae), and understanding them better can lead to knowledge more significant than of simply a leftover star.