Class notes for 16 November

Reminders
- Exercise 6 due Thursday
- Problem Set 6 due today – last one!
- Kitt Peak trip
- Poster Project coming up… Dec. 7
- Take home exam due Nov. 30 (last one!!)

15.1 Sirius B
- 1844 - Bessell found it wobbles...
- secondary not detected until 1862 apastron by Alvin Clark's son
- Amazing! Radius = 0.008 solar radii
- Effect on hydrogen lines (Sirius B is a DA white dwarf)
- Eddington (again) provided framework

15.2 White Dwarfs
- Very common, very dim
- White dwarf sequence – they come in all colors (blue, white, yellow, red…)
- Temperatures from < 4000 K to over 80,000 K
- Spectral types
  - DB (8%) – helium spectral lines
  - DA (70%) – hydrogen spectra lines
  - DC (14%) – NO SPECTRAL LINES, CONTINUUM ONLY
- Physical characteristics
  - Central pressure 1.5 x solar
  - Central temperature several x 10^7 K
  - Implies no hydrogen at the center, otherwise it would produce too much energy
- Origin – The cores of low and intermediate mass stars (less than 8 or 9 solar masses)
  - Mostly carbon/oxygen
  - Masses sharply peaked at 0.56 solar masses
  - Most of the stellar mass must be lost
- High gravity affects surface and spectrum
  - Heavier elements sink, hydrogen rises, atmosphere stratifies in 100 years or so
  - Thin outer layer of hydrogen
  - Sequence of DB-DA-DC still not clear…
    - Do the non-DA types have no hydrogen,
    - or is it mixed by convection zones
- Pulsating variables
- The instability strip passes through the white dwarf sequence at about 12,000 K
- ZZ Ceti variables (discovered by Landolt)
- Non-radial g-modes
- Periods between 100 and 1000 seconds
- Hydrogen partial ionization zone drives the oscillations
- Hotter DBs also pulsate due to the helium ionization zone

15.3 – Physics of Degenerate Matter

- What supports white dwarfs if there is no energy generation to provide pressure?
- Normal gas and radiation pressure are inadequate
- Electron degeneracy pressure: as temperature falls, electrons forced into lowest energy states, but only one can occupy any state.
- Even as T approaches zero, electrons will produce pressure, and the calculated electron degeneracy pressure is comparable to the estimate pressure at the centers of white dwarfs

15.4 – Chandrasekhar Limit

The pressure in a degenerate gas is independent of temperature and total mass:

\[
P = \frac{3\pi^2}{5} \frac{\hbar^2}{m_e} \left( \frac{Z}{A} \frac{\rho}{m_H} \right)^{5/3}
\]

Substituting in \( \rho = M_{wd} / \frac{4}{3} \pi R_{wd}^3 \)

We find that \( R_{wd} \propto M^{-1/3} \) (mass times volume is a constant)

So the more massive the white dwarf, the smaller it is (and the higher density)!

But if the density gets too high (above about \( 10^6 \) g cm\(^{-3} \)), relativistic effects begin to reduce the speed of electrons in a degenerate gas, and hence the pressure, and the star must be even smaller. This leads to a maximum mass for a white dwarf, or a maximum mass that can be supported by electron degeneracy pressure. The star becomes dynamically unstable (a small perturbation causes a collapse). The degenerate core implodes, pressure and temperature rise, and the carbon/oxygen core ignites suddenly – Type II supernova.

The Chandrasekhar limit occurs at 1.44 solar masses. No white dwarfs have been found with masses above this value.

15.5 – White Dwarf Cooling - How fast does a white dwarf cool?

They start at fixed, well understood conditions. If we can understand the cooling rate, we can learn the age of a white dwarf.
• Energy is transported by electron conduction.
  o Highly efficient
  o Interior is nearly isothermal
• Non-degenerate outer later insulates the interior.
• The energy radiated by a white dwarf comes from the thermal energy of the nuclei.

A crude estimate of the cooling time can be obtained from the thermal energy of the nuclei divided by the observed luminosity. That time scale suggests that white dwarfs cool in a few hundred million years. Actually, the temperature (and luminosity) declines faster when the white dwarf is hot, and very slowly when it is cool.

As the white dwarf cool, the nuclei in the interior gradually "crystallize," beginning at the center and spreading outward (the nuclei become locked in a lattice from the mutual electrostatic repulsion). The crystallization releases latent heat, providing energy to radiate and slowing the white dwarf's cooling rate. Once the whole interior is crystallized, the white dwarf's luminosity again begins to drop.

Crystallization has been observed in the gradual changing of pulsation periods in a D0V white dwarf (this is a tough, very precise measurement).

**The White Dwarf Luminosity Function**

Studying the number of white dwarfs as a function of luminosity can tell us about the star formation history of the Galaxy. The sharp decline in the number of white dwarfs with luminosities fainter than $M_V=16$ suggests that stars began to form at a particular time in the past, in fact about 9 Gyr ago.

This age is several billion years younger than the globular clusters, and the difference is still not understood.