Lecture Ten

The Life of the Sun

Salisbury University

The Fate of the Sun

The Main Sequence

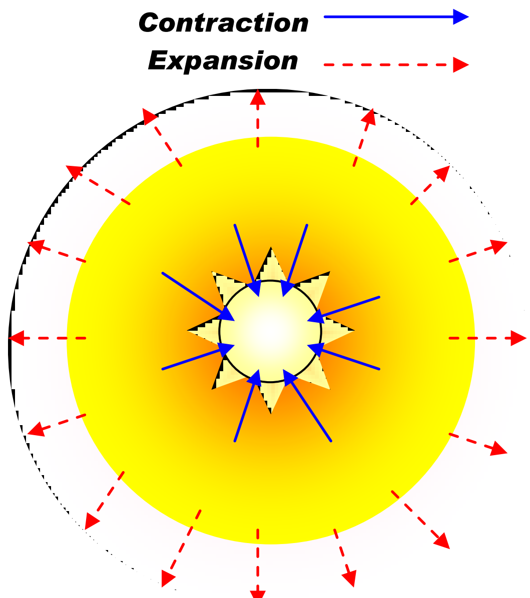


Figure 1: As hydrogen runs low in the core of the sun, hydrostatic equilibrium is no longer maintained and the star will adjust itself by doing something quite surprising - it will expand!

At the core, main-sequence stars are all very much alike. All main-sequence stars convert hydrogen into helium by the nuclear fusion processes of PP Chain (lower mass stars) or the CNO Cycle. This is often referred to as **Hydrogen Core Burning**. In reality, there is no real chemical "burning" going on the classic sense. It is not like "burning like a flame." It is only referred to a "burning" to indicate that the Hydrogen "fuel" is consumed and the result is Helium ("ash").

What happens to a star after the core hydrogen is used up? Well, the star undergoes some rather interesting changes.

It is time to remind you about "**Hydrostatic Equilibrium**." As you recall, this is what we call the ongoing balance between the **inward gravitational** pull wanting to collapse the star's core and the **outward gas pressure** that wants to cause the core to expand because the core has a strong energy (heat) producing thermonuclear reaction occurring. Remember these two competing processes.

With this reminder, which of these two ceases to exist adequately when the hydrogen fuel runs out to only leave the helium by-product in the core? And, then because of this, what does the core do?

- As the fuel runs out, the hydrogen fusion that was helping to produce the outward pressure is no longer present, thus gravity wins! (Gravity always wins, this will actually become a reoccurring theme, because outward gas pressure only puts up a short-lived fight.)
- So, gravity will cause the core to contract, getting smaller, getting denser.
- This compression raises the density of the core and also begins to greatly increase the core's temperature. There is yet, no fusion.
- The core, which is originally around 10 million degrees Kelvin (10^7K), is now getting significantly hotter! Something else begins!

Hydrogen Shell Burning

As the core contracts and heats from 10 million to 20, 30, 40…etc million K, the hydrogen still present around and close to the core (but not inside the core) suddenly finds itself in an environment that is hot enough and dense enough for its own fusion to begin around the contracting and heating core!

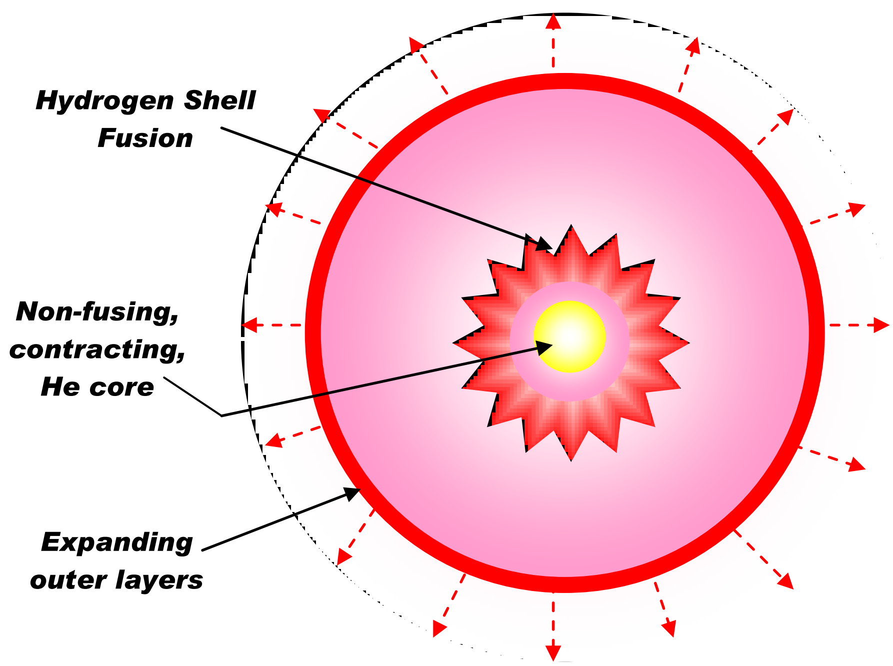


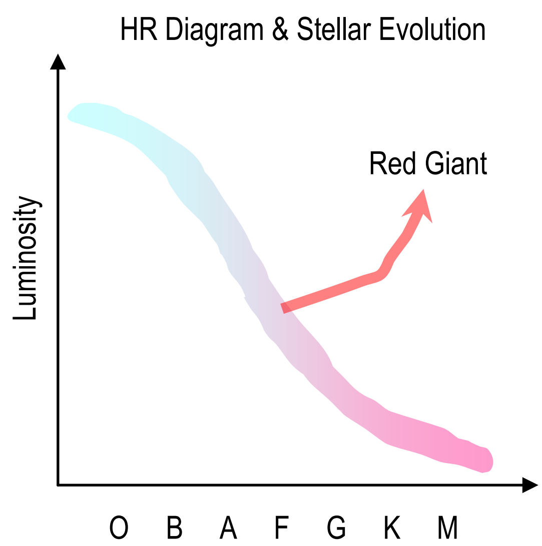
Figure 2: The evolving structure within a star like the sun as it becomes a Red Giant. The inner core contracts an heats up searching for another fusion source as the outer envelope expands and cools down in response to the change going on in the core.

And, then because of the core's behavior, the thin shell of hydrogen fusion around it, what will the rest of the star do?

Joe Physics: What would happen if you were to strike a match inside a large balloon? What happens to the balloon's size?

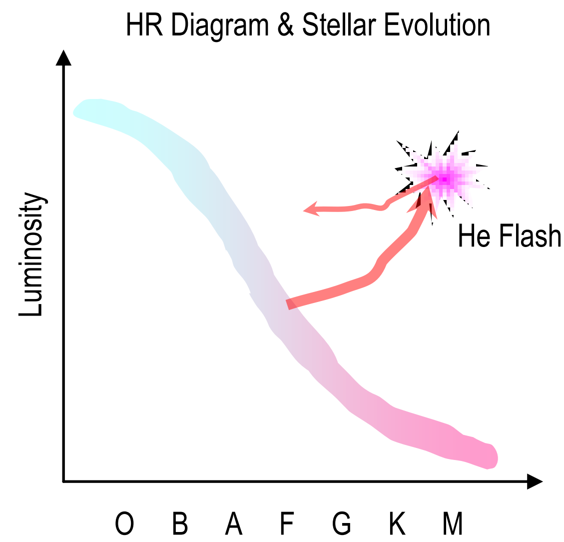
- The rest of the star actually expands as the core contracts and hydrogen shell fusion begins! Very interesting!
- As the core's density and temperature increases, this causes the outer envelope of gas to expand, and because the particles in the outer envelope are getting farther away from that hot core, the surface of the star will actually cool down.
- So, core contracts and heats as the rest of the stars layers expand and the surface actually cools down!

Note: It may seem strange, but the temperature in the core of a star actually increases when fusion stops!



- The tremendous expansion of the star's outer layers causes those layers to cool down, and the star's surface (**photosphere**) temperature drops.
- The star is getting to be very large, so how easy do you think it becomes to see? The star's luminosity greatly increases [even though its surface temperature decreases] because it is so large!
- As the temperature drops, what color does it become? [**Hint**: Remember that pesky blackbody radiation!].
- The star is getting much large and redder. The star is then appropriately given the name "**Red Giant**." Thus, Red Giants are stars that have finished their time as main-sequence stars and have evolved into a new phase of their lives!

A star is well on its way to becoming a **Red Giant** when the shell of hydrogen fusion begins around the nearly helium pure and contracting inner core. In about 5 billion years the Sun will experience changes like these as it evolves into its red giant stage. In a star like the Sun, at this time in the future, the dense helium core is about twice the diameter of the Earth while the rest of the star's bloated remainder has a diameter of nearly 1.0-2.0 AU. [[Yes folks, that is AU as in astronomical units. Yikes!]]



Let's get back to that contracting core, 60, 80, 100 million deg. K.

As the hydrogen shell fusion adds mass to the helium core, the core contracts even more, further increasing the star's central temperature and density. When the central core reaches the "magic temperature of 10^8K," **Helium Fusion** begins in earnest. For stars like the Sun, Helium fusion begins explosively, suddenly, and violently in the core. – **HELIUM FLASH**!

He Fusion

William Alfred Fowler (1911-) Pittsburgh, Cal-Tech, Nobel 1985.

$$^{4}He + ^{4}He \rightarrow ^{8}Be \quad \text{(but } ^{8}Be \text{ is unstable)}$$

$$^{4}He + ^{8}Be \rightarrow ^{12}C + \gamma$$

$$^{4}He + ^{12}C \rightarrow ^{16}O + \gamma \quad [[50\% \ ^{12}C \ ; \ 50\% \ ^{16}O]]$$

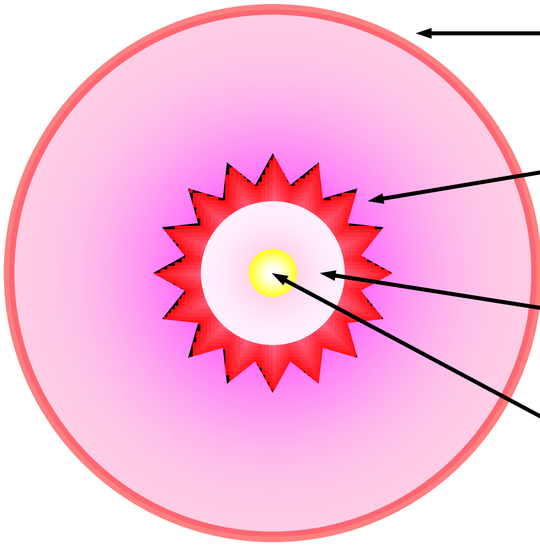


Figure 3: The internal structure of a Red Giant star. He fusion has begun in the core and it again returns to hydrostatic equilibrium.

Ah! We can get back to a nice balanced life; **Hydrostatic Equilibrium** is now re-established, at least that is for "a little while." Just before core helium fusion begins, the evolutionary track of the Sun on the **HR Diagram**, turns upward into the red giant region. After the Helium flash stars like the Sun shrink slightly and become less luminous and obtain a bit of a warmer surface temperature. This track is outlined in figure with the He Flash marked with the "pop-asterisk". This is often called the "**horizontal branch**." The Red Giant is now back in hydrostatic equilibrium because gravity is once again balanced by outward gas pressure created by a new energy source from He Fusion.

Helium Fusion creates the nuclei of carbon and oxygen. After a very short million years or so, we begin the whole internal readjustment again because the helium in the core begins to run out and the energy producing He fusion begins to dwindle. Without the fusion reactions to maintain the core's outward pressure, the core again falls to the power gravity and begins to contract. Like before, as the core (100 million degrees), begins to contract - it will heat up. What happens to the rest of the star? It will expand and cool some. The Sun enters another red giant phase! Stars, like the Sun, in this stage have entered the "**asymptotic giant branch**."

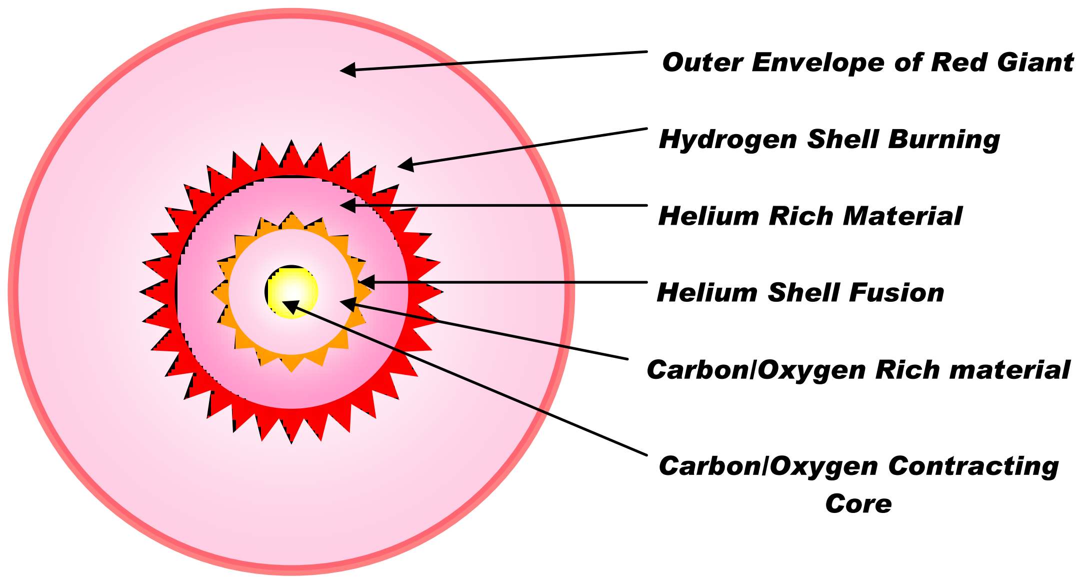
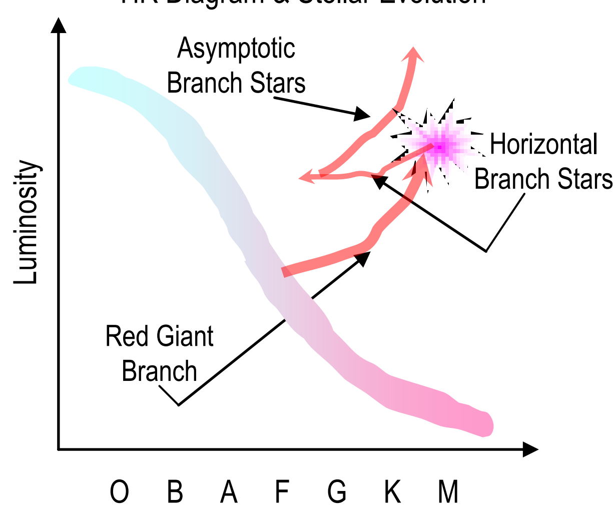


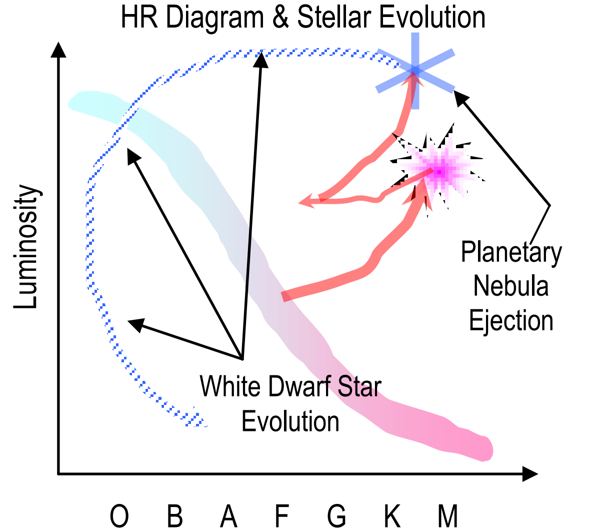
Figure 4: The death of a red giant star begins the process again. A contracting heating core causes the outer envelope to begin to, once again, expand.

<u>Here is a very important dividing line</u>: Sun-like stars (low mass stars which are less than about 8 solar masses) will have a very different continued evolution than medium mass stars (between 8-25 solar masses) and high mass stars (greater than 25 solar masses).



Low-mass, Sun-like, stars

These stars die gently ejecting their outer layers, creating a new an interesting structure around a hot dense stellar corpse. The **<u>Asymptotic Red Giant star</u>** has a **<u>hydrogen fusing shell</u>** that pulsates (turns on and off), a **<u>Helium fusing shell</u>** that also pulsates, a **<u>contracting C/O core</u>**, and an



expanding cooler envelope that is very tenuous and loosely held to the rest of the star. As the core contracts, the star is again looking for a way to restore hydrostatic equilibrium, it is needing another thermonuclear fusion fuel. Unfortunately, for low-mass stars this pursuit is in vain. The C/O core of Sun-like stars is just not going to be dense nor hot enough for it to ever fuse Carbon or Oxygen. Quite honestly, the star at this stage is a car engine that is struggling to run as it runs out of gas, it heaves, sputters, runs, partially stalls, etc.... The star experiences **"thermal pulses"** as the shell burning pulsates and sputters on and off. During these thermal pulses, the dying star's outer layers can separate completely from the hot dense carbon-oxygen core. The dying star literally pushes off, whooshes, and kicks-off its outer hydrogen rich outer envelope! The stellar corpse, becomes a structure with two distinct parts: the hot (nearly 100,000K) carbon-oxygen core which we call a **white dwarf** star, and the expanding spherical shell of heated gases of the ejected envelope called a **planetary nebula (PN)**.

> **Caution**: The name for this structure "planetary nebula" has nothing to do with planets. This name is a historical legacy because during early nineteenth century telescope observations these objects "looked like fuzzy planet-like objects."

We have already learned that the lower mass stars on the main sequence are among the most common stars in the universe, thus it stands to reason that their stellar deaths and the structures associated with them are fairly common as well. Astronomers estimate that there are probably 20,000 to 50,000 PNe in our galaxy alone. Also of note is that **PNe** (PNe is plural for PN) are relatively short lived when compared to other stellar objects. Why? Well, the material in the nebula is slowly getting dispersed as it continues to spread out from the cooling white dwarf and will simply fade away in a short 50,000 years after its creation.

Figure 4: The bright reddish-orange stars in this beautiful image of globular star cluster M10 are examples of the red giant phase of stellar evolution. Yet, the bright blue stars apparent in M10 have evolved beyond the hydrogen shell burning stage. These stars have become "horizontal branch" giants with core temperatures hot enough to burn helium into carbon. In this image, only the barely visible, faint, gray-looking stars likely still burning hydrogen in their cores. *(Image: Courtesy of T. Credner, Sven Kohle, & Hohner List Observatory)*

A Gallery of Planetary Nebulae / White Dwarfs

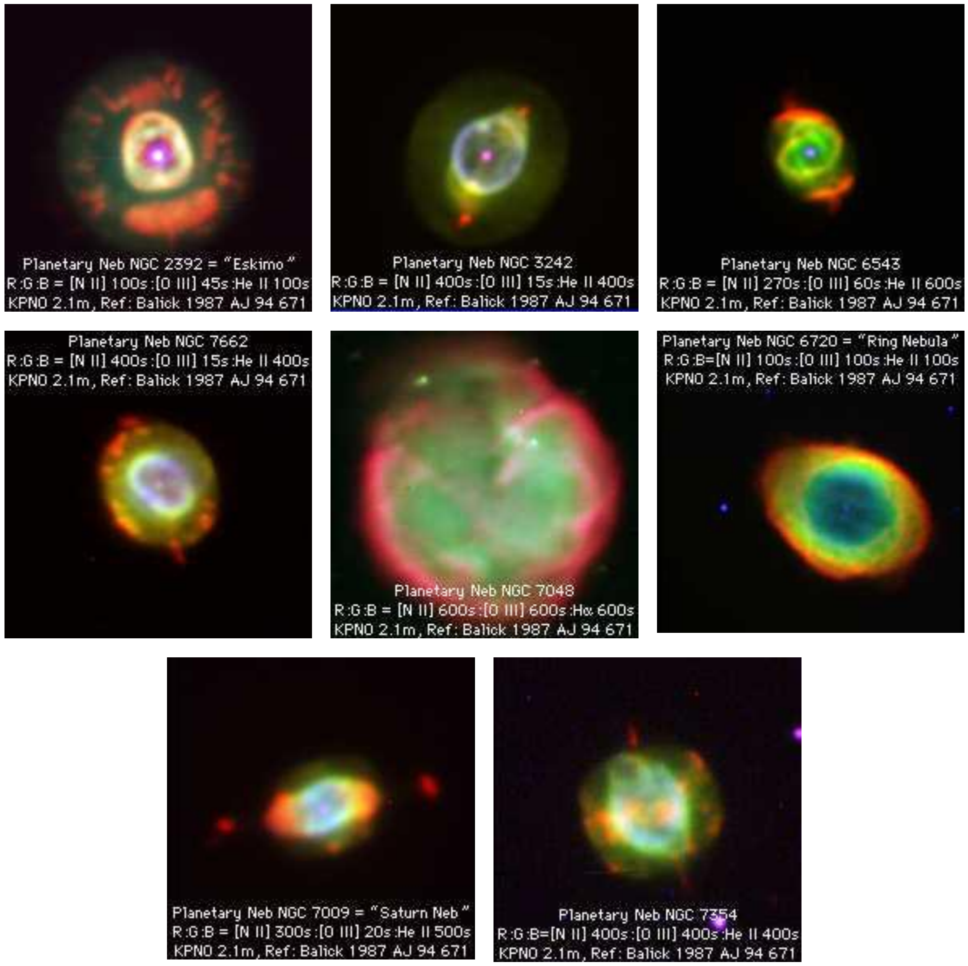


Figure 5: Planetary nebulae are characterized by a shell of material moving away from a hot (temperatures 20,000 - 100,000 K) faint white dwarf star at speeds of 10 - 30 kilometers per second. The glowing shell is made of various types of ionized elements. The greenish tints are due to the emission from doubly ionized oxygen (OIII) and the reddish tints are primarily due to hydrogen emission. *(Images: Courtesy of Bruce Balick)*

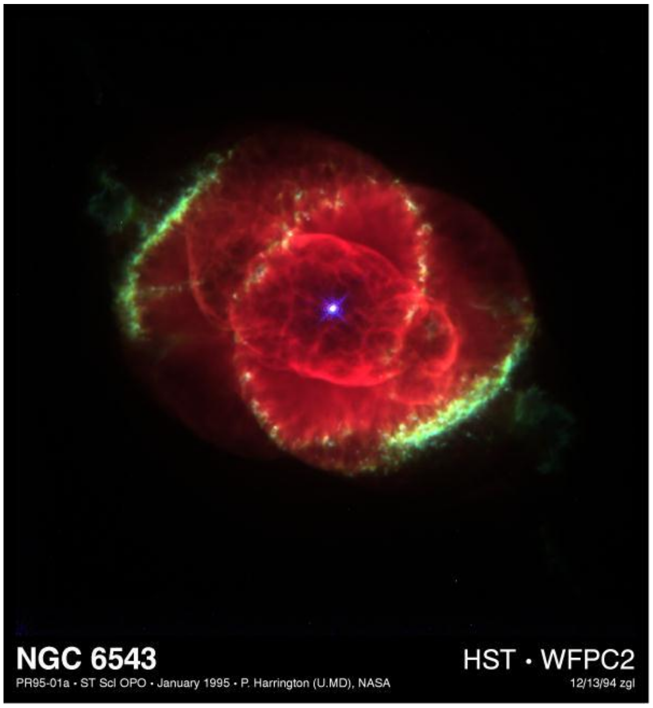


Figure 6: This NASA Hubble Space Telescope image shows one of the most complex planetary nebulae ever seen, NGC 6543, nicknamed the "Cat's Eye Nebula." Hubble reveals surprisingly intricate structures including concentric gas shells, jets of high-speed gas and unusual shock-induced knots of gas. Estimated to be 1,000 years old, the nebula is a visual "fossil record" of the dynamics and late evolution of a dying star. *(Courtesy of J.P. Harrington, K.J. Borkowski, & NASA/HST)*

Why do some of the planetary nebulae look hollow in the center, or ring like? I thought you said that the material is roughly a spherical shell of expanding hydrogen rich material? The answer is in "perspective." What are you seeing from your vantage point?!

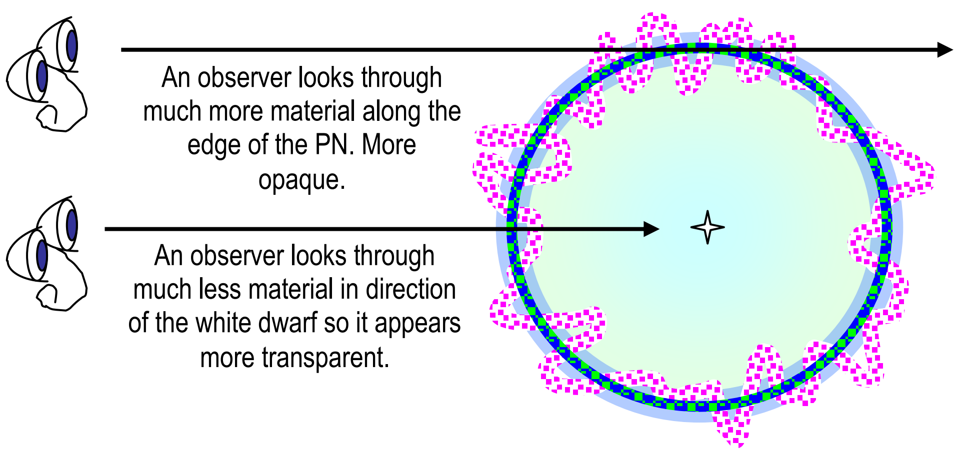


Figure 7: The reason a spherical distribution of gas appears as a "ring" is all a matter of how much material you are looking through.

What happens to the inner carbon-oxygen core that we call a **White Dwarf**? Low-mass star cores never develop the required density nor temperature to begin anymore thermonuclear reactions. These stars instead create the planetary nebula and a very hot central "glowing ember" made of mostly pure carbon and oxygen. With no thermonuclear reactions taking place, the core simply continues to contract and cool off until it becomes the white dwarf star. The gravitational collapse of the white dwarf is finally halted, not by any gas pressure as before, but by **electron degeneracy pressure**.

As the core contracts, the free electrons that are present in the highly heated and compressed gas, become so closely crowded that they will eventually begin to resist any further compression. Translation? Simply, you can not force two or more electrons to compress into the same location. [[**Joe Physics**: Analogy, it would be quite uncomfortable if I required every student in the classroom to occupy only the volume of one desk.]]. Electrons are excluded from being crammed to closely together. Once this **Pauli Exclusion** is reached and the electrons are acting under a **degeneracy pressure**, the core contracts no more. Since this new "outward pressure" is present to halt the further collapse of the white dwarf, the temperature of the core no longer really matters. There is no way for the white dwarf to maintain as an energetic heated source, thus the white dwarf begins a long slow cool down period. Once the white dwarf cools, in roughly 10 billion years, it will no longer shine and be a "**black dwarf**" and the planetary nebulae will have long since dissipated.

White Dwarf stars are quite small by stellar standards; approximately the same size as the Earth. However, don't let the small size fool you. The mass contained in the white dwarf is typically 0.6 to 1.4 solar masses. Yes, that is correct. You can have the mass of the Sun in the volume of that of the Earth in a White Dwarf! That is incredibly dense!

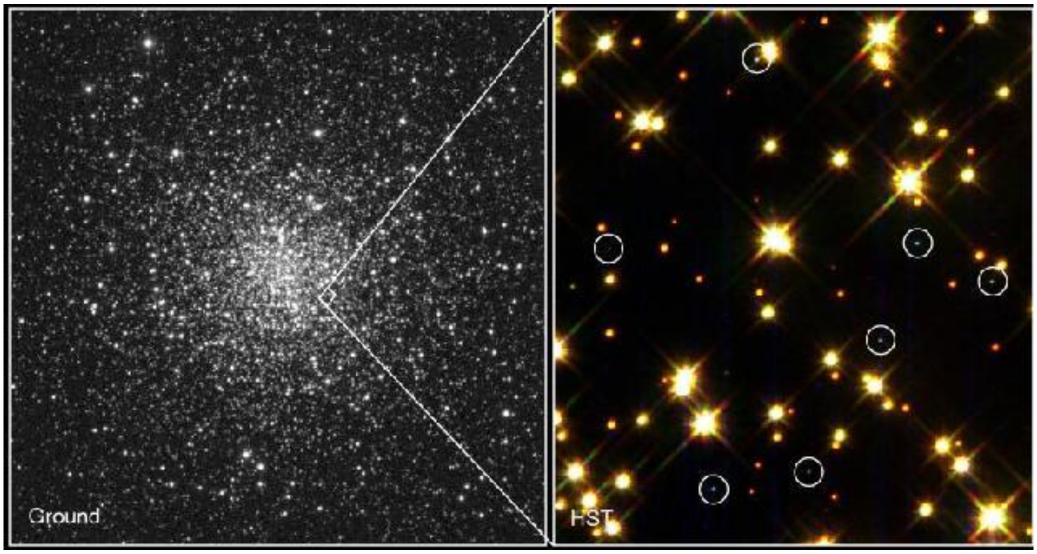


Figure 8: The image shows globular cluster M4, taken with a ground-based telescope. The right image is a small portion of the cluster. The Hubble Space Telescope found 75 white dwarf stars in the area it viewed. 40,000 are predicted for the cluster as a whole. (Image courtesy of NASA's Hubble Telescope & STSci)

Chandrasekhar Mass Limit

The maximum mass that a White Dwarf must have is called the **Chandrasekhar Mass Limit**, which is equal to 1.4 solar masses. Well, just as we have already mentioned, these stellar remnants come from a certain mass range of main sequence stars, so it stands to reason that white dwarf stars will also only have a certain range of mass. However, there is one more interesting fact at work here. White Dwarfs are supported from further contraction by electron degenercy pressure and do no like to be crowded further, this is not to say that electrons can not be "forced by gravity" to compress further. [[**Joe Physics**: Analogy. Suppose, even though you do not like it, I come along with a bulldozer and force every student in the class to occupy the one single desk. Realize I have nothing against anyone.]]. We will find this fact quite illuminating when we talk about the stellar evolution of medium and high-mass stars.