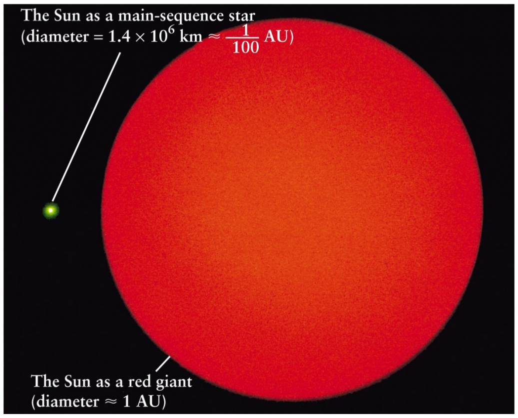
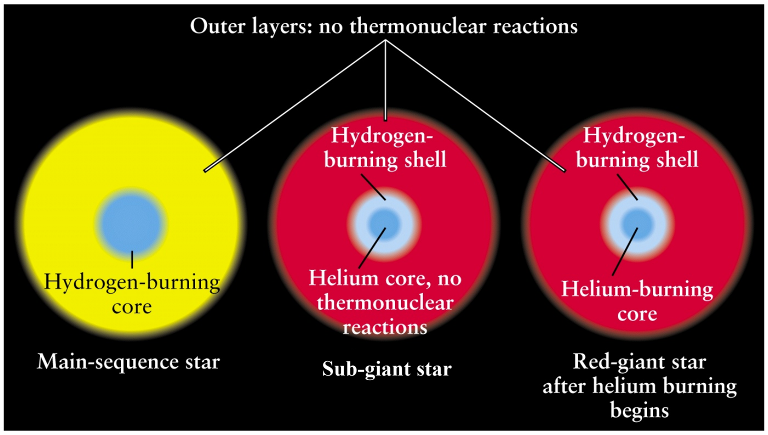
Stellar Death



Universe by Freedman, Geller, and Kaufmann

Interior Changes

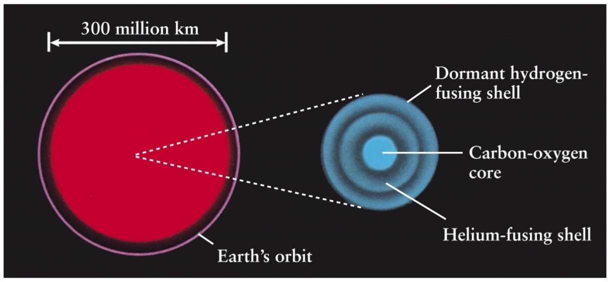


Universe by Freedman, Geller, and Kaufmann

Post-Helium Burning

What happens when He in the core is exhausted by burning it into C and O?

1. The core must contract, which increases the pressure and temperature of the overlying layers. 2. Thus, He ignites in a shell just outside the core, and H burns in a shell just outside of that. The star is now in a double-shell-burning stage. The mass of the inert CO core continues to increase, and it continues to contract just as the He core did when the star first left the main sequence.



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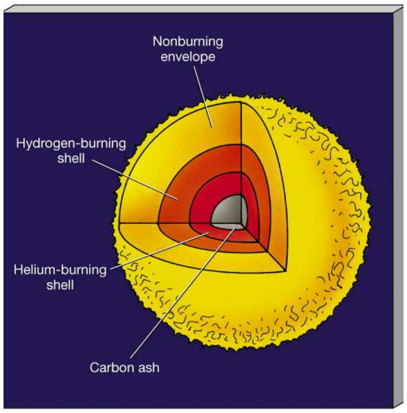
Post-Helium Burning

7. In stars with masses similar to that of the Sun, the formation of a Carbon-Oxygen core signals the end of the generation of nuclear energy at the star's center. These stars cannot make the CO core hot enough to fuse.

[However, larger mass stars can build up many layers of heavy elements that are fusing to form still heavier nuclei.]



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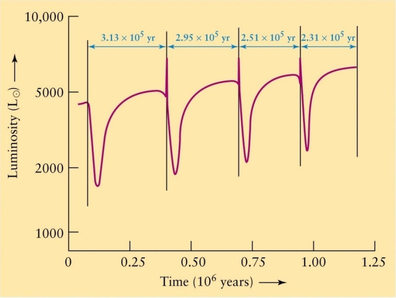
Mass Loss and Ejection



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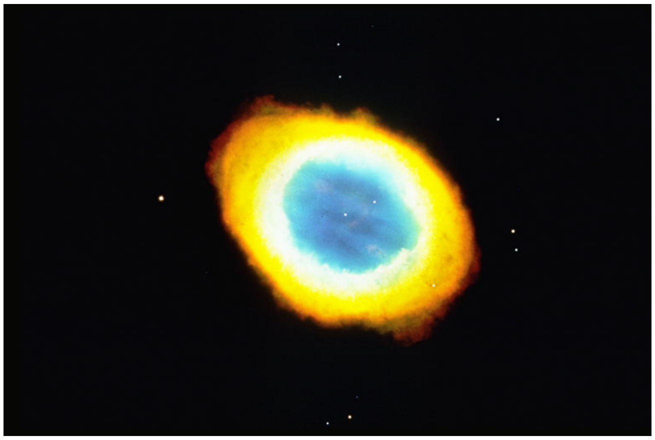
As the star undergoes a series of "**thermal relaxation oscillations**," the period decreases.

Can constructive interference of multiple periods lift off the outer envelope?

Actual process is still unknown.

Planetary Nebulae



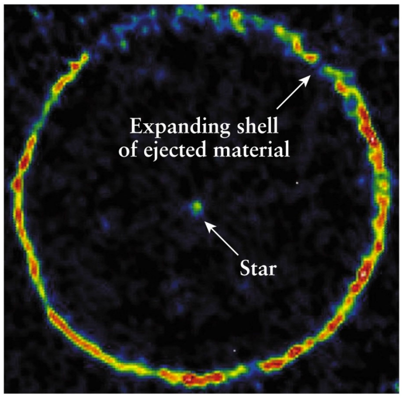
Ring Nebula

Discovery of Planetary Nebulae

In 1785 William Herschel [discoverer of Uranus] announced the discovery of a new kind of heavenly body in Aquarius, referring to its "**planetary**" (i.e., "disk-like") appearance. Further observations convinced him that the object and others he found consisted of some sort of "shining fluid."

The next year he discovered that (a) one of his "planetary nebulae" had a star in the middle of it and that (b) this star was clearly connected with the surrounding nebulous cloud. Nearly 80 years later, Sir William Huggins using a spectroscope proved that Herschel was right – emission lines in the spectrum showed that the nebula was a gas.

Planetary Nebula



H. Olofsson, Stockholm Observatory, et al. / NASA

For stars of no more than a few solar masses, one of the most important mass-ejection mechanism is the planetary nebula phenomenon.

The mass is 10% to 20% that of the Sun.

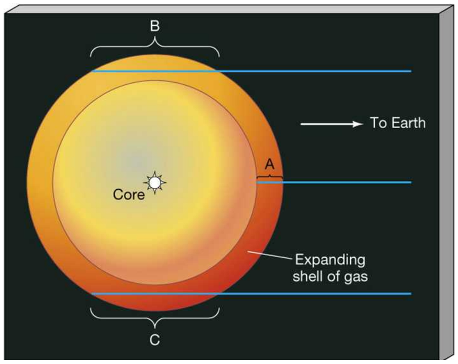
Escape speeds are 20 to 30 km/s.

Typical diameters are 0.1 to 0.3 pc.

The lifetime is about 50,000 to 100,000 years. The rarity is because they cannot be seen for very long.

Planetary Nebula

The gas shells shine by **fluorescence.** They absorb UV radiation from their central stars and re-emit this as visible light.

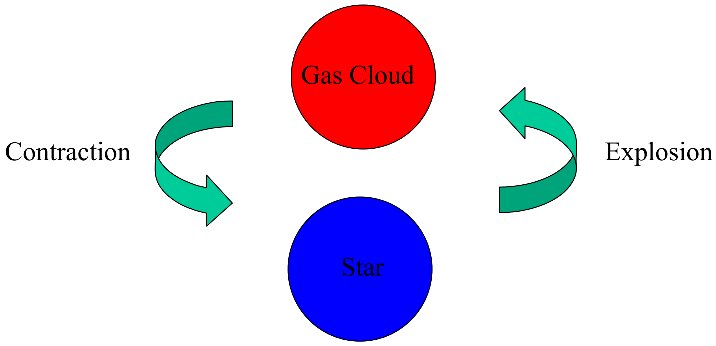


Planetary Nebula

Nearly all of the central stars are hotter than 20,000 K, and some are in excess of 100,000 K. But these stars are not bright. They must be small in size, such as white dwarfs.

Thus a **planetary nebula** may be the last ejection of matter by a red supergiant before it collapses to a **white dwarf**.

Planetary Nebulae



Gas Cloud

Contraction

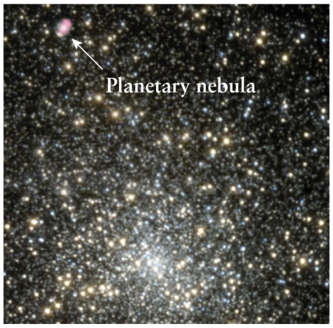
Explosion

Star

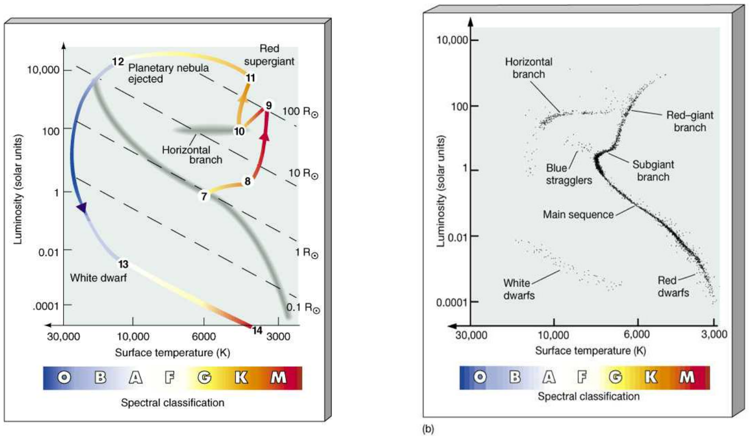
Herschel quite reasonably believed that the star was being born from the nebula. Now we know that the gas was ejected by the star and the planetary nebula is a sign of stellar death – not birth.

Consequences of Mass Ejection

The matter that is ejected into the interstellar medium is richer in heavy elements than was the material from which the star was formed. Originally all stars were formed of nearly pure hydrogen and helium. All other elements were synthesized by the stars.



Evolutionary Track



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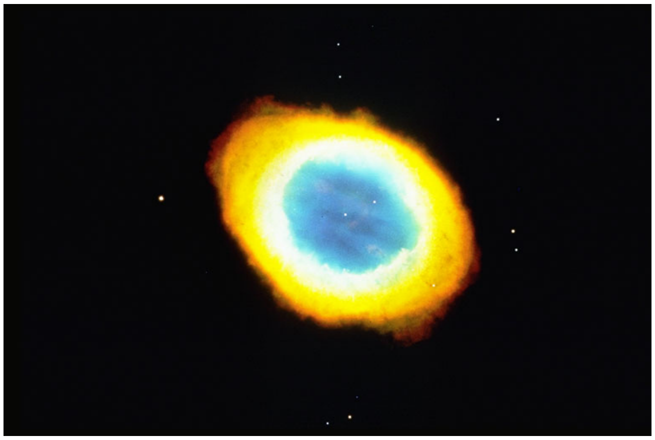
Planetary Nebulae

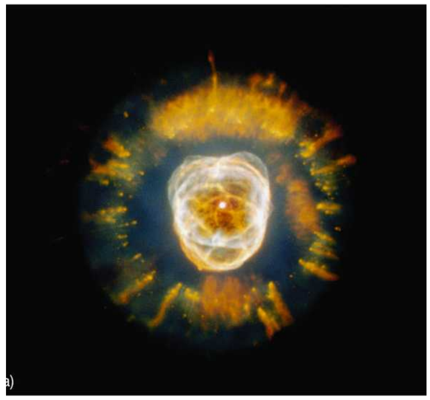


Ring Nebula

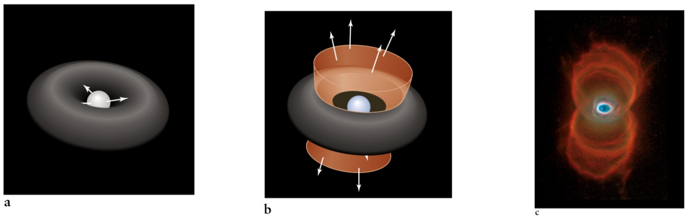
Helix Nebula

Glowing Eye Nebula

Eskimo Nebula



Bipolar Planetary Nebulae



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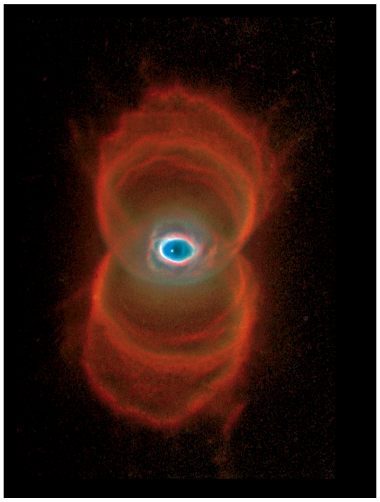
For some stars the lost mass is confined in a thick disk around the equatorial region – probably due to a binary companion. The fast wind will push farthest where the lost matter is the thinnest.

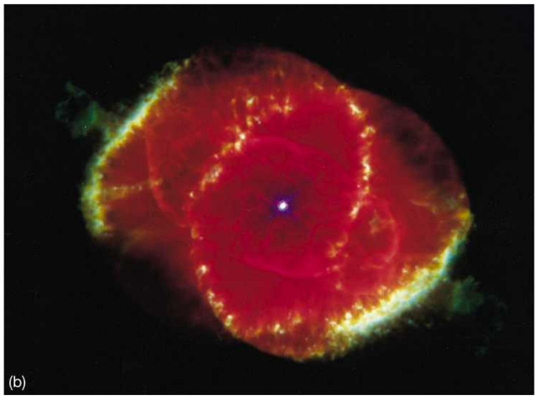
The wind will produce two distinct lobes above the star's rotation axis.

Hourglass Nebula

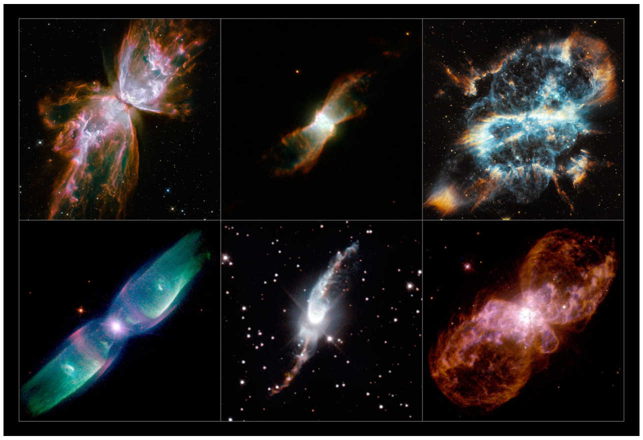


R. Sahai and J. Trauger, Jet Propulsion Lab; the WFPC-2 Science Team; and NASA

Cat’s Eye Nebula



Mosaic



Post-Helium Burning

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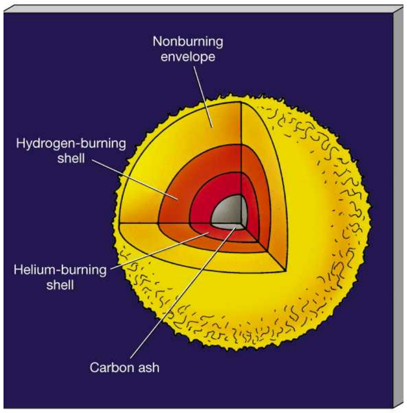

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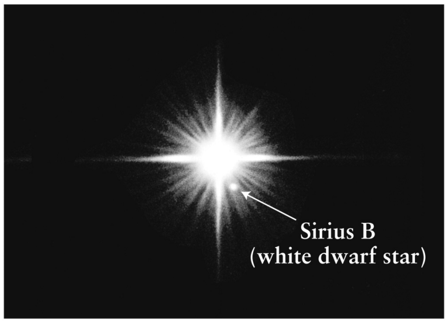
White Dwarfs



One of the first white dwarfs discovered is the companion to Sirius. In 1844 Friedrich Bessel noticed that Sirius was moving back and forth slightly over many years, as if it were being orbited by an unseen object. This companion, designated Sirius B, was first seen in 1862 by Alvan Clark as he tested out a new telescope.

White Dwarfs

When a low mass star exhausts its store of nuclear energy, it can only contract and release more of its potential energy. Eventually, the shrinking star will attain an enormous density.

White dwarfs have about 1 solar mass but are the size of the Earth.

Consequently, their density would be $100^3 = 10^6$ times greater, which is about **10^6 g/cm^3**.

White Dwarfs

What holds up a white dwarf against its own self-gravity?

White dwarfs are simple structures because the pressure that supports them is supplied almost entirely by **degenerate electrons**. In a white dwarf, the electrons are completely degenerate throughout the star, except for a very thin layer at the surface.

A White Dwarf is the "naked" electron-degenerate CO (or He) core of a low-mass star that has ejected its atmosphere as a planetary nebula.

Mass-Radius Relationship

The total pressure inside a white dwarf is virtually independent of the temperature. If you set the central pressure equal to the electron degeneracy pressure, the following relationship is derived:

$$\mathcal{M}V = \mathcal{M}R^3 = \text{constant} \qquad \text{or} \qquad R \propto 1 / \mathcal{M}^{1/3}$$

This leads to the following interesting relationship between the mass and radius: If we compare two white dwarfs of different masses, the **more massive** white dwarf has the **smaller radius**.

0.4 solar masses

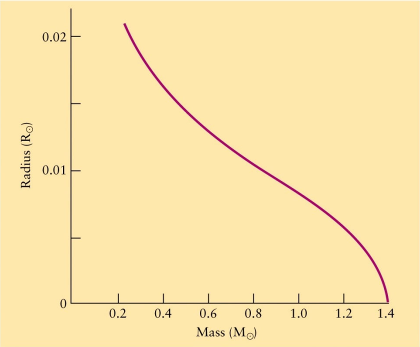
0.8 solar masses

Chandrasekhar Limit

If the mass was high enough, the radius of a white dwarf would want to shrink to **zero**. The limit is reached at a mass now known as **Chandrasekhar's limit**:

$$M_{Ch} = 0.20\left(\frac{Z}{A}\right)^2 \left(\frac{hc}{Gm_p^2}\right)^{3/2} m_p$$

where Z and A are the average atomic number and atomic weight of the ions.



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Chandrasekhar Limit

Because Z/A for most heavy elements is 0.5, the numerical value of Chandrasekhar's limit can be calculated:

$$\mathcal{M}_{\mathrm{Ch}} = 1.44 \text{ solar masses}$$

This is the maximum possible mass for white dwarfs.

All well-studied white dwarfs have masses less than this maximum.

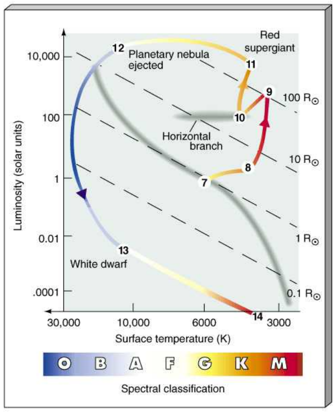
Mass Loss Issue

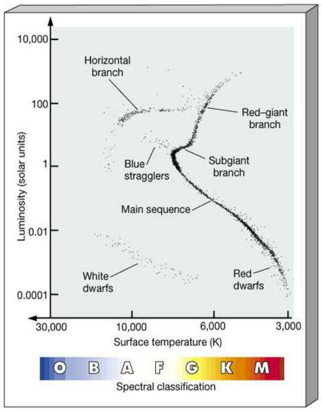
The critical factor is mass. White dwarfs can be no more massive than about 1.4 solar. Yet, observations indicate that stars that have masses larger than 1.4 times the mass of the Sun *at the time they are on the main sequence* also complete their evolution by becoming white dwarfs.

(We see in open clusters both main sequence stars of 2 solar masses and white dwarfs.)

Although we see high mass stars losing mass, but we have not seen 2 to 4 solar mass stars do so. Remember, most planetary nebulae have masses in the 0.1 to 0.2 solar mass range.

Evolutionary Track





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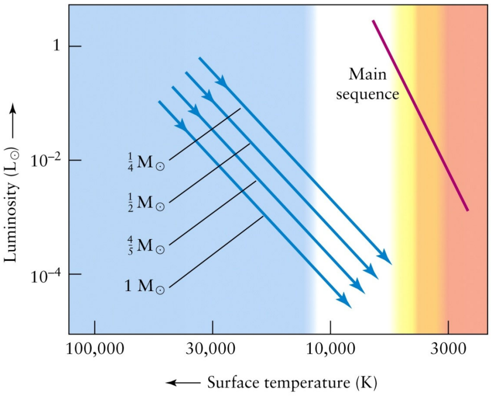
Evolution of White Dwarfs

Since the radius is constant, its luminosity is proportional to the fourth power of its temperature:

$$L = 4 \pi R^2 \sigma T^4.$$

Therefore it moves down and to the right on the HR diagram.



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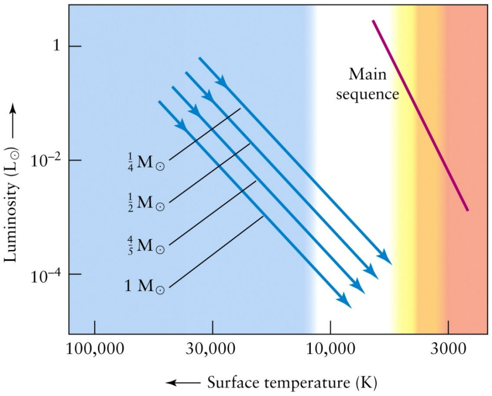
Evolution of White Dwarfs

The source of energy is the heat (**thermal energy)** of the non-degenerate nuclei of atoms. As the motion of these nuclei slow down, the electron gas conducts their thermal energy to the surface.

Gradually a white dwarf cools off.



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Evolution of White Dwarfs

Eventually, the white dwarf will cease to shine at all. A long time will be required for the star to cool off completely to the **black dwarf** state. This stage may take longer than the lifetime of the Galaxy.