# Chapter 10 The death of stars

Like the post-main-sequence evolution discussed in the last chapter, the final fate of a star is mainly determined by its mass. While some stars die a silent death when they no longer produce energy via fusion, others create some of the most energetic phenomena and exotic celestial objects ever known to us.

## 10.1 The fate of low-mass stars

Consider the main-sequence stars with mass $M < 0.4\ M_{\odot}$ - the **red dwarfs**, they are relatively cool, small and faint, and locate on the lower-right side of the main sequence. The energy generated in the core is transported by *convection* throughout a red dwarf, therefore the hot gas is constantly mixed. Hydrogen and helium ashes are distributed uniformly inside the star, thus no hydrogen burning shell is found, and they do *not* form giants.

Due to the low mass of red dwarfs, the hydrogen fusion reaction rate is low. Their life spans are very long, with a typical red dwarf spending hundreds of billion years on the main sequence.

The core of a red dwarf is not hot enough for helium fusion. As the hydrogen fuels at the core are slowly used up, the core contracts gradually and gets hotter. As a result, the star moves from right to left on the H-R diagram and becomes a **white dwarf**. (Fig. 10-1) The details of white dwarf will be discussed in section 10.3.

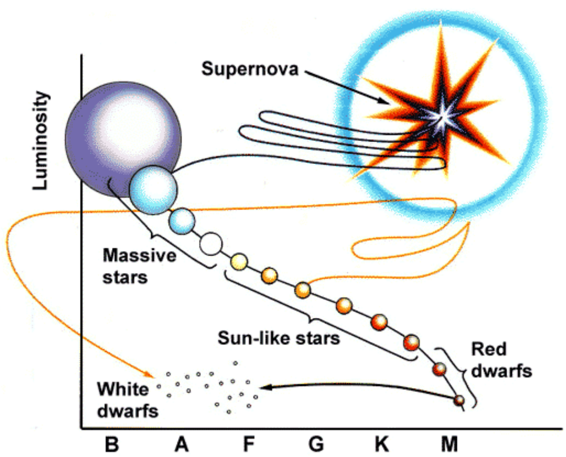

Fig. 10-1: This schematic H-R diagram summarizes the three major types of stellar demise. Low-mass red dwarfs live long lives and become white dwarfs. Sun-like stars become giants with cores collapse to white dwarfs. Massive stars become giants and explode as supernovae.

## 10.2 The fate of Sun-like stars

For stars with masses $0.4\ M_\odot < M < 4\ M_\odot$, the core collapses due to gravity, hence becoming *very dense* and *hot*. On the other hand, the radiation pressure generated in the hydrogen-burning shell is pushing the outer layer outward. Therefore, the outer layer expanded and swelled, hence becoming *less dense* and *cool*. Rapid expansion of the outer layer also causes the star to be more luminous. Hence, the star moves to right side of the H-R diagram, becoming a **red-giant star.**

When the core is hot enough (reaches at a temperature of about $10^8$ K), it causes helium fusion and form $^{12}C$ nucleus through the triple alpha process, but the core will not hot enough to fuse helium and carbon into oxygen. Like the hydrogen burning processes, helium fusion reaction occurs in the core and then in a shell. Massive cores of carbon and oxygen are accumulated. However, the cores are not heavy enough (and thus not hot enough) to create heavier elements via carbon and oxygen fusions.

*Helium shell flashes cause mass loss*

As helium in the helium-burning shell is gradually consumed, the shell contracts. As a result, peripheral hydrogen-rich shell collapses and heats up. It ignites hydrogen fusion, producing helium. ("First He Shell Flash" in Fig. 9-1) The newly produced helium rains downward onto the helium-burning shell. Therefore, while the helium shell is contracting, it gains helium by hydrogen fusion in the peripheral hydrogen-burning shell. As a result, helium burns more violently, producing **helium shell flashes** provided that the temperature reaches a certain critical value.

The released energy pushes the peripheral hydrogen-burning shell outward, making it cool off, then hydrogen burning ceases and no more helium supplies to the helium-burning shell. The process then starts over again. The helium burning shell begins to turn on and off quasi-periodically. When a helium shell flash occurs, the luminosity of the red giant increases substantially in a process known as a **thermal pulse**. (Fig. 10-2) Theoretical calculations predict that thermal pulses occur at intervals of about 300,000 years. This phase of periodic activity is evident in abrupt changes in luminosity at the surface. ("TP-AGB" in Fig. 9-1)

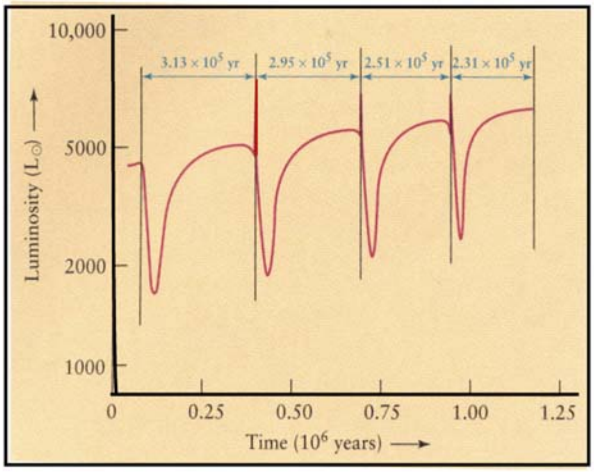


Fig. 10-2: The graph shows the luminosity of a 0.7-solar-mass star varies with time. The spikes in luminosity are called thermal pulses

During these thermal pulses, the weakly bounded outer layers of the dying star can separate completely from its core. Radiation pressure from the dying star propels them further away, creating **planetary nebula**.[1] (Fig. 10-3 and "PN formation" in Fig. 9-1) A red giant could lose 50% of its mass in about $10^5$ years in this way. The nebulae are visible because the gaseous nebulae are ionized by ultraviolet light from the central star, and light is then emitted as the ions recapture electrons, forming an emission nebula. The spectrum contains many characteristic lines from hydrogen, nitrogen and oxygen ions.

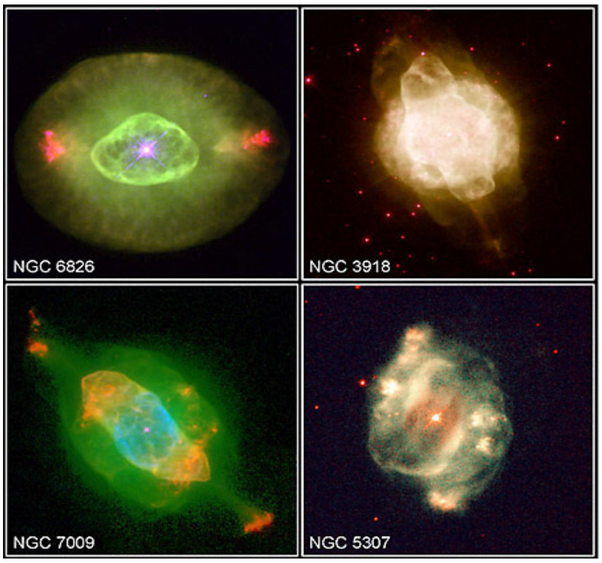


Fig. 10-3: A planetary nebula is the ejected surface of a medium-mass star.

[1] A planetary nebula is defined using its origin (and historically, its distinct look). Therefore it is not among the previous classification (Emission, Reflection, and Dark), which was related to how a nebula emits/absorbs light.

In addition, planetary nebulae can have complicated shapes, which may depend on their mass distribution before the explosions. Typical expansion of a planetary nebulae is at a speed of about 10-30 km/s in the Doppler effect measurement. The radii and the ages of nebulae are, respectively, about 0.3 pc and $10^4$ years. The nebulae will eventually dissipate into interstellar medium.

The remaining core is *small*, *dense* and *hot*. Finally, nuclear reactions extinguish and luminosity drops rapidly. With high surface temperature *but* low luminosity (because of its small size), they reside on the lower-left side of the H-R diagram become **white dwarfs**. (Fig. 10-4)

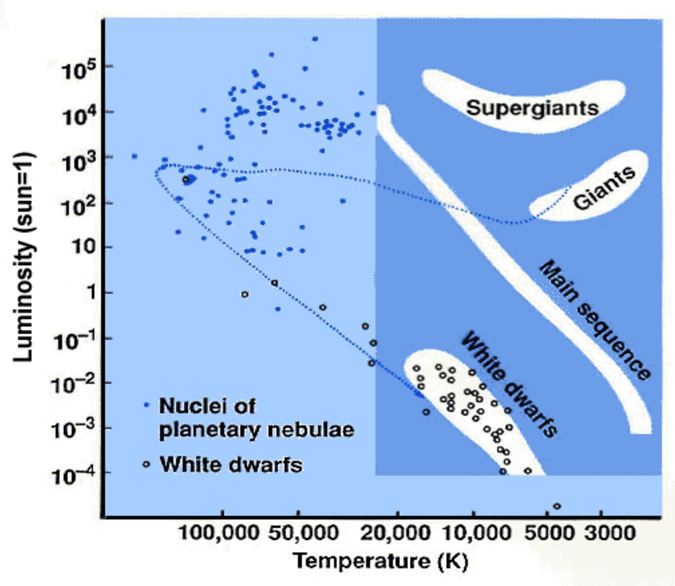


Fig. 10-4: Our customary H-R diagram, extended to higher temperatures to show the evolution of a star after creating a planetary nebula. Nuclei of planetary nebulae (filled circles) are hotter and more luminous than most white dwarfs (open circles). The dotted line shows the evolution of a 0.8-solar-mass star as it collapses towards the white dwarf region. The cores of planetary nebulae cool to become white dwarfs long after the nebulae have dissipated.

## 10.3 White dwarfs

In a main-sequence star, the *outward* thermal pressure (from nuclear fusion) counterbalances *contracting* gravity. However, when the fuels in a star′s core are exhausted, released energy is reduced gradually, hence weakening the thermal pressure. As a result, the star core contracts faster and faster. Eventually, the core becomes electron-degenerated (*Box*

***9.1***), and becomes a **white dwarf**. (Fig. 10-5) Since the pressure of a degenerate gas does not depend on its temperature, the pressure-temperature thermostat mentioned in Chapter 8 no longer works.

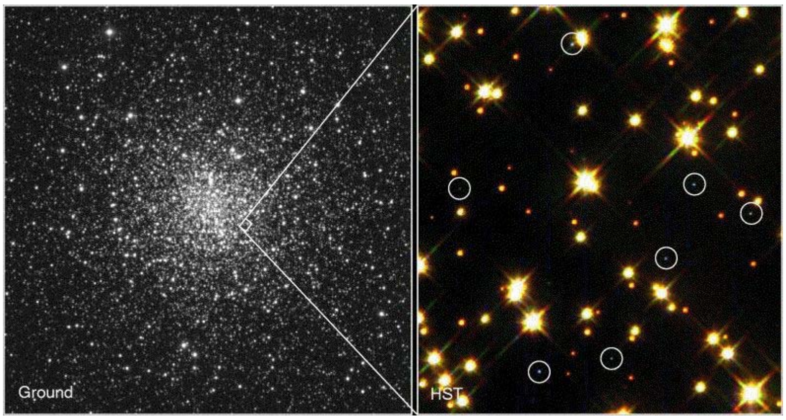


Fig. 10-5: (Left) A ground based photograph of globular cluster M4. (Right) Hubble Space telescope reveals a total of 75 white dwarfs in one small area within M4. (Credit: Harvey Richer/UBC, NASA)

As electron degeneracy pressure supports the star against the gravitational attraction, a white dwarf is in equilibrium. It is very small, dense and hot; thus, the surface gravity is very strong (~$10^5$ times that of Earth). For example, Sirius B is a white dwarf of about 1 solar mass, 0.76 Earth′s radius, surface temperature ~32,500 K, and density ~$3\times10^6$ g cm$^{-3}$. (1 teaspoon of matter ~15 tons!). It shines brightly in X-rays due to its high temperature. (Fig. 10-6) Finally, white dwarfs slowly radiate energy, and become cold and dark after billions of years. They become a **black dwarf**, ends with a quiet death finally.

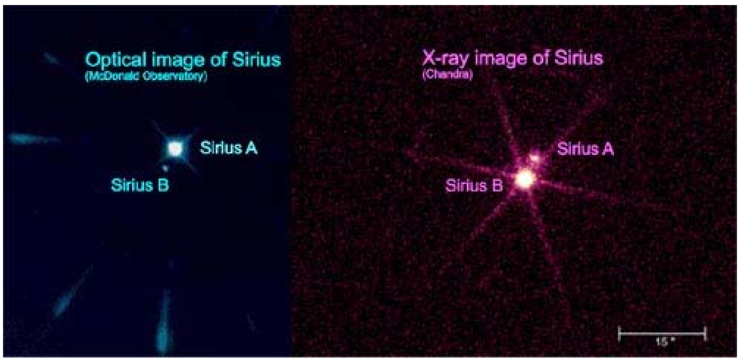


Fig. 10-6: Sirius consists of a main-sequence star (A) and a white dwarf (B). Sirius A is brighter in optical wavelength, whereas Sirius B produces much more X-ray. The spikes are instrumental artefacts. (Credit: McDonald Observatory, NASA/SAO/CXC)

**Chandrasekhar limit** states that the maximum mass of a white dwarf that the electron degeneracy pressure can support is about 1.4 $M_\odot$. Note that this limit is the core’s mass, but not that of the original main-sequence star. The degeneracy pressure cannot resist gravity beyond this limit, i.e., the star will further collapse.

## 10.4 The fate of massive stars

### *How are heavy elements created in the universe?*

For main-sequence stars of masses $M > 4\ M_\odot$, the central temperature is so high that fusion of carbon (~ $6\times10^8$ K) and oxygen (~ $10^9$ K) could occur. This fusion cycles allow the creation of heavier and heavier nuclei. The process is called **nucleosynthesis**. This process stops until *iron* is created. Having the highest *binding energy* (per nucleon), $^{56}$Fe is the most *stable* nucleus. Iron fusion will require (instead of release) energy. (Fig. 10-7)

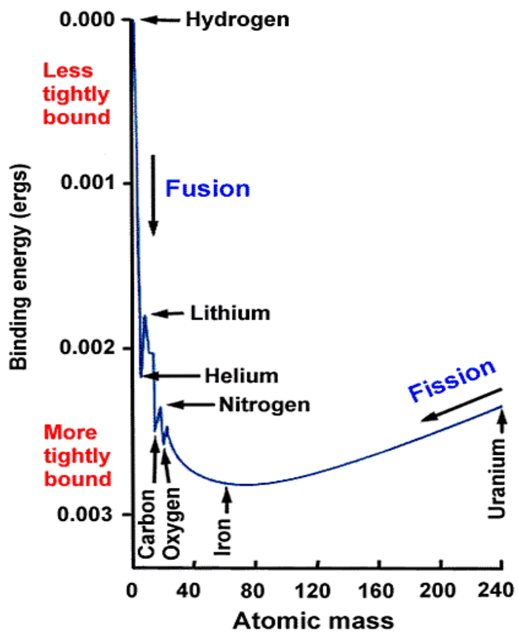


Fig. 10-7: Iron has the highest binding energy per nucleon.

As a result, an inert *iron core* is developed, surrounded by fusion shells of various elements. (Fig. 10-8) Progressively nearer to the iron peak, less and less energy can be generated. Time scale for each reaction sequence thus becomes shorter and shorter. For example, in a 20-$M_\odot$ star, hydrogen burns for ~$10^7$ years, helium burns for ~$10^6$ years, carbon burns for ~300 years, oxygen burns for ~200 days, and silicon burns for 2 days only! Consequently, the most abundant elements in the cosmos are, in order, $^1$H, $^4$He, $^{16}$O, $^{12}$C, $^{20}$Ne, $^{14}$N, and $^{56}$Fe.

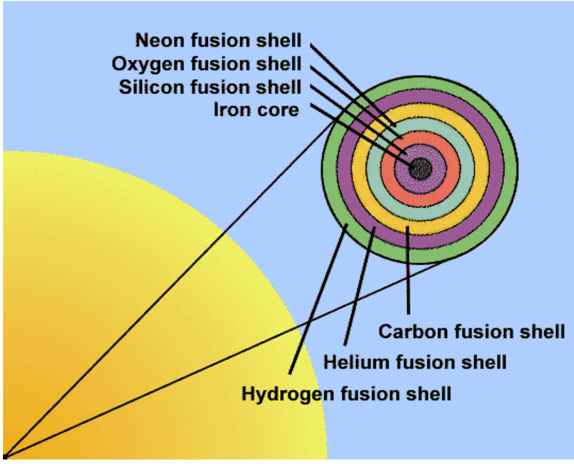


Fig. 10-8: Schematic interior of a massive star approaching the end of its life. This cool giant star, about the size of the orbit of Jupiter, contains a core about the Earth's size in which concentric layers fuse heavier fuels around the growing iron core.

### *Supernova explosion* [2]

When the core temperature rises to nearly $10^{10}$ K, the energetic gamma ray radiation emitted breaks down the iron into lighter elements in a process known as *photodisintegration*. The nuclear reactions, for example, are

$$^{56}_{26}\mathrm{Fe} + \gamma \rightarrow 13\,^{4}_{2}\mathrm{He} + 4n$$
$$^{4}_{2}\mathrm{He} + \gamma \rightarrow 2p^{+} + 2n$$

This process *absorbs* energy, and thus the thermal pressure is *reduced*. A massive star builds up an iron core via several stages of thermonuclear reactions in millions of years; yet within a short period of time, photodisintegration undoes much of those millions of years of effort!

Under an extreme environment (e.g., $T \sim 8\times10^{9}$ K, $\rho \sim 10^{13}$ kg m$^{-3}$ for a $15M_\odot$ star), the core is so dense that electrons within the core are forced to combine with proton via *inverse beta decay*, creating neutrons, i.e.,

$$p^{+} + e^{-} \rightarrow n + \nu$$

Thus, the core is now rich in neutrons. The escaping neutrinos carry away enormous amount of energy, causing the core to cool down and therefore collapse very rapidly.

About 0.25s after this rapid contraction has begun, the inner core reaches a typical diameter of 30 km, and a density beyond the nuclear density (~$10^{18}$ kg m$^{-3}$). Similar to the

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[2] The name "supenovae" was coined by Fritz Zwicky (1898–1974) in 1934.

electron degeneracy pressure in white dwarfs, the high-density neutron-rich core produces a **neutron degeneracy pressure** that resists the core from further contraction. It results in a sudden halt of the core's contraction, and hence the inner core bounces back, sending a powerful wave of pressure outward into the outer core. This wave accelerates as it encounters less and less resistance. After a few hours, this pressure wave reaches the star's surface. The energy released in this event is an incomprehensibly large $10^{46}$ J - a hundred times more energy than the Sun has emitted over the past 46 billion years, the outer layers of the star are then destroyed completely in a very short time. Such a violent explosion is called **supernova**.

The brightness of the star increases by many magnitudes. Examples include the "guest star" in Taurus recorded by Chinese astronomers in the Shung dynasty (AD 1054), and Tycho's supernova (AD 1572). The most extensively studied supernova, SN1987A in Large Magellanic Cloud, happened in 1987. (Fig. 10-9)

Fig. 10-9: SN 1987A – Before and after.

### *Supernova Types*

Supernovae are classified according to their spectra:

**Type II** supernovae have strong hydrogen lines in their spectra. They are created from the core collapse within a massive star as described above. Enough of the hydrogen from the outer layers remained with the star before exploding, hence hydrogen spectral lines are observed. Examples include the 1054 supernova in Taurus and SN 1987A in the Large Magellanic Cloud.

**Type Ib** supernovae have no hydrogen in their spectra, but have a strong absorption line of atomic helium (He I). These supernovae may result from the core collapse in a massive star that has lost the hydrogen from its outer layers.

**Type Ic** supernovae lack both hydrogen and helium lines in their spectra. These also result from a massive star that undergoes core collapse but lost both hydrogen and helium from their outer layers prior to the supernova explosion.

**Type Ia** supernovae have *no hydrogen or helium line in their spectra, but a prominent absorption line of ionized silicon* (Si II, $\lambda = 635.5$ nm). These supernovae are probably not the death of massive stars, but are produced by the explosion of a white dwarf star in a close binary system. As the red giant companion evolves and its outer layers expand, its mass is transferred easily to the white dwarf, getting its temperature increased and triggering catastrophic supernova explosions. Before exploding, the white dwarf contained primarily carbon and oxygen and almost no hydrogen or helium, hence no hydrogen or helium spectral lines can be observed. Silicon is in fact a by-product of the carbon-burning reaction and it gives rise to the silicon absorption line. Examples include Tycho's supernova in Cassiopeia (仙后座), Kepler's supernova in Ophiuchus (蛇夫座).[3]

All Type Ia supernovae show a similar light curve. (Fig. 10-10) The typical peak intensity at blue wavelengths ($\lambda = 440\text{-}490$ nm) is $M_B = -18.4$.[4] Hence, Type Ia supernovae can be used as a standard candle to measure extragalactic distance. Other types of supernovae are dimmer by 1.5 - 2 magnitudes.

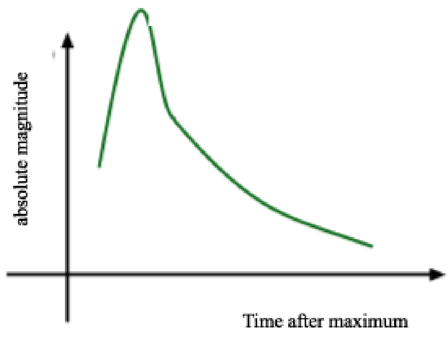


Fig. 10-10: Typical light curve of a Type Ia supernova.

Nebulous remains of a supernova explosion, called **Supernova remnant**, can be observed. (Figs. 10-11) Calculations suggest that about 96% of stellar material is ejected to

[3] Tycho's supernova was found in 1572 and called SN 1572, Kepler's Supernova in 1604 and called SN 1604.

[4] Carroll & Ostlie 2007, pp.526-529.

the interstellar medium, which may eventually be recycled into future generations of stars. The shock waves of supernova explosion are also important in triggering star formation.

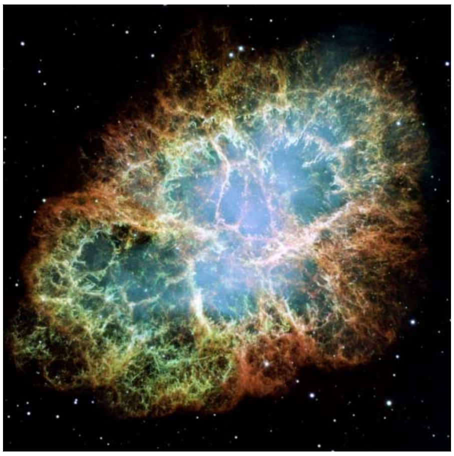

Fig. 10-11: Crab Nebula – a supernova remnant, corresponding to a supernova in 1054. Credit: NASA, ESA, A. Loll & J. Hester (Arizona State U.)

Before this material is ejected into space, it is compressed so much by the shock wave that thermonuclear reactions set in. These reactions produce many more chemical elements, including all the elements which are heavier than iron. These reactions require a tremendous input of energy. The energy-rich environment of a supernova shock wave is the *only* place where heavy elements such as zinc, silver, gold, mercury, lead, uranium can be produced. The small dense core of neutron matter that remains after the explosion, supported by neutron degeneracy pressure becomes a **neutron star**. If the initial mass of the main-sequence star is very large, the star′s core may be so massive such that it further collapses and becomes a **black hole.**

Post-main-sequence evolution of a star depends on its mass on the main sequence and the core mass in the giant phases. Fig. 10-12 summarizes the evolution of stars with different masses.

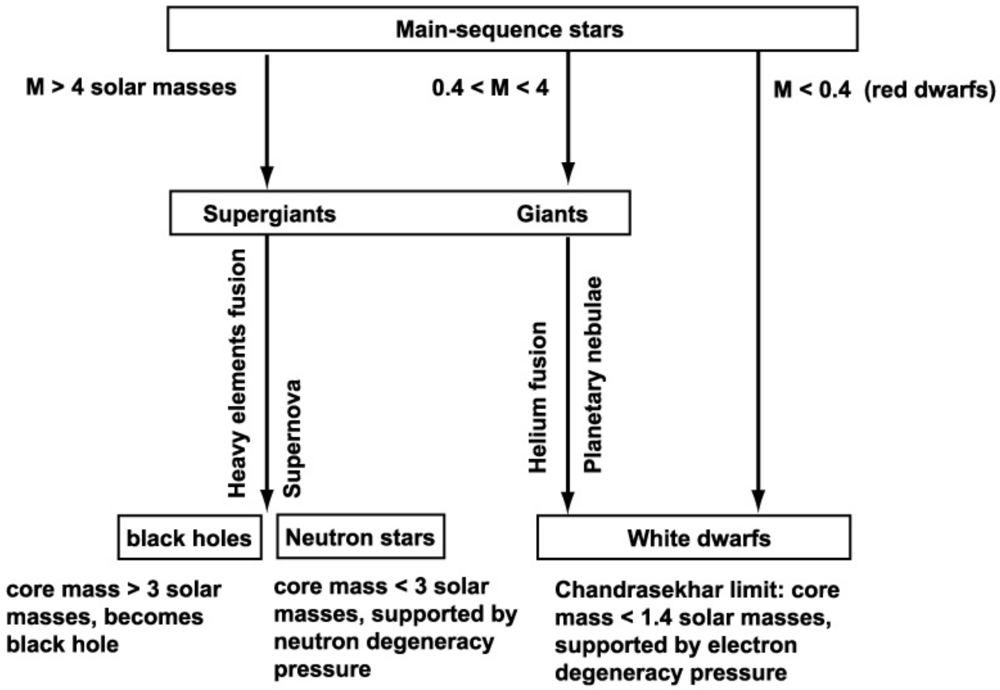


Fig. 10-12 A brief summary of the paths of evolution for stars with different masses.

## 10.5 Fate of binaries

In cases where the two stars in the binary are not far apart, and one of them becomes a red giant, its outer layer can be transferred easily to the companion. Suppose one member becomes a white dwarf. Due to the small size of the white dwarf and the conservation of angular momentum, the matter from its companion cannot be transferred directly to the white dwarf. Thus, the matter might form a whirlpool surrounding compact object. The structure is known as an **accretion disk**. (Fig. 10-13)

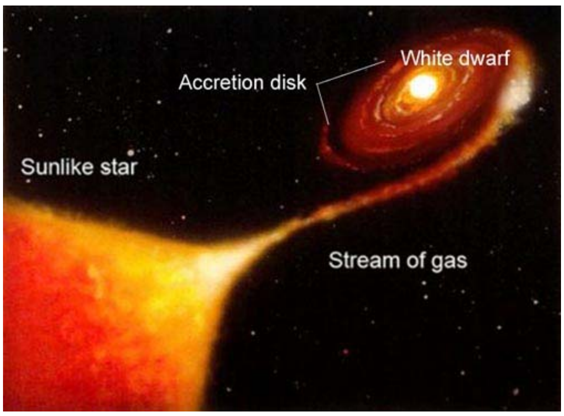


Fig. 10-13: In a typical dwarf nova, a Sun-like star orbits a planet-sized but massive white dwarf which draws material from the companion into a spinning accretion disk. *NASA*

As matters are accreted onto a white dwarf, its layer grows thicker, hotter and denser and eventually becomes degenerate. When the temperature is high enough to ignite hydrogen fusion, the ever-increasing temperature forces huge amount of hot gas to expand outward, which we see from the Earth as a **nova**.

Since the rate of evolution of stars depends on their mass, the greater the mass, the faster this evolution, and the more quickly it leaves the main-sequence, entering either a subgiant or giant phase. One would expect that the more massive companion of a binary should evolve into its giant phase earlier. However, Algol and some other binaries, something completely different is observed. The less massive star is already a giant while the star with much greater mass is still on the main-sequence. This is known as **Algol paradox**. The paradox has been resolved by considering the mass transfer between the companions.[5]

[5] Karttunen, et at., *Fundamental Astronomy,* 5th *edition* (New York: Springer, 2007), pp. 254 – 255.