Chapter 15. The Life and Death of Stars

Thermonuclear Reactions and Stellar Lifetime

At ZAMS, the core of a star reaches $\sim 7 \times 10^6$ K and starts to fuse H into He via the p-p chain or CNO cycle. Heat is produced. The outward push of gas pressure balances the inward pull of gravity. The structure of the star becomes stable.

The CNO Cycle fuses 4 hydrogen into a helium, using carbon as a nuclear catalyst. The CNO cycle is efficient at high temperatures, and is dominant in stars with masses >1.8 $M_\odot$.

The stellar lifetime τ is dependent on the amount of fuel (or the mass of the star) and the rate of burning (or the luminosity). τ is proportional to M/L. Since $L \propto M^{3.5}$ for the main sequence stars, $\tau \propto 1/M^{2.5}$. The more massive a star is, the shorter its lifetime is on the main sequence.

Examples of stellar lifetimes:			
	0.08 $M_\odot$	$> 10^{12}$ yr	late M stars
	1 $M_\odot$	10^{10} yr	G stars, the Sun
	10 $M_\odot$	10^7 yr	B stars
	30 $M_\odot$	a few $\times 10^6$ yr	O stars

Evolution on the Main Sequence

Stars on the main sequence adjust the structure of their interiors as the thermonuclear reactions burn away the hydrogen at the stellar core. The Sun at the ZAMS was 200 K cooler at the surface, 30% fainter, and 8% smaller than it is now. When the Sun leaves the main sequence, it will be twice as bright and 50% larger.

Evolution of Low-Mass Stars

The evolution of a star depends critically on the mass of the star. The table below describes the evolution of a 1 $M_\odot$ stars. Stars with masses of 0.8–8 $M_\odot$ all follow similar burning patterns.

Pattern of Burning	Locations in the HR Diagram
H burning in the core (p-p chain and/or CNO cycle)	ZAMS main sequence (MS)
H-burning shell He core collapses; degeneracy sets in	leaving the MS ascending the red giant branch (RGB)
He flash at core (10^8 K)	tip of the RGB
H-burning shell He-burning core	descending the RGB moving along the horizontal branch (HB)
H-burning shell He-burning shell C/O core collapses; degeneracy sets in	returning along the HB ascending the asymptotic giant branch (AGB)
exhausting fuel exposing the degenerate core	moving along a horizontal track toward white dwarf

Degeneracy and Helium Flash

Pauli exclusion principle states that no two identical particles with the same velocity can occupy a specified minimum volume of space. When the density of a gas is so high that these minimum volumes are filled, the gas enters a state of *degeneracy.* We can add particles to a degenerate gas, but only at higher velocities. Electron degeneracy provides powerful pressure.

When the degenerate He core of a star reaches 10^8 K, the triple-α process starts to fuse three He into a C. The energy produced does not immediately affect the pressure in the degenerate core, since the pressure of a degenerate gas depends only on density. As the temperature rises, the 3-α process ignites violently in a *helium flash.* The huge new energy source causes the core to expand, lifting the degeneracy.

Chemical Factory

As a star ascends the AGB, its dead C/O core is hot and dense enough to host a variety of nuclear reactions to produce heavy elements. The most important is the *s-process*, in which heavy nuclei are built by slow capture of neutrons. Convections in the stellar envelope bring the processed material to the surface. The radioactive ^{98}Tc, whose half-life is only 4×10^6 yr, is not present on the Earth, but has been observed in AGB stars. Stellar ^{98}Tc must be freshly made.

Formation of Planetary Nebulae and White Dwarfs

Stars lose mass as they evolve:

Stars	Winds	Wind Velocity	Mass Loss Rate
Red giants	slow winds	10–20 km/s	10^{-8} to $10-6$ $M_\odot$/yr.
Post-AGB stars	superwinds	10–20 km/s	10^{-7} to $> 10^{-4}$ $M_\odot$/yr.
PN nuclei (proto-white dwarfs)	fast winds	600–3,500 km/s	10^{-11} to 10^{-6} $M_\odot$/yr.

Stars below 8 $M_\odot$ can lose up to 80% of their initial masses near the end of evolution. Therefore, the C/O core is not hot enough to ignite C-burning nuclear reactions. As the post-AGB wind removes the stellar envelope, the degenerate core is exposed. The high temperature on the surface drives a fast stellar wind. The fast wind leaves the star, catches up the previous slow winds, and sweeps the previous winds into a dense shell. Meanwhile, the star is hot enough to emit energetic UV photons to ionize the surrounding gas. The ionized gas shell becomes a *planetary nebula.* The exposed degenerate core becomes a white dwarf.

Chandrasekhar's Mass Limit on White Dwarfs

White dwarfs are degenerate. The more massive white dwarfs have higher interior compression, and electrons have to move faster to be closely packed, according to Pauli's exclusion principle. As the electrons cannot move faster than the speed of light, a white dwarf cannot have a mass greater than 1.4 $M_\odot$. This limit is called *Chandrasekhar limit* in honor of its discoverer.

Mass Loss and Evolution of Massive Stars ($M \geq 15\ M_\odot$)

Massive stars ($M \geq 15 M_\odot$) are so luminous that the radiation pressure accelerates the outer layer of a star and drives a powerful stellar wind. Depending on the evolutionary status, a massive star loses mass in different ways:

Star	Wind	Wind Velocity	Mass Loss Rate
Main sequence	fast wind	1000-2000 km/s	$10^{-7}\ M_\odot$/yr
Red supergiant	slow wind	20-30 km/s	$10^{-4}\ M_\odot$/yr
Wolf-Rayet star	fast wind	1000-3500 km/s	$10^{-5}\ M_\odot$/yr
Luminous blue variable	outbusts	50-2000 km/s	$>10^{-4}\ M_\odot$/yr

The observed distribution of stars in the HR diagram provide clues to massive star evolution. The most massive stars evolve into luminous blue variables, while the moderately massive stars evolve into red supergiants. Both may evolve into Wolf-Rayet stars and eventually explode as a supernova.

Massive stars burn H, He, C/O, O/Ne/Mg, and Si/S successively, each new fuel being the product of the previous burning process. Near the end of the evolution, a massive star has a "nuclear onion structure" with the following layers:

H → He	H-burning shell	7×10^6 K
He → C/O	He-burning shell	10^8 K
C/O → O/Ne/Mg	C/O-burning shell	1×10^9 K
O/Ne/Mg → Si/S	O/Ne/Mg-burning shell	2×10^9 K
Si/S → Fe	Si/S-burning shell	3×10^9 K

As the evolution goes on, each new burning process releases less energy per unit mass and lasts a shorter duration. The evolution accelerates toward the end. When the core material has been converted into Fe completely, no new fusion process can be ignited to release energy, as Fe is the most tightly bound among all atomic nuclei.

Supernovae

The iron core cannot initiate any further thermonuclear burning, hence it collapses. It takes less than 0.1 second for the radius to drop from 1000 km to 50 km, and a few seconds more down to a mere 10-20 km. Protons and electrons merge into neutrons. Finally, the degenerate neutrons provide pressure and halts the collapse.

During the few seconds of core collapse, 10^{46} joules of energy fly outward. (By comparison, the 2×10^{11} stars in our Galaxy radiate only 10^{38} joules/s.) *The core collapse generates a power comparable to that of all the stars in the observed Universe combined!* However, 99% of the energy released in the core collapse is in neutrinos, which are difficult to observe.

The outer layer of the core rebounds, and produces a shock wave, transferring momentum to the envelope. The density contrast is so large that the envelope is kicked and sent flying outwards at thousands of km/s. A supernova is born!

Within the shock wave of a developing supernova, nuclear reactions go berserk. a vast number of neutrons are produced and captured by heavy nuclei to build even heavier nuclei. This *r-process* (for rapid capture) can jump radioactive barriers that the s-process cannot. The heavy elements produced are blasted into space, enriching the interstellar medium.

Supernova Remnants

Supernova ejecta shocks the ambient medium into a shell, called a supernova remnant (SNR). A SNR has a shell structure. The shell of compressed ambient medium emits strongly optical emission lines. The shell also emits nonthermal radio emission because of the enhanced magnetic field and relativistic particles. The SNR interior contains hot shocked gas at $10^6 - 10^7$ K, which emits X-rays. SNRs can be identified easily by their nonthermal radio emission and bright X-ray emission.

Neutron Stars and Pulsars

In 1967, a graduate student Jocelyn Bell found a series of radio pulses spaced only 1.3 sec apart. This was the first discovery of a *pulsar* (for *pulsating r*adio source). The short period requires that it be caused by the rotation of a body no more than a few tens of km across. This is precisely the dimension of a neutron star. Pulsars must be neutron stars!

Neutron stars have strong magnetic fields. The magnetic poles are the only locations where relativistic particles can spiral along the field lines and emit radiation. The radiation is beamed along the magnetic polar axes. The magnetic axis of a neutron star is tilted against the rotational axis. Therefore, the rotation of the neutron star makes the light beam spin. Only if the Earth is in the path, can the pulses be observed.

Neutron stars are degenerate, so they have a mass limit, ~ 3 $M_\odot$. (This is like the Chandrasekhar limit for white dwarfs, ~ 1.4 $M_\odot$.) Any degenerate neutron star with a mass higher than 3 $M_\odot$ would collapse into a black hole.

Black Holes

If the escape velocity on the surface of an object approaches the speed of light, no light from the object's interior can escape. This object would disappear from view and become a black hole. The Earth needs to be shrunk to a radius of 9 mm to become a black hole.

Event horizon is the radius at which the escape velocity is equal to the speed of light. The event horizon is the boundary within which no light, mass, and information can get out.