The 68th Compton Lecture Series

Stars: Their Life and Afterlife

Lecture 4: Massive Stars, and Supernovae

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Part 1. Evolution of Massive Stars

We saw last week that stars in the mass range ~ 0.4 – 4 $M_\odot$ at formation (when they join the main sequence) form carbon-oxygen cores that are supported against gravity by degenerate-electron pressure. They do not have enough mass for gravity to overcome this pressure. Having thrown off their outer layers of hydrogen and helium in thermal pulses (forming a so-called “planetary nebula” around the star), these stars become white dwarfs – exposed, hot carbon-oxygen cores that slowly radiate their stored heat energy and cool. We will discuss white dwarfs more below, and will see that in binary systems they are able to power novae and a certain class of supernovae called “Type Ia.”

There is a limit to how much mass can be supported by degenerate-electron pressure, and this limit – known as the Chandrasekhar limit – is approximately 1.4 $M_\odot$. Stars with initial masses greater than 4 $M_\odot$ form carbon-oxygen cores with masses greater than the Chandrasekhar limit. Electron degeneracy cannot support these cores, and so they contract under gravity. As they contract, they heat – and when the temperature reaches 600 million K, the stars are able to burn* carbon, fusing carbon nuclei and producing oxygen, neon, sodium, and magnesium.

For stars with initial masses below ~ 8 $M_\odot$, the carbon-burning stage is again the end of the road – they settle down and become white dwarfs similar to their lighter companions, but with oxygen-neon cores rather than carbon-oxygen.

Stars with masses above ~ 8 $M_\odot$ are able to go through additional contraction & heating stages after burning all of the carbon in their cores – burning in order neon, oxygen, and silicon and producing a variety of elements, up to iron and nickel. In these later stages, while the core is burning heavier and heavier elements, concentric shells of material outside the core continue to burn lighter elements, getting lighter further from the core.

Table 1 summarizes the stages of core fusion, starting with hydrogen and progressing through silicon, collapse of the core, and the supernova explosion, for a 25-$M_\odot$ star. Note how the time spent in each stage decreases rapidly, from 7 million years (the main-

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* Burning – fusion of nuclei (as opposed to the chemistry definition of oxidation).

sequence lifetime of a 25-$M_{\odot}$ star) for hydrogen to merely 1 day for silicon! This acceleration of the burning process happens for a couple reasons:

- the energy yield of the fusion reactions (the free energy released) is decreasing rapidly as the elements involved have more positive charges. This reduces the efficiency of the fusion process, meaning less free energy per fusion reaction is available to support the core.
- Above a few hundred million K, the cores are hot enough that their blackbody radiation is well into the gamma-ray range, and these energetic photons are able to produce a variety of nuclear reactions that result in the production of neutrinos[†]. The neutrinos are able to radiate freely out of the star's core, carrying energy with them.

In turn, this means that the fusion rate must be even higher, and so the fuel is exhausted faster and faster at each succeeding stage.

Table 1. Core fusion stages for a 25-$M_{\odot}$ star. Note the rapid decrease in duration, especially beginning with Carbon burning.

Fusion Stage	Core Temp (K)	Core Density (kg/m^3)	Duration of Stage	Notes
Hydrogen	$4 * 10^{7}$	$5 * 10^{3}$	$7 * 10^{6}$ years	Main sequence
Helium	$2 * 10^{8}$	$7 * 10^{5}$	$7 * 10^{5}$ years	
Carbon	$6 * 10^{8}$	$2 * 10^{8}$	600 years	Neutrino cooling begins to become important
Neon	$1.2 * 10^{9}$	$4 * 10^{9}$	1 year	
Oxygen	$1.5 * 10^{9}$	$1 * 10^{10}$	6 months	
Silicon	$2.7 * 10^{9}$	$3 * 10^{10}$	1 day	Produces iron – end of the road
Core collapse	$5.4 * 10^{9}$	$3 * 10^{12}$	0.25 seconds	
Core bounce	$2.3 * 10^{10}$	$4 * 10^{15}$	Milliseconds	Reaches nuclear density and forms proto-neutron star
Supernova	$\sim 1 * 10^{9}$	Varies	~ 10 seconds	

Fusion occurs when temperature and pressure are high enough to overcome the electrical repulsion between like charges and allow nuclei to get close enough to each other for the strong nuclear force to take over, binding them together with the release of some energy.

Fusion is only useful as a power source as long as binding two nuclei results in the release of free energy. As the charge of the nuclei rises, it reaches a point with iron (Fe) that even internal to the nucleus, electric and strong nuclear forces are roughly balanced and no energy can be gained by fusing iron nuclei together – instead, to fuse two iron nu-

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[†] Neutrinos – nearly massless electrically neutral particles that respond only to the weak force (and gravity, but gravity is negligible in this context). Because the weak force is so, well, weak, they rarely interact with other particles of matter. They play an important role in transporting energy out (cooling) of the cores of massive stars (both during late stages of evolution and supernovae) for this reason.

clei together requires extra energy as well. Stars do not fuse lighter elements to form elements much heavier than iron because it would be an energy sink rather than source.

By the time a star has burned through the silicon in the core and created a predominantly iron core, its central regions have an appearance much like an onion, as shown in Figure 1, while the outer regions of the star have expanded tremendously, turning the star into a red supergiant. Note the variation of scale in Figure 1: the central regions where fusion is taking place have a diameter of ~10,000 km, or roughly the size of the earth, while the star as a whole has ballooned to 1.6 billion km in diameter, which would fill the orbit of Jupiter!

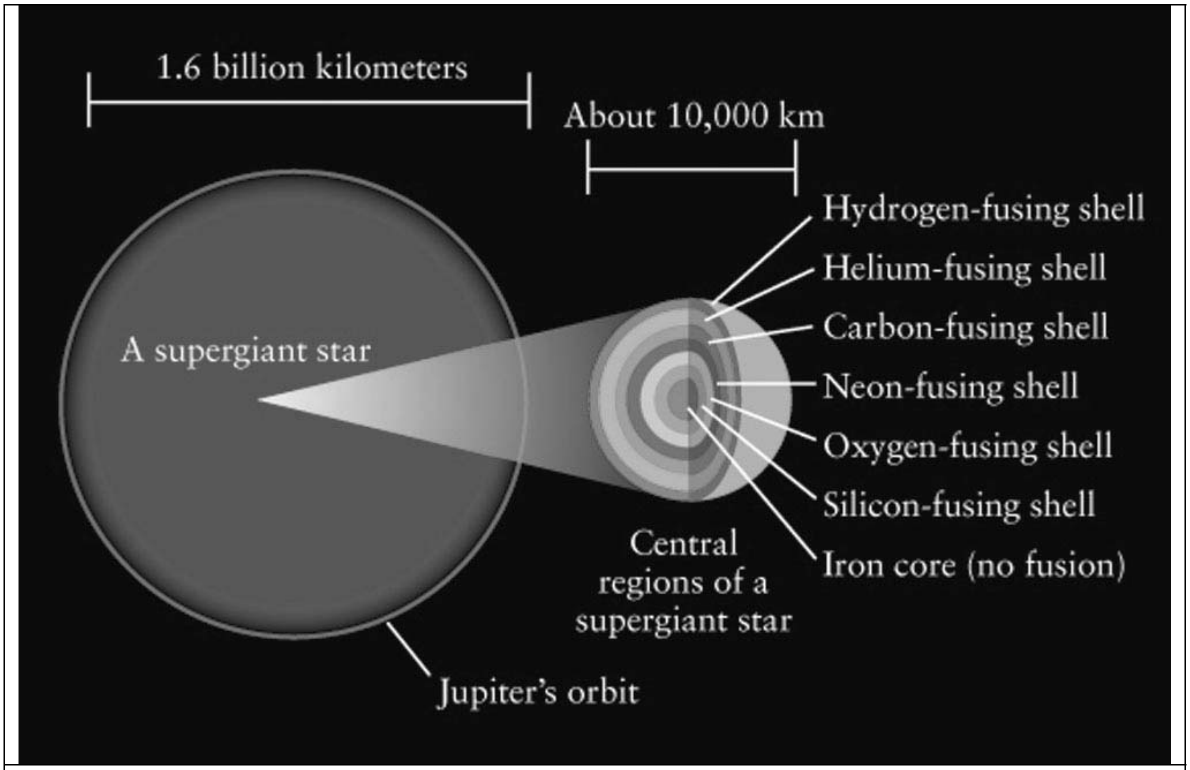


Figure 1. The onion-like structure in the central regions of a supergiant star. Note the difference in scale between the size of the central regions (~10^4 km) and the size of the entire star (~10^9 km).

Part 2. A Supernovae Zoo

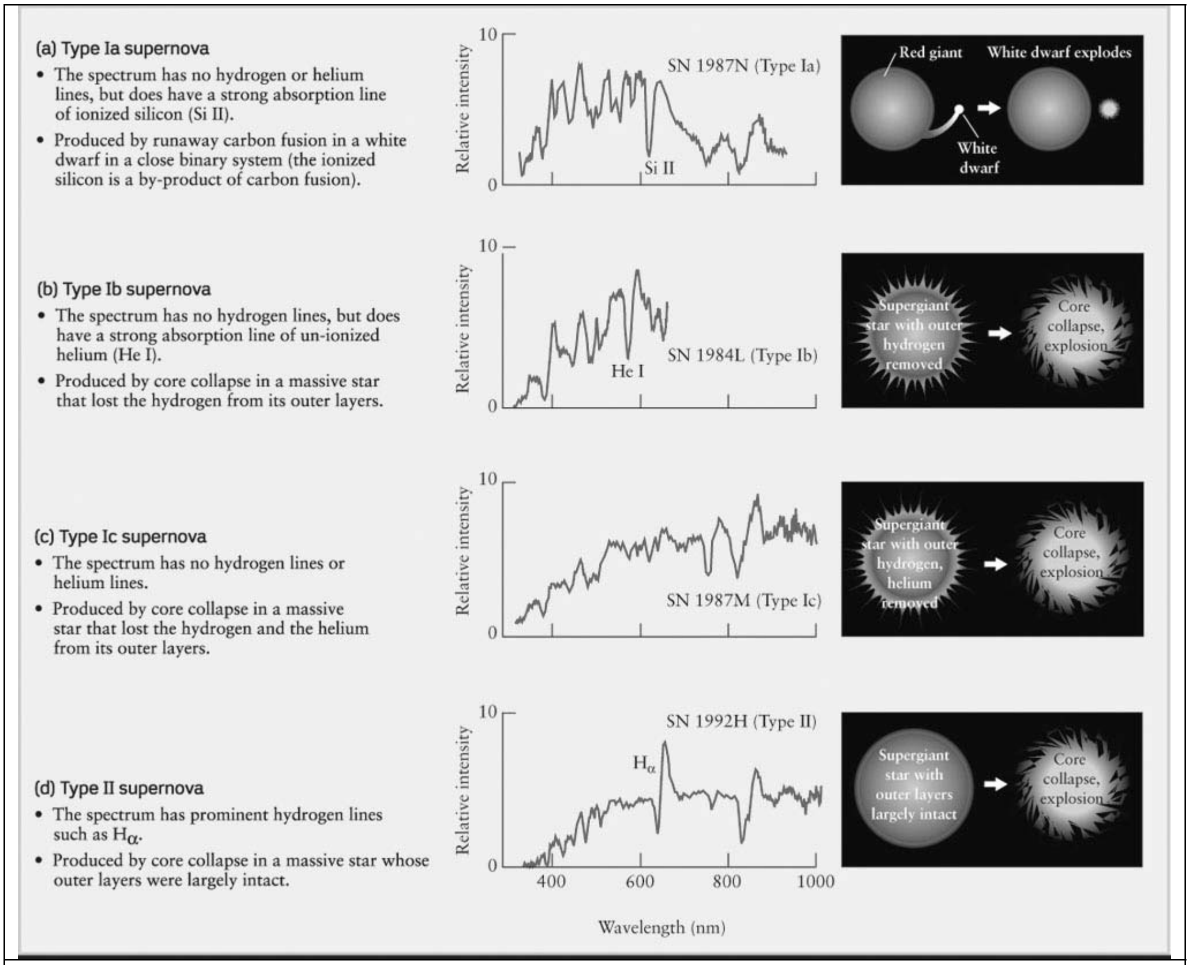
Supernovae are categorized by theorists on the basis of the energy source for the explosion. In *thermonuclear* supernovae, the primary energy source for the explosion is the release of nuclear energy during a runaway fusion reaction – this is believed to be the mechanism for the supernovae produced by white dwarf stars. In *core-collapse* supernovae, the primary energy source is the gravitational energy freed by the collapse of the star's core. This energy is converted into neutrinos, heat, and kinetic energy, and powers the explosion of the outer layers of the star.

Supernovae are categorized by observers on the basis of the spectrum of optical light that they emit. Table 2 lists the categories, and Figure 2 shows some example spectra for each class. There are two basic categories, Type I and Type II. Type I supernovae show no evidence of hydrogen lines in their spectra. This means that the progenitor star has lost its hydrogen shell. White dwarfs and some massive stars explode as Type I supernovae; other massive stars explode as Type II supernovae.

Table 2. Classes of supernovae, their spectral signatures, and their progenitors.

Supernova Class	Spectral Signatures	Progenitor
Type Ia	Hydrogen absent; Silicon present	Thermonuclear detonation of a white dwarf
Type Ib	Hydrogen absent; Silicon weak or absent; strong Helium lines	Core collapse of massive star that lost H envelope to wind or binary companion
Type Ic	Hydrogen, Helium, Silicon all absent; Calcium and Oxygen present	Core collapse of massive star that lost H envelope to wind or binary companion
Type II	Hydrogen lines in absorption	Core collapse of massive star with H-rich envelope
Type IIdw	Hydrogen lines in emission	Core collapse of massive star interacting with a dense wind from progenitor

As we will see below, classical novae are related to Type Ia supernovae, in that both types of events are believed to come from white dwarf progenitors and to be powered by thermonuclear fusion. However, novae are much weaker (and more common) than supernova and do not result in the complete disruption of the star.



(a) Type Ia supernova

- The spectrum has no hydrogen or helium lines, but does have a strong absorption line of ionized silicon (Si II).
- Produced by runaway carbon fusion in a white dwarf in a close binary system (the ionized silicon is a by-product of carbon fusion).

(b) Type Ib supernova

- The spectrum has no hydrogen lines, but does have a strong absorption line of un-ionized helium (He I).
- Produced by core collapse in a massive star that lost the hydrogen from its outer layers.

(c) Type Ic supernova

- The spectrum has no hydrogen lines or helium lines.
- Produced by core collapse in a massive star that lost the hydrogen and the helium from its outer layers.

(d) Type II supernova

- The spectrum has prominent hydrogen lines such as H_α.
- Produced by core collapse in a massive star whose outer layers were largely intact.

Figure 2. Example spectra and probable origins of several supernova, illustrating the different possibilities.

Part 3. White Dwarfs, Novae, Type Ia Supernovae

As we saw last week, stars with a mass in the range ~0.4-4.0 $M_\odot$ end their lives as white dwarfs, hot carbon-oxygen cores that have shed their outer layers of hydrogen and helium during their planetary nebula phase. White dwarfs are no longer powered by fusion, and they find balance against gravity in the pressure provided by their degenerate sea of electrons. They shine simply because they are hot. Left to its own devices, a white dwarf will slowly radiate away its heat, cooling and dimming into obscurity. After ~ 5 billion years as a white dwarf, the star's luminosity has dropped to ~10^{-4} $L_\odot$ and its temperature to ~4000 K. At this point, electrical forces between the constituent ions become important and cause the star's material to form into a regular lattice – the white dwarf essentially freezes into a solid.

Stars in the mass range ~ 4 – 8 $M_\odot$ also end as white dwarfs, but after going through one more round of fusion. These stars are massive enough to burn the carbon in their cores, forming additional oxygen, along with neon, sodium, and magnesium. However, they are too light to reach the temperatures required to burn neon, oxygen, and heavier elements, so after burning carbon they are finished with fusion and evolve similarly to lighter white dwarfs.

White dwarfs have a mass of ~1.2 $M_\odot$ or less. This limit is imposed by two conditions. First, if the mass were much greater than this, the gravitational force would be able to overcome the electron degeneracy pressure, and the star would contract and heat to the point where further fusion – and evolution – were possible. Second, at about this mass a process called “neutronization” becomes possible: the most energetic electrons in the gas would have enough energy to bind with protons and form neutrons and neutron-rich nuclei. The loss of free electrons means a lower pressure, and again the star is forced by gravity to contract in response.

The story is quite different, however, for white dwarfs in close binary systems. If a white dwarf is in a binary system with another star that is near enough, matter can transfer between the two stars. In some cases, an accretion disk can form around the white dwarf, and matter can steadily be added to the white dwarf’s surface. What happens next appears to be related to the rate of accretion, but the details remain unclear.

Novae appear to occur when a white dwarf acquires hydrogen-rich matter from its companion at a very slow rate. A surface layer of hydrogen forms, compresses, and heats. When the temperature reaches about 10 million degrees, hydrogen fusion ignites throughout this surface layer, and this surface explosion is what we see as a nova. Novae have an energy of ~10^{37} joules (10^{44} ergs), which is equivalent to the output of our Sun over 1000 years. The white dwarf and its companion survive the nova explosion, and in some cases repeated novae are possible!

Type Ia supernovae appear to be initiated by a similar mechanism, but the details are still being worked out. In a Type Ia supernova, the explosion begins with carbon fusion in the core of the white dwarf, but it is not clear what initiates the carbon fusion. It may be that a sufficiently high accretion rate increases the mass of the star to a point where the core’s pressure becomes high enough to start carbon fusion; alternately, it may be that explosive burning of a helium surface layer sends a shock wave through the star, compressing the core.

Carbon fusion raises the temperature in the core, but because the core is being supported by electron degeneracy, it does not behave like an ideal gas; instead, the pressure in the core remains essentially constant instead of rising with temperature. Thus, the increased temperature does NOT cause the core to expand! Instead, the increased temperature causes the fusion rate to accelerate, and this positive feedback causes the fusion process to run away. The fusion reaction spreads rapidly from the center of the star, and within seconds the white dwarf blows apart. These explosions are far more energetic than novae, releasing ~10^{44} joules (10^{51} ergs) of energy, comparable to the amount the Sun will emit in its entire main-sequence lifetime.

During the explosion, one of the byproducts of carbon fusion is silicon, and it is this silicon produced during the supernova that creates the spectral feature that distinguishes Type Ia supernovae from other Type I supernovae.

The power source in these supernovae is the energy released by the runaway thermonuclear reaction. This is in contrast to the core collapse supernovae we consider next.

Part 4. Core Collapse Supernovae

The beginning of the end for massive stars comes when they finish burning their supply of core silicon into iron. At this point, the core has a mass of ~ 1.5 $M_\odot$ in a region roughly the size of the earth. Fusion ceases, but loss of energy from the core continues in the form of neutrinos escaping. In addition, the core's pressure starts to drop because of two processes:

- Electrons are forced into nuclei, where they react with protons to form neutrons and neutrinos: $e + p \rightarrow n + \nu$. This is the same "neutronization" we saw earlier.
- The core's blackbody radiation extends up into the gamma-ray regime, and these gamma-rays begin to "melt" the iron nuclei: nuclei that absorb such energetic photons become unstable and release a helium nucleus. This process is called "photodisintegration."

Within a fraction of a second after the end of fusion, the core is in near free-fall in upon itself, collapsing at a sizeable fraction of the speed of light (10-25%). Collapse continues until the core reaches densities comparable to (or even a little higher than) in the nuclei of atoms, at which point the strong nuclear force becomes repulsive and stabilizes the core. The core at this stage is a neutron-rich sphere about 30 km in diameter, several hundred times smaller than before the collapse – and millions of times denser!

The inner core's collapse halts so abruptly while the outer parts of the core fall onto it that a strong rebound shock is sent racing outwards. Originally it was thought that this rebound shock is what powered the supernova. But it doesn't, at least not on its own. The energy of the outgoing shock is expended in photodisintegration of nuclei and by neutrinos escaping the core, and after a few milliseconds the initial shock is gone.

At this point, there is a hot, dense, neutron-rich core called a proto-neutron star that is continuing to accrete matter. If the core is massive enough, it may collapse into a black hole at this point.

If the proto-neutron star avoids collapsing into a black hole, it does so by radiating neutrinos prodigiously. Some 10% of the rest mass of the proto-neutron star is radiated as neutrinos in the next few seconds. This intense bath of neutrinos forms a neutrino atmosphere between the proto-neutron star and the infalling outer layers of the star, and is sufficient to heat the infalling matter and drive it back outward through the star's outer layers. As the outgoing matter accelerates, it quickly becomes supersonic (faster than the speed of sound in the star's matter) and drives a shock wave through the star.

Convection and turbulence play a key role in allowing the hot inner matter to escape fast enough (before cooling, like gas bubbles rising from the bottom of a heated pot of water) to drive the explosion. However, convection by its nature breaks the spherical symmetry of the star, and the explosion in its earliest stages proceeds differently in different directions. This asymmetry can give the nascent neutron star a “kick,” accelerating it to a speed of typically 300 – 400 km/s in a random direction.

Given how small the core is (~ 10 km) compared to the size of the star at this point (> 1 billion km!), it takes several hours for this shock wave to near the surface of the star. When it does, it creates the flash of light we see as a supernova.

This “flash” is not so quick – the supernova rises to maximum brightness within a day or so, and then is visible for months (or even years) as it slowly fades. This is the light curve that astronomers measure; its shape and spectrum reveals a lot of information about the nature and properties of the supernova and its progenitor star.

During the explosion, conditions are created that exist almost nowhere else in the universe: as the shock wave propagates, it compresses and heats the stars matter. Traveling along with the shock wave are a large quantity of free, energetic neutrons and neutrinos. These conditions set off a new round of nucleosynthesis[‡] that creates a lot of the elements heavier than iron, elements that require the input of a large amount of energy in order to be produced. These elements include all of the zinc, silver, tin, gold, lead, and uranium that we find on earth – all produced during a supernova. Many of these elements are initially synthesized in unstable, radioactive forms. In particular, ^{56}Ni and ^{56}Co decays provide most of the energy powering the visible light curve.

Back in the core, the proto-neutron star will cool and condense into a neutron star with a radius of ~ 10 km, supported by degenerate-neutron pressure (similar to the degenerate-electron pressure that supports white dwarfs, but relying on neutrons instead of electrons).

If the progenitor star’s mass was greater than ~ 20 – 25 $M_{\odot}$, the core may have enough mass to collapse into a black hole. Models suggest two way this can happen. It may be that a massive enough core will accrete matter faster than neutrinos can act to blow the infalling star away, causing the proto-neutron star into a black hole before the supernova occurs – in this case, there may be no supernova explosion! Alternately, after the supernova shock wave propagates outward there may be enough matter left behind that gravity will cause to fall back onto the proto-neutron star and form a black hole.

In contrast to thermonuclear supernovae, the energy source that drives core-collapse supernovae is the gravitational potential energy that is released during the collapse of the core. This energy is converted into a huge flux of energetic neutrinos that power the explosion.

[‡] Nucleosynthesis – formation of heavier elements from the fusion of lighter elements.

Coming Up Next Week: Supernova Remnants

Next week we'll cover supernova remnants, how they influence their environments, and how they accelerate cosmic rays.

References

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Credits for Figures

Figure 1: Reproduction of Figure 20.13 from Freedman and Kaufmann.

Figure 2: Reproduction of Figure 20.20 from Freedman and Kaufmann.