CHAPTER 14 II

Stellar Evolution

14-5. Supernova

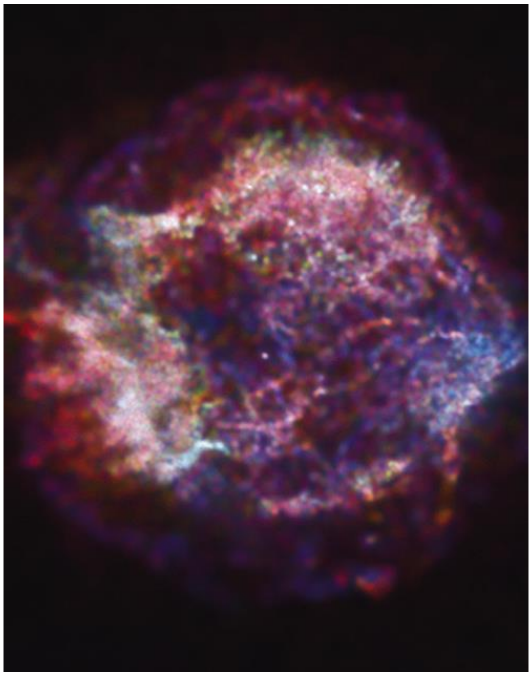
Exactly which stars become supernovae is not yet clear, but more than likely they are massive stars that become highly evolved. A star that develops an iron core will contract and get hotter but the iron will not undergo fusion, since this would be an endothermic reaction. Instead, a temperature is achieved where very energetic gamma rays dominate the EM radiation in the core. These gamma rays collide with the iron nuclei and cause them to undergo photodisintegration.

$$Fe + \gamma \rightarrow 13He + \nu^{o} + 4n^{o}$$

The neutrinos escape from the star and carry off thermal energy very rapidly. This causes the pressure in the core to drop precipitously and the core then collapses under the enormous weight of the upper layers. In some models. the collapsing upper layers of the star produce a shock wave while the electrons and protons in the core are forced to combine and form neutrons. The production of neutrons produces an outward flow of more neutrinos, but the density of the core is now so great that it is opaque to the neutrinos. This produces another shock consisting of an expanding shell of neutrinos. This interacts with the other shock of the in-falling outer layers so that it bounces off the core and propagates upwards through the star resulting in an explosive repulsion of the upward layers. Many nuclear fuels in the upper layers of the star may ignite explosively also. In addition to the direct fusion of heavy nuclei, many other elements are produced as a result of neutron capture or proton and alpha particle absorptions. This all happens within a few seconds.

This produces a Type II supernova, whose spectrum displays Balmer lines revealing the presence of a hydrogen envelope.

In other models, the collapse of the core overshoots and then bounces back producing a shock wave that propagates up through the star and sets off any possible nuclear reactions in the upper layers which then expand outwards explosively.

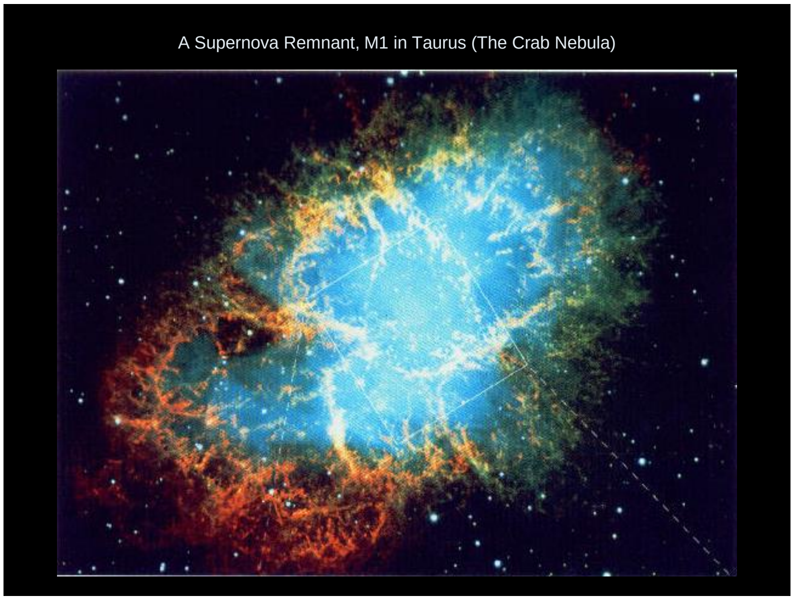


Observationally, a supernova event causes the star to brighten by a factor of 1 million or more and can outshine all the stars in the galaxy containing the event. To observers on the Earth, this event appears as a new star in the galaxy, because previously it was too faint to be detected. This is the origin of the term “Nova”. There are different kinds of novae, but ordinary novae outbursts are not as luminous as supernovae events.

The outer layers of the star blow off at very high speed, leaving behind the core of the star that is referred to as a supernova remnant. That remnant may be a neutron star, white dwarf, or black hole, depending on its mass after the explosion. The photo to the right shows the expanding outer layers of a Type II supernova.

The blown off layers continue to expand and eventually enrich the interstellar medium with the heavy elements the star produced. The Crab Nebula in Taurus is a good example of the expanding envelope from a Type II supernova explosion. This is shown in the adjoining photo. Historical records indicate that the explosion happened in the year 1054 AD. A pulsar has been discovered at the center of this rapidly expanding envelope. Pulsars are the observational manifestations of rapidly rotating neutrons stars.

So stars are slowly causing a change in the chemical composition of a galaxy. Successive generations of stars will then have a higher abundance of heavy elements. In this way, the age of a star may be determined by the relative abundance of metals. Some of the heavy elements will form microscopic particles that are called “dust”. Only in this way does it become possible to make planets and people. So we are made of “stardust.”


A Supernova Remnant, M1 in Taurus (The Crab Nebula)

A supernova event happens only for very massive stars. The Sun will not become a supernova. It and other low mass stars will shed their outer layers as they evolve to their final stage. The shedding of the outer layer non-explosively is called the planetary nebula stage. This name arose from the fact that these expanding shells appeared like fuzzy planets to early telescopic observers.

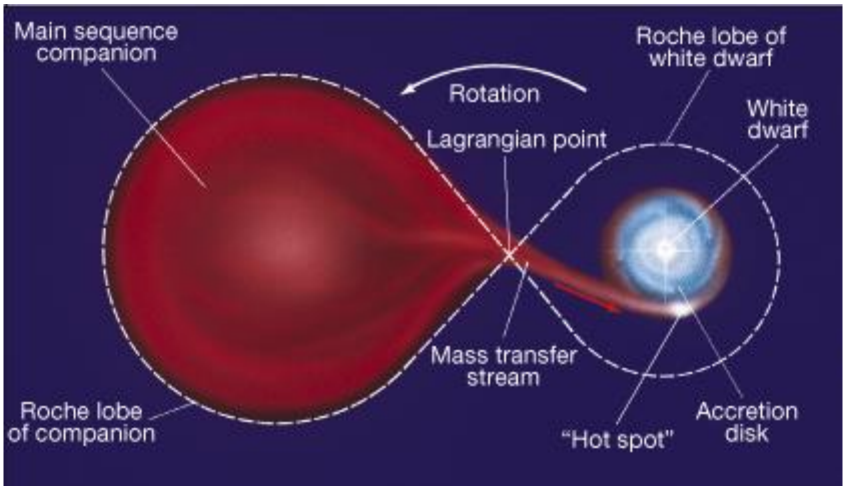
14-6. Other Types of Supernovae:

Type Ia supernovae are believed to be white dwarfs that have collapsed after accreting too much mass from a companion star and have exceeded the Chandrasekhar Limit (see section 14-8). Nuclear reactions then occur explosively within the star, such as the fusion of C, O, and even Si. These reaction generate so much energy that the white dwarf literally blows itself apart. The spectrum of the supernova reveals the presence of a hydrogen envelope. It also might be that a Type Ia supernova is the result of the merger of 2 white dwarfs.

Type Ib and Ic supernovae originate much like Type II, that is a massive star that undergoes core collapse after exhausting all nuclear fuel in the core. However, they have spectra with no indication of hydrogen. The precursor stars are believed to have lost their hydrogen envelopes to a companion star or by wind action.

14-7. Novae

A nova event is a much less energetic explosion than a supernova event. Novae are believed to be the result of the sudden detonation of hydrogen fusion on the surface of a white dwarf that is a member of a binary star system. This is depicted in the diagram to the right. Mass transfer from a companion star accumulates in a layer around the white dwarf. This layer is compressed and heated to the ignition temperature of H fusion, which occurs explosively. The brightness of the star then increases dramatically so that it is seen a “new” star in the sky. More details may be found in the textbook. The distinction between when a white dwarf becomes a nova or a Type Ia supernova is not exactly clear, but it may be related to the rate of mass transfer or the number of times it has exploded as an ordinary nova. Even though white dwarf may blow off some of the accumulated mass from its companion to become just a nova, there may be still a net gain in its mass. Therefore the next time it accumulates mass, the scales may be tipped to detonate as a Type Ia supernova. It may even go through several episodes of becoming a nova before it becomes a Type Ia supernova.



14-8. Final Stages

When a star is prevented from collapsing so that it cannot ignite another TNF reaction it enters into a final stage where it slowly cools off and dies as a star. The possible final stages, depending on what stops further contraction are:

(1). White dwarf
(2). Neutron star
(3). Black Hole.

Which final stage a star eventually reaches depends critically on its mass. Very massive stars may undergo a supernova explosion and then become either a white dwarf, neutron star, or black hole, depending on how much mass the star has after the explosion.

Stars like the Sun and those less massive than the Sun evolve to become white dwarfs. In a while dwarf, the repulsive forces between electrons is strong enough to balance gravity if the star's mass is less than 1.4 times the Sun's mass. The theory for this was first worked out by S. Chandrasekhar, for which he was awarded the Nobel Prize. This limiting mass for a white dwarf is known as the Chandrasekhar Limit. White dwarfs eventually cool to become black dwarfs, but the universe is insufficiently old for this to have occurred for any star yet.

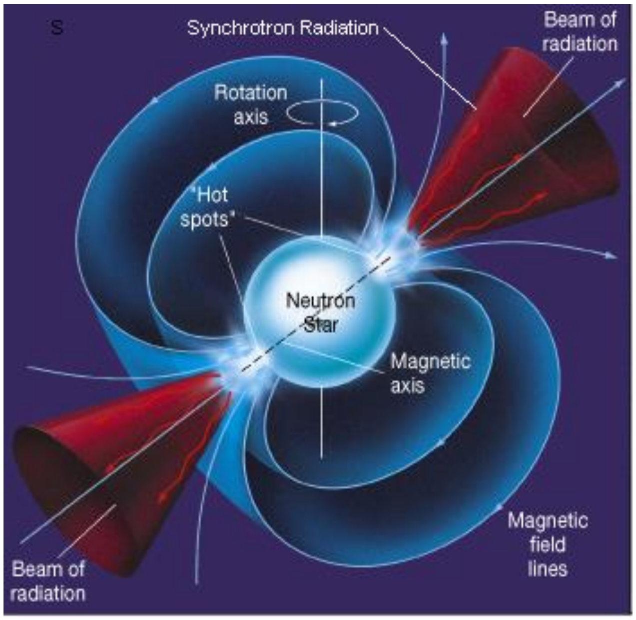
Properties of white dwarfs:

1. A very long lived stage of evolution: 50 billion years.
2. The star is supported against further gravitational contraction by degenerate electron pressure.
3. The upper mass limit for a WD is $1.4M_{\odot}$. This is known as The Chandrasekhar Limit
4. White dwarfs are typically range in size from $1R_{\oplus}$ (6,000 km) to $10R_{\oplus}$.
5. Density = 10^8 gm/cm^3
6. They have surface temperatures ranging from 50,000K to 5,000K.
7. They have no internal source of energy and are slowly cooling to become black dwarfs. However, the universe is insufficiently old for this to have happened yet.

Neutron Stars

Stars slightly more massive than 1.4 solar masses contract to the point where all electrons are forced into the nuclei to combine with the protons and form neutrons. The repulsive force of neutrons then balances gravity. This is a neutron star.

Neutron stars are very small, have intense magnetic fields, and spin very rapidly. The radiation emitted along the magnetic axis is very strong. If the magnetic axis is tilted with respect to rotational axis, we would observe the radiation coming from the star to be in pulses, much like a rapidly rotating lighthouse. Such objects have been detected and are called "pulsars".



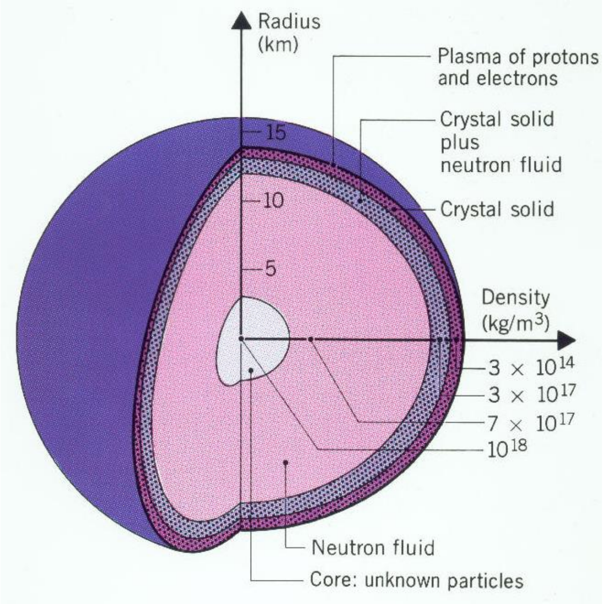
Pulsars:

1. Rapidly rotating neutron stars with magnetic axis different than the rotational axis.
2. Intense radiation from magnetic poles due to charged particles moving along magnetic field lines (synchrotron radiation).

3. Lighthouse effect, if line of sight is at the correct angle.

Hence, pulsars are evidence that neutron stars exist. A schematic of a pulsar is shown above.

A schmeatic showing the possible structure of a neutron star is shown in the adjacent diagram.



Black Holes

Stars that enter the final stage of evolution with more than 3 solar masses become black holes. Here the gravity of the star is so strong that light cannot escape from the star, so it is said to be black. There is no known force that can stop the star from contracting and this is a problem. Ordinary classical physics cannot explain what happens in a black hole and we must turn to the general theory of relativity. In general relativity, very massive objects distort space and time and gravity is viewed as the curvature of space-time.

14-9. The General Theory of Relativity

In the 19th century, the German mathematician, Riemann, developed the mathematics that describes the properties of curved spaces of any dimension, including what are known as hyperspaces (spaces of more than 3 dimensions).

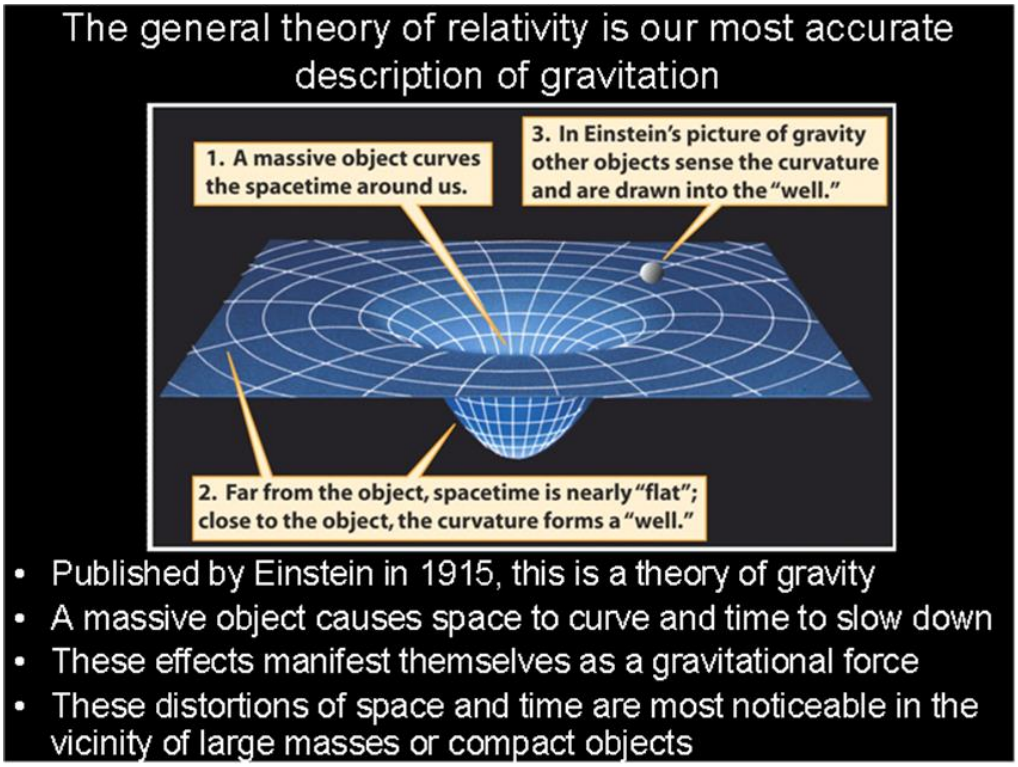
The terms "manifold" and "continuum" are synonyms for space.

By 1917, A. Einstein developed the General Theory of Relativity. In this theory, Einstein developed a new way of representing gravity that is superior to Newton's concept. It is superior since it is able to account for more phenomena, including many phenomena encountered in cosmology and wherever there are very dense objects, such as black holes.

In order to explain certain physical phenomena, Einstein introduced the idea of the Space-Time Continuum. That is, space and time make up a 4 dimensional hyperspace (manifold) or geometric fabric of the universe. Einstein applied the equations of Riemannian geometry to describe the properties of the S-T continuum. In general relativity, one imagines that empty space is at least 4D and has geometric properties. One of these properties is that S-T continuum is elastic and can stretch or be deformed. This means the properties of empty space may be altered. In his special theory of relativity published in 1905, Einstein had already introduced the idea that space and time are not absolute things but depend on your motion relative to the thing you are measuring. In the general theory of relativity, Einstein also introduced the idea that matter exists in the universe in such a way that it is embedded in the geometric fabric or S-T continuum and affects the shape of the S-T continuum. More specifically, matter bends the S-T continuum or gives it curvature. As something travels from one point in space to another, it must follow the curvature of the S-T continuum, even light. In an analogous way, as we travel from one place on the Earth to another, we must follow the curvature of the Earth. Though we can visual the curvature of the Earth's surface, which is 2 dimensional, we can not see or visualize the curvature of our 4D universe. However, the geometry of such a universe can be described by the mathematics developed by Riemann.

Now, since movement along a curved path is the result of a force, movement along the curvature of the S-T continuum is equivalent to having a force act on you. Hence, Einstein interpreted the curvature of the S-T continuum to be gravity.

This is a different way of representing gravity and replaces Newton's concept of gravity being a force of attraction acting over the space between objects.



The general theory of relativity is our most accurate description of gravitation

1. A massive object curves the spacetime around us.

2. Far from the object, spacetime is nearly "flat"; close to the object, the curvature forms a "well."

3. In Einstein's picture of gravity other objects sense the curvature and are drawn into the "well."

- Published by Einstein in 1915, this is a theory of gravity
- A massive object causes space to curve and time to slow down
- These effects manifest themselves as a gravitational force
- These distortions of space and time are most noticeable in the vicinity of large masses or compact objects

Einstein's theory is also able to explain phenomena that can not be explained by Newton's concepts. For example, Einstein's theory predicts that light is affected by gravity, but Newton's Law does not. The prediction that light is affected by gravity has been verified astronomically, thereby giving support to this theory. The general theory of relativity makes other predictions that have also been verified.

According to the general theory of relativity, gravity is the curvature of the space-time continuum, and mass causes this curvature.

In essence, what the general theory of relativity does is equate the laws of physics to the geometry of the universe. In other words, the laws of physics describe the geometry of our universe.

Saying the above another way, when the laws of physics are expressed using the mathematics developed by Riemann, they are of the same as the Riemannian equations that describe the geometry of the space-time continuum.

It is only by applying Einstein's theory of gravity to collapsing stars of large mass that we are able to understand what happens to them.

Such collapsed stars bend the space-time continuum around themselves so severely that this region of space becomes like a gravitational hole in the universe. The escape velocity from such a collapsed star is greater than the speed of light. This means light cannot escape from the star so that it would be black. Thus, the name "black hole" came about.

It was the German mathematician Karl Schwarzschild who first found a solution to Einstein's equations that indicated these properties for black holes. The size of a star when it shrinks to the point where light can not escape is called the Schwarzschild or "critical" radius of a star. To find this solution, Schwarzschild assumed the star was not rotating; otherwise the problem was more difficult. But such an assumption leads to the result that the star must collapse to infinite density. Obviously, this is a problem.

In the 1970s, a New Zealand mathematician, Roy Kerr, was able to find a solution to Einstein's equations for a rotating black hole. In this case, the star does not have to collapse to zero radius. Instead, the star opens a connection or bridge between one place in the universe to another far away in time and or space. This bridge or connection is called a "wormhole" and has been used in many science fiction stories, such as "Deep Space Nine" and a Disney movie titled "The Black Hole." The reality of Kerr's solution is not fully understood nor is there any observational phenomena that may be associated with this interpretation of the solution. This is a frontier of investigation.

Black holes have been detected when they are a member of a binary system, as is depicted in the adjoining diagram. The material in the accretion disk is heated by friction and compressional forces to temperatures equal to more than a million Kelvins. At these temperatures, x-rays are emitted which go away when the disk is eclipsed by the larger, expanding B-star. By analyzing the x-ray and visible band light curves and the radial velocity curve, it is possible to deduce the size of the black hole and its mass, thereby establishing the companion of the B-star to be a black hole. Sometimes the mass of the star that has the accretion disk indicates that it is neutron star rather than a black hole.