Stellar Remnants:
White Dwarfs, Neutron stars, Black Holes

White Dwarfs:

A White Dwarf forms when a low mass star, like the Sun, nears the end of its life. When the star swells into its second red giant phase, the outer layers are ejected to form a Planetary Nebula shell. Left behind is a hot compact core composed mainly of carbon and oxygen, with a surface layer of hydrogen and helium. The core shrinks and cools to form a White Dwarf. It has too little mass to heat itself so that it can ignite carbon.

The white dwarf continues to shine using energy it previously generated (stored energy) --- it emits stored energy. It takes 10 million years to cool to 20000K, and **Billions** of years to cool to a Black Dwarf.

The contraction of the White Dwarf star is halted by **electron degeneracy pressure.** Electron degeneracy pressure occurs because **electrons resist being pushed together** --- only so many electrons can be put into a given volume.

As the white dwarf cools the pressure, which is **independent of the temperature,** remains essentially constant. The white dwarf is thus in hydrostatic equilibrium.

A White Dwarf has radius comparable to the Earth, but may contain a Solar mass of material. It is very dense --- 10^6 gm/cm^3 --- a **million times the density of water**.

When mass is added to a white dwarf, its radius shrinks, so that the increased electron degeneracy pressure can stop gravitational collapse.

The Chandrasekhar Limit.

If the stars mass after the planetary nebula phase **exceeds $1.4M_{sun}$**, known as the Chandrasekhar limit, the forces due to electron degeneracy pressure are **insufficient** to overcome the gravitational forces attempting to push electrons into protons. Such a star **cannot** end its life as a White Dwarf.

Note -- A $4M_{sun}$ main sequence star will shed enough mass in the planetary nebula phase to leave a remnant less than $1.4M_{sun}$.

No White Dwarf has been found to occur with a mass greater than 1.4 Solar masses. Masses are found using the modified form of Kepler's 3rd law , or from the gravitational redshift of light. In both cases the White Dwarf must be in a binary system.

Gravitational Redshift.

A White Dwarf is very compact, and hence has a strong gravitational field at its surface. Light escaping from the surface of the star must overcome this gravitational field. In escaping from the stars surface, the light must lose energy. This loss of energy causes the light to be redshifted and is called a **gravitational redshift.**

NB Common experience suggests that the light would slow down. However **light always travels at the same speed (in a vacuum).** Thus a photon (particle of light) can only lose energy by increasing its wavelength.

The redshift occurs in all stars but in stars like the Sun it is very small (since the gravitational field is relatively weak). Doppler shifts caused by motions in the Sun's atmosphere tend to dominate over the gravitational redshift.

White Dwarfs in Binaries
Novae and Supernovae of Type I

Novae

Newly visible stars --- *not* new *(i.e young)* stars.

Become visible when a white dwarf star brightens by a factor of 100 to 1 million.

Occur in binary star systems in which one star is a white dwarf. Material from the companion star may be captured by the White Dwarf fueling an eruption on its surface.

A Classical Nova results when material from the companion star flows onto the white dwarf's surface. This occurs peacefully for many years, but over time the hydrogen accumulates on the surface and becomes hotter and hotter. **Suddenly**, nuclear reactions (fusion of hydrogen into helium) occur, releasing large amounts of energy, a rapid brightening, , and the ejection of material from the system.

If the White Dwarf accretes (accepts) too much material from the companion star it will exceed the Chandrasekhar limit. This may cause a collapse of the White Dwarf followed by a **Type I Supernova** explosion. A Type I Supernova explosion, unlike a Type II, leaves NO remnant star.

The energy supplied for the explosion comes from the release of nuclear energy --- the fusion of C and O into heavier elements (e.g., iron).

Neutron Stars

Result from the collapse of the core of a massive (greater than $8M_{sun}$) star.

When the mass of the core is greater than 1.4 M_{sun} the gravitational force is so strong that electrons and protons are pushed together to form neutrons and neutrinos. Since neutrinos pass easily through most kinds of matter, most escape the star.

The energy of the rebounding neutron core and some of the escaping neutrinos eject the outer layers of the star in a powerful (Type II) supernova explosion.

The core is now composed of neutrons. Since only the neutron core of the star remains, the star is called a **neutron star**. The condition of the matter in the star is called **neutron degeneracy**, because the neutrons cannot be packed any closer than they are without the neutrons being pushed into each other.

NB: If the mass of the neutron core is greater than 2 to $3M_{sun}$, even the neutron pressure cannot halt the collapse of the core, and a Black Hole is formed.

Typical Neutron Star Parameters:

Diameter:	20 km
Mass:	1.5 M_{sun}
Density:	10^{15} gm per cm^3

The material is so dense that a teaspoon of the material would weigh a billion tons on Earth. Density of a neutron star corresponds to compressing all the water in a volume of 1 cubic km into 1 cubic cm. The density is comparable to the nucleus of an atom.

In one sense, a neutron star is a SINGLE gigantic nucleus. Neutron stars are composed of a new kind of "matter". The properties of this "matter" are not well understood.

Neutron stars rotate very fast:

During the collapse of a star's core to a neutron core, the core must rotate faster and faster to conserve angular momentum. The effect is similar to what is seen when the arms of a spinning skater are pulled towards the body.

NB:

Even if the core of the star had rotated only once per month on the main sequence, it will rotate faster than once every second when it has a diameter of 20km.

Neutron stars have VERY intense magnetic fields.

When the core collapses, the magnetic field strength, like the gravitational force and the rotation rate, must increase. A neutron star has a magnetic field like a bar magnet. In general, a neutron star's rotation axis will not be aligned with its magnetic axis.

NB: Main sequence stars are known to have magnetic fields associated with them (eg sunspots are caused by magnetic fields).

A neutron star

(1) has a very strong gravitational field

(2) rotates very rapidly

(3) has a very strong magnetic field.

Pulsars (Rotating Neutron Stars)

Pulsars were first detected in the radio region in 1967. They emit short bursts of radio radiation, which is repeated in a very regular fashion.

eg. First pulsar discovered emits bursts that last about 0.01 second. The "bursts" or "pulses" occur every 1.34 seconds.

Because of the very small pulse duration (0.01secs), the emitting objects **must** be very small (smaller than a white dwarf).The short pulses, and their regularity, led to the identification of Pulsars as rotating Neutron stars.

NB.

1. An object will not vary appreciably on a time scale faster that its diameter expressed in light travel time. This occurs since, at any given instant, the light reaching the observer was emitted at slightly different times . This smooths the variations out over time.
2. The Diameter of Earth is about 0.04 light seconds).

Light House Model

If the rotation axis of a neutron star were pointed in just the right direction away from the Earth, the magnetic axis of the neutron star could be pointed directly at the Earth for a brief period of time once each rotation.

Charged particles from the Neutron star's surface are trapped in the magnetic field and emit electromagnetic radiation as they travel outwards from the surface.. The electromagnetic radiation is only emitted in a (narrow) beam about the direction of the magnetic axis.

Thus an observer sees a **pulse** of radiation --- one each rotation.

The energy for the pulsations comes from the rotation of the neutron star. To conserve (total) energy, the rotation rate of the pulsar MUST decrease with time. This is observed!

The intervals between pulses range from 0.0013 to 4 seconds. In the fastest case this implies that the neutron star rotates 885 times each second!

Pulsars make very good clocks. Until recently (last decade) they were comparable with the best clocks on earth.

Pulsars and Gravitational Waves

"The" Binary Pulsar.

Observations of one particular pulsar reveal it is in a binary system composed of 2 neutron stars. The orbital period is about 8 hours.

The binarity was discovered because it was not a "good clock" --- the pulse arrival times were not constant. This effect is due to the Doppler effect arising from the orbital motion.

Because we have 2 objects with very intense gravitational fields in orbit about each other, it provides an excellent laboratory for testing the **General Theory of Relativity (GTR).** In agreement with the observations, the GTR predicts that the position of the pulsar in its orbit will change by 4 degrees per year.

GTR is Einsteins theory which REPLACES Newtons theory of gravity. Newton's theory is still **extremely** useful, but breaks down in regions where the gravitational field is EXTREMELY strong. **In GTR a massive body warps the space around it.** It is this warping of space time that gives rise to the gravitational force.

The masses for the 2 components of the binary system have also been determined very accurately.

Taylor and Hulse received the 1993 Noble prize for this discovery, and their subsequent tests of the GTR.

The GTR also predicts that the binary system containing the two neutron stars will emit gravitational radiation. As this removes energy, the binary orbits should shrink. This is observed in THE binary pulsar.

Gravitational waves can be thought of as ripples in space-time (like ripples on a pond). **Gravitational waves are NOT electromagnetic radiation.**

Gravitational radiation (sometimes called gravity waves or gravitons) is emitted any time masses are accelerated, and in the case of binary systems with neutron stars the radiation is relatively strong.

Gravitational wave detectors on Earth are not yet sensitive enough to detect gravitational radiation (but the National Science Foundation is building LIGO --- Laser Interferometry Gravitational wave Observatory.).

Crab Pulsar.

Fast pulsar with a rotation period of 0.033 seconds (i.e it rotates 30 times a second) is detected in the Crab Nebula. It has a rapid rotation rate because it is very young. The Crab Nebula is the "spectacular" remnant of a supernova explosion that "occurred" in 1054.

This fast rotation period rules out a white dwarf completely. Pulses have been seen in the visible band, and the X-ray region. The detection of a neutron star in a supernova remnant provides strong support for current evolution models.

Milli-Second Pulsars.

Spin very fast:

e.g. 885 times per second (period 0.0013 seconds).

Believed to be old, as they are not being "spun down", and hence must have weak magnetic fields.

Believed to arise through accretion. The neutron star accretes matter from a companion star after it has evolved off the main sequence. The accreted matter contains angular momentum, and hence causes the neutron star to "spin up" (rotate faster).

X-Ray Binaries

Many of the X-ray sources that astronomers observe, with X-ray telescopes in space, originate in binary star systems which contain neutron stars.

Material from the other star in the binary system falls onto the neutron star causing X-rays to be emitted. The material is funnelled to the magnetic poles of the neutron star by the strong magnetic field.

When the orientation of the binary is right for observers on Earth, pulses of X-rays are observed.

SS433

One of the most spectacular objects in our Galaxy. It is an X-ray binary system containing a neutron star and an evolved O or B star.

The neutron star pulls matter off the O star, and an accretion disk forms around the neutron star. Matter is ejected from the inner parts of the accretion disk outward into space at about one-quarter the speed of light.

The matter is ejected in 2 narrow jets.

These effects can be studied by observing changing Doppler shifts in the spectra of SS433.

STELLAR BLACK HOLES

Form from the collapse of the core of a massive star. For a black hole to form, the core must be more massive than approximately $3M_{sun}$, otherwise a neutron star will (probably) be formed.

Once the core mass exceeds $3M_{sun}$ the pressure forces supplied by neutron degeneracy cannot prevent further gravitational collapse. Once the collapse of the star proceeds past the neutron core, there are no known forces which can stop the collapse. **It will continue collapsing "forever."**

A Black Hole gets its name due to its intense gravitational field. **The gravitational field of a Black Hole is so strong that not even light can escape its pull.** A Black Hole (effectively) emits no radiation, and absorbs all radiation falling onto it.

The effect of gravity on electromagnetic radiation (light) is described by The General Theory of Relativity (GTR). GTR also predicts that mass bends light. In strong gravitational fields, light will be significantly bent back towards the mass.

The Structure of a Black Hole

A black hole can be completely described by **3 properties**.

(a) Its mass.

(b) Its rotation rate (angular momentum).

(c) Its electric charge.

(Note: To describe a star we need to specify its radius, its mass, its composition, its structure etc).

We will mainly consider a non-rotating black hole, as this is the simplest. We expect, however, that a real black hole will rotate (since the progenitor star rotates). The electric charge of a black hole is of academic interest only, since we expect Black Holes to be electrically neutral.

Non-Rotating Black Hole

Two principal regions of interest in a non-rotating black hole are:

i) **The Singularity**.

Theory predicts that no force can stop the gravitational collapse of a black hole. Mathematically, all of the mass is predicted to reside in an infinitely small point at the black hole's center. This point is called a **singularity**.

ii) **The Event Horizon (Schwarzschild radius).**

Gravity is infinitely strong at the singularity, but becomes weaker at distances further from the singularity. If a 3 M_{sun} black hole is considered, light has no chance of escaping unless it is more than 9 km from the singularity. This location in the black hole is known as the **event horizon**.

Everything inside the Event Horizon is hidden from view!

Karl Schwarzschild first calculated the size of the event horizon in 1916 using the General Theory of Relativity, hence the event horizon is also known as the **Schwarzschild radius**.

The size of the event horizon is directly proportional to the mass of the black hole.

The Schwarschild radius can be derived (incorrectly!) using Newton's Theory of Gravity. Previously we discussed the escape velocity (V_{esc}) for an object to escape the gravitational pull of a body of mass M**.**

$$\mathbf{V_{esc}=(2GM/R)^{1/2}}$$

To derive the Schwarschild radius (R), we replace V_{esc} by the speed of light --- the maximum velocity. This gives

$$R=2GM/c^2$$

The same result comes from more rigorous calculations using GTR.

Because relativistic effects are so strong in the vicinity of a black hole, phenomena like length contraction, and time dilation, which go against common sense, occur. One way of investigating the properties of the space-time around a black hole is to consider the paths that particles or light follow.

A Rotating Black Hole

Event Horizon

The event horizon of a rotating black hole is smaller than for a non rotating black hole, but is still spherical in shape. The event horizon is smaller because the inward force of gravity is diminished to some extent by the outward force caused by the spinning.

The event horizon of a Black Hole rotating at its maximum possible speed is a factor of 2 smaller than for a non-rotating Black Hole.

A rotating black hole is much more complex than a non-rotating black hole. For example, just outside the Event Horizon there is a region (the Ergosphere) in which particles must rotate in the same sense as the hole (compared to the background stars.)

Theoretically, it is possible to extract energy from a rotating black hole.

Hawking Radiation

Due to quantum physical processes a Black Hole has a finite temperature, and thus emits radiation. This radiation ultimately comes from the Black Hole's mass, and thus the Black Hole "Evaporates." The evaporation times for solar mass objects is extremely long.

For a 1 solar mass black hole the temperature, which is inversely proportional to the mass, is $6x10^{-8}$ K. As a consequence, a 1 solar mass black hole will take 10^{67} years to disappear. Black holes of larger masses take even longer!

The Detection of a Black Hole

If we were to watch an entire star collapse into a black hole, we would simply see all of its electromagnetic radiation become infinitely redshifted, and then disappear, in a fraction of a second. There is little chance of observing such an event.

At the present time the only methods used to investigate the idea of a black hole are to search for matter which may be orbiting around one and to identify binary systems which contain invisible companion stars which have masses greater than $3M_{sun}$.

Extremely hot matter is expected to orbit around a black hole. The idea is that some of the matter attracted (accreted) by a black hole will not fall in but will go into orbit around it. This orbiting matter is called an accretion disk. The orbital motions will be so energetic that friction between the various parts of the disk will cause it to heat to high enough temperatures so that observable x-rays are emitted.

The best stellar black hole candidates are in X-ray binaries where the invisible companion star has a mass greater than $3M_{sun}$. Cygnus X-1 is one of the best candidates.

Gravitational Waves provide a possible means of detecting the formation of a Black Hole.

Non-Stellar Black Holes

So far, the formation of black holes during the late stages of evolution of massive stars has been considered. Black holes may also form in other ways, some of which will be considered later. For example:

1. Mini black holes may have formed as a result of great compressive forces present in the early Universe near the time of the Big Bang. [A black hole with the mass of an asteroid would be the size of a pin head.]

2. Supermassive black holes (with masses of 1 million to 1 billion M_{sun}) likely exist at the centers of quasars and some galaxies.

3. The Universe itself could be thought of as the interior of a black hole since light can not escape its boundaries and one day it may collapse back in on itself to form a singularity.