Chapter 22 Neutron Stars and Black Holes

Neutron Stars

What do you have left after a supernova? It depends what type of supernova you have. If you have a Type I supernova, most astronomers believe that it is blown to bits and nothing is left. If it is a Type II supernova, then it is quite likely you will have a remnant. The parent star is gone, but there is something left over. This object is highly compressed which gives it a high density. The density is much higher than a white dwarf star. If you remember (and even if you don't) when the star is going to go supernova, the protons and electrons are pressed together to make neutrons. At that time you have a great release of neutrinos that carry away large amounts of energy. When this happens you have the neutrons collapsing down until they touch. The shock wave that destroys the star does not start in the very center of the star so the center is left intact. When it is all finally over what you have left is a ball of neutrons. It is called a *neutron star*. The word star is very misleading though. It is nothing like a star. You have a ball of neutrons that may have $3M_{sun}$, but it is only about 12 miles across. This means that a thimbleful of this material would weigh 100 million tons. The neutron star is a solid object, which you could stand on if a cool one were found. You would weigh a little more than normal. A 150 pound person would weigh about 10 billion tons. The real problem is that the gravity would flatten you much thinner than a sheet of paper in your book.

Due to the law of conservation of angular momentum these bodies rotate very fast. They rotate in much less than a second. Also the new neutron star would have a magnetic field that is much stronger than the parent star. The collapse amplifies the magnetic field. It would be trillions of times stronger than the Earths. It will eventually slow down as it radiates away its energy to space.

Pulsars

Do the neutron stars really exist? The answer is yes. In 1967 a strange object was discovered. An object was found that emitted pulses every 1.34 seconds. The interval between pulses was incredibly uniform. They were so precise that it was suggested that they came from a life form and were called the LGM or Little Green Men. We now know that they are really an object called a *pulsar*. They are the most accurate natural clock known. They are actually a small rotating source of radiation. Figure 22.3 shows how the radiation is pointed by the pulsar. They refer to this as a *lighthouse model*. As the beam sweeps by the Earth we experience the radiation from the pulsar. The time between pulses is just the rotation rate for the pulsar. We now know of more than 1500 of these pulsars. A few of the pulsars are associated with supernovae. The most famous one is found in the Crab Nebula. Figures 22.4 and 22.5 shows what the pulsar looks like and what it is doing. This pulse is 33 milliseconds or .033 sec. You have a high energy pulsar wind slamming into the material around the pulsar. This heats the gas found there and we find X-ray emitting gas moving away from the pulsar. Most pulsars emit in the radio range of the spectra, but the Crab emits in X-ray and gamma rays. This pulsar emits slightly in visible light and not at all in the radio, but rather strongly in the gamma rays. Regardless the pulses are emitted at regular intervals. Most pulsars have very high speeds in space, much higher than the stars around them. This is thought to be from the supernova that formed them. The supernova was not perfectly symmetrical in it s explosion.

All pulsars are neutron stars but all neutron stars are not pulsars. There are a couple of reasons for this. They all have rapid rotation and a strong magnetic field, but that diminishes over time. Also, we may not lie in the line of sight of the pulses.

Neutron Star Binaries

Since many of the stars in the sky are found in multiple star systems, you will find many neutron stars in binary star systems. This means that the masses can be determined accurately. Most are around 1.4 M_{sun}, which is the Chandrasekhar limit for a white dwarf.

X-ray Sources

In the 1970's we discovered numerous X-ray sources in the galaxy. One such object discovered were called *X-ray bursters* because they have violent eruptions, each thousands of times more luminous than our Sun, but it is released in only a few seconds. These are thought to be from neutron stars in a binary system. The process is similar to the white dwarf in a close orbit around a main sequence star. The gas is pulled off onto an accretion disk around the neutron star. This material drops onto the neutron star slowly, releasing X-rays. The material accumulates on the neutron star until the temperature is hot enough to fuse hydrogen. This gives you the X-ray burst. After a few hours enough material has accumulated to burst again.

Not all of the infalling gas makes it onto the surface of the neutron star. One object called SS433 expels more than an Earth mass of material per year in 2 oppositely directed jets moving perpendicular to the disk. Doppler studies of the jets shows that the material is moving at 80,000 km/hr or 25 % the speed of light. Figure 22.9 shows this. The one nice thing about SS433 is that we can study both the jets and the disk at the same time.

Millisecond Pulsars

In the 1980's we found a new type of object: the *millisecond pulsars*. There are over 100 known now. These object spin at rates of hundreds of times per second. What that means is that you have an object maybe 20 km across spinning at nearly 20 % the speed of light. It is making nearly a thousand rotations per second. Many of these are found in globular clusters which are very old. But these would have come from stars that lived only tens of millions of years. That means that no new neutron star has been produced many years. The problem is that a pulsar is thought to slow down in only a few million years and after 10 billion years they should have pretty much stopped. For this to have happened they must have spun up somehow. The most obvious way is to draw off material from a companion star. As material spiraled down onto the neutron star the mass went up making it spin faster. The evidence is that of the 80 or so millisecond pulsars seen in globular clusters about half are found in binary systems. The other half must have already destroyed their companion or they had an encounter with another star that ejected the pulsar. This means that the millisecond pulsars are formed in a 2 stage process: formation of the neutron star and then pulling mass of a nearby companion.

Pulsar Planets

Another unique feature discovered while studying a millisecond pulsar in 1992 was that it varied its pulses in a very regular way. It varies on 2 distinct time scales: one of 67 days and 98 days. Why was it happening? The discovering group thinks it is because of 2 planets orbiting this pulsar. They are thought to be 3 Earth masses at distances of .4 AU and % AU. There has been a third planet discovered since. It is about .2 AU from the pulsar. The big concern is how these planets would have formed around a star that went supernova. One thought is that the companion that provided the material to spin up was pulled apart and the material formed a disk around the pulsar that formed the 3 planets. But, we just don't know for sure.

Gamma Ray Bursts

GRB's were first discovered in the 1960's by the military was looking for evidence of nuclear tests. It has become one of the hottest topics in astronomy today. It was for a time thought to be scaled up X-ray bursters, but we now know that it is something more.

Distance and Luminosities

Figure 22.13b shows the 2704 GRB's discovered by the Compton Gamma Ray Observatory during its 9 year lifetime. It found about 1 per day. They are found spread across the sky, not in the plane of the Milky Way. The bursts did not repeat themselves, so they were a one time event. CGRO was not able to determine the distances to the GRB's. We tried to associate the bursts with some objects, but since they are so high energy and penetrating their positions were not known to within a couple of degrees. Also the afterglows faded quite rapidly. The first distance determination happened in May 8, 1977 when it was imaged in the gamma ray, X-ray and optical wavelengths. When looking at the optical wavelengths of iron and magnesium were found to be redshifted by almost a factor of 2. This means that it is at distances of around 2 billion parsecs. Figure 22.14 shows a gamma ray burster and the host galaxy. This burst was almost 5 billion parsecs away from us. To date we have been able to measure distances to about 2 dozen bursters. These events must be very energetic because they give off so much energy. Finding the object associated with the burster depends on 2 things: accurate measurement of its position and fast communication.

What Causes the Bursts?

We really don't know what causes these bursts. Measurements have shown that the object causing the bursts can't be more than a few hundred kilometers across! Some theorists call them *relativistic fireballs*. This is an expanding region of superhot gases. The afterglows are from the jet expanding, cooling, and interacting with the surrounding medium. If this is true that explains why they are so bright. They are being directed directly at us and it appears to be much brighter than they really are. One model for the bursts is having 2 neutron stars in a binary system. As they spiral together they will eventually merge violently and release tremendous amounts of energy. The other model is called a hypernova, or a failed supernova. As the core of a large star collapses, it collapses directly into a black hole. The outward rush is stalled and an accretion disk forms around the black hole forming the jet. There is no consensus among the astronomers as to which model is the right one.

Black Holes

Neutron stars are supported by the neutron degeneracy. But imagine that you have enough gravity to continue past the neutron degeneracy. When that happens, you form a black hole.

The Final Stage of Stellar Evolution

Massive stars, more than 25 M_{sun}, that form a Type II supernova will leave behind a remnant. If that remnant is more massive than 3 M_{sun}, gravity will be so great that it will collapse the object past the neutron degeneracy. Now this mass is not set in stone because it doesn't consider magnetism and rotation. We also don't know for sure because all of the physics that we know doesn't do us any good when dealing with a an object like this. We call this a *black hole*.

Escape Speed

Newtonian physics can describe almost everything that we encounter. But when we start talking about a black hole we must start using the *theory of general relativity*. Two key facts of relativity are:1)nothing can travel faster than light and 2)all things, including light, are affected by gravity. A body's escape speed is the square root of the mass divided by the square root of the radius. The escape speed for the Earth is just over 11 km/sec. As the size gets smaller, the escape speed goes up. If we compress the Earth to about 1 cm, the escape speed would be around 300,000 km/sec or light speed. If the Earth could be squeezed smaller that a grape, nothing could escape the gravity because the escape speed would be more than 300,000 km/sec. The Earth would be invisible and uncommunicative. We would be a black hole.

The Event Horizon

There is a special place around a black hole where you can still escape it. It is called the *Schwarzschild radius*. This can be found by the following: R_S = _____ M_{sun} x 3 km. This imaginary boundary around the black hole is called the *event horizon*. When all of this happens, the supernova remnant will disappear below the event horizon in less than a second.

Einstein's Theories of Relativity

By the later part of the 19th century the speed of light was known. It was also understood that everything on the EMS traveled at that speed. But the scientists couldn't construct a theory where *c* was the natural speed limit.

Special Relativity

An experiment done in 1887 by Michelson and Morley showed that the measured speed of a beam of light is independent of motion of either the observer or light source. But this doesn't make sense in our minds. If we are in a car traveling at 100 km/hr and we fire a bullet at 1000 km/hr, an observer along the side would see the bullet moving at 1100 km/hr. But it is not so with light. If you were traveling at .1 *c* and you turned on a flashlight you would think that an outside observer would see the light moving at 1.1 *c*. It just isn't so. The special theory of relativity explains why this is so.

1) The speed o flight is the maximum possible speed in the universe.

2) There is no preferred observer relative to whom all other velocities can be measured.
3) Space and time are thought of as one component called *spacetime*. Observers' clocks tick at different rates for each observer depending on where they are and how fast they move.

Today special relativity lies at the heart of modern science.

General Relativity

According to Newton gravity causes things to accelerate. Einstein made the connection between the special theory and gravity in the following way: imagine that you were in a windowless elevator in space. You are weightless. Now you feel the floor press up against your feet. This could be due to 1 of 2 things. Either a massive object has come by and you feel the gravity, or the elevator is accelerating upward. There is nothing that you can do to determine which is right. Einstein reasoned that there is no way to tell the difference between a gravitational field and an accelerated frame of reference. This is known as the *equivalence principle*. To incorporate gravity with spacetime, the mathematics forced him to the unavoidable conclusion that spacetime is curved. The resulting theory is called the *general theory*. The main idea is that matter tens to warp or curve space in its vicinity. This is shown by figure 22.19. This affects matter and radiation both.

Curved Space and Black Holes

Much in astronomy can be described by Newtonian physics, but when you talk about black holes, you must use the general theory of relativity. Figure 22.19 shows how space is increasingly distorted as the mass increases. That means that space is extremely curved around a black hole. Space folds over on itself at the event horizon, causing objects to be trapped and they disappear.

Space Travel Near Black Holes

Despite what you believe, black holes don't cruise around sucking up everything in sight. An object cruising by a black hole is no more affected than if you were cruising by a star with the same mass. If you happened to pass close by the event horizon, only then would your orbit be different. And of course if you came too close and crossed over the event horizon, it's "sayonara."

Tidal Forces

Anything flowing into a black hole is subjected to incredible tidal stresses. If you were to jump into a black hole, you would be torn apart due to the incredible gravity. Since your feet are so much closer than your head, you would be stretched and made a lot thinner. You would also be accelerated to tremendous speeds. That would heat you up to millions of degrees and you would be emitting in the X-ray range.

Approaching the Event Horizon

The best way to investigate a black hole would be to go into orbit around it. Unfortunately it has been studied and a human can't withstand stresses more than about 10 – 20 times the pull of gravity on Earth. That would mean that for a 10 M_{sun} black hole you couldn't get closer than about 3000 km. Any closer and you would be torn apart. Let's send a robot to investigate our black hole. Our robot has a very accurate clock on it and we can read it from where we are. It also has a light source of known frequency mounted on it. Well as the robot gets closer to the black hole we see the light being red shifted. Even though the robot is maintaining its position around the event horizon we see a red shift due to the black holes gravitational field. This is known as the *gravitational redshift*. If the robot went right down to the event horizon, the light would be gravitationally redshifted to infinitely long wavelengths. It would be redshifted beyond our recognition.

As far as time goes we would find that the robot's clock would appear to tick more slowly than our clock. The slower it gets to the hole, the slower it appears to tick. At the event horizon the clock would cease to tick at all. That means that to an outside observer, the robot would never cross the event horizon. This slowing down is called *time dilation*. The interesting thing is that for the robot, it sees none of these effects. It is all relative to where you are.

Deep Down Inside

When we get inside the event horizon what you will find is what is called a *singularity*. Gravity has pulled the object inward until the entire mass is a point source. It doesn't matter how massive the black hole is, you still have a singularity. At this point we don't have the right physics to explain it. The theory of gravity is incomplete because it doesn't explain matter on a very small scale. There are all kinds of theories as to what happens when you go into the event horizon, but that is just what they are: theories. We just don't know.

Observational Evidence for Black Holes

Stellar Transits

Detecting black holes is difficult. One possible way to detect black holes is by observing a stellar transit. This would be where a black hole would pass in front of a background star. When a black hole passes in front of a star what happens is that the light is deflected and the star seems to get brighter as seen by us.

Black Holes in Binaries

Another way to find them is to observe their affects on another object. It usually occurs when a black hole is going around another star. The invisible partner emits in the X-rays. One of the first candidates was called Cygnus X-1. It has the mass of 25 M_{sun}. The X-ray region is probably the accretion disk around the black hole. There are others out there, but they are just hard to detect.

Black Holes in Galaxies

As time has gone on we have detected objects in the centers of many galaxies that could only be a supermassive black hole. Our own Milky Way has a black hole that is about 2.6 million M_{sun}. One of the first ones detected was in a galaxy called M-87. It has the mass of about 3 billion M_{sun}. We now believe that supermassive black holes reside in the hearts of all major galaxies.

Do Black Holes Exist?
Usually we say it is small and has a mass of blah blah blah. What else could it be. Well… Many astronomers don't believe this is the case. We have said that theories that are not supported by hard evidence don't survive. This one has survived. Have black holes actually been discovered? The bottom line is most likely yes.