Review

Last time we

- Discussed how supernova explosions enrich the interstellar medium by providing all the atoms in the periodic table.

- talked about the theory developed in the 1930s that a degenerate neutron star might exist.

- found that Jocelyn Bell discovered pulsars in 1967.

- discussed how an object which can get bright and dim in a millisecond must be less than 300 km in diameter.
Light Crossing Time

A basic principle in astronomy that governs how fast objects can change the way they appear is the light crossing time.

- An object cannot change its brightness significantly in an interval shorter than the time it takes light to cross its diameter.

Based on the duration of the pulse (0.001 s), astronomers can estimate the size of the pulsar to be less than 300 km in diameter. This rules out regular stars as well as white dwarf stars, and leaves only the theoretically predicted neutron star as a possible source for pulsar signals.
The Crab Nebula

Discovery of a pulsar in the heart of the Crab Nebula, a supernova remnant provided further confirmation that neutron stars are the sources of pulsar signals and result from supernovae.

This is an excellent example of observations confirming theory. Jocelyn Bell’s work resulted in a Nobel Prize in Physics, which was the first time this prize had been awarded for astronomical work, but it was given to her advisor, Anthony Hewish. This announcement was controversial as many people believed that Bell should have received this award or shared it with her advisor.
The Pulsar Model

Our current model for how a pulsar works is called the light-house model of a pulsar. The important points are

- A pulsar doesn’t pulse, emits radiation in certain directions and spins, causing that radiation to sweep through the sky like the light in a lighthouse.

- The beam is produced via high energy mechanisms that are not fully understood.

- We only can see those pulsars whose radiation sweeps over Earth.
Pulsar Evolution

When a pulsar first forms it spins very fast (100 times a second), as it ages it slows down. What causes this?

- Producing radiation requires energy.
- A pulsar uses its rotational energy to blast its beams of radiation outward.
- As it uses up this energy it slows down.

From this we deduce that the average pulsar is about 1 million years old, and the oldest we see is about 10 million years old. Older neutron stars may not have enough rotational energy to drive a radiation beam.
Flying Pulsars

Not every supernova remnant contains a pulsar. There are two reasons for this:

1. The radiation beam may not sweep over the Earth;
2. The neutron star may have zoomed out of the remnant.

Neutron stars can travel through space at a high velocity. Possibly due to the supernova explosion or because they occur in a binary star system.

Many pulsars do not have associated supernova remnants because the remnant only lasts 50,000 years, while the pulsar will be seen for millions of years.
Binary Pulsars

- We can detect the orbits of pulsars by looking for shifts in their pulse times.

- We can see radiation if the neutron star is devouring its companion.

In 1974 Joseph Taylor and Russell Hulse found that pulsar PSR1913+16 was orbiting a companion.

- Analysis indicated this was a system of two neutron stars orbiting each other.

- The orbital period is slowly growing shorter, confirming Einstein’s prediction of gravitational radiation which is radiating away the energy of the orbit.
Binary Pulsars

Matter which falls onto a neutron star releases a huge amount of energy. A single marshmallow dropped onto the surface of a neutron star from a distance of 1 A.U. would hit with the impact of a 3-megaton nuclear bomb.

- Even small amounts of matter hitting a neutron star will release X-rays and gamma rays.
- Hercules X-1 emits pulses of X-rays, but they vanish for a few hours every 1.7 days. This is an eclipsing binary system with a neutron star devouring a giant companion.
- 4U 1820-30 is an example of an X-ray burster. X-ray bursts occur when matter is transferred from a binary system to a neutron star where it ignites periodically.
Millisecond Pulsars

Some pulsars spin too fast.

- Theoretically a pulsar should only spin once over 0.01 seconds at most.

- Some pulsars defy this limit and spin nearly once every 0.001 seconds. These are called millisecond pulsars.

- Our new theory to explain these objects suggest that they absorb both mass and rotational energy from a companion in a binary system.

- The result is a pulsar which spins faster than when it was formed.
Planets Around Pulsars

Observations of pulsar PSR1257+12 revealed quite surprisingly the presence of objects with planetlike masses.

- Initial models of variations in the timing of the pulse arrival from that pulsar suggested the presence of 3 planets within 0.5 A.U.

- Due to the regularity of pulsar pulses it allows us to observe incredibly tiny motions of the pulsar caused by the gravitational tug of planets.

- It is thought that these “planets” are the remnants of a companion star which was brutally cannibalized by the pulsar, leaving planet-sized crumbs.
Black Holes

The final possible end stage of a star’s life is the most mysterious of all, a black hole. Black holes are a breakdown in our current understanding of physics.

- When neutron degeneracy pressure can no longer hold a star up (as happens if it is more massive than 2 or 3 solar masses), nothing remains which can stop the collapse of the core.

- The core will continue to collapse until it becomes a singularity, a point with zero radius and infinite density. The gravitational force at this point becomes infinite.

- Such a point is beyond the reach of current physical theory, but these points hide themselves from the rest of the universe in black holes.
Escape Velocity

To understand a black hole we need to learn a bit about escape velocity.

- If you launch something fast enough from the surface of the Earth, it can escape into space. This speed is called the escape velocity.
- The escape velocity depends on the strength of gravity at the launch point.
- This means that escape velocity depends on the mass of the object you are launching from, and its size.
- Escape velocity is higher the higher the mass is.
- Escape velocity is higher the smaller the size is.
Black Holes and Escape Velocity

So what does this have to do with Black Holes?

Black Holes represent an extremely high mass in an extremely small size, which means a very large escape velocity. This means an extremely high escape velocity. An escape velocity that turns out to be larger than the speed of light.
Event Horizon

When we refer to the size of a black hole we refer to that area near the infinitely dense point from which light can not escape.

- This area is bounded by a region we call the *event horizon* which bounds the isolated area around the dense point from the rest of the universe.

- The radial size of the event horizon is called the *Schwarzschild Radius* and is governed by the mass of the object. The Schwarzschild radius is

\[ R_S = \frac{2GM}{c^2} \]

where \( G \) is the gravitational constant, \( M \) is the mass, and \( c \) is the speed of light.
A Wild Ride to Nowhere

What would happen if you fell into a black hole?

- You would fall slowly at first, but more quickly as you continued to fall.

- Someone observing from outside the black hole would see you slow down as you approached the event horizon. This is due to time dilation.

- If you were to carry a flashlight to signal your friends as you descended it would appear to shine with the same color as you fell.

- From outside the light would experience a gravitational redshift appearing first red, infrared, and finally to emit at radio wavelengths.
A Wild Ride to Nowhere

In the end this journey would be extremely unpleasant. Well before you reached the event horizon. Imagine falling feet first towards a black hole.

- Eventually the gravitational force on your feet becomes much stronger than that on your head.
- The gravitational force on your left and right sides would crush you.
- Before hitting the event horizon you will have been pulled apart by the gravitational *tidal forces*. 
Observing Black Holes

How can we observe something from which light cannot escape? We can’t directly, but we can look for the effect of such a dense object on its local environment.

- Matter flowing onto a black hole would become very hot as a result of tidal forces and emit in X-rays. Such objects may be found in X-ray binaries.

- Accretion disks around black holes may drive strong hot jets which emit in X-rays and gamma rays.

- Extremely large explosions may be produced in the formation of black holes.

- A special type of radiation may be produced at the event horizon called Hawking radiation.