LECTURE 15: NEUTRON STARS AND BLACK HOLES

15.1 PULSARS

The possibility that neutron stars might be produced in supernovae was recognized in the 1930s, and the basic theory of neutron stars was worked out in the 1940s. But it wasn't clear that such objects really existed, or that if they existed they could ever be found.

In 1967, using a radio detector originally designed to study emission from the sun, Bell and Hewish discovered a pulsating radio source (*pulsar*) with a period of about one second.

More were soon discovered, with periods ranging from a fraction of a second to a few seconds.

Several explanations were proposed, including the idea that a pulsar was a rotating neutron star, with a radio beam sweeping over the earth periodically like the beam of a lighthouse.

The case for this idea was clinched by the discovery of a pulsar in the Crab nebula, the remnant of the supernova of 1054.

Conclusion: a pulsar is a rapidly rotating neutron star, produced in a supernova explosion.

Pulsars produce beams of radio emission by means of strong magnetic fields, but the details of this process are poorly understood.

About 750 pulsars are now known. The fastest of these rotates nearly 1000 times per second.

15.2 PULSAR TIMING

Pulsar periods are extremely steady; they can "keep time" more accurately than the best atomic clocks.

With a radio telescope, one can measure changes of pulsar velocity very precisely by timing the intervals between pulses:

pulsar moving away: interval lengthens

pulsar moving closer: interval shortens

Timing of pulsar periods shows that some pulsars are in binary systems; the interval gets shorter and longer periodically.

All pulsars whose masses have been measured are close to $1.4M_{\odot}$.

In 1992, timing revealed one pulsar that has two orbiting planets, with masses about 3 times the mass of the earth. This was the first detection of planets outside the solar system.

15.3 BLACK HOLES

If the collapsing core of a dying star is more massive than about $3M_\odot$, no pressure can be strong enough to support it against gravity. The core can only collapse to a "singularity" of zero radius and infinite density.

Close to the singularity, gravity is so strong that even light cannot escape from it.

The idea of an object whose gravity can trap light was first proposed by Pierre Laplace in 1798, using Newton's theory of gravity.

A proper description of such objects, now called "black holes," requires general relativity, Einstein's theory of gravity. It was first provided by Karl Schwarzschild, in 1917.

If an object of mass M collapses, light cannot escape to the outside world if it starts from inside the *event horizon* surrounding the singularity.

The event horizon has a radius $R_{\text{Sch}} = 2GM/c^2$ called the *Schwarzschild radius.* For $M = M_\odot$, $R_{\text{Sch}} = 3$ kilometers.

At a radius of $1.5R_{\text{Sch}}$, a beam of light can orbit in a circle around the black hole.

At distances much greater than R_{Sch}, the gravity from a black hole is the same as it would be from a star of the same mass.

15.4 A THOUGHT EXPERIMENT

You give a friend a steadily blinking flashlight, then drop him towards a black hole, while you stay in a rocket ship at a safe distance.

Your experience: As your friend falls towards the event horizon, blinks from the flashlight come further apart, and its light gets redder (even shifting to radio waves). The friend falls close to the event horizon rather quickly, but unless you wait for an infinite amount of time, you never see him cross it.

Your friend's experience: he passes through the event horizon, losing sight of the outside world, then is crushed into the infinite density "singularity" at the center, all in a fraction of a second.

Moral: The warping of space and time near a black hole makes events look very different to different observers.

15.5 X-RAY BINARIES

The orbital velocity near the surface of a neutron star is about 1/3 the speed of light. The orbital velocity near the event horizon of a black hole is close to the speed of light.

Gas moving at these speeds gets hot enough to emit X-rays.

Though they are very rare compared to typical main sequence stars, a number of stellar systems that emit X-rays have been discovered.

Many of these are binary systems, in which a red giant star is slowly dumping its envelope onto a neutron star or a black hole.

As with "normal" binaries or pulsar binaries, one can use the laws of gravity and motion to infer the masses of the orbiting objects.

15.6 ASTRONOMICAL BLACK HOLES

In some X-ray binaries, the inferred mass of the compact object is larger than $3M_\odot$.

These cannot be neutron stars, so it seems that they must be black holes.

It is also thought that supermassive black holes (millions of times the mass of the sun) reside at the centers of some galaxies, and are the power sources of quasars, the most luminous objects in the universe.

Note: We do not see radiation coming from inside a black hole's event horizon, but we *do* see radiation from gas falling in close to the black hole.

Note: All of our astronomical evidence for black holes is indirect — we find objects for which we have no other theoretical explanation, but we have not seen clear signatures that identify them as black holes.

15.7 BLACK HOLES AREN'T (COMPLETELY) BLACK

According to "classical" general relativity, an isolated black hole emits no radiation and lasts forever.

However, black holes must also obey other physical laws, in particular the laws of quantum mechanics.

Stephen Hawking showed that, when quantum mechanics is taken into account, a black hole should emit a very small amount of radiation and slowly lose mass.

A black hole with a mass of $3M_\odot$ would evaporate completely in about 10^{67} years, if the universe is around for that long. (The universe is now about 10^{10} years old.)

15.8 SUMMARY

When a massive star ends its life by exploding as a supernova, it leaves behind
a neutron star — supported against gravity by degenerate neutron pressure
– or –
a black hole — a completely collapsed object.

Rotating neutron stars are detected as radio pulsars. Timing of pulsars shows that some have binary companions, and that at least one has planets.

Neutron stars are also detected in X-ray emitting binaries.

According to general relativity, a black hole contains all of its mass in a singularity (point of infinite density) surrounded by an event horizon (the size of the Schwarzschild radius) from which light cannot escape.

Black holes are inferred to exist in some X-ray binaries, where the mass of the compact star exceeds $3M_{\odot}$, and they are believed to be the central engines of quasars. We see radiation from hot gas before it falls into the event horizon.

Even black holes can't live forever.