9. Stellar Mass Black Holes

Reading:

Main reading is Thorne Chapter 8.

You should skim Chapter 6, mainly for a general sense of the history, with closer attention to pp. 254-257.

Chapter 7 is interesting, but optional.

Theory

Above some critical mass ($2 - 3M_\odot$), stellar cores with no ongoing energy source cannot support themselves against gravity.

These cores must implode, but implode to what?

Oppenheimer and Snyder calculation (based on Schwarzschild solution):

- To a static observer at a large distance: never see surface of star disappear within event horizon, though it becomes increasingly redshifted.
- To an observer moving with the surface: pass through event horizon with nothing special happening, collapse to infinitely dense singularity at the center.

Finkelstein: Different description based on different way of assigning coordinates to space and time. Reconciles the two Oppenheimer & Snyder views, shows smooth transition across the event horizon.

Convincing demonstration that there is nothing “fishy” about the Schwarzschild solution.

Discoveries of “The Golden Age” (as Thorne puts it):

Departures from spherical symmetry do not prevent collapse.

Collapse of a spinning star produces a different spacetime than collapse of a non-spinning star. Event horizon is elongated not spherical. Spin “drags” nearby space into circulation around the black hole.

Black hole is fully described by mass, spin, and electric charge. No other information about how it was formed.

Wheeler (1967) coins the term “black hole.”

Finding Black Holes

If all stars with initial mass $M > 30M_\odot$ form black holes after they use up their fuel and collapse, then we expect something like 100 million (!) black holes in the Milky Way (compared to 100 billion stars in total).

If we suspect black holes exist, how should we search for them?

Even the nearest would be much too far away to see a “black dot.”

Gas falling onto a black hole would heat up as it runs into itself. Temperatures near event horizon would be high, producing X-ray emission.

Where can gas come from? Diffuse interstellar gas too thin to produce much glow.

But roughly half of all stars are found in binary systems, with an orbiting companion.

When the orbiting companion of the black hole expands to become a red giant, part of its envelope can get pulled over onto the black hole.

The same thing can happen for neutron stars.

X-ray Astronomy

X-rays are absorbed in the earth's atmosphere.

Can't see X-rays from astronomical sources from ground.

But stars aren't that hot, so in early 1960s no one expected to see many bright astronomical X-ray sources.

First X-ray experiments, launched on sub-orbital rockets, showed some very strong sources.

First X-ray satellite, *Uhuru* (1970), showed many X-ray sources.

Later satellites improved sensitivity and angular resolution of X-ray images. Two of the most important: *Einstein* (1978) and *Chandra* (1999, still active).

One main population of X-ray sources: neutron stars and black holes accreting gas from binary companions.

(Another main population, supermassive black holes in distant galaxies, will come up later).

There are now about 400 X-ray binaries known in our own Galaxy (the Milky Way). Probably $\frac{1}{4} - \frac{1}{3}$ are black holes; the rest are neutron stars.

These are a tiny fraction of the 100 million black holes we expect to be present in our galaxy, but the conditions for a black hole to "light up" are rare, and they don't last long.

We can also detect X-ray binaries in nearby galaxies.

Demonstrating that an X-ray Source is a Black Hole

How do you show that an X-ray source is an accreting black hole?

Need to show that its mass is larger than the largest possible mass of a neutron star.

How do we measure the mass of something we can't see?

Measure its gravitational effect on something we do see.

Spread out the light from a star into a *spectrum* (intensity vs. wavelength). Get bright and dark lines at particular wavelengths where atoms like to emit and absorb light.

These "spectral lines" are produced at known wavelengths, which can be measured in the laboratory or calculated from principles of atomic physics.

Measuring the observed wavelength of these lines gives velocity of star from Doppler shift.

If star is in orbit, lines shift back and forth periodically; period and velocity give acceleration, hence mass of object causing the orbit. Roughly like applying Kepler's 3rd law to get mass of central object.

For a black hole candidate, need to find the visible-light companion of the X-ray source.

This was hard because of poor resolution of early X-ray telescopes: many possible companions.

Once identified, measure motion of companion by Doppler shifts. Infer mass of X-ray source.

If this is above $3M_\odot$, then the object can't be a neutron star: must be a black hole.

Accretion disks

Gas coming from companion does not fall straight onto the black hole, because companion is moving.

Gas goes into orbit around black hole, forming a disk.

"Friction" causes some gas to slide inwards towards the BH.

This "friction" also heats the gas up.

(In reality, the friction is probably a complicated interaction involving magnetic fields and moving gas).

We see X-rays (and ultraviolet and visible light) from hot gas in the accretion disk.

In some cases, gas is ejected at high speed along jets perpendicular to the disk, producing X-ray, visible light, and radio emission.

In an accretion disk, gas gains energy from gravity as it "sinks" towards the black hole. Some of that energy goes into motion and heat of the gas, but some of it is carried away by radiation (X-rays, etc.), making the accreting black hole luminous.

For a non-rotating black hole, when the gas gets within $3R_{\rm Sch}$ it spirals in quickly without further friction because of the strong gravity of the black hole.

Accretion disk has an inner hole with little gas.

Around a spinning black hole, the gas can get closer to the black hole before it spirals in, because the black hole drags nearby space around it, producing "centrifugal" support.

For a black hole spinning at the maximum possible rate, gas gets to within $2R_{\rm Sch}$ before it spirals in.

Because the gas gets closer to the black hole, the temperature is hotter, and the gravitational redshift is stronger for a spinning black hole.

It's hard to measure gas motions very close to the black hole because that gas is emitting X-rays, not visible light.

Current X-ray telescopes can measure spectral lines from highly ionized iron atoms close to the black hole.

The shapes of the iron lines show the amount of Doppler shifting (from motion) and gravitational redshifting, can distinguish non-spinning and spinning black holes.

Some black holes appear to be spinning fast.

Event Horizons

In General Relativity, the fundamental feature of a black hole is an event horizon.

Since we are not close to any black holes, how can we tell whether these event horizons actually exist?

Suppose the flow of gas from the companion slows to a trickle.

The X-ray luminosity goes down. But if the companion is a neutron star, there will always be some emission when the gas strikes the surface of the neutron star and heats up.

For a black hole, the trickle could disappear down the event horizon without emitting much energy at all.

X-ray binaries vary in brightness, probably because of variations in the gas supply.

If you separate X-ray binary sources with estimated masses into those where the companion appears to be a neutron star ($M < 2M_\odot$) and those where the companion appears to be a black hole ($M > 3M_\odot$) based on mass, the *minimum* luminosity is much lower for the black holes.

This suggests that infalling gas really is disappearing down the event horizon of a black hole, not hitting the surface of a compact object.

While we have strong evidence for the existence of compact X-ray sources that are too massive to be neutron stars, this indirect argument is the best empirical evidence we have that these objects actually have event horizons.

Summary: Empirical Evidence for Stellar Mass Black Holes

We have previously reviewed the theoretical arguments that black holes *could* exist and *could* form from the core collapse of massive stars that have exhausted their nuclear fuel.

We can now characterize the chain of direct observational evidence for the existence of stellar mass black holes.

- X-ray telescopes reveal bright sources in the Milky Way and nearby galaxies, apparently gas falling onto compact objects from (normal) stellar companions.
- Some of these sources are neutron stars.
- But velocity measurements show that *some* of the compact objects have masses above $3M_\odot$. According to all we know about neutron stars and gravity, these can only be completely collapsed objects – black holes.
- With today's X-ray telescopes, we can measure the detailed spectrum of the X-ray emission (intensity of X-rays as a function of energy) of some sources, and find agreement with expectations for gas accreting onto black holes.
- For example, the X-ray lines from iron atoms show large Doppler shifts (gas moving close to the speed of light) and gravitational redshifts.
- Some sources show jets of material (seen in X-rays, visible light, or radio waves).
- Low minimum luminosities of X-ray sources believed (based on mass) to be black holes suggests that these source really do have *event horizons* rather than hard surfaces.