11. Waterfalls and Tornados: Measuring Black Hole Spin

Reading: Thorne, Chapter 7, pp. 286-294 (box 7.2 is optional). Also re-read Chapter 6, pp. 245-253.

Waterfall Analogy

In GR, the same spacetime can appear quite different from different reference frames, e.g., "frozen star" vs. "collapsed star."

One useful way to think about a black hole is that space is falling into the black hole, like water falling down a waterfall.

Freely falling observers are just dragged in with the infalling space.

Objects and radiation can move through this "falling space."

But at the event horizon "space is falling in at the speed of light" (relative to distant observers), so that even light rays moving outward don't make it beyond the horizon.

Inside the event horizon, space is falling faster than light, so that even outgoing light rays are dragged into the black hole.

This analogy has been emphasized by my colleague Andrew Hamilton from University of Colorado, who has done some of the most accurate visualizations of falling towards black holes; see links on the course web page.

Thorne's "parable of the ants" (pp. 245-249) is closely related.

Spacetime of spinning black hole

Collapse of a spinning star produces a different spacetime than collapse of a non-spinning star.

The solution to Einstein's equations that describes a spinning black hole was discovered by Roy Kerr in 1963.

The event horizon of a spinning black hole is elongated not spherical, bulging out along the equator.

The spin "drags" nearby space into circulation around the black hole.

An infalling object will be forced to rotate with the black hole spin before it enters the horizon, perhaps even reversing direction.

Space around a spinning black hole is not just falling like a waterfall; it is whirling like a tornado (or a whirlpool).

A black hole can spin up after it is born by accreting rotating gas. To reach high spin (enough to make its event horizon significantly flattened), it must increase its mass by a significant factor (e.g., double or triple its mass).

There is a maximum possible spin rate for a black hole, the one where a freely falling object just outside the event horizon would be moving at c.

Holes in the accretion disk

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

Thus, the 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 plunges 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 $1R_{\rm Sch}$ before it plunging in.

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

Two methods of measuring black hole spin

Method 1:

Use the X-ray spectral line of highly ionized iron.

Photons are emitted at a specific energy, 6.4 keV.

Gas is orbiting the BH at high speed, so some photons are blueshifted (higher energy) and some redshifted.

But all photons feel gravitational redshift, so we see more redshifted photons than blueshifted.

For a spinning BH, the gravitational redshifts are stronger because some photons come from cloer to the event horizon.

The emission line has a very long “red wing.”

Thus, the shape of the emission line can be used to measure BH spin.

Method 2:

Measure the full X-ray spectrum (not just the iron line) and look for the energy of peak emission.

The spectrum of a spinning BH peaks at higher energy because of hotter gas.

When both methods can be applied to the same BH, they yield consistent answers for the spin.

Some black holes, but not all of them, appear to be spinning fast.

Black hole spin and jets

Jets, which are seen in some stellar mass BHs and some supermassive BHs, probably come from material being ejected perpendicular to the accretion disk, at speeds close to c.

Magnetic fields wound up by spinning black holes may be important for producing jets, but this is not the only explanation.

However, some jets from supermassive black holes seem to have stayed very straight for many millions of years.

This steadiness of direction could be explained by the “gyroscope” effect of a rapid spinning black hole.