The 68th Compton Lecture Series

Stars: Their Life and Afterlife

Lecture 8: Fade to Black

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Introduction

In our final week, we will talk about the stellar-mass black holes that can be left behind by the explosions of very massive stars. We will also talk about X-ray binaries. These are binary systems in which one object is a normal (usually main-sequence) star and the other is a "compact object," either a neutron star or a black hole.

Part 1. Black Holes

Black holes are objects with gravity so strong that their escape velocity exceeds the speed of light. Since nothing can travel faster than the speed of light in a vacuum, nothing can escape a black hole.

Black holes can be completely described by only three quantities, making them in a sense, the "simplest macroscopic objects in nature." (Longair 1994) Those three quantities are the black hole's mass, electric charge, and angular momentum. These properties are determined by the matter that collapses in forming a black hole and that falls into the black hole later.

Figure 1 shows a schematic of the structure of a black hole. On the left is a non-rotating black hole, also called a "Schwarzschild" black hole for the physicist who solved the equations of general relativity that describe this type of black hole. There is a radius "R_g" that defines the "event horizon" of the black hole: anything that crosses inside this radius is trapped inside the black hole. The hole is "black" inside this radius because no light can escape. It turns out that this radius is just proportional to the mass of the black hole:

$$R_g = 2GM/c^2$$

where G is Newton's gravitational constant, G = $6.67 * 10^{-11}$ Nm^2/kg^2; M is the mass of the black hole in kg, and c is the speed of light, c = $3 * 10^8$ m/s. Plugging in these numbers, a solar-mass black hole (M = $1.99 * 10^{30}$ kg) will have an event horizon of only three kilometers! Table 1 compares this radius to some other size scales we have seen in these lectures – in particular, note that black holes are only a factor of a few smaller than neutron stars, the last stable form of stars.

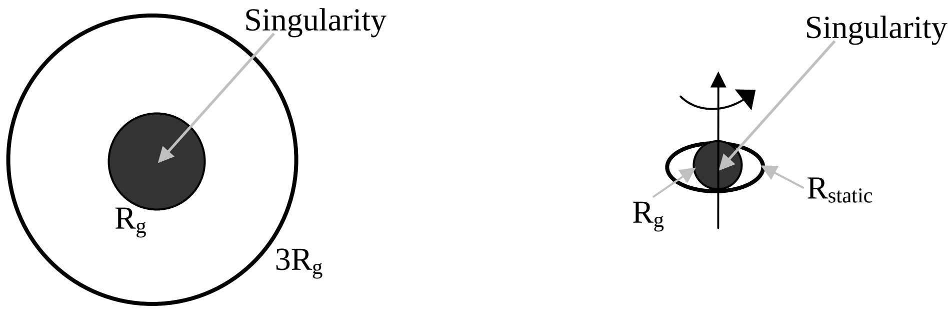

Figure 1. (left) A Schwarzschild (non-rotating) black hole. (right) A Kerr (rotating) black hole.

The circle at a radius “$3R_g$”, or three times the radius of the event horizon, indicates the smallest stable circular orbit around a black hole. The key thing here is that the kinetic energy of the object in orbit increases the gravitational attraction between the object and the black hole. As you move to smaller orbits, the speed of the orbiting object increases, increasing the gravitational attraction. Inside this special radius of three times the event horizon, this becomes a runaway process, and there are no more stable orbits.

At the center of the black hole, general relativity predicts a singularity. However, at such small distance scales, general relativity alone is probably an incomplete description of the laws of physics. One needs to also account for quantum mechanical phenomena to say what happens near, or at, the singularity. Developing a theory of “quantum gravity” is a vey active field of research!

Object	Radius
Black Hole	$3 * M / M_{\odot}$ = 3 km for a solar-mass BH
Neutron Star	~10 km
White Dwarf	~10,000 km (~Earth size)
Sun	700,000 km
Giant Branch Stars	~300 million km (Earth’s orbit)
Supergiant Stars	~1.6 billion km (Jupiter’s orbit)

Table 1. Typical radii of various types of stars.

The right-hand side of Figure 1 shows a rotating black hole. The black hole’s angular momentum gives it a smaller event horizon. In general relativity, rotating objects tend to drag spacetime with them. Ordinarily, this is a very small effect. However, this effect becomes very strong just outside a black hole, creating a region just outside the event horizon called the “ergosphere” where it is impossible to hold an object at a fixed position. For instance, a spaceship with powerful enough rockets could remain in a stationary position outside the event horizon of a non-rotating black hole. However, near a rotating black hole the dragging of spacetime can become severe enough that no spaceship (and not even light) can resist the pull, and the spaceship would be forced to rotate along with the black hole.

How do black holes form? In the case of massive stars that go through a core collapse, we saw a few weeks ago that stars with masses up to ~ 20-25 $M_{\odot}$ have their cores collapse into a neutron star, and the rest of the stellar matter is blown off in a supernova explosion. For more massive stars, there are two possible scenarios for black-hole formation when the core collapses:

- A "proto-neutron star" can form, as with lighter stars, resulting in a supernova. However, in the first few seconds during and after the supernova, there may remain enough matter near the proto-neutron star that when this matter falls back into the core, the mass is too great to form a neutron star, and a black hole is formed instead. This is the "fall-back" scenario.
- Alternately, the collapsing core itself may be too massive to form a neutron star, and the core collapses directly to a black hole. In this case, there may be no supernova!

It remains unclear which of these scenarios dominates, or if both are common. Further detailed modeling of stellar collapse and explosions is needed, as well as detailed observations of the supernovae explosions of the most massive stars.

While this lecture is focusing on the black holes that are created by the collapse of massive stars – black holes with masses of typically a few $M_{\odot}$ or so – it is important to note that black holes can come in all sizes. In particular, the centers of most galaxies appear to contain supermassive black holes with masses $10^6 – 10^9$ $M_{\odot}$. In addition, theoretical arguments suggest that much smaller black holes may have been able to form in the early universe, but this has not yet been confirmed observationally.

Part 2. X-ray Binaries

X-ray binaries are binary systems that contain an ordinary star and a compact object, either a black hole or a neutron star. Matter transfers from the ordinary star to the compact object.

In the case of a binary containing a neutron star, the accreted matter hits the surface of the neutron star, heating it to X-ray temperatures.

If, instead, the binary contains a black hole, there is no surface for the accreted matter to strike. Instead, the matter forms a disk around the black hole. The inner regions of this accretion disk, where the matter is approaching the last stable circular orbit, become very hot – and again, the matter is heated to X-ray-emitting temperatures.

Figure 2 shows a schematic of an X-ray binary system that contains a black hole. In some cases, the electric and magnetic fields associated with the accretion disk are able to accelerate particles and focus them into beams, or jets, that are emitted perpendicular to the disk. These jets are similar in nature to those seen in Active Galactic Nuclei, such as quasars. In both cases, the jets are powered by accretion onto a black hole. In quasars, the black holes are of the "supermassive" variety: $10^6 - 10^9\ M_\odot$. In these binary systems, the black holes are ~ few – 10 $M_\odot$, so these systems are known as "microquasars."

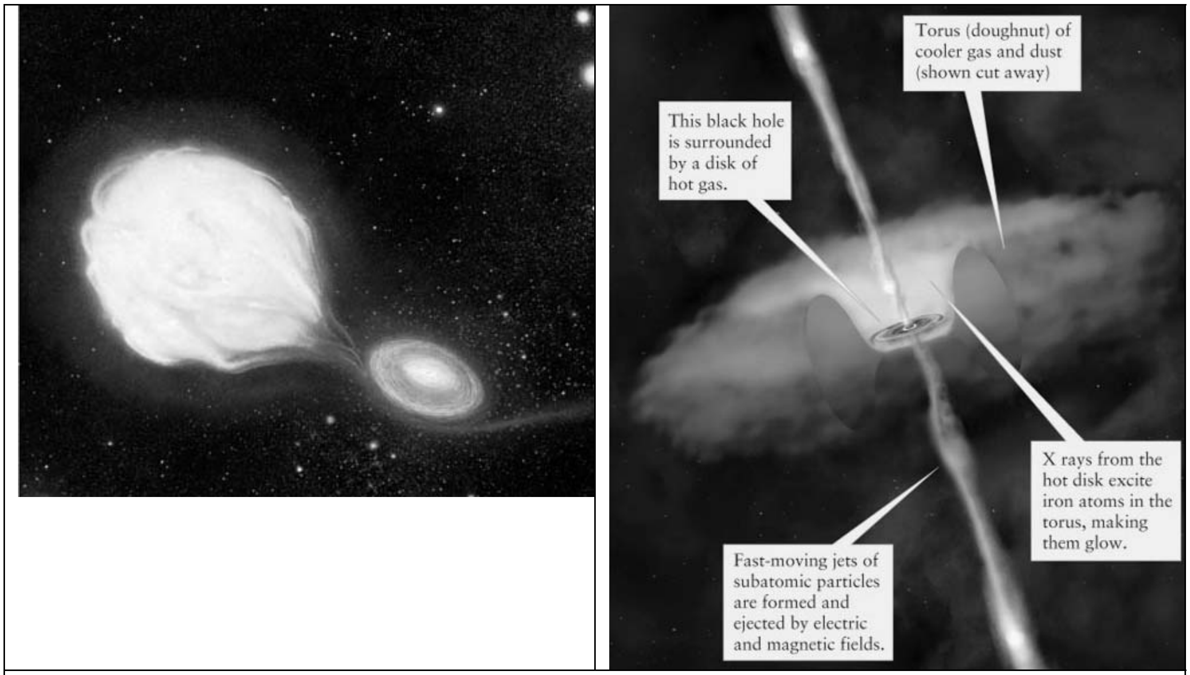

Figure 2. Structure of an X-ray binary. (left) Mass is transferred from a massive companion star into an accretion disk about a compact object. (right) Close-up of the accretion disk and torus around the compact object, along with jets of particles ejected by the electric and magnetic fields associated with the accretion disk.

Thanks for coming to these lectures!

I hope you have enjoyed attending them as much as I enjoyed giving them!

References

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