Black Holes

Transcript

http://quantumspotacademy.org/videos/black-holes/

Black holes are like massive swirling sinkholes in outer space. Whatever goes into one will never return. Black holes consume and destroy everything coming near enough to them, they hold galaxies together, and they are one of the most puzzling and vigorously debated areas of physics today. You might have heard of metaphorical black holes before, but do you know the truth about their amazing properties? How do black holes work? How do they manage to draw in and crush any objects passing by?

It turns out that a black hole's force is simply the force of gravity gone rampant. So, to truly understand black holes, we first have to understand how gravity works. Nowadays, most people are familiar with gravity, but it wasn't always so well understood. The first real theory of gravity was developed by Isaac Newton. We've all heard the story of Isaac Newton sitting under an apple tree when an apple falls on his head, sparking his realization of the nature of gravity. But why did it take the most brilliant physicist of the century and possibly of all time to discover something as seemingly obvious as gravity?

It's important to note that Isaac Newton didn't "discover" gravity, per say, because he didn't discover that things fall down; people have always known that things fall down. Newton's work was much more important. Instead, he identified a profound connection between two seemingly distinct physical realms: that of falling objects, and that of celestial bodies. Newton realized that the force pulling an apple down to the ground is the very same force holding planets and moons in their orbits.

If you think about it, this wasn't at all obvious at the time. You see, the fact that things fall down is just ordinary, everyday physics. But the planets were thought by many people to be under the control of supernatural powers. They had no reason to believe that the laws of physics here on Earth were the same as the laws of physics in outer space.

Newton, however, did see the connection. He realized gravity is an attractive force acting between all objects – everything from apples to planets – and he wrote an equation describing the gravitational force between any two objects. It reads

$$F = \frac{Gm_1 m_2}{r^2}.$$

In this equation, F represents the gravitational force. If F is large, then the force of gravity is very strong and if F is small, then the force of gravity is very weak. G is the gravitational constant. It's just a number that's been determined experimentally to be about 6.67×10^{-11} Nm^2/kg^2, but it's not terribly important for our discussion today. m_1 and m_2 are the masses of the objects in question and, finally, r is the distance between the gravitational centers of the two objects.

So what can we learn from this equation? Well, we can see that if at least one of the objects is very massive, then the gravitational force will be stronger than if both masses were small. Also, as the objects get farther apart the gravitational force decreases rapidly.

Now, it's important to remember that gravity acts between all objects, not just planets. This effectively means that everything is attracted to everything else. The only reason that we don't see things sticking together like magnets is because gravity is extremely weak compared to other forces. For example, you can pick up a paper clip with a magnet. The magnetic force from the tiny magnet is easily able to completely overpower the gravitational force from the entire earth. The only reason we experience gravity at all is because the earth's enormous mass creates a significant gravitational attraction.

Here on the surface of the earth, gravity seems inescapable; as they say, what goes up must come down. But we know that if you throw something hard enough, it will actually escape the gravitational pull of the earth and never come back. How fast do you have to throw something for it to never fall back and just keep floating onward forever? This special speed, the speed that it takes to escape an object, is called the escape velocity, and it's a very important value. If the escape velocity is large, it means that it's hard to escape and if the escape velocity is low, it means that it's easy to escape.

So, how do we calculate the escape velocity for a given object? The equation for calculating escape velocity is $v_e = \sqrt{\frac{2GM}{r}}$. In this equation, v_e stands for the escape velocity that we're trying to calculate, G is the gravitational constant we've met before, M is the mass of the object we're trying to escape from, and r is the radius of that object (we're assuming that it's spherical, like a star or a planet).

Now, with this equation, we can calculate the escape velocity for essentially any object as long as we know its mass and its radius. Let's try it for the earth. The gravitational constant is just 6.67×10^{-11} Nm^2/kg^2. The mass of the earth is about 6 septillion kg (that's a six with twenty four zeroes after it). The radius of the earth is about 6,400,000 meters (or around around 4,000 miles). Plugging these numbers into our equation gives us an escape velocity of about 11,000 $^{m}/_{s}$! You would have to throw something 11,000 $^{m}/_{s}$ in order for it to escape the earth's gravity. That's over three times the speed of sound!

If you think 11,000 $^{m}/_{s}$ sounds fast, the escape velocity of the sun is about 56 times bigger at around 618,000 m/s.[1] Of course, when we talk about the escape velocity of the sun, we assume we start from the surface of the sun. Even though it would be impossible to physically stand on the surface of the sun, since it's just a giant cloud of gaseous hydrogen, we can still calculate its escape velocity as a theoretical construct.

Escape velocity is a very important concept for people designing rockets meant to escape a planet's gravitational field, but it's also very important for thinking about black holes! We can use what we've just discussed about escape velocity to understand black holes – what they are, how they're made, and what they can do.

Let's go back to our example of the sun. Imagine you took the sun and shrank it to just half of its original size, keeping its mass the same. That would decrease the distance from the surface of the sun to the center, making r in our equation become smaller. Since the escape velocity is inversely proportional to the square root of r, that would make the escape velocity increase, which makes sense; for the same reason that gravity becomes stronger the closer you get to an object, gravity becomes stronger as you collapse the surface closer to the center of the object.

If you continued to shrink the sun to a tinier and tinier volume, the escape velocity would continue to get larger and larger. And if you shrank the sun until its radius became just 3 km, then its escape velocity would be even larger than the speed of light! The speed of light is very significant, because, according to Albert Einstein's theory of Special Relativity, the speed of light is a sort of cosmic speed limit; it's the fastest speed that anything with mass can have. So if you were standing on the surface of an object with an escape velocity greater than the speed of light and you wanted to throw something into outer space to escape the gravitational pull forever, then you would have to throw it faster than the speed of light, which is impossible! And this means nothing could escape the object, not even light itself! This amazing type of extremely dense object is called a black hole because no light can escape it, and thus it would look like a black hole in the sky.

Black holes have captured the attentions of many science fiction writers and have appeared to varying degrees of accuracy in films, books, television shows, and even music. Let's take some time to discuss the real science behind black holes.

---

[1] $M_{sun} = 1.989 \times 10^{30}$ kg $r_{sun} = 6.955 \times 10^{8}$ m

As we learned, a black hole is just a star or (in principle) any object that has been crushed into a minuscule volume. The radius of the sphere that you have to crush an object into in order for it to become a black hole is called the Schwarzschild radius. So, how do we calculate the Schwarzschild radius for a given object? Well, if we set the escape velocity equal to the speed of light (c) and then do some simple algebra, then we'll find that the Schwarzschild radius is equal to $\frac{2MG}{c^2}$.

I mentioned earlier that if you wanted to turn our sun into a black hole, you would have to compress it to have a radius of just three kilometers. Using this equation that we just derived, let's do a quick calculation to check that number. We know that the mass of the sun is about 2×10^{30} kg. The gravitational constant and the speed of light are both universal constants so we can just plug those in. Putting this into a calculator, we would find the Schwarzschild radius to be about 3 km.

Even though three kilometers is a long way to travel by our standards (it's about two miles), it's incredibly small on the stellar scale; as a matter of fact, it accounts for about four millionths of the sun's original radius and about one quintillionth of its original volume. The enormous mass that you have to squish into a tiny volume in a black hole leads to monstrously high densities. For example, if you were to turn the earth into a black hole, you would have to squeeze the entire planet into something the size of a small marble. That's incredibly dense.

So, why in the world would something compress itself into a black hole? We now know that black holes usually form when stars die and implode. You see, a star is in a constant struggle with gravity. Gravity tries to crush the star in upon itself, due to the enormous mass, but the force of the star's own internal pressure produces an outward force which counteracts it. When the two forces are equal to each other, they are said to be in equilibrium. At some point, however, the star will run out of fuel in its core and the internal pressure will no longer be enough to counteract gravity, so the star will collapse. If the star is massive enough, this gigantic collapse, brought about by the titanic force of gravity, will cause it to become a black hole.

After a black hole has formed, it can continue to swallow up other things unfortunate enough to cross paths with it. If something comes near to a black hole, it will be attracted by it's gravitational pull and fall in, making the black hole more massive and a little bit larger. This means that black holes can grow over time by eating other things around them. The largest ones are called supermassive black holes. These enormous behemoths are often found at the centers of galaxies and may have played a critical role in their original formation billions of years ago. In fact, the center of our very own Milky Way galaxy is home to a supermassive black hole weighing in at an unbelievable 4 million solar masses (4 million times the mass of our sun). The Milky Way's supermassive black hole, however, is quite small compared to some supermassive black holes that may reach tens of billions of solar masses.

These gigantic supermassive black holes sound pretty dangerous. After all, if you come too close to one, you will be pulled into it and torn into smithereens before being pulverized by the intense gravitational force. After a certain point, there is no way to escape a black hole, because you would have to exceed the speed of light to do so. This point of no return is usually called the event horizon. If you cross the event horizon, it's impossible to turn back, but as long as you're outside the event horizon, you still have hope for escape. So even though black holes devour everything inside of their event horizons, as long as you stay a respectful distance away from them, they aren't any more dangerous than normal stars.

For a long time, many physicists (including the famous Albert Einstein) thought that there was no force strong enough to crush an object into such an absurdly tiny volume, and thus it was assumed that black holes were merely a theoretical construct. But as theories of black hole formation became more and more convincing, physicists began to search for the signs of actual black holes, and by now many of them have been found. Black holes don't emit any light, so we can't technically "see" them, but we can still locate them using a few different methods.

The most obvious way would be to simply look for a black hole in the sky but, unfortunately, this isn't very practical, mainly just because a black hole would appear so small that we wouldn't know where to start looking. A better way to find a black hole is to look for other stars affected by its gravitational field. If we see stars orbiting an extremely massive object, but the massive object they are orbiting is invisible, we can be pretty sure we've found a black hole. A black hole is especially easy to find while it's devouring another star. When a star comes too close to a black hole, the gravitational pull tears the star apart. The material from the star then forms an accretion disc around the black hole. As the material in the accretion disc falls toward the black hole, it emits a ray of light that we can detect. Finally, we can actually sense the ripples in the gravitational field coming from a black hole.

Using these methods, we can find black holes and draw some conclusions about some of their properties, but since black holes don't emit any light, we still can't directly observe what's inside of one. However, physicists don't have to rely on direct observation in order to theorize about something. Even though we can't peer inside of a black hole, we can still deduce some of its properties based on the laws of physics that we observe in other areas of the cosmos. So far, however, this has turned out to be quite a perplexing issue because all of our understanding of the universe seems to fall apart in the intense densities and extreme forces involved.

One of the major conundrums relates to a black hole's physical structure. There are two main schools of thought on this matter. Some physicists believe that once a black hole recedes past the Schwarzschild radius, it continues to collapse until it becomes a single point. This point is called a singularity. A singularity is a zero-dimensional object, which means that it has no length, width, or height. If this were the case, however, it would mean that a black hole would have infinite density at a single point. Why would a black hole collapse to a single point like that? Well, currently there is no known force strong enough to counteract the gravitational force, preventing it from collapsing to a singularity. There are, on the other hand, physicists who believe that a black hole shouldn't collapse to a single point, but rather maintain some physical shape after it recedes past the Schwarzschild radius. This is one of many ways in which black holes continue to provide physicists with challenging puzzles.

Black holes are exciting and extraordinary objects, and they remain riddled with unsolved mysteries and perplexing conflicts. Black holes are especially problematic because they force us to reconcile the two very disparate realms of tiny quantum phenomena and vast cosmological properties. Our theories at the quantum and cosmic scales are currently incompatible with each other, especially within a black hole.

Indeed, beyond being phenomenally powerful, black holes have caused us to think about what we can and cannot know. Black holes bring us to the very edge of our ability to theorize about the universe. In the end, then, black holes are an unresolved challenge to us to see the invisible, to perceive the imperceivable, and to mentally grapple with the most extreme objects in the universe.