Black Holes: Crash Course Astronomy #33

Crash Course: Astronomy
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===== Intro=====

As we've seen over the past few episodes, a lot of really epic stuff happens when a star dies. If the star's core is less than 1.4 times the mass of the Sun, it becomes a white dwarf: a very hot ball of super compressed matter about the size of the Earth.

If the core is heftier, between 1.4 and 2.8 times the Sun's mass, it collapses even further, becoming a neutron star that's only 20 km across. The neutron soup inside of it resists the collapse and prevents the core from shrinking any more.

But what if the mass is more than 2.8 times the Sun's? If that happens, the gravity of the core can actually overcome the tremendous resistance of the neutrons and continue its collapse.

What force can possibly stop it now? It turns out, none. None more force. There is literally nothing in the universe that can stop the collapse. The core of the star is about to go bye bye.

(Crash Course Intro plays)

===== Escape Velocity =====

Way back in Episode 7, I talked about escape velocity, and it's about to become a major player in the unfolding events of the collapsing core of a high-mass star. In brief, It's the velocity at which you need to fling something off the surface of an object to get it to escape.

For Earth, the escape velocity is about 11 km/sec. Get something moving that quickly, and it's gone. It'll never fall back. The Sun, which has much stronger gravity than Earth, has an escape velocity of over 600 km/sec. A neutron star, with its immense gravity, can have an escape velocity of 150,000 km/sec -- that's half the speed of light!

Keep that in mind, and let's go back to the collapsing core of the star.

As it shrinks, its gravity gets stronger and stronger. That means its escape velocity gets higher and higher. When it's neutron star size, the escape velocity is half the speed of light. But if it's more than 2.8 times the mass of the Sun, the core will keep collapsing.

When its size drops just a little bit more, down to roughly 18 km, an amazing thing happens. The escape velocity at its surface is equal to the speed of light. And, well, that's a problem because in our universe, nothing can travel faster than the speed of light. Not a rock, not a rocket, not even light itself.

Once the core of the star shrinks down to smaller than that magic size, nothing can escape. No matter can come out, so it's like an infinitely deep hole. And no light can come out, so it's black. We should come up with a snappy name for such an object.

===== Black Holes =====

A black hole is the ultimate end state for the core of a high-mass star. Whatever happens in a black hole stays in a black hole. That region of space, that surface around the black hole where the escape velocity is the speed of light is called the *event horizon* for that reason. Any event that happens inside can't be known. It's beyond the horizon for us.

Black holes mess with our concepts of space and time. The math and physics of black holes is incredibly complex. So much so that even after several decades of study, physicists still argue over a lot of their properties. This has lead to a lot of misconceptions about them, too.

All right, let's get this out of the way right now: The Sun cannot become a Black Hole. It takes a stellar core at least about three times the mass of the mass of The Sun to overcome neutron degeneracy pressure. That means the original star must have something like 20 times the Sun's mass or more. So we're safe from *that* particular sci-fi scenario.

Here's another misconception: A lot of people think of black holes as cosmic vacuum cleaners sucking in everything near them. But that's not really true. They have very powerful gravity, yeah, but only when you're very close to one. The power of a black hole comes from it's mass, certainly, but just as important its *size* or, really, its *lack* of size.

If you could turn the Sun into a black hole, which you can't, but let's pretend you could, then the Earth would orbit it pretty much exactly as it does now. From a 150 million kilometers away, the Earth doesn't care if the Sun is big or tiny. We're so far away that it doesn't matter.

It gets to be a big deal when you get close. Remember, from episode 7 about gravity, the strength of gravity you feel from an object depends on how massive it is and your distance from its center. The closest you can get to the Sun is by touching it, being on its surface, about 700,000 km from its center. If you get any closer to its center, you're inside it. The material outside of your position is no longer pulling you down and so the gravity you feel will actually decrease.

But if the Sun were crushed down to about 6 km across, it would be a black hole. You could get much closer than 700,000 km to it, and as you did, you'd feel a stronger and stronger pull as you approached it.

So from far away a black hole with say, 10 times the Sun's mass would pull on you just as hard as a normal star with that same mass. You can orbit a black hole too, as long as you keep a safe distance between you and it. Orbiting a 10 Solar mass black hole would be just like orbiting a 10 Solar mass star... except not so hot and bright. Black holes are weird enough without the misconceptions.

Black holes also come in different sizes. The kind of black holes I've been talking about have a minimum mass of about 3 times the Sun's, and might get as high as a dozen or more times the Sun's mass if the parent star was big enough. We call these *stellar mass black holes*. If it happens to gobble down more matter, it gets more massive, and the event horizon grows as well. The black hole gets bigger.

The idea that huge black holes could form in the centers of galaxies was first proposed in the 1970s, and it wasn't much later that the first one was found in the center of our own Milky Way galaxy. We've measured its mass at a whopping 4.3 million times the Sun's mass. And now we think every major galaxy has one at its heart too, and in fact, may be crucial in the formation of galaxies themselves. I'll discuss those more in a future episode.

=====Tides=====

Here's a fun thought: What would happen if you fell into one? Say, a stellar black hole with 10 times the Sun's mass? You'd die. But what happens in the few milliseconds before you leave the known universe forever is actually pretty interesting.

As we've seen many times in our own solar system, tides are important. They arise because gravity weakens with distance, so a big object like a moon gets stretched by its planet's gravity; the far side of the moon is pulled less than the near side.

A black hole has incredibly intense gravity, so the tides it can inflict are serious indeed. They're so strong that if you fell into a stellar mass black hole feet-first, the force of gravity on your feet can be millions of times stronger than the force on your head. Remember, even the meager tides of a planet can rip moons apart. When you multiply that force by a million, you're in trouble.

As you fall in, your feet are pulled so much harder than your head, that you stretch, pulled like taffy. You'd become a long, thin noodle, kilometers in length, but narrower than a hair wide. Astronomers call this, and no I'm not kidding, *spaghettification*. This would happen pretty close to the black hole, just a few dozen kilometers out. If you fell in from a long distance, you'd be moving pretty near the speed of light by that point, and you'd only have a millisecond or so before it killed you anyway so... yay?

Note that this is only for stellar mass black holes. Supermassive black holes are far bigger, millions or billions of kilometers across. Compared to that size, the distance between your head and feet is small, so the tides across you aren't nearly as severe. You'd fall in pretty much intact. If that makes you feel any better.

But compared to either flavor of black hole, a star still has substantial size, and one that gets too close to any black hole can be disrupted via tides. In March 2011, astronomers witnessed just such an event. In a distant galaxy, a star apparently got too close to a black hole and was torn apart by the ferocious tides. As the star was disrupted, it flared into brightness, momentarily blasting out a trillion times the Sun's energy. That's how we were able to see it, even though it was several billion light years away.

===== Black Holes and Space-Time =====

But I've saved the weirdest thing for last. One of Albert Einstein's biggest ideas is that space isn't just emptiness; it's an actual thing, like a fabric in which all matter and energy is embedded. What we perceive as gravity is really just a warping of this space, like the way a bowling ball on top of a bed warps the shape of the mattress. The more massive an object, the more it warps space.

Not only that, but space and time are basically two parts of the same thing, what we now call space-time. You can't affect one without affecting the other. Einstein calculated that when a massive object warps space, it also warps time. Someone deep inside the gravitational influence of an object perceives time as ticking more slowly than someone far away from that object.

I know, its bizarre! We think of time as just flowing and everyone should see it move at the same rate, but the universe is under no obligation to obey our preconceptions.

Einstein was right. He was right a lot. This slowing of time is stronger the stronger the gravity of the object is, so your clock ticks a bit slower than someone far away from Earth, for example. The effect is tiny but real, and we've actually measured it on Earth with extremely precise clocks.

However, if you get near a black hole, the effect gets a lot stronger. In fact, black holes warp space-time so much that at the event horizon, time essentially stops. You'd see your clock running normally, and you'd just fall in, bloop, gone. But someone far away would see your clock ticking more slowly as you fell in. And this isn't a mechanical or perception effect, it's actually woven into the fabric of space. To someone outside looking down on you, your fall would literally take forever.

But then they wouldn't actually be able to see you. The light you emit would have to fight the intense gravity of the black hole to get out, and to do that it would lose energy. This is very similar to the Doppler red-shift I've talked about in earlier episodes, and it's called *gravitational red-shift*.

When you're right at the event horizon, just when an outside observer would see your clock stop, they'd also see the light coming from you infinitely red-shift. Your light would lose all its energy trying to leave the vicinity of the black hole and you'd be invisible.

And from your viewpoint? Buckle up, because this is... wow. You'd see the universe speed up, and just as you hit the event horizon, all of time would pass. All of it. And all that light coming at you from the universe would be blue-shifted, becoming such high energy that you'd be fried. But since you're about to fall into a black hole, you probably wouldn't care. See? Like I said, wow.

Black holes are so strange, with such fiercely complicated math and physics to explain them, that scientists are still trying to figure out even basic things about them. For example, some scientists argue that the event horizon as we understand it may not actually exist, and that when you apply quantum mechanics to black hole physics, you find particles can slowly leak out.

We're still new at this, and struggling to understand what may be the most complex objects in the cosmos. Black holes, as bizarre and counterintuitive as they are, keep popping up from here on out as we poke our noses into more and bigger astronomical objects. While they may seem scary and weird (and let's be honest, they are), they have literally shaped most of the objects we see in the universe.

===== Recap =====

Today you learned that stellar mass black holes form when a very massive star dies and its core collapses. The core has to be more than about 2.8 times the Sun's mass to form a black hole. Black holes come in different sizes, but for all of them, the escape velocity is greater than the speed of light, so nothing can escape, not matter or light. They don't wander the universe gobbling everything down around them. Their gravity is only really intense very close to them. Tides near a stellar mass black hole will spaghettify you, and time slows down when you get near a black hole. Not that this helps much if you're falling in.

===== Credits =====

Crash Course: Astronomy is produced in association with PBS Digital Studios. Head over to their YouTube channel to be sucked into even more awesome videos. This episode was written by me, Phil Plait. The script was edited by Blake de Pastino, and our consultant is Dr. Michelle Thaller. It was directed by Nicholas Jenkins, edited by Nicole Sweeney, the sound designer is Michael

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(Crash Course outro plays)