Neutron Stars: Crash Course Astronomy #32

Crash Course: Astronomy
https://youtube.com/watch?v=RrMvUL8HFlM
https://nerdfighteria.info/v/RrMvUL8HFlM

=====Intro=====

When an 8-20 solar mass star ends its life, it does so with a bang: a supernova. And when it's all over there's a couple of octillion tons of super heated plasma expanding away from the explosion site at a fraction of the speed of light; a whole mess of energy released in the form of light and neutrinos; and a bizarre little ball of quantum nastiness in the center, composed almost entirely of neutrons.

The properties of this neutron star are almost as bizarre as things get in the universe, and if it all seems rather alien to you -well- that's okay. For a little while astronomers wondered if aliens really were behind what they were seeing.

Now I'm not saying aliens...

(Intro)

=====Neutron Stars=====

When we last left the core of a high mass star it was in a bad way. Milliseconds ago it was fusing Silicon into Iron. But now it's collapsing under its own immensely powerful gravity. The collapse takes a fraction of a second, but a lot happens in that fraction of a second.

In lower mass stars the core supports itself via electron degeneracy pressure: the result of a rule in quantum mechanics that says electrons vehemently resist being squeezed together. But even electron degeneracy fails to stop the collapse if the core has a mass more than about 1.4 times the mass of the sun. That's just too much of a load to bear and the collapse continues.

Under these huge pressures a funny thing happens: protons, electrons and other subatomic particles get smashed together, and they merge to form neutrons. And this happens to almost all of them.

When the core collapses down to about 20 km in diameter it's essentially a ball of neutrons; with some protons and electrons here and there that survive; and a crust of normal, but highly compressed matter on top.

When this happens yet another effect comes into play: neutron degeneracy. Like electrons, neutrons resist being squeezed too tightly together, but this time the strength of the pressure is far, far stronger than for electrons.

If the core is less than about 2.8 times the sun's mass, the collapse runs into a wall: it stops. This generates a huge shock wave which -along with a flood of energetic subatomic particles called neutrinos- blasts outwards; blowing up the star.

What's left of the core after the metaphorical smoke clears is a neutron star: one of the most bizarre objects in the universe. Such a star would be extremely weird, or really just extreme. Its mass would be more than that of the entire sun; all packed into a sphere maybe 20 km across.

Now let's just stop there for a sec, and let that sink in. The sun has a mass 300,000 times the Earth. Imagine packing that all into a ball the size of a small city.

Too mind boggling? Okay, think of it this way: You are mostly empty space. Every atom in your body has a nucleus made of tightly packed neutrons and protons, and electrons whizzing around outside them. If you could magnify an atom to be a hundred meters across, the nucleus would be roughly the size of a marble. Imagine all that empty space between the nucleus and the electrons. That's a normal atom.

But in a neutron star, all of that space would be filled with neutrons. All of it. Every nook and cranny inside the neutron star has matter in it, all the way down to the scale of an atomic nucleus. This is what gives a neutron star its mind-crushing properties.

I'm now going to barrage you with very large numbers, so take a deep breath, and you might want to sit down. Neutron stars are ridiculously dense. A single cubic centimeter of neutronium, as neutron star stuff is usually called, has a mass of about 400 million tons.

Want some perspective on that number? Well, very roughly, that's the total mass of every single car and truck in the United States. Imagine a couple of hundred million vehicles crushed down until they could all fit inside of this six-sided die. That's neutronium.

It's so dense, that as far as it's concerned, normal matter is a slightly polluted vacuum. If you set it on the ground, it would fall right through the Earth.

Now anything that dense has a huge gravitational pull. If you were on the surface of a neutron star, well, you'd be very dead obviously, like... immediately flattened down to a thickness of just a few atoms. And that's because a typical neutron star has a surface gravity 100 billion times stronger than Earth's.

I have a mass of about 77 kilos, and here on Earth I weigh about 170 pounds. On a neutron star, I'd weigh 17 trillion pounds. That's 23,000 times the weight of the Empire State Building.

But wait! There's more! In our introduction to the Solar System, I mentioned that when you take a spinning object and shrink it, the spin will increase. The usual example is an ice-skater drawing in his arms, increasing his rotation until he's a blur.

The same is true for the star's core when it collapses into a neutron star. It may have had a very slow spin before the supernova, maybe even taking weeks to spin once. But when it shrinks down to just 20 km across and becomes a neutron star, that rotation will increase by a huge factor. A freshly minted neutron star might spin several times per *second*.

The magnetic field increases as well. A star like the sun has an overall magnetic strength not too different from the Earth's. But when that core collapses, the strength of the field skyrockets, and a neutron star can easily have a magnetic field several trillion times stronger than the Sun's.

That's strong enough to erase your credit card from a hundred thousand kilometers away. See, ridiculous. All of these properties are brain melting, but are they real? Could an object like this really exist? Oh, my, yes.

The first neutron star was detected in 1965. Though not recognized for what it was at the time. A couple years later, another one was found and this time was correctly identified as a neutron star, but then things got weird.

=====Pulsars=====

In 1967. Jocelyn Bell was a graduate student helping build a radio telescope. There was a persistent noise in their data they couldn't seem to fix. Bell studied it night after night, finally figuring out that

the pattern wasn't a problem with their data, it was from an actual astronomical object.

She had discovered the first known pulsar. What's a pulsar, you ask? Pulsars are neutron stars. In a nutshell, they're rapid rotation coupled with their incredibly strong magnetic fields, launch twin beams of magnetic energy away from the star, like the beams from a lighthouse.

The beams sweep around as the star rotates and from Earth, we see this as a pulse, a blip of increased brightness. This pulse can be detected in visible light, radio waves, and even x-rays.

The spin of a neutron star is amazingly stable, making these pulses act like a very accurately timed cosmic clock. In 1967, No one could believe a natural object could do this and this object was half-jokingly given the name LGM-1, Little Green Men 1. Now, we know of over a thousand pulsars in just our galaxy alone, and we know they're the leftover cores of massive stars that exploded.

Some spin with period many seconds or even minutes long. Some are in binary systems: another normal star orbits them. If they're close enough together, the neutron star can rip material off the other star and feed on it. This increases the pulsar's spin, and we know of a few that have incredibly rapid rotation rates. Some spin hundreds of times per second. These are called *millisecond pulsars*, and if they spun much faster, the centrifugal force would rip them apart, despite their tremendous gravity.

(7:30) Even after a thousand years, a pulsar can still be a force to reckon with. There's a pulsar in the center of the Crab Nebula, the remains of a star that exploded to create that supernova remnant. A substantial fraction of the light emitted from the nebula is powered by the pulsar itself. Its fierce output energizes the nebula, causing it to glow brightly, even after a millennium.

I'm telling you, thinking about neutron stars makes the hair on the back of my neck stand up. And I haven't even mentioned magnetars yet.

=====Magnetars=====

Neutron stars are more than just weird little balls of neutrons. They have a crust probably a few centimeters thick made of highly compressed, but more or less normal, matter squeezed into a kind of highly stiffened crystal state. The magnetic field of the star penetrates this crystalline crust and stretches out for quite a distance.

In some neutron stars the magnetic field is even stronger than usual, and can be, get this, a quadrillion times stronger than the Sun's. These uber-powerful neutron stars are given the name magnetars.

They're relatively rare, maybe 10% of all neutron stars are born as magnetars, and they have short lifetimes. The magnetic field is so strong it acts like the brakes on a car, slowing the neutron star's spin. That spin helps power the magnetic field, so the field weakens as the star slows. But while they're around, magnetars are the most magnetic objects in the universe. And with great power comes great responsibility... if your responsibility is to be one of the scariest objects in the universe. Why?

In a neutron star, the crust and magnetic field are locked together, so a change in one affects the other. The crust of the star is under incredible strain due to the intense gravity and rapid rotation. If the structure slips, it can snap, creating a star quake (like an earthquake, but just a wee bit stronger).

In an earthquake, huge amounts of energy are released when the earth's crust shifts and snaps, enough to destroy buildings and quite literally move mountains. But in a neutron star, this effect is multiplied, *hugely*. Remember, the crust is phenomenally dense and the gravity is enormous. If the crust strains and snaps, dropping just a single centimeter, the resulting release of energy is vast beyond imagining. This energy is released as a tremendous explosion in the crust, shaking it.

This also shakes the magnetic field, which reacts... poorly. When the Sun's magnetic field throws a tantrum, we get a solar flare, which can be as powerful as billions of nuclear bombs. A magnetar flare dwarfs that into insignificance. It can be trillions of times stronger than a solar flare. In a fraction of a second, a magnetar can release as much energy as the Sun gives off in a quarter of a million years.

In 2004, astronomers were stunned when a huge blast of x-rays slammed into orbiting satellites. One of these satellites, named Swift, actually had its detectors saturated with x-rays, even though it wasn't even pointing at the source at the time. The x-rays literally came right though the side of the satellite with such intensity that Swift, which was designed to detect powerful x-ray sources, was momentarily blinded by them.

The source of this x-ray burst was quickly determined to be a magnetar called SGR1806-20, and the effects were incredible. It actually compressed the Earth's magnetic field and partially ionized the Earth's upper atmosphere. Oh, did I mention that this magnetar is 50,000 light-years away? That's halfway across the galaxy. That's incredible. At a distance of 500 quadrillion kilometers, its effects were felt more strongly than a powerful flare from the Sun.

The good news is that there are very few magnetars like this in the galaxy, probably fewer than a dozen. Also, catastrophic explosions like the one in 2004 are rare. If one had happened any other time in the past 40 years or so, we would have detected it. And frankly, it's really cool that we had astronomical satellites orbiting the Earth that could study it.

We've come a long way in understanding neutron stars since they were first discovered, but there's much about them we don't understand. Every time we find out more, we find out they're even weirder than we first thought.

And yet, for all of that, they're not the weirdest things in the sky, not by a long shot. That place is held pretty securely by the other type of object created in a supernova: a black hole. Stay tuned.

=====Recap=====

Today you learned that when a star between 8 and 20 times the Sun's mass explodes, the core collapses to form a neutron star. Neutron stars are incredibly dense, spin rapidly, and have very strong magnetic fields. Some of them we see as pulsars flashing in brightness as they spin. Neutron stars with the strongest magnetic fields are called magnetars, and are capable of colossal bursts of energy that can be detected over vast distances.

=====Credits=====

Crash Course: Astronomy is produced in association with PBS Digital Studios. Head over to their YouTube channel to catch 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, and edited by Nicole Sweeney. The sound designer is Michael Aranda, and the graphics team is Thought Café.