High Mass Stars: Crash Course Astronomy #31

Crash Course: Astronomy
https://youtube.com/watch?v=PWx9DurgPn8
https://nerdfighteria.info/v/PWx9DurgPn8

Stars are in a constant struggle between gravity, trying to collapse them, and their internal heat trying to inflate them. For most of a star's life, these two forces are at an uneasy truce.

For a star like the sun, the balance tips in its twilight years. For a brief, glorious moment, it expands, but then blows away its outer layers, leaving behind the gravitationally, compressed core. It goes out with a whimper. Well, a whimper from a two octillion ton, barely constrained, nuclear powered fireball.

But, more massive stars aren't quite as resigned to their fate. When they go out, they go out with a Bang! A very, very, big bang.

(Intro)

In the core of a star, pressure and temperature are high enough that atomic nuclei can get squeezed together and fuse. This releases energy and creates heavier elements. Hydrogen fusion makes helium. Helium fusion makes carbon. And each heavier element, in general, takes higher temperatures and higher pressures to fuse.

Lower mass stars, like the sun, stop at carbon. Once that builds up in the core, the stars fate is sealed. But, if the star has more than about eight times the sun's mass, it can create temperatures in its core in excess of 500,000,000 degrees Celsius, and then carbon will fuse.

There are actually a lot of steps in this process, but in the end you get carbon, fusing into neon, magnesium and some sodium. What happens next hearkens back to what we found goes on in the sun's core as it ages. Fuse an element. Create a heavier one. Then that heavier one builds up until the core contracts and heats up enough to start fusing it.

So carbon fusion makes neon, magnesium, and sodium, and those accumulate. The core heats up, and when it reaches about a billion degrees, neon will fuse. Neon fusion creates more magnesium, as well as some oxygen. These build up in the core, it shrinks, heats up to about 1.5 billion degrees, and then oxygen fuses, creating silicon. Then that builds up until the temperature hits about 2 to 3 billion degrees, where upon, silicon can fuse.

Among a pile of other elements, silicon fusion creates iron, and that's trouble. Big, big trouble. Once silicon fusion starts, the star is a ticking time-bomb.

But, before we light that fuse, let's take a step back. What's happening to the outer layers of the star? What do we see if we're outside, looking back at it? Because the star was born massive, it spent its hydrogen-fusing days as a blue, main sequence star. Stars like this are extremely luminous, and can be seen for tremendous distances.

Like the sun, though, a massive star changes when hydrogen fusion stops. Its core contracts, and then helium fusion begins. It swells up, just as the sun will, but instead of becoming a red giant, it generates so much energy, it becomes a red super giant.

These are incredibly huge stars. Some, over a billion kilometers across. And they are luminous. For example, Betelgeuse in Orion is a red super giant and one of the brightest stars in the sky, despite being over 600 light years away. From that distance, you'd need a descent telescope to see the sun, at all. And that's nothing compared to VY Canis Majoris, the largest known star, which is a staggering 2 billion kilometers across. We even have a special term for it--a hyper giant.

As the core switches back and forth from one fusion reaction to the next, the outer layers respond by contracting and expanding. So a red super giant can shrink and become a blue super giant. Rigel, another star in Orion, is a blue super giant, putting out over 100,000 times as much energy as the sun.

OK, let's go back to the core. It now looks like an onion, with multiple layers. Iron is building up in the centers, surrounded by fusing silicon, outside that is a layer of fusing oxygen, then neon, then carbon, then helium, then finally hydrogen.

You might think massive stars would last longer because they have more fuel than lower mass stars. But the cores of these monsters are far hotter, and fuse elements at far higher rates, running out of fuel more quickly.

A star like the sun can happily fuse hydrogen into helium for over ten billion years. But a star twice as massive as the sun, runs out of hydrogen in just two billion years. A star with eight times the Sun's mass runs out in only a hundred million years or so. And each step in the fusion process happens faster and faster than the one before it.

In an extreme case, like for a star twenty times the mass of the sun, it'll fuse helium for about a million years, carbon for about a thousand, and neon fusion will use up all its fuel in a single year. Oxygen lasts for a few months. Silicon fuses at a ridiculously high rate. The star will go through its entire supply in, get this, a day. Yes! One day. The vast majority of a star's life is spent fusing hydrogen. The rest happens in the metaphorical *blink of an eye*.

Silicon fuses into a bunch of different elements, including iron. That inert iron builds up in the core, just like all those elements did before. And just like before, the iron core shrinks and heats up. But there's a huge difference here.

In all the previous fusion stages, energy is created. That energy transforms into heat and that helps support the soul-crushing amount of stellar mass above the core. But iron is different. When it fuses it actually sucks up energy instead of creating it. Instead of providing energy for the star, it removes it. This accelerates the shrinking, compressing the core, heating it even more.

Even worse, at these temperatures and pressures, the iron nuclei suck up electrons that are whizzing around, which are also helping support the core. It's a double whammy. Both major means for support for the star are removed in an instant. Silicon fusing into iron is happening so fast, this literally takes a fraction of a second once it gets started.

The core gets its legs kicked out from under it. It doesn't shrink; it collapses. The gravity of the core is so mind-bogglingly strong that the outer parts crash down on the inner parts at a significant fraction of the speed of light. This slams down on the central core, collapsing from several hundred kilometers across, down to a couple of dozen kilometers across, in just a few thousandths of a second. The star is doomed, because all hell is about to break loose.

Now, at this point, one of two things can happen. If the star has less than about twenty times the sun's mass, the core collapse stops when it's still twenty or so kilometers wide. It forms what's called a neutron star, which I'll cover in the next episode.

If the star is more massive than this, then the collapse cannot be stopped by any force in the universe. The core collapses all the way down; down to a point. The gravity becomes so intense that not even light can escape. A black hole is born.

We'll cover black holes in a future episode as well, but for now,

what happens when the core collapses and suddenly stops?

The core of the star, whether it's a neutron star or a black hole, is now extremely small with terrifyingly strong gravity. It pulls on the star's matter above it. HARD! This stuff comes crashing down at fantastic speed, and gets hugely compressed, furiously heating up.

At the same time, two things happen in the core. While this stuff is falling in, a monster shock wave created by the collapse of the core moves outward, and slams into the incoming material. The explosive energy is so insane, it slows down that material substantially. The second event is that the complicated quantum physics brewing in the core, generates vast numbers of subatomic particles called neutrinos. The total energy carried by these little neutrinos is almost beyond reason.

In a fraction of a second, they carry away one hundred times as much energy as the sun will produce over its entire lifetime! That's an incredible amount of energy!

Now, these little beasties are seriously elusive, and hate to interact with normal matter. One single neutrino could pass through trillions kilometers of lead without even noticing. But, so many are created in the core collapse, and material barrelling down on the core so dense, that a huge number of them are absorbed. This vast wave of neutrinos slams into the oncoming material, like a bullet train hitting a slice of warm butter. The material stops its in-fall, reverses course and blasts outward.

The star explodes. It explodes. (Explosion sound)

This is called a supernova, and it is one of the most violent and terrifying events the universe can offer. An entire star tears itself to shreds, and the expanding gas blasts outward at 10% the speed of light. The energy released is so huge, they can be seen literally half way across the universe. They outshine all the stars in the rest of the galaxy combined.

The expanding material, called the supernova remnant, forms fantastic shapes. The most famous is the Crab Nebula, from a star we saw blow up in the year 1054. The tendrils formed as the material expands into the gas and dust that surrounded the progenitor star.

As remnants expand and age, they become more tenuous. Some have bright rims as they push into material in between the stars. Others form complex webs of filaments.

I'm often asked if there are any stars near enough to hurt us when they explode. The quick answer is no. Even though supernovae are super violent, space is big. A supernova would have to be a least 100 light years from us before we start feeling any real effects.

The nearest star that might explode in this way is Spica, in Virgo, and it's well over 100 light years away. I say, might explode, because it's at the lower mass limit for going supernova. It might not explode at all. Betelgeuse will certainly explode some day, but it's too far away to hurt us. We're pretty safe from this particular threat.

I'll note, that after all this, there is another kind of supernova involving white dwarfs, which we'll cover in our episode about binary stars. Happily, we're probably safe from them too. Breathe easy.

As terrifying and dangerous as supernovae are, there's a very important aspect to them that you need to know. Supernovae are capable of great destruction, but they also are critical for our own existence. When the star explodes, the gas gets so hot, and is compressed so violently by the blast, that it undergoes fusion, what astronomers call explosive nucleosynthesis, literally creating heavier elements explosively.

New elements are produced in quantities that dwarf the Earth's mass. Calcium, phosphorous, nickel, more iron. All made in the hellish forage of the supernova heat, and flung outward into the universe. It takes millennia or longer, but this material mixes with the other gas and dust clouds floating in space. Sometimes, these clouds will be actively forming stars. Sometimes the collapse of the cloud to form stars may actually be triggered by the supernova slamming into it. Either way, the heavy elements created in the supernova will become part of the next generation of stars and planets.

Supernovae are how the majority of heavy elements in the universe are created and scattered. The calcium in your bones, the iron in your blood, the phosphorus in your DNA. All created in the heart of the titanic death of a star. That star blew up more than five billion years ago, but parts of it go on--in you.

Today you learned that massive stars fuse heavier elements in their cores than lower mass stars. This leads to the creation of heavier elements up to iron. Iron robs critical energy from the core, causing it to collapse. The shock wave, together with the huge storm of neutrinos, blast through the stars outer layers causing it to explode.

The resulting supernova creates even more heavy elements, scattering them through space. Also, happily, we're in no danger from a supernovae.

Crash Course Astronomy is produced in association with PBS Digital Studios. They have a YouTube channel with great videos. Go, just go over there. Check their videos out, they're fantastic. 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 Aranda, and the graphics team, as always, is Thought Café.