The Life of Other Stars

Fraser Cain: Last week we looked at the complete life of the Sun from birth to death. But, stars could be smaller and stars can get much larger. With the change in mass their lives change too. So, let's start the clock again and let's see what happens to the smallest stars in the universe and what happens to the largest.

Let's start with the smallest. I guess we're going to set the Sun as our baseline. Just as a quick refresher from last week. A cloud of gas comes together star settles down, fusion ignites; you get a main sequence star.

The star runs out of fusion, kicks into Helium, runs out of Helium. It turns into a red dwarf, foists out its outer layer turns into a white dwarf and then eventually cools down to a black dwarf. Did I miss anything?

Dr. Pamela Gay: No, I don't think so.

Fraser: Okay, so then let's get smaller. [Laughter]

Pamela: To get a significantly different life cycle for a star, you have to get way smaller. You actually have to get down to about a quarter of the size of the Sun. Once you get that small you actually get some really different physics.

There are a couple of different ways that energy can get transported through a star. One is you just send photons out. In this case you get what we call radiative transfer. The energy is transferred by a particle of light going from one atom to another in a kind of random walk through the star.

Another way of transporting energy is through convection. This is basically how a lava lamp works. You get a pocket of really hot material; the hot stuff is a little bit dense. It rises and as it rises it gives off its heat. As it gives off its heat it gets denser and eventually it sinks again.

Fraser: So which one is our Sun doing?

Pamela: It's doing both. But down in its core which is where it matters, it has radiative transport. So you have a core of hot nuclear reactions producing lots and lots of light. Light is radiating out going through a radiative zone where it's the light that's transporting the energy and then partway up there is a transition point.

At this transition point we switch to having a convective Sun where you start getting bulk transport of materials, bulk heat exchange and it's probably somewhere in-between those two layers that the magnetic field of the Sun is generated.

Fraser: If I understand correctly, that's kind of why the Sun – if you look at it with a good telescope with a good filter – the Sun has that mottled appearance.

It's like there are granules on the surface because it has bubbles of hot gas that are coming from down below popping off on the surface and then sinking back down. You get almost like boiling water.

Pamela: That mixing allows the outer layers of the star to be constantly mixing up the materials. Down in the center of the Sun, you're sorta stuck with things where they are.

You have light going through the material transporting heat through the material, but the material itself is pretty much staying put. So, you don't end up with any mixing of the Helium down in the center of the Sun with outer layers of the star.

Fraser: Right and that's the problem is that the Sun is running out of Hydrogen because it's not getting mixed up.

Pamela: If we could come up with some magical way to change where in the Sun the different energy transport mechanisms take place, we might be able to prolong the main sequence lifetime of our Sun.

Fraser: What about like a BIG stirring spoon? Come up and just give it a stir every now and then.

Pamela: [Laughter] Now unfortunately, the nature of the way the Sun is built doesn't allow that. But, if you take a star that is about a fourth the size of our Sun. Zero point 26 times the size of our Sun, in that case you can still end up with the Hydrogen burning in the core. That's the hottest, densest part of the star.

But in this case the lighter weight star is able to constantly convect the entire star convecting. So as you have these nuclear reactions going on in the very heart of the Star, the material in these nuclear reactions are producing, it is constantly getting mixed throughout the entire star.

You're constantly bringing new material into the center, taking the Helium that you're producing, mixing it outward and so you're constantly able to regenerate the source of fuel in the center of this little tiny star.

Fraser: Oh, so these little stars have no radiative zone, they only have a convective zone that goes all the way down to the core.

Pamela: So when these stars run out of fuel, they really run out of fuel. There is like no other alternative. It also means that they only go through one phase of life. They simply sit there and go: Hydrogen burn, Hydrogen burn for billions upon billions of years.

Fraser: Like how many billions? You said billions a lot. How many billions?

Pamela: Billions in this case translates out to a hundred billion years. Our universe has only been around for 13.7 plus or minus 2 billion years. These stars are essentially still toddlers. They have a long ways to go before they finally run out of fuel.

Fraser: While a star like our Sun only lasts 10 million, these ones are going to last a hundred billion because they're getting constantly mixed up.

Pamela: And they're also burning through their fuel a lot slower. They're smaller stars. The reaction rates go on at a much slower rate so they're effectively going to run through - at the end of the day – a lot less fuel. But they're going to do it at a slower rate. These are essentially the "economy cars" of the universe.

Fraser: Right but they're going to be very efficient. So let's say that a hundred billion years down the road they've been in their main sequence stage and then they've run out of Hydrogen – I guess they're what solid Helium at this point? What happens then?

Pamela: Pretty much solid Helium and they just cool off. The thing is as they just cool off they calmly transition into being little white dwarf stars.

The end point for these stars is the same as the Sun but they go through a whole lot less drama getting there.

Fraser: Do they turn into red giants?

Pamela: No, they just sort of run out of fuel one day and contract.

Fraser: Then it would be like a white dwarf. But unlike a white dwarf like our Sun which would be made of Carbon; these would just be made of Helium at this point?

Pamela: Yeah, so we're going to end up with Helium white dwarfs out of this. There is no planetary nebula; no exciting red giant phase, no Helium flash, just calmly, sedately for a hundred billion years burning Hydrogen to Helium. And then it contracts down into a white dwarf.

Fraser: Nobody has ever seen one because none have ever been born.

Pamela: Nope, but this is why we have mathematical models and computers.

Fraser: Now, does anything interesting happen when you get even smaller than that?

Pamela: If you get too small you actually end up with – what we argue about if something is really a star or not – this is where you get objects whether you call them brown dwarfs, giant Jupiter planets.

Brown dwarfs is the common nomenclature and we just don't know where to start calling things stars or not. If you get too small, stars only burn Deuterium. This is heavy Hydrogen – Hydrogen that consists of a proton and a neutron in the center. They'll do this for a few million years, run out of the Deuterium and then do nothing.

They don't even contract down to white dwarfs. They just sit there and do nothing. This is where you sort of go, is this a star? Is this a something that's not really a planet? What is it? And we argue.

Fraser: Right and so it's almost like a ball of Hydrogen and Helium just sitting there. If a bunch of them collided they could turn into a star but it's just going to sit there forever. It heats up because it's compressing down from the thermal heat….

Pamela: Right that's exactly what's happening.

Fraser: But then that's that. Once it gets to its "happy place" it just [Laughter] cools down and just sits there as a cold ball of Hydrogen.

Pamela: Right and these are objects that are bigger than about 13 Jupiter masses so here we're not even talking in terms of planetary Jupiter masses.

These are objects that you take Jupiter, multiply by 13 and do you call that a star or not – and we're not sure.

Fraser: Okay so the low end of the scale – very slow, very calm. Now let's kick around the other side. [Laughter] Let's start looking bigger and bigger. When does something interesting happen bigger than our Sun?

Pamela: Actually the interesting stuff starts to happen at as little as one and one half times the size of the Sun. With something the size of the Sun, you go through Hydrogen burning in the core.

When you're done burning Hydrogen the star collapses a bit. In the process of collapsing it ends up with something called a degenerate core. This is the same sort of material that white dwarf stars are made out of.

The Helium in this is packed together so tightly that the electrons basically form what we call a degenerate gas. Long story short, when a star like our Sun goes from having a Helium core with a shell of burning Hydrogen around it to collapse, collapse, eventually that Helium does what we call a Helium flash. It bloats up really big all of a sudden.

It's a rather catastrophic process. The star survives but it's rather sudden. If you have a star that's just one and a half times the size of the Sun, you don't have to worry about that flash anymore.

Instead you have actually a convective core here. So you go again to having a convective core with in this case a radiative envelope – you end up with more mixing, you end up with a smoother process to get the Helium burning in the center – and you smoothly transition to burning heavier and heavier elements in the core of the star.

Fraser: So how heavy an element will you burn?

Pamela: This is where it starts to matter again just how big a star are you looking at.

Fraser: Well let's look at that 1.4 times the mass of the Sun's star. How far is it going to get?

Pamela: With that star we'll actually end up with Carbon burning in the center. You end up with a nice happy, friendly star that doesn't do anything too catastrophic in its life and ends up as a white dwarf.

Fraser: Now, what would it be a white dwarf made out of? In this case, it has been able to burn Carbon in its core so it's not going to end up as a great big diamond like our Sun.

Pamela: No, here you're going to end up with an Oxygen-Neon-Sodium-Magnesium down in the center of the star.

Fraser: WOW! The world's biggest whatever that is.

Pamela: [Laughter] And I'm not quite sure at this point. Where it starts to get interesting is where you get stars that are bigger than 5 solar masses. This is where you start getting Neon burning going on as well.

Even though we don't think of it, once you start getting to these stars that are bigger than 5 solar masses, if they don't undergo vast amounts of mass loss, these stars can actually start undergoing different types of death in the form of supernova.

Fraser: When do we see neutron stars?

Pamela: Exactly when we get neutron stars – they're a product of supernova explosions and it depends on whose models you listen to.

Fraser: Okay, well then we'll come back around when we see the output being neutron stars.

Pamela: And it all depends on mass losses. But in this case what ends up happening is with the Neon burning. You start to get a degenerate core again just like you did the last time with our Sun.

Except in this case the Helium flash for the Sun – not too catastrophic – but when you start getting to more exciting forms of flashes, these can actually detonate the entire Star.

Fraser: So when you get like Neon flash or a Magnesium flash?

Pamela: In this case when you get Neon flashes going on, you get an exploding star. Again you can get this with the Oxygen burning, with the Silicon burning. So as we get to these more and more massive stars it's with 5 solar masses that you start getting the Neon burning.

With 10 solar masses you get Oxygen burning. With 20 solar masses you get Silicon burning. With each of these different sets of burning, when they hit their end result and start to collapse down, eventually that end result – except when you get to Iron – tries to ignite. When it ignites, it blows the star apart.

Fraser: Right, same thing. You've got each of these situations – so it gives off more energy. When you go from Neon to a heavier element, the output is still more energy and so that's where the energy from the explosion comes from?

Pamela: Yes, so with your 5 solar mass you happily burn Neon. But then the Magnesium flash blows the star apart. With your approximately 10 solar mass stars, you happily get Oxygen burning.

Again, here you're starting to get Magnesium to Sulfur forming in the core. When these ignite, they blow the star apart. Then once you hit approximately 20 solar masses you end up burning Silicon in the core. You end up burning all the way up to elements as high as Iron on the periodic table.

Iron can't burn, so in this case you have a star that starts to collapse and collapse and collapse and in the process it ends up causing massive thermonuclear reactions. And again the star blows itself apart.

Fraser: Now I understand that the more mass of the star the higher the element that it can burn, but why does Oxygen blow one star apart while something further up the chain blows another star apart?

Why don't they all just blow up when they get to Oxygen burning?

Pamela: It has to do with this crazy concept of degenerate gas. You can end up with gases in a lot of different densities. One particular situation you pack the atoms together so tightly that the electrons end up basically forming a matrix. Everything is packed together and it can't move essentially.

When you try to ignite this, the process of igniting a degenerate gas is a radical phase transition. It's like suddenly going from solid to gas except in this case you're going from degenerate gas to non-degenerate gas. That's violent.

Now if you have a star that is hot enough and dense enough that it never collapses down into degenerate gas, it can just smoothly go: "okay, I'm hot, but I'm not that dense so I'll go from burning Helium to burning Carbon."

The bigger a star is, the hotter its core is. The hotter the core is, the more energy is being created and that energy pushes out on the outer layers of the star allowing the center to be less dense.

Fraser: Oh, I see. It's like when you get it's almost like the right temperature of the core compared to the shell that you have next in line and you don't have enough heat and pressure to make it non-degenerate – or keep it all fluffy – then it collapses and that's when you get the eminent explosion.

Pamela: This is completely non-intuitive. Just the fact that our Sun – happy little star- is going through life and will eventually end up with a degenerate Helium core, which is denser than a non-degenerate Helium core (which is what you would get with a bigger star).

So, you take a star bigger than the Sun, it's hotter in the core and is able to be fluffier (to use your word) than a smaller star than our Sun that doesn't have enough heat to keep its core fluffy. It's mathematically fun to play with.

Fraser: It totally makes sense to me. It makes intuitive sense as well so don't worry about it being non-intuitive. [Laughter] You heat up the core, and when it's really, really hot it's like the heat is what makes liquids turn into gas. Heat is what makes the molecules go very quickly.

So, the hotter you can make it, even the farther along up the table of elements you can keep things buzzing around. But if you're not quite hot enough then it can get a chance to cool down enough to lock into that degenerate state.

Then when it is time to ignite as fusion instead of it just sort of smoothly starting up, it just goes ka-blamo.

Pamela: One of the things that we struggle with in trying to understand exactly how these stars die is this thing called mass loss. As the stars are blasting energy out from their core, sometimes they blast their atmosphere apart in the same process.

There are these very high mass stars called Wolf-Raet stars. They're burning energy in their cores so fast that they end up with these tremendous winds of particles. They're losing mass at a regular rate. The question is are they going to start generating energy a little less violently before they blow themselves apart entirely?

We think with a lot of these stars they actually end up going supernova. The thing is, if they lose too much mass then it calms them down and they're able to go on to less dangerous things in life. This makes it hard for us to figure out.

If a star starts off with say, 20 solar masses but is undergoing huge amounts of mass loss, it's not going to keep those 20 solar masses. So, which of these stars die violently, which is a type of supernova, which ones end up producing neutron stars, which ones end up producing white dwarfs?

I heard one scientist once say that any star that starts out with a mass less than 10 solar masses is going to undergo so much mass loss that it will end up reducing itself down to a star that only becomes a white dwarf.

But, there are some textbooks that you look in and they say that any star that is greater than 3 solar masses is going to end up becoming a neutron star.

So, trying to figure out mass loss ends up kind of putting a crimp on our estimations of what stars undergo which fate.

Fraser: This is not a scientific debate that has been solved to anybody's satisfaction. [Laughter] So you're going to get people arguing that small stars might become neutron stars.

And other people are going to say even if you start out with a star with ten times the mass of the Sun it's going to live such a violent life and give off so much of its mass that it might not even make it to supernova. Or it might just turn into a white dwarf.

Pamela: This is what keeps astronomy interesting. You also have to play into things like the metalicity of the star because that affects things. There are all sorts of neat things to play with.

Then there's just other little neat ways to kill a star. Lots of stars, most stars actually have companions. They're in binary systems; they're in systems of 3 stars in some cases.

If you put 2 stars too close together they can actually start to pull matter one off of the other using gravity. This will radically change the evolutionary path of both stars.

Fraser: Can you have them merge?

Pamela: In some cases yes. This is where it starts to get really cool. There's models of crazy systems in which you have 2 white dwarfs that spiral toward each other, heat one another up, become non-degenerate and end up reigniting as a new star.

There's a couple of papers – I don't know if they're to be believed or not – that say that our Aurora Borealis stars – stars that periodically just suddenly drop many many magnitudes because they're giving off a hunk of dust – that say that perhaps these are Aurora Borealis stars caused by the merger of white dwarfs.

This is not the primary thing that people say. They were just papers that amused me.

Fraser: Now there's one kind of star that we haven't talked about which were the population 3 stars, right? The first stars to ever form. They didn't have any metal so I'm just wondering sort of how their life cycle was.

Pamela: In this case you start looking at what sort of nuclear reactions are possible. If all you have is Hydrogen and Helium, you can do what are called the proton-proton chains.

These is where you take 2 protons, slam them together and get Deuterium and then take the Deuterium and Hydrogen and get a Helium^3 and then you throw the Helium^3 s and you can eventually get to Helium^4 which is completely stable and a couple more protons.

It's a not very exciting way to generate energy but it works and ends up burning Hydrogen into Helium. In some cases you can get the Helium burning into Beryllium.

You can get to Lithium but if all you have is the Hydrogen-Helium and trace amounts of Lithium and Beryllium it's very, very hard to get beyond this. There is a resonance that crops in at a temperature of 10 to the 8 degrees Kelvin. This allows you to start having Helium^4 atoms. These are atoms that have 2 protons and 2 neutrons in their cores coming together and going to Beryllium^8.

They go back and forth from these two different states pretty much in resonance. Because of this you can end up in some cases getting the Beryllium and the Helium coming together and producing Carbon.

This is where you're finally able to start getting the heavier elements. Once you have that Carbon, you can finally start to have the CNO 24:21 cycle but you have to get to that temperature of 10 to the 8 degrees Kelvin.

Fraser: What was the life cycle of those first stars probably like?

Pamela: Well, it's kinda cool. They were actually able to form much larger than we can get stars right now. Right now above a certain temperature you just burn Carbon because we have Carbon all over the place now. Because of this when you get a star of above I think 150 solar masses the star just goes straight to burning Carbon in its core.

"Fine, I'm big, I'm hot, and I'm dense in the core so I'm going to burn Carbon." But back then, they didn't have this Carbon right off the bat so you could get stars that were 250 solar masses or so. It was all because there wasn't any Carbon so you could grow much, much larger stars.

You also had regular stars going through the proton-proton cycle; burning through the fuel; burning into regular stuff and burning themselves out. What we don't know is what the initial mass function of these stars was. We don't know how many little ones were formed. Probably not many or any because we can't find them and they should still be alive.

Fraser: Right. Like even those red dwarf stars that were formed right at the beginning, we should see them still burning away. They would have no metal in them whatsoever. They would just be Hydrogen and Helium.

Pamela: And we're not finding them. We're not finding stars just a little bit smaller than the Sun that should still be out there. So this tells us something about the initial mass flexion 25:52 of the stars.

There weren't small ones that are still around to be found. It appears that it was the largest stars that burned themselves out the fastest that just collectively pulled themselves together in the first moments died almost instantly.

The biggest stars were only living for a few million years. As they died on cosmic scales instantly they spread throughout the universe heavier elements.

As they were appearing in random locations, dying in random locations they were able to enrich stars before that first generation of stars used up all the material.

You can just imagine the biggest stars formed first. They finished forming perhaps before the first small stars ever formed and thus enriched the very first little red dwarf star that ever formed.

Fraser: Hmm. And you can probably imagine that there was a tremendous amount of mass loss going on those stars. I've heard they had gigantic solar winds, right?

Pamela: Gigantic solar winds – it was a violent place early on in the universe. They were giving off gamma rays, X-rays, and they're just living and dying so fast. Small stars take more time to gravitationally collapse. Everything slowed down with the small star.

Fraser: Can you imagine what the sky must have looked like? Obviously there weren't even planets but you could stand there and it would be just like the sky around you just popping off in all directions. Amazing - pop, pop, pop… [Laughter]

Pamela: And galaxies were still forming. Everything was still sort of Picasso in nature you might say; those crazy colors and crazy shapes.

Fraser: Amazing. Okay well I think we've covered the life cycle of the smaller and the bigger. That was great.

Now we've actually done two more episodes about how stars are born and how stars die where we cover the different kinds of supernova in a lot more detail.

If you want more information on that, we've purposely glossed over that a bit, you can check those out.

This transcript is not an exact match to the audio file. It has been edited for clarity.
Transcription and editing by Cindy Leonard.