Astronomy Cast Episode 13:
Where Do Stars Go When They Die?

Fraser Cain: All right, onto the show. Now, last week we talked about how stars form, and we wanted to continue the stellar life cycle this week and discuss what happens to stars after that, all the way to the end. Now, when we last met our hero, the sun, it had formed from a cloud of dust and gas and it cleared out its neighbourhood with powerful stellar winds. What next?

Dr. Pamela Gay: Well, once it clears out its neighbourhood with powerful stellar winds, it happily sits there chewing up hydrogen atoms, and fuses them into helium. And it does this for billions and billions of years, to quote Carl Sagan. Now the thing is that the sun, while it seems to be our nice constant object in the sky, hanging out and doing the exact same thing day after day, year after year, it's not doing the same thing millennium after millennium. The sun is actually slowly heating up, and while it will keep doing the things it's doing for another five billion years or so, as it's doing it, it's going to heat up to the point that in just a few million years, our earth won't be the happiest place to be living.

Fraser: How many million years?

Pamela: Let's think of this in terms of a clock. The sun is currently about 4.5 billion years old. So let's call that 4:30 am. Well, according to scientists Peter Ward and Donald Brownlee, at about 5 am, our one billion year old reign of animals and plants will come to an end. The planet will heat up to the point that it's no longer comfortable for life to survive. That's only about 500 million years away.

Fraser: Now why is the sun heating up like this? That's not fair!

[laughter]

Pamela: Life is rarely fair, however. As the core burns more and more hydrogen into helium, it's expanding, and the larger and larger core is producing more and more radiation, which is producing more and more heat, which is heating up our solar system more and more over time.

Fraser: I always thought that, you know, we would have this long period, billions and billions of years, that we'd have nice comfortable temperatures, but that's not true.

Pamela: Well, many elementary school textbooks lie to young children. It's a good pasttime. And they say that the sun will be around for another 5 billion years, so don't worry about the fate of the planet. Well, yeah, it's going to be around as a main sequence star for 5 billion years, but all the problems seem to hide in the details, and the details here say the sun is going to be getting hotter. As it gets hotter, it heats up our planet until it's first too warm for life, and then by the time the sun is 8 billion years old (and it's only

3.5 billion years from now that that happens), our oceans are actually going to vaporize. The planet will be so hot that the oceans just can't stay liquid any longer. So it's all rather devastating. Now, our planet might be allowed to survive, it's just the life on the planet that won't survive.

Fraser: Okay, so let's keep going.

Pamela: So, the sun bloats up eventually, and it runs out of hydrogen in the core. So, currently, our sun is supported by the radiation given off by the fusion of hydrogen and helium. Well, finally, about the end of these 12 billion years, our sun is going to run out of easily burned hydrogen in its core, and the core's going to collapse back down. And as it begins to collapse, a shell of hydrogen around that core is going to ignite. So, the atmosphere collapses down, builds up pressure on that helium core in the center, and squishes a layer of material between that helium core and the outer atmosphere of the star. And the shell ignites. And when that shell ignites, our sun bloats up into a red giant star. And at this point, a few planets lose their lives; Mercury, Venus, definitely toast. Most models now think the Earth will safely escape being consumed during this phase of the sun's life.

So now we have hydrogen burning in the shell, and we have the helium core. Well, as that hydrogen burns, it's producing more and more helium, and heavy things sink to the centre. It's sort of like when you drop a rock into the water, it goes down to the bottom of the water. Well, when you create helium in that hydrogen shell, that helium's heavier and it sinks to the centre of the star.

The helium core is getting bigger and bigger and bigger until eventually the helium core is so dense and is experiencing so much pressure that it ignites. And now we're burning helium in the center, we have a shell of hydrogen, and the star, it becomes what's now called a horizontal branch star. This is the point in life when some stars actually become variable stars, they become RR Lyrae variable stars, which is one of my personal passions. Our sun probably isn't going to do that, its mass isn't quite right.

Fraser: What would happen in that situation, though?

Pamela: With pulsating variable stars, which are stars that aren't quite balanced, gravity tries to squish them down, and as they compress, they heat up. And the heat produces more light coming out of the centre. It accelerates the rate of fusion in the centre. And so the light goes pushing out, and the light pushes the star out past its equilibrium, and the star cools off. And then it compresses back down. And there's a lot of complicated physics going on here, but basically, radiation and gravity are playing tug of war with the atmosphere of the star, and it's constantly going in and out over a period of just hours. It's something that's really cool to watch because you can see something that is, over just six hours, expanding and contracting like a beating heart.

Fraser: And now does it leave material behind with each expansion?

Pamela: Not that we know of. Stars are constantly giving off mass, but in this case it's literally like a beating heart. The atmosphere of the star is pulsing outwards and inwards, outwards and inwards, like a coherent object.

Fraser: What I wouldn't do to be able to see that up close.

Pamela: Oh, it would be absolutely amazing. RR Lyrae stars were one of my first loves, because I've been a geek for a long time.

Fraser: But that's not our sun.

Pamela: That's not our sun.

Fraser: So what happens to our sun?

Pamela: Our sun just kind of hangs out burning helium in its core and hydrogen around it. But eventually it can't burn the helium any longer. It might start expanding out at this point, as it continues to now burn a shell of helium and a shell of hydrogen. And over time, it's not going to be able to have these fusion reactions going on any longer, either. And as the fusion reactions shut down, the star's atmosphere slowly drifts away. This is one of the sad parts of a star's life. As they get old, they can't hold themselves together anymore, and they puff off layers of their atmosphere. This is the old asymptotic giant branch star, and what's left behind as the atmosphere is poofed away in these very sad, elderly behaviours is just the core of the star.

Fraser: Now what do those poofed off layers look like from earth? Can we see any of those?

Pamela: They get illuminated as beautiful nebula. So the core of the star is still sitting there. It's really hot, and hot things radiate light. And that light is used to illuminate the puffed off layers of the atmosphere. This what we call a planetary nebula. As a star disbands into atmosphere flying away and core left behind, the core gets called a white dwarf star and that flying away atmosphere's called a planetary nebula. Over time, the atmosphere goes further and further away and white dwarf cools off more and more, and the entire system disappears.

Fraser: So what's in the white dwarf star? What's left inside there?

Pamela: It's whatever was left from the fusion process. You can end up with helium white dwarfs where you have just the helium core of a now dead star. You can have stars where that helium fused into carbon oxygen, and you're left with basically a diamond, a diamond's left behind. So you can end up with a diamond that's roughly the size of the earth left behind by a star that had sufficient mass to get a carbon core.

Fraser: Okay so the, under the pressure of the star, the carbon just kind of gets organized into its most compact form.

Pamela: And that happens to be a crystal diamond.

Fraser: So you would have a diamond the size of the earth...

Pamela: A diamond the size of the earth.

Fraser: Sitting in space. So how long would that take?

Pamela: Well, so, the diamond itself forms over the millions of years that the star's a giant. Now, the white dwarf, the diamond starts off as this giant glowing hot thing that, while structurally similar to a diamond, isn't exactly something you'd want to put on your hand even if your hand were big enough to support an earth-sized ring.

That white dwarf starts off at the temperature of around 100,000 degrees K. It does cool off very quickly initially, and in the first 100,000 million years, if you consider that quick, it cools 20,000 degrees. Then it takes another 800,000,000 years to go another 10 degrees cooler, and it's not for 4 to 5 billion years that the star finally cools down to the temperature of our sun's surface, which is 5,800 degrees K. So, it takes it a long time to get to the point where you'd want to get anywhere near it. But you do have this giant glowing really hot diamond left behind.

Fraser: All right, so it's not all hopeless. We get some bling in the end of it.

Pamela: Exactly.

Fraser: Okay, so let's go a little smaller. When we talked last week, we talked about a nebula of gas and dust and various knots forming, and some of the big knots were these massive stars, and we'll get to those in a bit, and then sort of medium stars were stars like our sun, but what about smaller ones?

Pamela: So, red dwarfs are objects that have more than 80 Jupiter masses. And they behave like normal stars; they burn hydrogen in their cores. But, they burn this hydrogen, in some cases, for trillions of years. A star that is a tenth the mass of the sun will hang out burning hydrogen into helium for about 6 trillion years, which is way older than our 13.7 billion year old Universe. So any red dwarf that has ever formed is still doing its thing. So we have no observational evidence of what these things do next.

But as near as we can guess, because they're such a low mass, they won't be able to contract and burn the hydrogen shell or do anything with their helium at later points in their lives. So once they stop burning hydrogen in the core, they're just sort of going to go out, and then thermally contract. So they're going to hang out, gravitationally held together, and squish themselves, and squish themselves, as gravity makes the star smaller and smaller and smaller, until eventually they squish themselves into a very small white dwarf star. And so eventually they'll organize themselves so that their structure is that same crystalline degenerate electron, which is a really complicated term which just means that the electrons are in their smallest possible way of hanging out together.

Fraser: So it's like over time, all of whatever material is in the star, once it runs out of fuel for fusion, it just organizes itself in the most compact form that it can, and then just cools down and that's that.

Pamela: That's that.

Fraser: But we've got to be looking at trillions of years before that happens.

Pamela: And we will not be there for that. But it's fun to think about what's going to happen at the end of the Universe.

Fraser: So it's neat that no one has ever seen any of this, it's just purely theoretical at this point.

Pamela: Yeah, and also, it's a neat thing to think about, that any red dwarf ever formed is still alive. Imagine saying that any of one specific type of mouse that was ever created on the planet earth was still alive. Life doesn't do that, but stars do.

Fraser: So, let's go a little smaller, then. The stars that have enough hydrogen, or size, in them to burn as stars, you know, these red dwarf stars, what if they don't have enough hydrogen fuel? Let's get smaller.

Pamela: It's not that they don't have enough fuel, it's that they don't have enough gravity to do anything useful with it. The next smallest objects are these brown dwarf stars. They range in size from about 13 times Jupiter's mass to somewhere around 75, 80, Jupiter masses -- we're still working on figuring out theoretical limits. These stars, they have a special type of hydrogen in them, as all stars do, called deuterium.

Deuterium is hydrogen that has a neutron in the center as well as a proton. Most hydrogen is just a proton and an electron, if it's neutral. But sometimes you get this extra neutron thrown in there. And when you have this extra neutron thrown in, the deuterium, this hydrogen plus neutron, it burns easier. So, in objects that are 13 to 65 Jupiter masses, they'll, for a short period of time, maybe about 10 million years, they'll be able to fuse the deuterium. But once they stop fusing the deuterium, they really can't do anything else. Some of the bigger ones, those 65 to 80 Jupiter masses, they can also fuse some lithium. Lithium just eats itself naturally, if you look at it too hard in a star it burns up. But other than that they can't do anything.

Fraser: So how can we see them, then? Because we're turning them up all the time, now.

Pamela: Luckily, for the first million years that they're around, as they collapse out of their parent's nebula, the molecular cloud that hey formed out of, they look like any other star except they have a lot of extra lithium in them, because lithium gets eaten very fast in other types of protostars. So, for the first million years, they look normal, they're at high temperatures, and they burn the deuterium, they're still thermally really hot, and then they cool off. And it's after they cool off that they sort of disappear, but initially, just thermal contraction heats them up enough that we can see them.

Fraser: So they're just the particles of hydrogen crushing together and rubbing against each other, and that's the heat, like all that remains from a fire.

Pamela: And any time you compress gas, the gas heats up. It's sort of like if you're pumping air when you compact the air inside your bicycle pump, it heats up. Well, a collapsing star is basically the same process as the squished air inside your bicycle pump: as it gets squished together, it heats up. Heated gas gives off light, and so it's just the fact that it's contracting gravitationally that allows it to heat up, and it's the heating up that we see as light.

Fraser: Right, I guess that's why we need the infrared telescopes like Spitzer to turn these up, because they see heat not light.

Pamela: And this is one of the reasons that the next generation space telescope, the James Webb telescope, is being built as an infrared observatory. It's going allow us to more effectively look for things like brown dwarfs. It's also going to allow us to look for things at the far distant edge of the Universe, but that's a different problem. So it's in the infrared that we're finding all of these fascinating things that we never imagined when we confined ourselves to looking at the optically luminous universe.

Fraser: All right, let's go big, then. So, you know, we started out talking about a main sequence star like our sun, and we sort of looked at where things go, smaller from there, so let's look bigger. So what happens if we get stars that are bigger than our sun?

Pamela: Well, as you get bigger and bigger, things start to get messy. Really big stars are giving off so much light that that radiation pressure is blowing off the outer layers of the star. And, so, the star can star off huge, and then make itself small rather quickly. These things burn for millions of years. Our sun burns for billions. The big stars are sort of like the Ferraris: they are bright, flashy, go fast, die young, and eat fuel like nobody's business.

Fraser: That's right, I remember last week we talked about how like, the earliest stars were mainly hydrogen, and could, you know, blow up or not necessarily have the same kinds of stellar winds as the ones that, these days, have lots of heavier elements. That's all brand new science, isn't it?

Pamela: Well, it's not brand new science but it's brand new stars that are doing it. It's fascinating to look at these things. They are literally blowing themselves apart. It's as though they are going so fast that they just can't hold themselves together any longer. There's so many analogies to Hollywood movie stars that I could go to, but I won't. So they live hard, blow themselves apart, and if they blow themselves apart too much, when they finally die, they explode as supernovae but they leave behind a white dwarf.

So, you have to end up with a core larger than 1.4 solar masses, which is this magical number. If you have more than 1.4 times the mass of the sun, then left behind after supernova, that material will collapse into what's called a neutron star. If you have less than 1.4 solar masses, you just end up with a white dwarf again.

Fraser: I see. So the star could start out quite large, but it could blow away so much material that it just, it can't make it down to a neutron star once it's done.

Pamela: Exactly. The cutoff, we think, is objects that, by the time they go supernova, which we'll talk more about next week, have more than 10 solar masses. They will end up, after the supernova, with a neutron star, and things that are below that end up with just another white dwarf.

Fraser: So, what is a neutron star?

Pamela: A neutron star is what happens when the gravitational power of an object is so great that it squishes the atoms to the point that the protons and the electrons go "oh no, I'm too big, I can't be here any longer" and they merge together, give off energy, and form neutrons. So, the matter compacts itself down to its smallest possible form, which in this case is basically a crystalline structure of neutrons.

Fraser: And this is one of those, a teaspoon amount weighs, what is it, like, a teaspoon amount weighs as much as a city or something like that.

Pamela: Here's a great way to look at it. A white dwarf that is just under the 1.4 magical solar masses level will be about the size of the earth. A neutron star that's more than 1.4 times the size, the mass, of the sun, is only 10 kilometers across. You could pretty much dump one on New York City. And gravitationally it would destroy the earth, but that's just how small they are. And then you have all that mass creating all of this gravitational attraction in a little tiny area.

Fraser: Now, do these megastars go through that same kind of red giant phase at the end?

Pamela: Because they're spewing off mass and going through reactions so quickly, they don't have as dramatic a change as they go from main sequence to red giant. They do make the transitions in terms of the way they generate energy. They go from having hydrogen burning in their core to having helium burning in the core, and they'll actually get to the point where they're doing things like fusing oxygen, creating neon, they get to the point that they actually end up creating iron in their core. So you end up with an onion shell of layer upon layer of progressively heavier atoms as you go from the surface of the star down to the core of the star, where all these different layers are fusing higher and higher atoms.

One of the neat ramifications of this is that any element that you have on your body, in your body, in the room that you're sitting in as you listen to this show, it had to have come from these giant stars. What's even cooler is any element that you have that happens to be heavier than iron, it came from a supernova, but again, that's for next week. So anything smaller than iron, and bigger than about carbon, nitrogen, and oxygen, was formed in these giant stars as they were madly spewing out light and throwing themselves apart as they had huge stellar winds spewing matter into space.

Fraser: And how long will they last?

Pamela: They last just millions of years. Some of them last as few as 10 million years. So, the little guys, they can last for 6 trillion years, and the biggest stars will only last for 10, 12 million years.

Fraser: And how big can they get?

Pamela: Well, we're still finding the limits. Occasionally people find objects that they claim are hundreds of times the sun's mass. Because these things spew their outer atmosphere into space so rapidly, we have to catch them right as they form to catch the moment when they're absolutely their largest. These are very rare objects as well. Really big stars don't form in large numbers. But we do find things now and then that we thinks just might be hundreds of time the size of the sun.

Fraser: And they'll die even faster?

Pamela: And they'll die even faster.

Fraser: Well, I think that's great. We've skirted around it, but next week - and we've had a bunch of emails of this, "why won't you talk about supernovae?" - we will talk about supernovae next week, and talk about the deaths of the really big stars. So, gotta wait until next week.

Pamela: Have an explosive time.

[laughter]

Fraser: All right, thanks Pamela. We'll talk to you in a week.

Pamela: Okay, see you later, Fraser.

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