Astronomy Cast Episode 107:
Nucleosynthesis: Elements from Stars

Fraser Cain: I hope everyone by now has heard our little surprise for the feed, which is that we've doubled the amount of Astronomy Casts. So if you like that great, if you don't like that, let us know. Hopefully we can grind through more of your questions, which really feels great. I actually really enjoy doing the shows and I really enjoy listening to them. I don't know why. I think it's just some of the cooler concepts come through the questions.

Dr. Pamela Gay: Yeah, you guys ask way harder questions than Fraser does.

Fraser: I know I feel like I should just pass the microphone over. [Laughter] Okay, everyone here it's your turn. We're done with our tour through the basic Forces of the Universe and so now we wanted to get back to some regular Astronomy. Nothing too complicated this time around.

Pamela: Well that depends on who you talk to. I think our talk is fairly complicated.

Fraser: All right then, fine. Something super complicated. Let's get on to it. So look around you. Breathe in some air. Everything you can see and feel was formed in a Star.

Today we'll examine the long journey that Matter has gone through, forged and re-forged in the hearts of Stars. In fact, the device you're using to listen to this pod cast has some elements formed in a Super Nova explosion.

Just think about that. I'm sitting here sorta spinning my wedding ring around and thinking it came out of a Super Nova.

Okay Pamela, today we're going to talk about how all of the Matter in the Universe came in one form or another, either from the Big Bang or from Stars or from Super Nova. I guess at the end it's all sort of the same environment.

I think before we can do that I think it's important for us to go into what are the Elements and why are they different? How do you know what's different from one Element to another? What differentiates them?

Pamela: It all comes down to Proton and Neutron number at the end of the day. The number of Protons tells you what type of Element it is. So, you have Hydrogen with one Proton; Helium with two Protons and you build your way up through the Periodic Table adding more and more Protons.

But the thing is there's also this thing called a Neutron. Some Atoms in order to be stable have to have both Protons and Neutrons in the core. You end up with things like Helium-4 which is a Helium Atom which is number 2 on the Periodic Table. That 4 means that it has four bits, two Protons and two Neutrons sitting in its Nucleus. Helium-4 is like one of the most stable things that you get.

Then we build our way up through the Periodic Table creating heavier and heavier things through different types of processes. In some cases we just add a Proton and it grows. In other cases we add a bunch of Neutrons and these Neutrons decide to flip what they are between Protons decaying through a process called the Reverse Beta Decay.

This is where the Weak Force gets involved and switches the identity of a Neutron into a Proton while emitting bits of other stuff like an Electron and the anti-Electron Neutrino.

Fraser: Then what is the definition of an Element? It's the Protons?

Pamela: It's strictly based off the Protons.

Fraser: Okay so one Proton is Hydrogen. Two Protons is Helium. Three Protons is Lithium, etc. So, that's where you go up with the numbers. Whenever you see Gold or Lead, the first number is the number of Protons and if you add another Proton, you have a new Element, right?

Pamela: That's exactly what's going on.

Fraser: But then the Neutron, that's where you get that number. Like you say if it's Carbon-14 you've heard about Carbon-14 Dating, that's where the total number of Protons and Neutrons add up to 14.

Pamela: And in the case of Carbon you start off with 6 Protons and then to get up to that 14, you add 8 Neutrons to it.

Fraser: Then those Neutrons can decay you could have six Protons and seven Neutrons and you'd still have Carbon but it just would be different in the number of total little balls at the middle.

Pamela: Yeah, that's right. So, when we talk about Atoms we often use the Periodic Table to figure out how many Protons there are, but in our shortcut language we'll say things like Lithium-7 where Lithium has 3 Protons in it and Lithium-7 has 3 Protons and an additional 4 Neutrons.

Fraser: Then all of the things we're going to be talking about today are the process of adding more Protons or Neutrons, right? The point being is changing one Element to a different Element through adding Protons.

So taking 2 Elements, mashing them together and you get something that is heavier that has more Protons. It has new characteristics. So, then the most common Element in the entire Universe is Hydrogen.

Pamela: And that's really nothing more than like a Proton by itself that decided to get a friend for an Electron.

Fraser: Okay and where did that all come from?

Pamela: It came from Energy. [Laughter] When the Universe first formed we were all Energy. As the Universe cooled and got less dense, eventually that Energy was able to solidify out into Protons.

Fraser: This is almost like the discussion we had about the Large Hadron Collider. The whole Universe, the Big Bang was like a great big Particle Accelerator that turned (to borrow one of your words Pamela) ginormous amount of Energy into Matter.

Pamela: The Big Bang was sorta the biggest Energy-creating moment of all time and it ended up leading to all the Matter we know. Originally, all that Matter was just pure Protons and pure Electrons that were happily bouncing off of one another and interacting wildly.

Fraser: Would that have been Hydrogen at that point or just Protons?

Pamela: There you're starting to get down to sticky names. A fully ionized Hydrogen Atom is a Proton. There is Ionized Hydrogen, Proton – same thing.

Fraser: So it is Protons without Electrons. So it's Hydrogen without Electrons.

Pamela: Pure raw Protons running around the Universe.

Fraser: So, then what happened?

Pamela: As the Universe cooled about 100 seconds after the Big Bang, we got to the point that the density and the temperature of the Universe kind of resembled the inside of the Sun. In fact it pretty much exactly resembled the inside of the Sun and we're able to get these Protons colliding together and in some cases sticking becoming what we call Deuterium.

One of the Protons would decay into a Neutron and we'd end up with a Proton and a Neutron crammed together and side-by-side with that there'd be a Positron flung off and a Gamma Ray flung off.

The nice thing about Deuterium is when it collides with another Hydrogen you start to get Helium. So you're starting to build heavier Elements through this process.

Fraser: This is exactly the same process that happens inside Stars. For a few brief moments, the entire Universe was just like one great big Star.

Pamela: In that one great big Star, we're able to build up from Hydrogen to Helium and we even got bits of Lithium and Beryllium. One of the really cool things about Big Bang Nucleosynthesis is because when it suddenly shut off we were left with residual Elements that don't normally end up by themselves in Stars because the process keeps going to completion.

Normally you end up with Hydrogen going to Deuterium, going to different species of Helium and eventually building itself up into Beryllium and then to Lithium. That Lithium generally quickly collides with the Hydrogen and goes into two different Helium-4 Atoms.

Because of the way the process was shut off in the Big Bang, we end up with Helium-7 left that didn't have a chance to end up combining to form 2 Alpha Particles. Alpha Particles is a fancy way of saying Helium-4.

Fraser: How long did this process last?

Pamela: Just 200 seconds, that's the really cool thing. All the Lithium-7 in the Universe pretty much was created in 200 seconds.

Fraser: Right. And even the ratio – what was the final ration? I think it was like 25 percent of the Universe is now Helium?

Pamela: Pretty much all the rest is Hydrogen. There are just trace amounts of Lithium and Beryllium left behind.

Fraser: Right, but that all got changed in just 200 seconds.

Pamela: If it wasn't for those 200 seconds who knows what would have happened.

Fraser: Okay so then we've got a Universe of expanding Hydrogen and Helium and other Trace Elements. Gravity takes over, starts to pull that material together and starts to form the first Stars. They were just like balls of Hydrogen, right?

Pamela: Right and because they were basically balls of Hydrogen with admittedly 20 something percent Helium, they underwent different characteristics than our current Stars. They were able to become huge. We think that some of these Stars were able to get as big as 250 Solar Masses. One Star 250 times the size of the Sun. In these Stars they had what we call Proton-Proton reactions.

This is pretty much the exact same set of reactions that were going on during the Big Bang Nucleosynthesis. Eventually, they start to be able to build heavier things. Eventually they are able to start building Carbon, building Nitrogen. There are Super Novas – we ended up with heavier Elements over time. But that first generation of Stars, because there was no Carbon around to start the Carbon-Nitrogen-Oxygen cycle which is the next cycle that you get to when you're done making Hydrogen and Helium, were able to build these giant Stars.

They burned quickly and they died quickly and seeded the Universe quickly with heavier Elements. Once we had those heavier Elements the size Stars that we were able to build changed. Different types of Nuclear reactions were able to kick in at high temperatures.

There is this process called the Carbon-Nitrogen-Oxygen Cycle that once you seed it with Carbon Atoms it's going to halfway chew away and it does this at the type of temperatures you get with bigger Stars.

A lot of times you'll learn in Astronomy 101 class that all the Stars on the main sequence – Stars that are on a strip through a diagram of brightness and temperature that our Sun sits happily in the middle of, Stars that sit on the main sequence are all burning Hydrogen in their cores.

That's actually not true. If you get yourself a big enough Star, it will actually start undergoing Carbon-Nitrogen-Oxygen burning in its core as well.

Fraser: So, what's going on? I think we understand with the Hydrogen burning you've got essentially a ball of free Protons there. Every now and then a Proton is being squished together with an Electron to create a Neutron. And then the Neutrons and the Protons are being pushed together and eventually you end up with Helium Atoms. I think it takes 4 Protons?

Pamela: You start with the Proton-Proton chain. This is what we have happily going on in our Sun. In this case you take two Hydrogen Atoms, squish them together and you get what is called the Deuterium. This is where you have one of the Protons decides it wants to be a Neutron and you give off a Positron and a Neutrino.

Then the next stage of this is to take that Deuterium and you smash it into another Proton and you get Helium-3 – a Helium Atom that has 2 Protons and a Neutron and you give off some Gamma Ray light.

Then you take 2 of those Helium (you have to let that process go a little bit until you get the 2 Helium), and you smash them together and you get a Helium-4 and 2 Protons go flying off. Well the problem is, once you have this Helium-4, it really doesn't want to combine with anything.

This was mathematically a serious problem trying to figure out how is it that the Sun keeps going. How is it that other Stars keep going? How do you burn this Helium-4?

Luckily, the there is something that we call a Resonance that we're not going to go into a lot of detail on where basically just the right energies and densities to cause Helium-4 to start turning into Beryllium and that Beryllium to start matching up with another Helium-4 to get a Carbon.

There is an energy resonance that allows this reaction to happen at about ten to the 8 Kelvin and it's perfect. It works and we call it the Triple Alpha Process and once you get that Carbon, then you can start, well Carbon mashed into a Proton that gets you Nitrogen.

Nitrogen will then decay back into Carbon but a different type of Carbon. So we're building things, feeding it through the cycle and we're starting to get Carbon-Nitrogen-Oxygen building up in the cores of Stars.

Fraser: Okay so that's the whole point. You've got your Hydrogen going to Helium and then the output of that is then turning into the Carbon-Nitrogen-Oxygen cycle and so you're boiling down Hydrogen – fluffy Hydrogen into a much more compact oxygen, right?

Pamela: And the Stars actually go through fundamental changes as they go from one type of cycle to another. You take a Star like the Sun and initially it will just burn through all the Hydrogen-producing Helium. Helium is not hot and dense enough in the core of a Star when it is in the Hydrogen burning phase to get to that C-N-F cycle.

Then you go through flashes and you end up with burning the Helium. It's a series of events where the Star collapses, changes core temperature, expands back out and you have the Star evolving in radius, evolving in core temperature, evolving in what type of burning is going on.

As it burns hotter in the core it burns heavier Elements in the core. It ends up actually creating shells of burning around that hot core as well so you end up with onionskin layers of Nuclear Synthesis.

In one part of the Star you're perhaps creating Silicon while in another you're still burning Hydrogen into Helium. You're just doing it at a higher level of the Star.

Fraser: What would be happening inside our Star?

Pamela: A Star like our Sun - we're boring. We're eventually going to produce Carbon but we're never going to get to burn the Carbon into something more exciting.

You end up needing to have a Star that is about 1.4 times bigger than our Sun. We're not there. But as you grow the Star you're able to grow the size Element you're able to build.

Fraser: That's interesting. So if we had a Star that was 1.4 times bigger than the Sun then it would take the Carbon and turn that into something heavy, Nitrogen, right?

Pamela: Well, we'd start ending up getting resultants of Oxygen and Sodium and Magnesium. So the Carbon burning will start to get us to even more interesting Heavy Elements.

Fraser: How far does this process go?

Pamela: As you get up eventually to a five Solar Masses Star, that's when you start to be able to burn Neon. Out of that you get more Oxygen and more Magnesium.

With bigger Stars yet at ten Solar Masses you start to get Oxygen burning. At twenty Solar Masses you start to get Silicon burning. Eventually though you get to the point that through the Silicon-burning process you're creating Iron through the nuclear burning.

Fraser: So your output is, like the end of a factory line, Iron is coming out.

Pamela: The problem that we run into is that with Atoms that are lighter weight than Iron. When you fuse them together they release Energy. They are happy to give off Energy through this process.

For instance during the Hydrogen-Hydrogen, you end up giving off 1.44 mega-Electron volts of Energy. So as we produce Helium-4 we're giving off more than 20 mega-Electron volts through that entire process. We're releasing Energy through all these different burning processes.

Once you get to Iron in the core, you can't combine two Iron Atoms. In fact you can't combine Iron and anything and have it release Energy. You have to add Energy into it to get that sort of process to take place.

Fraser: Right and I remember the whole Star is being held up against all that Gravity by the Energy that is coming out of this fusion reaction – the light pressure. So you've now instead of having excess Energy keeping the Star out, you've run out of Energy.

Pamela: In this case there's nothing supporting the outer atmosphere of the Star anymore. So the entire system collapses. As it collapses you end up with things colliding violently. You have that Energy getting injected and you're able to get all sorts of massive reactions going on. This is in fact a Super Nova.

We have Gamma Rays flying out radically. We have Neutrons flying out radically. It's this wash of Neutrons flying through the collapsing atmosphere of the Star that causes what we call the Rapid Process (R-Process).

Take a happy little Atom and bombard it with Neutrons and it is going to grow. If you bombard it with Neutrons fast enough, those Neutrons can't decay into Protons at a reasonable rate to keep it at a lower Atomic Number.

In fact you're able to build these crazy large Neutron-rich things that will eventually decay into nice stable Atoms. It's out of this R-Process that you get Gold, Silver and a lot of the Heavy Metals that we deal with day-to-day.

Fraser: How long does that process take? I know that we're talking way back when with the Sun that it takes hundreds of thousands of years for the light to get from the core of the Sun to the outside the Sun.

It sounds like this whole process, once you get like a train wreck on the one [Laughter] end of the process, it must take time for it to ripple through the system, right?

Pamela: Super Nova can have core collapse that takes place in the time scale of milliseconds. It's going to take time after that for all the radioactive particles that have been created to decay away.

This is part of what causes the slow decay of the light curve. It is part of the time scale of how long different Super Novas stay at different brightnesses depends on the ratios of the different Elements that occur and how they're slowly decaying away.

But Super Nova themselves, it's milliseconds with this radical environment of Neutrinos and Neutrons and Gamma Rays all passing out through these collapsing layers of the Atmosphere and creating a shock-wave and pushing things outward. It's an amazing process that people are struggling to try and do good three-dimensional models of to understand everything that's going on.

Fraser: But it's just amazing to think about that, right? I mean you've got a Star – I guess with a Super Nova Star they don't last very long. Let's say you've got a Star that has lasted for millions of years happily burning, upgrading the stuff that it's burning you know going up through the Table of Elements and then it hits this wall of Iron.

It's just like a brick wall. Like a car hitting a brick wall. [Laughter] Milliseconds later, the Star is gone from its previous form. Black Hole forms – you get the explosion and all these new Elements. It blows the mind.

Pamela: There is one other way to get some of the Heavy Elements. This is the way like nobody talks about. I love some of the things that we just propagate basically a Mythology of false information.

There's this thing called the S-Process where there are Neutrons getting produced in the cores of Stars all the time. In old Massive Stars, you're producing enough Neutrons in the center of the Star that as Neutrons pass out through the Atmosphere, they're able to bombard Atoms hanging out in the Atmosphere and get captured.

Then they undergo what's called Inverse Beta Decay where that Neutron converts itself into a Proton and Positron and a Neutrino. In the process you're able to build heavier and heavier Elements in the Atmosphere of the Star. So there is one other way to get at some of the Elements. This is for instance one of the ways we get at Strontium.

Fraser: Are you sure that's it? I mean that's it for Stars but what about Black Holes?

Pamela: Well, not just Black Holes but also White Dwarfs and Neutron Stars – anywhere you have an Accretion Disk you can end up building up again another situation with the densities and the temperatures are sufficiently high that you can end up with Nuclear Reactions.

When you see a Nova, not a Super Nova but a Nova, one of these situations where you have an exploding Accretion Disk, that's runaway Nuclear Reactions. So there are all sorts of random little extra places that we can start to get heavier Elements emerging.

Fraser: Right, so you've got material piling up around a Super Massive Black Hole and for just a moment there, the region has the right density and the right temperatures to act like a Star.

Pamela: And with Super Massive Black Holes their Accretion Disks can actually maintain some of this material for fairly long periods of time. It's the White Dwarfs that you end up with these short outbursts, these recurring Nova events where essentially the White Dwarf is sitting there, gravitationally sucking Matter off of a nearby companion. This only happens with binary systems.

As it sucks the Matter off, the Matter builds up and builds up until you end up with Explosive Accretion Disks. Once you've cleared it out, the process starts over again and then you suck Matter off, build the disks and build the disks… and it goes off again.

So this is again something that has found a model and here it's complicated because for reasons that we're still trying to figure out the rate at which White Dwarfs suck Matter off their companion isn't always constant.

The rate at which the Accretion Disks explode isn't entirely constant. So there's lots of neat Physics still waiting to be explored.

Fraser: Okay, so let's run through a couple of examples before we wrap this up. Just so people can get a sense of the story. Let's imagine you have a glass of water – where did the water come from, Hydrogen or Oxygen?

Pamela: The Hydrogen probably came from the Big Bang. There' really nowhere else that you get Protons. Then the Oxygen probably came from a Star bigger than our Sun. You can get Oxygen from a Star the size of our Sun but you're going to get more of it as you start to get bigger Stars.

You have to wait for these Stars to die. During the last years of the biggest Stars, there's mixing and they breathe out their Atmosphere's Planetary Nebula. It's this breathing out; this exhaling of materials that have been mixed that allows you to get at the Oxygen from the heavier Stars.

Fraser: So to make a glass of water you had to go to the Big Bang store to get [Laughter] some Protons. Then also you had to go to an old Massive Star that was sloughing off its outer Atmosphere firing out Oxygen. Then mix those together and you got water.

Pamela: And you could also have gotten the Oxygen from Super Nova. We can't know exactly where any of them came from.

Fraser: Right, right. Okay what about a tree?

Pamela: [Laughter] a tree is mostly Carbon. So Carbon, again we're getting this through the exhaling of elderly Stars where they're breathing out their outer Atmosphere, which has been enriched, with Carbon through different mixing processes. We're also getting that from Super Novas.

Fraser: And my wedding ring?

Pamela: That's all Super Nova.

Fraser: Right – only a Super Nova. It had to come from a Super Nova.

Pamela: And that's kinda cool.

Fraser: It's really cool. I don't think my wife would agree but…. [Laughter] That's the coolest thing ever. Well, I think that covers the show for this week. And now I hope that you'll look around at all the stuff and even the stuff that you're made of and you can think back to the famous Carl Sagan quote –we're all made of Star stuff.

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