Astronomy Cast Episode 75:
Stellar Populations

Fraser Cain: After the big bang, all we had was hydrogen, a little bit of helium, and a few other trace elements. Today, we've a whole periodic table of elements to enjoy, from oxygen we breathe to the aluminium cans we drink from to the uranium that powers some people's homes. How did we get from plain old hydrogen to our current diversity? It came from stars, in fact successive generations of stars.

Let's start back at the beginning. Pamela, can you give us what the conditions were like right after the big bang?

Dr. Pamela Gay: Right after the big bang, I'm going to skip forward and skip to right after the cosmic microwave background formed. Go back, listen to our shows on the big bang and right after the cosmic microwave background formed, we have a universe that's gas. It's gassy. It needs something to come along and clear up the gas, sort of like a person who ate too much.

In this gas, it's pretty much all constant everywhere, but there's slight inhomogeneities, slight differences from place to place, where some places have a little bit more matter (and by matter I mean both luminous matter and dark matter).

Fraser: But what is the gas?

Pamela: It's hydrogen.

Fraser: It's just hydrogen, a little bit of helium, trace elements.

Pamela: Yeah, and trace amounts of lithium and beryllium.

Fraser: Right, and the hydrogen is what was formed right at the big bang, the helium and others were formed when the whole universe was acting like a big, giant star and in a compressed state.

Pamela: Yeah.

Fraser: Yeah, and we covered that in the big bang episode. I don't want to over do it, but bring everyone up to speed.

Pamela: This universe of gas, these slight differences from place to place in the density caused it to start fragmenting. If you look at different images of nebulae, you'll see that in some of them you can actually see the chunkiness in them. You can see the fragmentation and the process of stars forming. You can see this some in the Orion Nebula and the Eagle Nebula. The entire universe was basically one of these giant star forming regions.

Because the universe was only hydrogen, some helium, and trace amounts of lithium and beryllium, the types of stars we have today wouldn't have been able to form. We actually require metals to get small stars. This is because the metals help the energy escape from the star and cool them down. Without that ability to cool off, the stars get really big, really hot, really powerful, and live very short lives.

Fraser: But what if you don't have enough gas? Like, right in the beginning the whole universe was a lot more compressed than it is today. I can see how there must have been gigantic quantities of gas that came together in various places, but if you had a small amount of gas, wouldn't that come together as a small amount of star?

Pamela: This is one of those things that there's a lot of debate going on about in the astronomy community. I have to admit that as a community, we aren't of a single mind. Observationally, if there had been any small stars forming, if any stars that were even 80% the size of the Sun, they'd still be hanging around. We'd be able to see them somewhere. Perhaps not in large numbers, but we probably would've found one by now that had this primordial ratio of abundances: had no iron, no carbon. We haven't found any stars like that.

Fraser: Oohh, okay. Right, because a star that's smaller than the Sun is going to burn its fuel more slowly and last a lot longer. It might not even be done its main sequence phase and we would see it. Because the universe is only 13.5 billion years old, we'd look at these stars and go, "that is a 13.5 billion year old star, it must have formed right from those primordial elements".

Pamela: We're not finding those stars.

Fraser: Ever? Not a single star has been found like that?

Pamela: None!

Fraser: Really! Huh.

Pamela: So, when we do the computer models (well not we – when other people who are far better programmers than I am go off and do the models) they're finding the stars are coming out naturally when you balance all of the thermodynamics, when you balance all of the energy generation and gravity. They're coming out huge, they're coming out hundreds of times the size of the Sun.

Fraser: I don't want to keep going into this – obviously the evidence is there. Aren't there clouds of hydrogen still out there in the universe that haven't collapsed yet?

Pamela: Yes, and those clouds that haven't collapsed yet aren't pure. They're not virgin clouds.

Fraser: They've been seeded from other generations of stars.

Pamela: So not all the fuel got used up. Think of it this way: when you're making bread dough on the counter, there's still flour on the counter when you're done. A lot of It goes into making the bread, but you still have leftover bits. In our galaxy, that first generation of stars didn't suck all the gas into star formation, in fact we think that the population II stars, the next generation of stars actually started to form before that first generation of stars had finished lighting up all the gas and clearing it out and making it transparent.

Fraser: Okay, well now you're just skipping to the second chapter. Let's go back to the first chapter here.

Pamela: Okay.

Fraser: You've got these gigantic clouds of gas coming together to make monster stars.

Pamela: Monster, monster stars. There's actually a few papers, though I'm not sure I believe them, that say that dark matter might've played a role and these first generation stars might've helped coalesce these giant stars, might've helped seed the early nuclear fusion that was very different from what we get in the Sun. it was a lot hotter because you didn't have any metals to help cool these stars.

Fraser: So let's talk about one of the lifecycles of one of these stars. So the vast cloud of gas with potentially hundreds of times the mass of the Sun comes together to form a star. What kind of star are we looking at here?

Pamela: We're looking at a supergiant. Not too different in some conceptual ideas from the giant stars that we periodically see in star forming regions today. What's different here is in real star forming regions in the modern universe, you might get two or three huge, ginormous, frighteningly scary-large stars. In the early universe, all the stars were like that.

Fraser: Right, so one of these stars would be as big as… is there a theoretical limit? Is there a limit to how big a star can be, and why?

Pamela: There is. The reason that there's a theoretical limit is because you have to look at the balancing of light pressure and gravitational collapse. Once a star gets too big, it starts generating so much light, heat and pressure in the centre of the star that it starts flinging off the outer layers of its atmosphere faster than that stuff can gravitationally collapse in.

Fraser: That's able to actually escape, right?

Pamela: Yeah, so the gas that's trying to become part of the star gets blown away – radiated away.

Fraser: Right, and that mass being blown away might bump into other clouds nearby and cause those to collapse. It's almost like you could get a whole pile of the largest possible stars everywhere you looked.

Pamela: Exactly.

Fraser: That must have just been insane to see.

Pamela: This lit up our universe. That's the cool thing about it. Up until that moment, all this gas had been like a fog over the entire universe, where even if you were there with a tiny mag-lite, you couldn't see anything because all this gas is opaque and there's nothing creating light.

When these stars turned on, not only did they create light, but the light they created ionized all the gas and made it transparent. It's like some of those new windows they have that you flip a switch and it changes the qualities of the material making the window so it goes from being completely transparent to completely opaque.

Fraser: Okay, so these stars were not only ionizing the gas and making it clear, they also had powerful ultraviolet radiation and stellar winds that were blasting huge cavities in this gas and sort of pushing it all away, clearing out space around the stars.

Pamela: The light itself was changing the properties, the transparency of the gas that wasn't getting pushed out. Stuff's getting blown and moved around. These stars are lighting everything up, and the light they're generating is making the universe transparent all at the same time. It was a tremendously dramatic period in the universe's evolution.

Fraser: Have we actually seen this? Or is this just theoretical?

Pamela: We can see the light of this first generation of stars, but we can't see the individual stars, which is a bit frustrating. There's actually a background glow that's in the infrared that we attribute to the first generation of stars. When we look at certain gravitationally lensed galaxies that are so far back that we couldn't see them if it wasn't for the fact that they're gravitationally lensed, we can start to get hints of this first generation, this first round of star formation taking place.

Fraser: One thing – you mentioned they're in infrared. Why are they in infrared? They must be really hot stars pumping out ultraviolet radiation. Why would they be in infrared?

Pamela: This is the crazy thing. Because of the universe's expansion, things like the cosmic microwave background weren't emitted in the microwave – it just arrived in the microwave. Light from most distant galaxies we see in the red, but it didn't start off there. In a lot of cases it started off in the ultraviolet. The same is true of extremely hot stars. They were extreme ultraviolet emitters, but as their light has travelled through the expanding universe, the wavelengths have gotten expanded, the velocities have Doppler-shifted everything. By the time the light gets to us it's in the infrared.

Fraser: These stars must not have lasted long.

Pamela: Only a few million years. It was a quick birth, a quick death and because of them the next generation of stars that were born were kind of neat. One of the weird things about this first generation of stars is they didn't create all the elements equally. For instance, they didn't do a lot of carbon or oxygen creation. What was left behind by this first generation of stars was a lot of iron.

Fraser: So in the final stages, as they died as supernovae, they went through the same process, fused heavier and heavier elements, hit iron… is that right?

Pamela: They hit iron and that was the signature they left behind. When we look at the next generation of stars that formed them, we see stars that have extremely low carbon and oxygen abundances compared to their iron abundances. All of their metals are extremely, extremely low.

Fraser: We've got this second generation of stars that formed out of the rubble leftover from that first generation. Once again, it's kind of astonishing when you think about it. The gas cooled down to the point that they started to gather into stars and after a couple millions of years, that whole time period was over. You had the next generation – the population II stars.

Pamela: That next generation of stars started forming before the first generation of stars was finished living. So you did have overlap between the generations.

Fraser: Right, so that first generation is called population III, right?

Pamela: We do generally refer to it as population III, though there are some sloppy individuals (and I have to admit I'm one of them occasionally) that refers to the most metal-poor stars that we find, the ones that have truly aberrant metallicities, that had to have their parents be that first generation stars, also sometimes get lumped in with population III.

Fraser: Right. That first generation of stars, some of them are still alive, while others had detonated and that's where the ones that had already detonated… their material started to form this next generation of stars while the first generation was still around.

Pamela: Yeah.

Fraser: Right. The overlap.

Pamela: We have this fascinating mixture. We've actually found two stars that we think belong to this very next generation of stars. They've terribly boring names: HE0107-5240 and HE1327-2326. These stars have iron abundances that are 200-300 times smaller than the iron amount found in the Sun, which is pretty spectacular.

Fraser: Would this second generation of stars have the same problem as that first generation? They'd still be fairly hydrogen-rich, so they would probably want to be fairly large – is that right?

Pamela: They're going to have different temperatures as a function of size. They're always going to run a little bit hot. Take a mass the size of the Sun, and you're going to get a star a little bit hotter, a little bit bluer than the Sun. you're still able to start getting the smaller stars though.

Fraser: Shouldn't you have the same problem? Shouldn't we see these stars everywhere, if smaller stars were possible? Since we've only found two, they probably didn't happen so much – or didn't last. They blew up too.

Pamela: This is one of the things we just don't know. We do refer to this as the missing G-dwarf star. We're missing stars the size of the Sun that should be out there and aren't. We're not sure why there aren't as many as we would expect, and part of this is knowing where they'd be located.

We are still sorting out the problem of how galaxies form. It could be that these stars are simply so far out in the halo that they very rarely get close enough that we can see these little tiny things well enough to get spectra to look for their extremely low mass.

Fraser: Okay, give me a bit of a contrast. What would a population II star look like compared to a population I star?

Pamela: Well, at first glance you can't tell that big a difference. They do have slightly different colours, as a function of their mass. But then you have to build and measure their mass. So if you're simply looking at two stars on the sky and all you have is a picture, you can't tell the difference.

Where you have to start looking for the difference is we take what are called spectra that spread the light out into a very detailed rainbow. This allows us to look for gaps in the rainbow that are caused by absorption of certain atoms of certain colours of light. Different atoms have specific fingerprints on what colours of light they absorb and emit.

We can determine what chemicals make up a star based on their intricate fingerprints. This is a very precise science, but it requires huge telescopes and a lot of time on those huge telescopes. If you're trying to pore through thousands of stars, that can be a lifetime's worth of work sometimes. So we're working on poring through the stars in the outer parts of the Milky Way, looking to see if we can find these extremely metal-poor stars.

We do look for hints in the colour: there are different fingerprints where if you use a filter when you look in just the red light, it might have a bunch of lines in the red light that caused the red light to be a little bit lower than the blue light when you also compare the green light. So you start using multiple filters and sorting things out and you can start to make guesses.

Fraser: Can you look at a galaxy as a whole and then say that whole galaxy seems fairly metal-poor?

Pamela: Not so much. There's so many things involved in the light from galaxies that you can't just get the metallicity of a galaxy.

Fraser: Right.

Pamela: You have light coming from nebulae, individual stars, random high-energy events, all of these different sources make it hard to get a big picture until you start to take detailed spectra. Then we're just basically looking at fingerprints and saying that's the fingerprint of carbon or iron and looking to see how they're layered on top of each other, which one's stronger, which one's weaker.

Fraser: Okay. So we've got this second population of stars. Was that one quick round, or would stars stay in that population II through successive generations?

Pamela: There were successive generations of population II stars. It's actually kind of fuzzy to define what makes a population II star and what makes a population I star.

Fraser: That's just all astronomy, right?

[laughter]

What's a planet?

Pamela: So now we start getting into much fuzzier definitions. With population III, at its core, it's the first generation of stars. Population II stars, these are made out of leftover materials, recycled materials. You start to see the abundances changing. The amount of carbon related to iron starts changing.

We also look at where they're located. Part of the definition of a population II star is they're in the halo of the Milky Way. they're in globular clusters. They're in places other than where our Sun is. So you also get a kinematical definition, but how do you apply that when you're looking at a small galaxy that's spherical with all the stars mixed together?

So we do have chemical definitions still. In general, the breaking point is when you start to get objects that are two or three times less metal-rich than the Sun. Mileage may vary on that definition. You start to get into some fuzziness as you get more and more metal-rich – is it population II or population I? Different people will give you different answers.

Fraser: Right, okay. Let's say these things have died, some exploded as supernova, some are still going, but the ones that exploded as supernova spread their elements out. When do we hit population I then?

Pamela: We have different ways of making the definition. You start getting population I when you get the disk of the galaxy starting to form. The stars in the disk of the Milky Way – these are what we call population I stars. The stars that are like our Sun in some ways.

You also start to get population I when you start getting metallicities – when you start getting carbon, oxygen, iron contents that are within a factor of two or three of the Sun.

These are the stars that can start forming planets. That's not part of the official definition, but that's what we're finding. When you look at population I stars, they can have planets. We aren't finding any planets around population II stars.

Fraser: Hmm. Why not?

Pamela: Well, it's these metals, these carbon atoms and all these atoms that are heavier than helium. They start to chunk up and form planets. You need these extra elements, these heavier objects that hang out, outside of the solar nebula's inner glowing, fusing part that becomes the proto-star, to start forming planets. Without the heavier objects, you don't generally get hydrogen-pure versions of Jupiter. You need to have other things in it. Planets are formed in that third magical generation.

Fraser: Right. That's where we are, right? The Sun is of that group.

Pamela: The Sun is one of the most metal-rich stars out there. We go from stars in the population II in these two most metal-poor objects we know of, with 200-300 thousand times less metal than the Sun to those in the population II that are 10 times less metal-rich than the Sun. The most metal-rich things we know of are only three and a half times more metal-rich than the Sun. So you go from 300 thousand times less to three and a half more, and not more than that.

Fraser: I wonder what impact having heavy metals in the solar nebula had as an influence on the planets and life. I wonder where – we might not even be able to get terrestrial planets.

Pamela: This is what we're trying to figure out. This is something we have to answer observationally, and where future programs like Darwin and the Terrestrial Planet Finder start to become so important. We can look out and say, "that star has this amount of iron/carbon/oxygen and it has a rocky planet. This star that has a little bit less has no planets at all."

Fraser: Right. We can't see rocky planets apart from going around pulsars.

Pamela: Right.

Fraser: So it's really hard to do. But we're close – there's Darwin, potentially the Terrestrial Planet Finder and I know there's a whole series of ground-based techniques that people are starting to develop: some super-large telescopes that we talked about, telescopes in Antarctica.

We should, within the next decade, start finding these terrestrial-sized planets, and I guess we can map them together. We might say that if a star has exactly this much metal or more, it will have terrestrial planets, and if not then it won't. then we could just stop looking for planets around certain kinds of stars.

Pamela: This is one of the most interesting but also one of the hardest things to deal with. We live right in the centre of the metal-rich area of the galaxy. It's easiest for us to look for planets around nearby stars. All the nearby stars unfortunately are just like us.

So when we start asking the question, "how different can a star be and still form planets?" now we have to start looking at things that are uncomfortably far away. It's going to take more technology. There are some people who have already done some pretty good work ruling out certain places.

The Hubble Space Telescope did a long campaign looking at the globular cluster M15 (I think). In looking at it, they're taking round after round after round of images. If there had been any planets transiting stars passing in front and causing the light to get a little bit fainter, they would've seen it. There was no evidence in their work that showed transits. They found some variable stars, lots of binary stars, but they didn't find transiting planets.

Fraser: So they're finding to put some limits on this.

Pamela: Yeah. Scott Gaudy's also done a lot of work on this: looking at different clusters of stars and seeing what he could rule out with his team of observers. Every time these people have looked at large populations that have lower metallicities, no planets have been found.

Fraser: Is there a limit to how much metal a star could have and still be a star?

Pamela: This is another question. We're still trying to figure out how to answer. We don't have any to observe.

As you add more and more metals, it allows the star to radiate away its energy much more efficiently. It cools the star down and makes it harder for it to build up temperatures in the centre. It could be that there's a limit eventually, but in the interim you can just build the star a little bit bigger and the temperature will get hotter as you end up with more mass.

It's this balancing line between effectively having smaller stars with some (but not a lot of) metals and are able to effectively cool but still be hot enough to burn. Then you start cooling too efficiently, so you need to build the star up a little bit more.

Fraser: I want to go back to the beginning for a second. With the James Webb Telescope, which is going to be a much more powerful version of Hubble, but specifically designed to look at the infrared… it should be able to look back at some of those most distant stars and galaxies. Is it going to be able to sense the population III stars?

Pamela: Only in terms of their aggregate properties. They're so far away that you'll never be able to make out individual stars. Not with James Webb.

Fraser: Right, they're going to be 13.5 billion light years away.

Pamela: Right. We struggle to see individual stars in our local universe. It will be able to look and see this little tiny blob of light is a galaxy that's light-output can only be described by these giant stars that we can't see individually. We're going to get there, we just aren't going to be able to get all the way there. That's always frustrating, but you can figure out the shape of an elephant if you have enough blind men observing it and they talk to one another effectively. Astronomers are pretty good at talking to one another.

Fraser: Right. Good. I think that’s it. Now, hopefully, everyone can really understand the successive generations that stars went through, from the big bang to today. When we talk about metallicity, metal-poor, metal absorption, and some of the requirements for being able to form planets, hopefully everyone will have a much better understanding of that.

I know it comes up a lot in a lot of the articles I do on Universe Today. It’s one of those things I think you kind of take as a given that either you’re not even going to talk about it or you assume that people know it. I think it’s good to go into that level of detail. Thanks Pamela.

This transcript is not an exact match to the audio file. It has been edited for clarity.