Astronomy Cast Episode 25:
How Galaxies Form

Fraser Cain: The Milky Way is our home, it got its start 13.7 billion years ago like everything else with the Big Bang, but how did our Galaxy go from an expanding spray of Hydrogen and Helium to the first stars and finally to the majestic barred spiral we live in today? What does our future bring?

Okay Pamela, let's start right back at the beginning: how do Galaxies get their start?

Dr. Pamela Gay: After the Big Bang, we had lots of hot stuff and we talked all about what happened to all that hot stuff in earlier episodes on the Cosmic Microwave Background. After about 400 thousand years, the Universe consisted of a fairly uniform spread of neutral Hydrogen with some neutral Helium and just a dash of Lithium and Beryllium thrown in. Luckily, there were some slight irregularities to this spread of material. Those irregularities gravitationally collapsed together.

Collapsing together first was the Dark Matter. We're not really sure what the Dark Matter consists of but we're really glad it was there, because as they collapsed down we ended up with a dark matter scaffolding. The Universe's structure formed with the dark matter first and then the visible matter fell into this dark matter set of large-scale structure shapes.

Fraser: This is a fairly new understanding, isn't it? I know that in the past people always assumed it was just the regular matter that was coming together.

Pamela: And now we're finding out that our Universe is almost entirely made of stuff we can't see or understand. It's this invisible dark stuff that only interacts through gravity, as near as we can tell, that really lead the charge in forming structures.

It was kind of weird preparing for this particular show because I was pulling out my graduate school textbooks and realising, "yeah, I can't use these anymore, they're way too out of date." I just finished grad school in 2002.

Fraser: Wrong, this is wrong, that's out of date…

Pamela: Exactly. So, Yeah. Our new understanding paints a picture of dark matter leading the charge into forming structures into which the visible matter began to fall. As the visible matter fell into these gravity wells of dark matter, exactly how it formed is still a little bit up to debate. There are a couple of different models. The one model is you ended up with giant things forming first and fragmenting, the other is you ended up with little things forming first and falling together. That's really the picture we're starting to understand is most likely correct most if not all of the time.

Fraser: When you say "little things coming together" we're still at the point where all there is, is this dark matter scaffolding and hydrogen and helium coalescing into big clouds?

Pamela: You have these big clouds of hydrogen and helium and within the big clouds you have stars starting to collapse out and you have as the stars are collapsing out you also have densities of stars that are all together.

The question is: are these densities of stars that are collapsing together Milky Way-sized clumps of matter that is all sort of gravitationally bound together and slowly collapsing down into a disk or do you have a bunch of smaller things, perhaps things the size of the Large and Small Magellenic Clouds (two nearby irregular galaxies)?

What we're thinking is happening is we most likely started off with small, odd-shaped things that were irregular galaxies that came together, and as they came together, slowly built up the larger galaxies like the one we live in today.

You start off with this smooth density of hydrogen and helium that's just completely neutral, not doing anything except hanging out being dark. Gravitationally, the places that are just a wee bit denser start to suck the stuff around them in toward them. The dark matter dominates this and it creates big gravity wells that the luminous matter can fall into. As the luminous matter falls in, you start getting star formation and the stars are forming in small, deformed groups – baby galaxies, irregular galaxies, that over time merge together into larger and larger groups until we had things that looked like the modern galaxies that we're used to seeing today.

Fraser: So can you give us some details about how this process goes from that first regular galaxy?

Pamela: As the regular galaxies come together what matters most is how they fall together. If you have them falling together at just the right set of angles, you can build up a spiral galaxy. You end up with a collapsing blob of galaxies that are falling together in much the same way that we've talked about stars forming. You have a large blob of material that, as it collapses, rotates and as it rotates it flattens out.

We currently think that the halos of galaxies, the big spheroid of stars that sort of diffusely surrounds us, forms first. These are the old stars, the metal-poor stars, the mostly-red stars. This is where the globular clusters like the cluster in Hercules that is so beautiful to look at through binoculars – all these things are in the halo. As those stars form and die and give off their materials, recycling heavier elements into this proto-galactic cloud, the disk continues to collapse and you end up with stars forming in successive generations in this disk that we live in today. So we live in the recycled materials that were created as the halo formed first and then the disk formed second.

Fraser: And how long would this process be taking?

Pamela: This process can actually take a couple billion years. It takes a long time to get all the material to come together, to collapse together. Stars can form over tens of thousands of years, but they're little tiny things. To get all the mass involved in a galaxy to go from a few irregular lumps of material that happen to be just falling toward each other to a nice, well-formed spiral galaxy takes lots and lots of time. Generations of stars come and go in the time it takes to form the Milky Way.

Fraser: What's the state of observing? I know that having those galaxies out one or two billion years after the Big Bang, that's 11 or 12 billion light years away from us. How far can Hubble and some of the other big telescopes see? Can they see the process in action?

Pamela: We're just now starting to catch glimpses of the first deformed, star-forming galaxies that are forming at the very beginning of this period of the Universe lighting up. They're hard to find, and of course what we're going to find first are the most massive ones that are forming. The more typical situations, the smaller galaxies that are forming are too faint for us to get to right now. Instead we see the most ginormous of all the galaxies forming. Those aren't necessarily all going to turn into pretty spiral galaxies. If you get too much stuff all coming together at once, all of the different angular momentums, all of the different velocities in a lot of different directions can end up forming, instead, an elliptical galaxy. So we can end up with lots of different shapes of galaxies depending on how the parts, the little galaxies come together to eventually build up a bigger galaxy.

Fraser: Let's talk about those different kinds of galaxies then. What kinds of galaxies can you end up with, what have astronomers found so far in the night sky?

Pamela: Hubble, who's probably responsible for more bits of our modern understanding of the Universe, more labels than just about anyone else, started off –

Fraser: -- the person not the telescope?

Pamela: -- The person not the telescope – Hubble was actually a person. Back in the 1920's and 30s and even before that, he catalogued everything that he could and looked for patterns. In looking at what were originally classified as nebula, (and he later, actually, was one of the ones who figured it were separate galaxies) he looked strictly at their shapes.

He said things that looked like perfectly round blobs were elliptical of type 0 galaxies. E0 galaxies. So, you end up with completely round blobs of stars. These can be many, many times the size of our own Milky Way Galaxy. These can also end up with elongated spheroids. I guess there you have just plain elliptical shape. If you have a flattened hotdog of a galaxy that is round and has no disk, we call that an E6 galaxy. You can also get pretty much a flat disk that doesn't have any arms in it. We refer to these as S0, these are also lenticular galaxies.

Then you start getting into the spiral galaxies. These are galaxies that are often the most photogenic. If you look out, we have the Whirlpool Galaxy, which has two very clear spiral arms. Our own galaxy is a spiral galaxy. But these spiral galaxies can be broken up into a lot of different sub-categories. You can break them up according to how tightly wound their arms are. If you look at a spiral galaxy and it looks like its desperately trying to hug itself with its own arms, those are going to be spiral type A galaxies. If instead, it looks like they're flinging their arms out like a whirling dervish trying to shred everything around them as they spin madly, those are Sc galaxies; intermediate wrapped arms, those are Sb galaxies.

Not only do you get spiral structures, but sometimes you get weird other structures in spiral galaxies. Some spiral galaxies have a bar that goes across the centre, so you have the nucleus of the galaxy, then you have these bars extending out and then the spiral arms actually appear to come off the ends of the bars.

Fraser: That's what we have for the Milky Way, right?

Pamela: That's exactly what our Milky Way looks like.

What's neat is some of these barred galaxies also have rings of stars in addition to just the arms, so you look at the galaxy and you see these normal arms, a bar cutting across the centre and then you can see rings sometimes in multiple locations in the same galaxy. We're going to have pictures of all of this in the enhanced version of this show as well as in the show notes for this show.

Fraser: Now what causes the different shapes? Why do you get a barred spiral with the distinct bar across the middle, as opposed to a different one where the spirals go all the way into the centre?

Pamela: You have to look at just what is causing these spiral patterns to crop up. Here the physics gets kind of hard to deal with. We have what are called spiral density waves: if you start off with a perfectly smooth disk of stars and just let it go, you're going to keep a perfectly smooth density of stars.

If somewhere in the disk of the galaxy you have an area that just has a few more stars than other areas of the disk, then those stars are going to gravitationally pull in other material. They're going to pull in clouds of gas, they're going to pull in other stars and they're going to build up an area that has a greater density than others. Over time, these densities will cause stars to come toward them and speed up into them and then slow down as they pass through this dense area. As the stars try and move away from the spiral density wave, they're going to stay slow as they try and move away.

So, as stars orbit around a spiral galaxy, they're going to end up lingering in these over-density regions. It's these over-densities that we see as the spiral arms. What's really neat is these spiral arms actually trigger star formation, because as clouds of gas come into the over-density, into the spiral density wave, they get compressed and this can trigger them to collapse. You also can end up with material piling up in the arms and as they collide with one another they collapse and all these different things trigger star formation.

Fraser: I'm going to see if I understand this one. These parts along the spiral density waves in the galactic disk, these are regions where matter is taking a break, slowing down as it passes through it, but these aren't permanent locations of stars, so if I understand correctly, are the spiral arms almost like a wave in a pool or say you're looking at a football game and people are standing up and sitting back down again as the wave moves across the stadium? Does that make sense?

Pamela: That's exactly the way to look at it. Another way to look at it is to think of a traffic jam. If you look at an aerial shot of where there's perhaps a fender-bender on the highway, human beings for strange reasons, naturally slow down to say "oh no, that person bumped up their bumper, that person burst their radiator" As they go by the traffic jam, they slow down and cars pile up around the fender bender just to see what's happening. So as you look from overhead you'll see a large density of cars near the fender-bender and then lower densities ahead up the road and further back behind the fender-bender on the road.

Fraser: But it's different cars involved in the slow down at any given time. Right. I did not know that. I think, normally I play the fool but in this situation I had no idea – I always thought those were just the stars that were always there and part of the spiral arms. The fact that different stars are taking up that position over time is really interesting.

Pamela: What's really cool is you can look at galaxies in different colours and actually directly see how this is happening. In general, blue stars are very young, a star that is bright blue can't live very long because it's burning really hot and it's going to burn through its fuel very quickly. So if you look at a spiral galaxy using a blue filter so you see predominately blue light, you're going to see the arms are very tight, they're nice, beautiful, narrow blue arms in a well formed "Grand Design" spiral galaxy.

If instead you look at that exact same galaxy in red, so that you're seeing mostly old stars, old stars are predominately red and cool. Then you're going to see these arms are much broader because the stars have had time to travel further away and we're seeing the stars that are starting to fall in and starting to move away. The blue stars just really never have a chance to get away from the arms.

Fraser: So they do get stuck.

Pamela: They do get stuck, and they die before they get a chance to leave.

Fraser: So they're born in this density wave and they die before the wave passes them.

Pamela: Or before they pass the wave.

Fraser: Right. I guess they're large enough that they explode as a supernova.

Pamela: Exactly, and that can actually trigger more star formation.

Fraser: Is that one of the places where people have seen most supernova? If want to look for supernova look in the spiral arms?

Pamela: Exactly. You look in the star-forming regions of any galaxy and that's where you're most likely to see a supernova from a type II. These are supernova from giant young stars exploding. If you're looking instead for the type of supernova that occurs when a white dwarf explodes, those can actually be seen absolutely anywhere. So, you look for different types of supernova in different places.

Fraser: So what causes those bars, then? Why does the spiral come all the way in and why do you get the bar first?

Pamela: With the bar, you end up with the stars enter into different types of resonances. Often these are set up when something falls into the galaxy. When it falls into the galaxy, it adds all sorts of weird velocity orbits. These weird velocity orbits can end up resonating with one another until you end up with a bar. The thing is, this bar's gravity ends up attracting gas and dust to fall into the centre of the galaxy. If the amount of material in the centre of the galaxy increases, it pulls on the bar and destroys the bar. So these are very transitory things that are set up by something probably falling into the galaxy that sets up these really neat, funky resonances that cause the orbits of the stars to line up into this bar and then the way they line up pulls on gas and dust, sucks it into the centre of the galaxy. That change in distribution then pulls on the bar and destroys the bar.

Fraser: So the bar is temporary?

Pamela: It's totally temporary. Our own bar probably results from the Milky Way galaxy eating some other little galaxy and over time that bar is going to destroy itself.

Fraser: What is the relationship between the galaxy and the supermassive black hole in the middle? That's got to have some effect on the galaxy.

Pamela: This is a chicken and the egg problem. As we look out at other galaxies, we're systematically finding black holes at the centre of pretty much every system we look at. The size of these black holes seems to be directly related to the velocities of the stars in the spheroid around the centre of the galaxy. So, if you look at our own Milky Way, we have this bulge in the centre. If you look at an elliptical galaxy, it's all bulge.

When you start looking at the velocities of the stars in these bulges, these spheroids, some of them are moving kind of slow, some are moving really fast, and those velocities and the supermassive black hole in the centre are directly related to one another.

Fraser: So the more velocity you get, the more massive the supermassive black hole you're going to get?

Pamela: Exactly. The problem is, we don't know which is a consequence of which. We don't know if the velocities just lead to things piling up to form the black hole – we're not quite sure how you get everything there.

Fraser: But do those two always go hand in hand?

Pamela: Those two always seem to be going hand in hand. This is a very new area of study. We just started finding direct evidence for supermassive black holes in the centre of galaxies at the beginning of this brand new century that we're in. So, as we look around, we're still trying to sort out our completely new understandings. People had been speculating that there were supermassive black holes at the centre of galaxies for decades. But the evidence wasn't there with certainty. Now we have it, thanks to Hubble and thanks to some really spectacular ground-based observations. Now we have to figure out how to put all of the pieces together.

The pieces most likely come from "small things form, they pile up mass in the centre, that mass becomes black holes" or you start off with a black hole and it collects matter around it. You then collide these things together and heavy mass centres are going to fall toward one another and eventually combine. You combine those with something bigger, their heavy mass objects in the centre eventually combine.

We also have predictions that say sometimes when you collide things together, perhaps one of the supermassive black holes escapes and goes flying through the Universe on its own direction, by itself, without anything around it. If that happens now and then, why is it that we consistently see supermassive black holes that have masses directly related to the velocity dispersion of the stars? So we're still figuring out what's going on. It's all quite confusing and fascinating. We're learning.

Fraser: We see those supermassive black holes as quasars?

Pamela: A quasar is a reflection of a supermassive black hole. Not all supermassive black holes are quasars. All quasars, however, do show that there's a supermassive black hole there.

A quasar is a quasi-stellar object. If you look around the sky you see lots of things that are small, perfect point sources. We think they're all stars, but occasionally when you look at this thing that looks like a star through a telescope and you measure its velocity, you realise "oh dear, I'm looking at something going so fast it can't possibly be inside the Milky Way Galaxy". And in fact, it's going so fast that the velocity can only come from seeing something that's extremely far away being carried away by the expansion of the Universe.

So these point-source objects are actually galaxies out toward the edge of the Universe, the edge of the visible Universe, that we're seeing far back in time, that are racing away from us because of the expansion of the Universe.

These point sources of light are just the centres of galaxies that contain a black hole that is madly feeding on in-falling gas and dust. As it madly feeds, that gas and dust lights up and we see that illuminated core and we often can't see any of the rest of the galaxy.

Quasars exist primarily in the early Universe, probably because there was a lot more gas and dust around back then to fall into the centres of newly forming galaxies. Today we still see things that are physically similar (we believe) to quasars. These are Active Galactic Nuclei. In some cases you look out at galaxies that are colliding and the gas and dust plunging into the centres of these colliding systems lights up and you get an active galaxy. In other cases you look at a galaxy that has just finished consuming another galaxy and there's still gas and dust pouring into its core lighting up. These Active Galactic Nuclei are the modern day, not quite so bright but still physically similar in how they work, versions of the quasar.

Fraser: Is it possible that our galaxy could get a quasar at some point?

Pamela: Getting a quasar is a little bit hard because we've used up a lot of gas and dust, but when we collide with the Andromeda Galaxy someday in the future it's pretty certain that we will become an Active Galactic Nuclei. The core of our galaxy, as it merges with the core of the Andromeda Galaxy and all sorts of wild fireworks take place, will probably cause in fact it *will* cause an Active Galactic Nuclei to emerge.

Fraser: I'd like to talk about some strange galaxies, because we've seen the spirals, we've seen irregular galaxies, but there are some weirder galaxies out there.

[laughter]

Can you give us some examples of those?

Pamela: There's this really great looking system called The Antennae that is one of my personal favourites because the way it looks is probably very similar to the way we and Andromeda will look when we start to collide. This is two spiral galaxies in the process of merging together and as they merge, their arms are getting twisted in weird directions and the parts of the galaxies that are colliding with each other are getting compressed. There are all sorts of shocks triggering star formation – it's really a twisted up train-wreck of two spiral galaxies forming something new.

There was a really great catalogue of weird looking galaxies put together by a man named Arp, who did really spectacular observational astronomy, took amazing photographs of very faint, hard to observe objects. He catalogued all sorts of galaxy collisions. All sorts of galaxies in some cases that were just getting distorted as they hit the dark matter halos of their objects. That's one of the really cool things about galaxy collisions: you can see the distortions begin to occur in the visible matter before the visible matter actually starts to touch each other between two systems. The visible matter and the dark matter interact and the visible matter gets pushed around by things we can't even see.

Fraser: I hate to say this, but we're out of time and we're only half way through the stuff we want to talk about.

[laughter]

So we're going to have to stretch this out to next week.

Pamela: Well, that works!

Fraser: Let's wrap up galaxy formation here, and then next week let's talk about the even bigger structures in the Universe – galaxy clusters and how galaxies are madly colliding with one another and what the future holds.

Pamela: That sounds great to me. So we've gone from a almost completely smooth Universe of neutral, opaque, boring gas, to small things forming that merge to form larger things that led to beautiful spiral galaxies and large elliptical galaxies – and now we have those starting to collide and we get twisted galaxies. Next week we'll put all of this in the context of the environment that this is happening in.

Fraser: And find out about some of the biggest things in the Universe.

Pamela: Exactly.

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