Astronomy Cast Episode 97:
Galaxies

Fraser Cain: This week we are going to look at some of the biggest objects in the Universe: galaxies. It was the discovery of galaxies in the early 20th century that helped astronomers realize just how big the Universe is and how far away everything is.

They learned how galaxies formed, how they evolved and changed over time, merging with their neighbors and what the future holds. Now, you know a lot about galaxies, don't you Pamela? This is like one of your specialties, right?

Dr. Pamela Gay: It's one of my areas of research. I did my Master's Thesis studying the Ursa Minor Dwarf Spheroidal Galaxy which is one of the smallest ones out there and deciding to mix it up a bit for my dissertation, I worked on studying galaxy clusters.

Currently I'm working on a project with a graduate student and Chris Lintott of Galaxy Zoo among other things to study galaxy clusters in the Sloan Digital Sky Survey.

Fraser: Crazy.

Pamela: They're fun.

Fraser: Well, let's start with a galaxy that we're fairly familiar with, Milky Way, and then see how we got here from there over the lifetime of the Universe. [Laughter] So can you give us some dimensions of the galaxy that we live in and then we'll go from there?

Pamela: Our giant galaxy wasn't always one beautiful, glorious spiral system. It actually started out once upon a time as a lot of smaller galaxies, elliptical galaxies of various forms that emerged out of the small irregularities in what we now see as the cosmic microwave background. These small galaxies merged together. Gravity pulled them together.

Because different sections of the Universe tended to have motions that were in similar directions, you ended up with a lot of things coming together and joining in a way that they ended up spinning a lot like pizza dough that gets thrown into the air is spinning. That spinning motion caused them as they collapsed and coalesced together to form a disk of material.

Fraser: So, after the Big Bang, we have these irregularities in the density of everything that remained. Material started to pool together, turned into stars. The stars were gravitationally attracted to each other and formed little irregular blobs of stars.

Those blobs came together into larger and larger collections. After enough of them came together, if you added up all the motions of all the stars, you ended up with this spin and that's how they disked out, right as opposed to being a bit of a ball.

Pamela: Most of the way there. There's one curiosity though. We don't know which formed first, the galaxy or the stars. There were these pockets, dark matter halos of gas and material that we believe started to collapse and form the dwarf galaxies. At the same time, these pockets of material are solidifying out of the murk of the Universe.

These stars started forming inside the pockets. So, the galaxy just sort of came together all at once with the stars forming in these pockets. You ended up with an entire galaxy of star formations.

Fraser: Wasn't the dark matter almost acting like a funnel?

Pamela: A box.

Fraser: A box, yeah. That was the dark matter. Once that was in place, that's what pushed all of the matter and pulled it all together to form the structures that we see. With all the dark matter it all would have just flown away, right?

Pamela: One of the crazy things about the Universe is that while we're pretty sure that galaxies like our own Milky Way formed from a whole bunch of small galaxies that formed independently and then gravitationally merged to form the Milky Way, we think that some of the largest galaxies in the Universe formed in situ as they were giants from the beginning.

That's kinda cool to think about that the largest irregularities in the original stuff of the Universe just sat there and said "Hi, I'm going to be a giant galaxy".

Fraser: Right and that's kind of overturning a lot of the thinking which as you mentioned with the Milky Way was merge, merge. Small galaxies coming together, bigger, bigger and bigger until you get like a big classic spiral.

With the dark matter doing the pushing of the material together, you could just get it all coming together in one fell swoop.

Pamela: What's crazy is just to watch how all this has evolved in just the past ten years. When I was a graduate student taking classes on galaxies we talked about if it was a top down or a bottom up approach or do you get big thing and big thing forms. Or, do you get a bunch of small things that fall together.

Now we're realizing it's not an either or, it's an and where at the very beginning of the Universe you did end up with this giant galaxy forming in one place. And you ended up with smaller galaxies forming that merged to form progressively larger structures that eventually formed more giant galaxies.

Fraser: So as we got to the point where the galaxy has spun up and has flattened itself out into a disk. Where would that have been in the history of the Milky Way?

Pamela: Timing we're still trying to sort out. As we look back at larger and larger red-shifts, we see things start to lose their structure. We're not sure at exactly what moment spiral galaxies started to turn on but it was probably in the first few billion years of the Universe.

As we start to get new telescopes like the James Webb Space Telescope, we'll be able to peer at the earlier moments of the Universe with greater clarity and be able to determine at what moment in time when you look in the infrared you see galaxies that are fragmented in structure or irregular in structure.

As you look at things that are more and more recent at a given point in time spiral structure starts to turn on. We're still sorting out when in time you ended up with pretty spirals.

Fraser: But I recall writing stories where the age of that keeps getting set earlier and earlier.

Pamela: This is the crazy thing. This is why I'm hedging saying anything because the James Webb isn't there to answer it for us yet. As we get more and more high resolution images coming out of various telescopes and spacecraft, we're starting to find that galaxies formed earlier than we thought and giant galaxies formed earlier than we thought.

I think that this is something that any number that is in your textbook you shouldn't believe until James Webb has had a good look at the Universe.

Fraser: Right, we'll just add this to the list of textbooks that are wrong. Lies my textbook told me. [Laughter]

Pamela: What's cool though, as we look back we're finding these theories we've had are proving to be true. As we look back in time we see the irregular galaxies. We see the smaller galaxies. We see the star formation that gets triggered with them coming together and shaken up through the collision.

Our understanding is proving itself to be true and that's always a good thing. I really like the fact that this is an 'and' which means the two theories that we were all forced to learn in graduate school were not a waste of our time.

Fraser: So they could both be right. Galaxies could form zip or they could be the slow accumulation of material over long periods of time.

Pamela: And that's just cool.

Fraser: And we do know that there is this slow accumulation because the Milky Way is in the process of consuming neighbors today.

Pamela: Yeah. The Sagittarius Dwarf Spheroidal Galaxy is in the process of being actively consumed by the disk of the Milky Way. As we look out with surveys like the Sloan Digital Sky Survey and map out the densities of stars in the halo of the galaxy it seems like at every big science conference there is the announcement of a new tidal stream. A new stream of stars representing the death of a dwarf galaxy is being found in the halo of the Milky Way.

Fraser: And this is when they look out and see a whole bunch of stars that all have kinda the same age and all the same kind of chemical constituents and assume that they all started as part of the same galaxy and if it's arrayed in a big long line that says tidal tail.

Pamela: Basically what's happened with these systems is you have a small blob of stars. In some cases they have no more mass than the pretty globular clusters some of you probably look at with your telescopes. Some of them aren't all that much bigger than say M13 except when you start counting the dark matter.

In terms of stars, they're not that much bigger but they have a lot of dark matter in them. These small blobs of stars with a lot of dark matter in them as they orbit around our galaxy, some of them have death spirals.

At a certain point as they get closer and closer to the center of the Milky Way, the gravitational pull on the leading edge of the galaxy that is falling in and the gravitational pull on the far side of that galaxy the difference between the pull on these two points is greater than the gravitational force holding that cluster together.

You can sort of imagine that you're pulling on the front edge of a piece of pie that is sitting on the counter and is not in an aluminum plate. If you yank too hard on that piecrust, you will get a handful of pie because you pulled harder than the molecular bonds of that pie held the pie together. What you've done is disrupted the pie.

As that spiral galaxy that is meeting its doom falls toward the Milky Way, the Milky Way's gravity reaches out and grabs the leading edge of that galaxy and gives it a good yank and disrupts the galaxy. This disruption leads to these beautiful tidal tails. These beautiful streams that are the relics of what used to be systems and over time the stars in those tidal tails are going to fall into the

Milky Way and be randomly distributed such that you'll no longer be able to see that this group of stars used to be one galaxy. Instead you'll just see a thicker halo of stars around the Milky Way.

Fraser: But wouldn't the addition of all these galaxies that are likely going in completely different directions sort of mess up the Milky Way's beautiful spiral? Wouldn't at some point you would just get a mixture of directions?

Pamela: Well, this is where you have to look at all the different parts the galaxy has. In fact, the in fall does affect the Milky Way in rather dramatic ways. When it comes to simply disrupting the pretty spiral structure the mass that's falling in isn't that much.

When you compare the size of a dwarf galaxy that might have a few thousand or tens of thousands of stars compared to the Milky Way with its billions of stars, looking out, we're not going to see more than perhaps the nucleus of the Milky Way gets a little bit bigger and a little bit bigger. What we do end up seeing that is quite dramatic is systems that have larger companion galaxies that are contemplating death. Like our large and small Magellanic Clouds. These larger nearby neighbors can generate all sorts of really cool features in a disk galaxy.

We talked about this in an earlier show. In our own Milky Way Galaxy, we have a bar at the center of the galaxy. If you could get outside of the Milky Way and look down you would see nucleus and coming off the nucleus a straight line. Off the ends of this line is where the arms finally emerge.

Structures like bars or rings in the center of galaxies are all generated by nearby companions. You see the same thing with M51, the whirlpool galaxy. So the in falling companions can generate neat features. They also can cause the disk of a galaxy to warp. When you look at a disk galaxy and you see the disk isn't flat but is rather twisted sort of like a sheet blowing in the wind.

Fraser: I've seen lots of those pictures of the warped disks. It kinda looks like someone left a record out in the sun for too long and it has this tweaked warp to it. [Laughter] Now what are some of the things that happen to galaxies as these mergers start to happen? I know there are bursts of star formation…..

Pamela: It all depends on the size of the system that is being eaten. If you just have a little dwarf galaxy coming in most of these systems have no gas or dust. Mostly what they have to contribute are senior citizens stars and dark matter. We're not going to notice the dark matter except by the rate at which stars end up rotating around the Milky Way. Things start going a little bit faster. That's the biggest difference. The stars coming in, yeah we now have some extra stars in the halo but it really doesn't do much.

Where it starts getting cool is where we are getting larger and larger galaxies falling in. As we start getting larger dwarf spiral galaxies instead of these little baby dwarf spheroidals, or you start getting irregular galaxies like large and small Magellanic Clouds hitting the halo of the Milky Way, it shocks the gas and dust in these systems and starts triggering star formation. You can end up with elliptical galaxies that are bright blue with star formation.

You can end up with knotty systems where you have pockets of nebulas and stars all mixed together in this heap that has no noticeable structure of any sort, no spirals, no nothing and they look absolutely incredible.

The most spectacular objects in the Universe are nebulas and colliding galaxies. If you take a baby galaxy and collide it with a big one and you get both nebulas and star formation. This is what makes large and small Magellanic Clouds so cool to look at.

Fraser: How much star formation will go on compared to just like a normal galaxy is?

Pamela: It depends on how much gas and dust is in the system that's colliding. When the Milky Way and Andromeda somewhere in about five to seven billion years get around to knocking each other about in their gravitational dance, all of a sudden all the gas and dust that is left will simultaneously start forming stars or fall into the super massive black holes at the centers of our two systems.

You will get simultaneously angry feeding black holes and star formation that can be hundreds and hundreds of times greater than what we normally experience. You'll end up with Super Nova going off. You'll end up with black holes, potentially jets, radioactivity…it will be spectacular to look at.

Exactly how big, bad and bright things get we have yet to figure out. If you look at the Mice, one of the more prominently featured in images, sets of colliding galaxies, that system may not be too different than what we're going to experience.

Fraser: The Mice is a pair of colliding galaxies, right?

Pamela: Two spiral systems not too different from our own that have been imaged by just about everything. There is a really cool catalog of galaxies called the Arp Catalog of Peculiar Galaxies that contains a lot of colliding systems and the Mice are one of the systems in there. They've been followed up over the decade since including by the Hubble Space Telescope.

Fraser: What does the future hold? We look out into the Universe and we're only really looking back in time because light takes time to travel and so everything we see is like this great big time machine that lets us see back. But, what does the future hold for the large spiral galaxies in general?

Pamela: Well in general, everything dies. That's the sad part of astronomy. We have all these magnificent events where the physics is just hard to take in with the energies, the temperatures and everything that's going on and all of it leads to one result: the end of star formation.

After the Milky Way and Andromeda collide there will be a terrific burst of star formation. Afterwards all the fuel will be used up. All of the building materials will be used up. Because our spiral galaxy and the Andromeda spiral galaxy aren't spiraling in the same direction, the collision is going to throw together a lot of stars with very different orbital paths. We will end up eventually forming an elliptical galaxy.

Eventually we'll probably end up colliding with more galaxies the size of our own forming an even bigger elliptical galaxy. As we look out at some of the denser regions of space, galaxy clusters, and groups bigger than our local group in some cases groups that contain thousands of galaxies what we see is interactions between galaxies always lead to death.

It doesn't always have to be a head on collision like we get with Andromeda. You can also have just random friendly blue galaxy bright with star formation, friendly with spiral structure falling into a rich galaxy cluster. As it falls in, this rich galaxy cluster has so much mass that all the galaxies in it are moving rapidly.

About every billion years it might end up with another galaxy blowing past it at high velocity. Even though the two systems don't collide, the gravitational tug of the other system will yank stars, gas and dust out of the friendly little blue galaxy and its blueness will fade to red as it loses the dust and gas necessary to form stars. Its spiral structure will go away, all these gravitational whacks destroys its structure.

Eventually as it plunges into the densest regions of the cluster where you end up with basically, as far as the Universe is concerned, thick gas in the center of the cluster, just the shock of hitting that gas will kill whatever star formation was left. In just a few billion years you can kill a galaxy.

Fraser: Right, so you force a galaxy to just use up all of its fuel in one great big burst of star formation or you blow its fuel out the…[Laughter]

Pamela: Out the wazoo!

Fraser: Yeah. If you impact it with something else, you can separate the gas from the galaxy itself. The point is you use up all of its fuel and there can be no new stars and then all of the really massive stars detonate a super nova or die quickly. All you are left with are the red stars.

So, that's what we see then these big, huge balls of stars, many times the mass of the Milky Way. They are balls of stars because they have added up all the random motions of all the galaxies and they haven't flattened out into a disk and they're red. All they have is just old red dwarf stars left, right?

Pamela: And lurking at the center of these giant elliptical galaxies are giant super massive black holes. And in some cases, M87 is one of the most famous cases, the gas and dust of an entire cluster as it settles toward the center of the cluster.

Sitting in the center of that cluster is often a very special type of elliptical galaxy that we call a CD galaxy (for lack of creativity). The CD galaxy may be alive with an active black hole in the center that is spewing jets of material out of the two ends. The shock from these jets hitting the gas and dust that is settled into the center of the cluster heats that material up.

As you start to look at the Universe with our x-ray glasses, we look out using Swift, using all the different x-ray imaging telescopes out there, what we end up seeing are knots of gas that are many thousands of degrees in temperature emitting x-rays. This really hot gas can never coalesce back into stars or anything that would allow structure to form.

Over time, the Universe will cool and over time, this gas and dust might be able to do something useful on its way to probably landing in a super-massive black hole. But for now it's just hot and sitting there emitting x-rays. It's in a place that it was stripped out of the galaxies and is no longer useful fuel or building materials.

Fraser: Were there any kinds of galaxies out there that we haven't talked about yet that people might want to know about?

Pamela: Well, the main classifications of galaxies are elliptical, lenticular galaxies, which are galaxies with identity crises. They're basically disks of stars that have lost spiral structure and then you focus your telescope and realize there is no structure, flat pancakes with no structure.

Then there are the spiral galaxies, the ones that are the most photogenic with their arms. There are the irregulars that I talked about. They have gotten whacked pretty hard and have massive structure.

It's when you start looking at the sub-classes of these objects that you start to get really cool things. There is what is called Seifert galaxies that have active black holes in the center and are giving off lots of radio light. We can look at these things and in some cases see pretty cool radio jets, radio in the center.

What we think is happening is the black hole in the center is actively feeding and as it's feeding it's giving off emission. How we see that emission depends on what angle we view the galaxy at. If we're looking straight down the top of the galaxy, looking in at the anger super massive black hole, we see one set of radio emissions. If we see the whole system edge on, we see something entirely different. So we call these Seifert one and Seifert two – for lack of creativity.

Fraser: Isn't another name for that a Quasar?

Pamela: This is where we start getting into what are the gradients? There are all sorts of different galaxies that fall into the category of active galaxy. The Seifert one and Seifert two aren't as powerful as a quasar. We think they're a family of objects. We're still working on unifying all of our different understandings as we start to get more space-based telescopes and get higher resolution telescopes here on the Earth.

Quasars are really actively feeding black holes. Such that when you look at them, the nucleus of the galaxy appears to be brighter than the entire rest of the galaxy. In some cases that nucleus is so much brighter that as we look at the system we just can't get at "where is the galaxy surrounding this nucleus." This is also why they're also called quasi-stellar objects - QSO because they appear as point sources in a lot of images.

Fraser: Well, we'll to a whole show just on Quasars. [Laughter] Don't give everything away.

Pamela: If you then have a black hole that's a little less energetic in how much it's eating, that's where you start to get down to radio galaxies that aren't quite as active. You have the Seifert ones, the Seifert twos that are probably the same physics of what we call quasars, but there are different emission lines that appear. There are different properties, cut-offs in the amount of radio emission that come out. This is where we start getting to the actual use of the words radio loud.

As we look at these systems, there are lots of different characteristics and we're still building a unified picture of taking the same object and looking at it sideways and head-on, these are the differences you see, versus "these are two different things and the physics in them is intrinsically different." We're still sorting all those bits out.

The Universe is cool. It has lots of unanswered questions. As you start looking at the Universe and galaxies in particular across radio x-ray and optical light and bringing in the infra-red for flavor, one galaxy can look dramatically different in all these different wavelengths.

Fraser: I want to touch on something that we've talked about already is what role does dark matter play on this? It seems that since dark matter was first discovered, it's been playing more and more of a role in galaxy formation and evolution and everything.

Pamela: This is where we struggle. We know that the luminous matter in galaxies is embedded in what we call dark matter halos. We're still sorting out what is the density profile. Is it denser in the center? How does it fall off? Is it denser on the outsides?

We're starting to get a feel for these things. There are lots of pretty plots that show how the luminous matter falls off. Here's how the dark matter is distributed through the system. We have a feel for these things. What's cool is we're also finding that you can have a glob of dark matter that doesn't have a luminous matter in it. We find that through gravitational lensing.

All luminous galaxies have dark matter halos but it's possible that there are also just blobs of dark matter hanging out by their lonesome without any stars embedded inside of them. These dark matter halos probably formed first. Their gravitational attraction caused the luminous matter that might not have had quite as lumpy a distribution.

We're still sorting out how all of this works, how is it that the dark matter is formed first. These dark matter halos then collected luminous matter in their centers. What's fascinating is not all systems have the same ratio of light matter, luminous matter to dark matter. As you look at the dwarf Spheroidal galaxies, they have much more dark matter. As we look at the larger systems, they have less. We don't know why.

Part of it could be that Super Nova blasted all of the gas out of the dwarf galaxies but why is the dark matter still there? It doesn't interact, that's part of the answer. But why did they form with all of this dark matter to begin with? We don't know all of these answers. We're getting at facts and once we have accumulated enough facts, the theorists can start figuring out what it all means.

For now we're going out and when we see something, we measure the ratio of luminous matter to dark matter there. We continue the process as more are found. Let's in detail map out what rate are the things we can see moving as a function of radius of galaxies. How fast are the stars in the centers of galaxies moving compared to those a third of the way out or half way out or at the very edges?

Making all of these measurements allows us to get luminous matter to dark matter ratios to get the distribution of dark matter as a function of radius. As we look at all of these factors for more and more different shapes and sizes of galaxies, hopefully we'll be able to figure out where all of this stuff came from.

Fraser: Right, but I think it sure seems like just because we can only see regular matter, we can only see the luminous matter, we focus on that. But it's almost like some alien or advanced culture would say dark matter is what you think about. [Laughter] The luminous stuff is just the pesky crumbs around the dark matter which is the serious thing to think about. Okay, I hope that gives our audience the overview of the galaxies.

I think we'll do a show on the Milky Way specifically and Quasars as well in coming weeks. I think we can then focus on them. Quasars and the Seifert Galaxies are so interesting topics about what is going on at the very heart of our galaxies.

Pamela: So, from Mars to the Milky Way. [Laughter] That's a good journey.

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