GALAXIES - Curated Transcript of BBC In Our Time podcast

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In Our Time is hosted by Melvyn Bragg. Melvyn's guests on this podcast are:

John Gribbin, Visiting Fellow in Astronomy at the University of Sussex;

Carolin Crawford, Royal Society University Research Fellow at the Institute of Astronomy at Cambridge;

Robert Kennicutt, Plumian Professor of Astronomy and Experimental Philosophy at the University of Cambridge.

Transcript:

[Melvyn Bragg] Hello. Ours is about 100,000 light years across. It's shaped like a fried egg, and we travel inside it at approximately 220 kilometres per second. The nearest one to us is much smaller and is nicknamed the "Sagittarius Dwarf". But the one down the road, called Andromeda, is just as large as ours, and in ten billion years, we'll probably crash into it. I'm talking about galaxies, the vast islands in space of staggering beauty and even more staggering dimension. But galaxies aren't simply there to adorn the universe. They house much of its visible matter and maintain the stars in a constant cycle of creation and destruction. But why do the galaxies exist? How have they evolved? And what lies at the center of a galaxy to make the stars dance around it at such colossal speeds? With me to discuss galaxies are John Gribbin, Visiting Fellow in Astronomy at the University of Sussex; Carolin Crawford, Royal Society University Research Fellow at the Institute of Astronomy at Cambridge and Robert Kennicutt, Plumian Professor of Astronomy and Experimental Philosophy at the University of Cambridge.

[Melvyn Bragg] John Gribbin, let's start with a simple definition. What's a galaxy? And what do galaxies consist of?

[John Gribbin] You've done it already... it's this flattened disc of stars. When we look up at the sky... if you're in the darkest place on earth, on a perfectly cloud free night, if you're very lucky, you might see a thousand or two [thousand] stars and you think that's big, that that's a big universe. You also see this band of light across the sky called the Milky Way. And if you turn a telescope on the Milky Way, you can see that it's made up of millions and millions and millions of stars, and that's looking at this disc of stars from the inside. So we're part of this system that's got well over 100 billion stars in this flattened disk 100,000 light years across, and that's just one island in space. And then there's emptiness as far as bright objects are concerned, until you get to other islands in space. And in very round numbers, we know about as many galaxies as there are stars in our galaxy. So there are a hundred billion or a few hundred billion galaxies containing each 100 billion or a few hundred billion stars. And it's an awesome insight into the size of the universe that we are just part of one of these little islands.

[Melvyn Bragg] I find it totally impossible to get my head around those numbers, John. I mean, I'm not doubting you for one second, but what do you do about numbers like that? It's almost a silly question. What would you do about it? Do you sit down and put another 400 billion?

[John Gribbin] Well, the way I look at these things is in terms of distances and time. I think that's how I personally get a handle on what's going on. And when you talk about something being 100,000 light years across, that doesn't mean much. But literally it means that light takes a hundred thousand years to get from one side to the other. And we know it takes a few minutes to get to us from the sun. So that gives you some idea of the scale compared with the distance from us to the sun. Space is big and galaxies are big.

[Melvyn Bragg] What do they consist of, galaxies?

[John Gribbin] The obvious feature is the bright stars. I mean, all the stars we see in the sky are part of our Milky Way galaxy. But there's a lot of stuff between the stars as well that we know about. There are dark clouds of dust and gas that we can see because they block out light from stars behind them. And so you can see how the starlight's affected as it passes through this material. And then something that you've talked about previously on this program, I mean, there's also other stuff that we can't see, there's dark matter that we know is there because of gravity and the way it affects galaxies. But the important thing, as far as we're concerned, as far as human beings are concerned, is that it's stars. It's an island of stars plus the material that stars are made of. So new stars are constantly being made in galaxies like our own, and old stars are dying and as part of that process, the sun and the solar system and ourselves have come into existence. So we're very much part of this whole dynamic system.

[Melvyn Bragg] What types of galaxies are there out there?

[5:21]

[John Gribbin] There's a variety. I talked about our Milky Way galaxy, which gets its name from the Milky Way, obviously, as a flattened disc system that sometimes are called "spiral galaxies" because many of them have a very pretty pattern of spiral arms, as they're called, trailing around them. But they don't all have that, so "disc galaxies" is a better name. There are bigger galaxies that are called "ellipticals", that are shaped rather like a rugby ball or american football, and they don't have this disc structure. And then with sort of characteristic carelessness, astronomers call the rest "irregular". It's the ones you can't fit into a category. You just call it irregular.

[Melvyn Bragg] Carolin, can we learn a bit more about our own galaxy? We are part of this massive project, the Milky Way. Can you go into more detail about the Milky Way, please?

[Carolin Crawford] Well, it's strange, given that we actually live in the center of the Milky Way and we live in this disc that John's described. So if you're fried egg model of the galaxy, we're somewhere about in the yolk, I'm sorry, in the white of the egg, about halfway out from the yolk to the outer edge of the fried egg. And even though it's our local galaxy, it's one of the hardest ones to know much about because we're right in the middle of it. The analogy often used is that if you're trying to build a map of a city when you're actually in the city, and the trouble with [our] galaxy is that you're seeing everything edge on, we get a much better view if we could go above the plane of our galaxy and look down on it. And what we expect we'd see is you've got this flattened disc. You've got a large bulge of old stars in the middle. And within the disk, you've probably about three spiral arms all winding out from this central bulge. And our address, if you want to know it, it's the "Local Orion Spur". We're just in a very minor spiral arm of the Milky Way. And again, you're talking about these big scales. It's still about 6000 light years to the next spiral arm within the disk. So we're very much a canonical spiral galaxy. Perhaps the bulge, if you like, the yolk of the fried egg in our galaxy is elongated into a bar and the spiral arms wind out from the ends of that bar.

[Melvyn Bragg] Why do we have these distinctive spiral arms? Can you just tell us, just get it absolutely clear so people know what these spiral arms are?

[Carolin Crawford] Well, the spiral arms are what make this galaxy so photogenic. And you see them in the disk because they're delineated by these fantastic bright, young blue stars. These are the sites of very current massive star formation within our galaxy. Now all the stars in the disk are rotating and the spiral arms give the sense, like a Catherine wheel of everything rotating.

[Melvyn Bragg] So a Catherine wheel is a useful image, is it?

[Carolin Crawford] Well, it can be a bit misleading because that spins a lot faster than a galaxy. I mean, the whole galaxy. The sun rotates once around the galaxy about every 250 million years. Again, you know, you said it's traveling 220 km/second it still takes us 250 million years to go once round. But anyway, back to the spiral arms. It's not the same stars in the spiral arms. You have to think of the spiral arms as, more or less, it's a region where you get, we call it, a sort of density wave or a compression wave that's traveling through the disc. You get some compression wave that travels through [and] compresses these gas clouds, that John's talked about, that lie between the stars and that triggers them to collapse under their own gravity and eventually go on and form stars which then light up the gas around them. So it's not like they're so obvious because they contain all the mass in the galaxy. It's just they're really prominent because they've got all…they're being lit up by these young stars and the gas that's around them.

[Melvyn Bragg] John talked about new stars being created. Are we in a position where this is happening? At what rate, in the Milky Way, in our galaxy, are stars being created?

[Carolin Crawford] They're being created all the time. I mean…

[Melvyn Bragg] What is all the time? I mean, in your time? I mean, time is important here because you think time is 100 million years or something. So what are they being created all the time?

[Carolin Crawford] Well, when I say a young star, of course, I mean one that's about a few million years old. I mean, in astronomical times that's young. I mean, everything is moving very slowly. So I guess in our human lifetimes it's still going to be a few million years for a gas cloud to collapse and then form a star, but it's still it's going on all the time within our galaxy.

[Melvyn Bragg] Robert Kennicut, as I understand it, galaxies rarely come alone, but they're in groups called "clusters" and even "superclusters". Does the Milky Way have any companions? Are we part, is the Milky Way part of a cluster?

[9:40]

[Robert Kennicutt] Galaxies do occasionally occur by themselves, but isolated galaxies are quite rare. In terms of the Milky Way, there's clustering on a whole multitude of scales, [it] has a ... swarm of companion galaxy satellites. The largest of these are the Clouds of Magellan that some of your listeners may have seen if they've ever been to the southern hemisphere. These galaxies are small, about one 20th the size of the Milky Way, and about 150,000 light years away, but that's comparable to the dimensions of the Milky Way itself. In addition, there are a series of dwarfs, about 20 little "dwarf galaxies". Each contains maybe tens of millions of stars. In absolute terms, that's enormous, but compared to the hundreds of billions of stars in the Milky Way, it's small. Then the Milky Way itself. This system of Milky Way and its satellites is in a larger clustering, a group of galaxies. Andromeda, which you mentioned earlier, is the largest of those members. It's about one and a half million light years away and it's slightly larger than the Milky Way. And Andromeda itself is surrounded by a swarm of companions.

[Melvyn Bragg] And how are we to imagine these clusters? How are we to imagine these clusters arranged across the universe, Robert?

[Robert Kennicutt] So let's continue this picture and step back a couple more steps. What we now know is if we look around the sky, that in fact the distribution of more distant galaxies isn't uniform in the sky. And in fact, we live in the periphery of a large cluster of galaxies. The center of that cluster is located in the direction of constellation Virgo. It's called the Virgo cluster. We're about 50 million light years, now, away from the center of that cluster, and there are maybe there are tens of thousands of galaxies in our collection, this what is called the supercluster. These clusters of galaxies are fairly common in the universe and over a wide range of scales. Now, finally, there's yet more. And that up to now, if you think in your mind's eye of this distribution, it's rather clumpy - roundish blobs of galaxies. But now if we step back and look on scales of hundreds of millions of light years and imagine in your mind's eye, a picture of the universe, this distribution stops becoming clumpy and it begins to take on the appearance of a network of spider webs. These clusters themselves are connected to one each other and the structures become rather filament or sheet like. It really does have the look of a spider's web from a distance, and then that structure propagates through the entire universe.

[Melvyn Bragg] The word "islands" has been used to describe this cluster, hasn't it? As if there are islands of galaxies with what seems like, but we now know is not very little between them - darkness, anyway. What we can't see between them, but we now know is full of matter and dark matter and dark energy. Is that useful, the idea of islands?

[Robert Kennicutt] That's right. It still has currency today, although we cannot see the dark matter and we have very little idea of what that stuff is in terms of particles, what kinds of particles they are. We know it's distributed like the light we see, so it follows the spider web pattern. And the material in between… islands is maybe a good analogy in the sense that, of course, on earth there's water between, there's an emptiness between the islands, there's water. In the case of the universe, the intergalactic space is not empty, it's full of gas and some dark matter. In fact, probably more material between the galaxies than in them, but spread out and rather difficult to observe, right now. We know it's there, but we can't look at it. We can't see it very well at this time.

[Melvyn Bragg] John Gribbin, do we have any idea how the galaxies were formed?

[John Gribbin] We have. I'm a little cautious about saying we're sure, because in my relatively short time in astronomy, our ideas have changed several times.

[Melvyn Bragg] From what to what? Just in a matter of interest…

[John Gribbin] Well, the particular, the most important thing is that there are two ways of looking at how things like galaxies might form, and one's called "top down" and one's called "bottom up". And you either start with a large cloud of material, whatever it might be, and it collapses and breaks up into smaller pieces and those pieces become galaxies, and within those pieces it breaks up and makes stars. Or you can imagine things happening the other way around where you've got some lump that's formed for whatever reason - I think we may get onto that later. And that lump has got gravity, so it pulls things towards itself. And so you start with a relatively small thing and you build bits upwards from there. And in principle, you could make galaxies either way, but it takes a lot longer to do it top down than it does from bottom up. And so at the moment, we think our best models are the bottom up models, and we think that very early in the life of the universe, concentrations of matter got together (and [we] still debate about exactly how that happened) so that you had something with a very strong gravitational pull which then held back other material as the universe expanded. And that's how these filaments and clusters and galaxies and eventually stars and people formed.

[Melvyn Bragg] Can we open up that lump a bit? I mean, when did… If we're going with the lump theory, the bottom up theory, if that's the one that you think is the prevailing theory at the moment, which may change of course, like other prevailing theories, but if we're going with that theory, when did that lump happen? And what is the lump? And why is the lump so effective? Can you just give us more detail?

[John Gribbin] Sure. The reason why we like the bottom up theory is because it happened very soon after the big bang, [Melvyn Bragg] Which is about 14 billion years ago....

[John Gribbin] ...People say 13.8 with some confidence, ...but 14 billion years ago and within a billion years now, with instruments like the Hubble telescope, you can photograph what look like galaxies so far away across the universe that the light has been traveling to us for about 13 billion years. So we see them as they were when the universe was a billion years old. And to get from what we think was a very smooth, not perfectly smooth, or it would never have formed anything, but a relatively smooth distribution of material coming out of the Big Bang to actually having galaxies in a billion years or so is tremendously fast. So something must have been concentrated in lumps very soon after the Big Bang. And almost certainly those lumps are black holes that formed very soon after the Big Bang from very large amounts of gas that collapsed and made very large stars, hundreds of times the amount of mass there is in the sun, which would then explode very quickly and make black holes. And the black holes held the rest of the material together and formed the seeds of galaxies.

[Melvyn Bragg] Can we go into black holes? Who wants to take this up? No? Right. Carolin, I turn to you because what's John's says there, I think, is something I want to know more about, and I'm assuming other people will, too. People generally think of black holes as everything's dumped in there. It goes away, and what a shame. But you're talking about black holes as driving something at the beginning, aren't you?

[John Gribbin] If it wasn't for black holes, we wouldn't be here, I think.

[Melvyn Bragg] Right. So, on that starting point, can you take us further into the black hole, Carolin, please?

[Carolin Crawford] Yes. Well, it's true. Even for our own galaxy, we think there's a black hole at the core of about 3 million times the mass of our sun. And again, it's not actively accreting at the minute. We know it's there because, as you said in your introduction, you see the motions of the stars nearby responding to its gravity, and that's how we know where it is and how much it weighs. But imagine a long time ago in the history of the universe, galaxies are young, they're accreting matter. These black holes are very active, and, yes, matter goes down the black hole, but it's not a totally efficient process. And there's lots of heat and there's lots of energy produced in the environments of the black hole, and that can actually escape and produce light and radiation in all wave bands. I mean, that's one of the key ways we know about active black holes in the early universe. You may have heard of things called "quasars", or "active galaxies". These are otherwise normal galaxies where you have a very active black hole in the center. So you've got all the light from all the stars in the galaxy, and you've also got this object at the center producing this prodigious amounts of radiation all the time. Now, when you map the active galaxies in the universe, you find there are very, very many more of them, like a thousand times more, in the earlier universe than there are now. So we think there's this crucial stage in the formation of all galaxies. They went through an active phase where the black hole was

...accreting, producing all this energy. And then it runs out of fuel in the center and gradually fades and dies. And nearly all the galaxies we look at now, if you look in the core, you find evidence for a dormant black hole at their center. So the crucial thing here is every galaxy went through a very active phase. And this is probably, as John says, a very important part of the actual formation of the galaxy.

[Melvyn Bragg] How did we discover black holes, given that they're black and they suck in light and they don't emit anything usually, I mean, how did people find out that there was a black hole?

[Carolin Crawford] Well, again, you've got to be careful. Yes, it's sucking in matter, but, you know, as matter gets accreted onto the black hole, there's a lot of friction. Stuff gets heated up, stuff produces light, produces radiation. You know, to be very clear, the radiation, the light you're seeing is from the immediate vicinity of the black hole. It's not the stuff that goes into the black hole. And so it's like a by-product of the black hole that you get all this light. It was first discovered, just from spiral galaxies, that had this enormously bright core. And from that reason, they began to think there was something extra going on in the center of them.

[Melvyn Bragg] Robert Kennicutt?

[19:28]

[Robert Kennicutt] Yeah, this is one of the most important, probably, discoveries that the Hubble telescope has made in the last ten years. Another way you can detect the presence of these very massive supermassive black holes is by measuring the effect of their gravity on the stars that orbit around the centers of galaxies. And what these measurements show is that these supermassive black holes are ubiquitous. They seem to be present in every large galaxy. And in fact, the size of the black hole seems to be related very closely to the size and mass of the galaxy itself. And that's what tells us, as John was mentioning, that it seems that the formation of galaxies and the formation of these black holes, must be be intimately connected.

[Melvyn Bragg] Sorry....just a second, John. Can I just plod through this ... just so that I get it straight in my head? And so you're saying that the black hole holds the galaxy together?

[Robert Kennicutt] That's actually a good question. No, it actually holds the center of the galaxy together. These black holes have a mass, if you would weigh them, of billions, well, hundreds of millions, and billions in the most massive case, solar masses. But they only represent typically one 10th of 1% of the mass of the galaxy as a whole. So they are very important. They dominate the motions... they dominate... they hold the galaxy together in its inner few-hundred light years. But in fact, it's the stars and the gas, the other stuff that John was talking about, that mainly holds the rest of the galaxy together.

[Melvyn Bragg] And where does dark matter fit in here? Will you say what you're going to say then? Unless the dark matter comes in...?

[John Gribbin] It's something very simple. But just to make it clear that there's nothing particularly clever about working out the mass of a black hole, as long as you can see the stars going around it. And if you imagine that the sun was dark, was black, and all you could see were planets, you know, the sun was there because the earth is going round in an orbit, it must be going around something, and it's just the same thing. You can actually see stars and trace their orbits going around the middle of our galaxy. So that's how you know that there's something dark and massive there. And you also know there's something dark and massive in the outside of the galaxy because of the way it rotates, it's quite clear that all disk galaxies, like ours, are being held in the grip of something that is much more extended and has a strong gravitational field, which is holding the whole disk together and making it rotate the way it does. If there was nothing outside the bright bit of the Milky Way galaxy, and galaxies like the Milky Way, then the outer parts would rotate much more slowly, and there's something holding onto them and making them rotate faster than they should be and that's the dark matter.

[Melvyn Bragg] The dark matter, because we've got... we can see this, but we can see about four or 5% of the universe, something like that. The rest is dark matter, dark energy and these black holes. What part? And we're very, as I understand you, not me, I'm the one still very tentative about notions of what that is... that dark matter, what part does that play in the formation and the distribution of the galaxies that we've been talking about, Robert?

[Robert Kennicutt] Yeah, well, I think, first it's worth saying that you're exactly right. The matter that we know about, the protons and neutrons and electrons, the hydrogen and the helium, the chemicals we know about, make up about 4% of all this matter-energy in the universe. We really don't know much about the other 96%, and that's rather humbling. Of that... the dark matter makes up about ... 25% to 30%. We know a few things about it. We know that it clumps in the universe in the same way that the stars and the gas do. We know something about what is called the "power spectrum", the way that it initially was distributed in the universe, and we know what it is not. We know it can't be protons, electrons, neutrons, what we call "baryons", [and] probably not leptons. It's probably a form of subatomic particle that is yet to be observed in nuclear accelerators, but some of which have been postulated theoretically. There are searches underway in laboratories - the Large Hadronic Collider that's being built in Switzerland by CERN, if we are lucky, may detect some of these alleged particles. And, of course, as we learn more about the structure of the universe, we will learn more about the properties of this dark matter. But it is a form of matter that is very difficult to observe.

[Melvyn Bragg] Carolin, you touched earlier on the...I rather skidded over it... the difference between black holes that can be "active" or "dormant". Can you explain the difference? And what's the significance of the difference between the active and the dormant black holes?

[Carolin Crawford] Well, the active, when I say an active black hole; it's one that's still accreting matter from its surroundings. The dormant black hole; it's still there. Once you've built a supermassive black hole, it still lurks about. You never get rid of it. It just maybe has exhausted all its surrounding fuel and it's no longer sucking stuff in and producing all this energy and radiation around it. And that's the case in the nearby universe for many of the galaxies. One thing that is interesting is that you might be able to restart the activity in a black hole. And sometimes, galaxies, they get pulled together by mutual gravitational attraction, again, you mentioned this in your introduction about the Milky Way in the Andromeda, perhaps another 6000 million years [in the future] they are due to have a head on collision. When we see galaxies smashing into each other like this.. and one of the side effects of that, maybe you get a lot of this stars and gas between the galaxies funneled onto the black holes that they cause. And this may be a way of restarting this activity and sort of flaring up at the centers of nearby galaxies when they interact like that. So mostly in the nearby universe, completely quiet, completely dormant. It just needs some kind of extraordinary circumstance to just kind-of jog them into a fuel supply and wake them up again.

[Melvyn Bragg] John Gribbin, can you explain to us galaxies are, in a sense, star factories? Can you tell us how stars are produced and destroyed?

[John Gribbin] Yes. I think it's worth mentioning that this process that Carolin was talking about maybe how elliptical galaxies are made, that you have spiral disc galaxies colliding and all their stars merge and get jumbled up. And that's why you get these different kinds of galaxies in the universe. And what you also see in those collisions very often is a very active process of star formation because… the gas and dust gets stirred up and gravity gets a chance to pull clouds of material together. And what's happening in a galaxy like our own is a very steady process of star formation. I think the rate works out at something like one star a year, if you average it out, that one star a year is being born in our galaxy.

[Melvyn Bragg] You mean a normal year, not one of your…

[John Gribbin] In an actual - 365 day - [year], you know, there's a new star born and one dies roughly once a year, it either just collapses and dies of old age or it explodes as a supernova, something like that.

[Melvyn Bragg] That suggests a symmetrical steady state notion, which is …

[John Gribbin] It's very nearly a steady state. What's happening is that gradually the material is being used up. There's a lot of material. So it takes a very long time to use it all up. But on any, not even the human timescale, even on the time scale of a star like the sun, you know, a few billion years, a galaxy like the Milky Way, unless it happens to collide with something else, will look the same externally. It will just be different stars that are being born, and they're born in these spiral arms that Carolin talked about, and then they go on their way round and go through the process of life and death and throw out material, and then new stars are born from that material.

[Melvyn Bragg] Robert Kennicutt, the Milky Way is about how old? I mean, say we're 14 billion years old, since the whole began, however it began, maybe somebody said something…[laughter]… And when did the Milky Way come into existence? And do galaxies evolve? So it's a double question. Yeah.

[Robert Kennicutt] So the oldest star we have age dated the oldest stars in the Milky Way. They are out in the outermost halo of the galaxy and in the yolk of the egg, in your analogy…[laughter]

[Melvyn Bragg] That's a good one, I nicked it from John Gribbin.

[Robert Kennicutt] It's a good one, I will use it myself. And they appear to be almost as old as the universe itself within a billion years. And that's about the precision, it's the limit of the precision with which we can measure these things these days. So they form shortly after the universe itself formed. And as John said, it's a challenge, theoretically, to understand how it can happen that quickly.

[Melvyn Bragg] So the Milky Way, sorry, ... if it's 14 [billion years old]… the Milky Way is about twelve? ...

[Robert Kennicutt] Oh, 13. I would say 13 out of 14 if you knew it around numbers. So 13 out of 14 in this 14 ...billion year old universe. Now, you have to get in this modern paradigm, though… remember that galaxy formation is not one event. In fact, there are stars falling in to the Milky Way as we speak. Another galaxy, the Sagittarius Dwarf [Galaxy], is being consumed by the Milky Way. One of these merger processes that we talk about is taking place in our own ... Milky Way right now. And in that sense, you could argue that the formation of the Milky Way is not yet completed. But most of the material, we think, came together about 13 billion years ago. And as John said, the stars making up the round portion of the galaxy probably mostly formed in the next billion years after that. So by about 12 billion years ago, the central component of our Milky Way had formed, and stars in the disk have been forming uniformly since that time.

[Melvyn Bragg] John and Carolin have talked about the spiral shape and elaborated, and I think we've got the hang of that now, the arms coming out and so on, the Catherine wheel was invoked and then rejected. But we're getting the idea of that. Do galaxies change in size and shape over the time? Let's just talk about one of many billions [of galaxies] the little matter of the Milky Way. Does it change? Can it change radically what's going on there?

[Robert Kennicutt] It can, and different galaxies have different histories in this regard. The change can be radical. For example, if two spiral galaxies merge with one another, those two spirals can transform themselves into an elliptical, a rugby-ball-shaped galaxy, a complete transformation. And in fact, we believe, for example, that in the very, very distant future, the Andromeda galaxy and the Milky Way will suffer such a merger. So what are now two beautiful spirals will eventually merge. We are talking about tens and tens of billions of years in the future, but they will merge and form an elliptical [galaxy]. For most other galaxies, the changes are subtle. There are two sorts of processes. One are accretion of companion galaxies or these mergers

[Melvyn Bragg] Like swallowing the Sagittarius Dwarf...

[Robert Kennicutt] That's right. Swallowing our companions. So eventually, the Milky Way will swallow the Magellanic Clouds, the Clouds of Magellan as well. There's another class of processes called nowadays, "secular" evolution processes. And those are processes in which the Milky Way even left to itself because of the spiral structure and internal dynamical processes, those spiral arms will gradually change the form of the galaxy. And particular gas and stars can migrate to the center.

[Melvyn Bragg] And just a little digression. All driven and driven by gravity, John.

[John Gribbin] Yes, it's all gravity. Gravity is what makes the stars, makes the galaxies.

[Melvyn Bragg] So Newton got it right?

[John Gribbin] He certainly did.

[Melvyn Bragg] Carolin, can I come to the history of the understanding of the universe, as it were? And it's not as in terms of real understanding. It's quite short in your terms, it's a millisecond. But the first person, as we think, to see a galaxy for what it was was Galileo. What did he see and what did he conclude from it? And why was that important?

[Carolin Crawford] Well, the key thing about Galileo was that he was using this new discovery, the telescope, and he was turning it on the heavens and discovering all these wonderful things like the moons around Jupiter and Saturn. But one of the other things he did is he looked at this arching band of light that John alluded to at the beginning that is our galaxy. Now, with the naked eye, you just see this very sort of dilute light, sort of cloudy light in the sky. The key thing he did is to actually turn his telescope to that and actually begin to separate it out into individual stars. To the naked eye, all these thousands of stars, their light is blended, and this is why it looks so diffuse. But he actually saw that it was made of all these thousands and thousands of stars. And that's the first sort of concept of this being this big island or this big collection of stars together.

[Melvyn Bragg] And we begin to enter the phase which is from [the] Tenaissance to now, where technology, which advances in fits and starts. But technology begins to drive the issue. Robert Kennicutt, at the beginning of the 20th century, with the better telescopes and people began to ask whether some of the stars that they were seeing belong to different galaxies. Because the idea was the Milky Way.... was the universe. I hope I'm being right all, I'm being brief right now. What was... there was a great debate between Harlow Shapley and Herber Curtis. Is that right? And what was the great debate in the 1920s, and what was each one of them saying?

[Robert Kennicutt] This was a debate held at the National Academy of Sciences in the United States about whether we lived in an island universe. In fact, the term island universe dates from this generation. Or whether these other smudges like Andromeda, these other collections of objects in the sky, were Milky Ways themselves. And so the debate was held at that time. The evidence was highly circumstantial, and it was not a decisive debate.

[Melvyn Bragg] Is that because of the level of technology?

[Robert Kennicutt] That's correct. The large enough telescopes were not available. Shapley had made, prior to that debate, a major contribution to the entire problem, however, by measuring the size of our Milky Way for the first time, using a set of variable stars whose brightness can be well calibrated as a yardstick. And it was Shapley who demonstrated how vast this island universe of the Milky Way was. But in fact, it was he who argued the proposition that, in fact, everything that we saw in the sky was part of the Milky Way. Curtis believed, in fact, in the modern view, that we were but one of billions of galaxies. But the evidence was based on photographs, and that all changed in the mid 1920s.

[Melvyn Bragg] Can you tell us about the change? So this argument at the time that it was held, because it's interesting, isn't it, the history of the... It was evenly balanced, as I understand it from what I've been reading about this between Shapley and Curtis... Either, to put it at its simplest, the Milky Way was everything, or...what we saw was just a bit further away, but still part of the Milky Way, which was everything. Or ...[that] much else was going on outside ...[of the Milky Way]. Now, how was that resolved, John Gribbin? Because it was resolved quite soon after that debate from much the same evidence...?

[John Gribbin] It was exactly the same evidence, but with better technology. It was the same kind of stars, these variable stars, that from the way they vary, you can work out how bright they are, and then from how dim they look, you can work out how far away they are. And first of all, they were used to map the Milky Way. And then as the technology improved, it became possible to detect these individual stars in what it turned out to be other galaxies.

[Melvyn Bragg] Enter Edwin Hubble...

[John Gribbin] And that was Hubble and his colleague Milton Humason, who often doesn't get the credit he deserves for doing the hard work...

[Melvyn Bragg] Well he does now....

[John Gribbin] They were able to measure the variability of these stars in, first of all, galaxies, like the Andromeda galaxy, relatively nearby.

[Melvyn Bragg] What did change? How were they able to measure it? When people as good as we've heard from Robert,

[John Gribbin] They had a bigger and better telescope. It was the telescopes that came in in California at the end of the second decade of the 20th century. They had just about the technology to photograph these stars. But it was incredibly painstaking work. It involved actually sitting in the dome of these things, open on top of a mountain, very cold nights, exposing photographic plates, not film, big glass plates, for a very, very long time. And although there was some automatic tracking, the observer actually had to sit there and make sure the telescope was pointing at the right place all the time because they weren't perfect. And then you wouldn't even get an exposure in one night. You might have to put that plate away, seal it up in a box in the dark, take the glass plate, lock it away, wait till the next night, come out in the dark, take the same plate out, put it back in the plate holder on the telescope, in exactly the same place, pointed at exactly the same galaxy, and expose it for another four or five hours before you could get these very faint images.

[Melvyn Bragg] So, so we're talking about ...the so-called technicians who mandate telescopes are crucial to this. Absolutely. They're not even, not even thought of, not nowhere on the list.

[John Gribbin] That's right. And that's where Humason came from. He worked his way up, literally from being a janitor to being a technician, till it turned out that he had this...ability to get these perfect photographs after a very long time. And Hubble was presented as the brains of the outfit, if you like, and he did the interpretation and presented the evidence. But the guy who actually sat there in the freezing cold getting the pictures was Humason.

[Melvyn Bragg] The word "red shift" came in about that time, didn't it? Carolin, can you tell us about red shift and why it is important in all this?

[Carolin Crawford] Well, red shift is the way that astronomers measure how fast something's moving, well, in this case, for redshift, away from you, and there are certain characteristic features in the light of galaxies. And again, this is another one of Edwin Hubble's fantastic discoveries was that when you look at the light from galaxies, you find all these features are shifted to the red. So it's analogous to the Doppler effect. If things are shifted to the red, it means that everything's moving away from you, and, in fact, all the galaxies are receding away from us. And so this red shift means that something's moving away from you. This is due to the expansion of the whole universe. And if something's...the further something is away from you, the faster it's moving. And this is, you know, Hubble's canonical law that the distance and the velocity are related. So, for astronomers, red shift is an incredibly useful term because it tells us how far away something is from us. You measure the redshift, you see how fast it's moving...you say it's part of this overall expansion. From that, you can work out how far away something is.

[Melvyn Bragg] So, as I understand it, Robert, the two radical things happened in the twenties which have radically changed...[our views]. One was that the discovery was made of external galaxies. Then away you go. You go into your billions, which we started, and secondly, that the universe is expanding at a rapid rate. Now, when did these two things, I mean, how did the world of persons like yourself, 50 years ago as it were, take that with incredulity, or what happened? What happened with that knowledge?

[Robert Kennicutt] I could tell you how the professional astronomers took it. The first discovery of the variable stars in Andromeda by Hubble was embraced immediately by the community. And I think both discoveries were stunning. They made the popular press at the time. I could add to what Carolin said is this Hubble Law, as it's called, this proportionality between the red shift and the distance to a galaxy is the signature of an explosion. It's precisely the relation you would have if anything in space exploded. The pieces that flew out at the highest speed will recede the farthest distance in a given time. And in fact, unlike some of the more recent discoveries of dark energy and so on, which took a few years, I think, to gain acceptance even within the professional communities, I think both of these discoveries were recognized almost instantly for their importance.

[Melvyn Bragg] And what else can we draw from these two discoveries, John? Do we draw the fact that therefore has to be a Big Bang?

[John Gribbin] That's the crucial thing. I mean, there was for a time, especially in the 1950s, a very respectable alternative, that the universe was in what's called a steady state and that it didn't have a beginning, that it's always, if you think of something that's infinitely big, it can expand, and it's still infinitely big, and it always was. And you would then have to have new material created in the gaps between the galaxies to maintain the overall appearance. And really, that's no worse than having everything created, or whatever you want to call it, in one go in the Big Bang. But the evidence soon showed that the universe has changed as time has passed. And so we're now very confident that there was a beginning. And if you know how fast things are moving apart, then you can work out how long ago it was when they were all gathered together in one place. So that's how we know the age of the universe and that there was a beginning, and everything else follows from that.

[Melvyn Bragg] Are we on the brink, Robert Kennicutt, of any discovery or revelation of anything as dramatic as those two?

[Robert Kennicutt] We hope so. Of course, if I could make such predictions with accuracy...

[Melvyn Bragg] You wouldn't be on this program. You'd be back in the laboratory, writing...[laughter]

[Robert Kennicutt] That's right. However, we think it's going to be a very exciting decade ahead. Earlier in the program, we talked about the very first stages of the formation of galaxies in the first billion years of the universe. We can look back quite far now. With instruments like Hubble, we can see galaxies that as they were within 2 billion years after the Big Bang. But even, as John said, even those galaxies are relatively mature. We know that their progenitors remain to be seen, but we need a more powerful instrument. And the next successor to Hubble is called the James Webb Space Telescope, a very large infrared telescope we hope will be launched early in the next decade. It is designed to try to see what we call first light in the universe, the signature of the first stars, first galaxies, and perhaps first black holes.

[Melvyn Bragg] Is it too trivial... Carolin, you would say something..It saves me asking the trivial question. [laughter]

[Carolin Crawford] I just wanted to add what Robert's saying. He's saying we need to look for these very first galaxies and see where they really do fit this sort of clumpy, bottom-up scenario. The other crucial thing that's going to happen is dark matter. We've talked about how it's so important to our whole understanding. This is the main mass component of our galaxy, ... and that's the gravity that holds the galaxy together. If you're going to build realistic models of galaxy formation. You need to know what the dark matter is and how it's distributed and just its very fundamental nature. And hopefully with the Large Hadron Collider we mentioned coming in line, we can understand more about particle physics and thats going to illuminate what we understand about dark matter.

[Melvyn Bragg] John?

[John Gribbin] I think its important to realise ... these big questions when astronomers and physicists and scientists in general are testing their current ideas, they actually hope to be proved wrong. It would be very boring if it turned out that everything fitted this picture we've been describing. The exciting thing will be if it turns out that in the first billion years, something happened that we've not even imagined yet, and that will be really exciting.

[Melvyn Bragg] Well, that's a bit of a stunner, isn't it? Yes. My trivial question was what odds now about something happening simultaneously in other galaxies? I mean, four people sitting around a table talking their own galaxy and saying we might reach the Milky Way one of these days. But that's just to fill in 15 seconds to tell you the truth, because your answers are so interesting that I don't want to abbreviate them. Thank you very much to all of you for being on... Thank you for listening.
