Astronomy Cast Episode 58:
Inflation

Fraser: We interrupt this tour through the solar system to bring you a special show to deal with one of our most complicated subjects: the big bang. Specifically, how it's possible that the universe could've expanded faster than the speed of light. The theory is called the inflationary theory, and the evidence is mounting to support it.

Einstein said nothing could move faster than the speed of light, and yet astronomers think the universe expanded from a microscopic spec to become larger than the solar system in a fraction of a second.

Pamela, can you sort all that out?

Pamela: It's all a matter of what is doing the moving. The idea is relative to the grid of space, I cannot move faster than the speed of light. I personally can't get anywhere near the speed of light, but even the fastest, smallest particles – the things that can get the closest to going the speed of light, can't ever go faster than it, relative to space.

Now, if instead space itself grows, that's something different. One way to think about it is: imagine you have a little kid who is walking away from school on his way home. The little kid's capable of moving at, say, four sidewalk blocks every couple of seconds. He can't go any faster than that. His family might see him moving toward the house at four sidewalk blocks a second – no big deal. He's going his typical speed.

Imagine there's some crazy sidewalk builder building a hill of sidewalk blocks between him and the school. As the school watches, they see not just his motion but also all these new sidewalk blocks getting built.

Imagine that crazy sidewalk block-building machine is building sidewalk blocks at a rate of 10 sidewalk blocks every couple of seconds. As those new blocks appear between the school and the child, you now have the expansion of the sidewalk and the rate the kid is moving, added together.

So the school might see the kid moving at 14 sidewalk blocks every couple of seconds. That kid is moving faster than he's allowed to go – but he's not. It's the sidewalk that's growing not the kid that's moving relative to the sidewalk. So you get these weird additive velocities coming in that cause things to be perceived as moving faster than they're allowed to move. They're not – it's space moving instead.

Fraser: Isn't that the kind of argument that people have with relativity? Let's say I'm moving at close to the speed of light, and then I shine a light, and you're moving at close to the speed of light and you shine a light. We're moving toward each other, but even though we're both moving at close to the speed of light, your light is moving at the speed of light, and my light is moving at the speed of light, so it's all relative.

So wouldn't the light appear to be moving at the speed of light? It's just the underlying object that can be moving further.

Pamela: The weird things are happening to light during inflation. If you let a light wave go and it's trying to cover one meter of space – but that one meter of space grows, the wavelength of the light will grow. So as the universe expanded, it stretched out the light and made it redder. The light we see redshifted – in general when we're dealing with fairly nearby galaxies, that redshift is due to the movement of the galaxy. The same way you hear the pitch of the sirens of fire trucks/police cars change because of the motion of the vehicle.

With the expansion of the universe, as the light travels through space it's getting stretched out by the expansion of the universe.

Fraser: Okay, okay, we're getting ahead of ourselves here. Let's go back to the beginning here,

Pamela: Okay.

Fraser: Right to the beginning.

Pamela: Okay.

Fraser: and start with the big bang and re-describe the big bang. Last time I think we oversimplified it. Let's go into very nitty-gritty detail at least for the first few seconds,

Pamela: Okay.

Fraser: and explain what physicists now think happened.

Pamela: Okay. As we understand it – and we can't actually observe this no matter how big a telescope we ever build, because the cosmic microwave background is at time equalling roughly 300 thousand years, and we can never see beyond that.

Based on the evidence left in the universe from the big bang, we believe there's a moment in time from basically time equals roughly zero, to time equals 10^-33 seconds, during which the universe had these particles called inflatons that pushed everything apart. They pushed things apart so much that the universe expanded by a factor of 10^26 in that little, tiny instance, that little, tiny, bazillionth of a tiny second.

Fraser: So it started as a 10^-33. How much bigger did it get then? Is it still microscopic at this point?

Pamela: The universe started off at moment zero, as something so small we don't have a way to describe it. Then it doubled and doubled and doubled. It wasn't necessarily doing this at a linear rate – it was doing it at an exponential rate. We can't tell you exactly what the curve was, exactly if it stayed the same function the entire time – we don't have a way to get at that information observationally. From the estimates of what we can see in the universe around us, the scale size of the universe was roughly solar-system-like at the end of that 10^-33 of a second.

Fraser: That's a fraction of a second. Wow.

Pamela: At the end of this period, what happened was these inflatons, these particles that were driving the expansion, decayed. They gave off their energy to re-heat the universe.

During this frantic expansion, the universe cooled off.

Fraser: I wonder what percentage of the universe would've been – now we say X% of the universe is matter, X% is dark matter – what percentage of the early universe would've been inflatons and what would've been regular matter?

Pamela: I can't tell you how much of the universe was tied up in inflatons, how much was tied up in energy. A lot of the universe was just energy at that point because matter hadn't started to freeze out of the energy yet.

The energy stored in those inflatons we think was on the order of about 10^15 giga-electron-volts. That's a lot of energy, which then went into re-heating the universe. It was the heat from all of those decaying inflatons that went on to drive the formation of matter, the culmination of the first protons that formed into helium and trace amounts of lithium. All the energy that went into heating the universe up and making things exciting again came out of the decay of the inflatons.

Fraser: I guess I wonder if we get a particle smasher big enough, could we make inflatons?

Pamela: I think it would sort of require the energy reserves of the entire planet – so probably not. We struggle to make a lot of particles that are heavier than the quarks that make up your standard protons and neutrons in particle accelerators. They just don't like to fall out. They decay quickly. The speed that we have to accelerate protons up to during the collisions is very hard to achieve. The inflatons are a high-energy particle, so trying to get there from here… I don't think we're going to get there. Hopefully in the next year or so we'll find things like the Higgs-Boson that carries mass.

Fraser: That's another show.

Pamela: That's another show, but every time we find one of these theorized particles it starts to tell us the entire puzzle is correctly put together.

Fraser: Here's where you're going to have to back this up. This theory just sounds crazy.

Pamela: (laughter)

Fraser: Why on Earth would physicists come up with this in the first place?

Pamela: The main reason is when we go outside and look left and right, the universe, on average, looks the same in both directions. The light that's coming from the eastern horizon and the light coming from the western horizon, that are just reaching the planet Earth – that's light that hasn't had a chance to reach each other. While I can see an object that's 13 billion light years away to the east, and I can see an object that's 13 billion light years away to the west, those two objects can't see each other.

This means that they've never seen each other. When the universe formed, we'd expect that one chunk of universe might have one slight temperature after everything spreads out, another might have another temperature, they'll have a different distribution of lumpiness and bumpiness…. but they don't. Everywhere we look, if we look at a large enough chunk of space, it's exactly the same. The only way for everything to e exactly the same is for there to have been some point in time when everything was close enough together that it could communicate. Or, if everything is spread out so much, that any differences in the original distribution have been smoothed out.

Fraser: I could understand if you take two objects at different temperatures and put them next to each other, they're going to average out there temperatures, right?

Pamela: Mm-hmm.

Fraser: So is it the same kind of situation? At some point all of the mass in the universe (or all of the energy in the universe which later became mass) had to have been in roughly the same place to even out its temperatures?

Pamela: Or another way it could've happened is if you take small piece of Silly Putty and put it on your Sunday morning cartoons and pick it up, you can see Garfield (or whomever) staring back at you. If you stretch that silly putty out, the more you stretch it, the more Garfield grows until if you look at a one inch section of that silly putty, everything in that one inch section now looks about the same.

You might only be looking at one small piece of what used to be Garfield's eye. If you look at one small section, everything looks the same.

If you take a universe that originally had a mass distribution that looked like Garfield, and spread it out enough, if you look at a section the size of what we're able to see, that section might've just been one small piece that was too small to have had any irregularities – or they got flattened out so much that the bright and faint spots are really about the same thing because it's been spread out so much that the differences go away.

Fraser: If all the differences go away, why do we have galaxies, stars and planets? Why don't we just have a spray of particles?

Pamela: They didn't go away entirely. They went away enough that the large-scale differences that could've been there, that would've caused the eastern and western horizon to look radically different – like if you only had galaxies on one side and the other was an even distribution of dead stars – that level of large differences got smoothed out.

The small differences that led to galaxies, that led to stars, those were still there, just like you might see a single dot of the ink from the Sunday paper spread out – it got spread out, but that dot is still there.

Fraser: So who came up with this theory then?

Pamela: The theory was developed by Alan Guth originally, to try and explain the smoothness we see.

Fraser: That's the smoothness you're saying – look to the left, look to the right, the universe looks roughly similar.

Pamela: Right. Exactly how it worked – couldn't get there originally. But Alan Guth was the first one to put forth the idea that if you take the universe and blow it up fast enough at the very beginning, all the inhomogenities, all the differences, get smoothed out.

Fraser: Sorry to be labouring on this – it's already giving me a headache. If the big bang just happened as a linear expansion, then you would've gotten clumping of a large scale right away, and so we would've seen, say, off to the left all the matter in the universe and off to the right, nada.

Pamela: Right. Exactly.

Fraser: Okay. So Guth said there had to be some moment where somebody spread the universe out fast enough that it couldn't clump it, so we'd get smoothness.

Pamela: Yes. He couldn't really come up with a good mechanism for how this happened. He was originally trying to use arguments with bubble nucleation, quantum tunnelling and a whole bunch of really scary quantum mechanical particle physics, all combined together. It didn't work.

Andrei Lind and (separately and independently) Andres Albright and Paul Steinhart (and I apologise for destroying pronunciation of names), came out with a different model that basically said the universe was coupled to some sort of a scalar field. As that field changed energies, it drove this inflation, and that's where the inflaton comes in. the inflaton is the particle that coupled the universe to this field.

This isn't a completely strange idea. When we talk about gravity, we talk about the massive objects coming from the Higgs-Boson coupling objects, coupling atoms, coupling particles, to a scalar mass field-type thing.

With the inflaton, it's another model where we have the entire universe coupled to a field that is changing energy levels. It's this change in energy that's driving this amazing inflation very fast.

Fraser: So where do we stand now, then? We've got these revisions to it. Have the experimenters gotten their hands on it?

Pamela: Right now we're at the stage of "oh my god, this has really, really hard math, can this be true? Can this be right? Let's see what kind of predictions we can get out of it." It predicts there will be specific distributions in certain properties of the cosmic microwave background. When you look at the polarization of the light, when you look at the distribution of irregularities in the light of the cosmic microwave background, you should see certain things.

When we got the original data back from the Wilkinson Microwave Anisotropy Probe (WMAP), it looked like inflation might not quite work out. The data didn't fit exactly, but that was the first round of data. It was sort of like only making one measurement. If you only make one measurement, you can't know if it was right.

When, at the end of three years, they looked at the WMAP data, one of the things they looked at is how the photons are aligned. This is a quality called polarization.

Fraser: Sure, I remember that. We did an experiment in school where you'd have like a piece of Sunglasses and if you put it one way you could see the way – and you had two of them. One of them, if you twisted it, would only let certain photons polarized come through. If you twisted the two pieces of Sunglasses it would darken. So you could tell which way the light was coming.

Pamela: What's really cool is, if you take a piece of plastic, like a plastic spoon, and shine light through it, and then twist it so there's stress, the twisting causes light passing through the spoon to gain different polarizations.

There is an amazing mural at the Boston Museum of Science that if you just look up at it doesn't look like much. If you look at it through a polarizing lens, all sorts of details and features that you can't even see – faces, landscapes – appear in the polarized light.

Fraser: What causes different polarizations of light?

Pamela: It's often a scattering effect. If I take light of a whole bunch of different orientations, where the waves are up and down, left and right, and I shine it at a surface, the surface as the light reflects off of it will tend to preferentially cause the light to have a specific orientation. If you think about throwing your show at the ground, depending on if it hits with the shoe going in toe first or the shoe going in side first, it's going to bounce a different way.

Fraser: I've got an analogy for you. We even did this experiment in physics. If two of you are holding a rope and you do a wave up and down, and the waves are coming at you one way or you can do the wave side to side and the waves are coming at you sideways.

Pamela: That's exactly what the waves are doing, and how they reflect off of surfaces is going to depend on their orientation as the wave hits the surface.

Fraser: So different objects can generate light where the waves are going to be coming at you at different polarizations.

Pamela: So when we look at dusty objects we see specific polarizations. Like you said, sometimes the light being created has different polarizations.

Fraser: Why would different polarizations give them what they're looking for?

Pamela: The polarized light is a diagnostic of what the light went through. For instance, astronomers studying active galactic nuclei measure the polarization of the light coming off so they can better understand the conditions inside the galaxy.

When we look at polarization from the cosmic microwave background, we're trying to diagnose the conditions inside the early universe, what the light experienced in the moment right before the cosmic microwave background was formed because the temperature changed just enough that all of the atoms combined and the light flew free.

That polarization is one of the echoes of what the universe looked like before the cosmic microwave background formed.

Fraser: What did they find?

Pamela: They found that the universe wasn't exactly the same everywhere. Instead there were areas that were a little bit fainter, or a little bit brighter – there were small inhomogeneities. The inhomogeneities exactly matched what had been predicted in Andre Lind and Albrich's theories of inflation.

So we had a universe that was the same on large scales, but it did have pockets of differences that were still allowed to be there by inflation theory.

Fraser: So where did these pockets of differences come from?

Pamela: They come from slight differences in temperature that still existed after the inflation period. You had waves that were propagating through space, and these waves would cause areas that were a little bit denser or more thinned out. These waves were echoes going through the basically closed geometry of the early universe. Sound waves propagating through space creating pockets of resonances, pockets of different temperatures, is how it ended up coming out.

Fraser: So the only reason we exist, or that we have galaxies and planets, is slight differences in energy levels from the early universe?

Pamela: Slight differences in energy levels that were created during the first fractions of a second led to everything we know today.

Fraser: So it was like the different energy levels changed the amount of mass distribution and that allowed things to start clumping together and then you got stars and galaxies and so on. If there had been no differences, then it just would've been expansion of a smear of particles and that would've been that.

Pamela: If the densities had been bigger, everything would've clumped up into black holes. If the densities had been less, then everything would've been a smooth spray of pretty much nothing. What's cool is when we look at the cosmic microwave background, we see a distribution that corresponds to the distribution and structure we see in today's universe.

What we see today is directly reflected in what we see that was given off at 300 thousand years after the universe began. Today we're 13.7 billion years after the universe began.

This isn't the only evidence for inflation. We look at not just the smoothness of the universe, but the flatness of the universe. These are two very different terms, mathematically. Smoothness says that if I look east or west, it all looks the same. Flatness says that the geometry of space is Euclidean. It's like the geometry we learned in middle school and high school: straight lines stay parallel to one another, and it's just nice and balanced.

Fraser: Right, I remember we covered this in the show what the universe is expanding into. We talked about how if I fire light in one direction, and light that's 90 degrees to that, and they both go out to the edges of the universe, you can still measure that as a nice, square angle all the way out. It's not like they curve at some point. People were concerned it would curve at some point.

Or if I'm sitting on the Earth and shoot a line in one direction and a line in another direction, they don't actually remain at 90 degree angles because of the curvature of the Earth.

Pamela: Exactly. One of the things we find is we expect the curvature of space would change with time. One way to think of this is if one of us went and we stood on the Moon. It's a small planet – small moon, actually. It's a small, round object you can stand on. You can see the horizon. You can see the curvature of the moon much more readily than you can see the curvature of the planet Earth.

Even on Earth, if you have binoculars and you're watching a ship in the distance you can watch it come over the horizon sail first. You can see the curvature of the planet.

If you go to Jupiter, which is way bigger than the Earth and way bigger than the Moon, the curvature becomes much less evident. The bigger something is, the less evident you expect the curvature to be.

Fraser: Right, and the universe is the biggest.

Pamela: Yeah. So looking around today and seeing that today n the nearby universe, the geometry looks pretty flat, that's fine: the universe is big. As we look back further and further, we'd expect to see the curvature crop up. We'd expect to see evidence of the curvature in the cosmic microwave background if our universe had been happily continuing to expand at a fairly constant rate since a moment where it was the size of a spec to today.

Even by the point in time when the cosmic microwave background was given off, the universe was so big that on the scale of the cosmic microwave background that we're looking at, the slice of space we're looking at that was located close enough to us 13.7 billion minus 300 thousand light years back, that place was already so big that it appeared flat. The only way to get the universe big enough when the cosmic microwave background was emitted to appear flat, is to have inflation.

Fraser: All right, so we've got two lines of evidence. Two hard fought lines of evidence. Is there anything else?

Pamela: There's one more, and it's totally esoteric (and I love getting to use that word occasionally). There are these imagined particles that come from theorists called magnetic monopoles. In a lot of theories for how the universe was formed you end up generating magnetic monopoles, but we can't find the suckers.

A magnetic monopole is where you end up with either just a north pole or just a south pole of a magnet.

Fraser: Right. If you cut a magnet in half, the new pieces both have north and south poles.

Pamela: Yeah, they're just smaller.

Fraser: Right.

Pamela: If you ever really want to mess with a company, ask to buy only north magnets.

[laughter]

I don't recommend actually doing this, but I know someone who did.

Fraser: That'd be the easy way to find magnetic monopoles – just have them cut. There you go. Nobel price please!

[laughter]

Pamela: We can't find magnetic monopoles in nature, and we've looked. One of the ideas is they weren't formed in large numbers in the first moments of the universe. If the universe is small, then we'd expect there'd be a few of them within the observable universe. But if the universe is truly huge, which it can only be if there was inflation, then it might be that the universe is so big, and we can see such a small fraction of it, that the probability of one of those magnetic monopoles being in the part of the universe we can see, is so low that we might not expect to see one.

It's sort of like the idea of there are so few panda bears in china that if you randomly drop yourself in any one park, you're probably not going to see a wild panda bear. If panda bears were as common as squirrels, you could go anywhere and see one.

We're thinking magnetic monopoles are more like the panda bear, and we live in north America instead of in Asia, so we have no chance of seeing a panda bear.

Fraser: So what implication does this have, then, for the size of the universe? How big is the universe?

Pamela: We can see out to stuff that occurred out to 13.7 billion minus 300 thousand light years out.

Fraser: Right, so I can imagine there's a sphere we can see 13.7 billion light years in all directions. But that's not the size of the universe.

Pamela: We think we only see three or four percent of the total universe.

Fraser: As a matter of the universe's volume.

Pamela: Yeah.

Fraser: Wow.

Pamela: So we are just three or four percent. It's a big universe.

Fraser: There's parts we'll never see any of.

Pamela: Right, it's not getting any closer.

Fraser: Every year that goes by, I guess we see another light year of the universe, but that's not fast enough to catch up with the expansion.

What do you think the future holds for inflation specifically, on top of the big bang?

Pamela: There are some neat side-theories that come out of this. First of all, our universe is still accelerating itself apart. We have this dark energy stuff, and maybe it's a little bit related to what triggered inflation. Dark energy is causing an acceleration that's way, way, way smaller, but it's still there. Maybe they're somehow physically related. These are theories people are still exploring.

Andre Lind has also put forward the idea that maybe there were pockets of the universe where inflation finished earlier or later. Maybe the entire universe didn't stop inflating at the same time. This means that there could be bubbles of universe coming off of our universe. When you blow up a balloon that has a defect in it, and the defect causes a pocket that sticks out further than the rest of the balloon – maybe our universe has pockets like that.

We're trying to put the pieces together. Every time we find a new high energy particle, every time we make better observations of the cosmic microwave background, we are able to add more pieces to our puzzle.

Currently we have a puzzle that cosmology has been able to put together a lot of the pieces with observations. We have holes where we can look at it and know there's a piece that fits inside it. We name that piece and develop theories about what that piece should look like when we can put it in there. We're getting there, but there are still areas where there's a giant empty segment and we know there's a lot of physics we don't understand that fits in.

There's a new satellite going up, Planck. We're hoping that Planck, which will make even higher resolution images of the polarization of the cosmic microwave background will be able to confirm our theories to even greater detail. The more details we have, the more we have to fine-tune our theories. We can't say "it's within a factor of 10 of this", we end up having to say it's within a factor of 0.1 of this.

So we're looking for more data, we're looking for more particles, and we're fine-tuning our theories. Now we have this dark energy thing to try and explain as well.

Fraser: I know we're running long on this show and I think I'm going to give up trying to hold us at half an hour because it's just going to go and go, but as the last thing I want to go back to what brought this up. We got all these emails from people asking how you can move faster than the speed of light.

It's back to that thing where if you consider the universe as a stretchy fabric, it is allowed to expand, any two pieces on it are allowed to get away from each other faster than the speed of light.

Pamela: But those pieces can't move relative to space at faster than the speed of light.

Fraser: Right, it's the space itself that can do the expanding. So if I'm on one side of the space and you're on the other and we're expanding away from each other, we actually can be moving away from each other faster than the speed of light. But if we try to travel to each other, it still all has to go at or less than the speed f light.

Pamela: Yeah.

Fraser: So space itself and objects in space can be carried faster than the speed of light, but if you're going to try and move in space, then you have that speed limit.

Pamela: Yeah. It's hard to think about. The way I usually try and explain it is with a giant imaginary Xerox machine.

If you imagine that you're trying to move across a piece of paper that is getting stretched out by a Xerox machine that can magically blow up the piece of paper (instead of creating a second piece of paper), and you're moving along at a constant stride but the grid you're moving on keeps getting bigger and bigger and bigger, it appears you're moving faster than you actually are. That's only because the grid is changing, not because you're moving faster.

Fraser: So if any of you still wonder how it's possible objects can be expanding away from each other faster than the speed of light, send in your questions and we'll have another run at it.

I think that is a really good explanation of that one spot of the big bang cosmology. I know it's a pretty technical discussion, but hopefully when you hear that term you'll have a much better sense of what people are talking about.

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