Astronomy Cast Episode 6:

More Evidence for the Big Bang

Fraser Cain: So Pamela, last week we started out with the big bang and discussed the cosmic microwave background radiation. Now, if people still aren't convinced that the universe began as a singularity 13.7 billion years ago, and has been expanding ever since, fine. We've got more evidence: take your pick.

Okay Pamela, continue convincing us!

Dr. Pamela Gay: (laughing) Well, no one should be convinced by one line of evidence. It's sort of like when you go to buy a car, you don't simply trust the one opinion of the salesman who's trying to sell it to you. You always want to get multiple opinions, multiple lines of proof. With the big bang, we've got lots of lines of evidence.

For the most basic, you look out in space and as you look at objects further and further away, they appear to be older and older. This is a function of the fact that light travels at a finite speed. As you look out at different stars and examine them, we find the oldest stars out there have a certain percentage helium and a certain percentage deuterium that was set by the big bang. As you look at the sky at night, you can actually find places in the sky that are dark. Darkness is itself, in part evidence that points toward the big bang. So we have multiple lines of evidence we can discuss in detail.

Fraser: I counted three there.

Pamela: Well, three plus cosmic microwave background gives us four lines of proof.

Fraser: Perfect, four. So let's go back what's your first one?

Pamela: Why don't we start with just the basic idea that things are older as we look at things that are further and further away.

Light travels at a finite speed. This means that were we to turn the entire universe off, then using the big, giant god switch that turns the universe on and off, turn it back on, we'd initially just see ourselves. As time passed, we'd be able to see things further and further away. The first object we might see in the sky is the Moon. It's 1.282 light seconds away – so 1.282 seconds after we turn the universe back on, there's the moon staring back down at us.

Fraser: Okay, that's a relief!

Pamela: It's a relief. The Moon will be there very quickly.

Fraser: There will be no Sun, so we wouldn't see the Moon.

Pamela: The Sun would come in about eight minutes later, so we'd only have to wait a little bit before we got light. The irony here is we wouldn't actually see the Moon until we had the sunlight, because the sunlight needs to come and reflect off the Moon, but in some imaginary universe, where we can see using gravity, we might see the Moon, and then see the Sun eight minutes later.

Fraser: Okay, so we've got the Sun, we've got the Moon…

Pamela: Continue to wait. It's going to be a few years before we start to see the nearest stars. The Alpha Centauri system is 4.26 light years away, which means we'd have to wait 4.26 years before the Sun and the Moon were joined by a star in the sky. So you've got a long wait before you start being able to compare our Sun to other stars.

Now, the thing is, when we do get that light from Alpha Centauri, we're not seeing the way Alpha Centauri looks at the moment we're looking at it. Instead, we're seeing the way Alpha Centauri looked 4.26 years in the past. So if you live someplace where you can go out tonight and see Alpha Centauri, you're not seeing the way it looks tonight. You're seeing the way it looked some night 4.26 years ago.

Then, our galaxy would be a lonely place with no other galaxies to look at, for about 2 million years. The nearest galaxy – the nearest big, giant galaxy – is over 2 million light years away. You'd have to wait over 2 million years before that galaxy would finally become apparent in our skies.

So there's a lot of waiting going on, and a lot of seeing the way things used to look. As we continue to look out across the sky, if we look at an object a billion years in the past, we see an object that isn't exactly identical to the things we necessarily see today. Really big structures take time to form, so a billion years ago is fairly close to the way things are (there's big structures), but as you start to look further and further back in time, the number of big structures goes down. The number of perfectly formed galaxies goes down.

In the Hubble deep field, we're looking way back toward the first few billion years of the universe; we're seeing galaxies that don't look anything like what we see today. They're these weird, mutant structures. There's lots of star formation going on. These early galaxies appear to be very blue because young stars are predominately blue. As we look around galaxies nearest us, we see lots of red galaxies because old stars are predominately red. So the universe even changes colour as we look back in time.

By seeing at greater and greater distances, younger and younger objects, it implies that if you could look back far enough, you'd see a newborn universe. That's sort of what we see with the cosmic microwave background.

Fraser: Right, and that's what we were talking about last week with the cosmic microwave background radiation.

Pamela: So the cosmic microwave background radiation is just the earliest structures in the universe, traced out on a large scale across the sky. As we look in all directions, those small irregularities we see in the temperature, those small irregularities grew up over time to be the largest galaxies and galaxy clusters that we see in our nearby modern universe. As we look back through time, we see the evolution of those structures from the irregularities in the background, to the giant galaxy clusters.

We see the galaxies evolving from these small, blue, mutant things, to the spiral galaxies of today, to the giant red elliptical galaxies of today. It's the growth of the universe, just like as we watch children grow. We see them going from small infant child with wrinkles and not enough or too much hair, to adult to old person, with a different form at each stage. Our universe has had a different form at each stage.

Fraser: So to use another analogy, it's almost like you're standing in the middle of a crowd of people, and everyone around you is old folks, but as you look further back everyone is adults in a ring around you, and if you look even further it's just children and babies until it's nothing.

Pamela: Exactly.

Fraser: I've got a question for you though. If the cosmic microwave background radiation is the first thing we can see because everything was opaque before then, how much further would you have to be able to see to see the actual big bang itself?

Pamela: The cosmic microwave background formed at roughly 400 thousand years after the big bang. There's 400 thousand light years, but that's a mistaken way, actually, to say it. To see the beginning, you'd have to look back 400 thousand light years, but that's not exactly where the edge is. There was a period during the big bang where everything was expanding apart so fast that the amount of the universe that we can see, the amount of the universe that's held within 13.7 +/- 0.2 billion light years isn't the whole universe. We can only see a few percentage of the whole universe, because when it expanded so quickly, things had a chance to escape to parts of the universe that there light hasn't gotten to us.

Each second we can see a light second further out into space. Each year we can see a light year out further into space, but we can't see all the way out. We can't see everything, because there hasn't been enough time for the light from everything to have gotten to us.

Fraser: Whoa. You just blew my mind.

[laughter]

Pamela: So we can see back to the beginning of time, but we can't see out to the edge. The real mind-numbing part is there really isn't an edge. Our universe just goes on and folds back, just like you can go all the way around the globe – you can go all the way around the universe.

Fraser: So what percentage of the universe do you think we can see?

Pamela: It all depends on what model you look at, and we don't know for certain which model is right. Some of the ones I've looked at most recently were stating on a few percentage of the entire universe is visible.

Fraser: Okay, I think we'll probably save up some of that stuff for some future shows.

So there's some additional evidence: you'd expect to see, as you look away, a younger and younger universe the further back you look. What's next?

Pamela: Then there's this thing called Olbers' Paradox. This is actually the first hint that our universe wasn't infinite in age and infinite in size.

Back, 2 centuries ago, before Einstein, before modern cosmology, people looked up and went, "hmm, it's dark. This must mean something." If you think about it, if our universe is infinite in size and infinite in age, then no matter which direction you look in, if you look far enough, you're eventually going to hit a star. If the universe has been around forever (where forever is defined as an infinite amount of time), the light from those stars (no matter how far away they are) will have had time to get to us. So every direction you're looking in, you're eventually looking at a star. All that light will have had time to reach us, and the entire sky should glow with the light of a million billion stars. It doesn't.

This implies that the universe can't be both infinite in size and infinite in age. We don't know which one, based on the fact that it's dark, is true, but we know that either light from the most distant objects hasn't gotten to us, or that there aren't objects beyond a certain point.

Fraser: Wow. Okay. This is Olber – when did he come up with this?

Pamela: Olber formulated this theory way back in 1823, so this theory's been around a while.

Fraser: Right. Then I guess the big bang was a handy explanation for that problem.

Pamela: It put all the pieces into perspective.

Fraser: It's interesting that people were think gin about it in that respect that long ago.

How does the big bang, as we understand it, match those expectations beyond just saying it isn't infinite in age? Does it make any predictions of how bright the sky should be?

Pamela: The big bang points out to the cosmic microwave background, it gives you a point at which you suspect you should start seeing galaxies. With the Hubble Space Telescope, the Very Large Telescope in South America and some of the other big telescopes, we can actually look for the very faintest, most distant galaxies in the sky. These are actually galaxies that if we were near them would be blazingly bright, but they're the faintest things we can see because they're so far back in time and their light has been travelling for such a distance to reach us.

So we can actually find the first galaxies at the time which corresponds to a distance we expect to see them at. More easily identified are the atomic abundances in the universe.

The big bang says that at a certain moment, roughly 100 seconds after everything got started, the universe was the density and temperature of the inside of a star. The insides of stars are places atomic fusion can take place, and that's exactly what happened in the early universe. You had protons slamming into one another, neutrons being created and decaying (but not decaying fast enough that they didn't necessarily get bound up into things). So a neutron would form, it would pass close enough to a lone proton, they'd bind together and you'd get deuterium. Deuterium doesn't like to be by itself, and will often bond into helium 4, where you have two protons and two neutrons. Then the helium happily exists. Occasionally miracles happen and you get lithium (this is a well described scientific miracle). All of this was raging on for about 200 seconds. The universe is expanding and cooling, expanding and cooling.

About 300 seconds after the universe started to do it's thing, it was cold enough that all these nuclear reactions stopped. It was one of these neat things where it's sort of like watching people play --- what's that game where music plays and when the music stops you have to sit in a chair and there's not enough chairs?

Fraser: Musical chairs?

Pamela: Yes, musical chairs. Things fall out occasionally! So it was sort of like a game of musical chairs, where the deuterium that hadn't found one another yet were left without a partner, and they were left behind. The rest of the deuterium did have enough time to form helium.

So the length of time that the universe was like a star, defines how much deuterium should be out there, how much helium should be out there, and how much hydrogen should be out there.

Fraser: That's amazing. So there was a moment, right after the big bang (or a period of time), when the size and consistency of the entire universe was like one great, big star, and during that period, a certain amount of that superstar fused into the stuff that we might see in the centre of our own Sun. Then it kept growing, so it cooled, and it was no longer like a star – it was something else, but in that brief moment it was recorded right there.

Pamela: It stopped before the processes had necessarily reached conclusion. Normally we don't get deuterium. Deuterium in stars gets blown apart and turned into helium. You don't build deuterium, normally, but because all of the reactions were just cut off by the change in temperature and pressure, we have residual fossil deuterium.

Fraser: Oh, the transition just happens so quickly that it didn't even get a chance to make that next step to helium.

Pamela: Because it didn't get to make that next step, because the music shut off and there was deuterium left without partners, we were able to get deuterium in our modern universe.

We can see it in ocean water. by looking at ocean water, we can say, "wow, there was a big bang." More importantly, we can look at stars and say, "where is the star with the lowest helium abundance?" (Because helium is created in stars) If we never find a star with a lower helium abundance than what existed in predictions, after big bang nucleosynthesis was complete, then we also have a comparison.

So we can look at two things: deuterium is only destroyed. The maximum amount of deuterium we find in stars should match the amount of deuterium created during the big bang. Helium is created in stars, so the minimum amount of helium we find should match the amount produced in the big bang. Those amounts are 70% hydrogen was left, 25% helium 4 was left, and about 0.01% of the universe (by mass) was deuterium, after the big bang. So those are the percentages we look for in stars.

Fraser: So if we're looking at a really distant star, you would see that star and be able to say it's going to be primordial. It's not going to have a chance to go through several supernovas and get all jumbled up. So you're going to see at least (because it's just the amount of original matter that fell together through gravity), it's going to have that minimum amount of hydrogen and deuterium in it.

On the flip side, the deuterium can't last, it has to be turned into helium in stars, right?

Pamela: The thing is, we don't even have to look for distant stars. Stars live a really long time. In our modern universe, we can look around and find the elderly star that are still hanging around from the second or third generation of star formation, and look at their abundances.

So we look around our own galaxy and find the oldest stars in our own galaxy, and we can prove the big bang locally.

Fraser: So can those stars – can there be stars as old as the big bang?

Pamela: Well, that's one of the problems. We can't find them, if they are there. The original universe was very low in heavy elements (defined as anything not hydrogen). So we had this 25% helium, a little bit of deuterium, trace amounts of lithium and beryllium and nothing else. When you have such a low atomic mass set of elements, stars tend to form really big. There's a lot of complex astronomy and astrophysics behind this, but the end of all these theories is stars that don't have a lot of heavy atoms in them are big, and big stars die quickly.

So the very first generation of stars blew itself apart. The second generation of stars had still very low atomic abundances. It was still a very close match to those original hydrogen, helium, deuterium abundances. Those stars we can find.

There's a man by the name of Tim Biers who's been making this a major part of his work for the last decade. He's looking for those oldest, most low atomic mass stars, and he's able to find things where you can say, "I know how many supernova went into creating this thing, because the ratios of the elements in the star match one supernova of one type, or a mixture of two supernovas of these types." He's able to reverse-engineer what stars are made of.

Fraser: That's amazing. That's really cool. Wow.

Have they tried to do that on our own Sun?

Pamela: Our own Sun has a whole lot of heavy atoms in it. If you look at solar spectra, it looks like someone's been throwing Chevy blazers and nuclear submarines and things like that into its atmosphere. You see titanium lines, you see scandium lines, you see all sorts of metal lines in the atmosphere. It's hard, when you have so many different metals, to reverse engineer what went into forming the Sun, because you start to get multiple things being possible. We can't say exactly how many supernovas of what types led to the creation of our Sun. You have to have simple systems where a supernova affected the star's formation. There was too many generations of stars. It's sort of like if you find your standard American mutt, and ask them what their ethnicity is, they might list off all of Europe.

Fraser: Right. So to re-cap a bit, we've got our four lines of evidence for the big bang: we've got the cosmic microwave background radiation, we've got the fact that as you look further, things look younger, we've got Olbers' Paradox, and we've got the abundances of elements in the universe (hydrogen, helium, lithium and some other trace elements). Are there any other lines of evidence – maybe they aren't as confirmed, but are just sort of theorized?

Pamela: We're always looking for the details that specify this theory with these specific parameters as correct, versus this theory with this slightly different set of parameters as correct. Nowadays, all the cosmological theories have to take into account there was a big bang, you have these set abundances after the big bang, and then you have the cosmic microwave background, and you have to match the details in the cosmic microwave background. It's matching the details in the cosmic microwave background where a lot of really neat stuff is being done nowadays.

The neat thing about the cosmic microwave background is it looks basically the same, no matter what direction you look in. this means that I can look to the left, straight out east, and then (say I'm looking south here), so I look straight out my eastern horizon, straight out across the universe, and I measure the distribution of these temperature irregularities in the cosmic microwave background. I then go 180 degrees to the other side and look straight west across the universe, and measure the temperature irregularities in that direction.

Things are identical in both directions, but there hasn't been enough time for things that happened on the eastern horizon to have affected things on the western horizon. That implies that at some point in the past, those two things were close enough to interact in some way such that they ended up mixed exactly the same way, but they got expanded apart at some speed so great that they were able to get far enough apart that their light can no longer reach one another. To do that, we have to have something called an inflationary epic, during the big bang.

This is probably a discussion for an entire show in itself, but the gist of it is, for a small amount of time, the universe expanded at exponential rates. The separation between things was moving at more than a linear speed. Instead of increasing at like, a gazillion km/s, it was going at a gazillion km/s one second, and 2 gazillion km/s the next second. It was an exponential inflation; an exponential expansion of the universe.

This also had the effect of smoothing out the cosmic microwave background radiation. It's sort of like if you have a piece of silly putty, and you rub it across a comic strip, you can get all the fine details in the comic strip, and have careful edges and sharp corners, but if you then stretch that silly putty, everything gets smoothed out. Everything eventually becomes a blurry blob. When you stretch the universe during inflation, you smooth out all the sharp edges, and you end up with a smooth cosmic microwave background.

It's in trying to design an inflationary period, in trying to design all of the mathematical models for things we can't see, that discoveries are currently being made in the numbers. Those numbers have to eventually build a system that matches all the details in the cosmic microwave background. There's people who are doing that.

Fraser: Right, I bet there's going to be many more Nobel Prizes coming out of the cosmic microwave background.

Pamela: Coming out of the details. All of the interesting stuff hides in the details.

Fraser: Great, thanks a lot Pamela. I think we've got a pretty good foundation for people to wrap their heads around the big bang, if such a thing is possible.

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