Astronomy Cast Episode 5:

The Big Bang and Cosmic Microwave Background

Fraser Cain: Last week we talked about dark matter (thanks to popular demand). There was still popular demand for another subject, and that's the big bang. So we thought we'd tackle it this week. What's your plan, Pamela?

Dr. Pamela Gay: I think a good place to start is at the beginning, or in this case, at the beginning of the Universe, and just give a broad overview of what the big bang was, what happened, and then we'll come back and look at each of the little details in detail.

Fraser: All right, let's go!

Pamela: In the beginning, there was a time zero. We don't know what happened before, we don't know what triggered it – those aren't questions science knows how to answer – but we know there was a time at which everything sort of sprung out of a singularity. Everything that is everything in our entire universe was, at that first moment, compressed down to a single point.

When you compress things, they get hot. When matter gets hot enough, it becomes pure energy. Matter's just frozen energy, and at that first moment of the universe, everything was pure energy and was expanding outwards. At that first moment, all of the forces were one force. Gravity, electromagnetism, all of the forces were tied together.

Then, a gazillionth of a second (or, technically 10^-35 seconds later) the different forces fell apart, and suddenly we did have gravity and the electromagnetic force, but everything was still energy. Then quarks and gluons began to form. Matter is just frozen energy, and the most basic of particles are the quarks that combine to form protons and neutrons.

As the universe continued to expand and cool, we eventually reached a point where we did start to get normal particles, like the protons we're used to that make up you, me and the table you and I are sitting at, but those protons were still really high energy, and it was sort of like being in the centre of a star, except the entire universe was like being in the centre of a star. There were actually nuclear reactions going on, and we had helium forming.

Everything continued to expand and cool down, and eventually everything cooled off enough that atoms that were neutral could form: we could get neutral hydrogen atoms. At that point, all the exciting stuff shut off until stars began to form a few hundred thousand years later, and galaxies began to form. That was when the universe started to look like what it's doing today.

That's a really big, broad overview, but the basic story is: take everything, compress it down really tiny, and then let it go and watch it cool and expand, cool and expand.

Fraser: What actually drove the expansion? What's the force pushing it outward?

Pamela: I'm not sure force is quite the right way to think of it. It's like the pressure in a can of compressed gas: you remove the walls from the can, and the gas in the can expands outwards, but that gas expands out into something. In this case, the universe *just* expanded. It wasn't so much as expanding into anything, as it just expanded.

It was driven in part by the temperatures, but beyond that we can't really say. Trying to figure out what drove the expansion is still a problem we have, because the universe is still expanding apart, and we're not quite sure what's driving that expansion.

Fraser: And we're not talking explosion here, we're actually talking about everything in the universe spreading apart, right?

Pamela: Yeah. It's a complicated thing to try and imagine. It's sort of like, if you take a piece of graph paper and put it in the Xerox machine, you can expand it so the squares get bigger and bigger and bigger. That's sort of what happened to our early universe: the areas between two things got bigger and bigger and bigger - but that piece of graph paper in your Xerox machine has edges. Imagine you had some sort of magical, mobius graph paper that had absolutely no edge, and *it* was expanding outwards – now you have in your mind a weird representation of what that early universe – and what our universe today continues to be – this expanding geometry that has no edge and is not so much as expanding into anything as it's just expanding.

Fraser: So our galaxy might be along one of the lines of that graph paper, expanding, and then maybe our nearby galaxies are on one of those other lines of graph paper, which is why we see it going away from us – the squares are just getting bigger and bigger.

Pamela: Exactly. The stuff that's gravitationally bound together is not going to change in size, so our galaxy is one giant gravitationally bound thing.

Fraser: So you and I aren't getting further away from each other right now.

Pamela: As much as your wife or my husband might accuse us of getting bigger heads, our heads are staying the same size.

Fraser: How was the big bang turned up in the first place?

Pamela: Historically, it started out at the beginning of the last century with Einstein sitting down and coming up with his theories of relativity, which mathematically said the universe should either be expanding or contracting. He went, "oh no, that's bad – our universe is the way it is, it's a static system" so he added the cosmological constant and stilled the universe.

Fraser: But nobody knew, he just said, "that's the way we've always thought it was, so I'm going with that."

Pamela: Even scientists are somewhat driven by their philosophical underpinnings to the way they see the world. If you anticipate that the universe isn't moving, and your equations say it is, and you don't have any evidence (and they didn't at that point) saying what the universe is doing, you can pretty much make your theory do whatever you want. So he created a constant which allowed him to stop the universe from either expanding or contracting mathematically.

A few years later, there were observations done out at Lowell Observatory by a man named Vesto Slipher that showed the majority of the galaxies that we can see are moving away from us. This implies a couple of different things: either we're in a very unique place, that causes everything to be moving away from us (like we've got some sort of a bad odour), or the universe is designed in such a way that no matter which galaxy you are, you see everything moving away from you.

Part of science says we can't ever assume there's something special about when or where we are. We have to assume that the planet Earth, the Milky Way galaxy we live in, everything is absolutely average, standard, normal. That leaves the idea that no matter where you're standing, you have to see all the galaxies as moving away. I could move to a galaxy a hundred million light years away and still see everything as moving away. I could move to a galaxy 3 billion light years away, and I'd still see everything moving away. That can happen if you live in an expanding universe.

Imagine you're some microbe on a raisin in a loaf of raisin bread. When the loaf is small and set out on the cupboard to rise, all the raisins are nearby. As the bread dough expands, you see all the raisins moving further and further away from you. It's not that they're moving away from you, as the space between you and them is expanding and they're getting carried further away in the expanding space. That's the universe we live in: it's a loaf of expanding raisin bread, and we're just microbes hanging out.

Fraser: How is the discovery further discovered?

Pamela: A man by the name of Edwin Hubble (for whom the Hubble Space Telescope is named), looked at Vesto Slipher's results, and then went and took more data of his own. He realised that the further away a galaxy is from us, the faster it's moving away from us, which was the mathematical evidence needed to say yes, it is an expanding universe. That was the start of it all. Then mathematics were built up around that to explain what the consequences of this are.

Fraser: Right, so this week we've got the Nobel Prize that has been won by two Americans that worked on the COBE satellite, which was one of the satellites that searched for the cosmic microwave background radiation. We were thinking that this week we'd talk about one of the big lines of evidence for the big bang, which is this discovery of the cosmic microwave background radiation.

Let's go back to the beginning.

Pamela: Hubble comes out with his results and these are results that did get used by John C. Mather and George Smoot to promote the building of the COBE satellite and the analysis of its data.

Hubble came up with these results – the universe is expanding. Well, if something's expanding, that implies at some point in the past it was much smaller, denser and you can trace it backwards. A man by the name of Georges Lemaître, worked out Einstein's theories to figure out the mathematical implications of this expanding universe. First you erase Einstein's cosmological constant (which has since come back, but that's a story for a later day), and he said, "okay, so once upon a time, our universe had to be much smaller." When you take gas, matter and all the stuff that's in our universe and compress it down, you make it hot. If you keep compressing it, it gets hotter and hotter and hotter. He worked through the implications of this and realised at some point, all of the matter was so dense that when a bit of light tried to move from point A to point B, it couldn't help but interact with the electrons and protons of the early universe.

More people came and worked on that. He was working in the late 20s and early 30s, then another team with the great name of Alpha Bethe and Gamow came and studied the problem more in the 40s. they kept working on this and eventually built up this detailed picture that said that all the energy and matter were interacting with one another, and then they cooled to a point that all of a sudden, the atoms could hang out by themselves being isolatory, and the light could go flying off into any direction it wanted.

Fraser: What would that look like then? I'm trying to understand. You've got all the matter and all the light bouncing into each other – what would that look like?

Pamela: Take a fluorescent light tube. Take it out of its case, take the cover off of the casing so you just have the light bulb, and very carefully put a comic strip behind it (or something). If you have a mostly clear tube, you can look through the tube and see the comic strip behind. When you turn on the light, you can no longer see the tube. What's happening is inside the tube, because you have the electricity flowing through it you have all of the electrons jumping around between energy states and they're emitting light as they're doing this. The light that's trying to get through the tube is constantly interacting with the electrons. Everything becomes completely opaque, so you have this glowing, can't-be-seen-through, hot gas.

That's what the early universe looked like, and then at a certain point it cooled off enough that it was just like when you turn off the switch for the light. Now you can see through the bulb again, and you can see that comic strip that you stuck behind the bulb. At that moment, all the light gets sent off running about your room, and you can see through the tube.

Now, if you had extra-ultra-mega-high speed cameras, you could see that light coming off the light bulb when you shut off the electricity, come out and sort of (in a packet) fly across the room. That same light, from the moment that the universe cooled off enough that the light and the matter stopped interacting directly, is still bouncing around the universe. It has a specific temperature.

Fraser: So if we had a big enough telescope, we could look out to the very edges of the universe and see that light in all directions, right? You're looking back in time, so if you look far enough back in time, you would see in all directions, right?

Pamela: In fact, it's not so much about a big enough telescope, as a telescope capable of seeing in the right colours. In fact, your television antenna, is (at a certain level) a big enough telescope. When you see static in your television, part of that static you're seeing is light from the moment when the universe cooled off enough that the photons could go flying off on their own.

Fraser: Okay, how is my television seeing light?

[laughter]

Pamela: This is one of those things where our language is hiding things from us. We talk about our television and our radio and what we see with our eyes as though they're three entirely different things. When you turn on your microwave, you're shooting light at your food. When you turn on your television, you're intercepting light with your TV antenna. With the TV it's light that's off in radio frequencies: it's so red, it's beyond what you can see with your eyes, beyond what Arnold Schwarzenegger can see with night vision goggles in movies… it's red, red, red in the radio spectrum.

Our microwave is a little bit less red: it's microwave-length radiation. We talk about things by the lengths of their waves. Radio waves can have waves that are metres or kilometres in length. Microwaves have lengths in the micrometres. Stuff we can see with our eyes is nanometre radiation. X ray is just another colour of light. Our cell phone antenna is looking at one colour of light. Our wireless routers in our houses look at another colour of light.

Fraser: So how did this original glow, that was once just whatever colour it was, move from that to microwaves?

Pamela: Originally it was really, really hot, and thus had a really blue, blue, blue colour. Every little kid that draws blue as cold and red as hot actually has his science backwards (but we don't need to explain this to five year-olds). Blue is actually really, really hot. If you watch Captain Kirk on an old *Star Trek* episode heat up a rock, it goes from red to blue (eventually).

Originally we had this really hot, really, really blue light, that was emitted as the universe cooled. As the universe has continued to expand, all the energy that was given off at that moment has had to stretch out to fill the universe. So we went from having this really blue light, in a hot, dense universe, to now having this really, really red microwave light that fills a much bigger universe.

Fraser: Hold on, let me see if I get this: so as the universe has been expanding, since the big bang, the actual light itself that's been bouncing around, has actually stretched out? I guess the point is the photons we're seeing from that very beginning, those very photons have kind of stretched out to fill the space between what they started out with and matching the size of the universe now.

Pamela: The energy has to fill up the space, and there's no new energy coming into the system. Light, which is just energy, has to stretch out to fill the expanding universe.

Fraser: So that's why the wavelengths, when they started out in the nanometres are now in the micrometres.

Pamela: Exactly. This was figured out in the 60s by a group out of Princeton lead by a man named Dicke, and he worked out mathematically exactly what colour the radiation should be today, having figured out when he thought the big bang might've been. He started building a dicke radiometer. At the same time he was building his device to look for his radiation, there was a group working at Bell Labs – Penzias and Wilson – who were going to do astronomy of a different sort, but were also building a dicke radiometer.

They finished theirs first, and they started to do their astronomy program, and had this really annoying noise in the background of their research. They did everything good scientists do: they fussed with their equipment, made sure their equipment was absolutely perfect. They looked at their equipment and realised there were pigeons living in their equipment, so they evicted the pigeons and cleaned up the things the pigeons left behind in their equipment (as pigeons do). When their equipment was completely clean, completely fixed, everything checked out perfectly and the noise was still there.

Rather than just saying "well, we can't find it," and moving on with life, they decided it must have some physical cause. They started looking around to see what science could explain this weird noise in the background of their data. Dicke up at Princeton got word of what was going on and stopped building his equipment, and there was much talking. Penzias and Wilson found out they had discovered the CMB. They had discovered this leftover light from the moment the universe cooled off enough that the light could go flying off on its own, and the neutral hydrogen was formed.

Fraser: So their detector was actually seeing the shifted wavelength of this original hot light, now in the microwave spectrum.

Pamela: They were seeing the cooled-off energy from the big bang. Pretty neat discovery – and Penzias and Wilson actually went on and got a Nobel Prize for their discovery. There were a lot of bitter theorists who'd done a lot of hard mathematical work and didn't get a Nobel prize – but the history books remember everyone that was involved.

Fraser: So there's one of the great lines of evidence for the big bang. The prediction was that if the big bang was right, and the universe was at this singular point in the past, you would see this microwave background radiation, and they found it.

Pamela: They found it.

Fraser: There was more work done with the microwave background radiation over time, right? That's where COBE comes in?

Pamela: With the original discovery of the CMB, they were using fairly limited technology. Trying to see microwaves through our atmosphere is not the easiest thing in the world. What you really want to do is get above our atmosphere. There were balloon experiments done, and it all pointed out that the background light was basically the exact same temperature no matter what direction you looked in.

This meant the material that formed the background radiation was all the exact same temperature at the moment that the neutral hydrogen formed. This implies the whole universe went cold at the exact same moment as well. Anytime you imagine the entire universe doing the exact same thing at the exact same time, you have to say, "wow, am I really seeing that?" because that's a lot of stuff to do the same thing all at once.

Scientists carefully measured over and over and over, trying to get the most exact measurements of how consistent the colour of the background radiation was. To do it right, it was realised we really needed to launch a satellite, map the entire thing all at once consistently with the same instrument.

This is where Smoot and Mather came in. they spearheaded the building and operational analysis of the COBE satellite, which was the first satellite to go up and map the entire cosmic microwave background radiation. They found that the entire background was exactly the same colour to one part in 100 thousand. That says that yeah – to 1 in 100 thousand, the entire universe did the exact same thing, at the exact same time, in the exact same way – and that's pretty cool when you think about it.

Fraser: So the universe – I don't know how long a time that was, but the universe went from opaque gas to transparent gas at the exact same time?

Pamela: Yeah. There are some very slight variations: these one part in 100 thousand variations, where there were sections that were a little bit hotter, or sections that were a little bit colder. These temperature variations lead to colour variations and imply there were density variations.

So there were places that were a little more dense, places that were a little less dense, and we can see that in these very careful maps of the colour of the CMB. What's cool is these very slight variations actually point to where we now have galaxy clusters, and where we have emptiness in the universe today. So these slight irregularities that we see in the background point to where all the structures in our modern universe would eventually be forming.

Fraser: So those are pretty important then.

Pamela: Those are very important. In fact, those are probably worth an entire episode just to themselves. It was these "anisotropies," these variations in the background, that have been getting the most attention in recent days. It's from these slight variations that we can figure out how our universe today is expanding, we can figure out how much matter there is in the universe (compared to energy). Very small things can sometimes have really huge implications.

Fraser: COBE was followed up by the WMAP satellite that was launched just a few years ago, and it sort of did the same thing, right?

Pamela: Right, the Wilkinson Microwave Anisotropy Probe. It went up and it had more sensitivity than COBE had, and went in and they were able to measure that the temperature of the background radiation is 2.728 degrees above absolute zero – above the temperature at which atoms stop moving (plus or minus 0.004 degrees).

They made an extremely accurate map in very high detail, looking at the distribution of the sizes of these irregularities, to see how many big irregularities there were, how many small irregularities there were, how many were a little hotter or a little bit colder. There'd been theorists who'd said, "we expect, based on the current distribution of matter in the visible universe, that the background should have the following numbers of irregularities of these given sizes." There were all these theories making predictions of what should be seen. What was cool, was WMAP exactly matched some of the theories, and they were able to say, "this set of theories, this specific theoretical model of our universe, is correct." It was also able to say, "the universe IS 13.7 billion years old (plus or minus 0.2 billion)."

Fraser: And that's where we're getting that 13.7 billion – the age of the universe.

Pamela: It all comes from WMAP

Fraser: From WMAP – and that only came out three or four years ago.

Pamela: that came out in late 2002 or early 2003. it's all new results. When I was in graduate school, which I finished in 2002, we were still talking about how we don't know the age of things, how there were still all these weird contradictions where when you tried to measure things one way you ended up with the stars older than the universe, but when you measured things other ways, you couldn't figure out when galaxies formed.

One satellite solved all those problems, and that one satellite was the culmination of Lemaître's starting in 1927 with his work, and the work done in the 40s by Alpha, Bethe and Gamow (mostly by Gamow), and then the 1965 observations by Penzias and Wilson. This was then culminated in the COBE satellite, with Mather and Smoot, and finally in the WMAP satellite, named after Wilkinson. Science just builds one thing after another.

Fraser: And we're only partway done, I think we've run out of time for this week, but we've got the big bang and we've got one very important line of evidence that people know how we know about the big bang, and how we know the universe started from a singularity. There's more lines of evidence that we'll talk about next week.

Pamela: You can never say something is true if you only have one piece of evidence. We have more than one, we know the big bang is true.

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