# Astronomy Cast 78:
# What is the Shape of the Universe?

**Fraser Cain:** Some of the biggest questions in the universe depend on its shape. Is it curved? Is it flat? Is it open? Those may not make that much sense to you, but in fact it's very important for astronomers. So which is it? How do we know? How did we figure it out? Why does it matter?

All right Pamela. First, can you explain in some way, the difference between open, closed, flat… what that all means?

**Dr. Pamela Gay:** This is one of the hardest things to try and understand in all of astronomy.

First of all, you have to realise that when we talk about the shape of the universe, it's not the instantaneous shape right this moment that you'd see if you were able to somehow step out of the universe into a higher number of dimensions.

The shape describes both the shape now, in terms of geometries, and also how things change as we look back in time.

**Fraser:** I'm going to need an analogy. You're going to need to give me something here.

**Pamela:** Let's start with something simple. Imagine you have a pair of binoculars, and your kid jumps in front of you a couple of meters away. At that distance, your kid fills your entire field of view with your binoculars. If you were standing on a perfectly flat surface that extended forever – not the surface of our spherically shaped planet, but a perfectly flat surface.

**Fraser:** Right – the flat Earth.

**Pamela:** The flat Earth.

Let's say you had a bazillion kids to use. That child right in front of you would fill your field of view. If you tell the child to step back and grab a friend, a step backwards might be two or three children across your field of view. As those children take steps backward, they have to keep getting more and more friends to stand with them to fill your field of view.

**Fraser:** Right, okay. I can imagine you've got a triangle coming out of your binoculars, and you're at one end of the triangle, and the legs are going on either side of you and that's making your field of view the binoculars can see in. Down at the end you've got a line of children. As the children move back further, more go into that line.

Got it.

**Pamela:** Because our universe has this problem where light travels at a finite speed, as you look at kids that are progressively further and further away, you'd be seeing them get younger and younger and younger until at some point, say 10 light years away, you'd have this field filled with a bazillion few-week-old children.

As we look back in space and time, we're able to see a larger and larger field of view and that field of view is filled with what the universe was filled with at earlier and earlier times. It's not necessarily totally flat.

Let's start now with a closed geometry. In this case, let's imagine that you were using some sort of weird fibre-optic pair of binoculars where you had fibres coming out and they conformed to the surface of our spherical planet Earth. As they spread out in straight lines to create your field of view, while sticking to the surface of the Earth, you can imagine taking two strings.

Let's say you're located at the North Pole. The left-most edge of your field of view and your right-most field of view are strings, fibre-optics that are extending from you down toward the equator.

This sort of makes a triangle, but if you try doing this on a globe, you'll see the angle in the point of the triangle there with you on the north pole is actually greater than what you would get if it were a normal triangle.

Instead of being that 60 degrees fro an equilateral triangle that you might get if you were on a flat piece of graph paper, now instead you get an angle that's greater than that.

**Fraser:** Right, and once again I can kind of imagine this. You're standing on the North Pole and you've got lines that are going to your left and right and they're going down to the equator. I guess when they hit the equator they start go converge again so that when they hit the South Pole they come back to a point. You get kind of an orange slice; I can imagine that kind of shape.

How would that affect the number of children you would see?

**Pamela:** At a certain point in time, you'd hit a maximum number of children who fit across your field of view. Then, as you keep looking back in time, now you're fitting fewer and fewer objects across your field of view. Now it's as though the volume of space you're seeing is getting smaller and smaller and smaller. That's kind of weird to think about: initially you see more and more objects, and then you see fewer and fewer and fewer objects until your field of view basically shrinks down to nothing.

**Fraser:** So it's the same deal, you're looking backwards in time as you go. There'd be a time when you see a gigantic number, and then you would see less and less and less.

All right. I think I can just barely understand this. What's the next shape?

**Pamela:** Imagine instead that we have this Western saddle-shaped universe where we sit up on the edge where the horn is and as we look back in time our field of view is heading down toward the seat of the saddle. In this case, our field of view is shrinking rapidly. It's as though we had a triangle where that point in the triangle that's somewhere as we look further and further back, the point in that triangle is actually less than 60 degrees.

**Fraser:** So right from day one, we're seeing a certain amount of the universe and then it's getting smaller and smaller and smaller, shrinking down to nothing. You used the saddle shape, so does it start growing at some point, back out to our initial size?

**Pamela:** This is where things get complicated to try and sort out.

**Fraser:** Oh, now they get complicated – okay.

[laughter]

**Pamela:** So they've been complicated the entire time.

Our field of view in all cases: we're seeing a larger volume of space, up until the geometry of the expansion starts to take over our observation. There's always this tug-of-war. If you look at a small enough volume of space, you don't have to pay any attention to the fact that the universe is expanding. But if you start to look at a large enough volume of space, the fact that the universe is a moving thing starts to dominate how you handle the geometries.

**Fraser:** I can imagine if you're a two-dimensional creature trying to work out this geometry, it would be very important. I think it would be testable – you could test, for example, with the triangle wrapped around the surface of the Earth. You could test the angles are large. You could follow, and they're always straight lines, but the angles are larger than 180 degrees and you go, "huh – that's weird."

**Pamela:** In fact, anyone who's tried to fly internationally (when the nations are spread apart by large amounts), you see this. You can imagine flying from somewhere in the United States to somewhere in Europe where you're both the same distance from the equator, but you don't fly straight along that line of 45 degrees latitude. Instead, you arc up north and down south following a geodesic across the surface.

**Fraser:** Right, you take the great circle route.

**Pamela:** Yeah.

**Fraser:** So I guess knowing how many objects are going to be in your field of view, this must be important to astronomers.

**Pamela:** This is how we sort out how many things we expect to see in our field of view as a function of distance. It's how we sort out our understanding of the large-scale structure. When you're looking at some clump of galaxies that's located a couple of billion of light years away, you probably want to know if a galaxy fills of this much of your detector, and this cluster fills up that much of your detector, how big those objects are. To sort out how big that cluster is, or that individual galaxy, we have to be able to understand how big our field of view is as a function of distance.

**Fraser:** If you're looking at some galaxy cluster and you measure it to be a certain size, you need to know the shape of the universe to know how big that thing really is or how far apart those things are, or how many galaxies are in that volume of space out there.

**Pamela:** Yes.

**Fraser:** Do cosmologists really take this into their calculations when they're… ?

**Pamela:** Oh my gosh yes. And it hurts. This is something I've been working on lately for some research I'm doing. One of the problems we're running into is the math is not simple.

It's much simpler if we live in a universe where there's no dark energy, where the universe is merrily going along its way trying to stop the expansion or where it's expanding at increasing rates as we dilute the mass in the universe, or if it has too much mass and is eventually planning to clump back in on itself in a big crunch. That math, I can do.

As soon as you add dark energy – this extra thing that is causing the universe to accelerate apart, the math gets way harder. I actually can't find a cosmology textbook that is new enough to work out all of these equations.

**Fraser:** Right, so if I was going to write a research journal article (and I promise I won't), it could say, "At ten billion light years away there's this galaxy cluster," I would have to include my calculations based on the shape of the universe. But would I have to include three calculations?

**Pamela:** We actually think, thanks to WMAP, which is just a wonderful mission – the Wilkinson Microwave Anisotropy Probe. It has done more for science than any other spacecraft that I can think of in terms of just answering the questions. Now we know the answer.

Thanks to this little probe that did such a great job, we know the universe has a flat geometry. Because of the supernova results, we also know the universe is accelerating apart. We're working toward understanding the density of the universe, the expansion rate of the universe.

**Fraser:** How do we know the universe is flat. Of those three shapes, closed is out, open is out, flat is in. how do we know?

**Pamela:** This is where that whole question of the angle in the triangle comes in. when cosmologists run through the numbers and say, "let's figure out what the distribution of the hot and cold spots in the microwave background should look like," they come up with a certain size. They say that these things, at this point in time, had this size.

**Fraser:** So they calculate it. They predicted that if the big bang works as we understand it, this is the size we should see in real terms.

**Pamela:** Yes. And you get some number that is a physical size for the size of the spot.

**Fraser:** Right, like measured in light years across.

**Pamela:** Yeah, something like that.

Then you work through and figure out how big that spot would appear today. The angle in my field of view that this spot takes up depends on the different geometries of space.

If you have that saddle shaped geometry, then the light rays are coming together and the spots should appear smaller. If you have a closed geometry, then the light rays are like when you're standing on the North Pole – moving out to the equator and then back to the South Pole. So you get a larger angle. If it's flat, you get an angle in between.

The angles work out to one degree, half a degree and one and a half degrees. Nice, simple, measurable numbers.

**Fraser:** Isn't half a degree the size of the full moon?

**Pamela:** Yes.

**Fraser:** Right, so these hot and cold spots in the sky, if they were a half-degree, the size of the full moon, they would be… ?

**Pamela:** Then we'd have a saddle-shaped universe.

**Fraser:** Saddle shaped – that's open?

**Pamela:** Yes, we would have an open universe.

**Fraser:** Then, if the spots were twice the size of the full moon in the sky, it would be…

**Pamela:** Flat, flat, flat.

**Fraser:** It would be flat. If it's three times the size of the full moon, then it's closed.

**Pamela:** Exactly.

**Fraser:** And the answer is… ?

**Pamela:** The answer is flat.

**Fraser:** So they calculated these spots to be about a degree. That's amazing.

**Pamela:** It's all about the measurements. This is something we measured.

Here's where it starts to get really weird.

**Fraser:** You keep saying that!

[laughter]

**Pamela:** Okay, here's where it gets even weirder.

**Fraser:** Even weirder! Okay, fine. Let's go to someplace this weird.

**Pamela:** One of the things scientists hate is when the universe is fine-tuned. We want things to be pre-determined by our equations, or we want things that, well, they have lots of span in what values are allowed. Fine-tuning without explanation drives us crazy.

Now, if you work out what flat means, in terms of looking out now and seeing a given density in the universe, a given geometry, you can put the two together and figure out what mass you need at different times to get this to work.

In one of the models that we look at, you need a density one nanosecond after the big bang, according to Ned Wright (who has the best cosmology website ever, from the UCLA, which we'll link to in the show notes), the critical density would be 447,225,917,218,507,401,284,016 grams per cubic centimetre. That's 447 sextillion (and then a bunch of other digits) grams per cubic centimetre.

If you took one gram per cubic centimetre away from that 447 sextillion, you'd change the model of the geometry of space. If you added one, you'd change it again.

**Fraser:** Would it go completely one way or the other, or would it be smoother?

**Pamela:** No. You completely change it. Adding that one extra gram per cubic centimetre closes space, where we end up with a big crunch at 80 billion years or so.

**Fraser:** Even with dark energy?

**Pamela:** Yep.

Doesn't that just send chills up your back because the universe shouldn't be fine-tuned that much?

**Fraser:** Yeeah… anyway.

**Pamela:** There's some sort of underlying physics we need to find.

**Fraser:** That's the thing. There's some way it all holds together, or that big bangs have been going off on nearly infinite number of times until you hit that magic number.

**Pamela:** We don't know what the answer is, but we know this number is fine-tuned and either there's a bazillion, sextillion universes out there and we hit the right roll of the die, or there's underlying physics we need to find.

**Fraser:** Right.

**Pamela:** We live in this wonderful flat universe that allowed enough time and the right parameters that we can look out and observe all of this.

**Fraser:** You say that things can change. Could you change, then, from one kind of shape to another?

**Pamela:** Yes. It's possible that we could have the critical density right now, but if you don't have, say, the acceleration parameter, then the density as a function of time changes. Without that acceleration the geometry would change. It could be that perhaps the acceleration wasn't enough. It all plays out together to change the geometry.

The universe is made out of a certain amount of mass, which is confined to a certain volume. As that volume grows, the density of the universe shrinks. There's this interplay between gravity trying to pull the universe back together and the fact that the universe started out moving outward.

Now we know this extra push that's going in, this extra pressure from dark energy that's pushing the universe out. The strength of the push compared to the strength of the pull effects how the geometry changes over time.

We're still trying to understand dark energy. It's kind of mysterious. What we think is happening is the dark energy is always hanging out pushing the same amount per volume. As the mass gets diluted more and more (as the universe expands), its ability to suck the universe back down is decreasing faster. This is balancing out to say we've always had this magical, flat, critical density to the universe.

**Fraser:** Right.

**Pamela:** It's really hard.

**Fraser:** No, no. I guess the implications of the dark energy for this must have just thrown astronomers in a loop. I think for the lay-people we kind of go, "there's an accelerating force in the universe. That's interesting, that's surprising." I'm sure for cosmologists who are right on the cusp of figuring out the shape of the universe, this threw in a layer of math that they were not ready for.

**Pamela:** That's an understatement. One of the funniest talks – and it wasn't meant to be funny, it just worked out that way – that I've ever seen was one that Chris Enke gave on how we teach astronomy. I can't remember where it was, it was an AAS meeting (I want to say it was one of the ones in Seattle). He stood up there and basically said we don't have the cosmology that theorists would ever have chosen because it's just too hard to calculate. It's much easier if you have these other geometries, and those are the ones we all learned in school.

He was so right. If you go back through the journals and look at all the models for the universe that have been worked over time, the ones that people spent the most time on are the ones that have no acceleration and have a flat geometry because that at least is fairly simple, or they have a closed geometry.

When we discovered our universe was accelerating apart, well that lambda had been in Einstein's equation since the beginning, but it made the math difficult. So, theorists weren't working in that direction. They were working in more simple directions.

**Fraser:** So now they all had to go back to school.

**Pamela:** They all had to go back to school.

**Fraser:** And take those courses to teach them how to incorporate lambda into their calculations and have another shot at it.

**Pamela:** I'm so glad that I took cosmology as a class before lambda was found, because I like myself.

[laughter]

**Fraser:** So where do cosmologists go from here, then, in trying to figure this out? What are the big, unanswered questions? It sounds like WMAP took one big one off the table. What's left?

**Pamela:** Now comes the question of what you do with this flat geometry. You can imagine flat in a lot of different ways. The definition of flat is when you make an equilateral triangle all the angles are 60 degrees, and when you draw two parallel lines, they stay parallel and the same distance apart at all distances, and when you draw two perpendicular lines they stay perpendicular at all distances. So the geometry works just like you learned it in tenth grade.

You can do this in different ways. One of the weirder ways is to start with a cube – nice, friendly normal cube. Wrap it around so that the two ends of the cube, the left side and right side come together and touch. What you've just made is a doughnut, a toroid.

Because it's a cube wrapped up on itself, you still have this flat geometry. If you're standing on the surface of this toroid (and if this is the way the universe is shaped, you now need to step into a fourth dimension to do this), when you fire two laser beams off side by side they stay the same distance.

You can take two strings and wrap them any which way you want around the doughnut and they'll stay the same distance apart at all points. You can wrap them around the sprinkle direction, around the top. You can go from the top around to the bottom and come back up. These lines always stay the same distance apart.

If you start out 90 degrees apart, one say, walking around the bottom of the doughnut and then back up and the other walking around the ring of the doughnut, you can stay perpendicular to each other. So we looked and said if the universe is toroidal-shaped, what are the consequences observationally? This implies that starlight can wrap itself around the universe in two different directions, which is kind of weird.

**Fraser:** We've got a lot of listeners who don't like us saying the universe is a big doughnut.

**Pamela:** I know, I know. Blame Joseph Silk.

**Fraser:** Done. It's all on you, Silk!

[laughter]

**Pamela:** The initial models with the doughnut-shaped universe, the four-dimensional hypertoroid, made a certain set of predictions. People got in the WMAP data and looked and looked and looked and said this first round of predictions doesn't seem to prove true, so it's probably not shaped that way.

The theorists went back to work and came up with more things. WMAP couldn't say whether they were right or wrong. Now we're waiting for the Planck mission.

**Fraser:** Planck is going to be the next telescope looking at…

**Pamela:** High-resolution, highly sensitive probe that's going to look at the microwave background fluxuations. It's going to see things in even more detail. We're going to be able to start figuring out if the universe is a hyper-dodecahedron (which is fun to say), or hyper-toroid, or if it's just plain flat going out in all directions with no edges so you can never quite work your way back around to where you started.

These questions are about if you could go on forever where would you get to? This gets into questions that we'll have to get into next week. Is the universe finite or infinite? What does this have for consequences in terms of what happens if light just keeps going forever in a straight line?

**Fraser:** All right. Let's do a third show then. Next week we'll cover whether the universe is infinite or finite and how much of the universe we can see and how much we can't see and so on. That'll be great.

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