Astronomy Cast Episode 71:
Gravitational Waves

Fraser Cain: Pamela you made it back to Illinois?

Dr. Pamela Gay: I am back in the middle of the country. It was great being able to record face to face with you last week.

Fraser: That was really fun and the AAS meeting was a riot too I have to say. Although I don't think I've ever written so much in my life as I did over those 4 days. I think I put out about more than thirty articles in 4 days.

Pamela: You put out more than Phil and I combined.

Fraser: I think so. But it was definitely a valuable experience and the next one is going to be in St. Louis?

Pamela: My hometown.

Fraser: Yeah, it's across the river from you, right? What's the date on that?

Pamela: It's going to start Memorial Day Weekend and run the first week of June.

Fraser: OK. So we'll probably be gearing up to do the same thing.

Pamela: And we'll have another meet-up except this time in the middle of the country for everyone else in the middle of the country.

Fraser: Right the meet-up was super fun. That was great to see all of the people who had driven down there. Some people came quite a ways. It was just great to see everybody and talk. That was a lot of fun.

Pamela: We can't thank George enough for helping put everything together for us.

Fraser: It was great. And in the end we did have about sixty people were there?

Pamela: Yeah, it was sixty.

Fraser: It was quite a crowd. The one last little piece of administration is that we're going to be probably posting this show a little later on Mondays. We have a few more things that we have to do these days to kind of bring the whole show together and it takes a little more time. So before we tried to post Sunday night and have it ready for Monday.

Now it will be later on and maybe even into the evening on Monday. So no promises but I think it will still be Mondays so I think the day still is the same.

When he first put together his theories of relativity, Einstein made a series of predictions. Some were confirmed just a few years later, but scientists are still working to confirm others.

One of the most fascinating is the concept of gravitational waves. “As objects move in space like black holes, they send out ripples across the universe that can actually distort the shape of matter”. Experiments are in place and in the works to detect these gravitational waves as they sweep past the earth. So Pamela, what did Einstein predict?

Pamela: Just like rolling a rock around on a stretchy sheet. Not that I would know why you would do this, but for educational purposes us teachers do this a lot. If you roll a rock around on a stretchy sheet, you can actually end up getting waves on the stretchy sheet.

What he figured was, if you take an object, a planet, a star, a black hole and you rolled it around in the fabric of space and time you can also build up waves in space and time. These waves as they propagate through space can actually cause objects to contract and expand out as the waves pass through them.

Fraser: So the waves that he was predicting rippling on this sheet of rubber could just include a vacuum. But if there happened to be things on that sheet of rubber like planets or stars or anything, those would also be distorted. So it’s not like the underlying space underneath is different from the stars and planets and so on it all just gets distorted.

Pamela: And this is actually kind of new to our way of thinking. When we talk about the expansion in the universe we understand that things that are gravitationally bound together, they are going to stay their same size.

But this space that they’re embedded within is expanding because of the Hubble Constant and because of dark energy and because of a lot of other things. With gravitational waves, everything is expanding and contracting. If a gravitational wave passes through me, I will expand and contract.

The way it works out is that for every one meter long object you’re going to get an expansion or contraction that’s actually way smaller than a proton; like a hundred thousandth the width of a proton. That’s one of the little pieces of an atom.

So I’m not really worried about getting noticeably expanded or contracted by gravitational waves. But when you start looking at planet sized objects, then you start to be able to actually get measurable expansions and contractions from these gravity waves.

Fraser: But the expansion and contraction would be hard to perceive because everything around you is being expanded and contracted at the same time, right?

Pamela: But the wave is actually moving at the speed of light. So it's not like the entire planet experiences the wave all at once. If you have a high speed enough way of measuring this, then I can see me expand and contract and then you way over in Vancouver a thousand plus miles away you're going to expand and contract later in time if that's the direction the wave is passing in. Or you'll expand and contract first and then I'll do it later.

So in trying to look for gravity waves, we actually look for this "it happens there now it happens here" change in when we make the measurements.

Fraser: Did Einstein know why this would happen? Was this just something that popped out of his calculations?

Pamela: Well it did come out of his calculations, but it actually makes sense when you start thinking of gravity as being a geometric effect. There are two different ways to look at gravity.

You can see it either as a standard force where you're flinging bosons all over the place and the bosons wandering from object to object are what are conveying the force. This is a standard model way of looking at things that all forces are mediated by bosons.

Fraser: So you have particles zipping back and forth, which are creating the force.

Pamela: Right. Or at least carrying the force.

Fraser: Carrying the force.

Pamela: There's another way to look at gravity. The other way to look at gravity is to see it as a geometric property of how the universe is put together.

When the sun sits in the center of our solar system, it is actually warping space and time around it to create this three-dimensional bowl. If we were able to see the grid of space and time from outside, that grid would get denser around the sun and things would fall into the denser part of the grid as they are attracted to the sun, and the planets are just rolling around inside this bowl.

In this different way of looking at the universe where really space and time is a fabric that can be deformed, that can be stretched, that can be squinched together.

In that view, once you start getting a massive object, something that deforms the fabric around it, that moving object can create waves just like a moving object on a normal stretchy surface can create waves. Here it just sort of comes out of looking at space geometrically and seeing masses as creating deformities in the geometry of space.

Fraser: How far could these waves propagate?

Pamela: That's the really cool thing. There is nothing out there to stop them. If I try to shine a flashlight from me to you, that flashlight beam is going to get stopped by the earth. It's going to get stopped by scattering in the air. It's going to get stopped by a lot of things. In fact light from the most distant galaxies is getting affected left and right. Its getting gravitationally bent by intervening objects. Its' color is being affected by the dust and matter that it goes through. Its' color is even sometimes changed by the effects of gravitational objects that it passes near.

All of these different effects alter the light that is between us and the most distant objects in the universe. Now a gravitational wave just doesn't care. It's just going to blow through the universe, expanding and contracting everything that gets in its path. But itself, it is not going to be changed at all.

Fraser: So it doesn't care about dust. It doesn't care if it's going through a vacuum or it's going through planets. Whether it's going through an area that has high gravity like could it just pass through a black hole?

Pamela: Yes.

Fraser: And not even notice and not get sucked into a black hole?

Pamela: Unlike light and matter, gravitational waves are the only thing that can just blindly pass through anything.

Fraser: That's cool.

Pamela: So it gives us a tool to find out about events on the edge of the universe that we might not otherwise have any way of knowing about.

Fraser: Okay, so it sounds like a great tool so why haven't we been able to use it so far?

Pamela: It's that whole "a two meter long object is only going to get deformed about a hundred thousandth the width of a proton."

Fraser: That small?

Pamela: Yeah, that's real small. It's really, really hard to detect and the problem is there are so many things that are going to interfere with our detections. We're trying, we really are trying, but these are stubborn and elusive creatures. We have however detected them indirectly.

Fraser: Okay, well let's talk about that then. What are the ways that we've detected it out in space? I think I know where this is going.

Pamela: Well, waves carry energy. They carry momentum with them. This is why when you get hit with a large ocean wave it actually knocks you on your butt sometimes. It's because the energy in that wave is being transferred to you.

Now that energy had to come from somewhere and the energy in gravitational waves has to come from the systems that they are in. When we look at really high math systems they contain a couple of different objects. You can't have a gravitational wave if you just have this lone black hole hanging out spinning by itself. It has to be interacting with something that creates an asymmetry.

Fraser: Okay. And would that be because like I know that we talked about finding extra solar planets around stars, we can see the star because it is being yanked back and forth by the planet. We can see its motion this is sort of the way the wave lengths of its light is changing as the star is being pulled away and towards us.

And in the case of two compact objects, the two of them are going to be orbiting one another right? They will be moving in space or in some common point of gravity.

Pamela: It's the motion that is so important here. If you can imagine you have a perfectly still cup of coffee and you very carefully drop cream in and you want to stir it in. The most effective way to stir it in is to take your flat spoon and move it away so that you muck up the fluid and get it moving the most.

Now if you take your pencil and put your pencil in end first and roll it between your hands like you're trying to start a fire so that the pencil is rotating about its center axis but isn't moving left, right, forward, backward, any of those things. It's just rotating about that axis, that pencil is going to do nothing to mix up your coffee unless it really has a rough surface.

Fraser: And so we want the situation where you have two very massive objects moving very quickly in space.

Pamela: Around and around, moving the fabric of space and time around.

Fraser: All right. So we can have two neutron stars or two black holes or two white dwarves or some combination…

Pamela: They're really just low energy ones. As the earth goes around the sun, we're creating gravitational waves with an energy of about three hundred watts. But that's kind of boring and small and the sun is giving off like ten to the twenty-sixth watt that's a one followed by twenty-six zeroes worth of watts compared to something my garage flood light gives off. So you can't really detect that.

Fraser: So what are the objects that astronomers have seen so far?

Pamela: Back in the seventies a grad student and his advisor came across an object that contained two neutron stars, one of which was a pulsar. Pulsars are fast rotating neutron stars that we can measure the rotation cycles because for reasons that we think are associated with their magnetic field they have a hot spot that flashes past us and beams light at us as many as several hundred times a second in some cases.

We can use these flashes, these pulses that make these neutrons stars' pulsars to measure the very careful, very small details of the dynamics of the system because those pulses are going to get Doppler shifted. They are going to get sped up and slowed down depending on whether the pulsar is moving toward us or away from us in its orbit. We can measure changes in the orbit by watching this over long periods of time.

What the graduate student and his advisor were able to observe was the period was actually decaying in this system. The two neutron stars were getting closer and closer to one another over time and the only way that's going to happen is if the system is somehow radiating energy. The rate at which the stars were getting closer and closer to one another matched with what you would expect if they were radiating energy in the form of gravitational waves.

Fraser: So regular energy gets converted into gravitational wave energy that gets radiated out and causes sort of a loss of energy in the system.

Pamela: Exactly. We have these stars that are orbiting, shaking up. They are rippling the fabric of space and time.

Just as it takes energy for you or I or ripple our sheets as we are trying to spread them out over our bed, it takes energy for these high mass objects to ripple the fabric of space and time and so they're losing energy and that energy is propagating through space causing objects to contract and expand and hopefully someday be observed here on earth directly.

Right now, all we've observed is these systems losing energy and we have assumed that energy is getting lost to gravitational waves.

Fraser: Right, but can we see that distortion of the gravity waves that would be changing the size or the shape of the pulsars?

Pamela: We hope. We haven't done it yet but we're trying.

This is where there are these two neat gravitational twin observatories that act as a single observatory, truth be told, called LIGO. Laser Interferometer Gravitational-Wave Observatory. It's actually a pair of different facilities one located out on the west coast and one located out on the east coast in Washington state and Louisiana state respectively here in the United States.

Each facility consists of a pair of twin arms off at right angles to one another. Inside of these arms there are tubes that have no air in them. They are complete vacuums and they're shooting laser beams back and forth down these tubes. At the ends of the tubes the lasers can interfere with one another. When laser beams are allowed to interfere in specific ways you get nice little diffraction patterns.

You can very precisely measure the distance between where the laser is emitted, where it reflects, and where it eventually ends up getting detected by looking at these interference patterns. You hope to use the fact that you have two beams so one on one axis hopefully is going to get contracted and the other beam on the other axis is hopefully going to get expanded at the same moment and we'll be able to measure this.

In a certain period of time corresponding to the amount of time that it takes to get from Hanford, Washington to Livingston, Louisiana or visa versa, we'll see the exact same thing happen on the other coast of the United States.

Fraser: Oh, I get it. The beams are at a right angle and if the length of one of these arms gets shortened or lengthened just a slight little bit, it's going to throw off the precision of the two lasers, how they're interacting with each other in a measurable way.

So you might get the one gravity wave passing over the one facility and then a fraction of a second later it's going to hit the second facility and in theory they should see the exact same length change in the one facility as they see in the other facility.

Pamela: Now the problem is, you also have things like UPS trucks. You have things like slight ground tremors, or all sorts of things all over the planet that are constantly causing bumps and jitters and skitters and all sorts of little motions in the system. All of these motions can wipe out the actual gravitational waves.

Fraser: I guess that's why they have to have the two facilities. If you just have one, then any little fluctuation, any bump, I'm sure me jumping up and down over the facility would probably mess up their measurement enough to make it look like a gravitational wave. But by having the two, then they can try and see one change and then the second. So have they turned up anything yet?

Pamela: No.

Fraser: Is that just because it doesn't exist, or does that mean they haven't turned up anything because it's not sensitive enough?

Pamela: It's a complicated issue. They've been working on LIGO for a long time. It has a new set of instruments. They've been working very hard to tune everything to get everything lined up and find things. But, it's hard work and they're still working on tuning the system.

They're still trying to figure out how to calibrate for everything that's happening here on the planet Earth that's mucking with their system. And there're going to get there, hopefully. It's been a long ride. When I was at Michigan State University as an undergrad one of my classmates was actually a summer intern down in Louisiana working on LIGO. They've been working to do this for a lot of years.

Fraser: How many events and what kinds of events were they hoping to see by now?

Pamela: It depends on where you look. Right now they're estimating that once everything is fully operational, they should be seeing something a couple times a year. It also depends on what the universe decides to throw at us.

Fraser: Right and what kind of thing would they be seeing?

Pamela: Well, for instance when two black holes merge. That's going to send out an amazing, whopping amount of gravitational waves. In some cases super novas that are asymmetric can send out gravitational waves. If you have an asymmetrical disk outside of a super massive black hole, you may also be able to see that.

All sorts of different things produce specific sets of gravitational waves. The shape of the waves the distribution of the waves is very specific to the type of object you are observing. Hopefully, some of these will become apparent.

There are also theorists out there that are constantly tuning their models. That's the other thing that is fun to watch. The theorists come up with an idea "If this happens, we should see", and then they lay out their plan and exactly what types of things will produce what size, or what type of black hole. We're still working on honing in on that as well. Or what size, or what type of gravitational wave we're still on homing in on that.

Fraser: But even when they don't see something that's still very interesting because that just means that this prediction might be incorrect or that prediction might be incorrect and that just lets them continue to focus their prediction.

At least they've got some kind of instrument that is checking that they can compare their theories against which the string theorists should be so lucky, right?

Pamela: Yeah, we are in the position where there have been a few events where I've seen press releases that have said, "LIGO did not detect something. That means the gravitational waves from this specific event that were also detected in light, could not have been bigger than" and then they give error bars.

So now we know at least the gravitational waves are smaller than a certain amount. And that's still new information that we didn't have prior to LIGO being constructed.

Fraser: But once they did make very specific predictions on how strong these should be.

Pamela: The problem is figuring out the physics of how exactly do things merge. What are the time scales? What are the fluid dynamics of your combining two different objects that are spinning, orbiting each other, or there might be a disk of material around them. It starts to get complicated when you're not dealing with non-spinning clean black holes.

Fraser: All right. So we've learned about LIGO and we're still waiting on the result from them, are there any other missions or any other experiments in the works?

Pamela: Well there are some other ground-based observatories. But the greatest hope that we have rests in a mission called LISA.

LISA is going to be the space-based version of that and LISA in fact stands for Laser Interferometer Space Antenna.

Fraser: So the Hubble Space Telescope is the optical detector of gravitational waves?

Pamela: Basically, except there's not going to be a lot of optical detectors involved. All they need to be able to see is their own laser.

Fraser: So it's kind of the same thing as LIGO. You're going to have space craft separated by a long distance pointing lasers at each other hoping to see that contraction and expansion.

Pamela: It's a really neat system. If you've ever played with Tinker Toys, LISA really looks like a giant Tinker Toy construction where you have these three little disks (and they're not all that little), on orbit separated by huge amounts and each disk is connected to the other two disks in this equilateral triangle with laser beams.

What they're looking for is any gravitational cause that will change the separation of these three spacecraft from one another. Now unfortunately, even though it's now in space, it's not as simple as you might think. There will still be stuff interfering with out ability to detect gravitational waves. This is not going to be an easy task no matter what.

Once you get into space you have to start worrying about solar particles, drift in the spacecraft over time where their orbits aren't quite as precise as we thought. The Earth's gravitational field isn't perfectly symmetric as you fly over different parts of the planet the gravitational pull is going differ from place to place. All of these different things have to be completely accounted for in trying to make sense of the data that we get out of LISA.

Fraser: Now what will be the sensitivity of LISA?

Pamela: LISA is actually going to be so sensitive that it may be able to, although it's not designed for this, actually be able to detect a continuum of gravitational waves that started back when the universe had just formed.

What's neat about gravitational waves is, if they were given off during the "Big Bang" during the whole period of inflation and during the three hundred thousand years leading up to the formation of the cosmic microwave background we can detect them.

We can't detect anything before the cosmic microwave background in light because the universe was opaque. We couldn't see through it. But, gravitational waves don't care about the universe being opaque. They just go.

And so it's possible once LISA is in orbit we may see this whole range of twittering in different frequencies of gravitational waves that are a signature of how our universe was formed and that's just kind of cool.

Fraser: It sounds like gravity waves offer astronomers a whole new way of seeing. It's not just the whole visible spectrum, it's a brand new way to be able to see the universe and in many cases, I guess they could look at something in infrared or visible and then also look at it with gravity waves.

Pamela: What's so cool about this is if you've ever looked at a pond on a really still day, you can tell when the motorboat goes by because you see the waves. You can tell when there's a bunch of rocks between you and the motorboat because of the patterns in the waves. You can actually start to guess what's going on out in the middle of the lake without actually having to look up and looking at the middle of the lake by looking at the waves that are hitting the shore.

Well, we can look out across the universe and see what's going on in other parts of the cosmos without actually being able to see what's going on in other parts of the cosmos with normal light. It's a whole new tool.

Fraser: I talked to a researcher one time and he said it was like you're listening. That it is such a completely different way. If you're using your telescope, you're seeing and if you're using gravity waves, you're listening.

Pamela: It's a new sense. It's something that's going to be really fun to play with as we begin to develop the technology to do this efficiently.

Fraser: Well, let's hope that we make a detection in the next few years and this whole new science opens up.

Pamela: The real thing to hope for is added budget for NASA. LISA's not doing so well in the budget. We hope to be able to launch it somewhere around 2015 but it's still in the formulation phase.

The money isn't there to start building a spacecraft yet so hope that NASA all around gets more funding so projects like LISA will have the funding they need to allow astronomers to explore the universe in a whole new way.

Fraser: All right, so NASA if you're listening, make sure you fund LISA. Let's see if that helps. All right, well thanks Pamela. We'll talk to you next week.

Pamela: Sounds good Fraser, talk to you later.

This transcript is not an exact match to the audio file. It has been edited for clarity. Transcription and editing by Cindy Leonard.