Astronomy Cast Episode 102:
Gravity

Fraser Cain: Let's get on with the show then. Everyone seems to like our series, our tour through the Solar System, our information about Mars. We've got a new series for you. I think people keep wondering about when we are going to run out of topics. Well, here you go.

We're going to handle all the forces of the Universe and this week we're going to do gravity. We haven't covered that show yet and here were are a hundred plus shows in. We're going to start with gravity, which is a force you're most familiar with. We know gravity happens when masses attract one another and we can calculate its effect with exquisite precision.

However, you might be surprised to know that scientists have no idea why gravity happens at all. Pamela, let's go back and just image you're in your class and you will be presenting gravity to people. Where do you typically start?

Dr. Pamela Gay: I usually drop something loud because that gets their attention. But I won't do that to our pod cast listeners because [Laughter] that might be cruel to their eardrums if they're wearing headphones.

Fraser: Preston, resist the urge to make a loud noise. [Laughter] He's our Editor. Okay.

Pamela: The way that we're most aware of gravity is things fall. We fall. We fall upstairs, downstairs and you always fall toward the center of the Earth. Keys fall, books fall, and I've fallen off of horses. Falling is one of these things that people have been aware of since they first stood up.

The question is why? Why is it that I always fall toward the ground and not toward the sky? Why is it that people on the North Pole and the South Pole both stay adhered to the surface of the planet and don't go flying off into Outer Space?

Fraser: You can imagine that gravity is such an all-pervasive force that ancient peoples almost didn't even think about it. You know? It's also like why when I breathe is there air in my lungs?

It's because gravity is holding the atmosphere next to the planet. But it's not something that you would even consider. So when did people start to realize there was something going on?

Pamela: It was often addressed as a philosophical question. Why down and not up? Why don't we go into the sky? This became even more troubling when we discovered the planet is round.

Galileo did our first scientific investigations of gravity. Everyone has heard the stories of Galileo dropping things off the Leaning Tower of Pisa. No one knows if that actually happened. If it happened, he certainly didn't document it. Galileo was one of these people who documented everything.

But, what he did do was roll balls down inclines, which doesn't sound all that exciting but prior to Galileo's investigations we had Aristotle's ruling the days ruling the day saying that objects started in motion always come to a stop. Everything comes to rest.

That was the way we viewed the Universe because friction does cause everything on the planet Earth to generally stop. But Galileo, through very careful investigations, realized objects of different masses, shapes and sizes only fall differently as a result of how they interact with air.

He realized that if you have an object moving across a smooth enough surface and it goes down an incline, it would go up an incline to the exact same height on the other side. He was able to start saying, gravity is this thing that is causing the ball to go down the incline and the go up the other side.

Fraser: Now as I remember Galileo used ramps as a way to slow the whole process down. That is was impossible to measure if you just drop things but if you put things on very slanted inclines there was a way that he could actually start to measure how long things were taking to drop.

Pamela: He was actually using water clocks. This was a really cool way to basically say if you have a bucket filled with water with a little tiny hole in it and there is a large enough surface area to that bucket – because surface area plays a role in how fluids flow - and it's a short enough period of time then you open up the spicket on the bucket and let the water start dropping out into the Galileo equivalent of a graduated cylinder. You measure the volume of water that comes out while the ball is rolling down the incline.

It's a surrogate for measuring time. If you assume that one drop of water falls per one second and you can figure out the volume of one drop of water, the volume becomes a measure of time. He was able to figure out this acceleration measurement for how balls fall down. They have this speed for the first second, this much larger speed for the second second; an even larger speed for the third second.

He was able to figure out all of this related to the angle of the incline, all sorts of really cool math. He did all of this using a water clock that he basically started and stopped by starting and stopping the water.

Fraser: And so the conclusion that Galileo came to was that the force of gravity is acceleration. I guess people always intuitively understood that. You fall off of a higher drop and you're going to get hurt worse. [Laughter] But I don't think they realized exactly how that worked.

Pamela: One of the coolest things about what Galileo did was he put together the whole notion that any two objects should fall at the same rate once you take into account air resistance.

This had actually been somewhat confusing before because if you imagine a barbell falling, if the rate at which something falls is a function of mass then if you replace the bar in the center of the barbell with a piece of string how does that know to fall at the same speed as the two bars connected solidly versus why would two balls without a string between them fall at a completely different rate.

Fraser: Right and you can always go back to that example of a ball versus a feather, right? I guess they thought that the feather was lighter and so it would fall more slowly while the ball would fall more quickly.

Pamela: Yes, and then you extend this idea out to small child falls slower than large man. Please don't do that experiment. It didn't really make sense though when you consider how does a man holding a child fall? Don't do that experiment either.

Galileo basically determined it was just air, its okay and moved on. We still don't know why though. This not knowing why was a problem that we continued to have for a while. Kepler came along and figured out equations to describe the motions of the planets. He didn't know why they were doing it but we had equations.

Galileo described mathematically how objects go down inclines and go up the other side but didn't know why. It was Newton who came along and according to the story saw an apple falls…

Fraser: Did this really happen – oh, he didn't get hit on the head, right? [Laughter]

Pamela: No, apparently not. I mean, who knows? But according to the story Newton saw an apple fall, looked up and saw the Moon and decided that the Moon was falling. It was probably a more complicated train of logic.

He worked out that if the Moon was so far away and a certain size – well we don't really need the size that much – but if the Moon is this far away, and the apple is this far away and we look at how they're falling and the Earth is this size…..

Using lots of cool mathematics that you can actually do with basic algebra, he was able to figure out that the Moon was just falling around the planet and managing to miss it as it goes.

Fraser: I remember the thought experiment for this was where you imagine that you have a cannon and you're firing it sideways and the ball hits the ground a few hundred meters away. Then you tilt the cannon back and you have much more powerful cannon and you shoot it and the ball will land further downfield.

You eventually get to the point where the cannon is strong enough that the ball just goes all the way around the Earth and lands back on the guy who fires it. Eventually you can keep shooting it harder and harder until the ball just goes all the way around and it's falling but it's like the Earth just keeps moving out of the way.

Pamela: Newton was able to take that idea and go: "Oh, Moon falling; oh, Earth falling around Sun." All of a sudden what we see is everything is falling but the curvature of its fall doesn't allow it to ever make it to the object it is falling toward. That is a kinda neat image and he had really neat math to go with it.

Then unfortunately there are things like oh, the planet Mercury that screwed things up. It was all well and good; we were able to find Uranus because of Newton's applications.

There were two different scientists, two different mathematicians one in England who did lots of equations and threw out lots of possibilities and one in France, who basically did one calculation, threw out one possibility.

Then an observer went out and looked at the Frenchman's coordinates and discovered a new planet. All of a sudden Uranus' orbit made sense. But, Mercury's didn't so we waited around trying to figure out what is wrong with gravity.

Then Einstein came along. Einstein was able to give a reason for gravity existing. Look at gravity as a curvature to the Space Time Continuum.

Fraser: Whoa! Explain that.

Pamela: Yeah, I know, it's a kinda big jump.

Fraser: Like I'm sure people thought well that was helpful. [Laughter] Thanks Einstein.

Pamela: Yeah, he just sorta reformulated how you're supposed to visualize all of everything. He came along and said basically imagine Space as more dimensions such that the gridlines of our three-dimensional grid get tightly packed as you get closer to the Sun because you're falling in toward the Sun.

Fraser: I think the analogy we always use is like a rubber sheet with a bowling ball on it.

Pamela: You can imagine that in our flattened Universe, our flattened Solar System, the Sun creates a deep pocket in our plastic sheet of Space. If you've ever seen crazy skateboarders, they can get themselves going around the edges of bowls.

If you watch crazy bicyclists, they'll get themselves going around the inside of velodromes which are curved surfaces. You can imagine the planet Earth as it rolls along Space moving around the rim of some sort of Cosmic Velodrome where it is the Sun that defines the center of the particular curve that we're orbiting around in.

Fraser: Just to backtrack for a second what exactly was the problem with Mercury?

Pamela: Its orbit wasn't going at the correct rate. We have an entire show on Relativity that people can go back and listen to that brings this up. Basically the problem is that its orbit precesses in a way that we couldn't fully account for.

Fraser: Ah, and the word precess?

Pamela: That means that it's an ellipse and where the end of the ellipse is changes over time.

Fraser: Okay, no I see. You've got like an oval like a loop and Mercury is going around the loop and you're sort of tracing this oval but the oval's position is slowly rotating like a Spirograph.

Pamela: Yeah, the kid's toy.

Fraser: Okay and so the position of where that oval of Mercury's orbit was supposed to be didn't match up what Newton had predicted. And Einstein said that's because of Space Time Continuum and all that junk.

Pamela: Right and then some mathematician came along and beat them with a stick and said it's an ellipse not an oval because mathematicians like to do that. So we have this problem with Newton's understanding of gravity and Einstein came along and announced he had a new formulation. It's all a curvature of Space. Gravity is nothing more than geometry.

The problem is gravity breaks at the beginning of the Universe and in centers of Black Holes. Things just get so dense that infinity signs start popping up and dividing by zeros starts popping up and much badness occurs.

About the time that people decided this is bad and math can't handle this, we also started building a standard model of particle physics where we look at other forces - which we will talk about in succeeding shows – such as electricity and magnetism, which is the electromagnetic force.

We started looking at them and realized there were photons, particles of light! They carry these forces. They cause the electric force they cause the magnetic force. The electromagnetic is one force.

We realized other forces, the weak force, the strong force, also had little particles we call bosons that walk around at extraordinarily high speeds and carry the force with them and communicate from one point to another.

In this particle physics way of viewing Space and time in particle physics, people began to say there must be some particle, some boson – we called it a graviton – that is the little particle that carries the force of gravity that communicates gravity from one object to another.

This causes objects to realize that an object in one place has moved and the realization that this move affects the other objects to be affected differently by the one that has moved.

It raises all sorts of all interesting questions like how fast is gravity communicated. All these questions pointed at this little particle, this graviton that we can't detect. This is one of the biggest annoyances in particle physics.

Fraser: Right, so we've moved on to the question that a 4 year-old would ask, right? Why is there gravity? [Laughter]

Pamela: And the answer if you listen to Einstein is it's the curvature of Space and time.

Fraser: But why is there a curvature of Space and time?

Pamela: Because there is. Because mass for reasons that we can't really explain causes the space around it to essentially grow hills and valleys that we can't see except in the motions of objects.

Fraser: But WHY?

Pamela: BECAUSE [Laughter] this is the way our Universe is ….

Fraser: [Laughter] The point you were saying is that the thought was maybe there are particles communicating back and forth somehow. And that's the attraction, right, is our defining the curvature of Space and we have these gravitons.

Pamela: That's the crazy thing though, once you invoke the gravitons you no longer need to invoke the curvature of Space. We now have two views.

Fraser: Right, the little rubber bands going almost going back and forth.

Pamela: Yeah and the crazy thing about this graviton notion is first of all it is a particle that has no mass because it moves at the speed of light as near as we can tell. There are gravitons flying through us all the time.

If we built a detector the size of Jupiter and planted it next to something like a neutron star we'd have to wait years before maybe one graviton caused something to happen in the detector. We couldn't tell the difference between that event and what neutrinos cause.

Neutrinos really don't interact with anything either so we can't ever really detect gravitons, except maybe through radiation. This is one of the cool things about particle physics – particles are little blobs of stuff but they're also waves.

We talked about the wave particle duality in a past episode. When we look out at things like pairs of neutron stars orbiting one another we see their orbits changing over time.

This is gravitational radiation at a certain level carrying energy away. This is gravity waves, something that LIGO and LISA are hoping to be able to detect. We are still working to get there.

Fraser: Okay so if the particle theory is right, if there are these gravitons then you have this gravitational radiation that would be given off. It should in some way be detected through some mechanism, right?

Pamela: Yeah through gravity waves.

Fraser: Right and that's where we get the whole thing about gravity waves which I think we've done a show on that as well. So that's the one camp and I guess would there be a way that you could detect these gravitons in a particle accelerator?

Pamela: No.

Fraser: No. Not at all? No chance?

Pamela: No.

Fraser: Not even theoretically? [Laughter] Okay, fine! I won't go with that line of questioning anymore. Then the competing thought is that it's just purely geometry. That is the way you might as well ask why are there triangles.

Pamela: The problem is that we know that our understanding of particle physics is incomplete and we know that the geometric understanding of gravity is incomplete because we can't describe the insides of Black Holes without math breaking. We can't describe the earliest moments of the Universe without math breaking.

Having gone from basically philosophical understandings of why things fall to mathematical descriptions of how things accelerate down inclines to Kepler's equations describing planetary motion to Newton's formulation of the Laws of Physics – or at least the Laws of Kinematics and Gravity – to Einstein's formulations of Relativity, we've been building and building a more comprehensive view of gravity. But we're still not complete.

We know that there still needs to be some way to unite Quantum Mechanics and gravity and actually be able to write down equations that describe the centers of Black Holes, to describe the earliest moments of the Universe.

We're not there yet. There needs to be a new brilliant person born into the Universe, or at least born onto the planet Earth. Someone on another planet might already have figured this all out.

Fraser: Now how fast does gravity move? I know that Einstein made some predictions.

Pamela: The belief – and there is some evidence for this – is that gravity propagates at the speed of light. That if you suddenly blink the Sun into some other part of Space using a transporter beam technology that will never exist, the Earth would merrily continue happily orbiting as if nothing had happened for 8 minutes.

Then at the end of that time, we would cease to receive light and we would start moving in a straight line instead of on the orbit that we're presently in because the Sun's light would stop hitting us and the Sun's gravitons would stop communicating with us that we should bend.

Fraser: What is the mechanism that they're trying to test this out? I guess gravity waves is one?

Pamela: Gravity waves are one. A neat experiment that didn't work – at least the theorists are saying the interpretation is wrong – was trying to look at how does light bend around objects?

And if that object that it's bending around happens to be moving can we separate out the object's motion and the rate at which light bends around it and learn anything meaningful?

There is a set of observations done in I believe 2002 where they looked at how Quasar light bent around Jupiter as Jupiter moved between a series of Quasars. The interpretations were messy.

The observations didn't have high enough accuracy. People are trying to find new and interesting experimental ways and like you said, we're looking for gravity waves.

Fraser: So the hope is that as a heavy object moves in front of some distant bright object you'll get the light beam tweaked, not instantaneously but at the speed at which the gravity is propagating out from the planet itself.

Pamela: Yeah.

Fraser: Okay, now I remember reading somewhere that gravity even though we think it is really strong, it's actually kind of weak isn't it?

Pamela: It is over large distances the force that tends to have the most affect on the Universe. On small scales, electrons and protons do not care about the gravitational pull of the one on the other.

All they care about is the electrical force. On small scales with small masses it's extremely weak and the other three forces all dominate on the smallest scales.

Fraser: Sure, you could pick up an object from a table – pick up a coin from a table – and the nuclear force holding the atoms in your hand together vastly overpower the meager force of the entire Earth pulling on that coin on the table and just your fingers can overcome that just the force holding your fingers together.

Stick a fridge magnet on the fridge and bang you've got that little magnet completely overpowering the force of the Earth. It's not until you get neutron stars in Black Holes where those forces are gone.

Pamela: An interesting thought experiment that basically came out of one of my classmate's mathematical errors when I was in graduate school was to just sort out what is the self-gravity of the human body?

If you take a human body and pull all of its atoms apart so that it's only held together with gravity all it would take is a breath to dispel all those atoms and shatter the human form.

So, it's all the chemical bonds, all the molecular bonds, all these things that are because of the strong force, the weak force, the electromagnetic force, that hold you and I together and gravity that holds us on the planet.

Really, it takes a lot to tear apart a chemical bond and it's only on the largest scales where chemistry no longer really has an effect that gravity has a chance to get noticed.

Fraser: Well, I think that covers our gravity side this week. Next week we will move on to the Electromagnetic Force and then we'll do the Strong Nuclear Force and the Weak Force and then maybe on the last episode – the fifth episode of our four-part series – [Laughter] we'll try and pull it all together.

We'll talk about the search for the grand unified theory. Pamela if you figure it out – Nobel Prize.

Pamela: You know, it's something to aim for but I don't think we're quite going to make it.

Fraser: Just do your research, [Laughter] get all your show notes prepared and if the solution seems to present itself then by all means put it in the show and we'll look forward to a Nobel Prize. [Laughter]

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