Astronomy Cast Episode 9:

Einstein's Theory of Special Relativity

Fraser Cain: After bending your brains with the Big Bang, we took pity on you and gave you a couple of weeks to recover with some lighter material: getting started in astronomy and meteor showers. Now we're going to crank it up again with some concepts key to all things astronomical: relativity.

So if you don't understand it yet, our hope is by the end of today's show, you'll be able to finally wrap your head around relativity. Alright Pamela, explain!

Dr. Pamela Gay: Relativity is one of those things that actually came out of the ether, and I've always wanted to be able to say that about something.

Back in the 1800s, scientists thought the entire universe (or at least the universe as we knew it then) was permeated by this substance called ether, and light propagated through the ether the same way sound propagates through air.

The problem with this is if it's true then as the planet Earth moves forward through the ether and light is let off of a flashlight, candle (or whatever source of light you want), then the velocity of the Earth gets added to the velocity of light. This means you have light travelling at one speed in one direction, but if you look at it at some right angle to that, you get light going at a different speed.

Fraser: This is a pretty normal or understandable theory they came up with, because waves moving through water, the wave moves and propagates through the water, or sound waves that propagate through air. The waves will speed up or slow down depending on what things are moving.

Pamela: It all seemed to make sense. If you have a wave, you must have something that's getting shaken. So since light was determined to be a wave experimentally, they figured there must be something the wave is "waving" in., so they used this ether concept.

Now, if I'm standing on a boat and I throw a baseball (being a non-baseball throwing type of person) at a whopping 30mi/h toward the person in front of me, and our boat is going 20mi/h relative to the shore, someone standing on the shore is going to see the baseball I just threw going 50mi/h, because the velocity of the boat got added to the velocity of the baseball.

Now, if I turn around and throw the baseball toward the back of the boat, they're going to see that baseball going a very sad 10mi/h because in this case, the velocity of the boat is subtracted off the velocity of the baseball.

Everything is relative. In this case, it's relative to the land.

A couple of really smart guys by the names of Albert Michaelson and Edward Morely said light should act like that baseball on the boat, and the velocities should add. Now, if I throw a baseball at a wall on that boat, and wait for it to bounce back to me, my friend on the land will see it going at a different speed in both directions because it's reflecting and as it goes toward the wall the wall is moving away form it. As it comes back toward me, I'm moving toward the ball because of the motion of the boat.

Fraser: So far that makes sense: all intuitive.

Pamela: Now, if I turn that wall and myself at a right angle, so I'm basically throwing the ball at the person on the land, but there's a wall in between, in this case the motion of the boat doesn't affect the velocity of the baseball. The baseball's going that same sad 30mi/h no matter what. So if I throw the ball perpendicular to my motion, nothing weird happens. If I throw the baseball in the direction of the motion, weirdness happens because the wall, ball and everything is moving and we have these weird relative velocities kicking in.

So if it works with baseballs, it should work with light. Michaelson and Morely set up an experiment in 1887 where they had two sets of mirrors. One set was perpendicular to the other; they were at right angles to one another. They very carefully measured the amount of time it took light to reflect back and forth from the starting point to the mirror and come back, in these two directions.

They figured the velocity of the motion of the Earth should affect things. They watched and watched and they waited to see the velocity of the Earth adding to or subtracting from the velocity of the light as the Earth moved through the ether and the light propagated through the ether, and nothing happened.

Fraser: What do you mean nothing happened?

Pamela: Everything kept going as the light moved at the exact same speed, no matter what happened. So it’s sort of like throwing a baseball and it goes, “yeah I’m going to go 30mi/hr regardless of what the boat is doing”.

Fraser: So even though they should’ve been able to detect the light going faster one way than it was going the other way, it travelled the same speed – even though theoretically it was getting a boost from its reflection.

Pamela: Yeah. So, imagine if, when you’re standing on land, you throw a ball at 30mi/hr. You go stand on a boat going 20mi/hr, let go of the ball and it changes velocities going, “unh-unh, I’m not going to go faster than 30mi/hr and you can’t make me.” That’s what the light seemed to be doing.

This experimental result required people to re-examine how they looked at the world. Some people started suggesting that maybe time and space change to compensate for this and make light always appear to do the same thing. It was actually George

Fitzgerald and Fredrick Lorenz that suggested time and space contract to keep light always going at the same speed.

In this case, as I move, the space around me changes. The lengths contract and in this case I end up seeing the speed of light as always the same thing. They didn't have a full physical understanding of what was going on, and it took Albert Einstein to come up with that in 1905.

He did a series of gedonkin experiments (German for thought experiments). He imagined people on trains (because back then people were on trains and it was something they were very familiar with).

Imagine you're standing in a field and I'm on a train. If we both have two sets of mirrors, we can bounce light back and forth between those mirrors because it's light and its cheap – we have light bulbs. It's possible to measure the amount of time it takes for the light to go from the bottom mirror to the top mirror if we have the mirrors one at eye-level and one at foot-level.

Fraser: Hold on. You're shining the light inside the train, from one mirror to another mirror?

Pamela: Yes. One mirror's at the floor, and the other's at eye-level. The light is bouncing back and forth, basically tracing out the length of my body. You have the same thin with you in your field.

Fraser: Right.

Pamela: If I'm on a train that's stopped at a railroad crossing waiting for some stupid stalled car to get out of the intersection and we're watching each other. You will measure the light going up and down and my clock (if our clocks are the exact same size) to be the same amount of time as I'll see your clock. If we put our clocks next to each other we can see the light going up and down completely in sync with one another. All is well with the world: we have light travelling in two clocks at the exact same speed, and it makes sense.

If my train starts moving, we now have a different situation. As you watch, the light in my clock bounces off the bottom mirror and then the top mirror starts moving to the right, because the whole train is moving. The light now has to shoot at a diagonal line to the right, going over this larger distance to catch up to where the mirror has moved to.

It bounces off the top mirror, and now the bottom mirror is also moving, so the light has to shoot over at a diagonal to catch up to where the bottom mirror now is.

Fraser: Right, so I'm seeing the light making a kind of zigzag as your train is moving past me.

Pamela: Exactly.

As you watch the light doing this, if your clock has light travelling at the exact same speed that light in my clock is travelling, the amount of time between reflections in my clock has to be slower than the amount of time for the light reflections in your clock.

Fraser: Right, because in the amount of time it's taking for me to see the bounce up and down, I'm seeing the light travelling that longer diagonal – if you imagine a triangle, the diagonal length of the triangle is longer than the up and down lengths.

Pamela: Exactly. Since my light has to go a further distance (because the mirrors move sideways as the train moves sideways), you see the time as going slower.

Now, if I'm on the train with the mirrors, I see those mirrors as one on top of the other, the whole thing always together, with the light bouncing up and down as the train goes sideways. For me, I see the light as just going up and down at the speed of light. All is right with the world.

That means that for me to see the light going at the normal speed of light, time for me has to have slowed down. If you (not on the train) see something going slowly, and I see something going quickly, that means my watch is ticking slower. For every 5 ticks I see, you might be seeing 10 or 20. I measure a time of 5, because my ticks are slow. I measure a shorter amount of time.

Fraser: Right, right. It's that backwards math like when you do high speed photography and see things in slow motion. People will actually run the camera faster – more frames, but you can then show the frames at normal rates in a projector and see things moving in slow motion. And vice versa – if you want to show something moving really quickly, you take a shot every second and then you can compile them all together and run that at normal speed and see things moving at a speeded up, hectic pace.

Pamela: Exactly. My watch slows down, and I see light moving at the speed it always moves. In order for me, on my train, and you in the field watching my train to see light travelling at the exact same speed, my watch has to slow down. It's not just the watch on my wrist, it's the time in which I live that slows down.

Fraser: There are other implications for this difference in time that we see, right? With the speeds.

Pamela: There are all sorts of different implications. One of the coolest ones is this thing called momentum. Mass times velocity is always the same thing as long as there's no outside force acting on a system. Velocity is measured in how far you go in how much time. For momentum to stay constant as your velocity increases, as I'm going faster and faster, time is getting slower and slower, my mass has to go up to keep this whole thing constant.

The faster I go, the slower time goes, which means to keep mass times velocity constant, my mass has to go up. Now, as I approach the absolute speed of light – my speed being 99.9999 times the speed of light, my watch has almost stopped. At this point, my mass has to be almost infinite in order for conservation of momentum to happen.

Fraser: You would actually feel this. You would be putting more and more rocket fuel into your rocket and be getting less out of it as you were going faster.

Pamela: Exactly. That's the other consequence. The more you accelerate yourself, the more energy you have to put into a system. The more energy you have to put into a system to move yourself as your mass is increasing – that energy is just mass itself. The more energy you use to try and accelerate yourself (because energy's also getting conserved), slowly but surely your mass is reaching infinity and so you end up with E=mc^2.

This huge, important equation, that basically tells us that two parts of a nuclei will actually have lower mass than the original nucleus just due to the nature of the process. That bit of mass that got lost gets turned into huge amounts of energy.

That all falls out of the consequences of time changing as our velocity changes, so that everyone always sees the speed of light as being the exact same speed.

Fraser: This is just special relativity, right?

Pamela: This is just special relativity.

Fraser: What's general relativity? If I understand right, with special relativity it only has to do with constant velocity – or constant acceleration?

Pamela: The real problem is, one of the things that comes out of this is you and I will never actually see the exact same thing as we're moving.

Think of it this way. If I'm on a train, and I have a light bulb in front of me and a light bulb behind me, I can switch on some switch that causes the light from both bulbs to come at me at the exact same time. To me on the train, moving with the light bulbs, if I see the same distance between the light bulb in front and behind me, the light ahs to travel both these identical distances, and I'll get the light at the exact same time.

If you're standing in the field watching me and these two light bulbs, you may see the light hit me from both at the exact same time, but you won't see the light turn on from both bulbs turn on at the exact same time. The light bulb in front of me has a shorter distance to travel to get to me. That light bulb will come on second. The light bulb behind me that has to catch up to me (because I'm on the train and moving away from where it was when the light turned on), that bulb you'll see turn on first because the light has to travel a longer distance.

I'll see both lights turn on at once, and I'll see them as both being the exact same distance away from me. You standing in the field will see the light bulb behind me turn on, light bulb in front of me turn on, light from both bulbs hit me at the exact same time.

What we both observe is very relative, and this means that I can never know exactly what's happening now, where you are. It takes time for the information to get to me. I can only know me at this moment now. I can know the history of you – I just can't know you as you are as I'm saying the word you.

The problem is that gravity was at the time thought to be instantaneous. If all of a sudden a giant black hole were dumped into our solar system, the gravitational effects it would have on the orbits of the planet (according to thought at the time), would instantly effect everything. Any change in mass anywhere would instantly affect the entire universe.

According to special relativity, you can't know anything in the instant it happens.

Fraser: Even feel the effect of the gravity.

Pamela: Yeah. It takes time for gravity to get to you, but the theories at the time didn't say that, so there was this contradiction where changing the mass distribution is an instantaneous knowledge, but turning on a light bulb isn't instantaneous knowledge. It wasn't working so well for people.

Einstein went back to the drawing boards and he thought about how to make it work. The idea he came up with was based on the realisation that you can't really tell the difference between being accelerated due to a rocket, due to a car, and the force of gravity. So if I put you in a big, enclosed box (he thought about elevators at the time), and I cut the cable holding the elevator up, for a brief moment before you die at the bottom of the elevator shaft (and I really don't plan to do this to you, Fraser)…

Fraser: All right – good. I was a little worried.

Pamela: (laughs) During that period of time you're falling, you won't feel gravity. Now, if I take that exact same elevator and throw it out into space far enough away from any big mass that you're not going to feel a noticeable amount of gravity, you can't tell the difference between those two situations.

Fraser: Right.

Pamela: Now, I take that same elevator in the middle of nowhere in outer space and accelerate it at a rate of 9.8m/s^2, you're going to think you're feeling gravity.

I can take that exact same elevator, plop it down on the surface of the Earth, non-moving and you're going to feel the effect of gravity.

Fraser: Right, I see. So all of your interactions with the elevator around you, you can replace gravity with acceleration interchangeably.

Pamela: Exactly. You always feel everything the same way: gravity, acceleration, your body can't tell the difference. Sensors can't tell the difference. He started thinking that perhaps gravity is just the geometry of space and when we're getting pulled onto our planet Earth it's because the space and time around us is actually curved.

When we look at curves, we're seeing a plane that is getting deformed into a third dimension. Our maps are perfectly flat, but if we look at the actual roads, the actual landscape around us, we see what's two-dimensional on our map getting expanded into this third spatial dimension.

Fraser: Right, so a road that goes all the way around the Earth, it's actually just a great big curve – an arc.

Pamela: Exactly. If you have switch-backs on a hill, those switch-backs are going left/right, left/right, but they're also going up. We don't see that up in our map.

Now, with his theory of general relativity, he said gravity is taking our three-dimensional universe and bending it in this other, fourth dimension, that gravity is curving the space and that light is following these curves. When I shoot a light ray straight past the Sun, it's actually going to bend as it goes past the Sun, as it goes through the Sun's gravitational field.

Fraser: I think we've seen enough of these nova documentaries and stuff, where they've got this kind of grid of space, but it's two-dimensions. Then you put in the Sun and it's like a bowling ball on top of this rubber sheet and it causes a deformation in this rubber sheet. If you roll a smaller ball past the bigger ball, it's going to follow the curve of this deformed rubber sheet and you could theoretically go into orbit right around it. To the point of view of the smaller ball, it's just going in a straight line.

Pamela: Exactly. That's how Einstein was able to visualise our entire universe. This change in perspective, this change in the way we look at things allowed him to say that gravity can't effect things, but it takes time for the changes in the curvature to propagate outwards.

He was able to express gravity as a curved space-time, and to discuss the way changes in mass, changes in energy effect the location where they are as a digging out of space-time. This leads to the neat concept that if you have two really massive objects orbiting each other, they can actually create waves in the space-time continuum, just like moving a fan in water can create waves in the water.

Fraser: So is the space-time continuum the ether? Is that what they're propagating through (though they're not really propagating).

Pamela: We're getting back to all of space and time being able to ripple. The effects of the ripples have actually been observed in systems where we have pulsars orbiting one another and pulsars orbiting black holes. There's actually projects out there that are currently trying to directly detect these waves as they propagate through the Earth causing it to contract a little bit and expand back out as the ripple goes through the planet.

Fraser: Einstein made a bunch of predictions, right? If his theory is correct, there are some things we should see in the universe – and they're only starting to figure them out now.

Pamela: Some of the things predicted is light bending around massive objects. We see that – we see light bending around different galaxy clusters. Predictions were made based on the theories of relativity that we should get these gravity waves around very dense, quick moving objects as they ripple space and time as they move through it.

Fraser: I think he made a prediction of frame dragging, where the Earth or any massive object will actually twist up space-time as it turns.

Pamela: Gravity Probe-B made a series of measurements that people are in the process of analysing to see if we actually do drag our gravitational frame around with us, and what effects that has on the gravitational field of the Earth as we move. So we're taking our gravity and we're bending the space around us as we orbit around the Sun.

Fraser: What impact did relativity have on the old-school Newtonian physics? You know – objects in motion stay in motion and all those calculations they were able to make that served us so well over hundreds of years.

Pamela: The great thing about relativity is the effect is not noticeable in any measurable level at normal human speeds. In fact it's generally not measurable with anything you will notice in your day to day life. Newtonian mechanics is just a rounded off version of relativity. You take the little tiny additive terms in relativity and they basically reduce to zero as velocities get much, much smaller than the speed of light. It's only when the velocity of something approaches the speed of light that we start to have measurable effects from relativity.

Fraser: This is where astronomy comes in. that's the only place you see this stuff.

Pamela: This is the only place we really have to worry about it. We can directly observe it in the procession of the planet Mercury. We can make some rather sad but still measurable detections of how time changes if you put a clock on a plane and allow the plane to circle around the planet Earth and compare the time on the clock on the plane with a matched clock on the planet Earth, but this is still a very small effect. When you get out and start looking at massive objects – pulsars, black holes, high speed jets coming out of galaxies – you start to see these effects where it's like, "oh – that's a several percent change".

Fraser: Right. Sometimes I'll write stories where things are moving at significant percentages of the speed of light. They're going so fast.

Pamela: That's where you start to get measurable time contraction, where you start to get all these different weird little behaviours that crop up and we can actually observe them. We use Newtonian when we're dealing with slow things, and it gracefully melds perfectly in to relativity as we get to dealing with fast moving things and extremely large masses.

Fraser: I think that's a wonderful example of science in action (or the scientific method). You started out with a theory that did a really good job of explaining how motion and objects worked – it made wonderful predictions, but it broke down at a certain point. People didn't throw out the Newtonian physics, they just said "here it works, here it doesn't – we don't know why."

Later on someone came along and said, "here's a theory that covers both – it matches the expectations for things moving at slower speeds and provides explanations for things moving at faster speeds where the Newtonian physics breaks down." Any new theories that come out have to be able to stand up to that rigor.

Relativity breaks down at certain point, doesn't it?

Pamela: It breaks down at beginning and end times and when you hit that light can't go anywhere anymore problem. Black holes (which I think we're going to need to do a show on at some point in the not too distant future) are one of those places where once you get to the black hole relativity breaks down.

Fraser: What about the small end? Relativity doesn't mesh so well with quantum theory.

Pamela: Exactly. Quantum mechanics describes what's going on with the internal workings of atoms, with how electrons and photons are able to be both particles and waves simultaneously. This sort of probabilistic view of physics is something that relativity doesn't know how to deal with. In fact, Einstein didn't know how to deal with it real well. He sort of wished for the last half of his life that quantum theory would sort of go away.

The holy grail of physics right now is looking for a theory that is able to somehow tie together relativity and quantum mechanics. We're just not there yet.

Fraser: Right. So that would be one of the biggest pieces of scientific discovery ever. If it shows up, we'll let people know. I'm sure you'll have heard it from other people before us.

Pamela: I think everyone will know when that theory's finally found.

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