Astronomy Cast Episode 44:

Einstein's Theory of General Relativity

Fraser Cain: So, this week we are going to be coming back and doing part two of an episode we started back at episode nine. Back at episode nine, we covered Einstein's theory of special relativity, but that's only half the relativity picture. The great scientist made an even more profound impact on physics with his theory of general relativity, replacing Newton with a better model for gravity.

Why don't we give a quick synopsis of special relativity for listeners, in case they don't want to hurry back and listen to episode nine again.

Dr. Pamela Gay: Special relativity basically covers things like the famous e=mc^2 equation, which has appeared everywhere from *The Simpsons* to just about every other TV and cartoon thing out there, anywhere.

From there it went on to work on trying to figure out what people/observers travelling at different speeds perceive relative to one another. We end up with neat effects like time dilation, mass getting bigger as you move faster… end up with just a lot of really weird, neat thought experiments that we went into a lot of in detail in show nine.

One thing that didn't come out of special relativity is how does gravity play into all of this. In general, everything discussed in special relativity is just sort of dealing with, "so, you're moving. Let's discuss the motion." It doesn't get into the details of the force of gravity and how it causes things to accelerate. Einstein worked to try and figure out how to bring in gravity, and it took him a few years. In 1916 he came out with his generalized theory of relativity that introduced in gravity.

Fraser: All right, so what are the basics of this theory?

Pamela: Prior to Einstein, people had viewed gravity as just a force: the larger mass something has, the more it's going to pull on other things with that mass. After Einstein, our way of looking at it had changed a little bit. It's best summarised perhaps by John Wheeler, who said that Einstein's geometric theory of gravity can be summarised as space-time tells matter how to move, but matter tells space-time how to curve.

What this means is instead of seeing matter as something that's exerting some sort of invisible, magical force, he instead was able to conceptualise the universe in four dimensions and see mass as a way of bending the shape of space, such that when I'm falling to the Earth, it's not that there's some force pulling on me, but rather the geometry has me going downhill into gravity.

Fraser: That's that picture you always see of a ball suspended on some sheet of rubber, and there's some grid on the rubber and the heavier the ball is, the ball is kind of pushed down into that sheet of rubber and so if you have some object orbiting the ball, you can see how it would be trying to follow a straight line but it's actually going on a curved line because the heavier object is actually warping the space-time around it.

Pamela: A satellite is basically nothing more than a ball bearing rolling around the inside of a curved bowl. It's just a different way of visualising space and time that Einstein was somehow able to come up with. Every experiment we've ever done has come out showing that Einstein was completely right with everything that he came up with.

Fraser: so where, then, do Newton's calculations for the universe and Einstein's' calculations for the universe diverge, with Einstein being more correct?

Pamela: As you get to higher velocities, as you get to larger masses, the two of them begin to diverge. When you start bringing in energy, one thing that Newton's theory of gravity doesn't take into account is that energy has mass. This means that a laser is able to exert some sort of a gravitational pull the same way a stream of ball bearings would be able to exert a gravitational pull. Neither is going to pull very hard, but that pull is still there.

Where it starts to come more into mattering is, say you take an electron. It's a little tiny bit of mass. As you accelerate it so it's moving faster and faster and faster, velocity is just another form of energy. We have the kinetic energy equation (0.5mv^2) for non-relativistic cases. When you start looking at a high-speed electron, its mass noticeably changes as you make it go faster.

Fraser: I guess Newton didn't know of electrons, but it's at these higher speeds, these high-mass and energies where Einstein's calculations come in. That's amazing.

Pamela: basically anytime the numbers start to get too large to work with in your head, then you start worrying.

Fraser: Right. Okay, so what were some of the predictions made by Einstein? How were people able to prove that his calculations were correct?

Pamela: There's a lot of different ways. For instance, gravitational redshift is something he predicted. This basically says that as light tries to leave a high-mass source, it's getting pulled on by that mass so it's colour is going to end up changing. We discovered this by looking at the white dwarf Sirius B experimentally in astrophysics (other people have done laboratory experiments).

Sirius B is a white dwarf orbiting the brightest star in our northern hemisphere sky, Sirius. As this little white dwarf gives off light, the light trying to escape from its surface ends up getting shifted to the red. Similarly, here on Earth there's slight differences between what we on the surface of the planet and what a satellite ends up observing in terms of colour. As the light comes toward the surface of the Earth, it slowly gets shifted in wavelength toward the blue as it comes toward the surface of our planet. All these different little shifts add up.

Now, because our planet is fairly low mass and it has a fairly large radius, these differences aren't ones we're ever going to notice, but when we start looking at high-mass objects with small radii, there the gravitational pull at the surface is so strong that we can actually see the colour change by the equivalent of over 80km/s in the light trying to escape from the star.

Fraser: so the light is pulled back as it's trying to get away from the star, and then sped up. I guess my question is how can it be changing the speed of light? Isn't the speed of light just the speed of light?

Pamela: It's not so much changing the speed of light as much as it's changing the colour of light. This is where we refer to it as redshifted.

Fraser: Oh, so it's stretching out the wavelengths.

Pamela: Yeah.

Fraser: Right, okay. So the light is staying the same speed, but the amount of energy that's hitting us at any moment decreases because the wavelengths have been stretched out. So we see the colour changing toward the right end of the spectrum.

Pamela: Yes.

Fraser: Okay, I understand. So how extreme can that get? As you say, with a white dwarf… do we see that with neutron stars? Can we see their radio waves doing that too?

Pamela: I don't know how many miles per hour or kilometres per second the shift is for a neutron star, but it will become more and more shifted as you increase the mass and decrease the radius of the object.

So if we're looking at 80km/s or more for a white dwarf, we're going to be looking at significantly more than that for light coming off of neutron stars.

Fraser: And if only light could escape from a black hole.

Pamela: Here the trick is get something right on the edge of the event horizon and see what sort of shifting you get from that, but we haven't done that experiment yet.

Fraser: Right. Okay, so what are some other predictions that were made then?

Pamela: One of the other neat predictions is the perihelion shift in orbiting objects. Watching Mercury over the decades and centuries, human beings have made very, very precise measurements of its location. After Kepler came up with his great theories for planetary motion, Mercury only sort of kind of followed his rules. When Newton came along, they still followed in the exact same, sort-of, kind-of way, that had mercury shifting a little bit every year.

What's happening is its orbit isn't a perfect circle. It's a slight ellipse, so it's a little bit closer to the Sun sometimes, a little bit further at other times. We can see those slight changes in about how far it appears from the Sun in the sky.

The point at which it is furthest from the Sun appears to be rotating. So if you look down on the system with the Sun in the centre and you're looking down on the orbit, you can see the orbit itself slowly rotating with Mercury going around and around, sort of like the old kaleidograph toys we had as kids. You end up creating a spiral instead of a perfect ellipse.

Why Mercury's orbit slowly spiralled was a mystery until Einstein's theory of general relativity came along. It was actually able to take into account where this shift came from.

Fraser: That's really convenient. As I recall he came up with the theory, and then they were able to confirm that prediction right away.

Pamela: Yeah, there was decades and decades and decades of data piled up, so he worked his equations, scratched his head a bit, and said, "well, does Mercury actually do this?" The data was already there.

Other parts of this theory they had to wait for solar eclipses, they had to wait for satellite technology to be invented, and some of this things we're still working on trying to prove today. But with that, all of a sudden, a great mystery was completely solved.

Fraser: Okay, so what's another prediction that he made?

Pamela: We also have gravitational time delays. This actually means that time slows down the closer you get to the surface of a high-mass object. Here, the Earth actually counts. So the GPS satellites up in outer-space are constantly pinging us with data, "here's where you are, here's the time you're at." Except the time is passing at a different rate up in orbit, so the information they're sending us if they didn't account for general relativity would be wrong. They have to make corrections with how far you are from the centre of mass of an object, what the mass of that object is, and all of the corrections that they have to make to keep all of these different clocks running in sync with one another match perfectly with Einstein's theories.

Fraser: So the satellites are actually changing their clocks based on their position around the Earth, the speed they're going, just because of relativity. That's amazing.

Pamela: They actually don't change their clocks, because atomic clocks are just beats of atomic decays. But what they do is before they send us the timestamp information, they say, "here's what my clock thinks the time is, here's the equation that tells me what the time is on Earth relative to me." They constantly have to run all these equations.

Fraser: I wonder what the shift is. It would have to be in nanoseconds, right?

Pamela: It's very, very small. What's neat though, is they're able to make different corrections depending on who they're sending information to. When the GPS information gets sent to another satellite that doesn't have the same offset, that other satellite knows how to take that data and say, "okay, I'm not at the surface of the Earth, so I need to have this different correction put into place." So in order to keep all of our satellites and all of the people talking in terms of the same standard time, we have to do all sorts of gravitational corrections for these different time dilations that are going on at different altitudes.

Fraser: That is very cool. So may of Einstein's predictions we use on a daily basis. It's amazing.

Pamela: People who try to say, "I've never seen this," or, "Einstein must have been wrong," aren't paying attention to the different kinds of technology that are used to make different types of correction all the time for what Einstein came up with.

Fraser: All right, keep going. More evidence!

Pamela: Okay! So, now we start getting into the ones that are harder to prove, or harder to understand. I have to admit, I haven't fully wrapped my head around this one, but there's experimental data and I am all-believing in experiments.

There's what's called a gravitational time-delay as well. This was figured out by Irwin Shapiro, and is called the Shapiro effect. If you ping a radar signal from the surface of the Earth to Mars, and you measure the amount of time it takes for that radar signal to go from the Earth to Mars and back, you can actually get a time delay depending on how close that beam passes to the Sun. that time delay can be up to 120 microseconds.

To do this test, first Dr. Shapiro did calculations, then they went to Haystack Observatory in Massachusetts (which is actually where I worked in high school) and they shot radar signals to Mars when Mars was very close to the Sun on the sky. So the radar signal had to go just barely past the Sun, get to Mars and come back.

Then they waited until Mars and Earth were aligned such that the radar signal didn't really have to go close to the Sun at all. There they found there was a delay of only about 60 microseconds compared to what you'd expect if the Sun wasn't there at all.

This delay is caused by the light having to travel through the well of the Sun. imagine if you're taking a car ride. It's going to take you a different amount of time if you go from mountain peak to mountain peak – but cars don't do that. Instead you have to drive into the valley and drive back out.

Fraser: So it's almost like it's changing the amount of time that occurs for the radio wave?

Pamela: it changes the amount of travel time for the radar wave to go from the Earth to Mars and back.

Fraser: Right, so it puts in more time or less time?

Pamela: It puts in more time.

Fraser: That's crazy. It's not because the radio waves are having to go any longer distance, it's just that as it passes the gravitational well that closely, it gets more time.

Now, that's got to go to extreme levels, once again, with some of those more massive objects.

Pamela: You're going to get larger and larger time delays, the larger the object your light beam is trying to pass.

In general, we have no way of knowing exactly what time a light source left where it came from and the mass of the object it's travelling by. This isn't something that's easy to measure in practical circumstances.

Fraser: Right, because with this experiment they were able to send the beam from the Earth to mars and then from mars, I guess it bounced back. So they were able to know the timing, but if we're measuring the light coming from some distant galaxy passing near a quasar, we don't know when that light was sent, so we can't know what kind of gravitational time delay it's experiencing.

Pamela: Right. One of the neat things in thinking about this is, light from an object is constantly getting held up in its path as it travels through these valleys that are invisible to the eye but real to an object travelling through gravitational space. So the light is constantly getting held up by this valley, and held up by that valley, where each valley is a divot in the space-time continuum created by a massive object.

Fraser: Wow. So light may almost be experiencing not stops and stars, because it's always going the same speed, but it's going to be experiencing a longer journey as it goes past various objects on its twisting path to reach us.

Pamela: Exactly.

Fraser: All right. More.

Pamela: Okay, so here we get to frame-dragging, which I didn't explain really clearly back in episode 9. frame-dragging basically comes from a mass rotating. A neat little way to visualise this that the folks behind the Einstein project at Stanford University came up with is imagine taking a paper plate and putting a super ball in the centre of it after piling honey into the plate. So you have a pile of honey, stick a super ball in it, put a couple of peppercorns in the honey. The honey represents the gravitational field of the planet, your super ball represents the planet and the peppercorns are satellites.

Keeping the ball in the honey, if you rotate the ball it's going to grab onto the honey (frictional forces do this) and the peppercorns that are closest to the super ball are going to end up orbiting in a really noticeable way. The ones that are slightly further away from the super ball are going to pretty much sit there, but maybe get carried along a little bit.

As our planet rotates, we twist space-time around us the same way that super ball is twisting the honey around it. This is referred to as frame-dragging. It actually has the weird effect of a light beam travelling in the direction of rotation will be perceived to travel a little bit faster than a light beam travelling in the opposite direction of rotation. It's just perceived time differences, because our space-time is slightly different in each orientation because of this weirdo frame-dragging effect.

Fraser: So when you say travelling faster, is that getting a longer journey or it's redshifted?

Pamela: In this case it's actually the distance the light has to travel is slightly different because of the frame dragging.

Fraser: This is one of the things that Gravity Probe-B was attempting to work out.

Pamela: Gravity Probe-B was this great satellite that had some of the most precisely built gyroscopes ever built by human beings. There were four different gyroscopes that were oriented in two different axes, so they're measuring the orientation of the satellite very accurately. They were immersed in super fluid, so that there's almost no friction between the parts as they're spinning.

Unfortunately, they made everything so precise and so well, but when they were dipping the ball bearings that things were rotating about, they dipped one side and then the other, so the surface wasn't constant on both sides. It's sort of like when you look at a plastic ball, you can see the same around the centre from how they made it in the mould. There were slightly different electromagnetic properties on the different parts of these ball bearings, and as they rotated they ended up creating electromagnetic fields that affected the final results.

So, they were hoping to release the Gravity Probe-B results by now, but at this point NASA's actually given the results an extension, and they're probably going to be publishing all of their results come December.

We still don't know the final results of Gravity Probe-B, but we've learned a lot about precision construction of gyroscopes. Luckily, they have the mathematical tools to correct for these inadvertent electromagnetic fields they ended up producing.

Now, all of that caveat said, when they get to their final results, when they've figured out how to correct for everything that needs to be corrected for, they should be able to look at their measurements of how the gyroscopes stayed oriented throughout the different parts of the orbit and be able to say "aha" these changes were due to the effects of general relativity, these effects were due to these different sub-parts of that theory, including frame-dragging.

Fraser: But there are also other places in the universe you can look to see things like frame dragging. Aren't there orbiting binary-neutron stars and things like that?

Pamela: Right. When you look at really high-mass systems, we call these double degenerate binaries. This is where you have either a neutron star and a black hole, neutron star and a neutron star, sometimes a neutron star and a white dwarf (but those don't have as amazingly gravitationally phenomenal effects where you see gravitational radiation and can hope to see gravitational waves).

When you get extremely high-mass objects orbiting very close to one another, they twist up the space around them creating gravitational waves. It's sort of like if you imagine stirring your finger around in water, you're going to end up creating waves. In this case, we have two high mass objects orbiting around one another, each of them carrying their little divot in space, their little hollow that they're making with their gravitational mass around in space with them. As they spiral, they end up radiating gravitational energy and creating gravitational waves as they move.

Fraser: I think you're going to have to explain gravitational waves then.

Pamela: (laughing) That's starting to get into an entire conversation.

Fraser: That's true, it will have to be a whole separate show, but at least give the short version.

Pamela: Okay, I'm going to link to this really neat animation because it's hard to understand it just verbally.

Start with your mental picture of a big heavy ball in your plastic cloth with the grid in it. Set that object rolling around in that plastic sheet. As it rolls around in the plastic sheet, it starts to generate waves in the plastic sheet. Those waves generally aren't going to occur if you only have one ball in real space and time, but they occur when you start getting two different balls orbiting around one another. They generate waves.

Now, you can also end up with these waves when you have almost anything that's asymmetric going on. If you have a star explode and it doesn't explode perfectly symmetrically, that sudden change in the distribution of mass in a not-perfectly-spherical way will end up triggering gravity waves. Basically, anytime you have an asymmetric event, you can end up with gravitational waves.

This also means that a flattened planet could in theory (if it was massive enough – like neutron star mass), as it rotated, create gravitational waves. One neat way to think about it is imagine a giant mountain. That mountain on top of a planet ends up stirring space as it goes around.

So anytime you have an asymmetry, you end up with gravitational waves at one level or another.

Fraser: Right, and I think in a future show we'll cover the experiments that are going on to actually work this out, both ground and space-based.

I did an interview with somebody working on that project, on the ground-based one, and as those gravitational waves cross the universe and pass over us, it actually causes us to grow and shrink, and that's what they're measuring.

Pamela: Yeah, the space we're occupying, the space-time continuum itself, ends up getting distorted by these waves. So if you imagine the grid that little ball is sitting in, in our stupid mind's eye picture that must have come from some TV show at some point in time… if you bounce up and down on that, like it were a trampoline, the grids are going to expand and shrink, expand and shrink.

If you're a person attached to that grid, you're going to expand and shrink. As a wave travels across the grid, different parts of the grid are going to expand and shrink at different times. With the detectors here on the planet Earth, we start from the knowledge (we think) or assumption that gravity travels at the speed of light. So we think, "if we get a growing and shrinking at this location and this time," then if we get a growing and shrinking at some other location delayed by the proper amount of time, then that's a single gravitational wave event.

Fraser: So where do Einstein's theories fall apart?

Pamela: They start to fall apart anytime you start dealing with quantum scales or you get to the point of things travelling at the speed of light that have mass. So when you get inside of a black hole, and when you get to the first moment at the beginning of the universe. Anytime you start dealing with the insides of an atom. Those three places, it falls apart.

People have been trying to use string theory to unite gravity and quantum theory, and it hasn't worked. One of the great searches of our current scientific generation is the theory of quantum gravity. We used to say, "we're looking for a grand unified theory of everything." Right now, I think we'd settle for quantum gravity, because once we get to quantum gravity, everything else should fall into place naturally. We've built theories that hold everything together except gravity.

One of the problems is how do you get from a geometric understanding of gravity, where you see gravity as a physical deformation of space, to a particle theory view of the universe that has everything being communicated via bosons, where everything is field and force based. There's a difference in thinking between the two different theories.

Einstein saw space as physically changed by a mass being put into the universe. A particle physicist will instead say a high mass object is associated with a lot of Higgs particles that give it mass and gravitons communicate gravity between the scalar gravitational --- it gets into all these particle, physical things where we're now talking about particles no one has even discovered yet.

It's a complicated issue and it's going to be interesting because if we do some day find these particles that communicate gravity, it means that gravity isn't just a geometric thing, it's still part of the particle physics universe.

Fraser: Einstein died trying to work this out.

Pamela: Einstein died trying to work this out and he really hated quantum theory.

[laughter]

One of the main premises of quantum theory is nothing in the world is certain. Everything is a probability. There is a probability that all of the electrons and protons in my body will spontaneously line up just right that I will fall through the chair, through the floor and land in my kitchen right now, to be closer to the coffee pot (for better or worse, that won't happen and I'll have to stand up, walk downstairs and get more coffee when we're done recording).

Einstein didn't like this. The way he referred to it as, "God doesn't play dice." He wanted there to be a, for this action the universe has this reaction, instead of for this action the universe has a probability for this reaction, a different probability of this reaction, and a really low (but not zero) probability of me falling through the floor right now.

Fraser: Well, I think we'll put another whole show just on quantum dynamics, quantum mechanics at some point, because it's key.

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