AstronomyCast Episode 236 for Monday, October 24, 2011: "Einstein Was Right"

Fraser: Welcome to AstronomyCast, our weekly facts-based journey through the Cosmos, where we help you understand not only what we know, but how we know what we know. My name is Fraser Cain, I'm the publisher of *Universe Today*, and with me is Dr. Pamela Gay, a professor at Southern Illinois University – Edwardsville. Hi Pamela. How are you doing?

Pamela: I'm doing well. How are you doing, Fraser?

Fraser: Doing really well. Once again, we're having a Google Plus hang-out with our eight close friends on AstronomyCast. Everybody wave.

Pamela: [laughing] Studio audience is unheard by the broadcast audience.

Fraser: Exactly because we've muted them all! Um, but it's really fun and it's been really helpful for all of our episodes. People have been giving us ideas and fixing our mistakes during the show, so it's super. So if you want to join us all you have to do is circle me or Pamela in Google Plus and then we send an invite when we're going to be doing the recording, and if you happen to see it, then come join us and hang out with us. So…it's really fun. OK, you're back from China

Pamela: China, France, DC, all points in between.

Fraser: Austria…yeah, you're here for a little while.

Pamela: It's going to be one of those episodes where my body is just like jet-lagged, "Why are you awake? Why are you awake?" There's this voice in the back of my brain saying, "the Sun should not be up, nor should you." So please pardon any exhaustion-induced word slippages.

Fraser: Alright. OK, So at least once a week we get an email from a theorist claiming that Einstein was wrong. Well, you know what? He wasn't wrong. In fact, Einstein made many specific predictions to help validate his theories, and each time, experiments have shown that Einstein was right. In fact, some of his more controversial theories were only tested experimentally in the last few years. And before we get into this, there's a great website that you might want to check out by Steve from our tree lobsters, and it says waseinsteinwrong.com, and if you go there, you'll find out whether or not Einstein was wrong. It's…so let's talk about Einstein. So last show we talked about Einstein; we talked about his history and his life and his theories -- less about special relativity and general relativity because we've talked about that in the past, but we talked about a lot of his love life and how he moved around from university to university, but the really great thing about Einstein is his theories. So Einstein is one of these great examples where you can see science at work, where a scientist makes these predictions about how his or her theories predict the way that nature seems to work, and Einstein is one of these wonderful examples where you've got just prediction-experiment-prediction-experiment, and so what we wanted to do was talk about the different kinds of experiments that he did. We've got the ones for special relativity and general relativity, and each one of these experiments just, you know, he said if you go and check out this, you should probably see that, and the experimenters went out and did and found what he predicted and everything worked out great. So, let's talk about…let's start with special relativity, because that was sort of the first…

Pamela: It's where he started.

Fraser: It's where he started, and right away he upset all of physics with a bunch of crazy ideas, but made some concrete predictions, and this is the big difference. When the woo-woo crackpots send in their theories, you know, they're like, "Einstein was wrong!" but they don't actually include the predictions they make about why he was wrong and what we should see instead. You have to explain everything that's already been seen, plus you have to make some new predictions about…to show what's different or explain something that is unknown. I'm talking too much -- Pamela!

Pamela: [laughing] OK, so the best place to start is with the speed of light because everything that Einstein did sort of hung off of the basic idea that the speed of light is the same for all observers in all directions, and the easiest way to prove that is to take some sort of a light source that you'll be able to tell if something changed. So good coherent light source, something like a laser beam, something that's been made coherent by passing through the right set of lenses -- all of those things count. So take a coherent light source and split it. You can do this with a semi-silvered mirror so that half the light gets reflected and half the light passes through (this is how those one-way mirrors work). Now, if you split the light just right you can have some of the light go off in the direction of, say, the Earth's motion, some of the light go off perpendicular to that, and then you can recombine the light, and if the distances that the light should have traveled if we weren't moving are the same in both directions, and you measure that the light took the same type of travel in both directions even though the earth is moving, well, that starts to show that, well, the speed of light is constant irregardless of the motion of the person who's doing the measuring and doing the light sending off into space as well.

Fraser: Right, so can you give me then an example? So he made the prediction that light should move at the same speed no matter where it's coming from?

Pamela: Right, so the first experiment of its kind was the Michelson-Morley experiment, which predates Einstein, but then Einstein went on to basically say, 'Look, here's why it's going on: really there's no ether,' and every experiment that's been done since then shows over and over and over speed of light is the same for all observers.

Fraser: Right, so they did this experiment they shone this light through a mirror, it split up and the speed of light was the same for both people, *even though* one group was moving one way around the Earth (I guess *with* the motion of the Earth), and the other group was moving *against* the motion of the Earth.

Pamela: Right, so what you usually do is you shoot two beams: one in the direction of motion, one perpendicular to the direction of motion, recombine them; if the light combines you get pretty little interference fringes in the right way, you know everything's good. Now, the next thing that came out of special relativity is that since the speed of light is the same for everyone, time is not. So this is where we've had to do experiments of launching atomic clocks, of flying clocks around the planet -- all sorts of crazy things to show that, well, time does change.

Fraser: Right. So he made the prediction, then, that if light has to stay the same speed, then the thing that has to give is going to be time. So if you're moving faster, then you're going to experience time differently than a person who is moving slower compared to each other. And so the experiment that they ran was they had to fly these atomic clocks in airplanes and later on spacecraft, right?

Pamela: Right, and sure enough, the differences between the two clocks was exactly what was predicted. So yeah, we have the speed of time changes even though the speed of light does not.

Fraser: OK, that's prediction #2. Were there any more?

Pamela: Well, so then we also have the whole relativistic mass and energy problem. So this is the idea that $E=mc^2$ – now, that wasn't part of the original special relativity paper, but the idea that mass and energy come together started with special relativity and evolved as he detailed out the theory. And so here we have things like cyclotrons that accelerate particles to extremely high velocities and then collide them together. Now, when these collisions happen you end up with a burst of energy concentrated in a small place, and that energy very quickly condenses into particles. Now, the neat thing about the way this happens is the particles all have a given amount of mass. When you add up all the mass of the particles, that mass is greater than the rest mass of the particles that went in, so you might fling a couple of electrons, or a couple of protons at close to the speed of light and circles and circles and circles around the cyclotron, collide them together and the array of particles that come out weigh more than a proton at rest, an electron at rest, and when you try and figure, "well, where did all of that mass come from?" and you take into account the kinetic energy that was built up during the motion at close to the speed of light…the kinetic energy isn't a function of 1/2 mv2 like it would be if relativity didn't exist, but rather there's relativistic effects that increase the mass as the particle starts going closer and closer to the speed of light. So we see the relativistic increase in mass due to the speed; we see the $E=mc^2$ all in these particles that come out of the collision.

Fraser: That's really cool. It's in the cyclotron that you're injecting energy from outside, and that energy is turning into mass in the collision.

Pamela: Yes.

Fraser: That's amazing. Yeah, and so he had made this prediction…I don't know did he predict? Did he say, "when you build particle accelerators, if you crash them together…?"

Pamela: For him it was a matter of if you take a mass, any mass, and you accelerate it to closer and closer to the speed of light, what you're going to see is the apparent mass of the object increases, the relativistic mass of the object increases.

Fraser: Yeah.

Pamela: So then, we saw that when we started actually well using cyclotrons to accelerate things to close to the speed of light.

Fraser: That's really cool. OK, so just to clarify then, we've got three, so were there any more? Sorry, before I…were there any more?

Pamela: So we had time contraction, we had mass energy equivalence…

Fraser: Speed of light being the same…

Pamela: And the speed of light – those are really the key things for special relativity; those are the big factors that we have to deal with.

Fraser: OK, so that wraps up the predictions that he made for special relativity, but then really his greatest theory, the one that blew everyone's minds was general relativity, and this is what I said at the beginning of the show -- that he made some predictions with general relativity that astronomers haven't had the capability to test until just within the last five years. It's crazy!

Pamela: And we're still working at getting things totally at the level where everyone's like, "Yeah, yeah, yeah, OK…you proved it."

Fraser: "…Einstein was still right." OK, So let's run through some of the predictions that he made and try to put them in order of when they were able to do experiments to prove that they were true with general relativity.

Pamela: Well, the easiest one, in some ways, was the perihelion precession of Mercury.

Fraser: What? So what was going on?

Pamela: Lots of fancy words there, so….

Fraser: Fancy astronomy words…so what was going on with Mercury?

Pamela: So, with any orbiting object, according to Kepler and later Newton, orbits are ellipses (flattened circles to perfect circle -- somewhere in there) that have at the foci of the ellipse (Google ellipse, you'll see what I mean)… you have the star, the planet, whatever's being orbited. The perihelion is the closest approach to the Sun. So as Mercury goes around on its elliptical orbit around the Sun, it has a closest approach, it has a furthest approach. Now, if you were to erase everything else from the Solar System – so you have no other planets, if you were to make the Sun a perfect circle, then Mercury's orbit would just happily be exactly the same orientation for all of time. Now, the truth is Sun's not a perfect circle; it's a bit squished around the middle – it's "oblate" is the fancy word. And so that oblateness causes some effects on the orbit, makes the orbit slowly change over time. Fact is, we do have seven other planets, and a bunch of other rocks and icy bodies, and over time those rocks and icy bodies and other planets for the most part have effects on Mercury, but when you add up all these other effects, and you look at Mercury's orbit, Mercury's point of closest approach to the Sun is slowly moving over time in a way that all those other effects can't take account of. It's precessing like the top of a spinning top at a rate that's faster than would be expected, and when Einstein integrated gravity into his theory of relativity, he found that precession was predicted, and the thing was is that he could actually predict how much the precession would be at a level that was greater accuracy than they've really done in their measurements at that point. And sure enough, as we've gotten more and more accurate measurements, we're able to find, "Wow! He nailed it! He was exactly right in being able to tell us where we can find Mercury at any given moment as it precesses around the Sun."

Fraser: And that is really just the perfect theory – that you take something that astronomers have been puzzling about for decades and come up with the math and the theory and go, "Oh, if you run my math, this will explain what you're looking for," and that's just getting out of the gate. That's just, you know, "just to warm up the engines, I'm going to explain some of the unsolved mysteries that you've got in front of you. And now, here's a bunch of crazy predictions that didn't even occur to you that I'm about to make about the Universe, so, you know, feel free to go out and prove that those are true too." So, that's fantastic. Right, so that precession of Mercury -- perfect. So, what was next?

Pamela: Well, and the thing that went in with the precession of Mercury is the exact same physics applies to Mercury going around the Sun, applies to binary stars, applies to binary pulsar systems, and we're seeing this in dramatic ways as we look at higher-massed compact objects over time. So there's a pulsar that we see…actually, it's precession is 4.2 degrees per year, so this is like high-speed precession with high-mass objects. Now the next big thing of evidence that he came up with was the deflection of light by gravitationally massive objects, so starlight getting bent around the Sun…and I have to admit, I and many other people are guilty of saying, "…and Eddington went out and showed this when he looked at the 1919 solar eclipse," and yeah, Eddington did see light bending, but the thing is people have argued over whether or not that's sufficient evidence ever since because, well, even Newton predicted that light would bend. It's the amount that it would bend, and when you look at the errors in Eddington's measurements, it's just not quite entirely conclusive, and so people are still…this is the one piece of evidence that people are still going, "OK, is it fully conclusive?" And we look at things like Einstein rings, where we don't know the mass as precisely, but we're starting to get as precise as you could hope for, not by looking at the optical light of starlight, but rather by looking at background quasars, using radio astronomy to get highly precise measurements, and with our most sophisticated radio telescopes, we're just starting to be able to say the error bars are small enough that, yes, the amount of deflection of light by massive objects does conclusively say Einstein was right.

Fraser: Right, and so this was this theory, right? That he said that we should look at gravity not as some kind of attractive force between objects with mass, that we should see it as a bending of the very fabric of the Universe, that in fact, it's this depression in the space-time. And so both massive objects and energy will follow the bended curves in the space-time caused by these massive objects, and this bending of the light that we see matches this prediction exactly, and as you said, they're still testing it out to higher and higher degrees of accuracy: "Why use a star going around the sun? Let's use a distant quasar that's been traveling for 12 billion years."

Pamela: Well, you can also just get more precise measurements that way because of the radio light; it's just easier to use radar -- radio rather -- and quasars aren't moving. The problem with stars is they're orbiting the same galaxy we're orbiting, and so it's the quasars in the background that are the most non-moving things in the sky.

Fraser: OK. Cool, cool. So next…

Pamela: Gravitational red-shift.

Fraser: Gravitational red-shift…so what is that?

Pamela: This is the idea that light, as it climbs out of a gravity well, light, as it shines perpendicular to the surface of the Earth, of a black hole, of a white dwarf, of anything with gravity will lose energy as it climbs. So it climbs at the speed of light, light travels at the speed of light for all observers, but no one ever said it wasn't going to change colors in the process. So sunlight as it falls to Earth gets blue-shifted, and sunlight as it climbs out of the Sun's gravity well gets red-shifted, and that's all well and good, but it's kind of hard to measure. So the key experiment was actually done at Harvard, and the place where it was done still exists, and if you go wandering the Harvard physics department with the right person in hand, they'll point it out to you. There's a tower there where they shined (or more or less emitted) gamma ray energy up the tower, and they measured the slight change in color of that light that was a result of climbing up the Earth's gravity well, and this is something that…what's neat about it is one of the problems with light getting off of a black hole is it not only can't go fast enough, but it actually gets red-shifted into oblivion.

Fraser: Right, so you can imagine astronomers now have demonstrated this in all kinds of different ways. I mean, they demonstrate it from light coming from different quasars, light coming from planets, from stars, from neutron stars, and all the different kinds of radiation, and they are able to make these predictions again and again and again -- so that's a good one.

Pamela: Yeah, so the more high-mass objects we look at, the more we're able to see that this is really going on out there.

Fraser: Really cool. OK, so that's three so far? Any more?

Pamela: Um…yeah. So…

Fraser: Hit me!

Pamela: So then we have frame dragging, which is one of my favorite ones. So this is the idea that a rotating body actually rotates the space-time continuum around it, and that the way time passes, the way your energy changes (depending on which direction you're going around an object) is measurable in terms of there's differences depending on the direction you go in. So the Gravity Probe B is actually *the* way we finally said, "Yes, there is frame dragging!" There'd been earlier experiments. We'd launched the Lego satellite, looking to try and measure it using that, wasn't entirely conclusive; we'd seen some evidence from the Mars Global Surveyor as it orbited Mars, but it was finally when we launched Gravity Probe B with its extremely precisely made balls in its gyroscope that we were able to by looking at how over time those spinning gyroscopic balls changed, we were able to see, "Yes, the changes are what was predicted by frame dragging." This is just one of those awesome things that we have to take into account when we measure things. They actually did it relative to the star IM Pegasus. They measured the alignment of the gyroscopes relative to a star, and it builds up over time, so what they were able to see was a change that added up to 37 milliarcseconds over the period of the experiment.

Fraser: So, just to understand this correctly, you've got the satellite, you launch it in space, you spin up these gyroscopes so that they are perfectly aligned with this star, and then you have the spacecraft going around the Earth in such a way that if there was no such thing as frame dragging, then you could go a million years and these gyros would still be perfectly lined up with this star, but instead because the Gravity Probe B spacecraft is moving through the Earth's gravity field, and the Earth is turning, you get this change in the orientation that comes purely from the way the Earth's gravity is warping space-time. Did I get that right?

Pamela: Yeah, now it's not that you have the pull of the rotation lined up with the star. You're looking at how the motion of objects change relative to the star, but yeah, it's…we actually see these differences over time, and it's really kind of cool.

Fraser: That is really kind of cool. What was that? Four? I think there's more.

Pamela: Well, we also have gravitational waves.

Fraser: Gravitational waves, right, and we've done whole shows on this. Gravitational waves – this is the idea that massive objects, as they move through space, should actually send out waves that stretch and contract space-time itself as they emanate out from the object, and the more mass of the object the more violent the events, the bigger the gravitational waves that we should detect. So, he made this prediction, and we still aren't entirely sure that they're there, right?

Pamela: So this is one of those things where we've actually given a Nobel Prize out for this one.

Fraser: That's got to count for something.

Pamela: What we've seen is, again, you go back to the idea that given Newtonian physics, you have two objects orbiting each other, they will continue to orbit each other forever at the same distance assuming there's no frictional effects, no external forces, no mass transfer, so you have two non-interacting objects with no external forces orbiting one another and they'll happily just keep doing that. Now, the reality is that when we look at high-mass objects orbiting each other, when we look at pairs of pulsars, when we look at white dwarf/black hole systems, any combination of white dwarf, neutron star, black hole, we start to see their orbits are changing, their orbits are getting closer, they're decaying over time. It's not due to an external force, it's not due to friction, it's not due to mass transfer. It's due to energy being radiated away from gravitational waves. Now, what we haven't detected yet is those waves propagating through space. We've seen the energy they give off, but the much-sought reality is as those gravitational waves propagate through space, they should actually, in the direction they're propagating, cause objects to temporarily get closer and further apart, and this is where devices have been built. There's several laser interferometers on the planet Earth that have been set up in giant triangles, where we'd expect that you'd see at one set of these interferometers, the distance getting closer and then further, and then at a speed-of-light-traveling-that-distance time later, we'd see the same thing at one of the other detectors, and we just haven’t seen it yet. And partially this is because, well, things like the UPS truck can get detected as well, so there’s a lot of background noise.

Fraser: Right. Right, but I think that the…I mean, I think people have known that a ground-based method of detecting this is not great. The way to do it is to launch spacecraft and have them keep track of their distance to each other, and then we’ll know with a higher degree of accuracy. And you’re kind of waiting for great, big violent events to happen nearby, and so you might not get enough of them. So, again, you don’t get enough chances of detection, so this comes down to really the quality of experiment, and we’re still waiting for the funding and for the approval for people to launch the spacecraft that will actually make this detection. And will that be it? Will that be the final prediction made by Einstein to be experimentally tested?

Pamela: That’s really the last one that people are really waiting for is gravitational waves, and LISA is the mission that is currently somewhat undead with NASA -- neither completely canceled nor actually funded to be built. It’s a set of three spacecraft that shoot lasers between one another to measure their separation and look for that change in distance that comes from a gravitational wave passing over them. So hopefully, we’ll get there.

Fraser: So, one questions though: you said that the energy gets lost. Where does it get lost *to*?

Pamela: It gets lost from the system. So the way to think of it is as a candle burns, it gives up its chemical potential energy to the room around it in the form of transfer of infrared radiation to the air molecules around it. So the candle is losing energy to the room. In the case of binary star systems, they’re giving up their gravitational energy and radiating it through space, and that energy’s radiating away and nominally changing the distance between things as it goes.

Fraser: Right. Across the whole Universe…

Pamela: So the Universe is conserving energy, but the star system isn’t.

Fraser: That’s really cool. So the next time someone tells you that they think Einstein was wrong, hold up eight fingers and have them run through the three special relativity and the five general relativity predictions that

Einstein made, and have them explain how their alternative theory gives…also explains all those predictions that Einstein made, and then makes further predictions…

Pamela: And take away their GPS unit because if they don't believe in relativity, they don't believe in GPS.

Fraser: Right. But that is the level of proof that they have to demonstrate. So that was great, Pamela, thank you very much, and we'll talk to you next week.

Pamela: Sounds great, Fraser. Talk to you later.

Fraser: Bye.