Astronomy Cast Episode 269 for Monday, June 11, 2012:
Mass

Fraser: Welcome to Astronomy Cast, 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 great. So once again, I want to remind people that we are recording this episode of Astronomy Cast as a live Google Plus hang-out on air, so if you want to watch us live, you just have to come to either the Astronomy Cast page, or Pamela's page, or my page on Mondays at noon Pacific, 3 Eastern, 2 Central, 9 in London time, and you can watch us record live, ask us questions, and just sort of watch us goof up recording the episodes, but the other thing that we want to announce this week that's really cool is that we now have a new…the Cosmoquest Academy, where we're going to be teaching you astronomy directly. So can you explain this, Pamela?

Pamela: So the first course that we're offering, we're going to have "Dear Astronomer," Ray Sanders teaching a course on Solar System 101. It's eight one-hour classes taught across four weeks, and our goal is to give you that Astro. 101 section on planets, teaching you about how the Solar System formed, the different types of planets, how extra-solar planets are formed, and the diversity of worlds that occupy our galaxy. If this works, we're going to continue to build more and more classes in the future. We are offering all teachers professional development hours for these courses, and we also have a certificate program, and so by taking this entry-level course, over time, you'll gain access to more advanced projects and more advanced courses. In the future, I'll probably be teaching something on CCD data reduction, and photometry so that you can get engaged in things like variable star observing.

Fraser: Yeah, and Ray Sanders is a great guy; he runs the website, "Dear Astronomer." He's constantly been educating people, and we've worked with him in the past, and it's going to be a really great fit to have him there teaching people. And I know, Pamela, you're going to be dropping into some of these courses as well, so this is a way to sort of take your astronomy knowledge to the next level without, you know, going in and plunking down all that money for a PhD. in Astrophysics.

Pamela: And we're restricting enrollment in the course to just 8 students, and we're doing this for a couple of different reasons: one is so that both Ray and I can both fit into the hang-out with you, but the other is that we wanted to have as close to one-on-one instruction as we can. It does have a price; it's $240, but that price was set based on how much would it cost to sign up for yoga, how much would it cost to take advanced karate lessons, how much do I spend on horseback riding lessons...and so we wanted this to be consistent with how much money you'd pay to advance a hobby interest.

Fraser: That's cool! So people can find out more; they go to cosmoquest.org/cosmoacademy. Is that right?

Pamela: I believe so. There's a link. Just go to cosmoquest.org; click on cosmoacademy.

Fraser: Alright. Well, let's get rolling with this episode then.

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Fraser: So last week we talked about energy, and this week we'll talk about mass, and here's the crazy thing: mass, matter, the stuff the Universe is made of is the same thing as energy. They're connected through Einstein's famous formula: E=mc2. But what is mass? How do we measure it, and how does it become energy, and vice versa? And so the really cool thing about this actually, I mean, although we said the date was June 11, we're actually recording this in early July, moments before a rumored big announcement from CERN about the discovery of the Higgs-Boson. So what's going on?

Pamela: So this is pure conjecture. People are saying, Fermilab folks are gossiping that on the Fourth of July, one of the American favorite dates to announce scientific things and to land things on other planets, rumor has it that on the Fourth of July, they're going to announce that the Higgs-Boson has been found, and that it has a mass equivalent to the energy of 125 electron volts, and what's kind of awesome to me about this is this is completely consistent with the standard model, which is an experimentally-based model that has no underlying, "it has to be this because" explanation. And I just love it when physics refuses to give in to the crazy, radical ideas out there. And there's a ton of people who are horribly upset about the projected mass of the Higgs-Boson because they want it to be weird, because if it was weird it would have confirmed the "Super-Symmetry" theory, it might have confirmed many of the other "here's physics, let's build particles on top of physics" vs. instead "here's particles, let's build the physics on what we observe," and the Universe is currently saying, "I just want to be observed, I'm not going to reveal my lower-level truths…not yet."

Fraser: Right so then this is fantastic, and obviously we're going to report this, and I think one of the things people have been asking us right from the beginning of this show is they want us to do an episode on what are the big discoveries that have changed since we started recording Astronomy Cast, and we're always really excited to do that, and then we sit down and we pull out a checklist and then we just kind of go "Hmm…Nope, not really, not much has changed. " This has changed…that five years ago when we started doing Astronomy Cast, the Higgs-Boson was a completely theorized particle. There was no way that the particle accelerators of the time could get to the bottom of this. It is now with almost whatever…6 sigma level of accuracy gotten to the point that it is a done deal. It is a slam dunk.

Pamela: And as we creep towards our 300th episode, we are starting to finally accumulate enough of these big changes that maybe for 300 we can do one of these episodes.

Fraser: For 300…yeah, yeah, but what's great is it means that Astronomy Cast is still as relevant if you want to go back and listen to the early episodes, and this is all part of the plan. So let's go back to mass and talk about sort of one of the things. You know, there's always the people who say, "I weigh 42 kg," there's always the pedants who always want to say, "Oh, you mean mass not weight," so what is mass? When physicists consider this concept of mass, what are they talking about?

Pamela: Mass is best defined as that property of your body that causes you to accelerate less effectively when a force is applied to you, so if you have a little, tiny mass, and someone applies a big force, you go shooting off. If you have a giant mass, and someone applies the exact same force, you might slightly move because there's this equation: force equals mass times acceleration, and this ties together how everything moves, and how things change the direction that they're moving. Acceleration is defined as either a change in the speed that you're going, a change in the direction you're going, or a change in both at the same time.

Fraser: And so, how is that different from weight?

Pamela: So, weight is the mass that you have multiplied by the acceleration of gravity, which is the rate at which you would accelerate if someone decided to drop you off a cliff, which I don't recommend doing. So your weight is your force on the chair, it's your force on the scale, and so one way that a lot of scales work is they have the equivalent of a tightly-wound spring pushing up on the top of the scale, and when you stand on it, your mass times the gravitational acceleration of the planet Earth creates a force back down on that spring, and by measuring how much the spring is compressed by your weight, your gravitational force down onto the scale, this is how we get at your weight. And the actual units of weight – that's going to be newtons, not kilograms, but people use kilograms anyway.

Fraser: And that's the confusing part is my scale does not measure in newtons. There is not even a setting for newtons, so when I write an article and I'll say if you weighed this on Earth, you would weigh that on Mars, and I'd say if you weighed, whatever, 200 pounds on Earth, you would weigh… I don't know, 70 pounds on Mars, and if you weighed 100 kg on Earth, you would weigh 30 kg on Mars, and people slap my wrist and say, "Whoa! You can't do that! A kilogram is a measure of mass, not a measure of weight." And I go, "You know, fine. Show me on my scale where I switch it to newtons because it does not exist." So until then…and then I have to write these big long explainers just to handle the pedants, so that's what you would…but when I say you would weigh 30 kg on Mars, that is completely wrong, right? The pedants are right; the scalemakers are wrong.

Pamela: It's quite confusing, and yeah, no. Kilograms is a unit of mass, newtons is a measure of force, meters per second squared is acceleration, and your weight is actually your force on the Earth.

Fraser: Right and so what's really important, then, is your mass never changes, no matter where you go in the Universe.

Pamela: Right, but your weight does.

Fraser: Your weight does, and so I guess this is an example: I take that scale, take it up into space, try to stand on it…weightlessness, it floats away.

Pamela: One of the neat exceptions is even though the planet Saturn has a much greater total mass than the Earth (it's huge!), and the force of gravity -- and we've talked about this in other shows -- the force of gravity is proportional to how much mass an object has, and how far you are from that center of mass because Saturn is huge and very low density. If you were roughly out at its outer cloud levels, your weight would be very similar to your weight on the surface of the planet Earth, and it's because of that relationship between mass and distance squared yielding the force.

Fraser: So then, what impact does mass have in the kinds of calculations…how to astronomers get at the mass of an object?

Pamela: There's lots of different ways. The base description is you push on something, and the amount that it accelerates gives you its mass, or you collide things, and this is the conservation of momentum idea: if you collide two objects, you know their velocity ahead of time. There's a relationship between their masses and their velocities, so you can get at things by looking at collisional systems, you can get at things by looking at how they accelerate, and then gravitationally by just comparing the forces between two objects.

Fraser: But obviously we can't collide things with super-massive black holes, right?

Pamela: And this is where the gravitational part comes in.

Fraser: Right. OK.

Pamela: And so here, when you're trying to get the gravity of a planet with moons, you can assume the masses have point like…their masses are so small you can basically ignore them, and so you look at their orbital parameters, and based on their orbital parameters, you can get the mass of the planet. So you look at how far are they from the center of the planet, you look at how fast are they orbiting the planet, and you can calculate using orbital equations the mass of the much, much larger planet that is getting orbited. You can calculate the mass of the Sun by looking at how the planets orbit the Sun. Trying to get at the mass of moonless planets, like Venus and Mercury, kind of meant we had to send spacecraft there. That was kind of annoying.

Fraser: Because you needed something to be orbiting the planet to be able to get an idea of what kind of gravity was there, and then once you got gravity, you could get the mass.

Pamela: So we use forces there, again, in this case, we're using the gravitational force between two objects to calculate based on the acceleration we see. This is the orbit which is constantly changing velocities, and it all basically through complicated means works its way back to F=ma.

Fraser: So how does mass then change? Are there any things that can change the mass of an object?

Pamela: Well, at a fundamental level, if you start decaying the atoms that are in a blob of matter, then it's going to give off radiation of some sort. Now, if it's giving off alpha particles, this is helium atoms, it's going to be radically changing in mass. If it's giving off gamma particles, which is a form of light, it's still going to be changing in mass as this energy flies away, but it's going to be changing to a much lesser degree, so through radiative decays that give off either particles or radiation, you end up with a change in the total mass of that object, but not of the entire system, so if you look at the amount of mass in a closed box, you still have the energy, you still have the matter, when you combine them together, the amount is conserved, so mass and energy combined are always going to be conserved.

Fraser: Now, will the mass of an object change if it's moving? Did Einstein have anything to say about that?

Pamela: That's actually one of those things that breaks people in fabulous ways.

Fraser: Yeah, and I think we actually have sent a few physicists to the insane asylum with a couple of our questions for them.

Pamela: One of them did retire shortly after we asked this question, but I don't think the two are totally related.

Fraser: Interesting…intriguing coincidence, don't you think? So if you move things…?

Pamela: So the issue is, at normal velocities, this effect is so small to be effectively zero, but as you move things faster and faster, the amount of momentum that they contain increases, and you can see this as effectively -- and there's people who don't like it when you say this -- you can see this as effectively increasing the mass, so what you say is the mass contained in an accelerated body that has been accelerated to the point that its velocity is now some significant fraction of c is going to be equal to its…so its inertial mass, the amount of mass it would have that you have to apply a force to is equal to the mass it would have when it's not moving divided over a relativistic correction term (c), which is the square root of 1 minus v squared over c squared, so it's one minus v squared over c squared is going to be between zero and one. The fact that you're dividing something between zero and one means that the mass always increases, so this means that as you go faster and faster and faster and faster, you're going to have that v over c getting smaller and smaller and smaller. As v approaches c, the one minus v squared over c squared is going to be getting closer to zero.

Fraser: This math is mind-bending.

Pamela: I know, I know, so as v gets closer to c, v squared over c squared gets closer and closer to one. One minus this thing that is getting closer and closer to one, gets closer and closer to zero, when you divide your mass by something that's getting closer and closer and closer to zero, your mass is shooting up, so that as you're going infinitely close to the speed of light, your mass is approaching infinity. Now, the issue with this is the amount of force that then has to be used to accelerate you to that higher velocity is increasing as well, and the amount of energy needed to change your velocity to the point that, well, our universe doesn't contain infinite energy, so you can't actually accelerate a mass to that point.

Fraser: Right, so now, I think that you sort of hinted at it a little bit earlier on, which is that in a closed system, you have a bunch of mass, and if, you know, parts of it are radiating away and you're going to get these particles turning into radiation, but if you consider that a closed system, the total amount of the mass and the energy that's being released still balances out to be the same amount, and this is what Einstein figured out, right, which is that energy and mass are connected together. They're really one in the same.

Pamela: And this has lots of fabulous implications. This, for instance, explains why stars don't burn out quickly. Up until we'd really started to really figure out nuclear fission and fusion, as we talked about a few weeks ago, people were trying to explain stars using chemical burning, and they weren't able to get significantly long lifetimes out of them because chemical burning is a very inefficient process, but if you're able to take the entire mass of an atom and convert it to energy, that's extraordinarily efficient. This is where nuclear weapons, for better or worse, are much more powerful than dynamite or plastic explosives. So he figured out that you can hold all the energy necessary to power New York City in a potato, for instance, and that was a kind of profound way to change how we view matter and energy. And it also allowed us to look at the Big Bang as something that produced a bundle of energy that froze out to become the mass that we experience today. You are frozen energy.

Fraser: Now, does energy want to be mass? Or does mass want to be energy?

Pamela: Well, that's a chicken-and-the-egg issue. So if you have sufficient energy in a small enough area, it will condense out to particles, and this is what they do at particle accelerators. They take two particles, whether it be protons, electrons, atoms…it all depends on the type of accelerator you have, they smash them together, and when they smash them together, all of the kinetic energy in the system, all the mass energy in the system is released in a very small volume. And all of the energy in that very small volume – and kinetic energy is ½ mass times velocity squared, so when they get these suckers going at relativistic speeds, that's tons of energy there, and "tons" is probably the wrong word to use in a show about mass, that's shedloads of energy there, and all of this energy will condense out into particles. Now, the thing is, when we start to look at the future death of our universe, we look at theories that project that protons might decay into energy. Now, people have been looking for proton decay for decades, and we haven't found it, and we've put limiting ages of 10 to the 33 -- I believe it's seconds or years…sorry, listen, look that number up – onto…it's a vast number, we've put a vast limiting number onto how long it's going to take for protons to decay, and hasn't been seen, but if they do decay, then eventually, you're going to have all these little, isolated protons decaying in their own little isolated place, and this energy will be spread out over sufficient volume that the energy isn't dense enough to condense into particles. So compact energy becomes particles, diffuse energy sort of lies around going, "I'm energy," and spreading out and cooling off, and getting longer and longer wavelengths.

Fraser: Right, and so it's only through this process of us turning energy into particle accelerators, pushing them through particle accelerators that we turn it back into mass.

Pamela: Right, and the awesome thing about the early Universe was it initially had so much energy packed so closely together that the energy had to stay pure energy until it had spread out enough to allow the particles to start to coalesce as things cooled off, and so our early Universe went from this tightly-bundled pure energy cooling off into matter, and someday the matter will decay back into energy that's diffuse. So it's this fabulous cyclic system if protons decay, and again, we don't have evidence of this. It's part of a number of different theories, but the Higgs-Boson is saying, "Hey! I support the standard model," so we may not need this.

Fraser: Whoa. We may not need this?

Pamela: Well, this is one of those things that has people really frustrated. As they've tried to come up with theories to explain our U&niverse, they need slightly more esoteric physics than the standard model, which basically says we have leptons, bosons, we have these set specific things and we know that we have a boson through the electromagnetic force, a boson for the strong force, a boson for the weak force, a boson for gravity, a boson for mass just to even things out, and we don't know why, we just do. And it makes certain predictions. It's a theory that many people declare as boring and ad hoc -- and it works. But folks trying to come up with complicated theories that have underlying First Principle physics that get you to the current standard model, they wanted things a little bit more radical, and we're not finding that.

Fraser: Alright. And now I'm going to ask the four-year-old question, which is the tough one, we'll save it for the end, which is why is there mass? And this is, but I mean, not like why, you know, but this is the Higgs-Boson, this is the whole point. So what's going on?

Pamela: And it goes to why don't photons have mass, for instance, and so according to the theory, the Higgs-Boson is coupled to this field that permeates all of space and time, and this field is everywhere. Don't think of it as a plane, think of it as this thing that just permeates the entire volume of the Cosmos. And if something has a lot of Higgs-Bosons associated with it, it's strongly coupled to that field, and once you get moving through that field, the sucker keeps moving at constant velocity -- that's inertia. That's the next show, but if something doesn't have that many Higgs-Bosons, it's really easy to get it moving. If something has a lot of Higgs-Bosons, it's strongly coupled, it's harder to get moving, and so the Higgs-Bosons, the thing that gives you mass, is an expression of how strongly coupled you are to that field. Now, that's a very, very four-year-old way to explain it.

Fraser: I got it!

Pamela: OK! Cool! So the neat way to think of this is if you have a movie star enter a crowded room full of people who are impolite and crowd the movie star, the movie star, if they make the mistake of stopping, are going to get a bazillion fans around them, and getting moving is going to be really difficult. Once they're moving, they'll probably keep going at constant velocity as everyone moves to keep up. Stopping is going to be hard because you have to stop the whole crowd of people, or you'll get knocked over. So the idea of all these things glomming onto you that you have to get moving and get stopped to affect your velocity – that's kind of the analogy of how the Higgs works.

Fraser: Right, well, an internet celebrity can slip through a crowded room without anyone noticing, so…I see what you are saying. So do I have a number of Higgs-Bosons?

Pamela: Yes.

Fraser: Associated with my body? Where are they? Does every atom have a Higgs-Boson?

Pamela: Every atom has many Higgs-Bosons.

Fraser: Has many Higgs-Bosons because we know that…

Pamela: Think about it – you have all these different particles that make up all your different atoms. And all of these things have mass, all of them are coupled in their own way to this scaler field that permeates everything, and so just like there's little photons flying back and forth between your refrigerator magnet and your refrigerator expressing the electromagnetic force, adhering your refrigerator magnet to the refrigerator, there are Higgs-Bosons flying around adhering you to the scaler field of the Universe.

Fraser: Whoooa!

Pamela: Yeah, kinda "meta."

Fraser: That's really cool. So is there anything then that could overturn at this point this discovery do you think?

Pamela: Well, if it turns out that the internet rumors are wrong, and they didn't find the Higgs-Boson at 125 electron volts of energy, that clearly…

Fraser: But I think we had talked a few months ago, that we were already at 99% certainty that the Higgs-Boson has been discovered. Now, they're at 99.999, which is the level of precision that physicists like to be, but they're already super-sure, so...

Pamela: The one thing that I personally get bothered by is gravity is supposed to have its own Boson attached to it called the graviton, but the graviton doesn't have a mass, so it's not detectable, and any time you have something that you can't prove in a laboratory, it bothers me because you have to make a belief choice, and so there's this belief choice involved in the graviton and expressing the Boson for gravity, so that's a personal bother that I wish they could experimentally say the graviton is there, but now that we can say the Higgs is there, it's much easier to believe that the graviton is there. If the Higgs wasn't there, I was going to have a lot of problems grasping on to the graviton.

Fraser: Right. If you’ve got a model that has nine of the ten pieces discovered, and the tenth piece is undiscoverable…there you go.

Pamela: And people talked about the top quark for a long time before it was discovered to exist at Fermilab back when I was an undergrad.

Fraser: Yeah. Cool! Well, that was great, Pamela. So next week we’re going to move to the next part of this process, and we’re going to talk about inertia, which is the whole other subject very related to mass, which is related to energy. So we’re going back and discovering all of these core concepts, so I think that’s going to be really helpful. I almost think we should have done this a lot earlier, but you know, whatever. Well, thank you very much, Pamela. It was great as always to pick your brain about mass, and we will talk to you next week.

Pamela: I will see you on the other side.

Fraser: Bye.

Pamela: Bye-bye.