Astronomy Cast Episode 263 for Monday, April 30, 2012: Radioactive Decay

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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 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. So I wanted to thank everybody who's been giving me lots of feedback on the presentation of the Astronomy Cast app because people have been finding bugs, and more just like tweaks and I have a lot of control over how I present the information, so it looks as best as you want it on the app itself on your iPhone or iPad, but if you haven't already got it, highly recommend you go and pick up the Astronomy Cast app from the iTunes store. I think it only costs $1.99, $2.99? It's not very expensive, and it's got the entire library. You can star your favorite episodes, you can run it on continuous, you can download pretty pictures from it, you can get the descriptions, and I'm happy to keep putting the energy into making that app experience better if you guys want to keep giving me feedback, so thanks for letting me know. And then, other than that, I think, why don't we get rolling?

Pamela: OK. That sounds good.

[advertisement]

Fraser: So nothing lasts forever, not even atoms. Heavier elements decay into lighter elements, releasing energy as radiation, but thanks to this radiation, astronomers can get a glimpse into what's going on outside and inside distant stars. Let's take a look at the whole process of radioactive decay, the different events that happen, and how humans use this fundamental force of nature for our own nefarious schemes. Alright, Pamela…so then, when we're talking about radioactive decay, what is the overall process that we're talking about here?

Pamela: Well, there's a whole variety of different processes, but they all boil down to one concept: you have one atom, it's in a high-energy state, and there's something not quite stable about it, and so it gets rid of that instability by releasing energy in some form or another, and becoming something new in the process. So it could be as simple as an atom that's at a slightly higher energy configuration that gives off gamma ray radiation and collapses into the same type of atom, but in a slightly different configuration of alignments of spin and things like that, or it can be something as complicated as it undergoes a decay process that causes it to give off a helium atom (an alpha particle), and it becomes an entirely new type of atom in the process.

Fraser: But I think it's important to understand the distinction between radioactive decay of elements, and the kinds of reactions that happen between molecules.

Pamela: Right.

Fraser: You know, we can have chemical processes that are giving off energy and recombining atoms together, or recombining molecules together, and that's different, right?

Pamela: Right, so you have…atoms bond in a couple of different ways. There's what are called ionic and covalent bonds, and basically, the idea is that they either share electrons, such that they're filling each other's energy levels, but the electrons belong to one atom, or you have molecules that are formed by electrons that are going back and forth between two atoms and are getting shared. Both of these different types of bonds…they may give off energy in the process of getting torn apart, they may give off energy in the process of coming together -- it depends on if it's exothermic or endothermic, but this is just temperature energy. Occasionally, you'll get "flameage." Drop phosphorus into water -- flameage occurs. It's awesome, but with radioactive decay, you actually have the atom itself is reconfiguring, and the energy that is given off here, you're getting gamma ray, which is deadly, or you're getting alpha particles, which can be deadly, or you're getting beta decay, again, can be deadly in large amounts, so it's a difference between heat – kind of exciting, or death, which is more than a little exciting.

Fraser: Right, but I guess to use an analogy would be the equivalent of having a big box of Lego, and you're moving the Lego around and making different cars and houses and airplanes and things…

Pamela: …or your Legos spontaneously become Tinker Toys.

Fraser: Well, that's exactly it, right? And so at the end of the day, you still have Lego. It's still Lego pieces, and you can still recombine them in different ways, and if you had a certain number of little square pieces and little guys, then you'd end up with the same number by the end of it, but as you said, radioactive decay is if your Lego was actually turned into something else, like Tinker Toys, or…I don't know, glue, and pencils and paper, or other creative elements, so it's a completely different process that's going on. Great! Well, I know you hinted at it a bit, but what are the different kinds of radioactive decay that will happen?

Pamela: So the three primary types of decay are ever so uniquely named alpha decay, beta decay…or alpha radiation, beta decay and gamma radiation -- so it's boring names, but they come from the history. When people first started realizing that there was radioactive decay going on, they had no clue what was happening other than if they took special, sensitive glass plates, put them in a drawer wrapped up in black paper, put Uranium salt on top of it, and the idea of uranium salt is a little bit terrifying…

Fraser: It's something that we all…how many times have I sprinkled some Uranium salt on black paper to find out what's going on?

Pamela: [laughing] And this is just where you have to remember that salts are something that is unique to chemistry, and does not refer strictly to food items. So they realized that when they put this uranium salt on top of this special, sensitive glasses (it was glass that was treated with various materials) that the glass was getting developed by *something*, and so they started experimenting, finding different materials that would do this, and as they played, they discovered that in some cases they were able to block the strange rays coming off with just a piece of paper: that's alpha decay. They realized in other cases that in order to block the strange rays that were coming off, they needed something a little more substantial like a sheet of aluminum: that's beta decay. And then, they realized in other cases that radiation was going to blast through just about anything, and lead bricks were required: and that's the gamma radiation. So it all started off with: "Let's break it down by what's needed to block that radiation."

Fraser: And so…and then, what is actually going on inside the elements themselves? Why are you getting different kinds of radiation coming off?

Pamela: Well, so with alpha decay, you have an atom that's in an unstable configuration, where it has more protons and neutrons that it's comfortable with, and so its way of getting out of this high-energy state is to literally spit out two protons and two neutrons, which makes up a helium atom.

Fraser: But why does it want more? Or why does it have more protons and neutrons than it's comfortable with? I mean…is there some magic number?

Pamela: Well, it's a matter of atoms have different energy states based on how much stuff is in the nucleus, and the protons are basically getting glued together through different forces that we don't deal with at the macroscopic scale, and as the atoms hit different configurations, it's sort of like when you're building with blocks. If you've ever played Jenga, there's certain energies of the Jenga building blocks that you're like, "Oh, only having one block going across the center -- that's not as stable as having two blocks going across on the edges." Atoms are kind of the same way. They hit certain configurations where there's just a few too many protons, and it's not as stable a configuration of those building blocks.

Fraser: And so can you go through waves, where it's unstable, getting worse, and then it gets stable again?

Pamela: Exactly.

Fraser: Right. OK.

Pamela: And so there are entire tables of what are called nucleotides. This is the different combinations of protons plus neutrons that make up all the different atoms, and there's all these different valleys of stability as you go up, and so even for smaller atoms…so carbon 14 is an example of this. Carbon 14: it's a perfectly normal atom, you and I both have it in our body, but it's not the most stable of atoms out there, and it would like to collapse to a slightly different energy that's more stable, and so there's just all these different peaks and valleys of stability and instability. So with certain heavy atoms -- atoms that typically have more than 52 protons in them -- you have these configurations where it doesn't want to just decay, but it wants to spit out an entire helium atom at a fairly high velocity, and that high velocity helium atom, when it hits you, it imparts a whole lot of energy in a fairly small distance, and all of that energy getting absorbed by human flesh can be a bad thing, so we prefer not to expose humans to large amounts of alpha particles.

Fraser: And so let's pretend that we did. So, let's say that you've got some quantity of an unstable element, and you put your hand next to it, on it…

Pamela: Yeah?

Fraser: You'll get a burn?

Pamela: You're going to get a burn; you're going to absorb radioactive materials, and what's bad about this is depending on how it hits (and this is true of all radiation) is it can actually damage your DNA, and damaged DNA sort of leads to cancers, and things like that, and so a lot of the early research on this -- they didn't know they were dealing with something that was dangerous. So Marie Curie -- she ended up dying from aplastic anemia which is believed to have been caused by working with radioactive materials, and the insane part about this is when they first discovered all this radioactive material, they started doing crazy stuff with it…making all sorts of elixirs and medicines, not knowing what it did.

Fraser: Tonics – drink it up! Yeah.

Pamela: And so all these tonics -- yes! All these tonics…and they were basically giving people all sorts of radiation poisoning, and it wasn't a good thing.

Fraser: OK, so back to our first example…so, we've got this situation where you've got an element (or a pile of Jenga blocks), and…

Pamela: A pile of Jenga blocks…yeah.

Fraser: …and it is unstable and it wants to kick out exactly a helium atom.

Pamela: Two protons, two neutrons…

Fraser: Together.

Pamela: Together – no electrons involved, so this is a fully ionized helium atom…kicks it out, and suddenly you have a new element, and you also have a particle that can do you a little bit of harm, but what's neat is because they are easy to block, it's fairly safe to deal with these things, and we actually have alpha decay around us all the time. So anyone who has a fire detector in their house, a smoke detector in their house (and everyone listening should have at least one, and preferably four or five smoke detectors in their house)…smoke detectors use americium (and I'm sorry if I mispronounced that)…americium 241 in the detector, and what the americium does is it ionizes the air in a small gap, and this ionized gap… there's current flowing through it, and when smoke gets into this gap, it breaks off the current, and it's that change in current that causes the smoke detector to go off. Now, it is possible (and there are cases of kids doing this for science fair)…it is possible to gather all this radioactive material and do bad things, but that requires a whole lot of smoke detectors, so in general, it's not a big deal. There's also alpha decay gets used in radioisotope thermal electric generators – these are RTGs.

Fraser: Yeah! Those are for space!

Pamela: Space RTGs are kind of awesome. They use Plutonium 238. Unfortunately, here in the United States, we're out of Plutonium 238 for RTGs, so we're hoping Congress will approve the reproduction of this, or turning back on the production lines for this particular radioisotope, but this is another example of alpha decays getting used to generate heat energy and power awesome things -- in this case, spacecraft.

Fraser: OK, and then, as you said, once that helium atom has been liberated, you've got a completely new element, and this is going back to our Lego box analogy. This is us taking a little Lego guy, and then popping off his head, and now he's actually a wing.

Pamela: [laughing] So you have like uranium goes to thorium, plus helium…

Fraser: Plus helium...

Pamela: So, that's one of the common things that we're looking at. So you take an atom, knock it down by two -- you have a new atom.

Fraser: Alright. Well now, you predicted three types…

Pamela: I did.

Fraser: …of radioactive decay, and you've only given us one, so let's hear another one.

Pamela: So the other type of decay is beta decay, and so here there's actually two different types of beta decay: normal beta decay, inverse beta decay, and in both of these cases, you have an atom that is almost stable, but it would rather that one of its protons was a neutron, or vice versa. So protons and neutrons are very, very similar in mass. The major difference between them is protons have a positive charge, neutrons have no charge, so neutrons are actually a more stable configuration for things like really dense stars, but in general, neutrons by themselves -- you stick one on a shelf, it very quickly decays into a proton, and it gives off an electron, and an anti-electron neutrino in the process. So depending on what you have, one configuration or the other is more stable; it depends on everything added together. Predicting what is going to happen requires many years of quantum mechanics. We're not going to get into that in the thirty minutes of this episode, but at the end of the day, what's kind of awesome is you can have an atom, it's sitting there, it's not quite content, and spontaneously one of its neutrons becomes a proton, and it gives off an electron and an anti-electron neutrino. Or you have an atom that's sitting there being not quite happy, and spontaneously, one of its protons becomes a neutron, it gives off a positron and an electron neutrino, so it keeps everything nice and conserved charge-wise, and in the process, you end up with a new type of atom again.

Fraser: But you don't lose…oh, that's right because one of your neutrons has turned into a proton, so you're actually going up one.

Pamela: Right, or down one because you can also have… so you can have a neutron that goes to a proton, or you can have a proton that goes to a neutron. It depends on…it's either a beta minus or a beta plus decay, so inverse beta decay, or regular beta decay.

Fraser: Right, but the point being…with the neutrons, I know, you can decay neutrons, and you can get different versions of the same element, though, right?

Pamela: Right.

Fraser: You can have carbon 14…you're measuring the amount of carbon 14 that's left in a piece of old wood because you're trying to determine how much of it has already decayed…

Pamela: Exactly.

Fraser: … but it's still carbon. It hasn't turned into…

Pamela: It's still carbon, so…

Fraser: …it hasn't changed into oxygen.

Pamela: When you have a proton change into a neutron, then the atom changes identity. When you have a neutron change into a proton, the atom changes identity. So either way you're going up or down, but with what you're talking about you simply have a gamma ray given off, in which case the number of protons stays constant, so you're jumping ahead.

Fraser: Whoa! Did I just preview the third…? I'm sorry. I'm sorry. Let's go back then. Pretend I didn't say that.

Pamela: [laughing] So with beta decay, you can…for instance, cesium 137 goes to barium 137, but you've now changed from having 55 protons to having 56 protons, and in the process, you've given off an electron, and you've given off an anti-electron neutrino, so with beta decay you always have you're either going up one or going down one, depending on which direction is going on.

Fraser: But is it always going to want to go on that same way? Is it random that it's going to go one way or the other way? Or will a certain…?

Pamela: A specific atom will always go one way,

Right. Yeah.

Pamela: So it's sort of like (I'm running out of analogies here)…it's really just one of those thing where it's just like, "I'd be happier if you added a Jenga block, or I'd be happy if you removed a Jenga block."

Fraser: Right. That makes sense. You can imagine the best strategy from this point on. Absolutely. OK, so that's our second form of radioactive decay, and then I gave a terrifying preview of the third one, so why don't we just get right into that one, then?

Pamela: So our third state – this is almost always coupled with the beta decay, and this is by far the most deadly form of all of these, and part of the reason it's the most deadly is it's a combination of very high energy, and very hard to block, and this is the gamma radiation coming off from gamma decay. So in this case, you have an atom will often decay via one of these beta processes I just talked about. This is where a proton converts to a neutron, or a neutron converts to a proton, and the atom that's left behind has an electron that's not entirely in its lowest energy state, so you have…or it has the protons inside -- they have spins, and so depending on how the spins are aligned, it may not be at the lowest possible energy state. It's close, but not quite there, and so in order to get to the proper energy state, it has to give off a photon of high-energy radiation. It has to give off this gamma ray to compensate for the difference in the spins, the difference in the alignments. There's lot of different little things that can change, and when they change, that energy from the change has to go somewhere, and it goes into a high-energy bit of light, a high-energy photon, a gamma ray photon. So we see this with cobalt for instance, cobalt 60 decays into nickel 60, this is going from 27 protons to 28 protons, and when it's done with this decay process, there's this slight energy difference that it's not happy with, and so it ends up giving off this slight energy difference via a gamma ray.

Fraser: And let's just be clear on how awful gamma rays are. And they turn you into the Hulk, as we know…

Pamela: Well, they turn you into the Hulk, but these are things that just basically blast apart your DNA when they hit it. One…so a helium atom you can stop with a piece of paper. That's fairly safe. If you spill materials that give off alpha particles, you close glass doors, and you pretend it's not there, and you put caution tape across this. I kid you not. I've seen this happen in a university laboratory.

Fraser: It's like, "Don't touch that over there. Don't open that door."

Pamela: Yeah, exactly. It may look like someone spilled chalk, but that gives off alpha particles. With gamma ray radiation, you're looking at brick walls with lead bricks, and still some of them are going to leak through. It's a BAD situation. And the gamma rays, they're just sort of blast up your DNA, and your DNA doesn't repair itself particularly well, so you're looking at all sorts of different cancers coming from this.

Fraser: So this would be removing our Jenga blocks by exploding them.

Pamela: Exactly. Exactly. You don't want to deal with this.

Fraser: We don't want to deal with that…OK, so we've got our three methods of radioactive decay. So then, how do we use these in our daily lives? I mean, you mentioned already that we use the decay of the…is it americium?

Pamela: Americium. Yeah.

Fraser: Americium in smoke detectors, you know, we've already talked a bit about radioactive decay for carbon dating.

Pamela: Right, so we end up with radioactive particles get used for a lot of different things. What's kind of awesome is we can actually predict from watching, basically, how long it's going to take for different materials to decay, and so there are a lot of medical applications where you want to treat a tumor with radiation over a prolonged period of time, and so you can do capsules, you can do inserts that they put into the body that have radioactive materials in them with a known half-life, where it's known over this period of time, this rate of radiation is going to be given off. It will irradiate the tumor; it will kill off the cancer. That's a good use. Similarly, we can use other forms of radiation for, as we said, for spacecraft radio thermogen – RTGs.

Fraser: And you know that it's going to be giving off a set amount of energy at a very precise rate that can be then turned into electricity on a spacecraft.

Pamela: And then we can turn this around when we're digging through Earth's soil, we can dig up a rock, we can count up how many atoms of the radio isotope, how many atoms there are of the daughter isotope – the thing that is produced via the radioactive decay, and we can figure out how old that rock is. We can, similarly, look out at the stars, and we can measure in the spectral lines what the composition of the different atoms in the star is, and so we can start to actually, with extremely long-lived radioactive materials, start to date the stars this way.

Fraser: Can you give me an example about how they actually will do that? I mean, I know they use Uranium, don't they, as one of them? There's a bunch of them.

Pamela: There's…strontium's another one. There's a whole bunch of different elements. It's a matter of just changing how many neutrons are inside of an atom, changes where the different spectral fingerprint lines are, very slightly, but if you have a high enough resolution spectrograph, you can see the shifting of the lines, so you can measure how much of each isotope of an atom is in a star, if you have a high enough resolution spectrograph once know how much of each isotope is there you can start to get at the ratios of the amount that's in the star and assuming that all of the material in the star was formed roughly the same time, that can start to give you a sense of what is the minimum age on that star. Now, here on the planet Earth, all of our material came from supernova, we look at stars, all of these things came from supernova, so we're really saying: it's been this long since a supernova went off, and that's kind of cool.

Fraser: And how long are we saying it has been since a supernova's gone off?

Pamela: Well, we know here on the planet Earth, the material that we have was last mixed about 5.5 billion years ago, and then the supernovas are older than that, clearly.

Fraser: And so this is a situation where you know the rate that the elements are going to be decaying at, you look at a distant star, and you measure those (you call them the daughter elements), you look at the two kinds of elements that should be coming out of this radioactive decay and then you just measure them, you just compare the ratios and then I guess do some math and look up a table, and just count back, and say, "OK, we've got 75%

uranium, and…whatever, 25% polonium," (I'm just making this up)… That tells us that the star is at least 2.5 billion years old. Now, I say the at least part because it could be older than that, right?

Pamela: Well, right. This is a matter of mixing, and this is where I say lower limits. So here on the planet Earth, for instance, our stuff that the planet was made from was mixed up at a given point. Now, prior to that it may have …that material clearly existed, but if you had a lump of uranium in the past and it happily decayed, but then it got mixed up later, those daughter elements could have gone off somewhere else, so you're actually looking at what is the age that things last got mixed up. And what's kind of awesome is we've observed radioactive decays over 55 orders of magnitude of time, so as precisely as we can measure on short time intervals, as precisely as we can measure on long time intervals, there are decay processes spanning 55 orders of magnitude of time.

Fraser: So there's just like these overlapping yardsticks that can be used to determine almost anything.

Pamela: Exactly. So we can work our way down to the shortest time periods, and all the way out to the longest time periods, and it's kind of amazing.

Fraser: Now, is everything going to decay? I mean, if we go from carbon 14 to carbon 12, we go from uranium this to uranium that, will we all just end up with protons in the end?

Pamela: Well, so some atoms we clearly haven't seen decay. There are things that seem to be completely stable, but then we hit this problem known as all the Grand Unified Theories think that protons should decay. Now, we've never seen a proton decay. People have been watching for protons to decay, and the way that math works is if you have a probability that one will decay over 10 to the 34 years, if you take 10 to the 34 and put them in a vat, one of them should decay on any given year. And this is how we're able to understand supernovae, for instance. We know that any particular spiral galaxy should have one supernova every 100 years, you look at 100 galaxies for one year, one of them should have a supernova go off -- same thing works with radioactive decays. Now, no matter how many protons we put in a vat, we aren't seeing them decay, so all the Grand Unified Theories say protons should decay, but we haven't observed this.

Fraser: So, but will helium decay?

Pamela: Well, if protons are going to decay, then yes.

Fraser: For sure – yes.

Pamela: But helium seems to be completely on its own, stable in that two-proton-two-neutron configuration. It's happy to stay that way. Leave it on a shelf, it stays helium, it stays unbonded, it's inert, doesn't play well with others kind of…

Fraser: Forever? So it would never…

Pamela: Unless…

Fraser: Unless protons decay, right?

Pamela: Unless those protons decay.

Fraser: Right, right. Unless its underlying protons are falling apart.

Pamela: So this is where you get the valleys of stability within the table of nucleotides.

Fraser: And so like I wonder like what kinds of experiments have been done to search for this proton decay? I mean, 10 to the 34 protons sounds like a lot, but I wonder, is that a lot? Is that like as big as a house? How much protons do you need? A big bag of hydrogen?

Pamela: [laughing] Well, it's actually a big tank of heavy water is what they use. So you take a big tank of heavy water, and you wait to see if decays take place.

Fraser: And so the math tells, with these Grand Unified Theories, the math is telling us that a proton decaying is going to release a certain kind of energy, it's going to give a very specific signature, and then you put these detectors all around and you wait and you wait…and they're still waiting.

Pamela: And you see nothing!

Fraser: And they're still waiting. Well, that's weird! Is it so unusual that it's starting to cause problems with the Grand Unified Theories?

Pamela: It is. It is kind of problematic. And here's the problem that we have with particle physics right now. We have this standard model that is based purely on observations, that explains the universe we live in fairly well, but doesn't explain the "why" of the universe that we live in because it's based on observations, not on first principles, and theorists would love to come up with a theory that allows you start from math to get to the universe we live in, and we can't figure out how to do that without proton decay. And there's other particles that we're looking for with CERN that if we don't find them, again, we can't get to those first principles. So we're looking for super-symmetric particles, we're looking for the Higgs. It looks like we've probably found the Higgs, but now we're looking for the super-symmetric particles, and without them, we don't have first principles, and we want that underlying math. It's not there.

Fraser: Right. Yeah, we've done a whole episode on that, and it's pretty interesting. I don't remember which episode number it is, but yeah, we've done a whole episode where we talk about the Grand Unified Theory, and talk about the search for the super-symmetrical particles, and the fact that really this journey is…of actually finding these things has only really begun. If we find the Higgs within the next year, which we kind of probably have…

Pamela: Uh, yeah…it's just a matter of re-[missing audio] the data.

Fraser: That's not the end of the story; that's really just the beginning.

Pamela: No, that's the beginning.

Fraser: Yeah. OK, cool. Well, thanks a lot, Pamela. This was great, and I hope this really helped people understand radioactive decay, and not take apart your smoke detector.

Pamela: And don't eat it. It's…

Fraser: And don't take any of those exotic tonics and elixirs that contain radioactive spirits.

Pamela: Sounds like a plan.

Fraser: Alright, we'll talk to you next week, Pamela.

Pamela: OK. Bye-bye.