Astronomy Cast Episode 206
Fission

Fraser: Astronomy Cast Episode 206 for Monday November 8, 2010, Fission. 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?
Fraser: Good! Big news this week! This just in... we’ve got schwag to sell!
Pamela: We have more than just schwag! We have posters... we have t-shirts... we have lanyards...
Fraser: CDs!
Pamela: Please... buy it! It’s all in my spare bedroom... if you don’t buy it, I don’t get my spare bedroom back.
Fraser: Right. So just specifically... we talked about the t-shirts and the CD when we did DragonCon, and we took them there and sold a bunch of stuff there. We’ve got Season 1 of Astronomy Cast which is episodes 1-25 on an mp3 CD.
Pamela: With transcripts...
Fraser: Mp3... it’s got the transcripts and all that... We’ve also got “The Universe is Trying to Kill You” t-shirt and our Cosmology t-shirt and our Scale of the Universe t-shirt. And then we’ve got a bunch of other knick-knacks... there’s the comic book...
Pamela: “The Universe is Trying to Kill You” poster...
Fraser: “The Universe is Trying to Kill You” poster, which is beautiful...
Pamela: It’s my favorite. Actually, you could frame it... I love it. And it’s cheap...
Fraser: Is that in your bedroom? Would you sign it?
Pamela: Yeah! If you put... if you drop us an email... and I’ll see if I can figure out how to put a special request on the Astrogear site... yeah, I’m willing to sign them.
Fraser: Ok, cool. So you go to astrogear.org And I know it’s not on the Astronomy Cast site, but that’s because this is going to be the place for gear related across all of our Astrosphere stuff. So Astronomy Cast and 365 Days of Astronomy and so on. That’s once again at astrogear.org and let’s help clear out Pamela’s spare bedroom.
Pamela: Please?
Fraser: Alright... so last week we talked about fusion... where atoms come together to form heavier elements. And this week, everything comes apart as we talk about nuclear fission—how it occurs naturally in the universe and how it has been harnessed by science to produce power and devastating weapons. Alright, Pamela, so last week we talked about fusion and this is the process where atoms are fused together under great pressure and heat to form heavier and heavier elements. And especially in the core of large stars we talked about how fusion works and produces energy all the way up to iron.
Pamela: Yes!
Fraser: And then beyond that, fusion no longer generates energy... but something else does.
Pamela: So at a certain point, you go from giving off energy when you combine nuclei, to giving off energy when you break nuclei apart. This is something that occurs in nature

all the time. Some of you out there may have radon detectors in your basement. These detectors are basically looking for the radiation that's produced by naturally-occurring nuclear decays that are often associated with granite. So if you live near granite mines... or I guess quarry is the better word... if you live near granite quarries and you have granite bedrock underneath your house, and you have a basement that can trap still air, it's best to get a radon detector to look for these radioactive decays.

Fraser: And so what's the process that's going on here?

Pamela: Well, there's a couple of different things that can be happening. On one level, some nuclei just aren't entirely stable, and given enough time, they'll undergo what's either called a beta decay or an inverse beta decay which is essentially the process where either a neutron decays into a proton, electron, and energy, or some other combination of those three things falling apart.

Fraser: So, can you give me an example, then... what's an example of an element that is commonly known to decay in this way?

Pamela: So, let's look at radon, in particular. Radon will give off an alpha particle—this is a special helium atom that has two protons, two neutrons—which will become polonium, which is another radioactive element. Then it undergoes either beta decay or more often gives off an alpha particle and becomes a radioactive form of lead that's often referred to as radium. So there's all these complex channels by which different things can decay. What started off as radium will go through a whole series of decays before it becomes a nice stable form of lead via bismuth and polonium and mercury in some cases in all these different processes.

Fraser: Now, I think when we think about fission, we think about things splitting up. The actual atoms.... they're not breaking up in halves... so you're not getting something with 100 protons turning into two atoms with 50 protons. They're losing them a couple at a time, right?

Pamela: Yes. In general, you have very boring decay processes, actually.

Fraser: And they're long... this loses one atom and an alpha particle and turns into that... then that loses two particles and turns into this... It's this big long chain.

Pamela: It tends to happen in leaps and jumps, I guess is the best way to put it. Some of these processes happen rapid-fire where in one second you might have something go through multiple steps where as other processes sit there for a few days... and then decay.

Fraser: Or a 100,000 years.

Pamela: Right... or a 100,000 years and then decay. But what's interesting is in many different cases, you can induce fission simply by nailing something over and over with neutrons.

Fraser: And this is the power and the bomb side of it, right?

Pamela: Exactly. This is actually what happens in stars, in a lot of ways. There's two different processes in stars that we talk about... there's the S process which is the slow process and the R process which is the rapid process. So when you and I talk about stars, we're usually talking about the nuclear reactions that go on in the core of the star. This is in fact what we teach in Astro101... in the core of the star you have nuclear fusion going on, and you build things up until you hit iron and then the world stops.

Fraser: Right. Iron being the moment when you can no longer extract energy from fusion.

Pamela: Right. Now, those are the energy-generating forms of nuclear interactions that are going on in stars. But you also have neutrons running loose in stars and occasionally hitting atoms and joining those atoms. What we find is in many long-lived stars, you slowly get this build-up of neutrons where, for instance, you might have an atom of argon capture a neutron and jump up through a beta decay process becoming cadmium. That cadmium might sit there and slowly grow by capturing neutron after neutron after neutron and then itself jump. You can get all of these different elements that are growing slowly in the outer atmospheres of stars one neutron and the occasional beta decay at a time.

Fraser: Huh... that's interesting because I thought that the heavier elements... we always talk about how we're all made of supernovae, and you look at a piece of gold and that was formed catastrophically at the center of a supernova at the moment that it hit that iron limit and then it no longer had any energy to keep the outer atmosphere of the star pushed out and so it collapsed inward... that's when all the heavier elements formed. But you're saying that....

Pamela: That's the R process.

Fraser: That's the R process. That's the rapid process, right. But you're saying that there's a slow process where it's more like where they grow over the millions of years into heavier and heavier elements.

Pamela: And it only works for some elements because you have to have things that don't immediately decay. A lot of elements... you throw a neutron at them and the neutron gets absorbed... it doesn't stay there very long. It rather rapidly decays into something else. You need atoms that are happy to sit there and gather one, two, five neutrons before they undergo some sort of decay to become a different element. It's through this slow gathering of neutrons in these semi-stable atoms that you can... for certain elements, and only certain elements... end up with this fission process going on in the outer atmospheres of stars. It's not a total lie when we're talking to the public because gold and silver and those pretty metals that we always point out... those do indeed come from supernovae explosions where you get this huge blast of rapid-fire neutrons so an atom doesn't have a chance to decay before it gets hit with five or ten or more neutrons and thus is able to rapidly gather neutrons and then decay into a new atomic number.

Fraser: Right, but you've got the fusion of them coming together into this slow process, but then I guess there's fission happening as well as they're slowing decaying in the atmospheres, and I'm guessing scientists find that helpful.

Pamela: Yes, and actually it explains a lot of the amounts of elemental abundances that we see looking out around the universe. You can't account for everything with just supernovae. But the thing that unifies all of these different processes is the way the fusion typically works is that you hit something with a neutron and this causes some sort of a decay. So neutrons are sometimes best looked at as the fuel source for the fission process. This is what we see in nuclear reactors. Now the only problem is that a lot of the reactions that we're looking at... you take for instance a Uranium-235, you nail it with a neutron and it becomes a Uranium-236. That new uranium atom—that new atom that still has the same number of protons, still has the same number of electrons—it's now got one too many neutrons, and that difference causes it to catastrophically decay into a couple of different elements and now gives off three neutrons. These three neutrons can now go off and hit three Uranium-235s that are now going to produce nine neutrons, and those nine neutrons are going to go out and hit uraniums and you'll have 27... it becomes this runaway process.

Fraser: Some kind of chain reaction...

Pamela: Exactly. And you can't shut it off once you start it unless you find a way to absorb those neutrons out of the system. That's where control rods are so necessary in nuclear power plants. They regulate the rate at which the neutrons can haphazardly fly around and cause all sorts of different fission reactions to occur.

Fraser: And so in addition to the additional neutrons being released, you're also getting a release of energy, right?

Pamela: Right.

Fraser: As long as we're above iron, we're getting some energy out here.

Pamela: Right.

Fraser: And it's that chain reaction, that cascade that can then be used to heat water and run a power planet or...

Pamela: Right.

Fraser: ...in the case of a weapon... so then in the case of a bomb... how is that working?

Pamela: What happens is we rely on the fact that you can sort of enhance whether or not something is likely to decay by changing its environment. What we do is we use regular everyday explosive to compress two pieces of Uranium-235 into a high-density mass. When this happens, they undergo rapid-fire fission. This produces more neutrons which produces more fission. It causes this runaway explosion. But to get that first generated set of neutrons given off, you have to compress the mass. Now one of the things that we've found is that you can actually get this sort of nuclear reaction occurring in nature here on Earth. This is a bit scary to think about... I mean can you imagine suddenly a farmer's field becomes a runaway nuclear reaction?

Fraser: So what's going on there? I know there has been evidence of these past reactions found.

Pamela: Right. So the key is you need a source of neutrons. Earlier in the show I mentioned granite. If you have naturally-occurring nuclear decays going on... and granite does this... near an area where there is significant uranium ore in the ground, and you compact this between different layers... say sandstone... those protecting, compressing layers can hold together the uranium ore, and if it gets compressed to a high enough density and hit with neutrons... and the reason the density matters is because when you get one of those uraniums to decay, you want its neutrons to be able to hit the other uraniums. So you get the uranium ore such that the uranium atoms are hitting more uraniums once one goes off. You can trigger chain reaction. There's an area in Gabon, Africa, where it was discovered back in 1972 that the ratios of the different isotopes of uranium... the different atoms that have different numbers of neutrons... didn't match with what's naturally occurring outside of nuclear reactors. Then they started looking at other atoms in the soil and started realizing.... wait, we're finding neodymium... we're finding ruthenium... I'm butchering these pronunciations... but they were finding all these daughter atoms in ratios that you'd expect to get out of a nuclear reaction.

Fraser: So there's some special situation where the uranium got compressed, it was brought near a source of neutrons, and it acted like a nuclear power plant.

Pamela: And the estimate is that for a few 100,000 years these naturally-occurring pockets of uranium that got compressed and then got blasted with neutrons from granite...

they were probably giving off about 100 kilowatts—that's 1000 light bulbs' worth—of power output at a time for 100,000 years.

Fraser: I wonder if walking over the top of it you would have felt the heat?

Pamela: You know, that's a really good question. You probably would have. It just depends on how deep it was, and I'm not sure how deep it was.

Fraser: And how dead you would be from the radiation, right?

Pamela: Right. All of that is bad stuff.

Fraser: Right, and so how... that part is the part that I think we understand. But the nuclear bomb, there's the bomb... but then there's the radiation and the fallout. What's going on there?

Pamela: So the problem is you start off with something semi-stable, like Uranium-235. Then you start it on the whole nuclear decay stream. You get it so that it's going through and it's breaking apart into two atoms. Those two atoms are only sort of stable. But it's the "sort of" that's the problem because it takes time for all these daughter particles to break apart and become something completely stable something that's not still periodically giving off an alpha particle, not still periodically giving off a gamma ray. This is the big problem that is causing us to want to figure out how to get fusion to work. Fusion does give off some radioactive particles, but the waste material of fusion reactors decay in a few hundred years—worst case. Now it's really radioactive while it's doing it, but it decays quickly. But the waste particles produced from uranium nuclear reactions and from plutonium nuclear reactions... these can last hundreds of thousands of years... at not as immediately lethal, but nonetheless lethal levels.

Fraser: Right, so they take a long time to degrade, but they're still putting out enough radiation that it's... you can get a lethal dose from it.

Pamela: Right.

Fraser: Now, back to astronomy for a second... how do astronomers use fission for their astronomy research? As we said, you can see some of the more slowly built-up atoms in the atmospheres of stars... how is that helpful?

Pamela: Well, so we use fission in a couple of different ways. Perhaps the most interesting and least talked about way is cosmochronography... where you look at stars and you identify different isotopes from their spectral lines, from the absorption lines where they remove a fingerprint of light from the star's starlight.

Fraser: Right... this is the process where you can tell essentially what a star is made out of by seeing what colors of the spectrum are being blocked or absorbed or brighter because of the elements that are in it.

Pamela: And we know how long different atoms last, we have figured through a combination of quantum mechanics and observation how long each of these particles should hang out before it undergoes a nuclear decay: 50% of the time. This is the radioactive half-life. We know what the child particle should be. So we start trying to figure out... ok, if this star started out this percentage of this radioactive isotope, and now we see this amount of the daughters, well this star must be a given age. So you can actually start to use the fission process and these naturally-occurring nuclear decays to figure out how old are some of the more enigmatic stars hanging out out there. This is just another way of getting at the age of our universe by putting limits on things by knowing this star must be at least this old to have undergone these nuclear decays.

Fraser: So just to give an example, I might look at a star, measure how much Uranium... what is it 238... 236... there is, and then also measure the amount of a different isotope of uranium. Then I know the star is going to decay at a certain rate and so I can measure the ratios and that should tell me how old the star is.

Pamela: And we use other elements... thorium is another one that gets used... we have whole lists of different atoms that have different decay patterns, have different decay rates as well. By looking at the radium, the thorium, all of these different elements, it allows us to bracket the ages of stars and thus put lower limits on the age of the universe.

Fraser: Over-simplifying, obviously, but that's a pretty handy tool... you can look at any star, measure those ratios and get a pretty good idea of how old that star is. And before the W-MAP mission, that was really the only way astronomers had of knowing how old the universe might be, right?

Pamela: It was the only check we had. We were able to basically say... ok, we know how quickly fusion reactions are going to happen, so we can say a star will stay on the main sequence this long... will stay on the horizontal branch this long... it will wander the red giant branch and the asymptotic giant branch for these different numbers of years... but we had no check on our calculations. It was the cosmochronography that gave us that check on what we were doing.

Fraser: So how else is fission used in astronomy?

Pamela: It also helps us figure out supernovae. As we go out and we're trying to figure out fundamentally... how long did it take the universe to get to the point where planets could form? How many generations of stars needed to come and go and die and explode while dying before we had enough gold and silver and silicon and... well, silicon doesn't come from supernovae... all the other elements that are necessary to build a planet? So there are theorists who are working to build very detailed models of... a supernova goes off... it has this blast energy... it gives off this number of neutrons... it has this sort of a dense environment from having mass lost to give off its atmosphere... neutrons hit this dense mass... What are the R process—the rapid neutron capture processes—that are going to take place that are going to produce this ratio of atoms? So, one supernova produces this ratio. Now, let's enrich the next supernova with those elements. And you can start to figure out if you see a given pattern of elements in a star, you know that one supernova went into that star. If you see this other pattern of elements, you know that's at least two or three different supernovae that went into that. It starts to allow us to get a detailed picture of the generations of stellar deaths.

Fraser: And right now, we don't have powerful enough telescopes to see those first stars, those first galaxies, those first supernovae, but maybe with the James Webb, we'll be able to chart that whole history from the first stars all the way up to the more complicated ones that we have today.

Pamela: And the biggest problem that we run into in trying to understand the first stars is that they died so quickly that we essentially need to figure out how to get a snapshot of a barely-formed galaxy within the first million or two years that star formation existed in the entire universe. That may not be something that we're ever quite able to do. But at least we have the computing power to figure out... well, if we see this it means that happened... if we see this other thing it means this other thing happened.

Fraser: It's like a Sudoku puzzle.

Pamela: That's exactly what it is.

Fraser: Right... you're kind of like... well, I've already got a one and a three and a five on this line, so it's got to be a seven or a nine. You can rule out X number of generations that went into building up a star. You won't know exactly, but you can definitely get a sense of how old, and then you can chart back knowing how long those stars might have taken to form and detonate a supernova. It's got to be complicated work.

Pamela: It is. It's the type of thing that we're so eager to get James Webb up there just to figure out how right and how wrong were we? We know that the first stars formed and died amazingly fast because if the stars, like our own sun, had had time to form out of the original chemical mixture of the universe, then some of those original stars would still be hanging around... because they die slowly. It takes time. But we don't see them anywhere. We only see stars that are enriched.

Fraser: Even red dwarfs we don't see anything... You would think a little pocket of original hydrogen would have formed... but we don't even see those.

Pamela: And we know large stars form fast. They just formed really, really fast and died really, really fast.

Fraser: Like how fast? Like 100,000 years? 1000 years?

Pamela: That's the thing... we're not entirely sure. It's only through continuing to observe and continuing to look for what we call Population III stars... the... well, it turns out, probably the second generation of stars to ever form. It's only by searching for these stars that only show the results of one generation of supernovae in their atmospheres that we can start to figure out what must have happened and how fast it must have happened to allow these stars to have had the ability to get enriched before they formed.

Fraser: Alright, well that sounds great. Thanks a lot, Pamela. That covers our fusion and fission two-parter.

Pamela: And so remember, iron is the turning point.

Fraser: Iron is the turning point... it's the middle... it's the stellar equivalent of ash. And don't forget to go to Astrogear.org and check out all our t-shirts and CDs and lanyards and other great stuff, and let's get this stuff out of Pamela's spare bedroom.

Pamela: All in time for Christmas, New Year's, whatever holiday you choose to celebrate.

Fraser: Alright, well thanks a lot, Pamela.

Pamela: Thank you... bye-bye.