Astronomy Cast Episode 74:
Antimatter

Fraser Cain: Sometimes, we don't get to decide what our show's about. So many threads come together at the same time driving the decision for us. This is one of those situations. We've gotten so many questions from listeners in just the last week about antimatter that our show had just been chosen for it. You command, we obey. Let's talk about antimatter.

So Pamela, what is – or should I say, what isn't – antimatter?

Dr. Pamela Gay: Well, antimatter does not have negative mass. It is not some weird, "going to destroy the universe because one particle of it comes into existence" stuff. It is actually just normal, everyday stuff that has its charge reversed and in fact, all of its quantum numbers are reversed. Because of this, it has the ability to find its normal partner and annihilate in rather dramatic ways that create gamma rays. It's kind of cool, kind of destructive, and kind of mysterious (which makes it fun to talk about).

Fraser: When you say everything is reversed, can you give me some examples? Lets say I've got an atom of antimatter. How would it be different from an atom of regular matter?

Pamela: Instead of having a proton in the centre, it would have an antiproton in the centre, which would have a negative charge. It would have the same mass but a negative charge, its magnetic quantum number would be opposite, if it was orbiting its orbital quantum number would be opposite, all of its quantum numbers would be the opposite. With protons we're mostly worried about charge (which ends up being negative).

Fraser: I know from my physics classes, a proton having a positive charge means you can move it through a magnetic field and affect it. If you moved an antiproton through a magnetic field, it would behave in the exact same way something that was negatively charged would. It wouldn't behave like a proton, it would behave like an electron, I guess?

Pamela: It would behave like an overweight/obese electron, because protons weigh a lot more. That's kind of how they were first discovered. Along with having antiprotons, we also have anti-electrons. We've given those the name positron, because when we first found them we were still trying to figure out what they were.

Fraser: So once again, these are like electrons except they behave like lightweight protons.

Pamela: Right. Here you have an electron that, instead of being a normal matter electron it's an antimatter electron. Which means its mass stays the same but it's now positively charged. When you send a charged particle through a magnetic field, it can end up spiralling if you send it in the correct direction. Depending on if you have an electron or a positron, you end up with things spinning in one direction or the other. We're able to sort out one from the other based on how they get spun, how they get rotated in circular corkscrew-shaped paths as they go through magnetic fields.

Fraser: Okay. So (as you said) everything is the opposite except for mass.

Pamela: Yes.

Fraser: So, you take an atom of antimatter, put it on your anti-atomic scale (so it doesn't explode) and it's still going to weigh the same amount. You wouldn't be able to tell the difference just by weighing them.

Pamela: In fact, if you took our Sun and were able to magically replace it with pure antimatter and then prevent anything from falling into it, we would orbit the exact same way. Because all the antimatter properties behave the exact same way with this opposition of charge, you could still have a lot of the same processes going on. That's kind of weird to think about.

Now, the only problem is, the second you have a normal piece of matter fall into our antimatter Sun, whatever it hits is going to annihilate and give off a huge amount of energy. Over time our Sun would get whittled down and the explosions would tend to be very disruptive to the Sun. We don't actually find antimatter stars out there – at least, we haven't seen anything hat has the explosive characteristics of antimatter stars.

Fraser: All right, let's talk about that collision. Why does matter and antimatter annihilate one another? What happens?

Pamela: When they come together, the opposites in charge go "oo!" The opposites in fact, of all the quantum numbers, say "okay – we aren't allowed to exist together" and self-annihilate into pure energy.

Fraser: What does that mean "we're not allowed" ?

Pamela: We have, in quantum mechanics, a bunch of different invariances. There's charge invariance, parody invariance and time reversal. What these different things say is when you have reactions they can go (in general, but not always) in both directions. So if I have pure energy, the pure energy, under certain conditions, will end up turning itself into two bits of matter (or in actuality, a bit of matter and a bit of antimatter).

These two bits will conserve charge. One will have positive charge, the other will have negative charge. They'll conserve parody, they'll conserve all their different quantum numbers and even angular and linear momentum, such that they shoot off in opposite directions.

Fraser: Is that part of the fact that matter and energy are interchangeable, like Einstein showed with e=mc^2?

Pamela: That's exactly where this is coming from.

Fraser: So if you take your energy and turn it into matter, can you just get matter or do you have to turn it into matter and antimatter at the same time?

Pamela: When you have energy and convert it into stuff, you have to have both matter and antimatter.

Fraser: So if I want to take light and turn it into I don't know – money

[laughter]

At the same time, I have to be creating antimony…

Pamela: So you're creating money and debt at the same time.

Fraser: And debt at the same time, yeah. Okay, maybe something else instead. Maybe I'm wanting to create I don't know – chocolate bars. So I'm beaming my light and using some tool to make chocolate bars out of it. At the same time I'm making anti-chocolate bars. I have to sequester them or else my chocolate bars are just going to turn back into energy.

Pamela: That's part of this time reversal problem. If you take energy and tear it apart into matter and antimatter and send those particles in opposite directions from one another, if you then reverse that and take the matter and antimatter and bring them back together, you end up with energy.

Fraser: Okay, so that's just the way the interaction goes: you take energy, you freeze it into matter, and you have to get the particle and the antiparticle, and then vice-versa. So this goes both ways. You take your particle and antiparticle and can turn that into energy.

Pamela: The best way to think of it is the tape has to look exactly the same whether you run it forward or backward in terms of the same stuff is going to happen. If you take energy and turn it into matter and antimatter, then when you reverse the tape and bring the matter and antimatter together, you have to get energy.

Fraser: All right. Now, where do we find antimatter?

Pamela: Well, it's right here every day, all around us. We just aren't always aware of it.

Fraser: Wha—what? Where?

[laughter]

Pamela: There are antimatter neutrinos flying through your body right now. Do you feel creeped out? Or invaded?

Fraser: No, no… I assume if that was dangerous, I would already have exploded. Since I haven't exploded, this isn't dangerous.

Pamela: That's one of the things. We've been programmed somehow, by television and books, that any time antimatter comes into contact with antimatter, everything is destroyed. The truth is with quantum mechanics only certain reactions are allowed to happen. Antineutrinos are created in the sun and in fusion processes and in nuclear reactors (in some cases – it all depends on what the decay process is). Those neutrinos are flying around everywhere and neutrinos just don't generally interact with things. You can have antineutrinos flying through your body and nothing's going to happen.

Fraser: That's because I don't have any neutrinos in my body for them to interact with.

Pamela: Or any pathways in general for them to interact with.

Fraser: I guess my question is does a neutrino have to hit an antineutrino to do the reaction, or can an antineutrino hit an electron and it be a reaction?

Pamela: This is one of those weird "only certain things are required" Feynman diagrams getting drawn all over chalkboards by people covered in chalk dust. There are certain things that are allowed to happen. Neutrinos allow protons to become neutrons and neutrons to become protons, and allow different nuclear decays to happen. In some of these decays, you end up giving off the neutrinos. At the same time, in theory, you can occasionally end up having the exact same thing happen in reverse. It's rare to get just the right alignment of all the different stuff.

Fraser: Okay. Antineutrinos are pouring out of the sun. Where else do we get antimatter?

Pamela: There's also this thing called beta decay. You can build an atom of sodium that's not all that stable. If you cram too many (or too few) neutrons into the centre of an atom, the proton and neutron ratio isn't stable and you get different types of decays. For instance, you can go from a sodium atom that isn't really happy, isn't really stable, that has 22 bits in its centre – 22 different combinations of protons and neutrons – and it can decay to have one of those protons become a neutron. You can end up with a neon atom that has the same number of protons and neutrons at the centre and is a lot more stable. In the process of that proton becoming a neutron (which has no charge), the charge had to go somewhere. To conserve charge, that decaying proton ends up emitting a positron and a normal matter neutrino.

Fraser: All right. Anywhere else?

Pamela: So, we have all different types of atoms that exist on the planet in the ground, in laboratories, in different places that are undergoing these beta decays and giving off positrons.

Fraser: Okay, so there are positrons just being generated through atomic decay of regular matter here on Earth, in our bodies – hopefully not too much – and around the universe. When this happens, you get these little positrons popping out, which are these anti-electrons and they'll probably find a piece of matter almost instantaneously and annihilate it.

Pamela: Yeah, and collide and give off energy. This is where radiation can become a bit bad for your body. You really don't want one of those things hitting say, a strand of DNA in your body. One of the reasons that radiation can be dangerous is you have positrons, gamma rays, x-rays – all these high energy or high energy-generating particles – whamming into molecules in your body that you'd really rather keep the way they were created. This can lead to cancers when you end up mutating things through high energy reactions.

Fraser: Okay, are there any other natural sources of antimatter out there?

Pamela: If you have a system that's generating gamma rays or some types of x-rays, when these photons – these high energy bits of light – pass just the right distance away from an atom, it can end up leading to the generation of an electron and a positron. When these positrons later end up colliding, it ends up generating new gamma rays.

Fraser: What kind of environment would create that? I'm thinking black holes.

Pamela: Black holes can do it, neutron stars can do it when they're in a binary system. You take one of these extremely high-mass, very compact, dead stars, stick them next to another rather normal, run-of-the-mill star, and let their gravity do its thing. If they get close enough to that companion star, they can actually start gravitationally cannibalizing their companion and sucking matter off of it. In this process, they're accelerating atoms, they're creating magnetic fields, all sorts of bad, high-energy things are happening, and they can end up creating these gamma rays that are necessary to start generating the electron-positron pairs.

We think there's actually, for whatever reason, this large family of these binary stars near the centre of our galaxy that are giving off basically a cloud of antimatter, a cloud of positrons that, when they end up interacting with rogue electrons in our galaxy, are giving off a very specific colour of gamma rays that corresponds to 511 kilo-electron-volts. So we can see in our own galaxy a place where there's a whole bunch of antimatter that appears to be getting generated from a bunch of binary systems with high energy, cannibalistic neutron stars and black holes.

Fraser: Right, so just to clear that up, when scientists here on Earth combine antimatter and regular matter, it gives off a very specific kind of energy, with a very certain amount of energy in the wavelength.

Pamela: That energy is carried in a packet of light, in a photon that's 511 keV in energy.

Fraser: So when they turn their gamma-ray telescopes out into the universe – or is it x-rays, I'm not sure where that sits…

Pamela: It's in gamma rays.

Fraser: It's in gamma rays, yeah. They see this exact same signature of radiation coming from this cloud around the centre of the Milky Way. So they say it has to be antimatter that's being annihilated out there with regular matter. This is the theory they think is backing it up – these binary systems.

There were some other ideas as well. I know that scientists thought that might be dark matter being annihilated. Through the annihilation of dark matter, it was generating antimatter which was then being annihilated. But now they've got more evidence it's the binary systems and not the destruction of dark matter. So that was one hope to figure out what the nature of dark matter is, but now it's looking like that's not so likely.

Pamela: One of the really weird things about this story is it's been in the news a lot because the Integral Satellite from the European Space Agency is the mission that figured out that this cloud of antimatter is probably being generated by binary stars.

This is the first I personally heard about this cloud, but it was apparently discovered back in the 1970s by balloon-borne gamma ray cameras that were carried up into the atmosphere. So we've known about this cloud of antimatter pretty much as long as you and I have been alive. People aren't talking about it in textbooks, and it's one of the coolest things in our galaxy (in my opinion) and yet nobody knows about it.

Fraser: Well, yet. These things take time… well, that's true though… if they've known about it since the 70s. But these things take time.

Pamela: Yeah, how many textbooks have been written since then?

Fraser: Yeah, it just takes time for this to move into the regular, mainstream science, I guess.

Maybe they don't like the mystery, they don't like to not know what's causing it. Here's a mystery, we don't know what it is, so they just won't even bring it up. I guess with some of the things like dark energy, it's a big mystery – nobody knows what it is – and yet they really have to at least talk about it in cosmology textbooks.

Speaking of cosmology, Since antimatter's just sort of a by-product of frozen energy, you would think that in the most energetic explosion ever, with the big bang, there must have been gigantic amounts of antimatter produced.

Pamela: As far as we know, there was actually almost (almost, almost, almost) the exact same amount of antimatter and matter created in the big bang. The numbers are somewhere on the order of 10 billion antimatter particles for every 10 billion and one particles of regular matter. We're not sure why the slight difference existed between the formation of the two different types of bits of material.

As far as we knew for a long time, the matter and antimatter should've been formed in the exact same amounts. We're finding new particle reactions that, for whatever reason, tend to prefer either creating matter or creating antimatter.

There are these particles, kaons, that for whatever reason during their decay process, tend to prefer to create positrons than to create electrons. We don't know what other processes there are out there that have a preferred direction of decay that prefer to go and form matter instead of antimatter or the opposite.

Fraser: So scientists used to think there was exactly the same amount of matter and antimatter in the universe, we just happen to live in a matter chunk? Or maybe we live in an antimatter chunk, right?

Pamela: It all depends on what you call it.

Fraser: Yeah, right – the opposite of us. The point being it's out there in the universe, it just didn't clump uniformly?

Pamela: Here's where the confusion came from. The theories said when the universe formed there should've been the same amount of matter as antimatter and it all should've self-annihilated and how did we get to a universe dominated by matter?

Everyone's brain froze. This is a problem – it's a violation of our understanding of the conservation laws that govern how particles are formed and destroyed. We realised there had to be something wrong with our understanding of particle physics.

In doing experiments and looking at how things are generated and how things decay and what different particle reactions are going on in the universe, we started to find different examples of decay processes that tend to prefer to go one way or the other. We call this CP-invariance.

Now we're finding that there are times when the universe prefers to generate matter or antimatter, and it appears that in the very first moments of the universe, our universe chose to prefer matter. Because of that, it generated, in the creation of the first bits of stuff, more particles of matter than antimatter. The very slight difference, that one particle out of a billion, led to our universe now causing us to be surrounded in normal matter that we're sitting in normal-matter chairs and are made of normal-matter bodies.

Fraser: Does that mean there aren't large quantities of antimatter out there, somewhere?

Pamela: As far as we know, there aren't. We'd probably know it if there were, because if you had cosmic rays (which we know are all over the place, flying all over the universe) of normal matter running into antimatter objects, you're going to get these flickers of this 511 keV (or other different energies depending on what the annihilations are). You're going to get these flickers of antimatter/matter distraction going on, and we haven't seen that except with this random cloud in our own galaxy.

As far as we know, there aren't antimatter galaxies out there. There aren't antimatter solar systems or stars. The universe is dominated by regular matter, and while antimatter is out there and antimatter neutrinos are passing through you, the antimatter isn't what makes up our universe. It's just this side stuff that's here today, gone tomorrow as it passes through and self-annihilates somewhere.

Fraser: I'm sure we're going to get this question, so I'll head it off at the pass. Are there other anti-things? Is there an anti-energy?

Pamela: No. Energy's zero point is defined on where we think the lowest possible energy point is – which is kind of a wussy way to do it. That zero is an arbitrary place, so we don't talk about something having a negative energy. Energy is energy. It's the ability to move something, to do something, to have something happen. That's just a quantity that is there. You don't get negative energy.

Fraser: Right. I guess it's because if you imagine it's like a fork in the road. You've got energy on one side and then it branches off to become matter and antimatter. If you go the other way, you bring your matter and antimatter together and get energy. It's not like there's some whole other combination that would turn into energy and anti-energy if you had something. That just doesn't exist, right?

Pamela: Right.

Fraser: Right. Okay – is there antigravity then? I guess gravity comes from both matter and antimatter, is there something that could maybe generate antigravity? Come on star trek!

[laughter]

Pamela: No, no. Unfortunately, while people will periodically refer to dark energy as antigravity, it's not. Really. The force of gravity is a strictly attractive force. Matter and antimatter both have the same mass quantities, and both can interact with gravity in the exact same way. if you could create that star of antimatter, it's going to cause things to circle the exact same way a star of regular matter would cause them to circle.

Fraser: All right… what about anti-time?

Pamela: Anti-time is called running your clock backwards, and as near as we can tell, that doesn't happen.

Fraser: Okay. So, just to beat those questions off at the pass: there's no antigravity, there's no anti-energy and there's no anti-time. That we know of.

Pamela: That we know of.

Fraser: We're waiting for someone to come up with a discovery and then we'll take it all back and erase this show.

[laughter]

All right. Once again, I think a lot of people think that antimatter is this theoretical thing. It's very practical. We use antimatter here on Earth all the time, right?

Pamela: Anyone who's had a PET Scan. In a PET scan, they create positrons in a medical cyclotron. They basically accelerate stuff and positrons come flying off. It's a much more complicated process, but let's just go with that simple way of looking at it. When you have a PET scan, they're shooting positrons at you. They're shooting antimatter electrons at you to make measurements.

Fraser: I guess they stick the positrons into your body and then when they decay, they can spot it. Right – when they collide and get annihilated, they're able to spot the explosion in your body?

Pamela: In a PET scan, they actually inject you with this sugar base. They call it radio-pharmaceutical stuff. It's radioactive, it gives off positrons and those positrons then get detected by the scanner they stick you in. it's a scanner that's looking for the gamma rays given off by those positrons colliding with something and bad things happening.

It's an interesting way to create digital pictures of the inside of your body that are three dimensional. It's one way that we use antimatter in our day-to-day ways of diagnosing diseases.

Fraser: I guess that's a good example as well. When you think about antimatter, I think people think it's going to cause these run-away chain reactions, where one little piece of antimatter is going to create an explosion and it's going to consume the whole body and then the whole Earth and then the whole universe. But that doesn't happen.

Pamela: No, and another one of the really neat things I came across in preparing for this show was back in July 2002, there was a big solar flare that it's estimated created an entire pound of antimatter during the flare. That's half a kilo, and enough energy being created in that antimatter then self-annihilating on other stuff to power the entire United States for two days. But once that energy was used up, it was gone.

So while antimatter annihilating normal matter does generate huge amounts of energy, it's not the type of thing that we have to worry about causing any chain reactions because once it's used up, it's used up and there's just gamma rays flying through the universe.

Fraser: Right. My last question was how can we use antimatter as an energy source?

Pamela: It's kind of hard to use it as an energy source, because right now we use more energy to create a particle of antimatter than it generates when it self-annihilates on something else.

Fraser: Right, but I guess it could be used as a storage… it's very compact. You could take that pound-worth of antimatter, put it on your spaceship, and bleed off the energy. Take a second pound, double your fuel load, and use that energy to power your spaceship. Right?

Pamela: If we had a way of containing a pound of antimatter and a pound of normal matter and very carefully, in a controlled way, mixing them and shooting the gamma rays out the back end of the spaceship to propel the spaceship forward, yeah – that would be really, really cool.

But, the problem is containing the stuff. Let's say you create a pound of just antimatter protons. You can contain those protons because they have charge, so you can use an electric field and a magnetic field to suspend them away from the edges of a container that is just otherwise complete vacuum. Those individual antiprotons aren't going to want to have anything to do with one another. They're going to propel each other. You're going to need a pretty big containment vessel, with really big electromagnetic fields to try to keep things from the container's edges. It gets really dangerous and really complicated.

We have managed to, for brief periods of time, create anti-hydrogen and anti-helium. Containing it is really difficult. Right now, it's not something that's practical. Another thing to think about is yes, this is the most effective way we know of generating energy, but 50% of the energy generated in the matter/antimatter reaction ends up getting lost to neutrinos that go flying off and those neutrinos, because they don't want to interact with anything, are just going to go out through the sides of your spacecraft and do nothing to aid in your propulsion. It's still a really effective means, but I think it's kind of cool you still lose 50% to something we can't use.

Fraser: Right, but we don't get that fraction of energy efficiency from anything else we can do, right? Fusion, fission, chemical reactions. Nothing is as efficient as an antimatter/matter annihilation. Right.

Pamela: Exactly.

Fraser: So yeah, I understand. The complexities of being able to actually do it are mind boggling, but not impossible. This is science. This is really possible. It's an engineering challenge of massive proportions.

[laughter]

Pamela: It falls in the category of something we can do today.

Fraser: But there's no reason it couldn't be done.

Pamela: Maybe someday.

Fraser: As opposed to going faster than the speed of light, which is not possible.

Pamela: Right, exactly.

Fraser: Great, I think that covered everything on antimatter. Hopefully for all the people who sent us in questions over the last week, I hope we were able to cover as many of them as possible. I guess we'll look over the next week to see the questions that come in for the next show.

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