Astronomy Cast Episode 205
Fusion

Fraser: Astronomy Cast Episode 205 for Monday November 1, 2010, Nuclear Fusion. 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: Good, good! We got the big Halloween chocolate bomb around here. Our kids are in these kinda sugar comas walking around... Jonesin'...
Pamela: I love that point in the evening when you have sugar-high kids and foot-sore parents who just want it to be done.
Fraser: Yeah... I didn't think my daughter could do this, but she sprinted to every house... it was unbelievable. Anyway... so, when the universe formed after the Big Bang, all we had was hydrogen. But through the process of fusion, these hydrogen atoms were crushed into heavier and heavier elements. Fusion gives us warmth and light from the sun, destruction with fusion bombs, and might be a source of inexpensive energy. And then there's that whole controversy of cold fusion... Alright, Pamela, well, let's go right back to the beginning then and get right to the heart of it. When we say nuclear fusion, what are we talking about?
Pamela: We're talking about any time you take two atoms, and you smoosh them together and get one atom and usually by-products and hopefully energy, but not always.
Fraser: Now, when you say smoosh, that's obviously a technical term, but what's actually going on?
Pamela: Literally... I don't know how else you'd describe it other than smooshing. Scientifically, you say that you take two particles and you collide them together at high enough velocities to overcome the repulsive forces in the centers of the nuclei.
Fraser: So, you could fire two atoms at each other, and if they hit perfectly, they would fuse.
Pamela: If they had sufficient energy to overcome the desire to repulse each other.
Fraser: Right, right... so there's some speed, some amount of energy that you would impart to these atoms, they would smash into each other and they would fuse. But then when we think about the inside of a star, we talk about tremendous gravitational energy smooshing.... so is that a collision or...
Pamela: No, those are literally collisions. So what you have in the center of the star... in the center of the star it's not actually so much the gravity that's holding it together as it's the light pressure of all the other reactions going on builds up the temperature in the center of the star. So you have all the pressure from the top layers getting sucked down. So the stuff on the top of the star, it's experiencing a lot of pull downwards. But when you're in the very center of the star... zero gravity... happy! But you have the weight of everything above you squishing down, creating pressure. Pressure builds, nuclear reactions begin to occur, nuclear reactions generate light, light increases the pressure... high density, high temperature, high pressure... all of this combines to allow the nuclei at

these high, high temperatures to collide with sufficient velocities and in sufficient numbers to have ongoing nuclear reactions.

Fraser: It's the high temperature that's imparting the fast giggling to the atoms and therefore they have enough velocity to... when they bonk into each other... to then fuse. So, if we had cold temperature, you would have to fire your atoms really fast. But at hot temperature, just the background heat is what's making them vibrate so quickly.

Pamela: You're confusing it... the temperature and the speed are the exact same thing.

Fraser: No, I understand.... I understand.

Pamela: So, at cold temperatures you don't have high velocities.

Fraser: Right... right... of course. Ok, so and then you said that there is energy released.

Pamela: To a point. And this is one of the weirdnesses about why we end up with supernovae. In the centers of stars, you have hydrogen burning, you have helium burning, you have carbon burning, you have nitrogen, oxygen burning, silicon burning... and you work your way up through all the lower elements until you hit iron. When you hit iron, there's this magical transformation in how the particle physics works. Prior to getting to iron, when you merge two things together it released energy. When you get heavier than iron, it takes energy in order to combine the two atoms into a single atom. But at the same time, what you have is higher than iron, if you break the atom apart, then it releases energy.

Fraser: Right, and that's fission.

Pamela: Right. And that's a different show.

Fraser: That sounds like a different show, yeah... perhaps a second show in a week. Ok, so then what kind of energy is being released? If you fuse two hydrogen atoms together, what energy comes out? How much?

Pamela: Not enough to light a light bulb.

Fraser: But that's just two atoms.

Pamela: Right. You don't get... in a couple of reactions... you don't get enough energy released to really worry about it. It's because you have so many reactions going on at once that together you're able to get enough energy released that you can support a star.

Fraser: So is the light that we see coming off the sun, is that the energy from those fusion reactions?

Pamela: Eventually. This is where things get a little bit weird. So what ends up happening is that deep in the center of the star you have all of these nuclear reactions going on, you have things like hydrogens combining forming heavy hydrogen which is a hydrogen that has a neutron... a whole series of different reactions.

Fraser: Right, I know it's like multi-stage, right? There's several steps that will happen to get you to the end result.

Pamela: And each of these is giving off something on the order of a mega electron volt of energy to a few mega electron volts of energy.

Fraser: And these are coming off as gamma rays, right?

Pamela: Well, they're coming off as gamma rays, you also have neutrinos released, you have a variety of different ways that the energy comes flying out. But when I say, like, for instance, the proton-proton chain might give off a few tens of mega electron volts down to less than one mega electron volt. That's strictly the light that's coming off.

Fraser: It's awesome to say mega electron volts.

Pamela: Now this light that's coming off, as it tries to escape the sun, it's not like we're getting blasted with gamma rays here on the planet Earth.... Instead we're seeing this blackbody spectrum that peaks somewhere in the yellowish colors... but when you average out the distribution, the sun is white if you can escape the earth's atmosphere. The reason we see this distribution of colors is this high-energy light, as it tries to get out of the sun, it does this crazy... what we call Brownian motion. It goes in one direction, gets absorbed, gets re-released in another direction, gets absorbed, gets re-released in another direction, and as it goes, sometimes you have an atom that gets excited... or actually an electron that gets excited, and it cascades down through a variety of different transitions, releasing a multitude of different particles of light, of different photons as it cascades through the energy levels. So what started off as high-energy light, ends up turning into this distribution of a whole bunch of different colors.

Fraser: And I remember when we talk about what's going on in the sun, that it can take a 100,000 years for a single photon to be generated in a fusion reaction and then to run through a whole bunch of different atoms, be absorbed and re-emitted, until it finally is able to be released from the surface of the sun.

Pamela: So, it's a long process, and it's this Brownian motion that takes forever and then eventually the light escapes what is called the radiative transfer part of the sun and hits the convective zone and then sort of rides up in thermal cells and gets radiated away as thermal light in the blackbody spectrum that we see.

Fraser: Is there a different process for fusion for hydrogen than for the heavier elements? Because I know that as the sun is running out of usable hydrogen in its core, it will switch to fusing helium, it will switch to fusing lithium, oxygen, and carbon... Is the process kind of different? Is the math different?

Pamela: Well it's different in terms of two plus two equals four, one plus five equals six, but you use the same math to figure it out.

Fraser: So two carbons merging together are going to release a different amount of energy and a different set of neutrinos and produce different intermediate particles.

Pamela: But there's always the same set of particle physics rules, and once you learn those rules, you can actually calculate very accurately what's going to happen in these different reactions.

Fraser: That sounds like a test question. You'll be given this atom and that atom...

Pamela: It takes too long to do it on a test... it's usually a form of torturous one-week long homework assignments.

Fraser: Ok... imagine some exotic star where carbon and uranium particles are being merged together.

Pamela: Yeah, that one doesn't happen. But...

Fraser: No, I understand... but you could do the math.

Pamela: Yeah, and it would be something like carbon-12 hits regular hydrogen... what are the resultants? And the resultants are hydrogen and gamma ray and energy released. What happens if you have nitrogen-13? Well it decays into carbon and a positron and a neutrino and energy. So there's all these different chemical reactions. But the neat thing about most of the fusion processes is that they all involve hydrogen for the most part somewhere in the stage. So it's carbon and hydrogen... not two carbons. It's nitrogen and hydrogen, not two nitrogens. So hydrogen really has its claws in every reaction in the universe.

Fraser: Alright, and so that's the same process that's going on in all the stars in the universe. Once they hit that fusion reaction in the core, they're releasing all this energy... it keeps the star inflated... right... but then here on Earth, this kind of fusion power is something that scientists have been trying to wrangle with as a source of power, as a source of destruction... so how is that different?

Pamela: It's the exact same physics, but we're kind of lacking a friendly containment vessel. With a star, you have the crushing pressure of all the outer layers of the star pushing in on the center of the star that confines the nuclear burning region and maintains its density and maintains its temperature through the pressure-density relationships. On Earth it's kind of hard to maintain the densities necessary and the temperatures necessary to drive fusion. So you need two things: you need temperature because the high temperature is what gets the atoms moving fast enough that when they collide they overcome the desire to repel each other, but the density is also important as well because if you have one atom moving as fast as it needs to go and it never hits a second atom because the densities are too low, fusion is never going to take place. So you need both the high density that allows the collisions to take place, and the high temperatures that allow the velocities that overcome the desire to repel. Maintaining those two things is something that we're struggling with. We've figured out a variety of different ways to do it, but all the ways that we know to create fusion, they take more energy to start than we get out through the fusion reactions.

Fraser: So because we don't have the mass of a star to act as a handy containment vessel, we have to figure out some kind of magnetic way to levitate the hydrogen, right?

Pamela: Well, it's either magnetic or it's lasers... which is just fun to say... or it's we try it with acoustic bubbles... not so much success there... We've tried a whole variety of things to get the densities and temperatures needed.

Fraser: And then once again because we need to work in a space that's smaller than planet Earth, we need to raise the temperatures a lot higher than they have to do in the sun, even.

Pamela: No, it's the same temperature.

Fraser: Oh, is it? Ok...

Pamela: Yeah, it's the same temperature because all that matters is that the velocities are right. So you get the same velocity at the same temperature in the sun and on the earth. But, the problem is that we have to maintain the same densities as on the sun, as well.

Fraser: And that's where you have to use the lasers and magnetic bubbles and things like that to keep that density. So, fusion is always 30 years away... they've been doing that for 50 years...

Pamela: Since the 70s...

Fraser: Yeah, so are we 30 years away right now?

Pamela: Well, we can generate fusion all we want... it's just a matter of it takes more energy to do it than we get out of it, which is a problem. For instance, for a while the big area of research was Tokamak reactors. These are small little fission systems that use magnetic fields to create essentially a donut of plasma, and you tune the magnetic fields to create high densities inside this torus, this donut, until you can generate the needed temperatures to drive nuclear fusion. But, it takes a whole lot of energy to set this system up.

Fraser: You've got your magnetic bubble, you've got lasers, you've got heat... it's all coming together at the same time, and the energy that comes back out isn't enough to run the reactor.

Pamela: Well, in a Tokamak, all it is the magnetic fields... no laser required here.

Fraser: No lasers, yeah...

Pamela: No lasers here. So in the Tokamak, you just have this toroid of plasma, and when you squish down that toroid... yes, you can get... what they see is the by-products of nuclear fusion. They see a surplus of neutrons. It's that surplus of neutrons that tells us... yay! something happened! But all the energy that goes into generating the plasma, that goes into maintaining the magnetic fields, that goes into the whole system... it makes it hard. Now the nice thing is, this also means, though, we're never going to get runaway fusion reactions the way we can get runaway fission reactions in nuclear power plants. All you need to do to stop the fusion reactions from generating energy is to turn off the magnetic field. Instantly... no more runaway nuclear reactions because they weren't running away... they were being forced to run against their will.

Fraser: Ok, I mean I know the Tokamak was as you said back in the 70s and 80s... we're 30, 40 years past that. So what's the latest advances in fusion research?

Pamela: Well, that works?

Fraser: Anything....

Pamela: Well, we know that we can also generate fusion through muon processes. You can get muons through various different decay processes. This means that you have to have some sort of a high energy collider... accelerator... something that's going to create the radioactive decays that will lead to the muons.

Fraser: So muons are subatomic particles that are released from particle collisions.

Pamela: Right... via decay processes involving usually pions... anyway, that's a lot of crazy particle physics.

Fraser: But that sounds expensive to collect your muons...

Pamela: Not only that but the energy necessary to get the muons from the accelerators isn't something that we've figured out how to overcome. The problem is... muons are not stable. So you set muons loose in something that wants to undergo fusion. For instance, if you have heavy hydrogen in the form of deuterium or tritium, this heavy hydrogen is fairly willing to fuse. That muon... it might undergo a hundred... it might undergo 200... various people argue over the results... we think we've gotten as high as 250 fusions before a muon decides to either bind with a special form of helium called an alpha particle or it decays or otherwise goes away. Well, the energy released in those fusion events is still less than the energy needed to get that muon in the first place. So, we're off by—on a good day—a factor of four, on energy out vs. energy in. And that's a good day.

Fraser: But it's so frustrating because the sun is sitting there... no technology required. Get a lot of hydrogen, put it near itself, it'll merge down into a ball and generate energy. Life-sustaining energy.

Pamela: All that gravitational potential is holding the system in a situation that enables the fusion to take place.

Fraser: But it's just so frustrating! It's the same thing as 100 years ago someone saying "No, it's not possible to fly." And you see birds flying around... and you think, "Can't be done... but there's birds!"

Pamela: Well, we're not willing to say, "Can't be done." We're simply willing to say, "This technique doesn't seem effective." So muon-driven fusion—not so good. Muon-catalyzed fusion—not so good. Energy in not equal to energy out. So we've tried other things. My favorite in terms of... ooh, that just sounds fun... is bubble fusion. This is where we...

Fraser: Mmm... bubble fusion... like bubble tea...

Pamela: Basically you create bubbling fluid... who doesn't like their fluid bubbling... and the bubbles you drive via different... they call it sonoluminescence... this is where you grow the bubble via slow expansion and then squish it as fast as you can! That sudden collapse of the bubble presses the center down very small and when you compress something you drive up the temperature and that high temperature region in the center of this collapsing bubble releases light, and there's controversial... most people don't believe it... but there's controversial potential evidence that you can get fusion out of this. Now the reason I say controversial is that the experiments that are done haven't been irrefutably repeated. We haven't always seen the by-products of fusion, lots of controversy. It's not something that you trust. When you have a good, solid experiment... it's the type of thing that you can hand to a grad student and say hey, go replicate this. It's a good homework project for your semester. We're not at that point yet that this is a lab project that you can give to a grad student and know it's going to work.

Fraser: Well, sounds like it's 30 years away!

Pamela: Yeah... I know. We have one more hope, though.

Fraser: Oh, ok.

Pamela: The one more hope is lasers... let's go back to lasers.

Fraser: Lasers! Everything's better with lasers!

Pamela: Exactly. There are lasers out there that are being designed that in a single pulse of the laser beam give off the same amount of energy that the whole United States used...

Fraser: In that nanosecond... in that attosecond... right.

Pamela: Yeah. So, that's kind of awesome. And what they're working to do is figure out...

Fraser: How to attach it to a shark, right?

Pamela: Well, that would be awesome, but unfortunately these lasers are the size of a drab office building... they're apparently not the size of awesome-looking office buildings because they're only built inside drab-looking buildings.

Fraser: Right.

Pamela: What they do is they take these lasers and they split the beam... and then focus all the light down on a single... basically, a BB. And these BBs are seeded with things that want to fuse... tritium, deuterium... and then they're often encased in something like gold. Then you fire on this BB from a whole bunch of different sides and all of the energy from the light goes into squishing the bejeezus... and I'll use that as a scientific term today... squishing the bejeezus out of this BB so that it's undergoing the same pressures that you experience in the center of a star. The idea is that this will create fusion. Now, we've gotten to the point where we know how to successfully fire at BBs... we think maybe there's been signs of fusion... repeatably... there's always the problem that when you fire these lasers the whole building shakes about six feet in some instances. So, it takes a while to be able to refire. But we haven't gotten to the point that with these large, basically laser ignition systems, we can't have sustainable fusion yet.

Fraser: Ah, I see.
Pamela: And we certainly aren't producing the amount of energy that goes into the firing of the laser.
Fraser: Right, right, ok. So, you fire at this BB... it generates fusion inside the BB for a second, you've used up the same amount of energy as the United States for an attosecond, and you didn't necessarily get out that much energy from the fusion of the BB. And you had to shake a whole building, and you have to cool down your laser and all the kinds of things that have to happen after that.
Pamela: Yeah... in order to be able to fire these lasers, they use giant capacitors that have to be stored in special fluids in essentially Olympic-sized swimming pools.
Fraser: Right... they heat up pretty quick. Ok, so that sounds 30 years away... so what about cold fusion.
Pamela: Yeah, cold fusion is one of those neat little fairly tales they told back in the late 80s.
Fraser: I don't think it ever reached fairy tale. I think it reached humiliating mistakes of science.
Pamela: It falls...
Fraser: I remember Pons and Fleischmann announced that they had figured out a way of doing fusion that you could do in a beaker on a very small lab set-up on the table of any science laboratory. Instead of going through the regular method, they went to the public and held a big press conference, and they demonstrated what they were doing, and it turned out to be wrong. Not fusion at all...
Pamela: So what was the name of that faked skeleton in Europe a while back that caught everyone's attention?
Fraser: Yeah... I know what you're talking about....
Pamela: And neither of us are having the ability to remember, but... this is that type of fraud in terms of... sounded great... everyone chased it... tons of money spent in trying to re-create it only to realize... no. This actually reached the fascinating level of... there was House of Representative investigations, Cornell had to do an in-house investigation, there were academics stripped of their ability to have graduate students, and the idea with this so-called cold fusion experiment was you set up a beaker filled with special versions of different fluids where you replace all the hydrogen atoms with deuterium atoms. Basically add a neutron to every atom of hydrogen in your solution. Then run electric current through your fluid... do electrolysis. In the process, this would squish stuff on one of your... on one side of the current... and this, in theory, would lead to fusion taking place. It's a good idea... it's a good idea that failed to work.
Fraser: But wasn't there something... from what I understand, there still was something going on, it just wasn't cold fusion as we all understood it. There was some kind of interesting chemical process going on. And I guess that's what I'm saying... if they had approached it properly... if they had just released a paper saying hey... we just found this interesting electrochemical process, then...
Pamela: Right, but it wasn't that interesting at the end of the day. Here are these two guys that spend $100,000 of basically their own money setting up their lab equipment, and they were working on a bigger grant proposal... the lifeblood of those of us who live on soft money... and they heard other people who were working on fusion—the muon-catalyzed fusion that I was talking about earlier that does actually work. They had each

seen interesting things... they were getting ready for a press release. The first thing that screams "Foul!" on this is Fleischmann and Pons had an agreement with another colleague at another university who was doing a different form of fusion that all of their papers would be submitted the same day to the same journal from the same airport via FedEx. Then Fleischmann and Pons decided that they were going to instead go to a different journal, two days earlier, and hold a press conference. So that's just sort of not playing nice with your professional peers. On one journal article that they submitted they just randomly added the name of some dude who they knew would help them get through the review process better, but who didn't actually didn't take part in the research at the level that they claimed. There was just a lot of weird academic borderline fraud going on... the type of stuff that you look at and you're like... dudes, you really should have done this a little bit better, considering what you're claiming.

Fraser: Yeah... that's all. And this is one of those situations where Carl Sagan says, "Extraordinary claims require extraordinary evidence." This is an extraordinary claim, you know... free energy. That required extraordinary evidence, and they did the opposite of that.

Pamela: Yeah... they did... pretend evidence.

Fraser: Yeah, and unfortunately it's really hard to distinguish them from any cranks.

Pamela: Yeah.

Fraser: That's how a crank operates, so that's too bad. They destroyed their careers... they destroyed what could have been an interesting whole area of research by tainting the whole thing. I know that now to even say cold fusion gets you treated quite poorly.

Pamela: Right. And that's actually bad for the entire fusion community because I have to admit I look at all the money the DOD is spending and the DOE is spending on fusion reactors and the National Ignition ????... the big laser projects that they're working on... and it makes me a bit sad because I don't think this is going to be the solution that everyone is hoping for.

Fraser: Oh, you personally think that fusion is not the great hope that everyone thinks...

Pamela: I don't think so. I don't think we can find ways to get more energy out than we put in. But it's still a fascinating area of research... there's a lot of fundamental physics going on. If we could look at this from the fundamental basic research of "ooh, cool, isn't that neat" instead of looking at it with the starry-eyed "we're going to save the universe" or at least save the planet Earth... that change in context might mean that people are more careful. It's the difference between digging... thinking you're going to hit gold and breaking every safety regulation in a desire to change the future of your children and grandchildren vs. the randomly walking around picking up petrified wood because it's pretty.

Fraser: Right. I can totally see that. The research into fusion is so valuable because it's the very heart of the way the whole universe works and the answers that come out of it are of the "we have no idea what benefits this will make mankind." But as soon as you narrow on the blinders and say "we must turn this into an energy-generating power source," then that sort of shuts down all of the more basic pure research that could be going on.

Pamela: And I'd just love it if we could see this same sort of fusion research going into the same bin that we see the search for the Higgs boson... as essential, cool, and awesome, and worth spending money on, but not as the hope of all mankind.

Fraser: There are some amazing outcomes from the particle accelerators... you think about anti-matter, which is now used in the medical community for positron-emission scanners, right? So there are these benefits that do come out, but in many cases it’s like let’s wait until the basic research has really been done and don’t jump to an engineering solution.
Pamela: Right.
Fraser: Yeah... I get that. Ok... cool! Well, thanks a lot, Pamela. I think next week we’ll talk about fission.
Pamela: Thanks a lot, Fraser. And that one’s a lot more destructive and cool.
Fraser: Yeah, alright, talk to you later.
Pamela: Ok, bye-bye.