# Astronomy Cast Episode 260 for Monday, April 9, 2012:

# The Technology of Lasers and Masers

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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 is Dr. Pamela Gay, a professor at Southern Illinois University – Edwardsville. Hi, Pamela. How are you doing?

Pamela: I'm doing well. How are you doing, Fraser?

Fraser: Doing great! So I wanted to give a big shout-out to a piece of technology that we've had for a little while, but I had never directly used it, which is the Astronomy Cast app, which…my kids love to listen to Astronomy Cast. It's what they go to bed to every night.

Pamela: [laughing] That's creepy.

Fraser: It's…I don't think a lot of it's getting retained. Every now and then I quiz them, but I think they like to listen to our voices, which I think is adorable.

Pamela: OK.

Fraser: So…and I decided to install, to give them the app because it gives them access to the entire catalog, and you don't have to download it and install it on your iphone, or whatever. I know there's a lot of people out there that like to listen to all the back catalog issues, episodes of Astronomy Cast, and I also had gotten a few complaints from people that some of the old titles weren't in, so I went back and fixed everything, so now it should be really tight. All of the episodes are there. You can get all 250+ episodes and just play them all instantly through our iphone app, and I think it's a $1.99 for the app itself.

Pamela: Yeah, it's something completely reasonable, and what you're paying for is someone other than us wrote the app.

Fraser: Yeah, that's exactly right, and… it's done through our audio/listening provider, but it's really convenient, and a really good way to get access to our entire library of episodes, and I highly recommend it, so do a search.

Pamela: Go download it.

Fraser: Yeah, do search on itunes for Astronomy Cast, and you should find our app and install it, and I think you'll like it. The only problem is that it never stops playing, so once you start it…sometimes I'll come in it's 4:00 in the morning the kids have had the thing going all night, burning through their batteries.

Pamela: There's a solution for that. If you use…there's a timer on the clock (I do this all the time). I don't listen to Astronomy Cast like this, but I do this for other things all the time. I'm not that creepy. But if you use the timer on your clock setting on your iphone, set it to "20 minutes turn off itunes," it will also turn off apps like ours, or audible.com's app, or the public radio player, or all these other players that are out there that allow you to listen to droning voices as you go to sleep.

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Fraser: So just when you think you understand it, light will do some amazing things. Just look at the discovery of lasers and their use in almost every technology you can think of -- from cutting, to transmitting information, to yes, astronomy. And nature has figured out its own version of technology called the maser, which has kept astronomers puzzled and excited for years. So I guess this week we're going to talk about the actual underlying technology, just to help people understand the physics of how lasers and masers work, and then we thought next week we'd actually go into its applications in astronomy. So I really resisted the urge to talk about sharks and lasers.

Pamela: So did I! We're both horrible humans!

Fraser: No, no, no. We just can't go that way. So then, let's talk about lasers…so what exactly is a laser?

Pamela: It is…and laser technically is only optical light, but we're going to, throughout this episode, end up interchanging using optical light, using infrared light, and all of these things. What we're talking about is a process by which light is amplified, so laser is a light amplification process, which means you start with one photon and you end up with a whole lot more than that one. So the whole acronym is Light Amplification by Stimulated Emission of Radiation, which sounds like you're doing something really dirty, and really it's not. So to break down all of these separate words, let's start with the stimulated emission. Stimulated emission means that you have in your atom…normally your electrons like to hang out at the low-energy levels, but if you get them excited, they'll jump up into higher energy levels, and stimulated emission means you have an electron hanging out at that higher energy level, along comes a photon and it interacts with that atom, and if the photon has the exact same energy as the transition of that electron from the lower to the higher energy level, for a lot of complicated quantum mechanical reasons, that fact that that interceding photon and that existing energy jumper exactly the same will cause the electron to spontaneously jump from the higher level to the lower level, and sympathetically give off a photon of the color of the original photon that's in the exact same phase, and so you end up with coherent light as a result of one photon triggering the emission of a second photon.

Fraser: Right, and I understand this part that essentially you're getting more of the same flavor of photon. You're going to get the right wavelength and you're going to get a very…and then so these photons are going to come pouring out in the exact same color, right?

Pamela: Right, so you have radiation initially – that's your incoming photon, that's causing stimulated emission between those two different energy levels, and the light amplification part means you start with one and you end up with two coming off on the other side.

Fraser: And now, radiation sounds scary.

Pamela: No. So, light is radiation.

Fraser: Right.

Pamela: "Radiation" is the most abused word in science in a lot ways – that and "theory." Theory gets it even harder than radiation…but if I shine a flashlight on you, I'm radiating you.

Fraser: …with visible light.

Pamela: …with visible light, which doesn't hurt you unless it's really intense.

Fraser: Really intense light…right, OK, so you are radiating, and then you are…then you're emitting photons kind of like copies of that first photon.

Pamela: Exactly, and so the actual hard part about this is electrons don't like to hang out in that higher energy level, so most of the time we don't end up with lasers. So the fact that there is light coming out of a light bulb in my ceiling is not causing stimulated emission all over this room. The gas in this room is not lasing me on a day-to-day basis; otherwise, life would be difficult. So in order to get lasing to occur, or masering activity to occur, the physics is the same no matter what the color of the light coming out of the system is. You have to somehow get what's called a population inversion. This means that you have more electrons hanging out in this higher energy level than in the lower energy level they'd like to be in. Otherwise, what's going to happen is you have an excited one up here, it collapses down, gives off a photon, that photon doesn't go very far before it hits another electron in the lower energy level and jumps back up, and you simply have absorption and emission processes going on. If, in fact, you have more electrons in the lower energy level than the higher energy level, you're actually going to end up absorbing the light at the end of the day. So the only way to end up with extra light coming out than you had going in is to start out with more of the electrons excited than not, and that's not a normal situation.

Fraser: But I think that explains the, I guess, the color of the laser, but what explains the shape? I mean, when you fire a laser beam it has very significant, you know, very straight shot that it takes. So what's going on there?

Pamela: That has to do with the mechanics of how they build the system. So the easiest example is the pulsed ruby laser, and this was one of the first lasers ever built. And so, basically, you take a synthetic ruby core, wrap it with a mirror, put a mirror on one end of it, so you have this ruby cylinder, wrap mirror around the long part of the cylinder, put mirror on the end of the cylinder, and put partial mirror on the other end of the cylinder. And what ends up happening is you end up getting a stimulated emission going in all sorts of different directions, but the only time the stimulated emission is allowed to escape is when it goes out the one end that isn't a pure mirror, and the rest of the time it's triggering more and more and more of these transitions to take place, so what ends up happening in one of these ruby lasers is they wrap it (so think one-way mirror), so they wrap the laser in the mirror, and then wrap the mirror in laser with a light source that flashes. When the light source flashes into the ruby crystal, electrons jump to higher energy levels. They're now in that higher energy level, and when one starts jumping, it causes all the rest to start jumping, and so this is what stimulates the emission.

Fraser: But they can only escape in that one direction that you haven't wrapped.

Pamela: Right, so that simply becomes a geometry problem.

Fraser: Right. OK, so it's not like a function of the way a laser works just in general, so if you hadn't wrapped the laser in this mirror, would you just be getting this color light going out in all directions?

Pamela: Kind of. Now, the trick that isn't having to do with the fact that you wrapped the sucker in a mirror is the fact that the light is coherent. This means that one photon's wave lines up with the next photon's wave, lines up with the next photon's wave, and so the light interferes coherently. This coherence is actually triggered from the fact that each of the stimulated photons picks up the phase of the photon that's stimulating it, so that stimulated, in-phase, coherent light part -- that has to do with the fact that it's a laser, and not the fact that you shaped the beam coming out. This is why flashlights, which also have mirrors, are never going to be the same thing as lasers.

Fraser: Right, and also, they're just not giving out the same…they're giving out light in all colors, not in that one….

Pamela: Right, right, well, you can have a diode flashlight, and a diode flashlight is all one color of light if it's well made, but the light is not coherent – this is the special thing about lasers is if you could stop all the photons and somehow actually see the wave (and you can't do this -- quantum doesn't let you)…but you can measure the interactions, and when you do this you find that all of the maxima of the waves, and all the minima of the waves are politely lined up in a coherent way that allows you to interfere the light with one another. You take a diode flashlight, stick it through a spectrograph, you're going to see that it's all nice, basically one color, just like lasers are all basically one color, but even though you have that one color, the photons are all scattered all over the place in terms of how the maxima and minima are lined up, so it's incoherent light.

Fraser: Right, OK…and so where did the discovery of lasers come from? And I know that masers plays into this, right?

Pamela: Well, it's a long and storied history, that it's interesting, if you start poking around the internet trying to figure out the history, you can see national biases in who wrote what when, and the Wikipedia article, in particular, shows definite national biases. So the idea for a laser can actually be tracked back, like many other things, to Einstein, who basically started to understand that stimulated emission could occur. This idea that you have an excited electron, a photon comes along at the energy of the gap between that electron and its next energy level, this triggers a coherent photon coming off -- he was the person who first figured that out. And it wasn't until almost 40 years later that various scientists working on a number of different projects started to figure out how to make this happen in a laboratory, and what's kind of interesting is the first group to do this -- it was a trio of fellows: Townes, Bosov, and Prokhorov (and I'm sorry for the deadly pronunciation on that one). They were working on trying to stimulate emission in molecules, and they'd spent a bunch of money on it, and there was a bunch of people complaining, and I'm looking at the numbers, and I can't take my eyes off of them because it's so funny how the scale of things have changed. So working back in 1954, there was a group of people who were trying to close down the research because they'd spent SO much money: $30,000!

Fraser: Oh, no!

Pamela: They'd spent SO much money!

Fraser: How could they spend that much money discovering lasers!

Pamela: I know! I know! And everyone just saw this as a horrible waste: "What was the purpose?!" And so when they finally got a working apparatus they called it a MASER: the Microwave Amplification by Stimulated Emission of Radiation – MASER device. But the folks who were mocking them, who didn't see a purpose for this said that MASER actually meant Means of Acquiring Support for Expensive Research, and I just love the way scientists find to mock each other. We're not a friendly, work-and-play-well-with-others profession all of the time. But this initial work in 1954 was really what started it all, and like so many other things in science, it's so much easier to work in the longer wavelengths (in this case, the infrared and microwave wavelengths), and over time, scientists were able to figure out how to build things that extended to shorter and shorter wavelengths. So, started with them, then moved on from there, and it was only after that 1954 discovery that we were able to finally start picking up… and despite all the demeaning that these guys got, they went on to get the Nobel prize for their research, so I think in the end they got their comeuppance. They got mocked, they got ridiculed, they got a Nobel prize. I call that a good day.

Fraser: See if you can work the Nobel prize into the acronym for laser somehow.

Pamela: But it was just a year later, in 1965, that the first natural maser (and we'll be talking about this more in the next episode), the first natural maser was found in the Orion nebula, and since then people have been steadily working to try and get better and better at building masers and lasers. So it's been a long process, but from that '54 maser to '60 optical to '65 Orion nebula, we've been steadily making progress on developing these things one at a time.

Fraser: And so, you know, I've got a laser in the house that we play around with sometimes, very carefully – it's very dangerous and terrifying actually, but I guess, what is the technological advances that have gone from that original microwave? I mean, now we're at what petawatt lasers; I mean, the technology has gotten pretty amazing. What are the technological advances that have brought lasers forward?

Pamela: Well, we've been working to try and figure out what are the different ways to create an environment where a stimulated emission can take place without having to put too much different energy into the system because, I mean, this is an energy-intense process, and the energy put into a laser is not all going to come back out as the laser beam, so what we actually have to do quite often is not just bump those electrons up one energy level to create this population of electrons ready to cascade down and stimulate an emission. Well, what actually ends up happening is you have to pump energy into the system to jump the electrons up *more* than one energy level. They get up into this higher, unstable energy level, and then drop down into a lower, semi-stable energy level, where they're happy to hang out until that photon comes along and stimulates emission. And what we've been figuring out are what are the most efficient transitions. How do we manufacture gases, dyes, crystals – all these different substances that are capable of being maintained at that higher energy level? How do we build things that are stable so that we're not breaking our crystals? It's mostly been just technological revisions over the time and trying to figure out the material science of building purer and purer materials that get us to the different types of transitions that we want to get to.

Fraser: But essentially there are these perfect transition points where you both can get energy in and the way the photons come back out, and I guess if you don't hit that transition perfectly, you're going to be, like, wasting energy and heat and things like that?

Pamela: Well, it's more a matter of trying to do things so that you're not spending too much time pumping. This is something that can only be done in a system that's not an equilibrium. If you have a gas that's happily hanging in equilibrium, it's always going to have more electrons in lower energy levels than higher energy levels, so you have to constantly be pumping this system with energy to get things higher up. Now, if I'm in a system where I'm pumping things up and they immediately cascade back down, that's ineffective because something might naturally cascade down to a lower energy level before that photon can come along and stimulate emission. So when a system that's stable enough at that higher energy level that it has a chance to be stimulated before it naturally collapses to a lower level…so it's a matter of we have to figure out how do you get electrons into those semi-stable places waiting for the stimulated emission, then once they're there, you have to figure out how do you build the system so that everything's nicely and politely focused, and how do you not melt things in the process and so that they're not melting, not blowing up -- these are all the same sorts of problems in some ways as you're building faster and faster processors. These are hot systems that have to be maintained very precisely, and if they're not, they melt. That's bad.

Fraser: And so what are the limits, then? I mean, if we're just looking at anywhere along the electromagnetic spectrum, could you make…I mean, a maserism is a microwave, right? Could you go to longer wavelengths? Could you make a maser out the longest wavelengths of radio light?

Pamela: Well, so there it becomes a problem of long wavelengths, particularly long wavelengths. It gets kind of hard to contain that in a cavity where they resonate nicely, so the containment vessels that you're using to build your lasers in are actually related to the color of light that you're using, and as the radio gets too long. So if you start looking at the longest imaginable colors of radio -- yet you could, but would you want to because you're starting to get into big systems? And then on the short wavelength, you start running to different sorts of…that gets really hard to contain issues for building the resonant cavities.

Fraser: Well, I know you can purchase blue…I've got a green laser, and I'm sure most people have had red lasers. I mean, my kids Nerf guns have a red laser on them, but and you can buy blue lasers, and I think you can even buy violet lasers now, which aren't terrifying.

Pamela: It's really kind of amazing. Scientists are slowly discovering that if you try hard enough, you can make almost anything undergo stimulated emission, make almost anything "las," and this means that if we work hard enough and are willing to throw out enough energy, we can create just about any color just by using the correct materials to find those transitions that get just the color that we're looking for to be emitted. Now, it does start to run into matters of you can do something and have a "wussy" laser fairly easily, but as you want to focus the laser better, as you want to get higher power energies, it gets more difficult.

Fraser: Are there ultraviolet lasers?

Pamela: Yeah. It's just a matter of finding the right materials, and so there you start looking at things that are doped with a variety of different metals, you're looking at rare earth substances. We've built lasers that go all the way out to 120-ish nanometers, so yeah, we're getting out into ultraviolet -- no big deal, we get out into 1-millimeter wavelengths -- no big deal. Well, it is a big deal, but we can do it. That's what's so awesome is we have the technology to span from the mid-ultraviolet out to the far infrared in laser light nowadays.

Fraser: And theoretically, then, you can go into x-rays.

Pamela: That starts to get into containment issues, so here it's how do you build a resonating container that allows the pulse, or the pumping energy in, but doesn't let the x-rays back out. You also…you're trying to get things to go to a higher energy level to start with, and x-rays are already pretty high up, so you're looking at most things are going to start ionizing there, so x-rays becomes technologically extraordinarily challenging. This isn't to say it's impossible. It's just sort of to say, "Yeah, that gets really difficult. We haven't got there yet."

Fraser: Now, why would we want to use different wavelengths of laser light?

Pamela: Well, it all depends on what you're trying to do. There's all sorts of different applications for lasers from let's do something simple, like at the grocery store, scan that barcode with the red light that's perfectly safe (sort of kind of) -- you still don't want to shine it in your eye. Anything that is more powerful than a tenth of a milliwatt is BAD, but for the most part, the reflected laser light of the beam on the grocery store thing is fairly safe. So that's a way of speeding out the check-out process. You scan the laser beam across it, you look at how the light is reflected back by the white and black bars, and suddenly your check-out clerk doesn't have carpal tunnel disease as bad as he or she might have a few years ago when they were typing all the numbers in by hand. Then with astronomical technology, we use lasers to actually ionize patches of gas in the upper atmosphere, so we need a color of light that is tuned to triggering those ionization processes, and then we focus our telescopes on that ionized pocket of gas, so that's a completely different color, completely different purpose. In medical lasers, they actually have lasers that are tuned to the point that they're able to eat away just fractions of a cell at a time, and in the process of doing this, they reshape the lens of your eye, which I think is a terrifying process, but people undergo this every day, every hour, all around the world, and for the most part, nothing bad happens.

Fraser: Right, so blue lasers are just an example where you're matching up the frequency of the laser with the density of the information that you're trying to read, right?

Pamela: Right, so when we go from using CDs to using DVDs to using Blu-rays -- in each of these instances we're using shorter and shorter wavelengths of light, and that in turn allows the bits of information to become smaller and smaller and smaller. The different wavelengths, they are also getting smaller, and so we're packing more stuff closer and closer together. It's also allowing multiple layers of materials to be used, and it starts getting to lots of complex materials, processes, and it just has to do with shorter wavelengths means things pack together closely.

Fraser: Right, but you can imagine that situation you mentioned earlier, right? You've got your great big barcode scanner, and you've got the laser slowly going across that barcode, and then it's reflecting light back to a sensor that's detecting the changes, and then, if you wanted to, you know, you're going to get those differences in brightness and dimness that's being detected, and so it's kind of the same thing with the way a laser is. It's shining a blue laser, shining on a very small…the pits on a blu-ray and you're getting these reflections back out.

Pamela: Yeah, it's exactly the same in this case where it's at hundreds of times a second going on-off-on-off-on-off as your CD spins, or as your CD or DVD or Blu-ray spins, and so you have very precise mechanics to figure out where they are on the CD, DVD, or Blu-ray, which is why they die so easily and violently.

Fraser: So what do you think are the future limits of laser technology? Where is this all going to go?

Pamela: I'm not sure that the limits can actually really be defined if we're allowing ourselves to pour in as much energy as we want. One of the most amazing things that's currently going on with laser technology is there's folks at a variety of different facilities, including the National Ignition Research Facility, trying to create fusion using lasers, so they're focusing lasers down to a single point on a glass bead that's doped with a variety of different materials, and trying to get fusion to take place in this glass bead when a pulsed lasers that's petawatts of power. So we're looking at all of the energy of New York City condensed down to a single point.

Fraser: …for a fraction of a second….

Pamela: It's kind of amazing! And these systems use capacitors that are so large that they're in special cooling material in Olympic-sized swimming pools. There are a variety of these places being built around the world -- and they're awesome! So here we're talking about lasers in places that you could have sharks swimming around the capacitors used for the lasers, except they'd all die when you fired the laser, so we won't actually do that.

Fraser: You somehow managed a way to sneak a "sharks and lasers" reference into this episode.

Pamela: [laughing] It was required.

Fraser: It was required. It was destiny. Cool! So I guess the last thing we want to talk about is lasers on spaceships shooting other spaceships in space in the far, far future.

Pamela: Well, it…yes. Yes, you can do it. There's actually folks working out at the NASA John Glenn Institute on lasers of destructive powers, so there's pictures you can find of lasers that have hit things and melted them and done bad things to them. There are people who are working on this, but it's huge amounts of energy! You're actually much better off with artillery, so…

Fraser: Right, throwing rocks at other spaceships.

Pamela: Yes, throwing rocks, at the end of the day, is the best way to get the most bang for your input energy.

Fraser: There was a classic quote – and, I'm sorry I'm going to mangle it because I don't have it, sort of, in my brain, but essentially it was like back in the 1980s when they were working out the Star Wars technology, and one of the directions that went down was to figure out if they could come up with laser weapons to actually shoot down missiles, and at one point, you know, I forget the total amount of energy that would be required would be like 10 to the power of 20, or something like that joules of energy to do it, and they had been able to push lasers to the point that they were 10 to the power of 10 joules, and so someone said, “Oh, so we’re halfway there!” [laughing] No, not halfway there…

Pamela: Yeah, exponentials do not work that way.

Fraser: Yeah, one tiny fraction of a fraction of a fraction of the way there… So you don’t see in the far, far future, I mean, with the kinds of energy you need to pour into it, the difficulty in containing the emissions as you’re trying to…or build up the actual coherent beam that’s going to come out, you’re going to irradiate your…everyone on your spaceship in the bad way to try and get things to those energy levels.

Pamela: Well, it doesn’t make energy sense that you have to put so much energy into the process that you might as well be flinging rock because it can retain more of the energy. Now, where it does start to make sense to have lasers in spacecraft is as communications devices because you can send a fairly coherent beam huge distances. This is why we’re spotting masers and lasers in space at cosmological distances. So you can potentially use these as communications devices rather than as war devices, so there’s a future for lasers in spacecraft.

Fraser: Alright. Cool. Well, thanks a lot, Pamela. We’ll talk to you next week.

Pamela: OK. Bye-bye.