Astronomy Cast Episode 261 for Monday, April 16, 2012: Lasers & Masers in Astronomy

Fraser: Welcome to Astronomy Cast, a 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 really well, and I think…once again, I want just to remind people that if you want a really cool way that you can enjoy Astronomy Cast wherever you are, in any way, to check out our Astronomy Cast app in the itunes store. It's $1.99 and then gives you a direct feed to every episode of Astronomy Cast, on demand. And so you don't have to have them filling up your local drive; you can just play them, stream them, directly from our server in whatever episode you want. You can go back, listen to the old episodes, the new episodes -- or like my children, you can just leave it on from the time they go to bed and it just keeps running all the way through until morning, burning our batteries.

Pamela: And kudos to Fraser. So I have to give him a shout-out because he went through and he cleaned up all the contents, so it's much improved. If you've looked at it before and gone "Eeew," it's fixed now because of Fraser. He's awesome.

Fraser: Yeah, I went through and did all the titles, and then I could see, people kept going, "you need to fix all the titles of the old shows," and finally I downloaded them and looked at them, and I saw what people were driving at. I see the problem here. And so then I went through and fixed them all, so yeah… And now we're trying to improve it even some more, and put some cool stuff into it, so anyway, if you've got an iphone – sorry, android people…

Pamela: Not there yet.

Fraser: Not there yet, but if you've got an iphone, then $1.99. It's the best thing you'll ever buy, ever.

Pamela: Maybe.

Fraser: Maybe…alright well, let's get rockin' with today's show.

[advertisement]

Fraser: So last week we introduced the science of lasers and masers and this week we apply that knowledge to our favorite field: astronomy. Learn how naturally forming masers teach us about the Cosmos, and how the artificially produced lasers help us gather better science. So just a quick recap: last week we talked about how lasers are this concept of coherent light that is produced by, I guess, excited electrons being connected in a kind of coherent fashion…?

Pamela: It's induced emission. So you have: an electron gets excited to a higher energy level, sometimes it gets excited to many higher energy levels and cascades down and settles to a higher energy level, and along comes a photon with a wavelength that has an energy identical to the jump between ground state and the excited state, and as it comes along at the exact resonant frequency it causes that excited electron to drop down, and to generate a photon that is in sync with the photon that caused the stimulated emission.

Fraser: And we also covered the naturally forming version of the laser, which is the maser, and that's…

Pamela: Well, actually, we talked about the technology of laboratory microwave.

Fraser: Well, we did mention that they'd been discovered naturally in science, too, but I guess the point is that a maser can be generated by nature, not just in the lab. So, OK…so then, let's talk a bit. Let's go back a bit and talk about the discovery of masers as a natural occurring phenomena. When did astronomers first start to discover that there are actually masers out there in the Universe?

Pamela: Well, this happened in the 1960s. It actually happened -- it was *understood* that it was happening after we had been able to create them in laboratories, so it was in 1965 that Weaver saw these really strong emission lines and it was at a frequency of 1665 megahertz. So this is a radio frequency, and people were still trying to put together the fact that molecules can exist in space. I actually…it's one of those things where you sort of look back and you're like, "Why didn't we think of that?" And for reasons that leave me somewhat baffled, for a long time, astronomers didn't think you could have molecules in space, and this was at that point where we were still figuring this out. And so they saw this wavelength at 1665 and they named it "Mysterium."

Fraser: Really?!

Pamela: Yes! I kid you not because they just didn't know what it was.

Fraser: That's amazing! Oh, why is it not still called that? I guess the mystery was solved.

Pamela: Well, because it turned out that it was just OH; it was just the stuff that makes alcohol interesting, so it was the OH molecule, and it was attributed to coming from molecular clouds, which are these…we see them as dusty, dark regions in the sky where stars are forming. It was later found, in 1969, that there were water molecules, and they went on to find CH3OH in 1970, and silicon oxate in 1974. So just over the years, we found more and more and more of these extremely bright radio sources that are extremely small, and when it comes to trying to figure out how you create something bright and small in radio, that was its own bit of perplexing stuff. And as people tried to figure it out, they realized the only thing that could be small enough and energetic enough to be producing such a bright emission line was a maser.

Fraser: And so they had already, at this point, created masers in the lab.

Pamela: Yes.

Fraser: …and so then when they saw these emissions out in space, it matched the characteristics of what they had produced in the lab, but not too far apart. I mean, we'd talked last week that masers had only really been developed probably, what, ten years before that?

Pamela: Yeah, so this was all a fairly new discovery. People were still working to figure it out, and when they first saw these in space, it was extremely confusing because to build a laboratory laser or maser, you have some sort of resonant chamber, and you have all sorts of things that force everything to be coherent, and it's often a high pressure system, and space isn't like that. And so people had to do some really hard thinking about what would cause this. Just the idea of a population inversion required some hard thinking, so here on Earth, when you have a gas in general the particles in the gas are constantly colliding with one another, and as they do this, they're distributing energy between one another, and all of these collisions cause the gas to be in what we call "thermal equilibrium." This is where you can describe the velocity distribution of the atoms, or molecules, in a specific mathematical way, and when you have a gas that's in thermal equilibrium, by definition, you don't ever have the energy inversion that you have to have in order to have a laser or maser. What I mean by inversion is if you look at the different energy levels, you have a greater population of the elections in the excited energy level than in the lower energy level. If you didn't have this inversion, what would end up happening is as that emission is stimulated, the emitted photon would very quickly get absorbed somewhere else, and you'd have more absorptions going on than emissions, and if there's more absorptions than emissions, then the light doesn't really escape as an emission line, so you have to have this inversion of where the electrons are located. Well, in space, you don't have thermal equilibrium all of the time. What ends up happening is you have these extremely diffuse gas clouds, where the atoms just don't ever collide into one another. The molecules just don't really collide into one another, and if they do, the collisions are so infrequent that you're able to have non-thermal equilibrium more often than not, and the rule of probability says you're likely to have an inversion just as much as you're likely to have a non-inversion of the energy levels.

Fraser: Right. We've talked about that a bit in the past, where you can have situations where you've got gas clouds that are millions of degrees, but in fact, you could fly your spaceship right through them and it's not like they'd be melting the hull of your spaceship. It's just that the individual particles have enough energy that it's the same as if they were millions of degrees hot, and yes, if you had it in one small area that would be hot gas, but the fact is that you've got this diffuse gas.

Pamela: So, not a problem. So looking out across space, we are seeing these extremely bright, extremely small sources of emission, and as they're trying to map these things out…so OK, we can understand where the energy inversion that's necessary comes from. It's just not thermal equilibrium, so the next thing we have to sort out that allows lasers and masers to exist is how do you get all of the light coherent? We talked last week about how when you're dealing with a laser, one technique is, for instance, you only allow light to come out one end of the laser, and that tends to get momentum going in one direction (momentum's not scientifically being used here, it's figuratively being used), so you're able to basically, by having mirrors around the sides of the cylinder and one end of the cylinder, direct all of this induced stimulated emission to come out one end of the laser. Well, in space, we don't exactly have cylindrical mirrored chambers generating natural masers, so the question comes, "How do you end up with the nice coherent light?" and it turns out magnetic fields play a very important role, where it's actually the magnetic fields are polarizing the light, lining up the electric and magnetic fields of the photons, getting all of this stimulated emission going in a coherent way through space.

Fraser: So just to understand -- we've seen all these pictures of electromagnetic fields surrounding like the Earth, or the Sun, or even just bar magnets, and you've got these magnetic field lines…and a good example is, like, look at the Sun, where you see sunspots, and you get these amazing magnetic field line loops, and you've actually got these cylinders of gas that are going from one sunspot to the next one with the magnetic field acting like almost like a piece of fiber optic, you know, channeling the gas and then these things twist up and then snap and release the…so you can see there's lots of situations out in the Universe where magnetic fields act like that, as you mentioned, that cylinder -- a capturing device, right? Is that what we've got going on here?

Pamela: Well, it's not so much capturing it as just making sure…

Fraser: Focusing? Holding it together?

Pamela: Well, lining it up, lining the little soldiers up, basically. So if you've ever played with a bar magnet and iron filings, you've seen all the magnetic field lines that you can get. Well, it's not lining it up quite like the way magnetic field lines are lining up the iron filings, but that starts to get you thinking in the correct idea. So what ends up happening is the magnetic field of the stars is capable of helping to polarize the light. So you have the electromagnetic fields lined up, you have the stimulated emission is causing new light being released to line up coherently with the last light released, and all of this adds together to allow very small localized areas around stars, around active galactic nuclei in some cases, even around comets to have emission that is coherent, and acts in every possible way like a laser or a maser.

Fraser: And so what are the different flavors that we see of these beams? And "beam" is the right way to describe it?

Pamela: I wouldn't go quite that far; it's not a coherent beam, like a laser that you use to torture your cat. You can actually…

Fraser: …by shining it on the ground and letting your cat chase it, right? That's how you torture your cat: to entertain it, to…until it's tired.

Pamela: Well, the frustration of a failed hunt. I mean -- it never gets to actually succeed in capturing the laser beam!

Fraser: Right, OK, fine. I'm just saying, we're not torturing a cat by shooting a high-powered laser at the cat for science purposes.

Pamela: No, no, no. That's true. It's all…

Fraser: Just want to clarify your definition of cat torture. Right. So then, I guess…what are we seeing? When we make these observations? So, we're not seeing this great, big laser beam zotting out of this super massive black hole right at us, right?

Pamela: What we're seeing is pockets of gas, a star-forming region, or the area around an old star is a great example. So, you have a star in the center, it's partially responsible for the magnetic field, it's surrounded by gas that is being ionized by the star, and within this surrounding material you have regions of different temperatures. As you move away from the star, things cool off, and so at different distances, you'll actually get different molecules excited depending on what temperature they need. Then you see also within these regions, materials are moving at different velocities, so in order to get masing to occur -- masers to be observed (masing causes masers)… in order to get masing to occur, you have to have a pocket of material that is all at the same velocity, so Doppler shifting doesn't cause that inducing photon to have the wrong wavelength.

Fraser: Right, they need to be connected on that front.

Pamela: Right, and you have to have a pocket that's all the right temperature to allow the inversion of energy levels to occur, so when we look at the gas and material (molecular material surrounding both young stars and very old stars), we end up seeing these different temperature regimes moving out, and what's kind of awesome is in the case of old stars that are somewhat unstable and tend to pulsate, we can use the very long baseline array. It's a set of radio telescopes that can span the entire width of the planet, basically. Using these very long baselines, we can get extraordinarily good resolution on the sky, and we're able to see that these little masing sources are moving, and we're able to see that they move in and out as the star itself pulsates, and this is an awesome way to start to get scale measurements of different regions just using geometric arguments.

Fraser: Yeah, well this was my next question: what do they use this stuff for? What do astronomers use these masers…? Now that they can detect, I'm sure just beyond just detecting them. They want to use them for something.

Pamela: What's awesome about them is since we can't go into space with a thermometer and stick the thermometer into the gas cloud, especially when the gas cloud is extremely diffuse, what we can do is look for masing activity. We know the very precise energy levels that each of these different energy jumps take place at, and so we're able to get a sense of what is the density of the material, what is the region based on variability that we see, what is the size of the region that's masing. And then, we can also start to measure the sizes of things using a variety of different arguments. So, for instance, we see these things, in some cases, what are called "mega-masers" around active galactic nuclei.

Fraser: Wow! I love that name!

Pamela: So we basically have systems that are 10s to 100s of times more powerful than the masers that are created in the environments of stars -- so that's just kind of crazy to think about. And we're able to track the rotation of the disks of material that they exist in, and we're finding that, unlike the outer parts of galaxies, these internal disks of material have what's called Keplerian motion. This means the distance that you are from the center of the disk is proportional to the rate at which you're moving in a way that Kepler's equations allow you to describe them mathematically. And by knowing how heavy the super massive black hole is in the center of that, and by measuring how fast these masers are zipping around, we can start to measure the size scale of these accretion disks, and get the distance to the active galactic nuclei. So this is a check on our understanding of distance scales in the Universe, where instead of relying just on Doppler shifting on how fast the recession velocity of that AGN is, we can instead go, "OK, so I know how big the black hole is, I know how far away the maser is, I see how far away they appear located on the sky -- let's do angular stuff."

Fraser: Right, anything -- so temperature, size, motion…any other things that we can use them for?

Pamela: Well, I mean, clearly, they tell us what molecules are out there, which is kind of awesome in and of itself.

Fraser: So composition, yeah…

Pamela: And they're just kind of cool. I mean -- it's space with lasers!

Fraser: Space with lasers, yeah…now, how far up the electromagnetic spectrum will the light go?

Pamela: There's actually been some stars that we've been able to identify -- some just within the optical wavelengths -- lasing (in this case) behavior taking place, but, in general, we're looking out in the radio wavelengths that you could almost get with your car radio, not quite.

Fraser: Right, and infrared, and the long infrared, yeah…so that's kind of exciting! So you've got a star that's generating a laser at the…almost at the red end of the spectrum, but it's just…you know, and although the wavelengths are all lined up in this kind of coherent fashion, it's not being focused like a coherent beam, so it's not like this is a star up there with a great, big, red laser zapping out of it, right?

Pamela: No, no, and one of the things that I think has been the most interesting, to look at the history of this, is from when we first started discovering these things, people didn't know there were molecules in space. So, you start from not even knowing there's molecules in space.

Fraser: Right, just "Mysterium." That's all there is out there.

Pamela: Just "Mysterium"…to realizing, "Oh, there's OH, and there's water, and there's all this other stuff with increasing complexity," to now we're realizing that if you leave molecules alone in a magnetic field, they're going to "mas," and so that's the other thing you're tracing is where there's magnetic fields, and we're finding them in neat places, like, even in supernovae remnants, you'll end up seeing masers where the shockwave of the expanding material hits the interstellar media, and there's charged particles in motion, there's magnetic fields being generated, and all of this leads to masing activity.

Fraser: That is really cool. Well, before we run out of time, I want to switch to the other technology, which is the lasers, and not necessarily how we're discovering them out in space (although I still want to find that star with a great, big, red laser zapping out of it), but how humans are generating lasers for use in astronomy. And I know there's sort of two interesting ones that we can talk about. There's a bunch more, but one is using them for distance, right? We know how far away the Moon is.

Pamela: Right, so there is laser, basically, laser ranging. This is the same thing that cops do when they're getting ready to give you a ticket if you're misbehaving while driving down the road, so the idea is that you can bounce a laser off of something, measure its distance, and if you bounce a laser off of something, and you do this over a period of time, you can get velocity, both from the initial distance and the secondary distance, and also from the Doppler shifting of the light that's coming back at you, so we don't deal with the Doppler shifting with the Moon quite so much, but we do get its distance down to millimeters by using pulsed laser light and measuring how long it takes those pulses to return -- and that's just cool.

Fraser: But partly thanks to the fact that humans landed on the Moon, and carefully placed these retro reflectors on the surface of the Moon, which then reflect a big portion of the laser light that's blasted at the Moon, as opposed to, I guess…I don't know if you would…I'm sure the laser range would still work to some degree if you didn't have these reflectors on the Moon, but…

Pamela: But at the end of the day, you waste fewer photons, and they're literally counting 1, 2, 4 photons coming back. It's…a lot of light gets lost in the process.

Fraser: Right. Right. And I always describe that as sort of my favorite -- one of my favorite reasons to know that humans did make it to the Moon, which is the fact that we can point a laser, and the laser will bounce off these reflectors, and there's no way that that wouldn't work if you didn't have those reflectors up on the Moon. So we've determined the distance to the Moon, and I know with accuracies, sub-centimeter accuracies, I mean, we know…

Pamela: Millimeters, really, millimeters…

Fraser: We know exactly where the Moon is at all times. The Moon is not sneaking up on us now.

Pamela: And what's awesome…this concept of lunar laser ranging made it into an episode of "Big Bang Theory," and it's so funny because what they did: the mathematics, the physics -- all of that works, but they're doing it with this little, tiny telescope, and a small laser, and the people who are doing this for real, they're using a 30-inch telescope, and they're using an extremely powerful green laser. They're actually using the mirror of the telescope to send the laser beam out, and yeah…so right concept, wouldn't have actually worked.

Fraser: Right, but now are we range finding other things in the solar system?

Pamela: Well, yeah, but we generally tend to use other wavelengths to do it. Again, we end up jumping down to the radio. So Goldstone radio radar facility was one of the first ways that we were measuring the distances to Mercury, to Venus, to Mars, to asteroids, and that was by shining radar – radio light – off of other nearby objects, so it's just a matter of jump around the electromagnetic spectrum until you find a friendly energy and wavelength for what you're trying to do.

Fraser: And then the other -- and just incredible application of radar -- is adaptive optics.

Pamela: So in this case, for adaptive optics, ideally, what you want is a nice, bright star in your field of view, and you look at how that bright star moves, changes from looking spherical to looking crazy-shaped, and you flex your mirror to compensate for all of the things the atmosphere is doing to that starlight. Now, the thing is, not every field of view has a bright star in it, but we can create bright stars by shining lasers at just the right wavelength that they excite parts of the atmosphere to ionize, so when we do laser guiding, what we're actually doing is exciting upper levels of the atmosphere to emit light that we're then studying.

Fraser: And then, I mean, just the technology that these great big mirrors can be modified in real time to react to the atmosphere distortions is still just absolutely mind-bending. Have you ever seen a video, or have you ever seen this in person, where the…?

Pamela: Yeah, I got to see the WIYN Observatory in person and it's this giant honeycomb mirror with actuators all over it, and…

Fraser: And they're like little pistons just kind of pushing on the mirrors, right?

Pamela: Yeah.

Fraser: And then the mirror just kind of flexes up and down a little bit. How fast do they go?

Pamela: It depends system to system, but they're looking at sub-second scales in some cases.

Fraser: So these little pistons are just distorting the shape of the mirror in fractions of a second with hundreds of actuators? Thousands?

Pamela: Again, it depends. It's not thousands, but yeah…

Fraser: But hundreds, yeah, yeah, and so you can imagine making these tiny little distortions of the mirror -- it's a phenomenal technology, and is…but I guess, the point being, way cheaper to take a great, big telescope, put in all those little actuators, fire a laser into space…

Pamela: Than to launch it into space…

Fraser: Than to launch it into space and get above the atmosphere, but if you did get it above the atmosphere, then it would be an even better telescope, so…

Pamela: But, I mean, the thing about keeping things on the ground that people tend to not think about is if it's on the ground, you can do experiments on your telescope. You can say, "I'm not sure if this will work; I'm going to try this filter and this other thing…" and that sort of learning in real time, we call it engineering time on the telescope, you got four nights, you don't know if you're going to get science out of them, but you're going to try a new instrument. That sort of engineering you can't do on orbit currently.

Fraser: Yeah, or you bring your own instrument that you work with a research group, and you bring it to the observatory, and you slot it into the telescope, place in the CCD, and gather science in a way that maybe no one had tried before. And you won't know if it's going to work or not until you do…so no, absolutely. So are there any other applications of laser in astronomy? Communication, I guess, with spacecraft?

Pamela: Well, so the other big thing is interferometry to tell the distances between two spacecraft. So there's a variety of different systems: Grail, which is orbiting the Moon is one of the more famous ones, where you have spacecraft that are lasing the distance between the two of them and by measuring using interference patterns how that distance changes, they can see how gravity is pulling on one before it pulls on the other to accelerate them and decelerate them in their orbits. We also see with the laser interferometry projects, we have LIGO on the Earth, and maybe someday we'll build LISA? Maybe?? So this is projects where we're very carefully measuring the separation of two points on the ground by looking at lasers interfere, and that's the awesome thing is this is coherent light with the wavelengths of the different photons happily lined up with one another as they…they don't actually swim. That's me trying to imitate…

Fraser: They form some kind of, uh, some kind of wave. So, well, you know what, this is great, Pamela. Thanks a lot! And I think we have two take-aways for today that, I think, if anyone can walk away with two concepts in their head, I think everyone should remember "Mysterium…"

Pamela: …does not exist.

Fraser: …and "mega-masers."

Pamela: And there are molecules in space.

Fraser: And there are molecules in space. Well, that was great, Pamela. Thank you very much, and we'll see you next week.

Pamela: OK.