AstronomyCast Episode 254 for Monday, February 27, 2012: Reflection and Refraction

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Fraser: Welcome to AstronomyCast, 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: I'm doing really well. So once again, we're recording this episode of AstronomyCast as a live Google plus hang-out. If you ever want to join us and watch us record this show live, you can just go to Cosmoquest.org/hang-outs, and we've got a listing of all of the really cool live hang-outs that we've been doing, but not just AstronomyCast. We're doing our weekly space hang-out, we're live streaming telescopes, we're interviewing astronomers and…

Pamela: So much more…

Fraser: …space scientists, and you know, you name it, we've been covering it, so check that out if you want to participate in any of this stuff. You can interact with us, you can ask us questions, you can jump into our hang-outs…we're having a lot of fun. And I got one more thing...

Pamela: OK. Go for it!

Fraser: …which is if you've never done this, one of the best ways to help out AstronomyCast is to go and write a review on us in iTunes. And so you can go to iTunes, search for AstronomyCast, and then you can leave a review and let people know what you think about the show and the stuff that we're doing. That's cool. That was all my stuff for this week.

Pamela: That works. You're wearing a kind of awesome shirt you can promote.

Fraser: That's right! I'm a walking, talking billboard for AstronomyCast! But the problem is the people who are listening to this won't be able to see it, but I am wearing my "Venus Transit Authority" shirt, which, I guess, anyone watching can see it…

Pamela: [laughing] No, they can't! Your mike is exactly eclipsing the shirt.

Fraser: There. There. That working? Anyway, we're really excited about this year's transit of Venus, which is going to be happening in June. Of course, we will be "live casting" that to pieces, but this is going to be the last year for anyone living to watch it.

Pamela: And we've created a shirt that will contain all of the pieces of paper you're most likely to lose on this shirt. It's…on the front of this shirt, there's a map of the path of Venus across the Sun, and on the back of the shirt is a map of where on the planet you need to be to see the transit.

Fraser: Right, so that way if all else fails, just wear the shirt and then you'll know, and you'll have all the details that you need, and anyone who's there needs to know where to look and what to see, they'll be able to do it. So that's awesome! I love this idea of, like, shirt as instruction manual. That's really cool!

Pamela: Yes! It's so…I lose paper. I'm not going to wear the shirt I'm wearing.

Fraser: Yeah, you should have one that just has like your physics formula, you know? And then just while you're doing your work, if you need to like "How do I calculate this? …spectroscopy of that? Oh, right!" then you just lift up your shirt, and take a look at the right corner and you've got the information there.

Pamela: "Maxwell's Equations" – it's a great shirt!

[advertisement]

Fraser: Alright, well let's get on with today's show, then. So light can do some pretty strange stuff, like pass through objects and bounce off them. It can be broken up and recombined; in fact, everything we see is just the end result of reflection and refraction of light, so it's time to understand how it all works. So this is the part, this is one of the situations…like, I've bent the mind's of my children when I was explaining to them. You know, the concept that when they see something that is like green, they're seeing the reflected photons that came from the Sun, and they're like, "What?!" Right? Furthermore, we're seeing the refracted photons that have come from the Sun passing through our atmosphere, and again, it's super-confusing, so let's start with like the journey of a photon, of a photon that leaves the Sun, travels to Earth, passes through the atmosphere, maybe goes through a window or two, bounces off something, maybe bounces off something again and goes into someone's eyeball. What's happening?

Pamela: Well, the first thing to realize is, while you may be following the journey of one ray of light, it may not be the same photon that gets to your eye that left the Sun originally, or in fact, was originally created because there's also a whole lot of absorption and re-emission processes that are going on, so…

Fraser: Well, we'll look at those too, but yeah…

Pamela: So you start off with something creates a photon, and the original photon that was created may not be the same photon that reaches your eye, so you have some sort of an event deep in the core of the Sun gives off energy, and this bit of energy as it travels through the Sun is going to get absorbed by an atom, re-emitted in a new direction, absorbed by another atom, re-emitted in another direction, and this entire process is one of what's called "Brownian motion." It's the path…the way they always explained it in physics books, which I think says something about the physics community is "you know how drunk people walk? That trying to get somewhere, but they're sort of going in all directions? That's the motion of light as it tries to travel to exit the Sun." Well, once the light finally breaks free of the surface of the Sun, then it's mostly a clean path straight to Earth, so assuming it doesn't end up hitting dust, doesn't end up hitting, well, Mercury or Venus, or anything else that lies between us and the Sun…

Fraser: Spacecraft…

Pamela: …spacecraft, yeah, Soho does intercept a fair amount of light, SDO intercepts a fair amount of light, but assuming that it hits a straight path toward Earth, then you will have a photon that may be the billionth photon that has been part of a journey of a piece of energy. It's going to hit the surface of our atmosphere. Now, light travels at different rates, through different materials, and this has a lot of complicated physics behind it which basically boils down to the way the light interacts with the materials, changes both for sound and for light and for pretty much any wave, it changes its velocity based on the composition of the material.

Fraser: Right, and that's why we always say "the speed of light in a vacuum." Right? Or you always add that asterisk, right? "In a vacuum"…the speed of light through glass is different than the speed of light in a vacuum, and that's why they, you know, physicists have said they can slow light down to walking speed.

Pamela: Yeah, and it's not hard to get light slowed to down to the speed of a Cessna aircraft just using hot rubidium gas. So different materials cause light to travel at different speeds, and different wavelengths of light respond in different ways, so suddenly it's very complicated, but looking in general, when light hits a material that isn't a vacuum, it's going to slow down and this is where something that I consider a bit of the Universe conducting Black Magic occurs. There's this property referred to as Snell's Law that basically says if you have light at point A and you're trying to observe light at point B, the path the light is going to take between those two points, is the path that causes it to have the shortest journey time. Now, the thing that makes this kind of Black Magic is if you can imagine that the light is passing through a series of different materials -- a pocket of hot gas, a pocket of cold gas, vacuum from the Sun, or vacuum from outer space, and we're looking at sunlight, well, as the light passes through each of the materials, its speed is going to vary, and just as you can imagine driving through a city, and you have to make these choices: "Do I get on the highway? Do I get on Main Street? Do I take the back roads with lots of stop signs?" and you optimize your path not for the distance you travel, but how are you going to get there fastest. Well, light does that same optimization, not what is the shortest trip I can take, but what is the fastest trip I can take, and so when you take a look at the passage of the light between those two points, the light is actually going to bend and spend a longer distance in the higher speed material and a shorter distance in the slower speed material to optimize its speed, and it's one of those "Wait, how did the light know ahead of time that this was the correct option to take?" And it's a matter of light's going in all directions.

Fraser: Right, so hold on, you just like blew my mind there, so let me just take a second to unpack it. So if I understand this correctly, that when we see light moving through water, and we see, you know, or like we see…like a you take like a stick and put it in water, and you can see the stick on top of the water, and it's sort of at one angle, and then as you're seeing the stick through the water it's shifted to this other angle, and so in other words, we know that the light that is showing us the stick has bent in the light, and so what you're saying is that light has chosen this angle because this gives it the shortest travel time?

Pamela: Yes, exactly.

Fraser: And it could be a further travel distance, but at the end of the day, it's most concerned about the shortest travel time, and that's when you see it bend?

Pamela: Exactly. Yes.

Fraser: Whoa.

Pamela: Yes.

Fraser: That's crazy!

Pamela: The thing is it's not like light is actually making a choice, it just happens to work out this way. And so when you start looking at things mathematically, and this is where I'm wishing I had better props in my office…

Fraser: Well, remember that people are listening to this show, so they will never see your props.

Pamela: Yes, OK, so if you have a surface, and light is going to hit that surface, then the surface has -- you can imagine there's always some line that's coming out from that surface in a right angle…now, when the light hits that surface, there's going to be some angle between it and whatever that perpendicular, that right-angle line is, and the way it works is when the light hits the surface, its angle relative to that perpendicular, relative to that -- we call it "normal to the surface," it's going to bend inwards, so this is where when you look at a pencil, the pencil always appears to bend in the exact same direction. Now, what's really cool is you can actually change how the pencil appears to bend by adding things to the water, by comparing side by side a pencil or a straw in a glass of alcohol, in a glass of sugar water, in a glass of regular water – it's very small differences, but it's still just neat that we can actually play with the path of light.

Fraser: And so if you can actually see the path of light refracting through that Rubidium gas, you would get a different angle.

Pamela: You would get a completely different angle.

Fraser: Right.

Pamela: And what's interesting about this is it also varies with the color of the light that's doing this. So say you had a red laser and you had a green laser, one interesting trick to do is to shine them into a cutting board, just one of those plastic-y, acrylic, um, they're usually a whitish color, boring, cheap cutting boards that you can get at the local dime store.

Fraser: I have one like right in front of me. You can't see it because my kitchen is dirty, but I have one. I'm looking at one right now, so I know exactly what you're talking about.

Pamela: Right. So get one of those cheap-y cutting boards that allows light to pass through it, well, shine a red laser into it, and shine a green laser into it, and make sure very carefully that the lasers are absolutely parallel to each other (you can do this by putting a piece of graph paper down), then look at how their light bends as it enters the cutting board, and if you're very precise you can see slight differences in how the light of these two radically different colors gets bent as it enters the cutting board.

Fraser: Wow! So the light will get bent from the laser passing through the cutting board?

Pamela: Yeah! Because…

Fraser: OK, hold on, hold on, hold on.

Pamela: [laughing] So for those of you who are out there listening, Fraser is in his kitchen, and he is going to go find a laser, and find a cutting board at this moment. This is actually one of those experiments that we used to have our students do as group projects when I taught astronomy, and so…

Fraser: Alright, so here we go…got a cutting board, got a green laser...

Pamela: You need to go in the edge of the laser, you need to go in the edge of the cutting board!

Fraser: What's that?

Pamela: You need to go into the edge of the cutting board.

Fraser: Like, this way?

Pamela: Yeah.

Fraser: OK. Alright, let's see…

Pamela: So you need to get the light…

Fraser: Whoa! I don't know if you can see behind me…

Pamela: So you should be able to see it through the surface of the cutting board.

Fraser: Yeah.

Pamela: Except we can't see the surface of your cutting board.

Fraser: I can see it. I can see it coming out the top of the cutting board like a line. [missing audio] There we go!

Pamela: Well, I'll try and do this experiment. I'll go get a cheap-y cutting board and I'll post pictures of it later.

Fraser: I don't know if I can actually do this, though. I love lasers.

Pamela: To do this experiment well, you need one of the really cheap cutting boards that's also like a quarter of an inch thick, and you literally shine the laser into the edge of the cutting board and you can watch its path across the top of the board.

Fraser: Yeah I could actually see the line of the laser across the top of the board, so that's really cool. Alright…I just don't have a red laser.

Pamela: But this is actually one of those things that allows you to understand how prisms work because if you think about prisms that create beautiful rainbows -- a lot of people buy them as wind chimes and hang them in their windows and stuff -- this is a case of light entering a material, (in this case glass or crystal), and when that light ray of white light (of all the different colors combined, usually made of sunlight) enters the prism, all the different colors get bent at slightly different angles, and it's that difference in all the angles that things are getting bent that ends up leading to beautiful rainbows, ends up leading to being able to do spectroscopy, and in this case it's a matter of the shorter wavelengths are getting bent the most, the longer wavelengths are getting bent the least, and the entire amount that things get bent determines how big a rainbow you're able to produce.

Fraser: Right, and so you've got this situation where you've got the sunlight coming from the Sun that contains photons of every color, they're all hitting that medium (in this case, the glass of the prism), and they're getting refracted at different angles because of their wavelength, and then they're coming out the other side and going in their various directions.

Pamela: Now, this is also the problem with refracting telescopes. So if you have a nice, little, cheap, doesn't-have-fancy-what-are-called-"apro-chromatic lenses," if you have a nice, normal, cheap refracting telescope, it will have *a* lens for the eyepiece, *a* piece for the objective that's the end that the light comes in through, and as light comes through each of these different lenses, different colors get bent different amounts, so you end up seeing different colors in focus in slightly different places, which causes what's called chromatic distortion. Now, we get around that by using compound lenses that use multiple materials and try and compensate for all of that. It makes the telescopes extraordinarily expensive, but is usually worth it to spend all that money for an astronomical view.

Fraser: And it's sort of about trying to bring the light back together, right?

Pamela: Right.

Fraser: Yeah, OK, so we got a little off-track here. So we've talked about the light coming through the atmosphere, or glass, or something like that, and its getting refracted, and we talked about the physics of that. Now, what about the reflection part?

Pamela: So the reflection part is actually way more complicated than anyone would ever imagine. It's one of those things that when I first saw it completely explained out in Quantum Mechanics, I sort of cursed the Universe for its complexity. So when we normally think of reflection, you think of like a photon of light comes down, bounces off of the surface, continues on like a ping…no! No! That has nothing to do with it.

Fraser: No? Nothing?

Pamela: No.

Fraser: OK.

Pamela: You actually have: photon comes down, interacts with the top level of atoms in the material, has all sorts of complicated things that involve skin effect, and the electromagnetic fields, and reversing of polarity, and a new photon comes out in the opposite direction with a completely different phase of the first photon…and so it's actually a highly complicated process.

Fraser: Can you…? I mean, we don't want to completely gloss over it, but so are you saying that reflection is…but it's not absorption, right? It's not like the photon is being absorbed and a completely different photon is being emitted?

Pamela: Yeah, it is.

Fraser: So all reflection is absorption? Is that what you're saying?

Pamela: So it's…it's an interaction with the surface of the material process, so the incoming photon comes in, interacts, new photon comes out.

Fraser: Completely different photon?

Pamela: Completely different photon, different phase, the whole nine yards.

Fraser: A brand new baby photon, and…but can the…'cause I mean from what I, you know, what we always talk about, we say, like you see a tree and the tree is green, and so you're seeing all of the light from the Sun is hitting, you know, all the colors of the Sun are hitting that tree, and then we're seeing the green, a prevalence of green photons being emitted in our direction, right?

Pamela: So what we're seeing is the material that the leaves are made of is preferentially re-emitting green photons, based on all of the stuff that's hitting during the skin effect at the surface of the leaf.

Fraser: And so if it's getting hit by more colors than just green, is it warming up, is it absorbing that? Is it turning the excess into heat?

Pamela: It's absorbing it, it's warming up, it's undergoing chemical processes…this is where you get into the whole ADP cycle that some of us were forced to memorize.

Fraser: Chlorophyll, it's making energy… right, right, but just like a regular object, and so but what about something like a mirror that is going to be reflecting the light, you know, almost you know some object with a really high albedo, right?

Pamela: So reflective surfaces -- this simply means that most of the photons when they hit that top skin effect layer of the material are ending up interacting and going back off in the other direction in very precisely mathematically described ways. Now, what's interesting is where you have diffuse reflection. This is where when you look at the light coming off a surface, it gets completely scrambled, and so you have a surface that's reflecting light, but it's not reflecting an image. It's because some of the light's actually able to pass deeper into the surface before it undergoes this reflection process and comes back out, so the diffuse reflection is where you're hitting all sorts of different angles inside the material, and you're hitting different depths inside the material, and so the light is coming out with a whole variety of different angles from what it originally had going in.

Fraser: So can you have situations where there's, like, reflection and refraction happening at the same time?

Pamela: That's called binoculars.

Fraser: Binoculars? Right.

Pamela: So think about: grab a pair of binoculars, and on a day, like, grab a friend and go outside and look at a bird, and have your friend look at the front surface of your binocular lens, and they're actually going to be able to see the daylight scene reflecting back at them because every glass surface actually both reflects some of the light, and allows some of the light to transfer through the material, and the light that's getting transferred through the material is what's getting refracted.

Fraser: So, I guess, as always, we try to bring this back around to astronomy, and so what are some of the ways that astronomers will use this? I mean, obviously, we talked a bit about the lenses that we use and the telescope, so what impact does that have on, like, the actual gear that astronomers actually use?

Pamela: So with things like binoculars and telescopes, the whole problem of some of the light getting reflected and some of it getting refracted through the surface means that we want to try and figure out how we can use chemistry to alter the surface of our lenses to make sure that the most light possible gets transmitted through the material, and this is where an expensive pair of binoculars will have this purplish multi-coat on the surface of the objective lens, and that strange-colored overcoating is actually a material that increases the amount of light that gets transmitted through the objective lens of your binoculars. We also worry about sometimes increasing how much light gets reflected, and this is where mirrors for reflecting telescopes also have very special overcoatings on them, so an extremely expensive mirror is going to have usually either a silvering on it or it's going to be "luminized," but the combination of atoms that the mirror gets coated with is usually some extremely-patented, highly-worked-out, experimentally-determined recipe that increases – optimizes -- the amount of light that gets reflected at the wavelengths that we're most interested in studying. So the whole point of building modern telescopes isn't just to make sure that the light gets as precisely focused as possible, but it's also to utilize chemistry to make sure that every surface that the light has to pass through passes through as optimally as possible, and every surface the light has to reflect off of it gets reflected off as optimally as possible, and altogether we end up talking about what's the "quantum efficiency" of a telescope, and that boils down to all of the surfaces combined, and then how well the detector (which is really where quantum efficiency comes in)…how well does the detector do at finally detecting the photons that make it to it.

Fraser: And I think we've talked quite a lot about the visible light, but obviously, you know, the entire electromagnetic spectrum runs from radio through to gamma radiation, so how does that play into this process as well? I mean, are gamma rays refracting through water? Or will x-rays kind of reflect off of things?

Pamela: Gamma rays kind of do what they want to do [laughing], so these really high-energy wavelengths of light…the surface that you need to use to end up stopping and reflecting a photon – that surface that you need depends on what the wavelength of light is. This is where you can build radio telescopes out of essentially chicken wire because radio wavelengths -- they can be several centimeters to several meters across, and so radio happily reflects off of chicken wire. Now, at the same time, gamma rays are extremely small and just want to pass directly through whatever you put in front of them until it gets extraordinarily dense, and this is where you start using lead bricks to stop them, and you can't really use lead bricks easily to reflect them, but when they start building gamma ray observatories and x-ray observatories, they are using special foils to try and very carefully scatter the light into a narrower and narrower area to detect it.

Fraser: Right. Right, but the point being that, you know, infrared is going to have that same effect, ultraviolet is going that have that same effect, but it's just going to be changed depending on the medium and depending on its wavelength.

Pamela: Exactly. All light has the same…reacts with the skinning of the material, reacts with…and different materials are opaque and transparent. Glass, for instance, will completely block ultraviolet for you, so any of you out there in the audience that have an iguana, if you're trying to shine your special solar lamp through the glass of your aquarium, it won't work.

Fraser: And that's why you can't get a sunburn when you're in the car window, right? Behind the car window…

Pamela: Right, But if you roll your window down, your driving arm will be toasty by the end of the day.

Fraser: Right exactly. Now, we've talked about how the astronomers will actually incorporate reflection and refraction into the gear, but how do they bring it into their actual techniques when they're looking at objects? I mean, are there things that they need to look through, or see reflected from?

Pamela: Well, we have to take into consideration the fact that where the stars appear in the sky is not where they're actually located, and as an object moves across the sky (because the planet's rotating it's not the object moving), the amount of atmosphere that the light has to pass through is constantly changing, which means that the distance the light spends within the atmosphere in the amount of bending that it is experiencing is constantly changing, and this all adds up to we can actually see slightly over the horizon because of the way light is bent, and we have to, when we're pointing telescopes, compensate for how the atmosphere bends the light, so we have to take all of that into consideration. When it comes to celestial observations, we're actually somewhat more worried about how gravity bends things at times because we can also get the same sort of refracting, bending of the light, not just from light passing through media, but also from light passing gravitationally near a star, or galaxy, or something else, but we've done entire shows on this. It's called "gravitational lensing."

Fraser: Right And there's a lot of situations I know where the reflection of the light…like there's things like Earth's shine, light echoes, things like that where you can actually see and learn a bit, you can see x-rays bouncing off, what? Jupiter, and things like that?

Pamela: And one of the more interesting things that's going on right now is light from Eta Carinae from when it had its 1800s outburst – that light is just now…it hit a background surface, a surface of gas and dust, has reflected off that surface and the reflection is just now hitting Earth, so we're able to re-observe the reflected light of that nova to actually get whole new observations out of it.

Fraser: Right, so if you miss it the first time around, you can just wait for the reflection, wait for the echo.

Pamela: Exactly.

Fraser: That's really cool. Alright, well, that's great, Pamela. Thank you very much again, and we'll talk to you next week.

Pamela: Sounds good, Fraser. Talk to you later.