AstronomyCast Episode 253 for Monday, February 20, 2012:

Rayleigh Scattering or Why is the Sky Blue?

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?

Fraser: Good. I can hear in your voice -- you're a little under the weather, aren't you?

Pamela: Yeah, colds happen, and our weather has been bouncing back and forth between high 60s F and 20s F, and my body said, "No." It just said, "No."

Fraser: Just kidding, but can we recover enough of your brain this week to answer some basic questions about Rayleigh scattering?

Pamela: I think this week's topic we're going with "Are you smarter than a fifth grader?" so I am smarter than a fifth grader, even when drugged.

Fraser: OK, Good, good, and so once again, as always, we're recording this episode of AstronomyCast as a live Google plus hang-out on air, so if you want to join in on the fun, we record these episodes every Monday at noon Pacific, 3:00 Eastern, 8:00 Greenwich mean time. You can go to cosmoquest.org/hang-outs, and you'll see more information on the show times, the last episodes that we did, and a viewer that you can watch when we record the show live, and a way to participate, so if you want to beyond just listen to the episode, but actually participate and join us because we open it up and people can jump in the hang-out and ask questions about space and astronomy. It's a lot of fun, so we highly recommend you join us if you want. So, go to cosmoquest.org/hang-outs.

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Fraser: Alright, so next time a kid asks you, “Why is the sky blue?” answer them because of Rayleigh scattering, and if they’re not happy with that answer, feel free to expand based on the knowledge we’re about to drop today right into your brain. Now, Pamela, before we get into Rayleigh scattering, you had an anecdote actually before we even started recording.

Pamela: So I go through a lot of life sleep-deprived on airplanes, and there was one time I was getting on a little, tiny commuter plane, and I was tired, and I don’t know what form of Pavlovian conditioning took over, but for some reason the stewardess hollers, she doesn’t get on her little microphone, she hollers down the aisle, “Why is the sky blue?!” and like call and response, I holler back “Rayleigh scattering!” And I then realized this is a rhetorical question, and I just wanted to like hide under my seat at that moment, but there was really nothing I could do other than pretend to be part of the fuselage. It turned out (she talked to me later), it turned out she and the pilot were having an argument over why the sky was blue, and she decided to embarrass the pilot by asking the entire cabin of passengers, and didn’t actually expect an answer, but was happy that I provided one and was interested to actually know the answer because it turned out neither she nor the pilot actually knew why the sky was blue. I still really felt like that nerd who doesn’t…I was Sheldon. I channeled Sheldon. It’s just that simple.

Fraser: Such a geek, such a nerd, well you know, for that pilot and for the stewardess, why don’t we get into it? So then, where do you want to start with the Rayleigh…so then why is the sky blue, Pamela?

Pamela: The sky is blue because it has sufficient density of stuff in it (gases, particles, things like that) that it scatters all of the light from the electromagnetic spectrum that’s able to get through down to the blue levels, so red comes straight through, yellow comes straight through, green…well green’s green, it doesn’t work in ways the eyes detect sensibly, but the blue light is getting scattered all over the sky such that a photon of blue light or anything with shorter wavelengths than the blue, as it comes through, it will hit a particle of dust, a molecule of gas, and it’s going to get scattered in a random direction, and it’s from all of the different scatterings that the blue light goes through that we end up seeing the entire sky as blue, because eventually, it’s going to get scattered back into our eyes.

Fraser: So, sorry, there's a couple of things there that you mentioned that I just sort to want to unpack them a bit. So when you say "scattering," what is…so I imagine a photon is passing into our atmosphere and -- what? Bumping into a …you know…

Pamela: It's…that's pretty much what's happening. You can talk about it as an absorption and re-emission process, but in a lot of ways, it's kind of like throwing a ping pong ball into a room with a lot of different things that it can ricochet off of, so if you send little tiny non-ping pong balls cause they're little tiny into a room, the way ping pong balls work is the little things are more likely to get straight through, and the bigger things are more likely to get ricocheted. Well, the way it works with light is the shortest wavelengths have the longest frequencies and they're the things that are most likely to get scattered all over the place. Sorry, I said that backwards, the things with the shortest wavelengths have the shortest frequencies, and it just works out that they're the things that are most likely to get scattered.

Fraser: Right, but you're saying like absorption and re-emission, so are these photons that are bouncing into particles in the atmosphere…then they're getting absorbed and then they're getting re-emitted? Is that right?

Pamela: Yeah.

Fraser: Right, which is different. I guess what I'm saying is it's kind of different from refraction, right? When you have water and the light comes through water and the angle of the photons bends…

Pamela: Right.

Fraser: …they're not being absorbed and re-emitted, they're just passing through like it wasn't there except that it's changing the angle that they're moving through…but in the case of the atmosphere, they're actually bonking into particles in the atmosphere, these atoms are absorbing them and then re-emitting them again.

Pamela: And the key for this happening is what the light is interacting with needs to be just the right size, so it's an elastic scattering process in some cases, where the photon does actually boink and bounce off like ping pong balls bouncing off of each other. You do also have the absorption/re-emission process, so it's that the elastic scattering is the Rayleigh part, but you also get the absorption and emission – it's all confusing at times and we have way too many equations to cope with all of this, but in order for this to happen, you have to have sufficiently small particles because otherwise, they're just going to block the light and nothing good is going to happen.

Fraser: That's like when you have like a volcanic eruption, or a forest fire, and you've got enough dust and large particles in the atmosphere that it actually just starts blocking out the light entirely.

Pamela: But what's cool is that even with volcanoes and stuff, when they go off, the finest particulates, the smallest dust grains actually add to the amount of scattering that's going on in the atmosphere, and the way Rayleigh scattering works is first you scatter all the shortest wavelength stuff, so you end up with the blue stuff scattered everywhere, and as you add particles, as the light has to travel through more and more stuff, the probability that you're going to start scattering yellow light, you're going to start scattering orange light goes up, and so when you have a lot of volcanic dust in the sky, you end up with much redder sunsets, you end up with…actually the color of daylight changes from that really light blue to a much deeper blue.

Fraser: Right, and just so, sort of, because I'm thick and not smarter than a fifth grader…

Pamela: That's a lie!

Fraser: …so we're seeing the blue because it's the blue particles are getting more scattered?

Pamela: Yes.

Fraser: And then, and so we're seeing…so the reds, and the yellows, and the lower, you know, the shorter, sort of, the longer wavelengths are passing straight through directly into our eyes…

Pamela: Yes.

Fraser: …but we're not seeing the light that would have missed us entirely, but is now getting scattered in our direction.

Pamela: And it's a probability. I mean, this is one of those things where science likes to play with dice, so the likelihood that any particular blue photon from the Sun is going to get straight through the atmosphere is a much lower probability than the probability that a red photon's going to get all the way through the atmosphere, but the more atmosphere you have, the more scattering has a chance to happen. So it's like if you throw more and more dice, even though the likelihood that you're going to throw a Yahtzee is always low, if you throw the dice enough times, you're eventually going to throw a Yahtzee. Now with our atmosphere, if the Sun is straight overhead, light is coming through the least possible amount of atmosphere. So the atmosphere is a constant thickness around the Earth. When the Sun is straight overhead, it only has to go through the atmosphere that's straight above you. Now as the Sun goes over towards sunset, as it goes, the angle through the atmosphere that the light has to go gets such that you're looking through more and more of that atmosphere, and it's maximum when the Sun is over on the horizon, and when the Sun's on the horizon, you start seeing red atmosphere, orange atmosphere because so much more scattering has happened that now it's not just the blue light being scattered, but it's also the oranges and the reds being scattered as well.

Fraser: Right, and so again it's that way to think of it that you look up into the sky, and there's the Sun, and so you're seeing all of the yellow, and the red photons that are streaming directly from the Sun right into your eye (now, don't look at the Sun you know that's a bad thing), but the point being, you're also seeing, I guess, less of the blue photons that are directly coming from the Sun because they're getting scattered away, but what's happening is you're seeing the whole sky, and so you're then seeing all of those photons that are getting scattered towards you across that entire sky, and that's why you see the blue…

Pamela: Right.

Fraser: …because it's just that it's such a huge surface area of sky that you're then able to see, and because the blue is getting scattered away, that's when you get a chance to see them. There's sort of a similar effect, although I think this has to do with refraction, like have you ever seen like a moon dog or a sun dog, where it's really high ice in the sky and you get this circle?

Pamela: That's actually a refraction process.

Fraser: No, I know it's refraction, but it's that same thing that you always see it at a very specific angle because you're seeing a concentration of the particles in that one angle more than you would see it in any other.

Pamela: That's actually an interesting case, and we should probably do our next episode on refraction, I'm thinking...

Fraser: Sure.

Pamela: …where with those, when the moonlight hits the ice droplets, ice flakes, I don't know, they're falling out of the sky currently where I live, when they hit the frozen bits of water in the atmosphere, they always bounce at the exact same angle and so if you and I are both looking at the Moon in two very different locations, and we see one of these rings around the Moon, we're actually seeing it through different ice particles because it has to have the exact right angle in order for us to see it. It's…rainbows have the exact same problem.

Fraser: Yeah, I did an article on this and it's just absolutely fascinating, and if you ever get a chance to see one... Yeah, but why don't we do that? Why don't we talk about refraction, reflection -- it's a whole optical thing. Right, so when we intro-ed this story, we're going to talk about why is the sky blue, but of course, Rayleigh scattering has a big implication in astronomy.

Pamela: Right, and...

Fraser: So where does Rayleigh scattering come into astronomy?

Pamela: Well, we start seeing it with all sorts of different nebula, so reflection nebula, in particular, are these beautiful, blue objects on the sky, and the diagram that we always draw in Astro. 101 is you take a hot star, so it has no absorption lines in it, so you have a nice, happy, hot star, which is just a continuous rainbow of light coming off of it, you shine that continuous rainbow of light at a gas cloud, and when the light hits the gas cloud, the reds are going to go straight through for the most part, so if you're on the other side of the gas cloud from the star, you're going to see a beautiful red cloud. Now, the reality is because lots of clouds are filled with hydrogen, the red isn't just from this effect. The red is also largely from excited hydrogen emitting red light. Now, the thing is if you're then at a right angle so that you have the star off to the side, the cloud straight in front of you, and you look at that cloud, you're going to see it as a beautiful, blue cloud because of all the blue light getting scattered in all different directions through these processes.

Fraser: And so what would scientists use this process for? Like what questions can we answer using this technique, or understanding this principle?

Pamela: Well, it allows us to get at things like what are the sizes of the particulates, what are the densities of the particulates… The thing about Rayleigh scattering is it only works when the particles are significantly smaller than the wavelengths of light, and so by realizing, OK, so we're seeing this particular amount of light, we know the colors that are going in because the star is over here, we know what type of star it is, we can start to get at the physical parameters of the cloud without actually being able to touch it and poke it, or sense it in any more definitive way.

Fraser: And so when you see the Rayleigh scattering, the wavelength of light that's being scattered toward you, that tells you the size of the particles in the nebula? I guess if you know the particle size of the nebula that tells you a bit about its composition.

Pamela: Yeah, and the amount of light getting scattered also helps us get at how dense is the material in the cloud.

Fraser: And is there like a direct correlation, will it always be if you see this kind of scattering, then you know the particles need to be this size?

Pamela: Well, it's a range. This is one of those things where I can't tell you that all because the light that I see is this wavelength that the particles are this size. It's a matter of as long as the particles are "smaller than," I'm going to get the Rayleigh scattering, so it places limits on it, but it's not a definitive thing that allows me to look at the amount of light scattering and say "Aha! That cloud is made of carbon monoxide!" No, I can't quite get there from here.

Fraser: Oh, you can't do that? Because that's sort of what I was driving at.

Pamela: For that we have to use spectroscopy.

Fraser: Right, and spectroscopy is that process where you can see which lines, I guess, in the spectrum are being absorbed or emitted to tell you what the…

Pamela: And the convenient thing here is that if you have that star off to the side, that's shining light on the nebula, the gas in the nebula is going to absorb only the wavelengths that correspond to transitions in the specific gases, so hydrogen has specific colors it absorbs, ethanol has specific colors it absorbs, crazy things like chlorofluorocarbons have specific wavelengths that they absorb, and when they absorb this out, they absorb the light coming from one direction, but when they re-emit it, they re-emit it all different directions, so we're able to see emission lines corresponding to what gas is in the cloud when we look at it from off to the side, so this is actually a very convenient geometry.

Fraser: Right, and I guess that's the question, right? Is because we see them coming from directions, I guess, from a larger area that lets astronomers gather more photons.

Pamela: Well, it's not so much the more photons issue as if you're on the other side and you have bright star behind the cloud, you have cloud, and you look at the spectrum of the cloud, you're going to see the light absorbed out, but it's easier to detect lines spiking up the emission than it is to get the absorption lines. It's…so absorption lines are fainter, and emission lines are brighter, and if you don't have a very powerful detector, emission lines are just easier to find.

Fraser: So if we were able to move to some other planet, if we were able to move to some of these crazy hot Jupiter worlds, or even sort of a…you know, super Earths orbiting other stars, red stars, blue, you know, yellow stars, or hotter stars, would we see a very similar blue sky in any kind of atmosphere that we were living in? I mean, I know you don't see that on Mars, right?

Pamela: Right, so on Mars you see a somewhat violet sky, and this is because violet is a shorter wavelength. They just don't have as thick an atmosphere as we have, but at the same time, the sky can get amazingly dusky because of all the dust that will get stirred up during dust storms. So just like here in the American southwest, or if you go out to the desert-y parts of Africa or China, when there's a dust storm coming, the entire sky turns red from all the scattering of light off the particulates in the atmosphere. Well, when Mars is having its storms, you have the exact same effects of this amazing deepening in color, reddening in color of the sky, but normally it's just violet because it doesn't have as much scattering going on. So you can start to get a sense of if you're on a planet with an extremely thick atmosphere, you're looking at redder skies, if you're on a planet with much thinner atmosphere, you're looking at bluer, or in this case, violet-er skies, like we have with Mars.

Fraser: And so that's the spectrum that you have to work with, then I'd have the rainbow, and then the thicker the atmosphere, the more it's going to push into that red direction, the thinner the atmosphere, the more it's going to go in the violet direction, and it also depends on the size of the particles themselves in the atmosphere, right?

Pamela: Yeah, and having suspended dust can compensate for lack of lots of gas in the atmosphere.

Fraser: Right. So are there any other implications in astronomy? What about back scattering?

Pamela: Well, so back scatter isn't something we generally have to deal with other than when we're looking at zodiacal light, which is a case of sunlight reflecting off of dust within the path of the zodiac on the sky that we can see back on the planet Earth, but in general, back scattering just isn't something that we have to deal with. Other places that we have to deal with this is, unfortunately, we do have an overall reddening when we look at things due to the scattering of the blue light. So when we look through parts of our galaxy that have a lot of material in them – a lot of gas, a lot of dust -- when we look through those sections, all of the stuff behind those sections of the sky appear to be reddened, so you'll often hear not only do we worry about the redshift of a galaxy, but we worry about the reddening, and the reddening is simply caused by stuff in our galaxy, stuff in our atmosphere affecting the color that we see of an object, and we have to correct for that, and so there's been very detailed maps made of the entire sky trying to figure out what is the extinction, what is the reddening, what is the change in color that is being caused by all of the gas and dust within our galaxy affecting how we see background objects in the Universe.

Fraser: And so you could see a distant galaxy, and you'd want to take the color of that galaxy to find out how much star formation is going on, or how old it is…

Pamela: How fast it's moving…

Fraser: How fast it's moving away from us or toward us, and then because there's intervening gas and dust in the Milky Way, or even in the Universe, maybe in between us and them -- that's going to change your measurement.

Pamela: So we have to apply corrections.

Fraser: And is that done sort of like if you know you're looking at a galaxy, through part of the Milky Way…

Pamela: You look it up in a table; you apply the table.

Fraser: Really! And then just subtract from your number?

Pamela: [laughing] Actually, it's just that simple. The tables that we look at are a function of what wavelength of light are you looking at, what is the overall color of the object that you're looking at, and how much stuff is in that direction, so when I say it's a look-up table, it's more than just an "x, y" look-up table; it's a multi-parameter, binary cube of data that you're sorting through, but yeah, there's look-up tables that have been produced that allow you to make the needed corrections.

Fraser: So, does that, you know, we talk about visible light and how we see the sky turning blue, but does it have implications, throughout the…I mean, it must for the entire electromagnetic, I mean, do radio-astronomers deal with scattering in this same way?

Pamela: This is where certain things become transparent to different colors of light, so as far as our atmosphere, as far as radio signals are concerned, for the most part, our atmosphere doesn't exist, so those colors pretty much just come through, and infrared is largely this way as well. This is where we can actually look through dust clouds using infrared light.

Fraser: Yeah, my house is invisible to radio lights.

Pamela: [laughing] Exactly. So different wavelengths -- it just doesn't matter. So you need to have the size of the particle is commensurate size to the wavelength of the light. Otherwise, this just isn't going to happen, so once you take all of that into consideration…yeah, radio, we don't care. Now then, our atmosphere also does things like it doesn't let ultraviolet through, and this has to do with the composition in the atmosphere. It doesn't let gamma rays and x-rays through, for which we're all grateful because that means life can exist, so there's a lot of chemistry involved, a lot of physical chemistry and quantum mechanics involved, so it's not just Rayleigh scattering, it's also what gets absorbed, what gets blocked, what is the different wavelength transparent to, what are the sizes of the wavelengths -- all of these things factor together.

Fraser: But, when we get situations where x-rays are getting scattered by nebula atmosphere, atmosphere of the Sun, things like that…

Pamela: X-rays pretty much just get blocked; they're pretty good that way, so you'll see areas where the x-rays just aren't visible, but if you have dense…I mean, it's also one of these things where extremely dense gas, it's not that it's blocking x-rays, it's that it's producing x-rays, so there's all sorts of "if-then" equations involved in figuring this out.

Fraser: Alright, so then let's wrap this up with a nice, sort of one-sentence answer for someone, you know, "why is the sky blue?" Beyond just Rayleigh scattering… The sky is blue because…

Pamela: …because the gases in the atmosphere scatter the photons like a bunch of ping pong balls trying to get through a crowded room full of chairs.

Fraser: The blue photons.

Pamela: The blue photons.

Fraser: They scatter the blue photons, let all the other ones just pass through.

Pamela: Right.

Fraser: We're seeing the blue photons scatter.

Pamela: Yes.

Fraser: Alright, alright…I think that works for people. Cool. Alright, well, thanks a lot Pamela.

Pamela: My pleasure.