Astronomy Cast Episode 284 for Monday, December 10, 2012:
Optics

Fraser: Hi, everyone! It's Fraser here. So this is a special episode of Astronomy Cast that we recorded on during the "Not the End of the World" cruise in December 2012. We did this in front of a live show, and I thought it went really well. It's going to correspond to episode 284 for December 10, 2012, and the topic was "Optics."

[begin live recording]

Fraser: Astronomy depends on bullying light. You reflect it, refract it, bend it, and mirror it through complex manipulation of light. Through optics we bring the distant Universe to our eyes. Alright, so the show we're going to be doing optics, we're talking about refractors, and reflectors and lenses and eyepieces and big telescopes and little telescopes and the weird tilt mirror lenses and the planetary lenses and all that, so first I'd like to go back through the history books and talk about where… what was sort of the first understanding of when we started to use optics? When did scientists really start to understand how lenses work?

Pamela: Europe in the late 1500s, early1600s we started figuring out things like magnifying glasses, microscopes, eyeglasses, but it was adding the lenses together into compound systems that really took off in the early 1600s.

Fraser: And so what was like the first application of lenses? Microscopes? Magnifying glasses?

Pamela: Well, a compound, it was microscopes, but in terms of lenses themselves, magnifying glasses which led to eyeglasses, which, if you think about it, humankind went through 1000s of years where if you were nearsighted that was basically "life over." Think of all the things that our glasses allow us to do that you couldn't do until eyeglasses were invented.

Fraser: And so you've got the situation where you've got people making discoveries that glass somehow bends the light you can see, they can make small objects appear larger, distant objects closer, and so then how do they actually start to piece this together?

Pamela: This actually led to a huge controversy over what light is. Is it a particle? Is it a wave? This is something we've done shows on before.

Fraser: Which is it?

Pamela: Both.

Fraser: OK.

Pamela: It's called the wave-particle duality, and this is one of those things that had people completely confused for a long time because there's this problem where if you send light through a really narrow slit, it spreads out into an interference pattern of bright and dark spots, but then it gets bent when it goes through a lens as though it were a particle, so interference patterns with adding together in a positive way and then destructively interfering – that was like water waves, so we imagined light (not we, I was dead, or not alive at least), [laughing] so water waves was one of the early ways people tried to imagine the constructive interference of light, but then the particle nature really came from trying to describe how lenses bent light, and mathematically both worked, and this led to all sorts of "but it can't be both!" Well, yes! Yes it can! And that was the problem.

Fraser: Right, and so then how…you actually started to talk about...we have the simple lenses, which is a magnifying glass, so where did this idea come to hook up multiple lenses together, and what benefit is that giving us?

Pamela: Well, I think in a certain level it's like what every little kid does. What happens if I put both of these in front of one another? And the truth is if you get it just right, if you get the distances just right, you can make either something that magnifies little, tiny objects that are close to the lens, or you can get something that appears to magnify very distant objects that are very far from the lens.

Fraser: So I guess if someone's got their magnifying glass at home right now and they could do an experiment, how would they do this? They would hold one magnifying glass in one hand, hold the other magnifying glass in the other hand, they're going to be moving the distance back and forth with these two magnifying glasses? What's going to be happening?

Pamela: So if you want to make a telescope, the way you can figure out how to do this correctly is take a sunny day and try and focus the light from the Sun onto a piece of paper through the magnifying glass. Make sure that you don't set the paper on fire.

Fraser: That's all I want to do.

Pamela: [laughing] Measure the distance from the piece of paper to magnifying glass.

Fraser: OK.

Pamela: Now if you have two magnifying glasses that are identical, take that distance you just measured and put the two lenses, that times-two distance apart, so what ends up happening is the light from the extraordinarily distant source, in this case the Sun...now do not look at the Sun this way. Look at the Moon, look at the stars…

Fraser: Too late.

Pamela: Look at the trees, so look at something extraordinarily far away, but not the Sun. And so the light from very far, all of its light rays are coming in essentially parallel to one another. As they pass through the lens, they get bent down to a point. That's the point that tried to set the piece of paper on fire. Now, they'll start diverging again as they go through that point.

Fraser: Because they're particles.

Pamela: Yes -- in this case. And as they diverge, they end up hitting that second lens which then bends them back to be parallel to one another, which is the most relaxed thing our eye likes, so if you're ever really tired, or thinking, you may notice your eyes drift off to focus of infinity. Well, that's actually the muscles in your eye completely relaxing.

Fraser: Right, but I guess I'm a little confused because the light rays all start parallel, they go through this convergence, they come back out and end up parallel again. Where is any kind of magnification happening? Shouldn't you just see sort of the same thing you saw before? [missing audio]

Pamela: So the way magnification ends up happening is you have to draw all the light rays, and this gets hard to think about. So your lens is way bigger than your eyeball, so it's taking light from a much bigger area, focusing it down, and when it comes back out, the angular size can get changed in the process.

Fraser: Right, OK, so I can imagine like if I had a bunch of parallel lines that I had drawn, and maybe they were, whatever, a centimeter apart on the one side, and then they come through and then they get converged, and come back out again on the other side. Now they may be more compressed together, and you're getting more of that light compressed into an area…

Pamela: And the truth is to get magnification, you don't use two identical magnifying glasses.

Fraser: Right, two different sizes, right, so you're going to change the size, you're going to go from a larger aperture to …

Pamela: So you end up taking large lens, which can gather as much light as possible, focus it down, and then it comes and you put a much, much smaller lens that had an exit pupil that hopefully is matched to the size of your eyeball. You take all of the light that was gathered by the first lens and bring it into your eye with that much smaller second lens.

Fraser: And so from this point on, we're going to talk about refractors, and reflectors, and eyepieces and Barlow lenses, and reducers, and all this kind of stuff, but it's all just based on that exact same principle, the same thing. We're doing the same thing. We're taking a bunch of parallel rays and one lens, allowing it to converge, allowing it to come back out again, and then go through another lens, but then it's sometimes multiple lenses?

Pamela: Sometimes it's multiple lenses, and the thing that gets really confusing -- and this really screwed up the people who were doing the particle-wave arguments -- was mirrors did the same thing. So when we have a curved surface of a mirror, the incoming light bounces off at an angle that so if you draw a normal [missing audio] to the mirror at any given surface along its curved surface, the angle to the one side of that perpendicular, and the angle to the other side of it that it bounces off, that's going to be the same angle, and so you're shifting where the light is, and in the process of bending it, you can make a mirror act like a lens.

Fraser: And so can we replace lenses with mirrors one-for-one in our telescopes?

Pamela: It's not entirely one-for-one because if you try to replace both the eyepiece and the primary with a mirror, you'd never get the light to your eyeball.

Fraser: Right, I can imagine you trying to put your eye in exactly the right place.

Pamela: Well, that and you'd have to stick your eye where the light is getting to the mirror in the first place -- doesn't work so well.

Fraser: Right. Exactly, although it works with sound.

Pamela: It does work with sound, but yeah, sound is a different critter.

Fraser: Yeah, Right. OK, so but the point being you can have the mirror serve the purpose for some of the lenses that are going to be involved with the telescope, but at the end of the day, to get those rays coming parallel out of the eyepiece, you're really going to want that [missing audio] refraction.

Pamela: And the fact that we can use mirrors has really increased our light-gathering ability. If you think about it, a lens -- you can only support a lens at its very edges, but with a mirror you can put support all across the back of the mirror. This means light comes in, hits giant mirror six meters, eight meters across, over twenty feet for a lot of these really large suckers, and you can't build a lens that is that big and doesn't deform under its own weight. You started to run into problems as lenses got up to just 30 inches in size, so if we could only use lenses, we'd never be able to see light coming from distant objects in our Universe.

Fraser: And who do we have to thank for these Newtonian telescopes?

Pamela: You know, it just might happen to be Sir Isaac Newton himself.

Fraser: I sort of digress, but did Newton come up with his idea of the mirror-based telescope once they had reached the limitations of what the refraction telescopes like the optics could do?

Pamela: Well, he was actually solving a different problem. One of the things that we run across is as light passes through just plain glass, different colors get bent different amounts, and this gets more and more noticeable as you look through larger and larger lenses. So this means when you look at something and see red on one side and blue on the other, and it's because light is spreading out essentially into the same rainbow that you see in raindrops. This is called chromatic aberration. He was trying to get around chromatic aberration, and mirrors don't care what color the light is -- they just bend it.

Fraser: So now I think I want to put this all together. We've got the kind of basics, I think. We've talked about objects, about how the mirrors work, how the lenses are going to work, but let's take a look at like a modern telescope and see how all those pieces fit together. So let's just start with a standard, pirate telescope that you're going to put up to your eye, and you're going to see some distant object. So if I would crack that open, a Galileo-scope...

Pamela: A Galileo-scope!

Fraser: ...for example, so if I was going to crack open a Galileo-scope, which I highly recommend everyone does...

Pamela: And they're designed for it. You can put them back together.

Fraser: They're designed for it, yep. Take it apart, put it back together...what would I see inside?

Pamela: With a Galileo-scope, that's actually not that simple of a system because they made it with very complicated optics, trying...

Fraser: Could I have picked a simpler device than an old-time pirate-y telescope?

Pamela: Let's just go with the old time pirate-scope. So if you pop open an old-time pirate-scope, you're going to find two lenses that curve out on both surfaces. This is a double-convex lens. So you have a double-convex at the front, you have a double-convex at the back, they're two different diameters, and what ends up happening is the one at the front, which is much bigger, focuses the light through, then it gets sent out to your eyeball through the one in the back. And the one in the back is the one we worry about most for how much angular magnification we get. So astronomers don't like to use just the plain word "magnification." The reason we use "angular magnification" is what we're changing is how much of the back of our eyeball, what angle of the back of our eyeball does the light take up as it hits it? So we're increasing the angular size of objects using optics.

Fraser: Right.

Pamela: Now, when you get a 4-mm eyepiece, for instance, stick it on nice, friendly Schmidt-Cassegrain 16-inch telescope…Schmidt-Cassegrain -- it's a spherical mirror, so saying it's 16 inches helps define how it focuses.

Fraser: Is this attached to my pirate telescope still?

Pamela: No, I've moved on with life.

Fraser: Have you really? OK, never mind.

Pamela: So when we talk about a 4-mm eyepiece, that 4-mm eyepiece -- that is about as small an eyepiece as you can use on the surface of our planet, or the atmosphere says, "No. You're not allowed to see what you're trying to look at."

Fraser: Right, but this whole concept of an eyepiece, I mean, this is the problem, right? When you're using my old time pirate telescope, I'm really stuck with what kind of angular magnification I'm going to be getting. I've got a set amount of light on the front, I've got a certain size of the other mirror on the other side, and it's only going to give me a certain field of view. If I want to see the fleet approaching, I'm not going to be able to see it. If I want to see and make sure it's the captain on the other deck, I'm not going to recognize him.

Pamela: So the old-timey pirate telescopes – they weren't really any better than a good pair of binoculars. They might have had at best at best a 50-mm lens that was the light gathering power, maybe a 10 or 20-mm eyepiece…

Fraser: Sure, but if I recall my pirate movies, that pirate is moving the two lenses apart from each other.

Pamela: Right, and that's because…

Fraser: Is that for focus?

Pamela: Yeah, so in the real world, objects aren't infinitely far away. At a certain point, the optics start going, "Well, that's good enough for infinitely far away." Depends on what lens you have. Now, with your normal everyday 55-mm camera lens or something, you have to constantly refocus as things move from maybe 5 feet in front of you to 50 feet to 500 feet, and the reason is the distance that something focuses is set by the distance to the object. There's actually a crazy equation for this that drives undergrads crazy because it involves all fractions. It's one over the distance to the object that you're trying to get focused plus one over the distance to where your image is going to end up, which is completely set by your camera. You're not going to move where your film is, where you CCD is, where you CMOS is, that is equal to one over the focal length of the lens that you're dealing with. So you have a set equation that only has one solution for your standard camera lens, your standard telescope lens, and you're stuck with that.

Fraser: Right, and so now to kind of take the technology to the next level from our pirate telescope. We're going to look at a situation where we do want to be able to change that amount of…amount we're seeing, the amount of…the magnification [missing audio].

Pamela: So from here it was swapping out eyepieces. This allowed us to put in eyepieces that had different amounts of curvature to them. A 4-mm lens is the equivalent of something that came off of a 4-mm sphere is the way to think of it.

Fraser: And so are you replacing that second lens, or are you putting another lens after that second lens?

Pamela: I'm replacing that eyepiece, that second lens.

Fraser: Right, with a different diameter.

Pamela: Right, so the 4-mm is going to create a much larger object image on your eyeball. It's going to spread the light out a lot more. This also means you're going to have to take longer exposures. You're not going to be able to see super-faint objects because the light is getting spread out so much. Now, if you go to something like a 20-mm, which is my favorite lens size, you get a fairly large field of view. This means your objects aren't as magnified, but because they're not as magnified, the light isn't spread out as much, so you have a better chance with your eyeball to see faint objects without having to resort to pulling out a camera and taking a timed exposure to get more light.

Fraser: Now, I originally gave you that example of the Galileo-scope, but you said it's got more complicated optics, so are there other lenses in there as well?

Pamela: So what we try and do is correct for that problem that Newton was dealing with, which is the fact that different colors get bent different amounts by different materials. So if you have what is called an achromatic telescope, it's one that has a pump-like set of lenses -- and there's a variety of different ways to do this, but the result is by passing through a variety of different materials and lenses of a variety of different shapes, it's eventually possible to get all the colors to focus at the same distance from the lens. So this way you can get that beautiful crisp, clear image through the eyepiece without having to resort to a mirror. Now, the thing with using a mirror is you always have to have somewhere in the tube above the mirror, some other device – another mirror, your camera, something in that optical path blocking part of the mirror. This starts to affect the contrast. You get a much more beautifully contrast-y image looking through some sort of a refracting system.

Fraser: Right. OK. So then, and I guess the…you can get really specialized and talk about a lot of [missing audio] as I said, you've got situation like [missing audio] right, which is that classic Celestron telescope [missing audio].

Pamela: Right, so these are nice, fairly spherical mirrors. So the original Schmidt telescopes, there's one out at Palomar that was used to do massive surveying of our sky, and it's getting reused today to create the digital. Well, now it's being reused to do the digital sky survey. It has a sister scope in the Southern Hemisphere. And the nice thing about these spherical mirrors... and they stick the camera up at the top so the light comes down, hits the single mirror, reflects up goes into the camera, and they actually bent the glass to correct for the deformation of the image that was created using the spherical mirror. They used bent glass plates originally to record glass plate images of the entire sky. They did Northern and Southern Hemisphere, and the amazing thing about this is we can now go back and look at those glass plates and see how our sky has changed. They went through, they redid this using modern detectors, and so now we have these two separated-in-time, complete images of our sky.

Fraser: And so then how does that relate to the kinds of telescopes if you went and bought a telescope Celestron. You're getting such a miniature version of that design, right?

Pamela: The other difference with what you're buying from Celestron, is they have a corrector plate up at the front of the scope, so as the light comes in it passes through a lens at the top of the scope, then hits the mirror, then it hits another mirror that's embedded in that corrector plate, comes out the butt end of the telescope, and that's where you stick either a camera or an eyepiece, and that corrector lens is to do what bending the glass plates do -- to correct for that spherical aberration.

Fraser: So then there's the Dobsonian?

Pamela: The Dobsonian is just an amount for a Newtonian telescope. So a Newtonian telescope is a mirrored telescope where the light comes in the top, hits the mirror, then hits a diagonal mirror that's suspended part-way up the tube, and that diagonal mirror sends the light out the side of the scope where it goes into an eyepiece, and you can swap that eyepiece out to get a variety of different magnifications. Now the problem with these telescopes is you can't easily put a camera on the side of them because it creates torque an unbalances the system. Now with just a plain old Newtonian telescope like Newton used, it's mounted on some sort of a fork mount where the hinges are halfway up the telescope, and that costs money. Now with a Dobsonian telescope, instead of having a beautiful fork mount on a tripod or anything complicated like that, they basically put it on the equivalent of a lazy susan, and so the lazy susan allows you to rotate it about the center and then it does come up on either side with basically a fork that it pivots around. The entire system is much more simple, and so Dobson basically came up with a simplified, low-cost way to build a Newtonian light [missing audio]

Fraser: Right. Now, I know the telescope that you really want has got a different [missing audio] a Chretien, am I getting that right?

Pamela: So Ritchey-Chretien…it's a small field of view telescope that has extremely precise optics. When you look through a Ritchey-Chretien system...you probably won't. You'll probably stick a camera on it. These are systems where your images are as close to perfect as most telescopes can get. Most professional telescopes that are used for things other than wide-field imagery are all Ritchey-Chretien optics. So that either a large one of those, or I'd love to have an overhead compartment-sized apochromatic teleview telescope, but those are out of my price range.

Fraser: Out of your price range, so what would one of those run?

Pamela: So to get the one I want with the tripod I want, we're looking at a few thousand dollars.

Fraser: Not bad. I mean, I know like the [missing audio]…they're like $30,000.

Pamela: Well, to get the Ritchey-Chretien I want we're looking at over $16,000 by the end of the day, so not going to happen.

Fraser: And the mount, and the observatory…

Pamela: Well, that's the whole thing is it's the mount plus the CCD plus the dome…

Fraser: Right, and the 500 acres in the Nevada desert, and the remote computer-controlled system, and the full-time astronomer who works it...yeah. No, I understand all that.

Pamela: No, No, I…yeah, I don't need any of it. This is the great thing about the modern era is we do have all these survey telescopes that give everyone in the world access to the entire sky through online databases, so I don't need a personal…

Fraser: So you don't need your own telescope.

Pamela: No, I can use the Sloan, I can use the Hubble archive, and I can subscribe to national observatories if I need to.

Fraser: So if anyone shows up and offers you a telescope, it would be turned down.

Pamela: I will say yes, and I will take it, and it will be used for the virtual star parties, thank you very much.

Fraser: That's true. Thank you very much. So, OK, I guess one last question I wanted to ask, which was we've been talking about this ground-based stuff, but we put telescopes out in space. How does the stuff that we use here on the ground relate to the stuff that's out in space? What would the Hubble space telescope look like [missing audio]?

Pamela: It's puny!

Fraser: Yeah!

Pamela: That's the crazy thing!

Fraser: Yeah, it's like a 1.6-meter telescope. It's teeny tiny.

Pamela: Yeah, it's a small telescope, and what allows it to do amazing things is its not getting its images screwed up by our atmosphere.

Fraser: It's the whole out in space [missing audio].

Pamela: And then we don't have things like x-ray or gamma ray telescopes on the surface of our planet because luckily we don't have x-rays or gamma rays on the surface of our planet from cosmological sources.

Fraser: But do they have to do anything to Hubble, or do they get any advantage apart from no-atmosphere experiments? Is there any part of the optics they don't have to do to deal with that?

Pamela: The only nice thing that you gain by going into space beyond getting above the atmosphere is with ground-based systems, as you point them lower to the horizon, the system will actually torque. So the telescope will slowly bend. It might go slightly out of focus as distances shift, and so you don't have to worry about gravity adding gravitational anomalies to your optical images. And they're not really gravitational anomalies; it's just gravity causing optical anomalies by torqueing your system.

Fraser: Right, and so in those big, ground-based telescopes, where actually the weight of the telescope is torqueing… [missing audio].

Pamela: Yeah, and you lose focus and you change focus as you point the lower toward the horizon parts of the sky.

Fraser: Alright, well, thank you very much, Pamela. I really appreciate it.

Pamela: It's been my pleasure, and we'll do this again tomorrow.

Fraser: Alright. Bye.

Pamela: Bye-bye.

[applause]