Astronomy Cast Episode 37:
Gravitational Lensing

Fraser Cain: This is such a cool topic: here we go. Astronomers have always searched for larger and more powerful telescopes, but the most powerful telescopes in the Universe are completely natural, turning the mass of an entire galaxy into a lens that astronomers can look through. We're talking about gravitational lenses, which let astronomers peer back into the earliest moments of the Universe.

Pamela, what's a gravitational lens?

Dr. Pamela Gay: It's basically this really neat way that the gravity of an object (a star, galaxy or cluster of galaxies) can work just like an optical lens to bend light. In this way, they can bend light that would otherwise go off in some other direction toward the Earth and increase the total amount of light from some distant object that we're able to see.

Fraser: What's the underlying principle that's bending light here?

Pamela: There's gravity! It's one of those things that, when you start to realise energy and mass are two sides of the exact some coin, and that light is just energy, and gravity can cause that light to be deflected, to move the same way it can cause you and I to move, it's possible to start using mass to focus light.

Fraser: So with a gravitational lens, you've got light from some more distant object passing some mass like a galaxy, and that mass is warping the space around it so the light follows a different trajectory and bends.

Pamela: A good way to think of it is, if you imagine that it goes: your nose, far, far away a galaxy, and even further back than that, a quasar, light from that quasar is going to be heading off in all directions filling a sphere. Some of that light would normally not just miss your nose and go above your head but miss your nose and hit a star somewhere above your head.

That light that would normally have gone up above you, as it grazes over the top of that galaxy between you and the quasar, it can get bent so that its new path brings it straight to the tip of your nose.

This also has the neat affect that if the alignments are just right, we can see two images of the exact same object. One is the straight view, and the other is seen reflected in a mirror, the same way you can take and use a mirror to look around a corner.

Fraser: Let's see if I understand this: you've got a sphere of light coming out of the quasar, and some of that light is going to be passing very close to this galaxy and what would go in a straight line gets turned in a little or turned as it gets attracted toward the galaxy and so we here on Earth, that's far down the path, see this light converging back on us because of this warping. So that's why we see a magnified version of what's behind it.

Pamela: In fact, the gravity can cause a bunch of different effects. It can distort the light from a background object, this is where you get galaxies that appear as strange arcs around Abell clusters. You can also get what's called a microlensing event, which is where a background object appears to be a great deal brighter due to an intervening mass.

You can also get neat affects such as double quasars, quadruple quasars, Einsteinian rings, where the light from a background object is multiplied into multiple images or twisted into a ring where there once was just a single point-like object.

Fraser: You say these are wonderful things to look at, but wouldn't a telescope manufacturer be trying to grind the mistakes out of the mirror? If they saw this kind of stuff?

Pamela: In a real telescope, you really don't want your telescope to produce fun house images. The reality is that looking at galaxies through gravitational lenses is sometimes just as distorting as if you look through the old deformed glass in extremely old houses, or if you are looking at yourself reflected in a carnival glass. But, we're allowed to see things we can't otherwise see, and sometimes the stuff that we're seeing is invisible stuff, like when the gravitational lenses are made out of dark matter.

Fraser: So I guess the astronomers are going to take what they can get. They don't have a telescope that powerful, so the fact that there's one naturally out there that does provide a bit of a distorted image but still allows you to look much further back… how much further back can they see?

Pamela: The very most distant galaxy that has ever been detected was found using an Abell cluster to gravitationally lens a background galaxy.

Fraser: So this is an Abell cluster, an intervening cluster of galaxies where it was able to focus the light from this more distant galaxy.

Pamela: In this case it was Abell 2218, and back in 2004 they were able to get a redshift to measure the recession rate of a smear of light that they were able to detect because it was being magnified, it was being lensed by the gravity of this giant cluster of galaxies.

Fraser: So theoretically, how far back could astronomers push this technique?

Pamela: It's all a matter of how good are we at taking a spectra of a smear of light. If the alignments are right, you can perhaps get multiple galaxy clusters that are gravitationally lensing an object multiple times that, with all of this combined lensing, allows us to look back to objects (that we currently can't see using existing telescopes) that were formed at the very edge of the Universe in the moments right after the Cosmic Microwave Background was formed. We haven't found those things yet, but the potential is there, as we look at the smears of light.

Fraser: I guess with a more powerful telescope or with a luckier alignment of foreground object and background object, we might find some of those first objects.

Pamela: We're also finding objects within our own galaxy (that we can't find any other way) using gravitational lensing. There was actually a planet, it had a truly terrible name: OGLE 2005-BLG390 (that's the parent star). It has a planet going around it that we found because the star and the planet gravitationally microlensed a background object and we were able to see the mass of both the star and the planet as the background star was lensed.

Fraser: So we're just talking about a star here, not a galaxy. This was two stars lining up in our Milky Way and we happened to be in the exact right spot to see the line up.

Pamela: What's neat in this case is as you have the foreground star passing in front of a background object, we can't see that star. This was a little red dwarf, too far away for us to be able to see with our telescopes because it just doesn't give off a lot of light. As it orbited in front of a background object, the background object was something bright enough we can see it every day.

That background object suddenly increased in brightness in a away that isn't characteristic of a nova or a flare event or any other normal brightening. It increased in brightness in a perfectly symmetrical way that indicated that an object was passing in front of it and then moving out from in front of it at a constant velocity.

In the process of doing this, there was a little blip on the side of that increase and decrease in brightness. That blip corresponded to the planet getting in on the act of microlensing the background light. We were able to find what we think was a rock or an icy planet (one of the smaller mass planets that have been discovered), because of this microlensing event.

Fraser: This is a once in a lifetime opportunity, to see this star and its planet, because you need that line-up, so unless it lines up with another star that we know of, we'll never see it again.

Pamela: This was a roughly 13-Earth mass planet that we have *a* observation of, and we have a observation of its star, but still it's cool!

Fraser: Right, but there's no chance for follow up observations.

Pamela: Not with current technologies. This is where you wait for the OWL telescopes and the other freakishly large telescopes astronomers are planning to build.

Fraser: I recall it was quite far away, it was like tens of thousands of light years away.

Pamela: It was a star out on the edge of our galaxy, but it's a new way to get at data in places that we otherwise can't observe.

Fraser: What's the process for this the, are astronomers watching stars to see them brighten like that?

Pamela: There are two different projects: OGLE and MACHO. These two programs are regularly looking at certain areas of the sky night after night after night waiting for microlensing events. What they do is take picture after picture of the same region, and as they take these pictures they subtract them off of a previous night's images and look to see what is different.

In the process of finding these differences, sometimes they're actually discovering variable stars like the Cepheids and RR Lyraes that I like to study. Sometimes they're finding nova, sometimes they're actually finding things like supernova light echoes that are moving through these regions of space. Really cool science.

They're also (unfortunately at lower events) finding microlensing events. They're finding lots and lots of RR Lyrae stars, lots and lots of other variable stars. Occasionally, out of the noise, they find these microlensing events that indicate there's a dark object (a white dwarf, a brown or red dwarf, a neutron star, something that we otherwise can't see) out in the outskirts of our galaxy, plugging along occasionally lensing light from perhaps the Large Magellenic Cloud stars, perhaps background objects. It's these lensing events that are allowing us to get a sense of how much of the dark matter in the galaxy is made up of perfectly normal stuff that we just otherwise can't see.

All the dark matter in the galaxy could be accounted for if there was roughly one ACME brick per solar system volume of space. If that were true, we wouldn't be able to see out of the galaxy really well. It's important to find the actual ACME bricks that are out there (which tend to be shaped more like brown dwarfs) and this is one way of doing that.

Fraser: Now, earlier you talked about how the larger gravitational lensing is helping astronomers map dark matter distribution. Can you go into that in some more detail?

Pamela: There was actually a really, really neat Hubble result that just came out. If you haven’t read about it yet, go over and look at our friend the Bad Astronomer's website. Hubble basically found a smoke ring of dark matter around a galaxy cluster, CL0024+1652.

What they do is, they look at background objects. They assume in this little tiny region on the sky, I have 100 background galaxies. These galaxies are going to have random orientations, random shapes. If I average together all these galaxies' shapes, they should average out to perfect little circles on the sky. But, if there's matter between me and those background galaxies, that matter is going to cause all of them to be systematically twisted a little bit, the same way as if all of them were reflected in the same carnival house mirror.

So we look for those slight twists, those slight ellipticities, the slight teardrop shapes that crop up in the background galaxies. When we find these irregularities in their shape, the deviations from being little tiny circles, then we know there's dark matter and we can map the distribution of the dark matter by reverse engineering what was necessary to make these galaxies not average out to a little disk.

Fraser: So in this case, we don't have a galaxy in front of another galaxy, we have this invisible dark matter that's acting as this gravitational lens, distorting the image from the background galaxy.

Pamela: What's really cool is this dark matter is forming a donut (one of my favourite shapes apparently) around the cluster of visible galaxies. This is the type of thing that can happen when there's a collision between two systems. You shock the system, one passes through the other and you end up with a ring of material. We've seen this in individual galaxies before and after collisions, but now we're seeing it in an entire cluster and it's not just the material of the cluster, it's the dark matter itself that forms the donut. That's just really cool. We're not used to thinking of dark matter as actually forming structures,(at least not forming structures on this type of scale), and it's a really neat, really hard to do discovery.

Every day we're learning more about the distribution of dark matter. Back in January, after the AAS, we actually reported here on this show about the COSMOS project, and how they'd mapped out the large scale structure of the Universe to find that the structures of the luminous matter generally fell within the structures of dark matter, but didn't necessarily have precisely the same centres.

Fraser: So I guess this was the same technique: they looked everywhere, looking for that distortion, and then carefully mapped it back to figure out where all the dark matter was.

Pamela: They mapped a fairly significant area on the sky, and they built a 3-D model of dark matter using gravitational lensing of galaxies at various distances away from us. Again, really hard to do, really good, solid science. We don't know what dark matter is, but every day we're getting a better and better map of where it is.

We can also use dark matter to sometimes get to repeat our ability to observe specific events. There are quasars out there that have been gravitationally lensed in such a way that when you're looking at the sky, you see two identical objects that are separated by a few arc seconds to more than a few arc seconds on the sky. This means that you can go out, look directly at the quasar or you can look at the lensed version of the quasar.

The first one of these was actually given the name, Old Faithful (or scientifically, Q0957+561).

Fraser: I like "Old Faithful"

Pamela: Yeah, I like "Old Faithful" too.

[laughter]

We can't name things well in astronomy. I admit to this fully.

Fraser: There's too many objects.

Pamela: Yeah, yeah it's kind of hopeless. But what's cool about this object is you have two quasars that are far enough apart that any good telescope can clearly resolve them. The two light paths, the one to look directly at the quasar, and the one to look at the gravitationally lensed quasar (where the light has already started to head off somewhere else and then deviates and comes back to us), it's a difference of over a year.

So if you catch the tail end of the quasar doing something cool (and quasars actually flicker and do neat things on short time-scales indicating stuff going on with the supermassive hole in the centre), if you only catch the tail end of an event, you just go back a year later and watch it occur in the lensed version of the quasar.

Fraser: Wow!

Pamela: You don't get to repeat observations very often. This is like the only way you can get to get a second try at getting your data.

Fraser: It's like a TiVo for the Universe

[laughter]

Pamela: Exactly, it just requires the mass to be in *just* the right place.

Fraser: That's amazing. Are there any other places where gravitational lenses come into astronomy?

Pamela: The primary neat places for them are: looking at these quasars where you get multiple images; mapping dark matter; using them to zoom in on objects at high redshifts and using them to zoom in on little objects (well, not zoom in… using them to *detect* little tiny objects) in the outer part of the galaxy. These are the main directions, but then there's also some nifty science that comes out of this just in terms of using theory to do funny things.

There was a scientist down the hallway from me at the University of Texas. Hugo, Hugo Martel. Great Canadian from Quebec. He figured out what distribution of matter would be required to create a lensed image that looked like a smiley face. It's just a great abuse of science, but that's the neat thing: you can take a perfectly normal quasar, with a perfectly normal, nice, happy, "I'm a disk" light and twist its light with intervening matter in ways that you can create arcs, in ways you can create smiley faces and all sorts of other neat patterns.

In the process of figuring out what distribution of mass is necessary to make a smiley face, he was able to also figure out what is needed to reverse engineer the distribution of mass between here and there so that when we do find these things that look like waves on the ocean, when we find these things that look like a three-year-old's version of drawing a seagull, we know what mass is required to get to that observed image.

Fraser: I guess that was my question, as you said earlier on, when astronomers look through telescopes they see these distortions, these fun house mirror images, which in some cases is great because you get a chance to see something and not nothing, but are there techniques to try and reverse engineer the light to try and get a better sense of what the object is? Could there be a day either now or in the future when astronomers can use these lenses and actually rebuild a spiral galaxy image as opposed to a smear around the outside of a galaxy?

Pamela: We're already there, at a certain level. Just as we had to figure out how to build a corrector for the Hubble Space Telescope based on the observed distortions in the early images, we have also figured out how to mathematically figure out how to get back at the original shape of these distorted galaxies.

What they do is say, "we have these 100+ galaxies that should average out to a nice polite circle on the sky. They don't." and then they do the trials. They do the simulations, to figure out where do I need to stick mass in the volume of space between me and these galaxies, to get the perhaps teardrop shape. Once you've figured that out, you can reverse engineer the path of the light to get at the original shape. It's really cool to look at some of these simulations.

With the COSMOS team, they can actually trace the pathway for a beam of light that gets lensed multiple times as it passes from high redshift galaxies to the modern epic. You can see it get bent over and over as it zigs and zags, getting bent by multiple intervening blobs of mass. It's a maze out there, and the light is forced to run this gauntlet of material because gravity bends light.

Fraser: Now does this technique work across the entire spectrum, does it work from radio waves all the way to gamma rays?

Pamela: Gravity bends everything. There are people, in fact, out there looking to see how gravitational lensing affects our views of the Cosmic Microwave Background. So we're looking at this in microwaves, we're looking at this in optical light and infra red light. We're looking across all the spectrum, trying to understand what is it that we can use this really great artifact of mass and energy being the same thing, to figure out about our Universe.

Fraser: Now there's one piece of terminology I wanted to talk about. I've done a couple stories on this, which are called Einstein rings.

Pamela: Yes.

Fraser: I know they have to do with gravitational lenses. Can you explain what those are?

Pamela: This is the neat situation where you get a perfect alignment between us and a distant galaxy or let's use a quasar (because quasars are neat little point sources).

Fraser: And quasars are the actively feeding supermassive black holes at the hearts of galaxies, right?

Pamela: Yes, exactly.

Fraser: pouring out tonnes of energy.

Pamela: So you basically have the very centre part of a galaxy pouring out gobs and gobs of light such that an active galaxy that is billions of light years away – so far away that the disc of the galaxy is extremely hard to observe with the largest telescopes – the very centre, the active part, is just the brightness of a normal, faint star. They're really powerful, fascinating things.

Now, if you take one of these (and they exist in the largest numbers in the early parts of the Universe, when there was just more stuff for central supermassive black holes to be eating). If you look at one of these in the distant Universe and plot a concentration of mass exactly on the line of sight between us and them (so it's a perfect, straight line: our telescope, the lensing object, the background quasar). The lensing object is going to block the light that's trying to get straight at us from what's being lensed, but the light that's trying to go above, below, left, right, diagonals… the light that's trying to go in a perfect ring off in other directions away from us, all that light is going to get bent toward us. If it doesn't make it all the way into focus, if it doesn't make it all the way down to a single point before it reaches us, we'll see that light that's getting bent as a ring.

Fraser: Is this a temporary situation, will this Einstein ring last for years or could we be anywhere inside the Milky Way and still see it?

Pamela: This type of gravitational lens, made up of quasars at large redshifts and galaxy clusters (or other large-mass objects) at moderate redshift distances, here… human life-scales, not seeing any motion going on. But on cosmic timescales, everything in the Universe is in motion, everything changes, some day those particular Einsteinian rings are going to lose their alignment, but other ones will step forward to take their place.

Fraser: And being an astronomer focussed on this is all about being at the right place at the right time.

Pamela: Well, the whole concept that we're never really at the exact right place at the right time… this type of thing is always out there, we're just at the right time for this one particular Einstein ring.

Fraser: Right. Great, I think that covers the concept. I think, astronomers who need to go bigger are just going to have to go out and find themselves a galaxy cluster to look through.

Pamela: Sounds like a plan.

This transcript is not an exact match to the audio file. It has been edited for clarity.