Astronomy Cast Episode 89:
Adaptive Optics

Fraser Cain: Hey Pamela.

Dr. Pamela Gay: Hey Fraser, how's it going?

Fraser: Good. Are you looking forward to the AAS?

Pamela: Oh, it's going to be a wonderful party. We're going to have everyone here and we're going to definitely do some sort of a meet up although we're still waiting for the final schedule to come out.

So, if you're going to be in the St. Louis area from May 31st through June 4th, you will have opportunities to meet myself, Fraser, Phil Plait, Chris Lintott and every other pod-caster we can get our hands on. It's going to be a great party.

Fraser: And some science will get done too.

Pamela: Oh yeah.

Fraser: Maybe we'll record another show there while we are at it. Oh, and Happy Victoria Day too. Anyway, since the dawn of humanity astronomers have wished to destroy the atmosphere. Oh sure, it is what we breathe and all, but that stupid atmosphere is always getting in the way.

Since destroying the atmosphere is out of the question, astronomers have figured out how to work with it, to distort the mirror of the telescope itself through the magic of adaptive optics. All right Pamela; let's talk about the problem, the hatred of atmosphere. [Laughter]

Pamela: Anyone who has looked down the road on a hot day has probably seen that it looks like there is steam radiating off the road or something. If you look for the steam, it is actually not there.

What you're seeing is, as light passes through the rising heat off of the road, the light gets bent and twisted. These mirages within the path of the light make it look like there's steam that is not actually there.

What that road is doing is a magnified version of what happens to every beam of light passing through the Earth's atmosphere. As light hits pockets of hot and cold and the different layers of the atmosphere it gets bent.

Rather than passing on a perfectly straight path from star to Earth, the light goes in fairly straight path from star to atmosphere, getting bent by gravity sometimes.

But then when it hits the atmosphere it's getting bent all over the place by different temperature layers and different turbulence layers and all sorts of crazy stupidness that is happening in our atmosphere, including absorption that just completely blocks certain wavelengths of light.

Fraser: I know that when you have a stick in the water and the part of the stick that is in the water looks totally at a different angle from the part of the stick out of the water and that is because the light is being bent as it goes through the water. In the case of the atmosphere, it can go through a hot pocket or a cold layer. It is almost like the light will be zigzagging as it makes its way down through the atmosphere. It's not like you can just measure the change and then remove it.

Pamela: What makes this even worse is that one stars light reaching your telescope, you are going to have photons that are some to the left and some to the right, some in front and some behind each other forming a disc in the sky.

Different aspects of that disc of light that are traveling towards your telescope, might go through different temperature regions and might have a slightly different zigzagging path as they reach for your telescope.

Fraser: Oh no, so it's almost like life from one part, even in the same image, it's not like all that light is going to the same parts of the atmosphere. That's rough. That's almost impossible.

Pamela: This is where we get into all sorts of chaos in trying to sort out our images. Over the decades we have come up with various different strategies. One of the most straight forward strategies is you just take an image as fast as you can and you get a snapshot of one set of distortions.

Then you take another image as fast as you can, just 3 flashes of a second-long images, and then you try and line up the centers of the images because as you take long exposures, the center of a star will seem to move around on the sky.

That perfect imagined disc of a star will go from looking like one shape of a squished amoeba to a different shape of a squished amoeba. If you take images fast enough, hopefully you'll be able to line them up and build them into something that has a nice high resolution. Most objects in the universe are too faint to take a picture of that lasts for a fraction of a second.

Fraser: That's what I was going to say is that really goes against the wonderful thing about telescopes is that they can stare at the sky for hours and days and just gather every single photon of light that is coming from that object.

Pamela: So as you look at something longer and longer and longer, it gets blurred out as the atmosphere first jogs it to the left and then the atmosphere jogs it to the right. Eventually you will probably get something that averages out more or less to a disc on your detector. But it's a big fuzzy disc.

To give some perspective, you might have an object that in all reality is a tenth of an arc second across, something that is one-tenth the size of a human hair held out at arms length.

As you look at it as it gets distorted by the atmosphere, it might get blurred out to as much as three hairs held out at arms length, three arc seconds as you observe it at sea level in a perfectly reasonable sight, like where I live in St. Louis. It is just the atmosphere blurs everything out.

Fraser: You mentioned one strategy is to move really quickly and just take quick pictures. What are some other ways that astronomers have tried to get around the atmosphere problem in the past?

Pamela: Well as I said it's really bad when you're here at sea level. If you go to someplace that's really high up, you're getting above a section of the atmosphere.

Anyone who has gone from the base of a mountain to the top of a mountain knows that the temperature changes just over that few thousand feet that you're traveling.

By going to the top of a mountain that is maybe five thousand feet tall, maybe even ten thousand feet tall in the case of some of the highest observatories, you can get above a certain amount of the noise that is coming from the atmosphere. You can also get above a certain amount of the water vapor, which is absorbing some of the light.

That helps mitigate the problem a bit, but in the end the best thing you can do is throw a telescope into orbit. That is what we have done with the Hubble space telescope and the Spitzer space telescope that works in the infrared.

Fraser: It's just incredibly expensive and complicated and is so much more work to try to maintain a telescope up in space.

Pamela: There are certain things you can't do. For example, McDonald Observatory where I got my graduate degree, we had graduate students who were working on building instruments. They could go out to the observatory with something that sort of kind of worked and stand out all night in the cold, in the dark tweaking their instruments to get it working perfectly.

You can't exactly send a graduate student up on the space shuttle to tweak for three or four orbits to get their instruments to work correctly in the Hubble, that's just too expensive and too risky.

Fraser: I think the perfect solution eventually will be when they build telescopes on the moon. Where astronauts can walk out over to the instrument and bang them with their wrench and make sure they are working properly and tweak the instruments and make sure they are working right or install new pieces of equipment and go back into the nice warm comfortable lunar habitat.

I think some day that will be the perfect balance between having something you can still work on but also has no atmosphere whatsoever.

Pamela: The moon even offers its own complications because it's a dusty place. You have some astronaut pounding around outside of the telescope and they're stirring up dust, which is a different way to interfere with your instrument.

But, there are solutions. It requires creativity and careful thinking and lots of money. The military is one of the best sources of extremely expensive projects that do cool things that do high accuracy images.

You can think of all the things the military might want to do, like image Chinese spy satellite and figure exactly what that thing is on orbit. It was our military that came up one of the coolest solutions and that is adaptive optics.

Fraser: All right I'll bite, since it's the whole topic of this show. Let's talk about adaptive optics.

Pamela: The idea is that as the light is coming through the atmosphere you can imagine this wave front of light coming from a distant star. Some of the light is going through to the left, to the right and each of it is getting intersected with different patches of weirdness, cold spots, and hot spots in the atmosphere.

It starts out as a straight wave front coming through the atmospheres. You can imagine a wave of light coming through the atmosphere, this plane coming across the sky sort of like a straight wave of water might approach the shore at the beach.

Just as rocks or other things might cause distortions in that straight wave that's coming towards the beach, the different warm spots and cold spots in the atmosphere can cause distortions in that plane wave of light that is coming towards the detector of your telescope. With adaptive optics, they look to deform the mirror so that it matches that deformed wave front so that all the light hits the detector at the same time.

Think of the beach analogy again, if you have rocks that are deforming that wave that is hitting the ocean. Imagine that you deform the beachfront so that the entire wave hits the deformed beach at the exact same moment. That is what they do at the mirrors.

Fraser: This leads to two very big questions then. 1) How do they know what the deformations are? 2) How do they deform the mirror?

Pamela: These are two very complicated questions. This is part of why it has taken so long to get adaptive optics working on telescopes. It's not a completely new idea. The idea has been around since the 1950s, it just took about three decades to get anyone working on actually building an adaptive optics system.

Fraser: Let's start with the first question. How do astronomers or engineers know how the wave front of the light is being deformed?

Pamela: We start with the assumption that hopefully the deformations are happening on the moderate sized fraction of a second level like a quarter of a second, a tenth of a second versus at the 1000th of a second level. They take the light that is coming into the telescope and split it and send some of it off to some sort of a wave front detector.

The way many of these work is you take a grid, something that looks sort of like a go board or chess board, where each square on the board has a lens in it and those lenses focus the light at a set distance.

If you have ever used a magnifying lens to focus the light of the sun to fry an ant, you know that you get the light from the sun coming in at an angle. It doesn't always, no matter how you hold the magnifying glass, go straight down and fry an ant directly centered underneath your magnifying glass. It might fry an ant to the left or to the right.

As that wave front comes in if some of the light is tilted to the left then the light that hits the lens is going to focus slightly to the left. If a different part of that wave function is focused a little bit to the right coming in at a slightly different angle it will focus a little bit off to the right.

If the light is all coming in perfectly straight, which never happens because we have this stupid atmosphere, then you end up underneath this checker board of lenses with a checker board grid of little bright spots. The reality is the bright spots form this twisted pattern that's a little bit to the left, a little bit to the right and what we do using this set of data is first you tip and tilt the mirror.

Most telescopes have two mirrors, one at the bottom of the telescope, the big primary mirror, and then a secondary mirror up towards the front end of the telescope where the light comes in.

The first thing we do is tilt or tip, or both, that mirror to try to get as much of the wave front lined up so that all the little beams of light are focusing perfectly under our chess board as possible. We tip and tilt.

The other thing we do is high speed imaging of what we assume is a round object. A star, a laser beam that's reflecting off something high up in the atmosphere, and we look at what this should be round object looks like on our detector.

It looks like a squished amoeba. That big primary mirror, the big giant mirror that defines how large your telescope is we flex to get it to un-deform the light and make it into a perfect circle.

Fraser: How do they flex it?

Pamela: These are the coolest things ever. They actually take and put a bunch of little pistons underneath the mirror, little jacks basically. They use flexible mirrors and they push on it in different points and it flexes just like a rubber skin spread over a drum that has fingers poking up underneath it.

Fraser: Okay so they have little pistons underneath the mirror that push and prod it to make it exactly conformed so that no matter where the wave front hits it looks perfect.

Pamela: The best way to think of it is the atmosphere is sort of like one carnival mirror where the starlight comes through the atmosphere and gets distorted. Then the mirror of the telescope, once it's been deformed, is sort of like the inverse carnival mirror. If you imagine something reflecting off of two carnival mirrors, it gets distorted by the first and un-distorted by the second.

The only problem is that as fast as we do this, the atmosphere is changing faster. We'll get most of the air out but not all of it. The extra little bits that we're putting in change rapidly. There are actually certain things that we can't do with adaptive optics because it only works over a very tiny region of the sky and it's not perfect.

Fraser: Okay, I'll bite. What are the things that are difficult for the adaptive optics to be able to image?

Pamela: The first thing we really can't do is look at giant gorgeous galaxies, nebula, and big things on the sky. With adaptive optics we can only correct at most a few tens of arc seconds of sky.

Take ten hairs out of your head, hold them out at arms length and that's the width of a region that we can comfortably correct. Maybe 30 arc seconds if we are having a really good day with a really good telescope.

Anything bigger than that you are starting to get a new set of deformities from the atmosphere. You can only correct one pocket of destroyed light at a time.

We can't take an image of the Andromeda Galaxy with adaptive optics. We can't take an image of even something tiny like the Owl Nebula with adaptive optics. They are just too big to correct all of them. The other thing that we struggle with is really highly accurate photometry, the type of stuff that is needed to look for planets transiting other stars.

The problem is to do the most accurate photometry, you take all the stars in your image and you look at the shape of them. In a perfect world, all of your stars form these gorgeous little perfect circles with a peak in the center distribution of light.

A Gaussian, a lorenzean the exact statistical shape that you fit to it depends on your system. There are always errors. There's tracking, just little things that cause them to be slightly smudge shaped instead.

All of the stars will have the exact same shape on your image and it might vary slightly from the corner to the center. But it's easy to map out. With adaptive optics everything has a slightly different shape.

For the high accuracy photometry, you take that precise shape you measure and you scale that shape up and down to match how much light is coming from a given star. You can take two stars that are overlapping and take the shape and scale it to their two blobs of light and accurately measure even the amount of light that is coming from two things that overlap on your image.

With adaptive optics those two things might not have the same shape. You have nothing to match them to so you are always going to have this inherent error of not knowing the shape of the light that's hitting your detector precisely.

You are introducing error in your measurement of the amount of light. So, extended objects are gone, accurate photometry is gone, but we have Hubble for those things. This does allow us to do point sources very accurately.

Fraser: So give me an example of the best candidate for adaptive optics?

Pamela: [Laughter] It all depends on your purpose. With adaptive optics, some of the neatest systems are actually smaller telescopes that they are doing things like imaging the space shuttle when it's on orbit. We actually are taking ground-based images of the space shuttle to make sure it's okay.

Small telescopes can do excellent jobs. They can look at things like Betelgeuse and look for star spots because Betelgeuse by itself is a small resolvable disc on the sky if you have high enough precision in your resolution. We can start to look for star spots with small telescopes.

Now with the biggest telescopes we can start to look for itty-bitty little tiny structures in distant objects and that's kind of cool. We just can't look at extended objects.

Fraser: Right.

Pamela: Binary stars. You can separate binary stars.

Fraser: What about finding planets?

Pamela: You can find planets, but you can't necessarily look for the transits of the planet with high accuracy.

Fraser: That's the photometry problem.

Pamela: That's the photometry problem. You can start to see planet next to star if the contrast is right. You lose contrast with this. But if you have a little tiny brown dwarf that's not giving off a lot of light and it has a giant Jupiter-like companion, that's the type of thing that we might eventually be able to resolve with these giant telescopes.

Fraser: I've done stories on adaptive optics in the past and one of the things that always seems to be there is this laser beam shooting up from the observatory. What's going on there?

Pamela: The problem is you have to have a really bright point source to use to calibrate how you're tipping and tilting the one mirror and how you're flexing the other mirror. Ideally you want to have a nice bright star near your field of view, but the sky doesn't have this nice evenly distributed grid of bright stars.

In the areas of the sky where there is no bright star to focus your adaptive optics on, to calibrate your adaptive optics on, we create a star.

Generally this is done with a laser beam and sometimes it's actually done in such a way that we're exciting sodium atoms in the upper most layers of the atmosphere into giving off light. That's just kind of cool that we can go out and make things glow in the upper parts of our atmosphere.

Unfortunately, this causes to live most of the time out in the infrared. Adaptive optics works best in the infrared and these laser beams work best for exciting fake stars in the infrared. It's a way to get at doing this type of science in areas of the sky without bright stars.

Fraser: What are the limits of the technology right now? How much better does adaptive optics make a telescope?

Pamela: At its best and over very small areas of the sky, we can from the ground get higher resolutions than the Hubble Space telescope. We can get fractions of an arc second (.6, .3, sometimes even less than that).

It's over small areas and typically in the infrared, but you can do this to separate out small binary stars, you can do this to start looking at small features, and that's kind of cool. What limits us is how fast we can flex things, how fast we can tilt and tip things, and what region of the sky we can quickly and accurately resolve the difficulties with.

This is where we start going, if we tilt and tip this part of the mirror, what if we tip it until multiple components of that one mirror so that we are compensating for a larger section of the sky. What if we use more than one bright object to compensate? What of instead of one bright star, we create four fake stars with laser beams and use those four fake stars that are all around our object on the sky to correct?

We're looking at new ways to speed up the technology, to speed up the pistons, to make mirrors that are more flexible. Currently it's not like you can flex the entire mirror using 10,000 pistons. They're just not quite that flexible. They might be someday and we're going to get there, we're just not there yet. In the end, space telescopes have their advantages.

Fraser: How many observatories out there are equipped with the adaptive optics systems right now?

Pamela: That's hard to count because you can actually get basic tilt/tip adaptive optics for amateur telescopes. You can get, from Santa Barbara Instrument Groups, home adaptive optics and it's kind of cool.

Fraser: I figured you'd need some huge observatory with custom pistons [Laughter] working on your telescope, but no.

Pamela: No this is just at the most basic level where all we're doing is taking out the big scale issues with the image by tilting and tipping things. There's a myriad of bigger telescopes. We have systems on the Lick, on the Keck telescopes, on the very large telescopes down in Chile.

There's Starfire in New Mexico. There are telescopes all over the world that are using this technology and they are getting fabulous images with it.

Fraser: Would you say it a standard issue now to every major observatory?

Pamela: It's becoming a standard anywhere that can afford it and anywhere where they are working in the infrared. There are certain exceptions. For instance the Hobby Eberly telescope, which is one of the largest telescopes in the world, is a multi-mirror system. They are not quite set up to do adaptive optics because they're a completely different type of technology.

Their focus is on spectroscopy and for spectroscopy you just want to get all of your light down the slit. They are looking at a different set of issues. When you're trying to get at pretty little tiny features this is where you want to go.

Fraser: As always, it sounds like the reality is a lot more complicated. You read into all the press releases and all the stories because they make a very simple comparison and say adaptive optics makes this telescope as powerful or as sensitive as the Hubble Space telescope.

There are things that Hubble can do, like gathering great big images of thousands of galaxies all at the same time and showing them in amazing detail that an adaptive optics system just isn't going to work for you. It almost sounds like with the adaptive optics there are certain jobs that Hubble was being used for in the past that now it doesn't have to work on those so much anymore because they can be done really well from ground now.

Hubble can be freed up to do more of the stuff that it's really best at. It's funny to hear all of the trade offs and where the advantages and disadvantages are because I think in the past, my understanding was that adaptive optics was as good as a space-based telescope and that's that.

Pamela: If you look at just the number of publications, people are still publishing more papers using the Hubble Space telescope than they are publishing using adaptive optics. It's slowly changing.

The number of papers of science results based on adaptive optics required results has more than doubled in the past ten years. Adaptive optics has basically gone mainstream on the big telescopes.

It's still a new science. It was only when I was in graduate school in the late 90's that people are starting to talk about adaptive optics and naming the big telescopes that were getting adapted to adaptive optics.

The first big telescope that was built from day one with adaptive optics in mind was the Wind Telescope on Kit Peak. That was a telescope that only started to function in the late 90's. This is a new science, a new field and it's a new technology. As always, things are changing daily and they're changing quickly. For now, Hubble still does things better even though it's small.

Fraser: As I always want to know, what does the future hold for this technology? When is this going to get really awesome? [Laughter]

Pamela: That's like asking how fast will the next new processor going to be for a laptop. It could just be a small improvement or it could be something we can't even imagine.

You can imagine, maybe, a day when we're dealing with membrane like mirrors that are extremely reflective and we're able to actuate them a thousand times a second because they're so flexible that they're easy with the smallest of little bumpy sensors to bump up and down. We're not there yet.

We still have to worry about if you make a mirror too flexible gravity takes over and gravity distorts your mirror when you start looking at things that aren't straight overhead.

It's going to all be a matter of revolutionizing yet again how we make telescope mirrors and it's in the new technologies in making highly flexible, highly reflective surfaces and figuring out how to not let them sag under gravity that the next breakthroughs are going to come.

Fraser: I can't wait.

Pamela: The brave new future of material science in this case.

Fraser: So get working on it. [Laughter]

This transcript is not an exact match to the audio file. It has been edited for clarity.
Transcription and editing by Cindy Leonard.