AirSpace Season 4, Episode 4: Supermassive Black Hole

Nick:

Carl Sagan almost said "big floating blue eyeball in space", but “pale blue dot” was much more popular with test audiences.

Intro them up then under

Emily:

Welcome to AirSpace from the Smithsonian's National Air and Space Museum. I'm Emily.

Matt:

I'm Matt.

Nick:

And I'm Nick. Over the last few years, there have been some huge breakthroughs in the study of black holes. We now know there is a black hole at the center of our galaxy and have an idea of what it might look like.

Matt:

A lot of space exploration is done in a way that allows scientists to view and actually see the phenomena they're studying. But black holes are a phenomenon that by definition are very difficult to see because nothing can escape them, not even light.

Emily:

So how do you see the unseeable? We're talking to two scientists who did just that, one that helped prove that there was a black hole at the center of our galaxy, and one who led the team that imaged a black hole back in 2019. That's today on AirSpace.

Theme up and out

Emily:

For a space scientist, I don't know a lot about black holes because they're not made out of rocks. But what I think is really interesting about black holes is that kind of up until recently, they've in some ways been really theoretical. They were theorized maybe a hundred years ago, but it's only until recently that solid physical data has started coming down from really special kinds of observations that people have been making with telescopes.

Matt:

Yeah. I think for a lot of the history of black holes, their existence has been both theorized and then also inferred by very indirect information. But now, I think the big revolution we're talking about today is that we're finally getting the closest thing to visible proof that could exist for a black hole.

Emily:

Right. So while it's kind of a hundred year old theory, it hasn't been until 2019 that we got the first image of a black hole. As Matt said, we weren't waiting around for a hundred years. There was a lot of other pieces of information, kind of puzzle pieces telling us that we were going to eventually find and observe this supermassive black hole. But none of it was the direct observation that you would want to make to prove it, right? And inference and theory, those are all good pieces of the puzzle, but you can't see the complete picture until you have that last puzzle piece.

Nick:

To get us started. We should probably define what a black hole is or what we think it is. So what's a black hole?

Emily:

I mean, they're really hard to define. There's a lot of things we know about them. There's a lot more that we don't know about them. So we should leave it up to the experts to maybe offer us some definitions.

Dr. Andrea Ghez:

Well, a black hole is a region of space where the pull of gravity is so intense that nothing can escape it, not even light.

Emily:

That first black hole definition comes from astronomer, Dr. Andrea Ghez who shared the Nobel prize in 2020 in physics for her work proving the existence of a black hole at the center of our galaxy called Sagittarius A*. She also teaches at the University of California, Los Angeles.

Nick:

Black holes are so complicated that we asked two scientists to describe them for us, Dr. Shep Doeleman puts it this way.

Dr. Sheperd Doeleman:

It is nature's invisibility cloak. It is where gravity is so intense that even light can't escape from that object. So we have to observe it through its effect on other things, on matter, on light. We can only see it indirectly. And in that sense, it's almost divine. I mean, you can't really look at it. You can only see it by its diaphanous presence, if you will.

Nick:

Dr. Doeleman headed to the Event Horizon Telescope team that imaged the black hole M87.

Emily:

So we'll get into the specifics of what Shep and Andrea study, but first it's important to note that there are two types of black holes.

Matt:

Yes, there's there's those that are formed when very large stars die and supermassive black holes, whose formation is still pretty much a mystery.

Nick:

Today, we're talking about supermassive black holes, two specific supermassive black holes, as a matter of fact. The one that Dr. Ghez studies is at the center of our Milky Way galaxy. It's called Sagittarius A*. And the one that Dr. Doeleman's team published an image of is M87, which is at the center of a neighboring galaxy also called M87. So far these two supermassive black holes are the only ones that scientists have been able to study directly.

Emily:

Yeah. And I think what's really interesting here, as we sort of talked about how do you see the unseeable. And Matt, you were talking about how a lot of the information we have about black holes comes from information that we've kind of inferred from other tangible data, but we've never really been able to see them in the traditional sense of the word see. But both Dr. Ghez and Dr. Doeleman use the gravitational pull on objects by black holes to study them. So how do we study these black holes? We talked about inferring information, but Dr. Ghez and Dr. Doeleman, they made really direct observations, which is what's new and exciting and why we wanted to talk about black holes today. So how does Dr. Ghez make her observations?

Dr. Andrea Ghez:

We're trying to find stars whose orbits we can trace that are very, very, very close to the center of the galaxy. And by measuring the orbital period and the scale of the orbit, we can show that there's 4 million times the mass of the sun that's confined to a scale that corresponds to the scale of our solar system.

Matt:

Well, if you think about gravity as, like, a set of relationships out there in a galaxy, then what you can look at is how different objects of large and smaller masses interact with each other, right? So if you have a supermassive black hole that is exerting a lot of gravity in relationship to other things that it's nearby, then you can sort of watch how stars that are near that black hole move and interact with that incredible mass.

Emily:

Right, so Dr. Ghez uses a variety of telescopes, but to make her observations of black holes, the ones that we're talking about today, she and her team used the 10 meter Keck Observatory telescope in Mauna Kea to study the stars around Sagittarius A*, the black hole at the center of our galaxy.

Emily:

And maybe one way to kind of describe this is if you were an alien looking at our earth, but for whatever reason, you couldn't see the earth, you would see our moon still. And you would see the moon kind of going in this circular orbit. And if you just imagine that they couldn't see the earth, they'd see the moon going around something. And they would know hypothetically about gravity because they're aliens and they traveled close enough to observe us. So they would be able to see that the moon was moving around something. And so they would know that there was something there, and they could even say something about how big the thing was. So they would actually get pretty close to being able to estimate how big our earth was based on how the moon was moving. And that's a really clunky analogy, but in the same way, Dr. Ghez was looking at stars going around a black hole. And even though they couldn't see the black hole, they could actually see how the stars were moving around it, which is how they can say something about what the stars are moving around.

Matt:

Right. It's like watching a dance, but you can only see one of the partners that's dancing, right.

Emily:

Yeah.

Matt:

It's kind of like that.

Emily:

I think your analogy might be better, Matt.

Matt:

I think it works together. I think it works together because your aliens, they could see that there's a nip norp, which is their word for planet, because they see the moon moving and they can infer because of weldertrop, which is what they call gravity affecting that moon and its orbit around a larger body.

Emily:

laughs Did you just make those words up?

Matt:

Yes. It's actually a transliteration of a much more complicated alien language.

Emily:

That you also made up?

Matt:

Yeah.

Emily:

Oh, Okay.

Matt:

Or I can make up if given enough time.

Dr. Andrea Ghez:

So really when we talk about finding a supermassive black hole, the key is to show that there's mass inside a volume or radius that corresponds to what's known as the Schwarzschild radius. And the reason that's important is that the Schwarzschild radius, or the event horizon, is the last point at which light can escape. Once you get to the Schwarzschild radius to show that there's mass inside that radius. At that radius, at that scale, gravity overcomes all other forms of force that can oppose the force of gravity. And the object collapsed to become the infinitesimally small object known as the black hole. So in a sense, the proof of a black hole is to show that there's some mass confined to within its Schwarzschild radius. And the Schwarzschild radius is a very simple relationship to the mass. It just scales linearly. So if you double the mass of the black hole, you double this size. So that the key to this experiment is to show that there is some amount of mass inside it's Schwarzschild radius.

Emily:

Okay, so black holes are massive.

Nick:

Black holes are massive with huge and just incomprehensible amounts of material that are compressed so tightly. And they become so dense that the gravitational pull inside of the relatively small area just distorts absolutely everything. Light can't escape, time breaks down, physics is soup and the English language fails us. Your metaphors all fly about in different directions and it's hard to, hard to tell anything for certain.

Matt:

Yeah. And part of the reason for that is, right, because gravity is this result of space-time. It's an acceleration in space time. And, I mean, that doesn't make any sense to me other than I learned it in a physics course once. But the idea essentially is that gravity isn't just this thing on its own. It's actually this thing related to distortions in space and time that result from mass and acceleration and all kinds of other things that do become kind of soup in your brain, if you're not a trained physicist.

Matt:

So that's not the only way to look at a black hole. Shep Doeleman was the head of the Event Horizon Telescope team, and their group used a network of radio telescopes positioned all around the world to create a virtual earth sized radio telescope pointed at the black hole at the center of our neighboring galaxy Virgo A or Messier 87, or M87 if you're on really friendly terms. We're going to call it M87 because that's the shortest most efficient way to refer to it.

Emily:

Well, and we're friends.

Matt:

Yeah, we're good friends.

Dr. Sheperd Doeleman:

And the exciting thing about M87 is that it weighs six and a half billion times what our sun does. So imagine that, a black hole that weighs six and a half billion times what the heaviest object in our solar system weighs. And the event horizon of that object is as large as our entire solar system. So our entire solar system would fit inside that black hole. And it is large enough so that the Event Horizon Telescope, this Earth spanning dish, can just make it out. So we can resolve the ring of light that is caused by light bending around the edge of this event horizon.

Emily:

Dr. Doeleman's team, that was making observations of black holes, M87, using the Event Horizon Telescope, which was actually a bunch of telescopes, right? It was so much data acquired on four nights of observing. They actually had to put the data on physical hard drives. It was too big to use some kind of cloud. They then had to put the hard drives on airplanes and fly them to four separate teams to use really specific computer algorithms to actually interpret the data and create this iconic picture of the M87 black hole. It was five petabytes of data. And if you don't know what that is, it's because it's a lot of data.

Matt:

And when we're talking about this network of radio telescopes producing data from which an image was then assembled, when we're talking about radio telescopes, we're not even talking about the types of telescopes that produce visible images, right, at least not immediately. They are basically big radio dishes that are pointed out to space and collect non-visible information.

Nick:

This information about the radio waves around M87 was coming in from eight ground-based telescopes all around the world. So when the earth rotated and one telescope couldn't receive the radio wave signals from the black hole, another one would have a straight shot. And this isn't a new technique. Other researchers have used arrays of telescopes to make a big virtual telescope bigger than any single source could be, for years now. Particularly the VLA or very large array telescope, which spans a large field in New Mexico that you may remember seeing in the movie Contact when Jodie Foster is sitting and listening, and you've got that acres and acres and acres of satellite dishes behind her, that's the very large array. And the Event Horizon Telescope is kind of the same premise. It's a bunch of individual telescopes that work together as one big one. This just happens to be by far the biggest telescope ever made. It's roughly the size of the earth itself, combining telescopes from all over the globe. And the bigger the telescope, the more detailed the picture.

Emily:

These are waves that on the electromagnetic spectrum, like light. Or it's the really, really, really tiny waves on one end. The radio waves are the really, really, really big meter sized waves on the other end, in some cases. So we're talking about waves that maybe you would recognize more from your AM/FM car radio. Does anybody listen to the car radio anymore?

Matt:

Of course.

Emily:

I don't know. I'm just saying I though people maybe, like, you know, streamed music on their phones. But Matt, you make a really good point. None of the observations we're talking about are the kind of thing that you could look through a radio telescope, like through a lens and actually see something on the other side. This is a totally different kind of information that's being collected.

Nick:

Right. And it's a ton of data that once they interpret it, the EHT team hopes will prove Einstein's 100 plus year old theory and show them a black hole.

Dr. Sheperd Doeleman:

The most important thing about this, is that Einstein's theory predicts what we should see. Einstein says, "When you look at a black hole, all the light from the hot, glowing gas around it should be lensed to give you a ring. And the dimensions of that ring encode everything we want to know about the black hole, it's mass, potentially even its spin." And when we trained all of the telescopes in the Event Horizon Telescope onto M87 and we imaged it, we found in a startling moment exactly what Einstein and scientists a hundred years ago had predicted. And that was a moment which left us all speechless.

Matt:

One of the things that people predicted using Einstein's theories was that black holes would be a consequence of this, that there would be spots in the universe where mass was so great that they would, in fact, exert so much pull on their surroundings, that they would pull in everything, including light. Einstein didn't like that theory, but now we know that in fact it is true. We've seen these black holes now and we've seen the consequences of them.

Dr. Andrea Ghez:

WhenI think about why should we study supermassive black holes, I think of this in two different ways. One is from a fundamental physics, or rather gravitational physics, like understanding gravity. But the astrophysical questions is the second reason. What role do supermassive black holes play in the formation and evolution of galaxies? And that's a separate question.

Emily:

Physicists and mathematicians, frankly scientists, they love to talk about the sort of theoretical case where like something-something equals zero or like something-something equals infinity. But you can never think of a practical moment in which those things are going to be true. And so I think that's kind of why this sort of fun fact that Einstein didn't actually believe that black holes could exist in nature, even though his theory sort of suggested it, there's all these moments when you're studying science where theoretically, this could be zero or this could be infinity or whatever the case may be. And everybody's like, "I mean, that probably isn't right, or that probably doesn't exist or can't exist in nature even though theoretically it can exist."

Dr. Andrea Ghez:

Supermassive black holes, we still don't have the physics to describe them. So while we can predict their existence, we actually can't physically describe the black hole itself. And the way we end up thinking about this black hole simplistically is that there's mass confined to zero volume, which means density, which is just mass divided by volume goes to infinity. And in physics, anytime you have a quantity going to infinity, it's known as a singularity or rather it's like a big, giant red arrow that says you don't have your description of the physical world right here. So I mean, it's so simple and yet so important because it tells us that while our knowledge of gravity has become more sophisticated, we went from Newton's version to Einstein. It's telling us that, in fact, there's probably something bigger or more comprehensive understanding of gravity than what Einstein has provided us. Whatever's next in the same way that

Einstein's theory encompasses Newton, there's something more comprehensive than what Einstein provided us.

Emily:

It's taken us a hundred years to get to this point to make direct observations of black holes, which I think is really going to lead to kind of an explosion in our understanding because no longer are we doing this, "We think it’s there. And so we think it's doing this stuff to all the other stuff around it." Now that there's been these direct observations of black holes, I think it's going to expand our understanding of black holes exponentially in the next 20 years.

Matt:

Yeah, and when you add the direct observations of black holes to discoveries like the direct observation of gravitational waves, it's really exciting that researchers are getting such proof of these phenomena that really help us understand our universe on a deeper level.

Musical transition

Emily:

Things like black holes that are century long mysteries in a lot of ways require a lot of innovation in order to make the kinds of direct observations of these, until recently, invisible things. And I think a lot of that innovation and these really huge data sets that are required to make these discoveries require an enormous number of human hours to dig into this information. And it requires really enormous efforts. And I think Dr. Doeleman does a really great job of explaining how much opportunity this creates for young researchers to not only create innovative ways to make discoveries, but also really opens doors to a lot of people because there's so much work that needs to be done in order to make these discoveries.

Dr. Sheperd Doeleman:

It's often rare for a grand scientific adventure like this to so incorporate the energy and the creativity of young researchers, but here the EHT was almost defined by it. I mean, yes, we had pioneers. And yes, we had experts, but it was a cadre of extremely capable, brilliant young researchers that propelled some of the new imaging algorithms that worked on the instrumentation. And without that energy and without the opportunities they had to take leadership positions in the project, I don't think we'd be where we are today.

Matt:

And it also kind of, in some ways, passes that Baton to another generation of scientists, right? I mean, one of the things that I love about astronomy is it's really one of the oldest sciences that we, we know of, right. And it's just sort of data that's been handed down from generation to generation with new interpretations and new instruments, new findings, revolutions in thinking and framing how everything fits together. But really, like, science is powerful because it's this thing that gets practiced generation after generation with new tools and new people.

Emily:

I think black holes are kind of the gateway for a lot of folks who get excited about space science. I know for me, astronomy was the thing that kind of, like, got me to planetary science. Astronomy was kind of my gateway science, if you will. And things that were really mysterious and felt like they were really hard to understand, like black holes, are kind of what got me here. And I feel like they're one of those things that make people really interested in space stuff.

Dr. Andrea Ghez:

I often think of astronomy and astrophysics as the gateway science, because so many kids are so excited about space. I mean, from a very early age, kids can look up and see the Moon. I mean, the fascination of really, really little kids with the Moon is immense. And to just be able to build on that excitement, to engage people with science, I think is so, so important.

Matt:

Well, Emily, you said that black holes are sort of one of the fascinating objects in space that draw people to it. I remember when I was a kid watching the 1979 Disney film The Black Hole, which was the first time I'd ever heard of black holes. And of course, black holes in science fiction are never accurately portrayed. And in that particular movie, you had a mad scientist type who was preparing to take his zombie crew on a trip through a black hole because he thought he was going to find some other world on the other side.

Matt:

And I just remember being terrified of that movie, but I also, over the years, have found that movie really fascinating in the way that they tried to make the black hole visible through practical effects. This was one of the last movies that Disney made that used practical as opposed to digital effects. And they actually built a fiberglass, like a clear fiberglass funnel and filled it with different colors of paint and let it sort of funnel through like a little paint tornado and filmed that as their black hole. And it's beautiful, but it looks nothing, of course, like a black hole does.

Nick:

And Matt, as a counterpoint to the Disney film, which you said was made back in the 1970s, 1980s?

Matt:

‘79.

Nick:

‘79.

Matt:

‘79.

Nick:

We didn't know very much about black holes. Nobody had ever observed the environment of a black hole. And you said that movies always get it wrong. And I mean, that's obviously, a 1979 Disney family adventure about a black hole. We're not expecting a lot of rigor, but then the fun thing about black holes is that the more accurately you try to portray them, the more extreme and utterly unspeakably bizarre they become. If you remember the black hole at the center of the story in Interstellar has all kinds of really bizarre story consequences. You land on a planet, you spend a few minutes there and you come back up to orbit and a decade or more has passed. That's actually a lot more faithful to what we know about how the physics around a black hole environment would operate.

Matt:

Right. You'd imagine that time would work very differently in a environment with that much mass, right, where the space-time is literally being bent.

Emily:

Well. And I remember when Interstellar came out and the special effects were pretty incredible. And the depiction of all the sort of weird space stuff that we only just tenuously understand, right, like black holes. All the weird space stuff was so visually interesting and exciting. And the story in Interstellar was so interesting and exciting. I remember less about reading in the news about how good the story was at Interstellar. It was how accurately did they get the science right, as far as we know it. And I remember being really surprised to learn that Interstellar did a pretty good job for the most part at understanding what it would be like in space around black holes. And I think that kind of goes back to some of the stuff that you were talking about, nick. I think it did a pretty good job, but I think it maybe even made it weirder.

Nick:

Yeah. And I think that was the spectacular joy and triumph of Interstellar, is the weirder it got, the more real you knew that it was up to a point. You know, they couldn't really help themselves. And spoiler, it is unlikely or rather we have no evidence that if you get too close to a black hole, you will be sucked into a tesseract that takes you back to your family's house. That's not likely the way that it works, but again, we have no evidence one way or the other at this moment.

Emily:

But you don't know. You don't know. I think what I find so exciting about stuff like black holes is that not only are they the kind of thing that suck people in the space sciences...

Nick:

That was good. I'm glad you went there.

Emily:

But I also think that even if it's something that maybe your brain can't quite handle, I always struggle with these things. When we start stretching space-time continuums, like, I kind of shut down. But at the same time, I think, thinking about how big things are in space and how fast they move and how dense they are and how old they are. And thinking about all these really big kinds of concepts is really, really fun. And I think it's where science fiction really shines. Like, it doesn't have to be right. It's just the fact that in a lot of cases, we don't know. I mean, maybe.

Matt:

Yeah, it's fun to sort of speculate and run with the conceits that science fiction presents, right. But none of really expect science fiction to be a hundred percent accurate, but engaging and on some level that it will feel true or feel right, even if it's not accurate.

Emily:

Well, just things that are that big, things that are that dense, things that have so much influence, but are unobservable up until recently do a really good job of opening up space for fiction writers to kind of build really interesting worlds and plots around these things that feel un-understandable.

End theme up and under

Emily:

That's it for this episode of AirSpace. AirSpace is from the Smithsonian's National Air and Space Museum. You can follow us on Twitter or Instagram @airspacepod. AirSpace is produced by Katie Moyer and Jennifer Weingart, mixed by Tarek Fouda, distributed by PRX.

End theme up and out

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