Astronomy Cast Episode 213 for Monday, December 27, 2010:
Super-massive Black Holes

Fraser: Welcome to Astronomy Cast, our weekly facts-based journey through the Cosmos, where we help you understand, not only what we know, but how we know what we know. My name is Fraser Cain. I'm the publisher of *Universe Today*, and with me is Dr. Pamela Gay, a professor at Southern Illinois University at Edwardsville. Hi, Pamela. How are you doing?

Pamela: I'm doing well, Fraser. How are you doing?

Fraser: Did you get hit by the monster snowstorm?

Pamela: Oh, my God! Yeah, so campus closed mid-day Monday, was closed all day Tuesday, all day Wednesday, and today we all drug our sorry selves to campus, and most of us just drove on top of the snow because it was on top of 3 inches of ice that we knew we couldn't get up, so the snow, at least, provided traction.

Fraser: So, how much snow did you get?

Pamela: The snow wasn't bad. We got about 2 and 1/2 to 3 inches of snow. The problem is that for about two straight days, ice pellets fell from the sky. It looked like it was raining those little annoying Styrofoam beads you sometimes get in things, except they weren't the density of Styrofoam beads, and so if you can imagine shoveling Styrofoam beads the consistency of ice… yeah, you don't want to do that.

Fraser: Ball bearings…yeah, we haven't had any of that weather here. Alright, so let's move on then. So, it is now believed that there is a super-massive black hole lurking at the heart of every galaxy in the universe. These monstrous black holes can contain hundreds of millions of times the mass of our own sun with event horizons bigger than the solar system. They're the source of the most energetic particles in the universe, some of the brightest objects in the universe, and the place where the laws of physics go to get mangled. Alright Pamela, super-massive black holes… now we talked about black holes in general in like episode 4 – it was super early on – but I think we just wanted to focus on the super-massive variety this time around.

Pamela: Yeah, and these are something we've talked about a couple of times just because if you've got a galaxy, you've got a super-massive black hole, we think, except for maybe a few of the little dwarf ones – they're squirrelly.

Fraser: But, I mean, super-massive black holes are one of these discoveries that had been made relatively recently. I mean, in your professional career, a little before my reporting career this gigantic discovery was made to solve a mystery that had been around for a long time, for more than fifty years.

Pamela: Right, so through pretty much all of my undergrad, through most of my graduate school, when we talked about active galaxies, when we talked about quasars, there was no unified model. It was "quasars have a giant monster in their center that are producing vast amounts of light!" and active galactic nuclei, Seyfert galaxies – all of these were considered different objects, and they were characterized by their spectral characteristics, by their radial characteristics, and I think for a while every astronomer that gave a talk on extra-galactic astronomy had one overhead (because this was back in the pre-powerpoint days) where someone had drawn a galaxy with a giant eating mouth of a monster in the center. If you read "Oatmeal," these were like the tumble beasts that were just designed. So, you have all these "monsters" in the centers of black hole, and the daring astronomers would say "…and we think it's probably some sort of a super-massive black hole," and in the 2000s it started to coalesce into a firm picture of "yes, this is exactly what it is." We started to make definitive measurements of stellar mass black holes…being willing to say: these objects with accretion disks and jets, these are not neutron stars, not something weird, but these are black holes. And the physics that we saw locally on the small scale matched the physics that we saw on the giant galactic scales we looked out across the universe, and this allowed us to piece together a coherent model of all of this physics.

Fraser: And what's really interesting is that even just the search for the regular black holes was still coalescing. I mean, people were still…some people believed in black holes, and some people weren't sure because the laws of physics don't really predict it properly, and so the actual search for the X-ray emissions and gamma ray emissions from the accretion disks of regular black holes – all this science is still going on, and then suddenly from the whole other end of the spectrum, there's the discovery and the theories of the super-massive black holes. It's interesting to see the two lines come together at the same time.

Pamela: Well, the really great thing about astronomy is there's a lot of physics that is the exact same physics both in stellar systems and galaxy-sized systems. When we look at the accretion disks around white dwarf stars that are eating the trail off of their companions – that's the same physics as the accretion disks in neutron star systems, and stellar mass black hole systems, in quasars, in quasars in the biggest galaxies we know about. The complexities change…you start sometimes dealing with significantly higher rotation rates, you start dealing with different rates of the material falling onto the inner body. There's the point at which the density in the accretion disk gets such that the accretion disk itself starts undergoing nuclear reactions, but it's still the same physics on all of these objects, on all of these scales.

Fraser: Right, it's all the same. So then, what is a super-massive black hole? I mean, we know that a black hole is what you get after a star several times the mass of our own sun collapses under its own gravity and forms this object with such powerful gravity that nothing, not even light, can escape it. How does that compare and contrast with a super-massive black hole?

Pamela: Well, these are basically a hundred million solar mass objects (10 to the 8th solar mass objects) that sit in the centers of galaxies. Figuring out how they got there is a bit difficult, but we think we're most of the way there, and the history by which they formed and pulled matter around them has such an influence on the galaxies that they're in that the size of the sphere of stars around the stars, the bulge of stars around the center of a galaxy is determined in part by the size of that black hole: where giant elliptical galaxies will have giant super-massive black holes, whereas little tiny galaxies, with little tiny bulges…they'll have, not little tiny, but they'll definitely have smaller super-massive black holes. We see relationships between how those stars move, the dispersion of their velocities. So the physics of the stars, the physics of the mass that makes up the bulge of galaxies is dictated, in the modern universe, by these super-massive black holes in the center.

Fraser: But the formation, right, like a regular black hole, as I said, a stellar black hole, forms in this catastrophic event where a star dies, goes through supernova, and then collapses into a black hole. Is there a formation event for the super-massive versions?

Pamela: This is something we're still struggling with, and the problem is that, how do you get that much mass to collapse all at once without fragmenting into stars? If you think about all the episodes that we've done on star formation: you start out with a giant cloud of material, something nudges the giant cloud of material, and it starts to collapse, it starts to rotate, it starts to fragment, it starts to form stars… Well, what caused (in the early universe) some of those collapsing bits to, instead of fragmenting into stars, to just go “Whump! I’m a super-massive black hole?” And we know the super-massive black holes formed fast, formed early, because as we look at galaxies further and further back in time, we notice that this relationship between the size of the black holes and the size of the galactic bulges starts to break down. It starts to be that the black holes are bigger than they should be, which tells us it’s the black holes that probably came first and drew everything in around them. So we have to figure out how to compensate for well, why didn’t it fragment into stars?” So, the way that for a long time, people tried to sort this out was they said, “Well, maybe with the primordial mass it was low in metals, so it couldn’t as efficiently radiate energy (“cool” is the word we use), so maybe it was able to collapse down in different ways instead of fragmenting, but it becomes a deck of cards with an inconveniently particular set of initial parameters being required, and it’s the type of thing that you look at and think, “Yeah, that probably just can’t really actually happen.” So the idea of an individual cloud of material collapsing down into a super-massive black hole the same way an individual cloud of material might collapse into a star that forms a stellar mass black hole, seems to be pretty much ruled out by too many unlikely things have to happen all at once.

Fraser: Sorry, so if I can understand this correctly, you have this big cloud, just like we might have with a star like our sun, the gravity… some event kicks this cloud into starting to collapse. As it collapses it’s going to start to rotate, and the faster it rotates, what happens with nebulae is chunks of this material break apart because they’re rotating so quickly that the whole thing tears apart, and then these separate little balls of gas turn into their own stars…you would get that, but even on a vaster scale with a super-massive black hole, but you wouldn’t get this nice orderly all particles all collapse together all at the same time to get your black hole. Is that the problem?

Pamela: Yeah, so you take the amount of matter that you might need to form a super-massive black hole and the surrounding accretion disk, sort of like you take the amount of mass that you need to form a solar system.

Fraser: Right, or a bathtub filled with water to get down the drain, right?

Pamela: Right, and you kick it, and that cloud of material fragments into solar systems instead of collapsing into one super-massive black hole, and that's kind of annoying when you're trying to form a super-massive black hole instead of a whole bunch of stars. So we needed to find a different physics, and we had hints. So one of the things that's true about the early universe is a lot more galaxy collisions were going on than we see today. When we look out, we do see a lot of beautiful galaxy collisions: there's the Antennae galaxy and the Mice galaxy…and if you haven't seen these objects, and don't have these names embedded in your brain, they're the type of thing you look at them once and you're like "oh, I'm never going to forget this object – ever!" These fabulous destructive situations where two galaxies – not too different from our Milky Way and Andromeda (just angles usually) -- are coming together and getting distorted by the collision. These types of events do happen today, but in the past, as today's modern large galaxies were forming, we had constant collisions of smaller galaxies – one against the other. These were often systems where the two colliding systems were what are called "major mergers." This is where the difference in mass between the objects is less than a factor of three. And in these major mergers, everyone loses. If you have a large discrepancy in mass, basically the large galaxy just kindly eats the little one, but in major mergers, you end up with neat physics that can, on one hand, drive material into the center of the colliding systems (and that's the type of thing you need to feed a super-massive black hole in the center), and at the same time, can shoot angular momentum out through, basically, what look like arms in the models, and so you're able to take care of both "well, how do you get stuff to fall in rapidly?" (which is an angular momentum issue), and "where does that stuff come from in the first place?" -- all in one gap. And so we think now it’s through these major mergers that we’re able to get all the material. And the catch about this is as this material streams in, unlike when you had that collapse we were talking about earlier -- well, the whole thing is so chaotic, so turbulent, that all that chaos and turbulence prevents stars from being formed in the collapsing gas.

Fraser: So, it’s through these collisions that you get things all being mixed up and almost being forced together?

Pamela: Right. So we’re building a model of “throw two things together violently, and the violence prevents star formation at the scales needed to drive super-massive black hole” [missing audio].

Fraser: Now, is it possible that more regular-sized black holes, like stellar mass black holes, have just grown and grown and grown?

Pamela: The problem with this is one of time period. We are looking to try and form something that, well, to get a million mass super-massive black hole, you pretty much have to start off with a trillion solar masses of stuff, and the problem is, while some of the material will fall onto the black hole and grow its mass, other material gets jettisoned through jets, other material gets blasted out of the center. We talk about the growth in terms of “material falls in at a rate at or greater than what’s called the Eddington Limit which is the point at which the ability of gravity to hold something together and light trying to push it apart is just barely in balance, so as it’s lighting up, lighting up, lighting up, all that light pressure is trying to clear out the center of where the black hole is forming. This has the effect of choking off all the material that’s trying to fall in and pushing it away. So, the black holes basically do themselves in by clearing out the area around them by having a brightly-lit accretion disk.

Fraser: So once again, it’s like they’ll control their own size, so they have to get started early on. Is it possible that they were just formed in the Big Bang, and are just left over?

Pamela: No. All of our models for how we got the universe we have have such a smooth distribution of mass, that while you might have had microscopic black holes embedded in it, you didn't have the seeds necessary to build the super-massive black holes that we see today.

Fraser: That's neat. So this is really an area of research, and although, as you said, there's a bunch of models, I think the biggest thing is that you've got the stellar black holes and you have the super-massive black holes, you don't have stuff in between. You don't have these intermediate, like where are the ones with one million times the mass of the sun or with 20,000 times the mass of the sun. So, there's got to be some different process going on.

Pamela: Well, we're actually starting to find those mid-range ones. We're finding them in little tiny galaxies. So, there's actually this really neat system…it's a fairly minor dwarf galaxy: Henize 2-10. It's 30,000,000 light years away, and it's tiny. It's about 3000 light years across, compared to the 100,000 of our own galaxy, and the super-massive black hole in its core is much smaller, but it's also grabbing mass, and this is the system that's gone through some sort of collision. It has fairly significant star formation, and star formation is also part of one of the side effects you get of galaxy collisions. It has no bulge yet, so this is an intermediate example. This is a system that may look like what the majority of the systems looked like in the early universe. So since galaxies are still forming today, as we get the technology to peer into these small systems, we're going to start finding those missing, mid-range super-massive black holes.

Fraser: So, then what is the effect that a super-massive black hole has on its galaxy and its environment?

Pamela: Well, if you have a quiet super-massive black hole in the center like we do, its primary effect is just controlling the orbital velocities the stars going around in the center because you do have this huge lump of mass in the center, and stars do have to go fast to go around a huge mass. That's not the most exciting effect in the world: "Yay, they get to orbit quickly!" but in other systems where you do have an influx of dust and gas toward the center of the galaxy, the super-massive black holes can end up having giant accretion disks around them, and it's the accretion disks that are far, far more interesting than the super-massive black holes. The accretion disks can generate their own nuclear reactions and light up, they can have massive magnetic fields that drive giant jets that can be many times longer in their length than the galaxy is in diameter, and it's this accretion disk physics that is linked to jets, that's linked to quasars, that's linked to all of this physics that's actually kind of cool and violent.

Fraser: Right, I think I've mentioned that some of the most energetic particles in the universe are coming from these, right?

Pamela: Yes, so what ends up happening, is these magnetic fields, as material tries to fall into the black hole, it instead gets caught up in these magnetic fields that essentially act like rail guns firing particles, and what's amazing is that as these particles shoot away at basically relativistic velocities, they heat up the surrounding galactic media. Hanny's Voorwerp, if any of you have seen pictures, David Letterman actually made fun of it as being a frog sneeze on glass. It kind of looks like a dancing Kermit the frog. This is an object being lit up from the jet of one of these now-dormant accretion disks associated with a quasar.

Fraser: And I can remember, again, we were reporting on this maybe eight, nine years ago, where astronomers were finding particles that had too much energy, you know, like "bumblebees can't fly" [laughing]. "These particles have too much energy," Yeah, but there they are," "Yeah well, you know, that can't be." "Well, here's the deal: something's got to be causing them." "Well, no, no nothing. It's not possible." Well, here it is. Here's the reason: super-massive black holes. Well, yeah now the models make sense. Now you've got, as you say, these gigantic rail guns that perfectly happy to drive energy from the equivalence of hundreds of millions of stars into this gravitational speeding-up process, magnetic coil – it's amazing.

Pamela: And it's really cool how in some ways, these things are self-regulating because as they get so amazingly bright, they just completely clear all the other gas and dust out of the center of these galaxies, and thus in some ways limit their own future and limit their own ability to grow, but that's kind of a good thing because you don't want all the gas and dust in the system going into the black hole. You kind of want some of it forming stars. And I appreciate the self-regulating nature of these monsters.

Fraser: Right. But more than that there's a thought that these super-massive black holes are actually providing some of the essential heavier elements for life.

Pamela: Right, so you do have it's not the black holes providing them, but again…the physics of the surrounding…you have all these high-energy collisions, you have a mixing of materials, you're driving star formation, which of course produces supernovae, which produce heavy elements – all of this physics churns everything up, spews it out in all directions, and enriches -- literally enriches with gold silver platinum -- the universe that we live in.

Fraser: You think about the have you ever seen a satellite photograph of the Mississippi River flowing out into the Gulf of Mexico and you have this beautiful nutrient-rich stream of material coming out of the Mississippi, and it's kind of the same thing where you can imagine these black holes, this fire hose of denser elements being sprayed out into the host galaxy and maybe into other galaxies.

Pamela: Right, and that's the neat thing is that we do get high-energy, relativistic particles coming our way off of these systems, and what's kind of cool is in the systems where the jets are pointed almost directly at us, but not so directly at us that we can't just make out the jet pointed away from us. There's neat physics where since these jets are moving at near the speed of light, we actually see them appearing to move faster than the speed of light because of the extra time lag between how long it takes the light from the back jet to reach us and how long it takes the light from the front jet to reach us.

Fraser: Right, we've got such speeds here! I know, once again (we did an article on this a couple of years ago), that some super-massive black holes are rotating at speeds that are sort of predicted by Einstein's relativity that they can't go any faster because they've hit these relativistic velocities -- any faster and I guess they'd become more massive…that's acting as a brake – the very limits of physics are acting as a brake – relativity. So you can imagine then, the kinds of physics are going on right around the edges of these black holes.

Pamela: This is definitely one of the situations where, at least once or twice a week, I get -- either through Facebook or my email -- someone saying, "I can prove that Einstein was wrong! Look at the math my stomach produced!" And usually there's actually no math involved. It's just the logic of their stomach.

Fraser: Their gut, you mean?

Pamela: Yeah, and your gut isn't nearly as intelligent as Einstein's brain, but the thing is, we can take all of our crazy observations of the effects around super-massive black holes: the physics of the rotation of the disk, the physics of the magnetic fields that produce the jet, all of the predictions of how they're going to clear out the centers – we can take all of this physics, much of which requires using relativity either just to understand the light coming out of your telescope, or relativity to understand the physics of the rotation, or relativity to understand the physics of the jets…it's involved at every single step, and with all of these different places for relativity to be wrong, we can still match our theoretical predictions with the numbers coming out of our telescopes across radio, X-ray, ultraviolet, and optical radiation.

Fraser: Thanks, Einstein!

Pamela: He got us most of the way there.

Fraser: So, I love to sort of think about what it would actually look like to see these things in person. I think we've all seen enough pictures of a regular-mass black hole as this dark spot against the back of the star field, and it's bending the light and you can kind of see this warping of it, but I mean a super-massive black hole is a different story. If you could actually get close, and say it wasn't actually feeding, just a regular super-massive black hole, sort of like what we have at the center of the Milky Way, what would you see?

Pamela: It would actually look identical to a stellar mass black hole. If you were at the right distance for the background stars to have the same scale size. As you got closer it would, of course, take up more of your field of view, but it's fairly boring. The most exciting part would be watching how quickly the stars orbited around it because we can see stars on solar system scale orbits zipping around in, well, basically graduate student lifetimes, so these are projects that have been studied by students, in some cases.

Fraser: Right, stars that are almost acting as comets as they whip around the center of the super-massive black hole… Now, if you actually approach the black hole, if I understand correctly, the gravitational field isn't as intent, or the sheer forces aren't the same way. You wouldn't "spaghettify" the same way you that if you hit a regular black hole. You would take a lot longer to die.

Pamela: Yes, that's one of the problems. So, because these things have so much more mass, the short shield radius is at a much greater distance, and this rescaling of how far you have to be from the center means that if you are over a human body length, the difference in force experienced by your feet and your head isn't as dramatically different when you're standing at that short-shield radius, as it would be for a stellar mass black hole, where you're basically taking everything and "squooshing" it onto a much, much, much shorter scale. So you could be hanging out at the short-shield radius of a super-massive black hole being rather unhappy, but not shredded into individual particles in a long string.

Fraser: Right, you could pass through it in your space ship and not really notice, and then after a while…but you are doomed. There's no way to get back out again, but you might not feel it in the same way that you would with a stellar mass black hole.

Pamela: And one of the neat things about these things, and it's kind of really weird when you think about it – is because we don't really have any mechanism to discuss what's happening within the short-shield radius of a super-massive black hole, we often discuss the densities of super-massive black holes as the density of the volume of the short-shield radius divided by the mass. And looking at that, because volume goes up with the cube, you end up with the density of these things going down dramatically as the black holes get bigger and bigger, so that you can end up with super-massive black holes that have the density of water, or in fact, less density than water. The idea that a super-massive black hole could float, while devouring whatever it was floating on, is a little bit traumatic if you think about it, but we don't understand anything inside of the short-shield radius, so that's just one of those footnotes of "this is one of those sets of words we use that make no sense."

Fraser: It's kind of weird. This is kind of weird. Yeah, yeah, that's great. Alright, well I think that covers our super-massive black hole conversation for this week. Thanks a lot, Pamela.

Pamela: It was my pleasure, Fraser.