Astronomy Cast Episode 48:
Tidal Forces Across the Universe

Fraser Cain: Last week we talked about tidal forces within our solar system. This week we're going to expand our view and encompass the entire universe. Some of the most dramatic events originate from tidal forces caused by gravity: other worlds, galaxies, black holes and even entire clusters of galaxies are under this influence.

All right Pamela; let's give a quick recap. What are tidal forces?

Dr. Pamela Gay: Tidal forces are what you get when you take an object and you put it next to something that exerts a gravitational pull. It has its own self-gravity hopefully holding it together, and the side of it that's closest to that massive object is getting sucked toward the massive object. This can cause distortions, it can even cause destruction of things.

Fraser: So the tidal forces are the differences in gravity that matter experiences across an object.

Pamela: Yes.

Fraser: So in the example of the Earth, the water on one side of the Earth is experiencing more gravity than the water on the other side of the Earth.

Pamela: Yes.

Fraser: All right, and it's that difference that makes things go crazy.

So let's go to another solar system and let's see some things that could be experiencing tidal forces that we don't have here.

Pamela: Let's not go to any specific solar system, because there's all these things called hot Jupiters and they're all over the place. Currently we know of over 300 planets orbiting other stars. Many of these planets are bigger than Jupiter and have orbits smaller than Mercury's orbit.

So we have these giant worlds really close in to their stars and they have significant amounts of mass. As they orbit their stars, lots of weird things can happen.

First of all, they can create tides on the surface of the stars. They can actually disrupt and change the physics that controls the outer-most layers of the stars, just by yanking on the stars gravitationally.

Fraser: When you think about the way these planets are discovered, because they're yanking at their stars with such a high amount of gravity that the velocity of the star is moving back and forth, toward and away from us that it can be detected, it's got to be causing some pretty serious tidal forces.

Pamela: We have these planets zipping around their stars on orbits that are 3 days, 10 days – really, really short orbits. The stars themselves often rotate on tens of days scales – 20, 30 days. So as the planet zips around, it's moving faster than the surface of the star is moving, and this can cause the star's surface to move out toward these Jupiter-mass (or larger) hot planets.

Fraser: So would you get a bulge on the star that follows the planet, or would you get more like what we have on earth, where the water moves around or changes its height but it's fairly evenly distributed on the side that's facing toward the Moon?

Pamela: We're still trying to sort that out. Unfortunately we can't just go and take a picture of it, so a lot of what we're dealing with is computer simulations where we see all sorts of slight oddities in the behaviours of these stars. We're translating these slight oddities into the idea that there must be tides.

Gravitationally, it makes sense. If you get two masses that close, they're going to start distorting one another's shape. In the most extreme cases, you actually end up with the planet getting part of its surface ripped off and ripped toward the star.

Fraser: Now, we talked about what's happening with the star, but what's happening with the planets?

Pamela: The planets are getting forced to constantly keep the exact same face toward the star.

Fraser: So they're tidally locked.

Pamela: They're tidally locked. This means that one side of the planet might be hundreds of degrees in temperature, while the other side is not just below freezing, but it's down around the temperatures of liquid nitrogen.

So you can end up with these massive convection events going on if you have a planet with an atmosphere. This is sort of like if you go into a room where you have air conditioners that are venting at the ceiling. You have the cold air falling and the hot air rising, so you end up with circulation of the air naturally. Here, you have one side of the planet has a lot of cold, the other side of the planet has a lot of hot, and this can end up causing massive circulating winds on these planets (if they have atmospheres).

Fraser: I heard the winds can go super-sonic.

Pamela: We're still figuring it out, and they can go amazing speeds, we're thinking.

Fraser: Yeah, thousands of kilometres an hour – the strongest winds ever seen in the universe.

Pamela: This is created by tidal locking and extreme heating. If they get a little bit closer, their atmosphere starts getting pulled off.

This can also happen in binary stars. If you have two binary stars that get too close to one another, you can actually end up with them swapping mass back and forth between them.

Fraser: So the two stars would be bulged toward each other. Would the stars be inside the Roche limit of one another?

Pamela: We look at this in terms of gravity and potentials. If you take two objects and bring them close enough to one another, there's going to be this shape around them (you have to think in three dimensions, unfortunately). If you are walking along this surface, you're getting pulled the exact same amount by both objects. There's this point (the Lagrange-1 point), between the two objects where you're balanced between the two.

Now, if gravity pulls on a star such that its mass exactly fills this equi-potential surface, this surface where the gravitational pull is the same everywhere, and something hiccups, you can end up with mass flowing off that surface, and toward the other object.

There are actually binary systems out there that constantly swap mass back and forth between two stars. You can end up with two stars, in a nice, happy binary system, evolving along and if they don't have the exact same mass, one of them will bloat up as a red dwarf first.

When it bloats up, it might, as it changes in size, overflow its limits and pass the mass to the other star. Or it might successfully going on evolving, eventually shrink back down, bloat back up, go through all sorts of evolutionary stages until it becomes a white dwarf.

At this point, it's going to lose some of its atmosphere, and this is going to change how the two stars interact with one another. So in the process of becoming a white dwarf, a star basically sheds the outer parts of its atmosphere and only keeps the core.

Fraser: So this must change its mass, then.

Pamela: It changes the mass, and it changes how the two objects orbit.

Now, if that white dwarf ends up still fairly close to that other star, when that other star then expands back out in its evolution of becoming a red dwarf star, that white dwarf, that now dead object, might be able to grab that mass that's starting to overflow this Roche-lob, this equi-potential surface, and suck it over.

If it sucks enough mass over, it might actually bloat itself back out and become a normal burning star in a second generation of life. It's actually possible for a star to get re-kindled if it grabs mass in just the right way.

Fraser: That's amazing. There's a just the wrong way for it to grab mass too, isn't there?

Pamela: Exactly. So if it grabs mass the wrong way, instead what you end up with is an exploding system. This is where we get the type Ia supernovae.

So if you instead take a white dwarf star, throw mass onto it and don't trigger nice, happy nuclear reactions that cause the star to bloat back out and be a real star, you can end up, instead, with the mass piling up and not having anything to support it.

In a nice, happy, normal star, we have nuclear reactions going on that are generating light. That light pushes out the outer layers of the star, supporting the star. If you don't have that light exerting this pressure, then gravity is constantly trying to squish the star.

If you throw too much mass together, that pushing from gravity, that contracting of the mass from gravity, is eventually going to cause it to explode like a nuclear bomb. In this case, that nuclear explosion is a type Ia supernova. This only happens in binary systems where you have a white dwarf grabbing mass off of a binary companion that has overflowed its Roche lobe.

Fraser: Are there any other interesting kinds of solar systems, or any interesting situations you could have with tidal forces?

Pamela: There's always black holes.

Fraser: All right!

Pamela: (laughing) So, with a black hole you can end up with the whole filling of the Roche lob, stripping of stars, but here things get taken to the extreme (with black holes everything gets taken to the extreme).

Say some nice, friendly, lost, asteroid/planet/some object isn't politely orbiting a black hole, but is rather wandering through the black hole's solar system, and is sort of on a semi-collision course. As that object heads toward the black hole, it's going o get elongated. As it starts to fall into the black hole, it's going to get elongated to the point that you end up with an effect called spaghettification (which is perhaps one of the funnest things we've named in astronomy, most things have terribly boring names).

Fraser: Hold on a second, you've got it getting elongated because the force of gravity on the front of the object is different from the force of gravity on the back of the object?

Pamela: Exactly. If you have a piece of Silly Putty, and pull on just one edge of the Silly Putty, it's going to stretch out.

Fraser: Okay, but I'm a little confused. If I understand correctly, if you take two objects under the force of gravity, and you drop them, they're going to fall toward that object at the same speed.

Pamela: The catch is, with these two objects falling at the same speed, we're assuming they're structurally rigid, they're structurally holding themselves together. It's their centres of mass (in a human being, the belly-button) that are falling at the same speed. Now, something that is closer is going to get pulled on more, so it's going to have a greater acceleration than something that's further away.

So in theory, if I drop an object from a height of 10m while standing at the top of Mount Everest, that object is going to take a different period of time to fall 10m than an object that I drop from a submarine sitting on the bottom of a ocean trench - I don't think you can actually do this, I think the sub would probably not survive – but if I had a sub that had a 10m height that I could drop something in, that I planted at the bottom of the ocean, that object would fall faster. It all depends on how far you are from the centre.

Fraser: I see, so in the case of a black hole that makes a big difference.

Pamela: So my feet might be falling faster than my head, and my body can't structurally hold itself together. This works with people, it works with spaceships, it works with asteroids. Pretty much anything you throw at a black hole.

Fraser: You kindly chose an asteroid, but go on, use a person. Let's get spaghettified!

Pamela: (laughing) Okay, so you throw a person at a black hole. You assume they're in a fairly wussy spacesuit that will shred itself if you pull on it hard enough. As they fall into the black hole, the feet get pulled on much more strongly than the head, so they experience a greater acceleration. The body gets stretched out.

It's going to slowly render itself asunder (another one of those fun phrases that comes out of science now and then). It's basically going to get torn into multiple pieces, might break apart at the weakest point in the body (which is about the waistline) first. Legs, head… all of these things are going to slowly come apart.

Each of these parts is going to get stretched out and made more skinny in the process, sort of like as you pull on your Silly Putty, it gets skinnier as the pieces move further and further apart. Eventually you're just going to end up with this atom-wide chain of former-human being atoms falling into a black hole.

Fraser: This whole process is only going to happen in a millisecond, right? So don't worry about the horror of it.

Pamela: Yeah, you're not going to be aware of what's happening to you.

Fraser: Yeah, just ZIP! And that's it.

[laughter]

But the physicists know what really happened.

Pamela: Oh yeah, and we get to give it fun names.

Fraser: What about larger black holes, like the supermassive black holes?

Pamela: The physics is all the same, it's just matter of scaling. With the supermassive black holes, you're going to have, perhaps, entire stars falling in and getting spaghettified in the process.

Supermassive black holes, especially in the early universe, can eat things in the most dynamic of ways. Our own galaxy's supermassive black hole doesn't have anything in the process of falling in. it's already gobbled everything nearby that had an unstable orbit, so it's just sitting there.

In the early universe, galaxies had a lot more gas, a lot more dust. Things hadn't been made into stars as much yet. Everything was still knocking about, so you'd get things on bad trajectories that just happened to send them straight into the centre of black holes.

As the material goes into the black holes, it first gets shredded into an accretion disk, then as the accretion disk falls in, some of that material is going to get spit out along magnetic poles. So you have these magnetic fields getting driven by accretion disks, everything's in motion, there's lots of high-energy physics going on and you occasionally have, basically supermassive black hole burps that can just send high-energy shock waves through the entire inner parts of galaxies.

So this isn't just tidal forces in action, this is tidal forces combined with magnetic fields, combined with jets, combined with all sorts of really neat frictional forces in the accretion disks… lots of dynamic forces and lots of death and destruction.

Fraser: All right, so let's talk about how galaxies interact. I think you'd mentioned there was going to be some galactic interactions.

Pamela: Anytime you end up with any two masses interacting, you have tidal forces. Sometimes, when astronomers say, "an object," we're actually referring to families of objects: a galaxy is a family of stars, gas and dust that are all gravitationally bound together. It's possible to break these families up.

Our own galaxy is in the process of disrupting a number of different things, for instance there's this little dwarf galaxy called Carina that we're in the process of slowly shredding as it orbits in the halo of the Milky Way Galaxy. As it goes along, it's evolving from being a nice, friendly, (we think) originally completely elliptical or spheroidal collection of stars, to being this stream that marks the orbit of where Carina used to happily revolve around our Milky Way Galaxy.

Fraser: I guess it's a similar situation to Comet Shoemaker-Levy 9, where it used to be a comet, got to close to Jupiter and, I guess, overcame the Roche limit and got broken apart into a stream of objects. That's just what's happening to this Carina galaxy, right?

Pamela: Exactly. We also end up with what are called tidal tales in some of the most spectacular-looking galaxy interactions. For instance, the antennae galaxies. As these two galaxies approached each other, the leading edges got attracted much more strongly, so they reached out for one another, and ended up with these leading arms reach out to grab each other as the galaxies approach.

At the same time, you have stars on the backside of the galaxy that aren't getting pulled on as much. They're just hanging out, lagging behind. So you have these two arms streaming behind the galaxies, and you end up with these amazing leading and trailing arms as gravity elongates galaxies during these tidal interactions.

These tidal arms, these tidal tails, can end up twisting and spiralling as the two galaxies don't necessarily go for head-on collisions, but perhaps initially go past each other and gravity in these side-swipes is actually able to create these streams with really fascinating spiral shapes.

Fraser: I've seen some amazing simulations of gravitational interactions where they're simulating all the stars in two galaxies, and then have them ram into each other or pass by each other. The dynamics, the tidal tails that come out – it's almost like sprays, like if you just took a galaxy and sprayed it. It's quite amazing to see what the interactions turn out to be.

Pamela: Josh Barnes of the University of Hawaii has some really amazing to look at simulations on his website. You can go in, and see for instance, what did the Mice galaxies look like through the process of their evolution. He can basically say, "I know what this looks like today, let's figure out how it got there." He can reverse-engineer the formation of these gorgeous, self-destructing galaxies.

We can also move this forward, and since we know what the Milky Way and Andromeda galaxies look like today, we can imagine what they'll look like in the process of collision in the future. How are tidal effects going to cause our galaxies to stream out and disrupt each other? How is the gas and dust going to get moved around? What's going to trigger star formation, and what's going to kill star formation?

Fraser: What is the final result, after all these interactions settle down – what do you get?

Pamela: Eventually in every case, you end up with objects basically getting torn apart and settling into a nice, spherical shape.

The universe seems to want everything to eventually be a sphere. This may, perhaps, be Aristotle's greatest revenge. He said the most perfect shape is a sphere, and the universe seems to be attempting to comply.

So you take things, shred them apart, reform them and they generally reform into elliptical and spherical shapes.

Fraser: So eventually, galaxies will just be spheres as much as they can be, but at the same time if they're rotating they're going to flatten out.

Pamela: Exactly. Now with some of these mergers, you can actually end up with giant elliptical galaxies that don't have a collective rotation in any one particular direction. So you have stars that are al mutually orbiting the same central point, but the orbits are completely chaotic in their orientation and you can end up with truly spherical systems that have no net rotation at all.

Fraser: So can we go larger, then? To the biggest structures in the universe?

Pamela: We also have tidal effects as clusters fall into one another. We can look at how the dust from one cluster – and the gasses in particular (gases are much easier to see, we use the Chandra X Ray Observatory to look for hot gas as things collide), how does the gas and dust in clusters interact as two clusters merge? How do the galaxies get distributed as the galaxy clusters merge. It's this constant story of things getting stretched out as they pull one another together and then in the process of the collision settle back down to spherical shapes.

Fraser: I guess instead of the spray of stars, we have sprays of entire galaxies.

Pamela: We have sprays of galaxies, and we have sprays of gas and dust, and even dark matter. That's one of the coolest things. We can actually see the dark matter getting in on the gravitational interactions, thanks to some of the new work done using gravitational lensing.

Fraser: That was going to be my next question. What impact does the dark matter have on the tidal forces? I know the dark matter doesn't clump into objects in the same way that normal matter does.

Pamela: But the gravitational pull of a cluster's dark matter can cause something coming toward it to get stretched out, to get elongated. It can do the gravitational pulling that causes the tidal effects. It can also get elongated and tidally stretched out itself. It does all sorts of neat gravitational effects, and gets effected by gravity. We just don't see any of the heating and getting shredded and things like that happening with dark matter. It's just this happy to be there, non-interacting stuff.

Fraser: All right, was there anything else we missed? We covered a pretty big chunk of the universe there.

Pamela: From planets to galaxy clusters, tidal affects are just about everywhere. While saying it's being tidally-affected is about the most boring-sounding thing I can say, tidal affects are some of the neatest and most ignored bits of physics, and it's all about differential-pull on an object.

Fraser: I'll think about that next time we go to the beach.

Pamela: Exactly.

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