Astronomy Cast Episode 47:
Tidal Forces

Fraser Cain: Consider the following: we've got tides here on Earth, there's the fact that the Moon only shows one face to the Earth, we've got volcanoes on Io, and ice geysers on Enceladus, and all these phenomena originate from a common cause: the force of gravity stretching across space to tug at another world.

So Pamela, those are all connected. Explain how.

Dr. Pamela Gay: There's this thing called tidal forces. It's a name that hides a lot of really cool physics.

So here on the Earth, we have gravity from the Earth itself pulling us down. If the planet Earth was hanging out completely by its lonesome, isolated from everything else in the universe, you could walk around the entire planet and the pull of gravity on your body would be exactly the same everywhere (ignoring effects due to being on top of a mountain, in the bottom of a valley or something).

In this isolated-Earth situation, the oceans would be perfectly smooth other than waves driven by the rotation of the planet. There wouldn't be any tides: all the waves would have the same height (barring wave interference things, which is completely different physics). The waves would come up the beach the same amount (ignoring weather – there's all these things you have to ignore when talking about the planet Earth, because it moves and has weather.)

Without a moon, our planet would be a lot more boring. Now, if you bring the Moon in, as the Earth rotates, different parts of the planet are closer and farther from the Moon. The Moon exerts its own gravitational pull on the planet. So if you're on the side of the planet that's closest to the Moon, you're getting pulled toward the Moon and you're getting pulled toward the Earth.

The Earth wins in this battle, which is why we stay on the planet Earth and we don't float off into space. But this additional pull from the Moon causes us to get lifted. If you're an ocean you can get lifted several feet toward the Moon. The planet Earth itself, if you're standing on a rocky section (which is usually what we stand on) can get lifted as much as 30cm.

So the entire planet flexes toward the Moon.

Fraser: I thought it was only the oceans that were moving toward the Moon, but the actual rock of the planet is doing it too?

Pamela: The actual rock – our chairs are moving up and down, twice a day, roughly 30cm in response to the Moon.

Fraser: Wouldn't you feel that?

Pamela: It's a gradual thing. If I move you up and down over 12 hours by 30cm (that's only about a foot), you'll never notice it.

Fraser: Wow.

Pamela: So if you do anything slowly enough, no one notices.

Fraser: What are we doing to the Moon?

Pamela: The Moon is hanging out, completely locked to the Earth. Since it's not rotating relative to the Earth, it maintains the same shape all the time as it goes around.

Fraser: Is that our fault?

Pamela: That's our fault. The Moon isn't a perfect sphere, and the part of it that's a little bit denser, the part of it that's a little bit bulged, always points toward the Earth.

Once upon a time, the Moon was probably rotating, but as things rotate, if they have a part that's a little bit bigger than another part, that bigger part creates a gravitational friction. This is actually still happening with the Earth and the Moon. The Earth's rotation is getting slowed by the tidal effects of the Moon.

As our planet fluxes toward the Moon, it tries to rotate away. Our planet is rotating on about a 24 hour period. As the bulgy part rotates past the Moon, the Moon tries to grab onto that and creates what's called a torque. The Moon gravitationally pulling on the bulged part of the Earth (which it created with its gravity) causes the Earth's rotation to slow down, as the Moon tries to pull that bulge backwards toward it more and more.

Fraser: I could imagine, say you had a ball with a little magnet attached to it on one side, and then you had another magnet, and you spun the one ball (let's say they couldn't actually click together). The one with the magnet on it would spin around and then it might get to the point where the spin is so slow that the magnet actually pulls it back and then the two magnets are just facing each other, and that's it; there's no more spinning of the ball.

Pamela: That's exactly what's happening with the Earth and the Moon.

Now what's weird about this (it's not weird physically, but it's weird to think about), because the Earth is slowing down in it's rotation (and there's all sorts of conservative forces going on), as the Earth slows down, the Moon has to move further away from the Earth to conserve angular momentum. So as our planet slows in its rotation, the Moon moves further and further away.

Currently we have solar and lunar eclipses because the Moon is able to completely fit within the Earth's shadow (which is when we get a lunar eclipse), and the Moon is (most of the time) able to completely cover the Sun (causing a solar eclipse). As the Moon moves further away, it's going to get smaller in apparent size, just like when you watch a friend walk away on a sidewalk, your friend appears to get smaller and smaller in size as they move to a greater distance.

Now, as the Moon moves away, it's eventually not going to be able to block the entire face of the Sun, and we're going to stop having complete solar eclipses, and instead we're going to end up with solar donuts whenever we have annual eclipses.

Fraser: That's right, and we talked about that in our episode about where the Moon came from. It's a total fluke that the size of the Moon matches the size of the Sun in the sky perfectly. It won't be that way millions of years down the road.

Pamela: Sometimes we just get lucky. In this one case, we happen to live in just the right time to see something pretty cool happening in the sky.

Fraser: Okay, so apart from the tides, do the tidal forces actually cause an effect to our planet or to the Moon?

Pamela: Between the Earth and the Moon, there aren't that many dynamic affects, but here we're dealing with two fairly large objects that are gravitationally holding themselves together fairly effectively.

If you move out to other places in the solar system, where you have larger mass differences between the objects involved, you can actually start to get some pretty dynamic things happening.

For instance, the poor, innocent moon Io, which orbits Jupiter, is constantly getting squished and stretched by the differing gravitational pulls it experiences not just from Jupiter but the other Moons that are orbiting Jupiter as well (Europa, Callisto, Ganymede). All these different moons are playing tug-of-war with Io, and this causes it to have a molten core and dynamic volcanoes and it's a really amazing object to look at images of.

Fraser: The forces have to be much different than the fairly tame ones we've got here on Earth.

Pamela: Yes, and in this case… if Io was just by itself, happily orbiting Jupiter, it would settle into a stable orbit where it probably always had the same side facing Jupiter, and not much would be happening. Because Europa, Callisto and Ganymede are going past it on further out orbits, it can end up with times where it's getting stretched out between Jupiter and three other Moons, and its orbit is constantly changing as It's getting pulled out by the other Moons and pulled in by Jupiter. As it changes its distance from Jupiter, Jupiter also changes its shape. All of this constant stretching ends up heating the inside of the planet: it's compression heating.

Fraser: You mentioned it has volcanoes, but that's a bit of an understatement for Io.

Pamela: It has some of the largest, most dynamic volcanoes in the solar system. This is a planet that doesn't have all that many craters, because the surface is constantly getting re-coated in lava. We've actually been able to see these volcanoes erupting constantly, using both satellites and occasionally we can even catch them exploding using the Hubble Space Telescope.

The entire moon looks like some kind of mad chemist's experiment as its volcanoes are constantly emerging, erupting, resurfacing and changing the entire surface of the moon.

Fraser: So what impact is happening to the rest of Jupiter's moons? It's got to have quite a fearsome tidal effect on them as well.

Pamela: Europa is also experiencing this tidal heating of its core. Here we don't end up with anything quite as exciting, but with Europa, the constant, slight stretching and expanding of the planet is just enough to keep its inner parts liquid water. We don't know if this is strictly H_2O water, there's other chemistries involved.

The surface is frozen, but beneath this frozen surface there's liquid, and this liquid is able to come through the surface and cause constant resurfacing of this moon as well. It leads to all sorts of neat structures where you end up with spiral patterns through the ice that are marking how the planet's orbit and orientation toward Jupiter have changed over time. You end up with cracking and all sorts of really neat effects in the surface that are caused just by gravity tugging on this giant ice and liquid ball orbiting Jupiter.

Fraser: So unlike Io, which is so torn up that volcanoes are bursting out of the surface, Europa is still being maintained as fairly warm, so there's believed to be an ocean of liquid water on the surface, with a crusty shell of ice surrounding that. How thick is that shell believed to be?

Pamela: It's measured in metres. It's nothing we can't dig through with a space probe. One of the really cool things about Europa is it's possible for us to send probes to Europa, tunnel through the ice and explore the water beneath the ice. It's some place that might actually be possible to have life.

Fraser: Wherever they find water on Earth, they find life.

Pamela: And tidal stirring mixes up the chemicals, making it possible for nutrients to move around, making it possible for thermal dynamics to exist (where you have a hot area and a cold area exchanging energy) everything is there to encourage all sorts of neat chemical reactions to take place.

Fraser: Now is there anything else in the Jovian system that's interesting, or should we move further out?

Pamela: I think the next set of really neat objects are all orbiting Saturn, so let's move out one more planet in the solar system.

Around Saturn, we have this moon called Enceladus. It's generally a boring little moon, but if you watch it closely, and you watch it with a satellite that's orbiting in the Saturnian system, you'll see geysers going off. These geysers are (again), being caused by tidal heating of the planet. As the planet is getting flexed by the differences in the politic experiences from Saturn on its slightly elliptical orbit, it's getting pulled on by other things in the system - it's getting heated. This heat, and the fluid that's made fluid by the heating, has to escape so it escapes as geysers.

Fraser: So this is less extreme than what's going on, on Io, but still, this process is keeping it warm. What affect do these geysers have? I've heard they might even be helping to create the rings.

Pamela: When the geysers go off, they're shooting liquid out into the cold of space. Now the thing is, just like a snow machine, when you spray mist into the air, it freezes into ice crystals. These geysers are basically the largest snow-making machines in the solar system.

This ice then gets gravitationally trapped and it ends up forming part of the material in the rings. What's cool is the distribution of these particles actually forms a kind of double-ring. You don't end up with a perfectly flat ring, instead you end up with two rings slightly above and below one another.

Fraser: Astronomers were able to trace back these particles right back to Enceladus.

Pamela: Exactly. So we know where they come from, we know what's creating them, and we understand the physics behind them. It's just a really neat thing to get to experience because these are all discoveries that have just been made in the past year and a half. This was a discovery made back in March of 2006. Now we're starting to find geysers around other moons as well.

Who's to know how may of these things we're going to end up finding? It's an active and dynamic solar system out there, and in these cases, what we're seeing isn't created by the Sun heating things up, but by gravity heating things up. We've identified a new source of heat that can be used to cause planets and moons to be geologically active .

Fraser: If there is life, that could be almost like a completely different ecosystem from the one that's dependent on the Sun.

Pamela: This would be similar to the life that we have in our deep ocean trenches where underwater heat vents and volcanoes are creating the heat and the nutrients necessary for life to exist in the depths of the ocean where sunlight is unable to penetrate.

So we could find twins to our underwater life on these tidally-heated worlds out in the outer solar system.

Fraser: Is there anything else in the solar system – our solar system – that you thought was relevant?

Pamela: So far we've been talking about things that are nice and safely held together gravitationally but are getting heated, distorted or having their orbits changed. What we haven't talked about is how tidal effects can actually destroy things – which is kind of cool (death and destruction is always cool).

Fraser: That's what I like to hear!

[laughter]

Pamela: So, the planet Mars has these two little moons, Phobos and Demos. They're not at all like our moon, they actually resemble a couple of potatoes orbiting the planet. Now these potatoes have two very different orbits. Phobos is extremely close to the surface of Mars. It's in fact so close that the only thing holding it together right now is the chemical connections between the atoms in the moon.

The moon is so close to the planet that its self-gravity, the ability of the moon's mass to hold itself together, is actually overwhelmed by Mars' gravity. So if there weren't the atomic and molecular connections between the atoms in the moon, the moon would completely shatter and we'd end up with basically a Phobos ring around Mars.

Fraser: Is that going to happen?

Pamela: It's probably actually going to happen.

Now, there's two different ways that a system can evolve spatially. With our Earth and Moon, the Earth is rotating faster than the Moon is orbiting. As the Earth rotates it's getting slowed in its rotation by the Moon and the Moon is moving further and further away to conserve angular momentum.

In the Mars-Phobos system, Phobos is actually orbiting Mars faster than Mars is rotation. As it goes around, the gravitational drag it's experiencing is actually causing it to spiral inwards. So here we have the moon moving inwards and as it does, the gravitational tidal forces are getting stronger and stronger and stronger.

Currently, it's about 1400km inside of what's called the Roche limit. The Roche limit is the point at which an object is exactly held together by its own gravity, versus if it goes any closer then the gravity of whatever it's orbiting starts to be stronger than its self-gravity. So it's inside that limit. As it continues to migrate in, the gravitational tidal forces are going to overcome the molecular forces and pull the planet apart.

We don't know exactly when that will happen. We don't know how strong the molecular bonds are between the different rocks, gravel and constituencies that make up this asteroid. It's sort of like if you pull a stick out of your yard, some sticks are easier to break in half than others.

We know it's going to happen in the next 50 million years, because if it doesn't, Phobos is going to crash into the surface of Mars (which is interesting in its own right).

Fraser: But that will end it anyway.

[laughter]

Pamela: That will end it anyway.

So sometime within the next 50 million years, Phobos is going to get completely torn apart (gravitationally) by tidal disruption.

Fraser: Now, one planet you haven't mentioned, but I think there must be some impact, is Mercury.

Pamela: Mercury has this really neat orbit rotation dynamic going on. Mercury has an orbit that is the most elliptical in shape of all the orbits in the solar system for planets – Pluto (former planet, not a real planet) has a more elliptical orbit, but of the eight standard planets, Mercury has the most elliptical orbit.

As it goes through this orbit, it rotates one and a half times every time it goes around the Sun. this means that for every two years on Mercury, someone standing on the planet would experience three days. This weird 3:2 resonance of day length to year length is caused by the planet actually being egg-shaped.

Normally we expect that when things are tidally-locked, there's a 1:1 resonance, like with the Moon (the Moon rotates about its axis one time for every one time that it goes all the way around the planet Earth. This is why we always see the same face, but if you compare what face of the Moon is facing the Sun, you can see the Moon actually rotates all the way around its axis).

Fraser: Right, the Moon has a far side, but it doesn't have a dark side.

Pamela: Exactly.

Fraser: I guess if Mercury was to end up being tidally locked to the Sun, it would have a dark side.

Pamela: Exactly.

The reason it's not actually in a 1:1 resonance like our Moon is because the shape of its orbit is changing constantly. Mercury is this little tiny planet that's getting yanked on not just by our Sun, but by all the other planets in our solar system. As it gets yanked this way and that way, its orbit is constantly changing a little bit. It's this constant changing and all the weird dynamics with its egg-shaped planet-ness that leads it to have a 3:2 resonance instead of a 1:1 resonance (It's a lot of really complicated math, that's really neat).

This is again a fairly new discovery. It's only been in the past 100 years that we figured out Mercury isn't always showing us the same side. We thought it was tidally locked, with this 1:1 resonance.

The reason we thought this is Mercury is really hard to observe. At most it gets about 28 degrees away from the Sun. this means if the Sun has just ducked below the horizon, if you hold your fist out at arm's length, with your little finger on the horizon and place your other fist on top of your thumb and walk up three fists from the horizon, Mercury never gets more than those three fists above the horizon at sunset. That's under ideal circumstances; most of the time it's not that high in the sky. The only time it's at its best viewing, because of this weird resonance, it's also showing us the exact same side.

So whenever we looked at it under ideal circumstances, we were always seeing the same face of Mercury. It was only after we developed radar technologies and were able to shoot radar beams off Mercury, we were able to see that it actually is orbiting faster than it's rotating.

Fraser: All right. With a lot of the things we look at, we can try and predict into the future what's going to happen. Are there going to be some interesting situations in the future where there will be these tidal effects that we don't see today?

Pamela: It's hard to predict exactly what object is going to have what tidal effect, but there are certain things we know happen on a regular basis.

For instance, the comet Shoemaker-Levy 9 was torn into a bunch of different pieces through tidal disruption by the planet Jupiter. We got to see this comet get disrupted and then plunge into the surface of Jupiter. That's kind of cool.

These disruptions of objects happen on a fairly regular basis, we think. As we look around the solar system, we see all these different objects that have craters we think were formed at the exact same time – these are basically chains of craters that appear to have been formed by similarly sized objects.

Fraser: I've seen those pictures. It looks like someone took a machine gun to the Moon

Pamela: Exactly.

Fraser: And there's maybe 10 craters all in a row.

Pamela: We think what has happened is we're seeing the death march of an object that first got gravitationally shredded and then gravitationally sucked into something and destroyed in the process.

So these are objects that had a very hard life.

Fraser: Would that be an example of say, a comet or passing within that Roche limit?

Pamela: That's exactly what happened. A comet got within the Roche limit of some object and it got torn apart.

Now, there's a different Roche limit for every pair of objects. You have to look at the two masses of the objects, the distances between the objects and take all of these different things into account, and the tensile strength plays in.

If you throw an asteroid that is very loosely held together, it's basically a conglomeration of rocks that are just barely gravitationally held together, that's going to get shredded a lot more easily than an iron-based metallic asteroid that's basically a large chunk of metal.

Different objects will get torn apart in slightly different ways, but there's lots of stuff out there just waiting to get shredded. This happens to comets, it happens to asteroids. There are a few really weird-shaped asteroids that are extremely elongated, and they're just waiting to tear themselves apart.

Fraser: Well that was great. Now this is only half this conversation, because we've only covered the solar system, but in fact these events span the entire universe. Next week we'll talk about some of the tidal forces we can see acting outside of our solar system.

Pamela: Sounds like a great plan.

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