Astronomy Cast Episode 181
Rotation

Fraser: Astronomy Cast Episode 181 for Monday March 15, 2010, Rotation. 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 Edwardsville. Hi Pamela, how're you doing?
Pamela: I'm doing well. How are you doing?
Fraser: Excellent, as usual. Alright, so everything in the universe is spinning. In fact, without this rotation, life on Earth wouldn't even exist. We need the conservation of angular momentum to flatten out galaxies and solar systems, and to make planets possible. Let's find out about the physics involved in everything that spins and finally figure out the difference between centripetal and centrifugal force. Man, there is nothing that makes physics geeks madder than to misuse centrifugal and centripetal force. Honestly, I have no idea of the difference, barely care, but I know that if I'm going to be having polite conversations with physicists and I don't want to get socked in the nose I dare not make this difference. So, when I am spinning a bucket of water and the water is sitting inside the bucket, that's centri**al force? Is that right?
Pamela: So, the water staying in the bucket is centrifugal force.
Fraser: Centrifugal force.
Pamela: The bucket moving in a circular motion is because it's experiencing a centripetal force.
Fraser: Oh, I... ok... alright... so start from the beginning. Start wherever you like.
Pamela: So I have to admit when I teach class, over fear of saying the wrong thing--and everyone in my classes knows the difference because they read "XKCD"--I actually say it's the mv^2/r force.
Fraser: That really simplifies it!
Pamela: It really, really does. It says what's going on. So, you take a mass, and you want the mass to move in a circle. Well the force that mass has to experience is directly related to how fast it's going and how big a circle it's moving in. So, take a car... set it rolling down a hill. It wants to keep going in a straight line, it's the desire of every object in the universe to move in a straight line. And it's only because of forces that anything ever doesn't go in a straight line. So in order for that car rolling down the hill to go around the curve at the bottom of the hill, some force has to act toward the inside of the curve to push the car around the curve. Now with cars, it's frictional force acting on the wheels... you turn the wheel, friction prevents--hopefully, if you're not going too fast--the car from veering off the edge of the road, and instead the car stays on the curve, so here the key is the centripetal force points to the inside of the circle and is an external force acting on an object.
Fraser: So, the external force is the friction of the car's tires on the road, and it is pointing towards the... it's as if it's the string that the car is sort of being pulled around in a circle by...
Pamela: Yes.

Fraser: And it's the force... the force of that road on the tires that pushes the car in a perpendicular direction of what its motion is.
Pamela: Right.
Fraser: Ok, and that is the centripetal force.
Pamela: Yes.
Fraser: So when I'm in the car, and I'm going around the corner, and the kids are mashing up against the side window, they are experiencing a centripetal force... is that correct? NO!
Pamela: No, that's the problem.
Fraser: No, I got it wrong! Ok...
Pamela: They're experiencing a normal force.
Fraser: A normal force. They're being pushed by the window...
Pamela: Right! So the window is pushing them towards the center of the circle. They want to move in a straight line... it is their desire to move in a straight line. And the window that they're up against is preventing them from moving in that straight line, and pushing on them with a normal force, pushing them towards the center of the circle.
Fraser: Which is different from the centripetal force that's pushing on the car tires?
Pamela: Well, so... so, the thing is... the mashing them against the window which is what you talked about, them being mashed against the window... that, to them, feels like a force pushing them out of the center, but it's actually... what you want to think about is they're trying to move in a straight line, as they try to move in a straight line they slide across the seats because there's not enough friction on the seats. They end up smooshed against each other and against the door telling... whoever's against the door is telling the other one to get off of them. And the door is exerting the centripetal force on them through a normal force... pushing them towards the center of the circle. But the whole sliding out towards the outside of the car, that's not a force... that's just them trying to move in a straight line.
Fraser: Right, but it's the force that they're feeling pushing back, that's the centripetal force, right?
Pamela: Yes.
Fraser: Then what is the centrifugal force?
Pamela: So, the centrifugal force is that fictitional they're sliding out towards the outside of the car that if all you could see was the inside of the car, you taped up all the windows, you were in a Mythbusters remote-controlled full-sized vehicle, you don't know if you're moving in a straight line or in a circle. But all of a sudden you notice that your kids who are tiny and sliding around, and this should never ever happen... they should always be in child safety devices... so we're pretending we're in the 1940s... So you're in a 1940s Mythbuster vehicle with no seatbelts, and going at safe speeds... You know your children will experience no harm, and they start sliding across the back seat...
Fraser: Just use a bowling ball... let's just use a bowling ball just so you don't have to be more politically correct about this... using a bowling ball... bowling ball rolling around-- who cares what happens to it?
Pamela: Exactly. So the bowling ball all of a sudden goes from minding its own business sitting in the center of the back seat to radically rolling towards the door.
Fraser: Hey, there's a force pushing on that bowling ball... I say... ignorantly...

Pamela: Right! And so here you are in this crazy environment where you don't know if you're moving forwards or backwards or side to side, and this apparent force, that you don't know where it comes from, that's the centrifugal force... that force that makes it appear like the bowling ball has something pushing on it, pushing it towards the door.
Fraser: But it doesn't.
Pamela: No, it's just trying to go in a straight line, minding it's own business and the car around it is moving.
Fraser: So, it's the car that's doing the moving and it's the bowling ball that's still sort of moving forward as best it can until it bonks against the door and then it's experiencing a centripetal force from the door pushing against it.
Pamela: Well, technically it's a normal force pushing against it... but yeah...
Fraser: A normal force, right. But the car is experiencing the centripetal force because of its tires, because it's turning.
Pamela: Right.
Fraser: Alright.
Pamela: Mathematically, this all works out quite ugly, because normally when we're handling forces what you do is you write down all the forces you know about and hopefully they add up to zero. So the car has, if it's a perfectly flat road, has normal force from the road pushing up against the tires, gravity from the mass of the car pushing down... those two balance out... car is trying to roll forward, so you have the tires are experiencing friction and there's some force that is turning the tires and those two equal out. You have drag pushing on the car that eats up whatever is left of the force being exerted by the tires on the road. Everything adds up to zero, life is good. Then you start dealing with circular forces. And what you have, just imagining a bucket on a string, is you have... depending where you are in a spinning system... you have gravity trying to pull the bucket towards the earth, you have tension in the rope, and when you add everything together, it doesn't add up to zero... it adds up to mv^2/r. And it's that excess force left over when you add up everything... that's your centripetal force.
Fraser: Right. Ok... I think... so when you say it's a fictional force, it's not... so centrifugal is fictional... it's not really happening. It's a perception...
Pamela: It's a frame of reference... yeah, it's a frame of reference problem...
Fraser: That sounds like something that Einstein would appreciate...
Pamela: Yes... very much so.
Fraser: Ok, now let's... now that we've got that figured out... let's talk about conservation of angular momentum... because that plays into this, right?
Pamela: Yes. Well, it's one of the things that's highly related to it.
Fraser: That sets things spinning...
Pamela: It keeps things spinning. So, normally with regular linear momentum, you have an object, it's at rest, it stays at rest. You exert a force on it... it starts moving, and the amount of momentum... its mass times its velocity... keeps it moving until some other force acts on it. And that force that acts on it might be--it collides with something else, and through the collision transfers some of its momentum to another object. Another way of looking at force is to say force is just related to the change in velocity an object experiences and how long that change in velocity takes. So, if I change your velocity and I do it by pushing on you for five minutes with a gentle push. That isn't going to require me to push you very hard, but I can get you going fairly fast because I pushed you for a

long time. Now, I could rather radically shove you... I wouldn't do that, but if I chose to rather radically shove you, that's a huge force and over a very brief period of time I could get you to have the same change in velocity.
Fraser: Right.
Pamela: Now that's all in straight lines. Once you start rotating something, well, objects have that same desire to stay in rotation that they have to stay moving in a straight line. Except now you can't just look at what's the center of mass. Because when something's rotating, its center is the thing that is the least concerned about the rotation in many ways. It's those outer edges that are radically whipping around that center point that are experiencing the most trauma, you might say, from the rotation. They're experiencing the most centripetal force on them... and you can actually change how something rotates by changing where its mass is located.
Fraser: Right, but the centripetal force that those... you have an object that's rotating... its feeling is just its bond to the atoms next to it, right?
Pamela: Yes... yes and so with pizza dough... take a blob of pizza dough, throw it into the air, and the atoms are held together, but they're not held together really well. It's easy to tear apart, stretch, deform pizza dough. So, when you throw that pizza dough into the air, and set it rotating, it's going to flatten itself out because this centrifugal force, this fictional force, is going to cause those atoms to try to move into a straight line, and in their effort to try to move into a straight line, they're going to end up flattening the pizza dough out. This happens to planets, this happens to stars, and once things do get themselves rotating and they're held together, they're going to want to stay rotating. So if you try to stop the rotation, that rotation has to go into something else... some force has to be exerted or something else has to absorb the rotation and start spinning itself.
Fraser: But, I guess in the case of an object the... everything wants to move in a straight line, but it's the fact that it's connected to other things that want to move in a straight line--that want to move in different straight lines--that's where the rotation comes in. It all balances out. You end up with... you know, everyone has to agree, and you end up with... you know, fine, I can't go in a straight line, I'll have to go... and you're yanking me to the left, but that's the best I can do. Right?
Pamela: Right.
Fraser: Two ice skaters, holding hands, moving in opposite directions, grasping hands as they go past, they would both prefer to keep moving straight, but the fact that they're holding hands is gonna force them together to start rotating.
Pamela: And this is where you have to start worrying about concepts like torque... which is how far from the center of mass is a force given, and what is the angle that you exert that force. If you just take a door, if you push on a door at a right angle to that door, in the direction that it's willing to open, it will open really easily if you push on the edge furthest from the hinges. Now if you exert that exact same shove, tap, gentle push, but right next to the hinges... the door's not going to move.
Fraser: Right, it's super hard, yeah.
Pamela: So the further you are from the center when you exert that force, the more something's going to start rotating... and that's torque.
Fraser: Alright, so let's bring it home. We've talked about conservation of angular momentum and rotation, and it's the average... right? Everything has got to agree, everything has got to sort of compromise in which direction they're going to be able to

move, because they're all holding each other together. So now as it comes to astronomy, what role does this play in the kinds of structures that we see in the universe?
Pamela: So what we end up seeing is if you have a coherently rotating body that has that same ability that pizza dough has to flatten itself out... if you start all the planets, if you start all the gas and dust, everything in a solar system... and it's usually before the planets have formed that this happens, if you start all the materials that are going to form a solar system rotating in the same direction...
Fraser: Well, I mean it even starts earlier than that, right... you get this great big... just a cloud... just like an amorphous cloud of gas... can somehow turn into a rotating thing.
Pamela: In the earliest moments of the universe we're actually finding there were localized areas, bigger than individual galaxies, where objects were co-rotating. So you take giant blob of space... and tap it... and it starts rotating. Then out of this giant blob of gas and dust you can get individual galaxies then collapsing through some sort of uneven distribution of the materials. So one set gloms on gravitationally to one another, and another set gravitationally gloms on to one another, and you end up with a pair of galaxies side by side rotating like pair skaters. And this is one of the neat results that's come out of Galaxy Zoo, actually, is by looking at the direction of spiral galaxies rotating on the sky, we're able to figure out that when two spirals form together side by side, more often than not they formed spiraling in the same direction.
Fraser: Hmm. So even in a galaxy where you've got a star-forming region, you've got this great big cloud of gas and it starts to tear itself up into smaller and smaller pieces as the rotation kicks in.
Pamela: And you end up depending on what forces have hit one particular section of the cloud or another, all sorts of co-rotating things.
Fraser: Right, but what's causing that rotation? I mean it was a big cloud of gas before, why did it start to rotate? Why did the pieces inside of it rotate?
Pamela: Finding the initial cause of the entire universe... that is a little bit tricky... we haven't quite got there.
Fraser: No, no, no... sure... but, like... you know, a star-forming region...
Pamela: Right, well in terms of star-forming regions, what you end up with is it's just that there's some force that doesn't hit on the exact center. Think about just how hard it is to get any two objects moving so that when they hit, they hit exactly head-on, and exactly centered. I can't even line up tiles across the kitchen floor that end up going in straight lines. So, when an explosion goes off, when two objects collide in space, when gravity from one big object affects some small object... those pulls are rarely absolutely symmetric, they're rarely exactly hitting dead-on, dead center, in the middle of a mass, so that it's the center of mass of the object that experiences the force. The second a force hits an object off-center, then it becomes a torque, then it becomes the opening of a door, then it becomes the spinning of pizza dough, then it becomes a rotating object. So all it takes is one off-center force to start rotation.
Fraser: Right. And then the gas cloud collapses down, but then what gets the rotation happening from there?
Pamela: Well, once it starts rotating, it's gravitationally held together, so objects that want to fly off in different directions can't. So it's gravity that's playing the role of the string on the bucket or a child on a swing.
Fraser: Right. The hands... the skaters holding hands...

Pamela: Right. So you have gravity holding the object together. And once something is rotating, it stays rotating, just like once an object starts moving, it stays moving. So you end up with objects that start rotating and stay rotating, flattening out as they collapse down, in some cases because gravity will try and squish things. And the desire to keep moving in a straight line, well the straight line is something that you experience more at the equator than at the pole. So you end up with things bulging out at equators, flattening into disks, and this is something we see all across the universe. When we see big puffy spherical elliptical galaxies, it's because the stars moving in those galaxies are moving in all sorts of crazy random directions. If they rotated coherently, if they orbited in typically but not always the same direction, the same way they do in our Milky Way, then we wouldn't have giant ellipticals, we'd just have spirals.
Fraser: Hmm. So, then let's take a good look at our own solar system, right? What forces do we have at play there?
Pamela: Well, once upon a time we were a big non-rotating cloud of gas and dust happily orbiting its way around whatever the early Milky Way looked like. And one day something hit that cloud of gas and dust... we don't know what the culprit was... it could've been a supernova, it could've been some sort of a gravitational interaction... a collision that sent shock waves through the system. Whatever it was, it sent the cloud that we were in fragmenting, and our fragment was rotating.
Fraser: But shouldn't a rotating fragment just pull itself apart into little pieces? I mean if it's sitting perfectly stable as it is, shouldn't the rotating cause it to just tear apart?
Pamela: If gravity is stronger than the desire of an object to go in a straight line, then gravity will hold it together. So the way to think of it is if you take a bucket and a piece of fabric-binding thread, you can hold up a bucket with fabric thread. But if you start rotating that bucket like a lasso over your head, so it's going round and round and round, as you get it going fast enough, its desire to go in a straight line is going to cause the tension in the string to snap the string. As long as the string is there, as long as there's enough force to pull the object towards the center, you're good. And with clouds of gas and dust, it's gravity that's doing the role of the string. Now yes, if something starts rotating fast enough it will tear itself apart. But, luckily it takes a whole lot of rotating to get something going that fast, and our solar system wasn't that fast.
Fraser: So then it collapsed down, as it... like the skater pulling his arms inward, it rotated faster and faster, and then it flattened out.
Pamela: Exactly. And what we end up seeing in our own solar system is that a lot of angular momentum is tied up in the sun, but not all of it. And as we look around the solar system we even see a few odd objects that are doing their best to rotate in the wrong direction and do bad things to the sum of the angular momentum in terms of making the calculation a lot more difficult. We are missing some angular momentum that we need to figure out. But, that's just another challenge for theorists trying to figure out the solar system, and I think everyone's willing to admit that solar system formation is one of the open questions of science today.
Fraser: Now are there limits in rotation? Is there a limit, a maximum speed that something can rotate at?
Pamela: Every object has its own maximum speed. If something gets going too fast, the gravitational force isn't enough to hold it together, the chemical force isn't enough to hold

it together. You can rotate your pizza dough too fast and you end up with pizza everywhere. Or dough at least, which is even messier...
Fraser: Chunks of dough all over the place, yeah... and same would go with a planet or a moon or a sun...
Pamela: Exactly. So this is where you start looking at that internal frame of reference, the bowling ball rolling across the inside of the car. And you figure out what is the force causing the bowling ball to roll. And is that force enough that when that bowling ball hits the wall of the car, the bowling ball is going to go through the side of the car. And when you solve that problem, that tells you if the object will hold itself together or not.
Fraser: Is there a name for that?
Pamela: Well its just... that's when you start looking at tensile strengths.
Fraser: Ok, so but let's say, perhaps, that we had an object with the mass of hundreds of millions of stars, compacted down, where the gravitational force between the pieces was a lot... is there a limit?
Pamela: Well, at a certain point, you can't get going faster than the speed of light. At a certain point you have to put things together and figure out... ok, how fast are things going, and say... no, we're reaching the speed of light and the amount of energy needed to maintain this rotation can't exist, you can't get moving that fast, and you start to hit limits in terms of the energy needed to create the rotation, and the limits of just how fast things are allowed to go in this universe. So when we look especially at super-massive black holes in the centers of galaxies, there are limits on how fast they can rotate. And so far they are behaving nicely and none of them are rotating too fast.
Fraser: Well, I know that there are some galaxies rotating at the limits predicted by Einstein. So they're right at the edge of the 99.999 whatever percent of the speed of light. So is it just that it's taking more and more energy to try to speed them up?
Pamela: It takes more and more energy to speed them up, but the thing is they've been building up speed for a lot of time. And with black holes, they actually have to absorb the angular momentum of objects that are merging into them. So you take an object that is happily rotating at a great distance, happily orbiting at a great distance and gravitationally pull it in. As it gets closer and closer in, in order to conserve its angular momentum, it has to move faster and faster and faster. And so as you make things get smaller, it's like that ice skater speeding up as she draws her arms into her body. And as these objects fall all the way into the black hole, the black hole has to speed up over time to absorb all of that angular momentum.
Fraser: And you get the situation... isn't there a theorized situation where a black hole can spin so fast... like a regular-mass black hole... that it actually bulges outside of its own event horizon?
Pamela: So with naked singularities, which is I think where you're trying to go, you run into... and we haven't found one of these... you run into situations where the geometry of space... the size of the Schwarzschild radius, the way it wraps itself around the black hole, goes from being a nice perfectly spherical, don't pass this distance or you have to go faster than the speed of light to escape, to instead being this twisted surface through space and time that flattens out to the point that in theory the surface of the black hole might start to be revealed beyond the surface of the Schwarzschild limit. Now we haven't experienced this... as far as we know there aren't any naked singularities out there in

space somewhere. But it is something that's still neat to look at and think about inside computer simulations.
Fraser: Right. But you couldn't have a black hole spin so fast it would tear itself apart.
Pamela: No because gravity does hold it together.
Fraser: To that limit of the speed of light. If you could go faster than the speed of light, then no problem... but... that's amazing. Well, thanks a lot Pamela. And now I think I can successfully have this kind of cocktail conversations and not get bopped on the nose by an angry physicist, so I think that's good. Thank you very much.
Pamela: My pleasure. And just remember... straight lines--easy, curved--requires a force.
Fraser: Right. Alright, we'll talk to you later.
Pamela: Sounds good... talk to you later.