### Astronomy Cast Episode 171

## Solar System Movements & Positions

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**Fraser:** Even in ancient times astronomers realized there was something different about the planets--they move! The movement of the planets and their moons are governed by gravity, and as we all know, gravity can do some funny things. So, let's kind of go back to ancient history and sort of get an idea of what the ancient people thought... the way the universe worked.

**Pamela:** Well, originally it was all based on philosophy, looking up and imagining how the pieces fit together and, using philosophy, it was Aristotle who led the idea that all the planets orbited on perfect circles and the stars were embedded on a perfect sphere that embraced the planet Earth. And so it was all nested circles with the earth at the center moving outwards and outwards.

**Fraser:** And standing on the surface of the earth, that's the natural conclusion that you would come to. You look up into the sky and the stars seem to be moving and so it seems like the stars are moving around you, the sun is moving, the moon is moving, the planets are moving...

**Pamela:** And from one season to the next you don't see the stars move relative to one another, which is what you kind of expect if we were in a little tiny system where stars weren't that far away. Since the stars didn't seem to move, they just seemed to rotate around and around and around, it seemed natural... ok, they're just embedded on a flat... well they're embedded on the inside of a sphere that's not too big that embraces the planet earth.

**Fraser:** Right. And how well were astronomers able to use this model to do astronomy?

**Pamela:** It made some predictions, but they weren't particularly accurate. You couldn't, for instance, using simply descriptions of... well, here's the sun on a circle, here's the moon on a circle, come up with a precise day and time for when an eclipse would be visible on the surface of the earth. You couldn't accurately say this planet was going to be right next to this star at this moment in time. So we had a theory, we just didn't have a way to back it up with evidence.

**Fraser:** Right. And then along came Copernicus.

**Pamela:** Well, Copernicus was one of the first ones to move that we should instead of having the earth at the center, have the sun at the center. Now this was again in part for philosophy and religious reasons. Unfortunately, his theory, while having at least the sun in the right place, it didn't do anything to really improve our ability to predict where things are located. And sadly at about the same time we had Ptolemy's theory with his earth-centered system and his epicycles that circles on circles trying to control the planets' positions... his theory was able to make much more accurate, but not completely accurate, predictions for where things would be located.

**Fraser:** Right. So Ptolemy's got these circles within circles, Copernicus's got just circles... but Ptolemy's math actually works out better?

**Pamela:** Right. Because he was able to correct for things by simply adding in extra cycles, adding in extra corrections, moving things around until everything worked out just right. He still wasn't able to make precise predictions, but he was better than Copernicus at being able to say where things would be at a given point in time.

**Fraser:** So when did the astronomy finally get accurate?
**Pamela:** Well, we finally figured out the math thanks to Kepler. He was working about the same time as Galileo--400 years ago. He was working with a man called Tycho Brahe who was the observationalist behind the team. Kepler was very much a theorist. So, Tycho Brahe had taken books and books and books worth of observational measurements of exactly where the planets were located. Kepler poured through these patterns looking for ways to mathematically match what had been seen on the sky. He tried all sorts of things... nesting circles mathematically within invisible geometric solids in the sky, and none of it worked. After a lot of mathematical head beating, he came to the realization that it's not circles that the planets are orbiting on, but instead... the ellipse. It's a slightly flattened circle in some cases, and by just making this minor change, by saying ellipses instead of circles, he was able to very accurately, within the ability of us to make measurements 400 years ago, he was able to finally predict where things would be located in the sky and when.
**Fraser:** And I guess part of the problem is that as a planet or some object's following an elliptical path around the sun, the speed that they're orbiting changes, so as they get very close to one of the nodes of this ellipse, they're going to go very fast, while when they're at the very far point of it, away from the sun, they're going to go slower. So, any time you're looking at the speed of the planet moving and trying to use that to predict where it's going to be, you have to know the shape of that ellipse or it doesn't do you any good.
**Pamela:** And for the planets that they were able to see back then--Mercury, Venus, Mars, Jupiter, and Saturn--they were very close to circles... with the exception of Mercury. It was just that slight difference that kept doing them in, mathematically, and he was able to overcome that slight difference. Now the problem is, the differences between Kepler's predictions, which only used the sun, even though he didn't quite know that at the time, differences between Kepler's predictions and reality slowly began to crop up. It wasn't until Newton came along that we were finally able to start understanding the differences and where they came from, thanks to understanding gravity.
**Fraser:** Right, apple dropping on his head... there's gravity.
**Pamela:** Right. And it turns out that you can use the exact same mathematics to understand that apple falling that you use to understand the moon falling around the planet earth.
**Fraser:** Now, I don't want any more mail about how that's probably never really happened.
**Pamela:** But the original documents describing how Newton told that story to one of his colleagues are now posted online and we'll try to link to them. So there is original documentation about this bit of gossip...
**Fraser:** Right. He saw an apple fall, yeah... so he said... but ok, please continue...
**Pamela:** Newton came along and he realized that it's forces that are controlling the motion, that the planet Earth... it gravitationally tugs on the moon and the moon tugs back. Our mass and the moon's mass, we orbit the sun and our planet is tugging on the moon, we're tugging on Venus, all the different bodies are gravitationally tugging on one another. And some of the variances we see in planets' behavior year after year after year, they're coming up from... well, Jupiter's giving Mars a good tug here and there, and Earth is giving Mars a good tug here and there, and together we're slowly evolving its obit,

causing its orbit to change over time. In fact, all the planets' orbits are slowly changing over time.

**Fraser:** Ok, so let's then take a look at sort of the big picture here... all the planets orbit the sun...

**Pamela:** Yes.

**Fraser:** Why?

**Pamela:** The best way to imagine this is that all the planets are basically racing around the gravitational equivalent of a cyclodrome, where you have essentially a dimple in space-time. And if you have enough velocity racing around the inside of this bowl, you're just going to keep going in a circle. Now, not all of these bowls are perfect circles. The sun's gravity essentially creates a pit in space-time, and as long as the planets keep moving, they keep staying on the wall of this hole in the continuum. There's other descriptions where we mathematically start saying there's gravitons flying back and forth, and it's the gravitons that are communicating, "hey, there's gravity... you need to stay where you are." But the basic idea is the planets are trying to move in a perfectly straight line, and the gravity from the sun is going, "no... come to me." So as they try and go in a straight line, the constant yanking of the sun going "no... come to me" bends that straight line. So, they move a little bit forward, they move a little bit towards the sun... they move a little bit forward, they move a little bit toward the sun. And if any of you ever used the Logo computer language back in the '80s, this is how you draw a circle... you move forward... you turn. You move forward... you turn. And that's exactly how an orbit works.

**Fraser:** Right, and in this situation those forces are in perfect balance. If you made the sun more massive, the planets would all spiral inward and be destroyed. And if you made the sun less massive, the planets would all spiral outward into space and be lost forever. If you made the planets move any slower in their orbits, they would all spiral inward and be destroyed, and if you made the planets any faster they would all spiral outward. It's this exact, perfect balance. And that's leftover from the creation of the solar system way back when...

**Pamela:** It's not quite that deadly... if you varied something slightly, it would just move to a stable larger or smaller orbit. This is happening all the time because the sun is constantly losing mass due to its stellar wind, and at very miniscule levels the planets are slowly migrating away from the sun... and this is good! Because when the sun bloats itself up in a few billion years and leaves the main sequence, the earth will have migrated to a possibly safe distance away. But yeah, slight variations in any parameter cause the orbits to change.

**Fraser:** Alright, so let's take one planet, let's take a look at say Mercury, for example...

**Pamela:** Mercury, of course, is one of the completely...

**Fraser:** It's one of the more complicated ones, but sure... so then what way is it going around the sun... what direction...

**Pamela:** If you look down on the solar system in such a way that all the planets are moving in a clockwise direction, then this is said to be looking down on the north poles of every thing except for Venus which believes in standing on its head. So, looking down from the north at the solar system, Mercury appears to be going around and around and around in an anticlockwise direction. But its orbit is fairly elliptical. If you speak eccentricities, it has an eccentricity a little over 0.2 and this means you can actually see how flattened that circle is with your eye. On one side of its orbit it's a lot closer to the sun than on the other side of its orbit. And when it's closest to the sun, tidal forces... these are the same forces that cause us to always see the exact same side of the moon... tidal forces make it not want to rotate. So, during that period of time when it's closest to the sun, the sun pretty much stands still in the Mercurial sky. It's only as Mercury gets further and further away from the sun that it's able to orbit a little bit more freely. Luckily, it's moving really fast when it's close to the sun. It's moving really slowly when it's far away from the sun. So, the rate at which it rotates on its axis actually stays completely constant, it's just relative to where it is in its orbit, at that point when it's closest to the sun, the sun appears to completely stand still in the sky.

**Fraser:** So then if I could stand on the surface of Mercury and watch the sun, over the course of a day, or a year, what would I see?

**Pamela:** Well, you'd have to do a whole lot of waiting to see very much. A day on Mercury relative to its year is a fairly long, long thing to wait through. In fact, for every three times the planet experiences a day, it goes all the way around the sun twice. This is what's called a spin-orbit resonance. For the longest time, astronomers actually thought that Mercury was completely tidally locked. It's really hard to try to image the surface of Mercury from here, and it wasn't until the 1960s when we started imaging Mercury using radar that was sent from big radar dishes here on the planet that we realized oh... it is rotating, and realized over years... Mercury years... of watching it that it has this resonance in how long it takes to rotate and how long it takes to experience a year.

**Fraser:** And this is where I think we should distinguish between solar days and sidereal days...

**Pamela:** Right.

**Fraser:** A solar day is how long it takes the sun to return to the same position in the sky, while a sidereal day is how long would it take if you could look above the planet and not really think about the sun... how long does it take for it to turn back to the same spot. And here on earth, those are fairly similar... which we'll get to in a second, but on Mercury, they're totally different.

**Pamela:** They're totally different. And this is because we do have this strange rotation rate, where in order to get the sun geometrically in the same place in the sky, back to exactly noon straight overhead, you have to keep going and going and going around the sun, whereas well before you get the sun back in the same place, you've already gotten the stars back in the same place.

**Fraser:** Right. Now Venus... let's move on out, Venus is even weirder. I mean it's going around the sun in the same direction... all the planets in the same direction. They're all going in that counterclockwise direction, right?

**Pamela:** Right. Now the problem with Venus is when you look at... well where's its north pole? Its north pole, if you define the north pole as where your standing such that when you look at your feet everything is going around in an anticlockwise direction, its north pole is actually opposite of everything else in the solar system. In fact, when you look down, you see all the rest of the planets, happily you can see, for the most part--we have another problem when we get to Uranus--you can look down and see all their clouds going around in the same anticlockwise direction that they're orbiting around the sun. But with Venus, you look down and its clouds are going about in a clockwise direction as it orbits in that anticlockwise direction about the sun.

**Fraser:** Right. So imagine... look at the whole solar system from above, you're going to see all the planets all moving in the same direction... so Venus is obeying that rule. But yet, if you actually look at the planet itself, from the position of the stars, you would see it turning slowly backwards. And of course Venus is even more weird because a day on Venus is longer than its year... it's backwards day is longer than its year.
**Pamela:** Right. Yeah, so Venus is even weirder. First of all you have this upside-down motion, but then when you start looking at how long it takes for the sun and the stars to get back to where they started, well it's year... let's start with what it's year is. To get all the way around the sun is 224 earth days. And to an observer standing on the surface of Venus, you have the sun rising in the west and setting in the east, and from one noon to the next noon, that's going to be 116 days. So, that's most of the time that it takes you to get all the way around the sun. But because everything's going from west to east, the amount of time it takes to get the stars back in the same place that's actually going to be longer than an entire year. So, to get the stars back to where they started out at the beginning of the year takes 243 days. This is kind of weird and kind of special to Venus.
**Fraser:** Now I think we're fairly familiar and comfortable with our days here on Earth, right...
**Pamela:** I hope so...
**Fraser:** We've got the earth... well we say that a day takes 24 hours, and I think we've mentioned that that's a solar day. So it takes 24 hours for the sun to come back to the same place, while a sidereal day is shorter than that.
**Pamela:** Right, and that's to get the stars back to the exact same place they were in the sky.
**Fraser:** And that's actually the true rotational speed of the earth.
**Pamela:** Right. It's just not useful for when you're trying to make plans for the future because the stars vary a little bit too much from one point in the year to the next.
**Fraser:** Mars is similar to Earth, right... just a little over 24 hours. Jupiter has a crazy-fast rotation speed.
**Pamela:** Jupiter... it has an amazing speed of 9.9 hours to get the sun back to where it started. And then Saturn we don't know. Saturn's a bit problematic. Its atmosphere refuses to let us understand what's going on down in the center. We're trying to understand it using magnetic fields, but I'll just leave it at... we don't know.
**Fraser:** Right. We kind of approximately sorta think it's about 10 1/2 hours, but...
**Pamela:** We don't know.
**Fraser:** We don't know for sure.... because there's many ways to measure that. But I think, you know, the really interesting one is Uranus.
**Pamela:** Right. And this is the planet that apparently had a very bad life in the past. It's tilted completely on its side. And there's really only two ways to have a planet have that particular fate. One is that you just hit it with something about the size of the planet Earth, and if I were Uranus, I certainly wouldn't want to get hit with something the size of the planet Earth. And the other way is to be a victim of gravitational abuse from Saturn and Jupiter going through a weird resonance period during the early part of the solar system. We're not sure which one happened... it also could have been a combination of Uranus getting knocked about gravitationally by Saturn and Jupiter and getting hit by something smaller. We don't know. All we know is it's 97 degrees tilted over.
**Fraser:** Right. Which is essentially tilted over on its side.

**Pamela:** Right. So for all intents and purposes, its pole points at the sun when it has its winter solstice and when it has its summer solstice.
**Fraser:** Right. And this is where you sort of got to think about it. Imagine Uranus tilted over on its side, but it's not like it's rolling around the sun.
**Pamela:** No, it always keeps its pole pointed at the same set of stars.
**Fraser:** Right. So sometimes that pole has to go through the sun first to get to those stars, and other times the sun is on the opposite side of the planet, but still... Now, Pluto is not a planet anymore, but it used to have... I guess it still has a highly eccentric orbit.
**Pamela:** Right. And the thing is, though, we talk about it having a highly eccentric orbit, but its eccentricity isn't mathematically all that different from Mercury's. Mercury's eccentricity is 0.206 and Pluto's is 0.248, so those are pretty similar. The reason we notice Pluto's eccentricity is because its orbit cuts back and forth in front of Neptune. So sometimes Pluto is closer to the sun than Neptune is and sometimes Neptune is closer to the sun than Pluto is.
**Fraser:** And that difference in distance actually has a fairly interesting effect on Pluto which is that at its closest point it warms up to the point that its atmosphere pops up. Then when it's further away, its atmosphere freezes back down onto the surface.
**Pamela:** Right. So we have a planet that sometimes has an atmosphere and sometimes doesn't. This actually led Mario Livio to make a quote that I will forever love and that's "if you took Pluto and brought it in close to the sun it would turn into a comet, and that's no way for a planet to behave." So, what we're seeing is as Pluto gets closer to the sun it starts to "fuzz up" the same way a comet does as it gets closer and closer to the sun.
**Fraser:** It's exhibiting very comet-like behaviors. That's pretty funny. Ok, so now we've talked about the planets, and talked about how they're rotating... I want to talk a bit then... if we imagine the solar system as a flat... like a record... that is the plane of the ecliptic. And the planets are mostly orbiting on that, but not quite.
**Pamela:** Each of the planets' orbits is (relative to the earth's) a little bit tilted in one way or another. Exactly how much they're tilted varies. And for the most part, they aren't tilted very much. So we have for Mercury the orbital inclination--it's the most--it has a 7 degree tilt, Venus has about 3.4. All the rest are tilted less than 3 degrees. This is very slight and not the type of thing that's going to be very easy for you to get out and start measuring with your protractor.
**Fraser:** But this is why we don't see Venus pass in front of the sun...
**Pamela:** All the time...
**Fraser:** All the time... right. It's sometimes above the sun from our vantage point and sometimes it's below the sun.
**Pamela:** So the slight tilts that are out there do create a much less interesting observational universe. But what's neat is when we start looking out at the dwarf planets, at all the trans-Neptunian objects. They do have all sorts of different crazy tilts, where we see that Pluto is tilted 17 degrees and Himae is 28 degrees, so is Mak-mak, and Eros is 44 degrees tilted. We also start seeing the asteroids with tilts... where Ceres has an 11 degree tilt relative to the earth's orbit. So it's just the planets that seem to be locked in to this disk where we start looking at asteroids and comets and dwarf planets, these small-mass leftover bits in the solar system, they sort of end up on much more catawampus orbits around the sun.

**Fraser:** That is the first time you've used that word in this podcast, I think... catawampus...

**Pamela:** It's the best way to describe these objects...

**Fraser:** But still, if you were going to go look to discover new planets... this is Mike Brown's approach, the best place to look is on the plane of the ecliptic. That's where you're going to see them all. You're not going to look straight up above the solar system and see them, or down below. You're going to see them somewhere in that zone... helps you constrain your search.

**Pamela:** And every one of these objects crosses the ecliptic, so no matter what you're looking at, at some point it's going to be in the disk of the solar system.

**Fraser:** Now, what about the comets and the asteroids? I mean, the asteroids have kind of weirder... some weirder orbits and the comets can have really bizarre ones.

**Pamela:** The asteroids have a bunch of varied orbits, and for the most part they constrain themselves to being between Mars and Jupiter. But within all of these orbits we see occasional collisions... we think we just saw the remnants of one recently out in the asteroid belt. We also see asteroids that periodically decide that they're going to come in and start crossing our own Earth's orbit periodically. These are more of the Near Earth Objects. For the most part, yes... they do have more elliptical orbits but they're not ranging over the entire solar system the way comets do. Comets in many cases will start out in the Kuiper Belt, so they're starting out at a distance, in many cases, at a distance greater than Neptune's orbit, and then plunging all the way in... in some cases to plunge straight into the sun, but often to come in and dance between the orbits of Mercury and the sun or Venus or Earth and just coming right in to the inner part of the solar system and growing huge tails as they melt away in the heat.

**Fraser:** And when they're at their closest point, they're moving very quickly and then they slow back down. That's why we'll see them accelerate as they approach the sun and then slow back down as they're heading back out into deep space. They can go in orbits that last tens of thousands of years.

**Pamela:** And many of them will have, the one's that we're happy to keep observing over and over and over again, like Halley's comet, will have orbits that are measured in tens of years, but the period of time that they're in the inner solar system is a very small fraction.

**Fraser:** I guess the last thing to talk about is how the movement of the moons is governed as well by gravity.

**Pamela:** And again, we start seeing these interesting resonances, these interesting beat frequencies, when we start looking out at systems that have multiple moons. There're people that believe that the reason that Venus has such a really long day is it's in resonance with the planet Earth so that we're pretty much always seeing, when we're on closest approach, the same part of Venus. When we start getting out and looking at Jupiter's moons, we see different orbital resonances that keep its moons coming in so that they line up the same way every few orbits. We see this in particular with Io and Europa which are both being tidally heated leading to, on Europa, liquid water beneath its surface and on Io, massive amounts of volcanism.

**Fraser:** There's a resonance between those two moons, so every time Io goes around Jupiter twice for every time Europa goes around once?

**Pamela:** There's actually a really neat 1 to 2 to 4 resonance between Jupiter's moons Ganymede, Europa, and Io, leading to Ganymede goes around once for every 2 times

Europa goes around for every 4 times Io goes around. We also see a 2 to 3 resonance with Pluto and Neptune. Resonances like this happen all over the solar system. And what's great is we can see the exact same mathematics applied to Jupiter and its moons that we see with the planets. This was one of the things that really made it clear that Kepler's physics and Newton's physics were right was we had Galileo looking at Jupiter's moons at the same--relatively, in the grand scheme of human history--that Kepler was coming up with his orbital mathematic equations... Kepler's three laws. Scientists in the following decades were able to say, oh... this applies to Jupiter as well. So we can look out and we can apply the same mathematics to Jupiter, we can see it at Saturn, we can see it orbiting all of the planets. We know that these gravitational tugs tend to lead to things ending up in resonant orbits.

**Fraser:** Of course, that story is going on at even larger scales with the movements of the galaxies and the interactions of the galaxies in the whole large-scale structure of the universe. But that's another story... that we've already told, I think. Alright, well thanks a lot, Pamela.

**Pamela:** It's been my pleasure, Fraser.

**Fraser:** Talk to you again...

**Pamela:** Bye bye.