Episode 72: Moonquakes
Physicists: Briony Horgan, Meg Rosenberg

Transcribed by Denny Henke

Ben: Never be afraid. There's nothing which is known which can't be understood. And there's nothing which is understood which can't be explained. For over fifty episodes now my team and I have brought you to the very frontier of knowledge in physics and astronomy. And still our mission goes on: to present you with your birthright, an understanding of the universe. I've traveled the world seeking out a certain type of genius, masters of not only their academic disciplines but also at explaining their research in understandable ways and I've bestowed upon these women and men the title of Titanium Physicist. You're listening to the Titanium Physicist Podcast and I'm Ben Tippett, and now allez physique!

[1:47]

Ben: I've had a particular quote echoing through my mind for quite some time and it has to do with the moon. It has to do with how intimate an experience it is for two people to look at the same thing together, to read the same books side by side on a couch or to watch the ducks from a park bench or to lie down on the grass and stare up at the clouds. I mean, being a part of an audience to witness a sporting event can bring two complete strangers together as friends how much more powerful is the effect among people who actually like each other. So, when two people are separated and vast distances keep them apart they can still look up at the same moon and know that somehow they are spending time together. And the moon is actually a lovely object for us to use at the center of this fantasy. Unlike the constellations which change depending on your latitude, unlike the sun which will burn out your eyes in their sockets if you try to look at it, the appearance of the moon doesn't change depending on your location. If two people are looking at the moon on the same night, guaranteed they are seeing the same thing and heck, the moon hasn't really changed over human history either. The moon I look up at tonight is the same moon my grandparents watched, it's the same moon that oversaw the construction of the pyramids. So, it's such a sweet and romantic and common image that I was sure as I was preparing today's show that the whole sentiment would come out of a single quote. Bethany suggested that maybe it was the *American Tale* movie but I figured it was somewhere fancier. So, I google searched it and you know what I found. Nothing concrete. Taking consolation from the fact that both you and your friend are looking at the same moon is so old that I have no idea where that sentiment originated. The most interesting quote I found involved the story of Sojourner Truth, an important person from American history. Sojourner was born a slave in New York State around the late 1700's. And when she was 29 she escaped to freedom and spent the rest of her life working as an activist for the abolition of slavery and for women's rights. Sojourner was the second to youngest child in her family and her parents had had all of their other children taken away from them and sold. Her mother, in her sorrow, used to take Sojourner out to look at the stars and told her that even though they were impossibly far apart all of Sojourner's brothers and sisters were staring up at the same moon. It sounds lonely maybe bit it's a earnest and hopeful action. Even though we will never meet, our hearts are still together. I'm looking at the same moon that Albert Einstein watched when he was formulating his theory of general relativity and it's the same moon that inspired Issac Newton to write the universal theory of gravitation and it's the same moon that hung in the sky when slavery was abolished and it's the same moon as when the Universal Declaration of Human Rights was proclaimed by the United Nations General Assembly. Even though chasms of space and time separate us we can still inherit their dreams. It is a lovely, romantic notion. Too bad it's not quite true. Today on the Titanium Physicists Podcast we are talking about how the moon is slowly shrinking! Oh weird. Okay, this week's guest is an expert on examining how pleasant fictions can be the glue that holds our lives together. He's a public radio reporter and producer and he's done things on NPR Morning Edition, Marketplace and 99% Invisible.

He came to my attention with his fantastic podcast, *Imaginary Worlds* on the Panoply Network. His show is about the shoreline between the worlds of popular fiction and real people's lives. He interviews people and discusses how works like *Harry Potter* and *Star Wars* affect their lives and society in general. Welcome to the show Eric Molinsky.

5:15

Eric: Thank you! Great to be here.

Ben: Awesome Eric. For you I have assembled two amazing Titanium Physicists. Arise Meg Rosenburg.

Meg: SHhhhhhhhhirp. Hi!

Ben: Dr. Meg got her PhD from Caltech on the moon's surface. Not Caltech on the moon's surface. She was researching the moon's surface. She's currently a science communicator. Her personal website at www.megrosenburg.com has all her works and a link to it can be found off of our website. Now arise Briony Horgan.

Briony: Da da dun.

Ben: Dr. Briony did her PhD at Cornell University and she's currently an assistant professor at Purdue University where she studies the geology of the moon and Mars. Alright everybody, let's talk about the evolution of the moon.

Eric: The only thing I know about the moon in terms of physics is that the distance from the moon to the Earth is really important in terms of the tides. That is literally the only thing that I know and that is interesting to me. Like, I just think, that it's interesting that the moon is anything more than a rock in the sky so I'm curious about that.

Ben: But that's all it is. It is just a rock in the sky. But the important thing is, where did it come from?

Meg: Yeah, so, actually, I think people have been wondering that for a very long time and lots of different types of theories have sort of been proposed over time resulting in, sort of, one that we have come to generally accept as probably the right answer. But some of the crazier ones leading up to that point are still really interesting to sort of look back on. So, for example, there was once this idea that maybe the Earth, when it was first forming was spinning so fast that it actually spun out a blob of material that became the moon and that's sort of this fission idea. Or, maybe, the moon is like a captured asteroid like the Earth was just going about it's business and an asteroid came by and it was captured by the Earth's gravity and that became the moon or maybe they just formed together like, in place. Like the solar nebula is where all the planets condensed when the sun was formed and maybe all these solid particles just condensed in place and we got the Earth and we got the moon orbiting it and then, you know, we were just together forever from the beginning. But what has happened over the years is that we have sort of developed these tests for these theories. We've sort of accumulated little bits of evidence about the Earth and the moon and how they behave with each other that gives us clues as to which of those models or a different model might be the right one. So, to sort of introduce the idea that has currently taken hold, we think we condensed from this solar nebula which is like a cloud of dust and gas that was originally all gas. And as things started to cool down this cloud started to flatten out and rotate into a disk and then solid materials could eventually precipitate out of that and clump together. Then all of these little clumps of solid particles would be mutually attracted to each other either through surface tension or then later through gravity. Eventually those little clumps could form bigger clumps and then they would start to wiz around and hit each other. And so the theory that has sort of taken hold for how the moon formed today is related to that idea where we have these bigger and bigger objects and they are zooming around the solar system and at the very end of planet formation we would have had just a few of these giant planetesimals. So, not quite planets yet but in that very last round a very large body like the size of Mars would have hit the proto-Earth and that giant impact would have peeled off like this plume of material from the Earth body and that would have eventually re-condensed again and formed the moon. So, that's sort of, that's sort of where we think now, the moon came from.

Eric: Wait, wait, hold on. So there was a cloud of stuff. Is that cloud of stuff the proto-Earth or had the Earth already formed and that's the future moon?

Meg: The cloud of stuff is after the collision or before?

Eric: Before.

Meg: So, before there were any planets we think that the whole solar system formed as this condensing cloud. So it would have been, like, the Sun, would have been the hottest and densest part in the middle and basically if you have a cloud of anything, a cloud of dust and gas and it's shrinking over time if it has any sort of random bit of rotation at all then that rotation, as it shrinks, will speed up because of the conservation of angular momentum. And the action of that will sort of flatten this cloud which was maybe more like a sphere in the beginning. It will sort of flatten it over time to a disk and this disk will be spinning up as it shrinks further and further. And then out of that sort of spinning and collapsing, rotating disk we're getting sort of, solid particles are starting to accumulate together into little clumps and those are the building blocks of what eventually becomes the planets.

[10:11]

Eric: Is that disk like, the sort of what we see around Saturn? I can imagine like a gigantic Universe sized version of that kind of floating material?

Meg: Um, there are definitely similarities in the way that Saturn's rings behave and the way that we think the solar nebula would have behaved. So, the reason that they are so flat like that is very similar and also become of Saturn's massive gravity is also sort of keeping them in that midplane. But, it is a little bit like that.

Briony: Um, the cool thing is that we actually see new solar systems forming around other stars. So, we have actually observed this process with new planets forming out of these giant disks that are around these new, brand new baby stars. And so we think the same thing happened in our solar system. And it's kind of like, you can imagine, you know, you have this giant cloud of gas, it condenses to form the sun. And it's all this sort of leftover junk, it's like less that 1% that's left over after the sun formed, condenses to makes the planets. And most of that makes Jupiter because Jupiter is gigantic. Then 1% of that that's left it goes to make the terrestrial planets, you know, Earth, Venus, Mars and Mercury. So, we're kind of like the crumbs, the left-over tiny crumbs from the formation of the solar system.

Eric: Wow. The Earth at this point is actually being formed, proto-Earth without the Moon existing.

Briony: Yes. At this time in the solar system, it's total chaos, right. You have all of these bodies orbiting the sun. They're all kind of pulling on each other with their gravity. So you have this proto-Earth orbiting the Sun and you have this other kind of proto-Mars sized body orbiting the Sun too and then their orbits overlap and all of the sudden, one day, boom. You know, and they hit each other and they shear off all this material and actually this is really cool because it feeds into your first question, you know the distance between the Earth and the moon. Because initially this material that forms a disk, kind of like Saturn's rings, we were talking about around this new Earth. Um, and that, eventually condenses to form the moon but it's really close to the Earth. You know, the moon, it's like ten times closer to the Earth than it is today and since then it's been gradually moving farther and farther away from the Earth over time.

Eric: Huh. So, if you were to time travel back to that time where the moon is ten times closer to the Earth and you looked up into the sky, how huge would it be?

Briony: It would be really big. It would be like, 10 times bigger. It would be gigantic and that has huge consequences for what the tides would have been like because like the moon causes tides on the Earth and not just ocean tides but also rock tides inside of the Earth. It would have been really chaotic because the Earth was still molten, right, at that point, too. So it was a pretty crazy time in the Earth's history.

Meg: Yeah, we wouldn't have been very happy time travelers.

Briony: Yeah.

Eric: Yeah. So then, why is the moon moving away? Or why did it move away?

Meg: Well, it still is.

Eric: Oh, it still is moving away.

Meg: So it's actually those tides that Briony mentioned, especially the tide that's actually in the bulk of the Earth. So the rock does deform in addition to the oceans and it's that sort of tidal bulge, you know, the part that's closest to the moon that's facing the moon, is tugged just a little bit more strongly than the side of the Earth that is furthest away from the moon so it raises this, like, tidal bulge. And the same thing is happening on the moon. So, the Earth also raises a tidal bulge on the moon and those two sort of mass distributions pull on each other in such a way that they tend to slow each other down in their rotation. That's actually, eventually, why the moon has come to only show us the one face because its rotation has been slowed to just be synchronous with the Earth. And because they're slowing down in their rotation, again because of that conservation of angular momentum, the moon actually has to actually move out further in its orbit because that angular momentum, it's going into the moons orbit.

Eric: I don't know if I quite got that. So, first of all, what is a tidal bulge, first of all?

Briony: Yeah, so, basically the part of the Earth that is closest to the moon, is basically being pulled toward the moon. That includes the ocean as well as the rock underneath it. So it's actually deforming the Earth, it's actually making this bulge in the surface of the Earth. So, it's the same reason we get tides in the ocean, right? You get these tides every 11 hours passing through the ocean, you get a high tide every 11 hours. And so, as the Earth is rotating under the moon, and so that bulge is actually moving along the surface of the Earth over time. And it's basically that process of, you know, creating this bulge and moving it along the surface of the Earth that's gradually draining energy from the system which makes the moon move gradually away from the Earth.

Ben: If you were to look from space, above the North Pole, at the tides, let's just focus on the water tides, okay? The effect is the same for rock and water and anything can slosh, frankly. Ah, but, if you were to watch the Earth from above you'd notice that the oceans are kind of getting deformed by the tides of the moon, right? You get a little bit of the oceans poking towards the moon and on the opposite side of the Earth there is a kind of bulge of ocean pointing away from the moon .

Eric: I didn't know that, that's interesting.

[15:07]

Ben: It's not just that the water on the Earth is attracted to the moon, it's that there is a difference between the direction and magnitude of the force from the moon onto the water depending on where on the Earth you are. For the far part of the Earth the water feels slightly less force pulling it towards the moon. And if you're on either side of the

Earth, not closest to the moon, the direction that you feel a force, it's kind of sideways and the overall affect is that the oceans get kind of kneaded into maybe, a kind of football shape, ah, superimposed on the surface of the Earth. And that's why the tide is higher when you are either closer to the moon on the moon side or on the far part of the Earth. So, the height of the ocean above the surface of the Earth changes depending on where you are relative to the moon.

Eric: Sorry, but why is water specifically so affected by the moon.

Ben: It's because it's liquid. There's no rigidity to it and so water will flow in whatever direction external forces push on it in order for the overall pressure to be the same. And so the deal is if the distribution of water was perfectly spherical the forces from the moon wouldn't be the same everywhere on the surface of the water and so the water reforms itself in order for the forces to kind of equalibrate, cancel out.

Briony: And rock does the same thing but it's a lot harder to deform the rock to do that, right. And so the scales of the tides of the rock of the Earth are much, much smaller than the ocean.

Ben: So, if you were to look at this picture of the oceans from above you would notice that the bulge from the tides isn't really changing relative to the moon. The pointy part of the football is always pointing directly towards the moon. The reason we get changing tides on Earth is because the moon goes around the Earth once every 28 days but the Earth spins once a day. So, the Earth is spinning underneath that football of water and so, depending on where you are at what time, the tides at your location can be high. Like, if you're going through the pointy part of the football or it can be low if you're going through the flatter parts of the football. So, the reason the moon is moving away from the Earth is a matter of coupled rotations. The fact that the tides aren't circulating around the Earth at the same rate as the rock in the Earth means that the tides are kind of kneading the Earth as the Earth rotates under them and that kneading is a kind of dissipating force. It's taking energy away from the system so the Earth is going to slow down until it's rate of rotation matches the rate of the rotation of the moon around the Earth. But conversely, because of equal and opposite forces, as the Earth feels a force slowing it down it's rotation, the moon is going to feel a force speeding up it's orbit. And so as the orbit speeds up it moves farther away.

Eric: So wait, is the moon now set in orbit it is going to stick with or is it going to, millions of years from now, be even further away than it is now.

Ben: It's going to move further away and the Earth's speed of rotation is going to change and slow down until it's always going to be the same face of the Earth facing the moon so this kneading affect no longer occurs.

Briony: That probably won't happen during the lifetime of our solar system. Like, we'll all be destroyed by the sun before that happens, so.

Ben: It's a very slow effect.

Eric: Oh, okay. So it sounds like we're in a kind of Goldilocks zone now but how many millions or billions of years will it be before, you know, the Earth is no longer in that zone?

Briony: Pretty sure it's billions of years. Like, it's really, the Earth will be completely destroyed by the expanding, you know, future red giant sun before we get to the point where we loose the moon, basically.

Eric: Okay. Those descriptions of the end of the Earth are always so depressing but yeah.

Ben: See, the overall idea here is that there are different models for the formation of the moon. And how can we tell which one is right? That's the question, right? Did the moon hatch out of an egg or did it form at the same time as the Earth or is it a passing meteor that got captured in Earth's orbit? Which one of these things is it. And Meg was saying that it was the planet smashing together hypothesis, that there was once a planetoids the size of Mars that ran into the Earth. And that's a pretty dramatic picture. And so the question is, why do we think that's the right one over all of the other pictures. And the deal is that every different scenario that Meg went though at the start corresponds to the moon being made out of slightly different material. So, if the moon was made at the same time as the Earth, in orbit around the Earth, then it would have the same constituent material as the Earth does. The Earth has a core made of iron and then there's the mantle and then the crust. And that distribution of different types of material would match in the moon. Alternatively, if it was the passing meteor that formed further out in the solar system its constitute matter would be slightly different. So, the idea here is that this collision scenario predicts that the moon would pretty much be made only out of stuff that was on the outside of the proto-Earth, the crust and the mantle of the proto-Earth. And that's essentially what we see in the moon when we do measurements of what the moon is made out of.

[20:08]

Briony: Well, it sort of works the other direction actually. Really, what it is, when we look at the moon we have several lines of evidence that first, the kind of general stuff that the moon is made of is pretty similar to the Earth. The general kinds of minerals and their compositions, they are mostly pretty similar to the Earth. They're not identical but they are similar. That tells us that it kind of formed in the same part of the solar nebula. But, when we look in detail at the structure of the moon has way, way less iron in it. You know, the Earth has this big iron core, it's, almost half of the Earth is made of this big iron core. When we look at the moon, we know from multiple lines of observation, it doesn't have that. It has a really small iron core, it's mostly made of rock. It's mostly made of, the mantle, you know, the hot part of the planet, it's rock and then cool crust on top of that. Whereas the Earth, again, it has this big iron core and so that tells us that something was different about the way they formed. And so, the way to connect that back to the formation models is that basically when you have this planet smashing event it didn't just smash the planets together. What actually, what the model suggests happened, was that you had this Mars sized body that came in and kind of sheared off the top of the proto-Earth, right. Just sheared it off and tore it off and then the iron of the two bodies kind of came together because it was heavy and what was left floating outside this proto-Earth was basically just rock, just crust and mantle and that's what formed the moon in this disk outside of the proto-Earth.

Eric: How many billions of years ago was this?

Meg: This was 4.5 billion years or so and we know that because we have samples of the moon that formed really shortly after this. As well as the, you know, the very early samples of the Earth. You know, tiny minerals of zircon that have survived for 4.4 billion years since that time.

Eric: Hmmm. I mean, when we went to the moon and I assume brought back moon rocks, what did we learn that we couldn't learn by observing it from Earth?

Meg: So, one thing that comes to mind, to me, is that, I study impact craters quite a bit. And those are the giant circular shapes that are all over the moon and we have some here on Earth but not as many. And they actually are our biggest way of keeping track of time in the solar system by counting all of the impact craters and keeping track of their sizes we can sort of put together a timeline, like, which one came before which other one and generally sort of, which areas on the moon are older than which other areas because they had more time to accumulate impact craters. But that's really a relative timescale. You can only tell things like this section of the moon is older than that section of the moon but you can't say what the number is that goes with it. So, one thing that is really important for just chronology in general and trying to piece together when everything happened, not just in the moon but everywhere in the solar system is bringing back these moon rocks gave us a chance to actually use geochemistry to date them to a much higher precision, actually, you know, look at the minerals that are in the moon rocks and use radioactive decay to actually get like, a much more concrete age on those. And that sort of anchors The whole relative timeline that we put together with the impact craters.

Eric: That makes sense.

Briony: Yeah, so the other really cool thing that we learn from the moon rock. You know, we can't necessarily tell exactly what the mineralogy of the surface is from orbit. That's my job, that's what I do, on Mars, the moon, I'll tell you there's a lot of stuff we can't see. So one of the things we learned from bringing back moon rocks is that the crust of the moon is actually really weird, right? So, when you look at the moon and you look at the man on the moon, the face of the moon that you can see from Earth, you see there's kind of the black spots, right, in the middle that's surrounded by all this white other stuff. And so it turns out, those black spots are all big lava flows, flood basalts. Huge, huge lava flows, you know, filling all these ancient impact craters. But the white stuff around it is actually the really ancient crust of the moon and is made of this mineral called plagioclase feldspar which is this really white mineral in a lot of rocks here on Earth. But it turns out, this is really crazy. The way that that crust formed was that you had this molten blob of a moon and because it was molten, as it started crystallizing minerals out the lighter minerals floated to the top and the heavier minerals sank to the bottom. And this feldspar mineral is really light, right. It doesn't have much iron in it and you can tell that because it's white. And so the crust of the moon is basically this float crust that formed out of this ancient, what we call a magma ocean, that was originally present on the moon. And so when we got samples back from the moon with Apollo we were able to see that. We were able to see that yeah, man, these are weird rocks that we really don't see on Earth because on Earth, we don't think, or at least there's no sign that it's preserved, of this ancient magma ocean. That's something that's really pretty unique to the moon.

Eric: I didn't know that. I just assumed that when the moon formed it was cold dead rocks just formed into a big clump. You're saying that there was like, lava in an ocean of magma.

Briony: It was literally a ball of magma floating in space.

Eric: Huh.

Briony: Yeah.

Eric: Wow. The thing I love about physics too, is how visual it is. You know, like, I'm imagining like the best special effects in my mind of this stuff.

[25:03]

Ben: So, the topic at hand is how do we know what the moon is made of on the inside. I mean, at the outset, we said, hey, how do we know what kind of material it's made out of and you could go well, they sent the Apollo astronauts and they brought back moon rocks which we can then analyze and find the answers to some of these questions, right? The Apollo astronauts didn't just bring stuff home. They also left stuff there.

Briony: They did. So, the Apollo astronauts brought back all these great moon rocks and they tell us all about how the crust of the moon formed. But they don't necessarily tell us a whole lot about the inside of the moon. They don't tell us about the interior structure of the moon and all that. So, the thing that they did that was really amazing was they left behind this whole suite of instruments which included a bunch of seismometers. So, seismometers are instruments we use on Earth to measure Earthquakes and the goal here was actually to measure moonquakes which are, you know, tectonic events, Earthquakes but on the moon. And so the seismometers, they were just one part of this Apollo instrument package. You know, every Apollo mission that made it to the surface, so, everything but Apollo 13, left behind this instrument package and it included the seismometers as well as one of the best pieces of evidence that the Apollo missions did in fact happen and weren't just in a movie studio somewhere in the backlots of Hollywood. Ah, this is the Apollo retro-reflectors which are basically these giant mirrors they left behind on the surface of the moon that you can shine lasers at from the Earth and by measuring the time it takes for the lasers to go from the Earth to the moon and back you can figure out how far away the moon is. Ah, you know, you can actually do this with a powerful enough laser here on Earth and so it's one of the best pieces of evidence that we actually did put people on the moon.

Eric: I'll use that the next time I talk to a conspiracy theorist.

Briony: Yeah.

Eric: So, hold on a second, but moonquakes. I thought that Earthquakes were because of plate tectonics and continent shifting around.

Briony: Right. Yeah, so, that's how we get Earthquakes here on Earth. Right, so, on the Earth we have the crust, it's broken up into these plates that are moving and kind of running up onto each other and under each other. The whole crust is really active. And that's actually really rare in the solar system. There's no other planet that has that. The rest of them are what we would call one plate planet, right. They're not broken up in the same way. So, that's actually interesting right, so what does that tell us about the history of the Earth. Does that have implications for, you know, why we have life on Earth, right? Because it's an important way to recycle the crust and keep it fresh and keep our atmosphere fresh. But the moon doesn't have that. The moon doesn't have plate tectonics, there's no giant plates rubbing together to make earthquakes but it does have a lot of other stuff that's going on, right? Like we talked about tides. The Apollo seismometers that we left behind, so they were active for about five years until the late 70s. And so, in that time they recorded, you know, more than 10,000 moonquakes and the most common ones they saw occurred really deep inside of the moon. They were really weak. So, like, on Earth we would call it a magnitude 2 on the Richter scale which is strong enough that people who are really sensitive could feel it but most people probably wouldn't so they were pretty weak Earthquakes. And those we think were probably due to tides, right. So, the tides from the Earth, you know, were deforming the moon, from the moon moving away from the Earth, you know, getting closer and farther in its orbit compared to the Earth but those are pretty weak. We also see Earthquakes, or, moonquakes, sorry, due to thermal stresses, day/night change in temperature that the moon goes through, ah, sort of changing how big the rocks are, basically shrinking and growing, causing moonquakes. We also see moonquakes due to impacts so, you know, stuff is still raining down out of the solar system onto the planets and so that causes moonquakes too. But the really interesting ones that we saw, there were only a handful of these. There were about five or six big moonquakes that we saw, these were a magnitude 5 or greater. So, a magnitude 5, here on Earth, an earthquake that can cause a decent amount of damage in places not ready for it. You know, most people will feel it, it will wake them up, it's a pretty decent sized quake. So, on the moon we saw a couple of these over a period of five years. So, they're not uncommon but they're not happening all the time. And these are the ones we think are from really shallow places in the crust. So, from right in the crust, near the surface, and we think these are actually due to the moon shrinking. Which brings us back to our big picture. Hey, the moon is changing and we know because of these seismometers the Apollo missions left behind on the moon.

Eric: And so, was that a big surprise, when we discovered the moon was shrinking?

Briony: Yeah, it is. I think that we did not expect to see these bigger, um, moonquakes. But, it turns out, there are surface features that we see that are due to this which is really cool, confirming this kind of general idea.

Meg: So, I think that the Earthquakes that you mentioned were kind of a mystery for a long time. So that five years of Apollo seismometer data, that's from, like, 1969 to 1970 something. And we've been using that five years of data since then to sort of piece together what we know about these moonquakes. And it wasn't until just the last several years when you have this new satellite orbiting the moon, it's called the Lunar Reconnaissance Orbiter, and it has really amazing cameras and there's been a few other international missions to the moon as well. And with all of this new data we've actually started to see these features on the surface which are called Lobate Scarps.

[30:06]

And they are called that because, like, lobes, so like if you look down at the surface they kind of look sinuous. They kind of make big sweeping curves and they have, like, sort of a lip to them. But if you were to sort of look straight on, like you were going to climb over this scarp then it would have like this really steep but rounded face and as you got up over the peak of it it would sort of level out and be shallow.

Briony: It's kind of a cliff, a cliff that's jutting out over the surface of the moon.

Meg: So, they found many of these cliffs all over the surface of the moon that we hadn't really seen before because the resolution of the cameras has just gotten much better. And the implication of those, we've actually seen them other places in the solar system so we think we have an idea of what they're doing. In particular we think we see very similar features on the planet Mercury which is also shrinking. Actually, Mercury is like a really good example of a shrinking planet because it has a really giant iron core compared to it's total size. And that iron core, as it continues to cool, the inside of it, just like our planet, the inner core that will continue to freeze, to go from the liquid phase to the solid phase and when it does that it compresses. It goes to a more dense state of matter. As it does that you're sort of shrinking the entire radius of the planet. And as you do that the surface has to sort of accommodate that. So, what happens is you get this shrinking interior as the whole planet is cooling and this rigid crust on top is just like trying to also shrink but has to sort of wrinkle itself in order to do that. So, on Mercury we see these really gigantic lobate scarps and we can use those to estimate how much Mercury has been shrinking since it started forming these scarps. And the really neat thing about the moon is that now that we have started to see these there as well we can start to link that to those mysterious moonquakes that were these large magnitude would really cause a problem, potentially, for future structures that we want to place on the moon. So, we can sort of start to connect the dots and start to, actually see the mechanisms that are behind what we have been observing since the 1970s.

Eric: That makes total sense. I understood that completely. It's funny because I was thinking about, like, I wonder how much that would affect moon colonies and I thought oh, I'm thinking too science fiction again. But, I guess that really is something people are keeping in mind.

Meg: Yeah, I think, um, I don't know exactly where the guidelines are but I believe that is something that any future longterm structures are going to have to take into account because that's not a small earthquake, at that point. A 5.5 magnitude or so.

Briony: Yeah, imagine San Francisco. You have to earthquake proof all of your buildings. On the moon it's an even bigger problem because it's not just that you have to make things structurally sound, it's that you have to make sure that you're not going to, you know, burst your air bubble basically. You're not going to leak all your atmosphere into space because you shifted something underneath. So, it's a really big deal and it's something they have to consider.

Eric: I assume that the moon and Mercury are shrinking in such tiny amounts that this will also not eventually affect the tides, you know, or anything else. It's just sort of an interesting fact, right.

Briony: Well, you know, on the moon it's a pretty small amount so it won't really have a big effect but on Mercury, it's actually, it's shrunk a huge amount. It's like tens of kilometers of radius that it has shrunk over the course of the planet's history so right now, on human scales it's slow but for a planet, I mean, that's a lot.

Eric: Huh. So, within the scale of human life that's really not much but if we were to fast forward to the future, you would imagine, would Mercury change dramatically because of that.

Briony: Ah, probably not. It would just get bigger and bigger ridges over time.

Meg: So, these are basically, they are like thrust faults. So, like, it's, on the Earth we have plates that sort of, you know, shove up against each other and then one will go under the other one and that's also a kind of thrust fault. It's not the same reason that it's happening on Mercury and the moon but it's sort of the same kind of surface feature. So, what will happen is the section of the crust that's being pushed under the other section will just continue to go further so you can kind of create a thicker crust eventually by sort of just continuing to shrink and double up everything.

Eric: So, the lunar recon orbiter, this satellite, was this the purpose of why it was put up, to discover this or was it a more general let's see what else we can find out about the moon and this was a surprise.

Briony: So the Lunar Reconnaissance Orbiter, LRO, was actually partly funded by the human exploration side of NASA and part of it's mission was to scout future sites for human exploration of the moon so that's where, actually, part of the money came from. The rest of it was just a general scientific exploration of the moon. I mean it has a ton of different, really cool instruments on board but the amazing thing that it has done is it has mapped the entire moon at 2 meter or better resolution, So that means, that we can see, you know, boulders and all kinds of interesting things like that. We can actually see the footprints of the Apollo astronauts as they traveled away from their ships in these images.

[35:06]

Eric: Wow! That's really cool.

Briony: Yeah, and the thing that you see when you look at these images, it really hits home at how little of the moon we have explored. We can actually print out one of these big, we call them LROC, Lunar Reconnaissance Orbiter Camera images and lay it down on a table and see this little tiny postage stamp in the corner that has all the little human footprints in it. And you know, people say, oh, we've been to the moon, been there, done that but man, when you see it in the scale of the actual geology of the moon, we really haven't seen anything yet.

Eric: So, if we were to land more people on the moon what would we want to find out by having more boots on the ground, so to speak? That we can't so far just from analyzing it from afar?

Briony: Well, so, you know, the Apollo missions, ultimately, did so much to revolutionize our understanding of the moon. Just bringing back so many samples and leaving behind all of these different science experiments like the seismometers, right, that we talked about. So, we could do a lot more of that. We could visit other places with one of the constraints on the Apollo missions, that they had to go to the near side of the moon, right. They had to go to the part of the moon that we could see from Earth so that they could communicate real easily. And they wanted to go to the really flat parts because you know, if you're an engineer at NASA you want to land in the safest place possible, so, they send you to the parking lots. You know, we had the same problem landing on Mars too, that engineers always want to go to parking lots and the scientists always want to go to the mountain ranges. So, on the moon we had same problem so most of the places we landed on the moon were actually pretty similar. They were all these giant lava plains that you can see in kind of the dark parts in the side of the moon that we see. But we've only sent a few missions that went to other kinds of terrains, basically. Like the highlands, this ancient, you know, this light, kind of white crust. We only had one mission that really sampled those kinds of materials. There's a whole other part of the moon too that NASA is trying to get a robotic space craft to visit. It's actually the biggest impact crater on the moon. It's called the South Pole-Aitken Basin. You can't really see it from the near side so we really didn't know it was there until recently. But it's this huge impact crater that goes from the South Pole and curves up the far side of the moon and it's like a quarter of the size of the moon. It's huge. This was a gigantic impact and it was actually so big it dug into the mantle of the moon. It actually dug through the crust into the mantle and excavated the mantle. And so, if we could send either humans or robots there to get samples back that would tell us so much about the history of the moon and how the moon formed. So, that's one of the things that NASA is really excited about. Um, and that's a mission that's being proposed right now and it's called the moonrise mission. That's the robotic version of that sample return. So, the one thing we never talked about and that was why the moonquakes are important for understanding the inside of the moon.

Eric: Okay.

Briony: So we didn't really talk about it but the reason that having the seismometers and detecting these moonquakes was so important is because you know the way we interrogate the interior of the Earth is by using Earthquakes right. You have an Earthquake that happens on one side of the Earth and then you detect it on the other side of the Earth with a bunch of different seismometers and by understanding how long it took for that Earthquake to, the signal to get there, you can actually figure out what the wave passed through on its way through the Earth to get to you. And so we can do things like say, oh, we didn't detect Earthquakes on this whole part of the Earth, it's because they are being blocked by the liquid part of the iron core on the inside and we can use that to figure out how big the core of the Earth is for example. So, on the moon we've done a very similar thing. We have this network of seismometers for five years and measured all these quakes. And by measuring where these came from and how long it took to propagate through the moon we can do things like figure out how big the core of the moon is. And so we figured out that the moon has a core but it is really, really small. It's much, much smaller than the Earth's which is one of the things that tells us that the moon must have formed in a different way than the Earth did.

Eric: Hmmm. I think that makes sense.

Ben: Alright, you know how like, if you have a wine glass you can tap it and tell, based on how it rings, whether or not it's full of wine?

Eric: Yeah, sure.

Ben: The more drink that's in the wine glass the different tone you'll get out of it?

Eric: Yeah, yeah, that makes sense. Okay.

Ben: So, essentially, what's going on there is the vibrations that come from you tapping it travel through the system differently depending on what's inside of it. So, on Earth, one of the reasons we know we've got a big liquid, molten core is essentially just paying really close attention to how seismometers in, say, Iowa, detect Earthquakes that happen in Japan. So, an Earthquake happens in Japan, that doesn't just make the Earth in Japan rattle, those vibrations travel through the Earth, they bounce around through the insides of the Earth and then we can measure them in Iowa. So, from that we can reconstruct a model of what's going on inside the Earth and that's how we know on the inside of the Earth there is a big molten core among other things. So, we do the same thing with the seismometers on the moon. You can backtrack how vibrations travel through the moon and from there you can tell that the moon doesn't have a molten core and also that the core of the moon is relatively small. Smaller than it would be if the moon had been made out of the same stuff that the Earth was originally. Because the Earth has lots of iron in it. So, if the moon formed independently of the Earth it would have the same percentage of iron in it, you would expect a fairly big core And that's not what we see so we know that the moon is mostly made of the rocky stuff that comes from the edges of the planet Earth. So, it must have formed by being sheared off of the Earth, the proto-Earth.

[40:15]

Eric: Okay. Okay, I think I've got that. So, the moon is shrinking and this is something that we know because of the moonquake. Is there any other ways in which this is going to affect us on Earth in the future?

Meg: So, this is completely indirect, but I think we were mentioning before about whether this was a surprise that the moon was shrinking. In a certain sense I think that the answer is no. Because the way that planets have formed in our solar system's past and the way that we expect them to evolve after that always involves a certain amount of cooling over time because when you first put together all of the material to form a planet you are sort of bringing in all of these pieces from very far away and they are all sinking into a mutual gravitational well when they come together. And there's a whole bunch of energy that is released when they all do that. So you have all of this gravitational energy that is released when you get all of this material gathered together into a planet and that's basically the energy that is being emitted over time as that planet evolves. It's sort of being, it starts at a very hot temperature and then it inevitably cools down over time and each planet has a different way of doing that based on how much energy it started with and how big it is. So, the moon is relatively small compared to the Earth and has cooled much faster so we can see, you know, the effects of it cooling. But the Earth is cooling as well and Mercury is cooling and all the other planets in the solar system are going through a similar sort of planetary evolution in that sense. So, in a very indirect way I would say that it doesn't affect a lot about our life on Earth to know that the moon is shrinking but it is a reminder of all of the planets in the solar system go through as sort of the general lifetime of a planet in general.

Eric: Hmmm. At what point in millions or billions of years from now will the cooling of the Earth have any affect on life on Earth.

Briony: Well, the Earth is actually mostly cooling through plate tectonics and again, plate tectonics is one of the things that makes Earth so fundamentally different from the rest of the planets. And so it has a much bigger impact on what we experience then, you know, the fact that the Earth is gradually cooling. But again, it's the cooling of the Earth that's driving plate tectonics, right. It's the heat inside of the Earth that's causing, you know, the plates to move, the plates to subduct and all of these things. So, that's really the impact of the fact that the Earth started out hot for us whereas with the moon the fact that it started out hot is now leading to the fact that it is shrinking.

Eric: Right. So, if it's cooling does that mean fewer or more earthquakes in the future?

Meg: So, just like Briony mentioned, we're in this plate tectonic state of things because the Earth is so hot that the most efficient way to get rid of its heat, to sort of bring the heat up from the core and get it out through the surface is this convection of the mantle which is driving plate tectonics and we don't know of any other planets that have that exact state going on which is sort of a mystery because there are other planets like Venus that are just as big as the Earth and would have had the same initial heat budget and would be more efficient for them to also cool in this way. But they never broke up into plates in a way that allows them to actually recycle their crust and get rid of heat as quickly as the Earth is getting rid of heat. So, I would say that eventually, it's that cooling rate that is driving plate tectonics. So, as the Earth cools we may fall into a regime where we don't need plate tectonics to most efficiently get rid of the remaining heat that we have. But at what point that would be I'm not sure.

Eric: Yeah at this point humans might not exist anymore.

Meg: Yeah, could be.

Briony: The other really cool thing about plate tectonics, too, and one of the reasons we think it might be happening on Earth but not Venus is the fact that we have liquid water here on Earth. So, Venus, you know, as far as we know has always been a pretty hot place and so hot water has never been stable at the surface. And so we think that the reason that Earth might be able to, you know, move it's plates around and you know, shove one plate under another is the fact that we have oceans and we have liquid water sitting on the surface that can help lubricate this process. And Venus, if it was too hot for that to happen, it never developed plate tectonics and instead what we think might have happened with Venus is that you know, instead of having plate tectonics when it tried to release its heat, just through, you know, more inefficient things like volcanism it couldn't. And so eventually what happened is that the entire surface of Venus melted. Molten, it just totally underwent what we call catastrophic resurfacing and so it actually built up so much heat in its interior that the whole surface melted and reformed and this is within the past billion years that we think this happened. And so that's actually, the fact that we have plate tectonics here on Earth we think is actually critical for life. You know, first it tells us we had water but it also means that our surface is relatively stable compared to a planet like Venus'.

[45:13]

Ben: There's one more thing that I think is notable in this whole picture. So, it has to do with that picture where we talked about the moon moving out further away from the Earth, right? That's kind of an incredible claim, isn't it? I mean, to say that the moon's orbit is increasing in width? So is there any direct evidence of that and there is and it has to do with these moonquakes and it has to do with these weird cliffs on the moon. So, I want you to imagine, deliberately, a model where we have, what are these lunar cliffs called, they're the...

Meg: They are lobate scarps.

Ben: Lobate scarps, right. So, I want you to have an image in your head of these lobate scarps forming. Um, so, let's imagine that you wanted to build a soccer ball, okay? You've got a nephew and he's really into soccer but you also know he's pretty lazy and so you don't want to actually spend real money on a soccer ball. So what you do is you go to the dollar store and you buy a whole bunch of construction paper and some tape and a balloon. Okay? And you inflate your balloon into a nice, pink spherical balloon and then you're going to cut out hexagons out of construction paper and then glue them in place and what you get is a soccer ball. It looks like a soccer ball, right? And you give it to your nephew who's maybe a little bit short sighted and also lazy and he says thank you, I always wanted a soccer ball. And you go sure kid, that's $50 I just saved there. So, over time, the balloon, because balloons are balloons, it's going to start shrinking. It's going to start letting some air out and as its radius decreases the edges of the construction paper panels that you made, they're not going to fit tight with each other anymore. So, instead, they're just going to kind of overlap it and slip over each other. Can you kind of see what I'm drawing in my head?

Eric: Yeah, hopefully my hypothetical nephew will have lost interest in that thing by now.

Ben: Right, right. Yeah, exactly. You know he will, what a lazy kid. So, as it becomes dramatically smaller these things are going to overlap quite a bit and those are, essentially, what we've been talking about. That's what happens on the moon, the crust is solid, but as the radius is shrinking there's no where for these solid chunks to go. The volume the area must contain is shrinking and so these kind of overlapping plates just kind of shift over each other. If the moon was all alone out in the middle of the void of space the locations where the crust, the solid surface of the moon that's overlapping to make these cliffs. It would kind of appear randomly over the surface, kind of like when you crack an egg and the egg cracks just go everywhere. Okay, so, here's the interesting bit, the moon, as it orbits the Earth, it feels the tide from the Earth, the same way that we feel the tide from the moon. So, the Earth is also applied a kind of kneading force kind of trying to reshape the moon into the shape of a football pointing towards the Earth. So, where these cracks have occurred is consistent with the tidal forces that the Earth has applied to the moon over it's lifetime. So, from there we can track the fact that the Earth, the moon has indeed felt the tidal forces of the Earth and is indeed increasing in orbital radius.

Eric: So orbital radius meaning that it is moving farther away.

Ben: Yeah, that's right.

Meg: Yeah.

Ben: So, in other words the cracks in the moon that we are tracking, these fault lines, aren't occurring in random locations. They are occurring in locations that are recognizably from the tidal effects of the Earth squishing the moon.

Eric: But the moon is not going to move far enough away within any reasonable amount of time that it would really significantly affect the tides on Earth?

Meg: Within our lifetimes? Or human lifetimes...

Eric: Yeah, or even, I mean, yeah, this is something that, I think you were saying before that, by the time the moon moves far away from the Earth we have much bigger problems to worry about.

Ben: Oh yeah.

Meg: Right.

Ben: We're talking about geological timescales here.

Eric: Yeah.

Briony: The incredible shrinking moon everyone.

Meg: It's actually kind of an interesting parallel to Mercury because for a long time we knew that these scarps were there, we were just trying to map them well enough to be able to tell if they were in random orientations or not and then use that to try to say something about Mercury's history of either slowing down in its rotation because Mercury is in a resonance also. Sort of like how the moon only faces us with one, you know, we only see one face of the moon. Mercury is sort of in a similar situation with the Sun and it had to get into that configuration sometime. So, for a long time we were mapping these scarps on Mercury and trying to look at their orientations to say whether or not they were just completely random and if they're not random what do they say about Mercury's past. And I'm not quite sure what the current state of that is right now. But I think that's definitely, there's a paper on that, about the lobate scarps on the moon too. Tracing out, sort of, that the pattern of tidal forces that you mentioned.

Eric: Yeah, I guess studying any planet is interesting regardless of whether it's Mercury, Venus, or Mars. Or there are some planets that are definitely more interesting and more relevant to us to study.

Briony: I think that depends on your own personal biases, right? So, if you look at NASA and you look at where NASA has sent missions. Pretty much every major planetary body in our solar system, with the exception of some of the really far out ice giants like Neptune and Uranus have had dedicated missions. So, we've sent a mission to Mercury and Venus, we've sent a ton to Mars.

[50:16]

But if you look at how many we've sent to different planets you see huge disparities. We've sent, you know, one mission to Mercury. We've sent kind of 1 and a half missions to Venus but we've sent dozens and dozens of missions to Mars over the course of the past 40 years and that's because, you know, again, we think about really big picture science questions, you know there are lots of interesting things we can answer by looking at places like the moon about the early formation of the solar system and Mercury, about you know, what did these weird little planets with giant iron cores look like and what do tectonics on that kind of planet look like? But if the question you really care about is what is the history of life in the Universe, there's only really a couple places in the solar system where we can really get at that question and that's been the question that's been motivating not all of NASA but a lot of NASA science for a very long time now. So, that's why we keep sending missions to Mars and that's why we are trying to send a new mission to the icey moons of Jupiter, to Europa. Because we think it actually has an ocean under a surface layer of ice that we've seen from Earth and past missions. And so if you look, again, they're all interesting, all of the planets are awesome but some of them can answer different questions that some people might prioritize more highly.

Eric: Yeah, that makes sense. Yeah.

Ben: Well, that was wonderful. Thank you Meg. Thank you Briony. You've pleased me. Your efforts have born fruit and that fruit is sweet, here is some fruit. Briony, you get a cantaloupe!

Briony: Nom, nom, nom, nom.

Ben: Alright. And Meg, you get a watermelon.

Meg: Nom, nom, nom, nom, nom.

Ben: Awesome. I'd like to thank my guest, Eric Molinsky, host of the Imaginary Worlds podcast, thank you Eric!

Eric: Thank you!! Do I get no fruit?

Ben: Well, I mean, you've been dining on the fruit of knowledge this whole time.

Eric: You're right. I'm being gluttonous.

Ben: Would you like some fruit? I think I've got a potato here.

Eric: No, I'm good, don't worry about it. Don't mind me.

Briony: Hey, potatoes are great for Mars

Eric: It's true. That's true. No, thank you. This has been so fascinating and great, thank you. You can find links to Eric's work and Meg's work and everybody's work on our website.

Ben: Hey everybody, it's announcement time. Okay, first, please give us an iTunes review or tell other people about us online. You know the drill. If people find us on iTunes they're going to find us because lots of people have given us reviews. And if they find us online it's because somebody has gone onto Reddit and told them hey there's this podcast you should listen to, it's totally not crummy. On another note, we're still humbly soliciting your donations. Your donations go to paying our server fees and our project to transcribe the episodes as they come out. That's right. Thanks to your support we've transcribed the entire back catalog. And our newest project is to buy new, decent microphones for all of the regular Titanium Physicists.

So, if you want, you can send us one time donations through PayPal off of our website or you can go to our sweet Patreon site and give us a recurring $2 donation. This particular episode of the Titanium Physicists has been sponsored by a collection of generous people. I'd like to thank the generosity of Randy Russer, Anne Farnell and Elise Campbell for their donations. I'd also like to thank Randy Dossil, Ms. Teener Rotiol, the enigmatic Ryan, Atipeer Jones, a person named Crux and Gabe and Evan Weens. David Dee, and Dan Vale. A Mr. Alex W.T.L. A Mr. Per Proden, Andrew Waddington, Mr. Jordan Young and John Leesy. A Brittany Crooks, James Crawford, Mr. Mark Simpson, Two Songs Gang of One, Mr. Lawrence Lee, Sixton Linason, Mr. Simon, Keegan Ead, Adrian Shonig, Andreas from Knoxville, Cadby, Joe Campbell, Alexandra Zany is great, Weena Brett, Eric Duch, Atein Raymond, and a gentleman named Peter Fan, Gareth Easton, Joe Piston, David Johnson and Anthony Leon as well as Doug Bee, Julia, Nora Robertson, Ian and Stu. A Mr. Frank, Phillip from Austria and Noisy Mime. Mr. Shlowmo Delow, Melissa Burke, Yaseem Omarasazee, Spider Rogue, Insanity Orbitz, Robert Johnson, Madam Sandra Johnson, Mr. Jacob Wick, a Mr. Jon Keyes, a Mr. Victor C, Ryan Klaus, Peter Clipsham, Mr. Robert Haupen, Elizabeth Theresa, and Paul Carr. A Mr. Ryan Knewl, a Mr. Adam Kay, Thomas Shiray, a Mr. Jacob S, a gentleman named Brett Evans, a lady named Jill, a gentleman named Greg, thanks Steve, a Mr. James Clausen, a Mr. Devon North, a gentleman named Scott, Ed Lowington, Kelly Weinersmith, Jocelyn Read, a Mr. S. Hatcher, Mr. Rob Arizato, and a Mr. Robert Stietka. So, that's it for Ti-Physicists this time.

[55:00]

Remember that if you like listening to scientists talking about science in their own words there are lots of other lovely shows on the Brachiolope Media Network. Find it through iTunes. The intro song to our show is by Ted Leo and the Pharmacists and the end song is by John Vanderslice. Good day my friends and until next time remember to keep science in your hearts.

[56:14]

Eric: Now all these, of course this week the, I don't know when you're going to post the episode, but this week the big news is about the seven, seven more Earth-like planets that we found. Are all these Earth-like planets so far away that we can't tell if any of them have plate tectonics?

Briony: Yeah, so we haven't had followup observations yet. Because really when you look at planets that are that far away, these are more than 30 light years, these planets, and so and they are really small, they are the size of Earth. And so, relative to their sun, these are pretty small. And so we can't really directly observe them yet, that's going to take much more powerful telescopes. But the way that we've been learning about exoplanets, you know, extra-solar planets, alien Earths in the past has been by looking at their atmospheres because we can actually see, when they pass in front of their host star we can see the light from that star passing through the atmospheres and so from that we can figure out what their atmospheres are made of. This is how we determined that there are some planets out there that have water in their atmosphere. Basically, the fact that they have water means that there might be, it's possible for them to be habitable for life. And so, something that we will have to keep an eye out for is, you know, do we, I'm not sure if we have the instruments yet that are powerful enough to do this for these planets because they are so small. What are the atmospheres of these planets like, you know, do we see water which might tell us about, if they have plate tectonics. Do we see evidence for oxygen, right? Which is actually, oxygen is mostly produced by life and so if we see oxygen in their atmosphere that could be in indication that there might be life forms on their surface. And so that's going to be the next really big step for looking at these planets.

Eric: And so if we do the sort of moonrise mission and we start having some kind of human habitation or just even, sort of, scientific labs down there, what is the eventual goals once we have set-up some kind of human outpost there?

Meg: I was going to say what you mentioned earlier about the South Pole-Aitken Basin having excavated all the way into the mantle and brought that material up and I think one of the immediate goals there is to sort of understand what that material is like in order to get at the interior of the moon that we don't really have access to otherwise. So, that's really exciting because, you know, we can only do so much from the surface so it's no convenient that this giant impact basin has sort of brought it within reach for us.

Briony: Yeah, but then also going back to the moon too, a lot of it is just about learning how to live outside of the Earth. Right, so, the moon is sort of the closest place we can go to to set-up a colony and learn how to live, you know, in a place that doesn't have the atmosphere and all the resources we need right there. So, I'm mostly a Mars scientist and so I mostly look at Mars so I really want to go to Mars some day and there's a lot of arguments that if you go to the moon first you can learn how to build that colony, how to live off another planet. You know, we need to learn how to, how do you get water? Right, how do you mine water on the moon? You need water to survive. How do you build building materials out of lunar regolith, lunar soil. I mean, these are really basic questions and you can go to the relative safety of the moon and test out before you go onto other places like Mars which for me, you know, the big picture science questions is in going to places like Mars. I want to know what is the history of life in our solar system and Mars is one of the best places we can go to understand that because it used to be Earth-like. We think that maybe it used to host life. And so the moon is kind of, in some ways, you can think of it as a staging ground for exploration beyond our Earth system.

Eric: I saw an article years ago in Wired about 3-D printing like houses and things using the material on the moon which sounded pretty cool. It made sense to me. Is that something people are still talking about?

Briony: Yeah, so, we're actually doing experiments here at Purdue that directly relate to that. So, we're basically trying to take lunar soil, this broken up, nasty regolith that has been generated over billions of years by impacts smashing everything on the surface. You know, can you turn that into cement and put it through a 3-D printer to make bricks and to make roads and to make pipes and all these different things. Yeah, because one of the big constraints on living on other planets is that it is really expensive to launch stuff off the Earth and so one of the big goals for NASA and a lot of the international space agencies is to learn how to live off the land on other planets. So yeah, can you do things like mine water on the moon. Can you build bricks out of lunar soil, you know, questions like that.

Eric: Wow. As Tina Fey likes to say on Thirty Rock , I want to go there. How many decades, or what time frame are we looking at for that to happen?

Briony: Ah, it depends on who you ask. Ah, if you ask Elon Musk he'll be retiring on Mars in his lifetime. If you ask NASA, right now, and this of course will change, depending on what the Trump administration wants to do, but right now they are talking about going to Mars in the 2030s and actually bypassing the moon altogether. But that wasn't the plan ten years ago. Ten years ago the plan was to go to the moon, set-up a colony and then go on to Mars eventually. The problem is it changes with every new president, right? So, the president comes in and sets up a plan for NASA and then NASA has to try to implement that with whatever they have, or whatever projects they are already working on. And so, a lot of the work that is going on at NASA right now is trying to take the rockets and equipment they were building to go back to the moon under George W. Bush and they were trying to turn that into Mars vehicles to get to Mars under the Obama plan and now with Trump there are rumors he wants to go back to the moon. We don't know. We'll have to wait and see what happens but NASA is still building the rocket so hopefully we'll get somewhere eventually.

Eric: But you really feel that the moon, it's much wiser to have the moon as kind of the testing ground, the sort of dress rehearsal.

Briony: I don't know. I've heard really good arguments on both sides. One of the arguments against going to the moon is if your real goal is to get to Mars do you want to risk getting stuck on the moon? Right, there are a lot of people who would argue that we kind of got stuck in low Earth orbit with the International Space Station because it was really expensive to maintain and you know, everybody wanted a piece of it and so it took way longer to build than we thought. And so there is a risk that going back to the moon you do that too and so you would just never make it to Mars. There's an argument for lets just go to Mars and figure it out and answer the big science questions by doing that. But you know, honestly, I just want to see us land humans anywhere outside of the Earth. If we went anywhere and had boots on the ground on any other planetary surface I would be ecstatic so, I'd be happy with any plan.

Eric: Yeah, as long as it's not Matt Damon. Because I've seen two movies now where we have to rescue him. That's really not a good idea.

Eric: How long is a flight time to the moon?

Briony: A couple days. Like, it took the Apollo astronauts 3 days to get to the moon.

Meg: Yeah.

Eric: I assume that would be another reason too is, I mean, Mars is kind of, Mars is like a life sentence. You know, but, I mean, presumably until the, until the technology gets, flight technology gets a lot better, but, I mean, yeah, you...

Briony: NASA is trying really hard to make Mars not a life sentence, right. So, that's part of the goal is to figure out how to get humans back from Mars too. So that's a big difference too, if you go to the moon and you land on it you can be in constant communication with Earth, right. Real time communication. You can basically have the same kind of Apollo mission thing where it's like hey Houston, we have this problem or whatever and figure it out. But, if you're on Mars you're anywhere from 7 to 20 minutes difference in terms of communications time. Right, there's this big lag that because Mars is so far away it takes that long for the radio signal to travel from Earth to Mars and so basically any astronauts that are on Mars are pretty much on their own. They have to figure out what they are doing, it's a very different exploration strategy from being on the moon. And it way more dangerous. You can imagine sending a lifeboat to the moon if something went really wrong. You know, it's just three days. You could shoot a rocket off, you probably would have one standing by to do that. But man if you're on Mars you are totally on your own. So, yeah, there's a huge, huge risk factor with going to Mars.