Episode 63, "Worldbuilding"
Dramatis personae:
- Ben Tippett
- Patrick McHale
- Catherine Neish
- Brian Jackson

The Titanium Physicists Podcast
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Ben: Never be afraid. There's nothing which is known which can't be understood. There's nothing which is understood which can't be explained. For over 50 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 Physicists. You're listening to the Titanium Physicists Podcast and I'm Ben Tippett. And now... *allez physique*!

01:11

[Intro song; *Tell Balgeary, Balgury Is Dead* by Ted Leo and the Pharmacists]

01:46

Ben: Science fiction is one of the most popular genres of speculative fiction. Star Trek, Star Wars, Stargate, Doctor Who, Aliens. The books and the movies and the television shows - this genre has fueled our imaginations and shaped the history of technology and achievement which marched us from horseless carriages to driving horseless carriages on the Moon. From speaking to one another wirelessly to people surfing the Internet on their smartphones. I want you to think about the most powerful element of this genre - that there are other worlds and that they're out there, floating somewhere. Somewhere above our heads, waiting for us to explore them. There's something appealing about the idea. I mean, I love it, you love it, the big movie studios that make billions of dollars love it. But think about it - you could go to another planet and get away from your horrible neighbors and their dog, get away from the reprehensible national politics of your nation, get away from the crowding and pollution and endless social intrigue. Go live the simple life on another planet where land is cheap and you'll have lots of room to plant tomatoes and the only thing to worry about are the two-headed purple bears. Well, there's something appealing about it. That appeal is based on a really dark part of our culture. Most heroic interplanetary science fiction is in one way or another a heroic romanticization of stories from the era of European colonialism. Think about it - one or two space empires fighting over the resources of a planet, clashes of two unquestionably powerful civilizations, stories of shipwrecks, stories of isolation, stories of a visitor turning native and allying himself with the priorities of the planet's indigenous cultures, stories of heroic savages who were tragically forced to abandon their whole culture or aspects of it in the face of fitting into a galactic civilization who - unironically - all speak with American or British accents. We imagine these settlers like Adam and Eve setting forth into the wasteland, planting and pruning until the deserts bloom. Think about the origins of this picture! It's clear that the last hundreds of years of humanity - the era of European colonization - are full of stories of oppression and injustice. It's clear that our settler culture needs to come to terms with not just the injustices which were perpetrated by our ancestors but also the dark narratives in their souls which told them that they had the right to murder and oppress and enslave and divide the world at their pleasure. And so it's kind of skewed that science fiction - this beacon of hope for the future, these stories that reassure us that the future can be kind, that the future can be plentiful, that the future will be hopeful and just - it's skewed that these narratives that we used to sell ourselves these wonderful ideas are narratively mounted on a framework of history which was fundamentally oppressive and unjust. Am I saying science fiction is bad? No, no. I love science fiction - it's awesome. But I'm saying: think about it. See if you can separate for yourself the good from the bad. See if you can separate the hope of the heroes getting everything they want from the principle that no one should have the right to take everything they want. Let's question: if humans had the power to shape a desert world into a paradise why don't they just fix the Earth? If humans had the discipline to travel interstellar distances and get away from their horrible neighbors' dog, why don't they have the discipline to just walk next door and talk to their horrible neighbors about their horrible dog? If we visit other worlds with the wrong intentions, we risk carrying our injustices with us. And I'm sorry - I'm rambling but in the last decade we've heard all sorts of fantastic news. That astronomers have indeed detected planets around other stars - this is no longer merely speculation. That maybe in some way these dreams of walking on the soil of other worlds circling other stars may indeed come true. And I said to myself: hey, let's talk about those planets, let's talk about how they form and why they form and how common they are and whether we'll ever be able to visit and Earth-like planet. And then I said to myself: hey, we're gonna get pretty excited about things, maybe we should start off with a short essay, bringing everybody down before we start talking about how one day I'll get to live on a planet made of puppies, except somehow, when you walk around you don't have to step on a puppy and there'll also be a breakfast planet where you can eat breakfast at every meal of the day and the main industry will be napping between breakfasts. So today on the Titanium Physicists podcast, we're talking about the hows and whys and wheres of planet formation. And speaking of world building, our guest has been on the show before and I'm delighted to have him back. He was the creative director for the Adventure Time cartoon for its first few seasons and he went on to create and produce Over the Garden Wall - an animated television miniseries masterpiece which won him an Emmy! Welcome back to the podcast, Mr. Patrick McHale!

06:49

Patrick: Hello! Glad to be here.

Ben: So for you today I've recruited two of my favorite Titanium Physicists. Arise, Dr Catherine Neish!

Catherine: Boop boo roo too!

Ben: Doctor Catherine did her undergraduate with me at UBC and she got her PhD from the University of Arizona and now she's Assistant Professor at the University of Western Ontario in Earth Sciences where she studies planetary surfaces. Now arise, Brian Jackson!

Brian: Daa Tara Ra Taaaa!

Ben: Dr Brian did his PhD at the University of Arizona where he's now an Assistant Professor of physics at Boise State University where he studies extrasolar planets! Alright everybody, let's talk about planets around other stars! So let's start talking about planets around other suns because it's crazy, right? I guess it's not crazy that there are planets around other stars but it's crazy that we've been able to detect them. And it's crazy because we have been building models of how our Solar System formed and we can use what we observe in terms of other solar systems to modify and refine our story of how solar systems form. And so why don't we talk about that today? 'Cause it's absolutely fantastic.

08:04

Catherine: Right, and we didn't even know about this till 1992. I mean, this has been last 20 years, this field's opened up and it's fundamentally changed our understanding of how planets form.

Ben: So why don't we start by talking about how we can see other planets around other stars? Because planets from this far away are very small and so are stars. It's not like we can look at them, can we?

Catherine: We can, yeah. There's been some observations. Those are hard, those are hard to do. That is by far not how most planets have been discovered. But really the first planets that were discovered were quite large. Because they have a noticeable gravitational pull on their suns and that can be measured. We got to the point where the instrumentation was good enough that you could start to measure this slight offset in the wavelength of the star. And it would be Doppler shifted as it moved back and forth with this planet orbiting around it. So the first planets that were discovered were quite large because they had a bigger pull on their sun.

Ben: So, what you're saying is: so, just like we're in orbit around the Sun, right? And to a much lesser degree, the Sun is in orbit around us. So the Sun moves as the Earth goes around it. The Sun will feel a pull towards the Earth. And so it kind of swivels around in its chair while we make large circles around it, right?

Catherine: That's right, yes. So our center of mass - it's inside he Sun but it's not the exact center of the Sun. So the Sun has a slight movement because the Earth is orbiting it. And it has much bigger movement because Jupiter is orbiting it. And so you'd see the pull of Jupiter much more than you would see the pull of the Earth.

09:33

Ben: So the star will just kind of emit a certain spectrum of light. If an object is moving towards us, that light gets shifted a little bit blue because of relativity and if it's moving away from us, it will get shifted a little bit red, because of relativity. So what we're saying is, we look at these stars and we see the color coming from the star changing slightly, periodically. So sometimes it gets red and then normal and then blue and then normal and then red and normal and we say that that is because there's a planet going around it.

Catherine: That's right.

Ben: Pulling it forward and back, periodically.

Catherine: That's right. That's how the first planets around solar type stars were discovered, using this technique.

Ben: And as a result we preferentially detect really heavy ones that are really close to the stars because those are the ones that pull the hardest. So it'll be shifted more in those cases than if it's a piddly Earth-sized planet.

Catherine: Right. And so we would get, you know, a planet or two here or there from 1995 onwards but really the explosion in extrasolar planets came with the launch of Kepler in 2009 and it's/ maybe Brian you wanna talk a little bit about how that detects planets?

10:38

Brian: Yeah, so the Kepler mission is a spacecraft in orbit around the Sun. So it's not like the Hubble space telescope - it doesn't orbit the Earth - it's actually off on its own little orbit around the Sun by itself. And it monitors the brightness of lots of stars in its field. And in some cases planets around those stars will actually pass in front of the star and block out a little bit of the light. So the star will appear to dim a little bit and then that often is the clue that there's a planet orbiting that star. So usually when you see something that looks like a planet transit - that's what this is called - when you see a planet transit, you'll usually point other telescopes to that star and try to figure out whether the little shadow you're seeing is really due to a planet or some other thing. And the Kepler mission uses this technique to find planets. It's managed to find more than 7000 things that look like planets and among those 7000 things that look like planets there's 1000 that we've confirmed are planets. So the number of extrasolar planets, if you look a plot, over last few years is just like blown up exponentially, it's just huge number of planets discovered these last few years.

11:43

Ben: Okay, so do all the solar systems that we see look like ours?

Catherine: No. [laughs]

Brian: Yeah, none of them really looks like ours. [laughs]

Ben: Do any of them look like ours?

Brian: Well, that kind of depends on what you mean by "looks like". You know, we've found about a dozen planets that are about the same size as the Earth and they get about as much starlight from their sun as the Earth does. That's a little bit like the Earth. But, you know, we haven't really found anything exactly like the

Solar System. It turns out that the Solar System is kind of a hard collection of planets to find. We're not that great at finding planets yet. And so finding a system like ours is still kind of challenging.

Ben: Does the way our planets interfere with our Sun make it so that if there was a planet in another solar system like ours in a nearby galaxy, would we even be able to detect it?

12:27

Brian: Yeah, in fact someone pointed out there's a very interesting planetary system that was discovered by Kepler whose orbit is lined up just right that if that planetary system had a civilization that had launched a Kepler-like telescope, they could point their telescope back at our Sun and actually see the transits of planets in our solar system. So there are certain ways that we could have detected our own solar system if we were orbiting a very distant star but we would only just be able to do it now.

Catherine: Yeah, by far the easiest planets to discover are big planets that are really, really close to their sun. So picture taking Jupiter and moving it to Mercury's orbit. That would be easy to discover. But Jupiter is a lot further out than Mercury so it makes it lot more difficult to discover.

13:06

Ben: Before we go, we've imaged a planet around another star...

Catherine: Yeah! Yeah, there's been a few. They're big and they're far from their star and they're difficult to detect because stars are really, really bright. [laughs] But there've been a few detections that way, yes.

Ben: So like we've taken a photograph of another planet around another star.

Catherine: Yes, and I think we'll get more of these observations in the future as we get better at blocking the starlight and looking for planets around the star.

Ben: So what do you do? Do you just look at the star and then take your thumb, put it over the star to see if there's a bright thing nearby?

Catherine: [laughs] Yes, essentially. Essentially.

Ben: Actually that's how kind of we see regular planets, right? Around our star. You see the reflected light.

Catherine: Right, and Mercury is really difficult to see. You can only see it right after sunset because it's so close to the Sun that it makes it quite difficult to observe Mercury.

13:52

Ben: Alright. And now let's talk about how planets form. 'Cause this is the crazy part. Oh my Gosh. It's crazy.

Catherine: [laughs] Brian, you wanna tackle that one?

Ben: Yeah, yeah, Brian!

Brian: Yes, so planets... Essentially they form from the leftover gas and dust from the formation of the star so what you start out with in the Universe is a big cold cloud, gigantic big cold cloud of gas and dust. So that cloud of gas and dust starts out huge, even potentially light years across and it begins to collapse under its own weight. Eventually the very center of that gas cloud will collapse a lot to form a star and sort of material left over that didn't quite collapse in to form a star, it'll form a little disk in orbit around the star. So it's a little bit like the rings of Saturn. So you can imagine the Saturn is the Sun and the rings of Saturn, that would be our little protoplanetary disk. And so that gas and dust that's left over from the formation of the star eventually collects together to form planets and we can get into all those details.

14:47

Ben: So the stuff collapses down to a star and all that's left over is like essentially, well a disk - it's shaped like a record, rotating around the Sun.

Brian: And it's worth saying that the amount of like material in that disk is really tiny - really tiny compared to the star itself. So I like to think of planets - they're the round-off error of the Universe.

Ben: So are the constituents of the protoplanetary disk - is it all the same material all the way out? Or does it change depending on how far it's from the star you go?

Brian: It's worth kind of having a picture in mind. If you were to go back in time and look at our solar system right as it was forming. What I imagine is sort of very thin disk of gas in orbit around the Sun. If you were actually in orbit around the Sun in this disk, you wouldn't really notice that much. You'd have this transparent gas which/ you couldn't see it. And all throughout will be sprinkled these little tiny dust grains. Close to the star the little dust grains would be made mostly out of rock. So at those close distances, like where the Earth is, the temperatures in the disk are relatively high. The closer you are to the star, right, the hotter the disk is gonna be. So close to the star only rocky stuff can kind of condense out and make little dust grains. And so if you were to go further away from the star, eventually the temperatures in the disk would drop below the point that ice can begin to condense out. So then you'd start to form little dust grains that would maybe have a little ice on them. Kind of in orbit around the star. And so the further out you go, the cooler the temperatures are and eventually other things could condense out. Other than just water ice you could condense out like ammonia and methane ice, carbon dioxide - all kinds of little things would begin to crystalize and form these little solid grains.

16:23

Ben: So, the chemical constituents are the same everywhere but depending on how far away from the center you are, the temperature's changing, 'cause you're closer to something hot. And so different things can be solid the further out you go.

Brian: Yeah, I would say compositionally the disk is very, it's fairly uniform. Although there are hints in the compositions of planets in our own solar system that there's some variation in the compositional makeup of the disk, as you move from one point to the other. And exactly why that is, we don't understand.

Catherine: And there's some evidence there's been mixing as well. When they got particles from a comet with the Stardust mission, they discovered/ So, comets form far out from the Sun where we think things are mostly icy. But there was evidence of really high temperature materials in these grains from a comet. So it seems like there's been some mixing that went on with things from the inner Solar System getting out to the outer Solar System and probably vice versa. This was years ago, they flew through a tail of a comet and they picked up grains from that comet in an aerogel which then landed on Earth and they analyzed it in a lab.

17:26

Ben: Okay.

Catherine: Yeah. Pretty cool.

Ben: Okay, so there is a difference in constituents but we don't know why there was mixing?

Brian: Well, we have some ideas. There's, you know, while we talk about it, the dust grains themselves can move inward - they tend to spiral inward and that can induce some mixing. Once you start to build up sort of large rocky and icy bodies, those can kind of gravitationally stir the disk. So there's ways to mix the disk. But exactly how you explain this sort of subtle chemical variations that we infer were present in our protoplanetary disk, we don't exactly know how you explain all of them.

Ben: Huh. Any questions so far, Pat?

17:59

Patrick: Just to get back to basics for a second. So, you're talking about a big disk, right?

Catherine: Yup.

Ben: Yup.

Patrick: And we were talking about how that leads to planets?

Ben: Yeah. So that's the stuff that the planets are eventually made from.

Patrick: Okay, okay. That's what I thought.

Ben: Alright.

Patrick: I just wanted to make sure.

Ben: So, there's a weird selection effect. Initially when there's a big cloud of gas, it's all going to end up collapsing down into the center, into the star in the middle. But, you know, all the gas - they're not all moving directly towards the center. They all have kind of little randomized velocity. Some are moving a little bit up, some are moving down. And so there's going to be some of them that are kind of in orbit around where the star's going to be. And so those ones will kind of stay in orbit. And there's a weird selection effect here where eventually the only gas that doesn't end up in the middle is the gas that's kind of in orbit around where the Sun will be. Not very much of the initial gas satisfies that criterion but eventually everything that isn't in orbit, ends up in the middle. So you end up with a big disk of gas that's in orbit around the middle. Does that make sense?

19:04

Patrick: Yeah.

Ben: So, we have/ "We" [laughs]. Cooler people than me who are physicists have been working on doing simulations with computers to see how those disks will evolve. Like to see at what rate they clump together, at what rate they accumulate mass and how they go from being essentially a great big disk of clumpy gas/ So they said, the further out from the Sun you get, the more different types of solid materials you get, right?

Patrick: Mhm.

Ben: So, close into the Sun it's too hot for there to be ice 'cause it's warm enough from the radiation form the Sun to melt the ice. So there's just water vapor - it's a gas. But further out from the Sun, maybe around Jupiter's orbit, it's cool enough for ice to form and not get melted from the radiation from the Sun. And so further out you get a different composition, not in terms of molecules but in terms of what's solid and what's not. These are called ice lines, incidentally. It's like on a mountain. If you get further enough from the Sun, just like if you get at high enough altitude, ice will form and not melt. And so you get at different radiuses, different types of ice will be able to form solids. So further out you get weird ices. Water ice, ammonia ice.

20:20

Catherine: And these are some of the most exciting places to look for life. 'Cause you've got a world that's made half of ice and so there's so much water there. So if you're looking for life, actually these solid surfaces in the outer Solar System are an amazing place to look for life.

Ben: So, let's start talking about what happens in these simulations. So what happens next: you start off with those little specks of/ what, they're the size of like sand specks or smaller, right?

Brian: Yeah. I would say the dust particles are even smaller than that, yeah.

Ben: There's gas and dust particles that are smaller than sand. Tiny little grit. And then they start to clump together?

Brian: Yeah, so we know not just from simulations that there are these little dust particles out there. Like, we can actually find them. These are interstellar dust particles, these are actually collected among the material collected by the Stardust mission that Catherine mentioned, they're sort of interstellar dust particles. So we know that these things exist outside of any sort of computer simulation. And as far as I can tell these are some of the oldest solid material in our solar system and so we think that those little dust grains, they were sort of building block of all the planets that we see today. So now the question is how do you take things that are smaller than a grain of sand and build them up to things as big as Jupiter? And we have some of the details of that story filled in. A lot of it comes from as you say, these sort of computer simulations. We have a pretty good understanding of gravity and how gravitational bodies will interact. So we have some sense of how some of that clustering and accumulation occurs but a lot of the details are not all well understood. And some processes that we think go on in the Solar System, so far as we can tell, they would have prevented the formation of planets in the first place but our solar system and all those other planetary systems somehow got around these difficulties.

21:53

Ben: So what forms first and where?

Brian: So you got all these little dust grains and close to the Sun they're mostly rock and so that's where you form the rocky planets, we think. These little dust grains can begin to accumulate - they kind of stick together. Again, we don't quite understand how they stick together, how well they stick together, but somehow they begin to stick together. And eventually you go from little tiny, smaller than sand, up to things that are sort of asteroidal size. We're talking about, maybe - you know - several meters to maybe even kilometers across. But once they get to be about a meter across, these little bodies that are building up via accumulation of dust grains, they actually feel a really strong interaction with the gas disk around them. The gas disk can actually go streaming past these meter size bodies and remove energy from their orbits. So basically they feel a head wind the same way you feel a head wind when you stick your head out the car when you're driving on a highway. And that headwind, we think, it ought to cause these meter sized bodies to very quickly spiral into the star. Apparently that did not happen because we have planets in our solar system. So somehow these meter-sized bodies build up from begin a meter-sized up to much larger bodies and avoid this so called meter-sized barrier.

23:02

Ben: This barrier is called the one meter barrier?

Catherine: We're very creative. [laughs]

Ben: Yeah, yeah. This is a fantastic thing. Okay, so we gotta talk about orbital dynamics for a second. Do you know, Patrick, why something stays in orbit?

Patrick: You know, I think I was wondering at one point, I looked it up and I've no/ don't have no recollection of the answer.

Ben: Let's just imagine ourselves on the Earth, right? And let's suppose I had an Olympic athlete and I was the world's best Olympic athlete trainer. So, I'm training this guy and he's good at the long jump, right? And so he starts out and he can run really, really fast and he can jump and he can land 2 m away, right?

Patrick: Mhm

Ben: Ooh, 2 m away is pretty good. But I've trained him harder and I make him run even faster and then he can jump, you know, 1 km away before he lands. I'm like: oh, yeah, that's pretty good. You can do better, though, so I make him like ice packs and energy drinks and stuff and I train him so hard that I can make him run and after he jumps, he jumps so far away that he's gonna land past the horizon, alright?

Patrick: Uh-huh.

24:05

Ben: Now the thing is: we're standing on a globe, right? It's circular so what happens is you're always being pulled by gravity towards the middle of the globe, the center. But because it's a circle if you travel sideways fast enough, you can't get pulled towards the middle fast enough/ geez, this is the worst explanation/

Brian: Basically, as the person launches over the horizon, you know, he's still falling toward the surface of the Earth but he's gone so far now, that because the Earth is curved, the Earth's surface actually falls away more quickly than he can fall toward the center. So basically that's what it is for something to be in orbit. It's that it/ the surface of the Earth falls away so quickly that the thing can't actually crash into the surface.

Ben: So, there's two elements to being in orbit, okay?

Patrick: Mhm.

Ben: How strongly gravity is pulling you towards the center and how fast you're travelling, right?

Patrick: Okay. Yeah, yeah.

Ben: And the idea is: you're travelling sideways faster than the Earth can pull you down towards it. And you can travel so fast that you completely escape the Earth. That seems possible, right?

Patrick: Mhm.

Ben: And you can travel slow enough so that you don't really travel very far and you just fall straight to the Earth. There's kind of a half way between the two where you travel sideways just as fast as the earth pulls you down toward it and instead of falling to the Earth, you'll end up looping in a circle around it.

Patrick: And so with planets, it sounds basically like Douglas Adams explaining how to fly, right?

Brian: [laughs]

Ben: Yes. It's exactly like that. You try to hit the ground but you miss, right?

Patrick: Yeah. And then you just/ yeah.

Ben: That's essentially what's going on. So the deal is that there's an interplay between how fast you're moving and how strong gravity is. And the further away you get from an object, the weaker the pull of gravity is gonna be from it, right?

Patrick: Mhm

25:51

Ben: And so the moral of the story is: there's kind of like a velocity profile. The further you get from the Earth, the slower you need to kind of move to stay in orbit. Okay, so the Space Shuttle goes around like/

Catherine: When it was in orbit. [laughs]

Ben: The Space Shuttle, when it was in orbit, when it could go in orbit, would go around once every 90 minutes, right? So that's pretty fast. Whereas, like, the Moon goes around the Earth once every 28 days.

Patrick: Mhm

Ben: So it's travelling slower. So essentially the same thing is kind of happening around the star. The further you are from the star, the slower you move to stay in orbit. So out by Pluto you don't need to go very fast to stay in orbit. In close to the Sun, you need to move pretty quickly. So, moral of the story is, there's something interesting that happens when it comes to gas.

Brian: Yeah, yeah. So the gas in the protoplanetary disk, it feels not only gravity from the Sun but the gas actually exerts an outward pressure, right? Like, gas in our atmosphere can exert a pressure, gas in this protoplanetary disk can also exert pressure. And so it very slightly counteracts the gravity from the Sun. And so because it feels an effective gravity that's a little bit less than it would feel if there were no pressure, the gas actually has a slightly slower orbital velocity for its distance, the way that Ben was describing. That sort of velocity - distance profile is slightly modified. So gas at a certain distance is orbiting more slowly than it kind of ought to. If you have a meter-sized object in orbit around the Sun at that distance, it doesn't feel the gas pressure. And so it feels the full gravity of the Sun. And so it wants to go in a circular orbit at a certain velocity, the gas nearby is going in orbit around the Sun at a slightly less velocity and so the upshot of this is that there's a head wind that the meter-sized object feels, which is very strong, from the gas. And that's the effect that causes the meter-sized object to spiral into the star. Basically it's constantly losing energy to the gas.

Patrick: Mhm.

27:40

Ben: So the result is this crazy thing where when we're doing simulations and they say: okay well, you can have the gas and the grit mixed up in the gas, like, clumping together, making bigger and bigger objects. But once they reach about a meter in size, the drag from the gas - it's moving through the gas, plowing through the gas, the gas bounces off of it - slows it down. If it slows down, its orbit is gonna decrease. So it loses energy to bouncing off to the gas, it gets closer and closer and closer and closer to the Sun until it falls in. And this is bad because these meter-sized objects are supposed to be the seeds for, you know, kilometer-sized objects. Which are then supposed to be the seed for Moon-sized objects. And so this is a current mystery in the science of figuring out how solar systems evolve from a protoplanetary disks.

28:28

Patrick: What's the makeup of the planets that are closer to the Sun?

Brian: They're mostly rock. Yeah, they're mostly metal or rock.

Patrick: Mhmm.

Catherine: Yeah, it's silicates, it's something called olivine and pyroxene which are just a fancy way of saying iron silicate. And then iron, pure iron - that's mostly what they're made of. With this veneer of water on top. It's actually a little bit strange that the Earth has an ocean. And so people are still trying to figure out where that ocean came from.

Patrick: Yeah.

Ben: But that's interesting, right? Because it says: there's two mechanisms for small objects becoming larger objects, right? One of them is essentially you throw two snowballs at each other and they stick together - two kinda slushy objects collide and kind of stick together - that's one of them. And the second is if you're heavy enough, other things will come to you and stick to you because you've got a lot of gravity. So, the Earth, for instance, is surrounded by gas, right? Our atmosphere. That atmosphere isn't sticking to the Earth with molecular bond, it's kind of stuck to the Earth because of the Earth's gravitational field. So those two effects are going to determine how big a planet gets and how fast. Now the interesting thing is, to address your question, if you're going to build a planet by making things stick together, then you're gonna build a planet out of whatever is solid at that radius, right? Because the further out from the Sun you get, the cooler it gets because you're further away from the hot radiation of the Sun and the more different types of crystals can form without getting vaporized. So in our distance from the Sun, you know, rocks, iron, metals - things like that. They can be solid. But things like water ice, ammonium ice, they're all gonna turn to gas at our temperatures.

And so planets that form closer to the Sun are gonna be made from things like metals, rocks. Whereas planets further out in the Solar System will be made of these weird ices and also, if they get heavy enough, gases. Does that make sense?

Patrick: Yeah.

30:21

Ben: Okay, so, Brian. So we were talking earlier about this one meter wall.

Brian: One meter barrier.

Catherine: Please Ben, get it right. [laughs]

Brian: [laughs]

Ben: The one meter barrier.

Patrick: [laughs]

Ben: Okay, so we were talking about the one meter barrier earlier. Suppose then, you know, so nature has evidently figured out a way past that. Probably to do with complicated/

Catherine: Or it was just really fast. And they didn't have time to get slowed down.

Ben: Okay. So yeah, for whatever reason you get past the one meter barrier and then where are you guys?

Brian: Yeah, you start building things that maybe look a little bit like asteroids and then the asteroids can begin to accumulate together under their own gravitational pull. Till they're things the size of the Moon and maybe the size of Mars and then basically you're left with probably a few hundred, maybe thousands of things that are about the size of the Moon that start to feel very strong gravitational attraction toward one another. And so very latest phase of planet formation you get these gigantic collisions between objects the size of Mars crashing into each other to form planets. And one of the most important collisions of that kind actually formed our Moon. The Earth was actually the target of a collision between the proto-Earth and this giant Mars-sized object that came crashing into the Earth and launched all this rocky material into orbit around the Earth, making the Moon. So that sort of last phase of planet building was really dramatic and violent.

31:37

Catherine: Yeah, and there's evidence this happened at Mercury, too. Mercury has very little rock, it's mostly iron. So people have hypothesized that a huge impact blew off its rocky crust. There's evidence of this at Mars. The whole northern hemisphere of Mars is lower than the southern hemisphere. So again, people think there was a huge impact that sort of took off a bunch of material in the northern hemisphere of Mars. So it seems like this end phase was really violent.

Ben: To reiterate what she said with an underline under it, something hit Mars so hard that half of Mars is a crater/

Catherine: Basically, yes. [laughs]

Ben: /of the other half.

Patrick: [laughs]

Ben: You know, one of the criteria of calling something a planet is that it clears its orbit, right?

Catherine: Oh, let's not get into that IAU definition. [laughs]

Brian, Patrick: [laugh]

32:17

Ben: But is this what they're talking about?

Brian: That would be the process by which the planet would clear its orbit, essentially, yeah. It could either eat other sort of similarly sized objects or it could throw them out of the Solar system altogether.

Ben: So at this point in the game is the protoplanetary disk still around?

Brian: No, this protoplanetary disks, they tend to stick around for just a few million years. So far as we can tell. We can actually see protoplanetary disks around other start that are much younger than our Sun. So we have a pretty good sense for how long these things last. They last for a few million years and then in this final phase when these giant sort of planet-sized objects are crashing into one another the protoplanetary disk of gas is long gone at that point.

32:53

Patrick: Is there any sense of, like, how much stuff ends up going into the Sun and not becoming planets?

Brian: Uhhh... I don't know if we know exactly how much but yeah, probably a lot of material that would have formed planets does actually end up falling into the Sun.

Catherine: Or getting scattered out of the Solar System entirely.

Brian: Yeah, exactly.

Patrick: Out of league game. Yeah, yeah.

Ben: Is that/ that's where comets come from?

Catherine: Well, comets are like, the remnants of whatever started out there. There were probably a lot more comets and a lot more asteroids when the Solar System formed. And as the planets have slightly shifted over time, they've all gotten scattered to bits. And so we've lost a lot of asteroids, we've lost a lot of comets from when the Solar System formed.

Patrick: So, when you're talking about, like, some massive object hitting a planet or a protoplanet and, like with the Earth or with Mars. Is there something that's also going around in our Solar System or is it something from elsewhere?

Brian: So, those are all things that were forming in the Solar System. So, like, the giant Mars-sized object that struck the Earth and produced the Moon - that was a planet on its own. That was its/ a Mars-sized planet that was happily going around in its own orbit around the Sun before it collided with the Earth.

Patrick: I see, yeah. Okay, that makes sense.

Brian: Does that answer the question?

Patrick: Yes, it does.

34:05

Ben: So let's talk about the different types of planets that can form and why and the stages of their evolution maybe?

Brian: [laughs]

Ben: 'Cause there are gas giants and the terrestrial planets and ice giants, right?

Catherine: Yeah, we classify planets, you know, in these three different categories. The rocky planets, or the terrestrial planets, would be Mercury, Venus, the Moon and Earth and Mars. The Moon gets included 'cause it's pretty big. These are things that are made of rock and iron and they're close to the Sun. Then we have Jupiter and Saturn which are called gas giants. They're the biggest things in the Solar System, they're made mostly of hydrogen and helium. And then we go out and we get to Uranus and Neptune. These are slightly smaller and they're made mostly of ice - hence the name, ice giants. So they do have a large atmosphere as well. In addition to hydrogen and helium there's also methane and other things in it. So this is how we sort of classify the planets of our Solar System and when we look at other planetary systems, we give them similar names. Interesting, the most common planet in the Universe, or at least in our Galaxy, seems to be ice giants. Kepler has found a peak in planets at that size range.

35:17

Brian: Yeah, it's worth pointing out that the most of the planets that the Kepler mission have found are these planets that are kind of intermediate in size between the Earth and Neptune. So these planets are sometimes called "super-Earths" or "sub-Neptunes". We don't have a really good name for them because we actually have no idea how they form. The process that gives rise to planets, we think that, as a planet starts to grow in mass, when it starts eating more and more of these dust grains and eating more and more of these little protoplanets, it gets bigger and bigger. It eventually reaches this critical mass where it basically eats a lot of stuff very quickly. So you have something that goes from being about the size of several Earths, maybe several times the size of the Earth, to suddenly growing up to be the size of Jupiter. And, you know, like a million years, so very, very quickly on astronomical time scales. We have really no idea, like, how planets, kind of, grow up to be several times the size of the Earth and then kinda stop there. That doesn't make any sense as far as we can tell. But these super-Earths or sub-Neptunes, they're the most common planet in our Galaxy, as far as we can tell. So, we're just not that clever, apparently. Nature's got a lot more going for it than we do.

Patrick: I wish I had things to add but it's just really fascinating/ [laughs] /to listen to.

36:23

Ben: Okay. So, before we go on, how much heavier is Neptune than Earth?

Brian: So Neptune is 17 times the mass of the Earth and it's about 4 times the size in radius.

Ben: So these heavy Earths, these light Neptunes, they are somewhere between our mass and 17 times our mass, right?

Brian: Yeah, right, exactly.

Ben: It makes vague sense that Neptune would be heavier than the Earth because it formed way out in the Solar System where more things can condense and solidify. Is that argument reasonable?

Brian: That is exactly it, yeah. So, because temperatures in the protoplanetary gas disk were low enough out at Neptune-like distances for ices to condense, that meant that there was a lot more solid material from which you can build a planet. And so, at least as far as we can understand, that's why the biggest planets in our Solar System are out further away from the Sun.

Ben: Okay, so where in their solar systems are these light Earth, heavy Neptunes forming?

Brian: Oh, my Gosh, they're all over the place. We see some of these guys really close to the star, way closer than they're ought to be. They're called hot sub-Neptunes. [laughs] And then there's/ they're further away. As we were describing earlier, we're a little bit biased in terms of our ability to find small things far from the star. But as far as we can tell, there's no end to the distribution of these things. They seem to be distributed kind of all over the place. And that may not be just a symptom of the formation process. That may also be a symptom of what happens after the planets form. We're starting to learn that planets can actually around quite a lot after they form.

37:53

Patrick: Oh, it's really weird to me. [laughs] You'd really think that there'll be a lot of similarity between them. Like, if the distribution of different, you know, gases and solids is relatively similar. I guess there's so many variables in the Universe that it would just cause things to be different.

Ben: I think I see what you're saying. Which is like: if the distance scale at which different stuff forms from the star is about the same everywhere, you get metals in close and, like, more ice the further out you get, you should see that in all solar systems but it's not the case.

Patrick: Yeah, I mean, if they can move/

Ben: Is that what you're saying?

Patrick: Yeah. As Brian was saying, if they can move around, then the variety that you would have would be a lot more than you would first expect.

38:38

Ben: Okay, Brian, why do planets move in?

Brian: Yeah, why do planets move in? Okay, so first it's worth pointing out, like, how far these planets are moving in in some cases, right? So, Mercury is about half the distance from the Sun that the Earth is. We now know of hundreds and even I think thousands of planets that have orbits way closer to their star than Mercury. In fact, some planets we've discovered orbit, like, almost at the surface of their star. They're right on the verge of plunging into their star. And nobody expected to find planets that close to their star. The other very puzzling thing about these planets is not only are they much closer to their star than they ought to be. Some of these planets are, like, the size of the Jupiter and that close to their star. And, as we described earlier, like, you shouldn't find Jupiter-sized planets in orbits right up against the star. They just shouldn't be able to form there. And so apparently planets can move from distances like where Jupiter is now, which is much further from the Sun than the Earth is into orbits that are almost at the Surface of the star. That's a lot of motion. So how do these planets move that kind of distance? The short answer is: we don't really know. But there's two ways people have thought of that can explain this and it's not clear which one is more important than the other. One process is called gas disk migration and it's a little bit similar to that process we described earlier with/ there's a strong interaction between the growing planet and its gas disk. The interaction is a little bit different from the head wind we described earlier. Instead it's more of a gravitational interaction but the upshot is basically the same - that the planet's orbit will very quickly spiral in and the planet can end up parked in an orbit very close to the surface of the star. So that's gas disk migration. The other mechanism that people have proposed involves gravitational interactions among a multiple planets in the system or even, if the star has a companion star out at a very distant orbit, interactions between planet and that distant star can also do this. The basic idea is: the planet will form where it should form, like a good, well-behaved planet, and then gravitational perturbations will significantly modify its orbit and can actually throw the planet into an orbit that takes it very close to the star. And that process/ there's kind of a lot of different ways of doing it and you might call all those different processes, you can put them all under the umbrella of dynamical excitations. So they're gravitationally or dynamically exciting orbits of these planets and putting them into these close orbits.

41:00

Ben: So when you say that it's a gravitational interaction, do you mean like the slingshot effect that we used to get Voyager probe way out afar?

Brian: Yeah, it's similar at a basic level that basically there's gravitational tugs among the different planets which causes their orbits to change dramatically. So you can take a planet like Jupiter, in a Jupiter-like orbit and then send it into an orbit much closer to its star than Mercury is in our Solar System just through these sort of gravitational give and take between the different planets in the solar system.

Catherine: There's actually some evidence this happened in our own Solar System. In particular there's a model that suggests that Uranus and Neptune switched spots, basically. So it used be Jupiter, Saturn, Neptune, Uranus and due to these slight interactions between the planets they ended up switching places. So you would have had to remember a different mnemonic if you were around, you know, 10 million years into the formation of the Solar System.

Patrick: This is a weird question, maybe but how normal is our Solar System in terms of/ or, like, how average is it? Do we know?

42:05

Catherine: Not average at all.

Patrick: Not average.

Brian: That's a really good question. We don't really understand exactly how normal our Solar System is. Partly because it's hard to find solar systems like ours but to the extent that we can compare our Solar System to the systems that we see, our Solar System is really different.

Patrick: Hmm. I guess that makes sense.

Catherine: There's a huge variety of solar systems and none that we've found so far really looks much like ours.

Patrick: Yeah.

Ben: Okay, so another thing that can happen that is mysterious is that Jupiter-sized planets end up really, really, really far away from their stars, right?

Brian: Yeah, that's totally true, uh-huh.

Ben: Is it caused by, you know, interplanetary gravitational interactions, the same way inward migration might be?

Brian: Yeah, I think that sort of dynamical excitation that I just described, it can throw planets in and it can also throw planets out. That's one of the ways we think you can explain the presence of some of these planets that are hundreds of times further from their star than the Earth is from the Sun. Planets also can't form that far away because there's nothing basically out there to make a planet, to make the planet out of. So, one way you can explain them basically is they formed closer in and then got thrown out into these distant orbits.

43:15

Catherine: Like planet X. [laughs]

Ben: Yeah, yeah. What about planet X, Catherine?

Catherine: I don't know anything about planet X. [laughs] Just that there might be a Neptune that's very, very far from the Sun.

Brian: Yeah, so this is this famous planet 9 that has been recently proposed. So it's important to highlight the fact that this is just a proposal, we haven't made any observations of it - it's not confirmed, it's just an idea but it's a really good idea. Basically the idea is: we see these Kuiper Belt objects - these are object kind of like Pluto out in this very distant orbits from the Sun - a big ice balls, essentially. These objects have orbits that are elliptical, right? All the planets in our Solar System have elliptical orbits and these Kuiper Belt objects, they have elliptical orbits. And the elliptical orbits for these six particular Kuiper Belt objects are all aligned in a very specific way. So basically they all point in very nearly the same direction. And that's weird. We wouldn't expect by chance the orbits of these objects to all be aligned in this way. And so one way to explain that is that there's some other big object out there, maybe the size of Neptune, which is sort of stirring the orbits in just the right way so that they all line up. And so that's the basic idea behind this recent proposal of planet 9. It's a really great idea and so now people are basically scrambling to point telescopes to the sky and try to find this object.

44:32

Ben: Incidentally, if we know where the Kuiper belt objects are that are doing this why haven't we seen that one planet?

Catherine: Yeah, I was just thinking that, too. They've had a really, really hard time finding these really distant Kuiper belt objects. And people have been looking and finding very, very little.

Brian: Yes, so the basic idea is that it's just really hard to find things like this. The proposal for this planet 9 is sort of carefully tuned so that it's small enough that we wouldn't necessarily have seen it yet. So basically they're just saying "well, it's out there but we just haven't seen it yet". And that's not totally crazy. The sky is really, really big and space is really, really big. It's just hard to search everything.

45:11

Brian: Oh, yeah. So, we were talking about these hot planets, these planets that are really close to their star. Well, it turns out that even once you put these planets close in, they're not done moving around. And some of the research that I'm doing and my group is doing here at Boise State is showing that these planets can actually continue to spiral into their star. In some cases the stars can actually eat the planet. And there's a good evidence to suggest that this sort of thing has happened in a lot of the solar systems that we could see today.

Ben: Wow. How can you tell if there was a solar system that ate a planet?

Brian: Yeah, how can you do that? Well, it turns out that one thing that happens is when a planet crashes into a star, it can actually spin up the star quite a lot. And so there's a lot of stars that have been discovered that have anomalously high spin rates. The stars spin a lot faster than we would expect them to. And one way that you can explain that is by saying that they've eaten a Jupiter-sized planet.

Ben: Fantastic. Alright, okay. Let's summarize.

46:07

Patrick: Sure.

Brian: Yeah, do it, do it.

Ben: So what we're saying is: okay, you start with this protoplanetary disk, you get different types of solid matter the further out from the center you go but also the distribution of matter, it gets more rarified the further you go out from the center. Which is why we don't get really, really, really big things out past Pluto - you just kind of run out of stuff. What happens is, these kinds kinda start sticking together. Eventually you end up with some distribution of Mars-sized planetoids that are all flying around their star and then it's a royal rumble. And who knows what happens? It all depends on, like, the initial clumps of matter and how fast they're going. And so in our Solar System, everything ended up nice and happy where we've got small planets in the center, heavier planets out further out. Everybody is orbiting in kind of harmony, so they're not smashing into each other all the time. But in other stars different things happen and you can get all sorts of chaotic weird outcomes where planets get thrown everywhere - you get Jupiter thrown way out, 10 times further out than it should be. Or you get, you know, these Jupiter-sized planets making their way through the solar system. Other planets steal their rotational energy end they end up slowly moving towards the center and they end up orbiting at really, really narrow orbits. And so they didn't form at those really, really close in orbits, 'cause they're dynamically not going to form at those radiuses. So instead what happen is they formed further out and then migrated in by throwing away all these other planets. Is that it?

47:41

Brian: That's basically it, yeah. And I think it's worth pointing out, like Catherine was saying earlier, that although we used to think that our Solar System was this sort of well-behaved poster child for formation, it turns out that our Solar System probably had an early phase of dynamical chaos where planets were also getting thrown around all over the place. And we wouldn't have known that if we hadn't discovered these very strange and surprising extrasolar planetary systems.

Ben: So these other extrasolar planetary systems have been feeding the subtlety with which we understand the formation of our Solar System.

Patrick: Well, what's it all leading to? I mean, maybe that's like a final question, is like: the planets are forming, you know, there's bunch of chaos. Some of them end up kind of hanging around orbiting. Are we just waiting for the Sun to go out?

Catherine: Yeah. I mean, we still get hit by things. I mean, asteroids still collide with the Earth. Just not as frequently. You know, the dinosaurs had a run-in with an asteroid 65 million years ago. But nowhere near as often as it would have been billions of years ago. And then, yeah, in a couple billion years the Sun will engulf the Earth and, you know, Jupiter is gonna be a really nice place to live for maybe a hundred million years and then, yeah, then it'll turn into a white dwarf and we'll see what's left over.

49:02

Brian: And it's worth pointing out, it's worth pointing out that we actually know of some white dwarfs that have planetary systems around them. So even when the Sun turns into white dwarf, it won't necessarily spell the end of the planetary system.

Patrick: Oh, yeah. That's interesting.

Ben: But when our Sun turns into a white dwarf, will that be the end of the Earth? I mean it will, right?

Catherine: It's unclear. It's unclear.

Ben: It's gonna eat the Earth, right? When it turns into a red giant?

Catherine: But as Brian said, we find white dwarfs with planets around them. So maybe it won't totally destroy everything. Or maybe they'll recondense and, you know, we'll have this whole process all over again, a second genesis forming new planets.

Brian, Patrick: Hmmm...

Ben: Oh, so you're saying that the planets around the white dwarfs might have formed after the star blew up?

Catherine: Yeah, I mean I'm not sure we know exactly how these planets formed.

Ben: So they're not necessarily the first stars that lived in that particular real estate? They might be new/

Catherine: Yeah, Brian correct me if I'm misspeaking.

Brian: Yeah, you got it. Yeah, there's this idea that you can have a whole second generation of planets to form out of the debris of the original planetary system. In fact, the very first planet discovered outside of our Solar System were discovered around pulsars. And it's very unlikely that the planets could have survived this phase when the star left the main sequence. The sort of middle age for a star. Those planets almost definitely couldn't survive that phase. And so the planets that we see now around these pulsars almost definitely formed from the remnants of that earlier planetary system.

Patrick: Cool

50:26

Ben: It is cool, isn't it?

Patrick: [laughs]

Catherine: I do love this idea, though, that when the Sun goes red giant, obviously that's bad for the Earth, but it will be really good for the outer Solar System. It'll be a lot warmer out there and my favorite place in the Solar System is Titan. It's an icy moon of Saturn and it's covered in organic molecules. And so it's an icy moon that's gonna melt when the Sun gets really hot and it's got all these organic molecules on top of it - they'll mix with the water and maybe we'll have a very brief episode of life on Titan before the Sun goes into its white dwarf phase.

Ben: How much longer will it be a red giant than a regular main sequence star?

Catherine: I think like a hundred million years, something in that order of magnitude.

Ben: Okay. So not very long.

Catherine: No, but it looks like life happened pretty quickly on the Earth. So it doesn't seem very complicated to get life started.

Ben: Oh, so we like go like throw eggs and stuff at Titan so that life starts, right? Dandelion seeds?

Catherine: That's right. [laughs]

51:20

Ben: Well, that was pretty fun. Thank you Brian and thank you Catherine. You've pleased me, your efforts have borne fruit and that fruit is sweet. Here's some fruit. Brian, you get a banana!

Brian: Om nom nom nom nom.

Ben: And Catherine you get some strawberries.

Catherine: [teeth chattering] Can you hear my teeth? [laughs]

Ben: That was uncanny. I'll keep that in. Alright, I'd like to thank my guest, Patrick McHale from Over the Garden Wall and the Adventure Time and many other things. Thanks, Patrick!

Patrick: Thank you for having me.

Ben: Right. I hope you had fun.

Patrick: Yes, I did. [laughs]

Ben: Alright. That's it.

51:57

Ben: Hey everyone, that episode was pretty fun. Sorry it took so much time to get out of. That LIGO stuff threw me for a loop. Okay, so, it's announcement time. First, please give us an iTunes review or tell other people about us online. Why? Because people like physics but they don't tell other people they like physics 'cause they don't wanna think that they're nerds. So, if somebody you know likes physics and tells you that they like physics, you could say "wow, I like physics, too" and if they say "here's a podcast you can listen to" and then you'll go listen to it. And then they'll listen to us. And they'll hear us talk about physics. And we'll have fun and they'll have fun and everybody around us will have fun. So, please do so. Anyway. On another note we're still humbly soliciting your donations. Your donations go to pay for our server fees and also our ambitious project to get all of the episodes transcribed. And they are going gangbusters, let me tell you! You can send a one-time donation through a PayPal off of our website or you can go to our sweet Patreon site and give a recurring small donation that will get collected every time I manage to release an episode. About once a month. This particular episode of the Titanium Physicists has been sponsored by a collection of generous people. I'd like to thank the generosity of Greg Blake and Gary Puckeran for their donations. I'd also like to thank Frank, Philip from Australia and Nosy Mime. Mr. Shlomo Dlal, Melissa Burk, Yaseen Owarzazee, Spider Rougue, Insanity Orbits, Robin Johnson, madam Sandra Johnson, Mr. Jacob Wick, Mr. John Keese, a Mr. Victor C., Ryan Close, Peter Clipsham, Mr. Robert Halpen, Elizabetha Theresa Paul Carr. A Mr. Ryan Noule, Mr. Adam K, Thomas Shayray and Mr. Jacob S. A gentleman named Brett Evans, a lady named Jill, a gentleman named Greg, thanks Steve, thanks Mr. James Clawson, Mr. Devin North, a gentleman named Scott, Ed Lowlington, Kelly Wienersmith, Jocelyn Read, a Mr. S. Hatcher, Mr. Rob Aberzado and Mr. Robert Stietka. So, that's it for Titanium Physicists this time. Remember that if you like listening to scientists talk about science in their own words, why, then there are also many other lovely shows on the Brachiolope Media Network. Follow the link on the iTunes webpage and you can see all of the Brachiolope Media shows. Now, 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.

54:41

[Outro song; *Angela* by John Vanderslice]

55:33

Patrick: Okay

Ben: [laughs] Alright, now the intro's over I get to drink some water...

Catherine: [laughs]

Ben: And it starts.

Catherine: That was depressing, Ben. [laughs]

Brian: [laughs]

Ben: I know. A little bit, right? I wanted to write a really optimistic one but everybody always writes really optimistic ones. And I was thinking about how Doctor Who is really just like a really brutal story about a guy who/ It's essentially a - what's it called? - English Empire Fanfiction where a guy goes into weird planet where all the natives have it backwards and he tells them how to do it right and he goes away and I'm like "ooo-hoo". So I'm like "let's spread my depression around just a little bit".

Patrick: [laughs]

Catherine: You wanna see it from the Daleks' perspective?

Patrick: One thing I noticed that there was missing from the intro was there's also a lot of science fiction that's the other way. Where, like, outsiders come to our planet and do the same thing to us and gives us a perspective of how it, you know. Of that feeling of being taken over and messed with and then, you know, usually it shows us, you know, rebelling and winning.

Ben: Yeah. [laughs] I know, suddenly we're the noble savages but we do it right. I mean, it's [sighs] It's like [sighs] I think it's just like a clash of heroic fiction with/ which is fundamentally kind of weird in that it's not very nice at its heart with speculative science which is totally awesome. But yeah, I mean I guess there's lots of science fiction that isn't this way. I don't know. Maybe I should rewrite the introduction and repeat it after the show.

Catherine: No, no. It's fine, it's fine.

Patrick: Well, I think the other think I would say/ I mean, I'm/ I tend to just pick holes in things [laughs] That's what I always do. But then I think the other thing is - I don't know if it's limited to, like, European colonialism. I think it's, I mean like rabbits do it in Australia, too. Where it's like when there's space and opportunity then they take it.

Ben: Right.

Patrick: And so as soon as we have another planet that we can live on, then we're gonna destroy it, you know.

Ben: [laughs]

Patrick: Or we're gonna get destroyed on it and then we're gonna be "I gotta go and live somewhere else".

Ben: [laughs] So we're the bad guys in Independence Day.

Patrick: Yeah. I think we're everybody. All the time in all of our fiction.

Ben: It's true.

Catherine: Although it's just/

Patrick: Like kind of showing all the different sides of what humanity can be.

Ben: Hmmm.

Catherine: I was just reading a book by Kim Stanley Robinson, his most recent book. And he hypothesizes that if there was a planet

Patrick: But as it applies to finding new worlds for us, I think, yeah, we wanna be the heroes.

Ben: Mmm. Yeah. I think so. What were you saying, Catherine?

Catherine: So this idea of colonizing other planets - there's this new book by Kim Stanley Robinson where he hypothesizes that if there is a planet that we could live on, that is compatible with our biochemistry, there's probably something living there that would then infect and kill us. So there really aren't any other planets we could live on.

Ben: Right. Or we'd infect and kill them, right? It's a coin flip.

Catherine: Sure, sure. But microorganisms are very prevalent and that tends to be what infects us. So.

Ben: Yeah. We'll see. We'll see. Maybe there's big giant people that we can live inside and infect them. We'd be like the space plague. Okay. [laughs] Maybe I shouldn't have written such a downer intro to such a cool topic, I don't know. Oh, editorial decisions.

59:33

Ben: Can you list off other weird solar systems that you've heard of?

Brian: Yeah. Pat, Pat, could you list off the other solar systems for us?

Ben: Yeah Pat, get on it. There's the one in the NASA posters - X125... Oh, geez