Episode 10, “Neutron Stars”
Dramatis Personae:
-Ben Tippett
-Bethany Murray
-David Tsang
-Jocelyn Read

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Ben: Over the course of my studies in theoretical physics, I’ve travelled across the continent and around the world, sampling new ideas and tasting different answers to the questions of “How?” and of “Why?”. And still I find there remains a deep hunger, which lives within me. A burning desire to share these great ideas with the people around me. And so, I have assembled a team of some of the greatest, most lucid, most creative minds I’ve encountered in my travels. And I call them…my Titanium Physicists! You’re listening to the Titanium Physicists Podcast and I’m Ben Tippett. And now…*allez physique*!

01:12

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

01:48

Ben: Jocelyn Bell Burnell and Antony Hewish were British radio astronomers. In 1967 they detected a very strange signal coming from the constellation Vulpecula, the fox. The signal they were detecting was a series of pulses with a period of 1.33 seconds. Aliens. I mean, no one wanted to say it in *public*, but in private? Definitely aliens. Surely, they thought, the signal was too steady, and too clean, and too fast to be any natural system. They even named the source of the pulse LGM1, for “little green men.” And it was the first pulsar ever discovered. Like good scientists, they kept their outrageous opinions to themselves, and it was a good thing they did. Since their discovery in 1967, thousands of other pulsars have been discovered. So, actually, the source of the pulsing signal is surprisingly mundane compared to the “little green men” theory, but it’s interesting in its own way. It’s actually as simple as a lighthouse. So, there’s a type of very small, very heavy, ball-shaped object out in space called the neutron star, and it’s spinning. And there are spots on the neutron star located at the poles of their magnetic fields which emit beams of radio waves. And as the ball spins, the beam sweeps around like the light from the top of a lighthouse. The historical importance of Burnell and Hewish’s discovery wasn’t really the little green men, but instead it was one of the first observed neutron stars. So, today we’re going to be talking about neutron stars.

03:24

Ben: Today my guest is Bethany Murray, my wife and the inspiration for this show. So, Bethany, today I've assembled two of my favorite Titanium Physicists. Arise, Dr. David Tsang!

David: Muahahaha!

Ben: Very good. Dr. Dave was an undergraduate UBC and he did his PhD and Master's degree at Cornell. He's currently at Caltech working as a postdoc astrophysicist. Arise, Dr. Jocelyn Read!

Jocelyn: Uraaahhhh!

Ben: Very good! Dr. Jocelyn did her undergraduate at UBC, her PhD at University of Wisconsin Milwaukee, and she's currently at the University of Mississippi working on neutron stars. In fact, she's recently accepted a faculty position at Cal State University Fullerton and will be moving there this summer. Congratulations, Jocelyn!

Jocelyn: Thanks!

Ben: So today, Bethany, we're talking about neutron stars.

David: Well, neutron stars are these incredibly dense dead stars. They're formed after a large star has collapsed when it runs out of fuel and, um, these neutron stars are incredibly, incredibly dense. They basically pack something one, one and a half times, roughly, the size of a sun down into something that's only about 12 kilometers in radius. So, across they're about the size of a small city, but they contain one and a half times the mass of the entire sun.

Bethany: Well, how big is the sun? Just for comparison purposes.

Jocelyn: Okay! So, I've got a good analogy for this one. So, to put this into a scale of things you might be familiar with, you know the little round balls on pins? Like, pushing pins and stuff?

Bethany: Yeah.

Jocelyn: If the Earth was shrunk down to that size, the Sun would be about the size of a basketball.

Bethany: Okay!

Jocelyn: The sun is about the same density as water. It's not super dense, but there's just *so* much of it, it's huge. And all that mass is compressed down into something that—again the pin head is the size of the Earth, and then this is like the size of a mountain on the Earth, so it's just unfathomable orders of magnitude density increase.

David: Some material from the crust of this neutron star, um, the way you can think about it is if you took every single person on Earth, put them in a trash compactor, and what—

Bethany: Soylent Green style?

David: Yeah, Soylent Green style. And crush them all down to the size of a sugar cube, that's the density of some of this neutron star crust material. And what keeps this stuff so squished down is the intense gravity of al this matter being in this small, confined space. The acceleration due to gravity at the surface of this neutron star is something like a thousand billion G. Um, so humans basically die when you go beyond 10 or 20 G in acceleration, so there's no way you'd be able to survive being near the surface of a neutron star. In fact, the highest accelerations that we can, sort of, obtain technologically are at the Large Hadron Collider, which accelerates things with basically, I think, 190 million G, which is very, very tiny in comparison to just dropping something onto a neutron star.

06:34

Ben: Yeah. So, if you went in a jet that accelerated you to 5 G, you'd pass out pass out because all the blood would leave your brain, it would flow out to your extremities, right?

Jocelyn: Right.

Ben: So, if you stood on a neutron star, your feet would explode and all the blood would rush out of your body before, you know, the rest of your body got crushed.

David: You'd also, yeah, you'd also just be crushed down to almost

Ben: A pancake.

Jocelyn: You'd be compressed so much that your nuclei smash together and set off a thermonuclear explosion.

Bethany: Wow. That'd be cool.

David: Okay, so neutron stars are kind of weird objects. They're supported by what's called "neutron degeneracy pressure." This comes about because neutrons are fermions and you can't place two neutrons in the same quantum state. That means that you can't fit an infinite number of neutrons in the same area, so they resist you pushing them together with what's called a degeneracy pressure and *that* is what's holding it up against the force of gravity.

07:17

Bethany: So that's why they don't entirely collapse? That's why they exist?

Jocelyn: So, one of the ways you can think about this is by looking at the uncertainty principle, where the more you know about something's location, the less you know about the speed that's, that's moving around it.

Bethany: Right.

Jocelyn: And as you have all these fermions inside the volume of the star, because they can't overlap each other, they're confined to smaller bits of volume, on average. And therefore, there's a lot more uncertainty in their speed on average, and the average speed of all these, of these quantum particles increases enough to produce a pressure. Kind of the same way that a gas of randomly moving atoms produces a pressure, here you have the quantum average movement from the uncertainty principle as producing the pressure that supports the neutron star against collapse.

08:09

David: Now, these—

Beth: Can I back you guys up a sec?

David: Sure.

Jocelyn: Yes.

Bethany: 'Cos I don't know what fermions are. You're gonna have to describe that for me.

David: So fermions are—basically, they're subatomic particles that obey these, what's called "Fermi statistics," which basically means that you can't put 2 of them in the same state, um, together.

Bethany: Okay!

David: That's all.

Bethany: Got it.

David: So, like, electrons are fermions, for instance. And, uh, the fact that they're fermions is what leads to, um, sort of, electron structure in different atoms.

Bethany: Right.

Jocelyn: So, if you hear about energy levels in atoms, the electrons go into higher energy levels because the lower ones are filled already, and the rule is you can't put more fermions into existing states, so they have to go up to different states, and that's how you get different energy levels being filled.

David: The other types of particles are called bosons and they basically can, sort of fill the same state. So, like, photons, for instance, are bosons and you can have just as many in a given area as you like.

Beth: Okay.

09:05

Jocelyn: Oh, I wanted to say my cool description of the neutron star! ‘Cos this is basically as dense as you see in the universe before everything just collapses into a black hole. So this is—sort of the story in astrophysics is gravity is pulling stuff together and other forces are resisting this. So, in the Sun, the force resisting is the radiation of the thermal pressure from all the nuclear reactions in the center of the Sun. And in other stars there can be electromagnetic things like in planets that prevent them from collapsing down, and neutron stars are basically the densest, most compact thing where matter is resisting the pull of gravity. So this is matter’s last stand against the overwhelming force of gravity that’s trying to pull everything down, collapsing into black holes.

David: Now, these atoms are extremely close together.

Jocelyn: They’re not even atoms anymore.

David: Right. So, like, just at the surface of the neutron star the atoms are so close together they’re basically—all the matter there is as dense as nuclear matter, so basically the atoms are basically pushed up right against each other so that they’re like, you know, their wave functions are starting to overlap.

10:10

Jocelyn: There’s no electrons orbiting them anymore, like, you don’t have that sort of picture of electrons going around a nucleus. One of the things that happens is there’s this reaction where the electrons and protons combine to form more neutrons, and so what you have is basically mostly neutral particles next to each other, kind of the way you have protons and neutrons in the nucleus of an atom, now you just have mostly neutrons in the star.

David: In the upper part of a neutron star you still have atoms with electrons around.

Jocelyn: That’s true

David: But as you go deeper and deeper into the neutron star these atoms become more and more neutron rich as electrons combine with protons to form neutrons.

Bethany: Oh.

David: And eventually, these things get pressed so close together that they sort of—the surface of the neutron star you have basically, uh, a little bit of an atmosphere, and then this sort of crystal lattice of these really really heavy nuclei. And as you go down deeper and deeper, um, you're pushing them so close together that they can't even maintain this lattice anymore. So, as you get further and further down these get pressed so close together that the atomic shape starts to deform into these strange atomic shapes, and people call them "pasta phases" 'cos they get stretched out and, you know, pushed into planes like, you know, spaghetti and lasagna. So they're called pasta phases. And then they become superfluid and so, the very core in the neutron star, the densest matter anywhere in the universe is thought to be in a superconducting superfluous state.

Bethany: So, what's superconducting superfluid?

David: Uh, a superfluid is a fluid that can, based on quantum effects, basically can, um, move with no viscosity.

Bethany: So no viscosity, so no...like, friction? No…

David: No friction, right. So, basically you can think of it as a fluid with no friction.

Bethany: Okay.

David: Um, a superconductor is, similarly, a conductor, something that conducts electricity, but with no resistance.

Bethany: Right. This might not be a good time to ask this, but, uh, how do we know so much about these neutron stars? They seem kind of mysterious, and yet we seem to know, you know, what it's like at the surface, and then what it's like in the interior. How do we get to know that sort of thing?

Jocelyn: So, there's a combination that goes on here. So, you know, the first thing that happened was that these regularly pulsating objects were observed with those regular radio wave pulses that were happening so fast that if you want to have an astrophysical system producing irregular pulse that quickly, the object has to move all together in each period of the pulse, and it has to do that at less than the speed of light. So the time for light to cross the object has to be small enough to be less than the periodic, um, emission that we're observing. So, that's one of the reasons we know that they're really small.

David: The idea is that, um, because these things were pulsating so fast, you basically need something small enough such that in the time period of the pulsation, which is really, really fast, light moving in that time period is about the size of whatever it is that's causing the pulsation.

Bethany: Okay.

David: So you need something very very small if something's changing very very quickly.

Bethany: Right.

David: Um, but Bethany's question was, "How do we know about the structure of the neutron star" that we were telling her about earlier, and the answer is, we know vaguely the size and mass of these objects, and so based on that, we can do theoretical calculations to try to explain, uh what the, um, structure of the matter has to be for something that's so massive but so small.

Bethany: Right.

David: In terms of knowing about the core of a neutron star, it's pretty much just theoretical calculations, but um, we can write down, um, theories about how matter behaves in this, uh, in this way, and then we can compare that to different sizes and masses of neutron stars that we see and if we can't make them match up then we can throw that theory away and we can see what remains.

13:52

Bethany: Really.

David: Yeah. So, way back in the 1930s, after the discovery of the neutron, Fritz Zwicky quickly proposed that you could have a star that was basically a nuclear density that was supported by neutron degeneracy pressure. It wasn't until, uh, Jocelyn Bell discovered pulsars that they were seen in nature.

Bethany: Huh.

Ben: So, Fritz Zwicky was interesting historically because he came up with one of the best insults of all time. He was known for being a very abrasive person and there were some people he referred to as "spherical bastards."

Jocelyn: Actually, everyone. He referred to all his colleagues.

Ben: Yeah.

David: Everyone at Mount Wilson, which is—which I can almost see it from my house.

Ben: Right. Uh, and a spherical bastard is somebody who, no matter how you look at them, they're still a bastard.

PAUSE

Bethany: That's pretty funny.

Ben: *laughs* Yeah, I know.

Jocelyn: The pause there is like, oh, maybe this is only funny to other physicists.

Bethany: *laughing* No, I just had—I had to take it in for a minute.

14:50

Ben: So, um, interestingly enough, there's a historical perspective on the first neutron star detection. So, Zwicky proposed that neutron stars could form.

Bethany: Alright. So, he was a real jerk.

Ben: He was a real jerk.

Bethany: He figured out all this stuff.

Ben: He figured out all this stuff.

Bethany: That they exist, and also postulated how they form.

Ben: Postulated that they form from supernovas.

Bethany: Right.

Jocelyn: And it turns out, he was basically right.

Ben: Yeah! So, the first neutron star ever discovered wasn't this pulsar, it was a different neutron star that was discovered in 1965. And it was located in the crab nebula.

Bethany: Okay.

Ben: And this is important because in 1054 when historians go back and look through different accounts that the Chinese, the Japanese, and the Arabic societies were taking of the night sky, they noted, essentially, supernovas happening in that location in the sky in 1054. So, you know, essentially 1000 years later we look back through telescopes and we see a big cloud, and in the middle of this cloud, this remnant of the supernova, there is a neutron star. Yeah, and so this neutron star that is, you know, historical, and that all these older societies 1000 years ago noticed the supernova, we can see the neutron star left behind, and that was actually the first neutron star historically ever discovered.

Bethany: Well, that's cool.

Ben: Yeah!

16:09

Jocelyn: So, one of the ways that a spinning neutron star, if it's got a mountain on it or some little bump going around, it can produce gravitational waves, which we've talked about before.

David: People at LIGO (Laser Interferometer Gravitational-Wave Observatory, Caltech/MIT) look into their—look into their signal and try to detect these gravitational waves that may be coming from the, uh, crab pulsar, but because this frequency that these gravitational waves would be at is 60 Hz, which is the same frequency as all the electrical noise generated by normal power supplies, it's basically hopeless.

Bethany: I see. So, you guys keep saying, uh, pulsar, and then you say "and other neutron stars." So, is a pulsar is a certain kind of neutron star and there are other kinds, or what? I'm, I just—

David: A pulsar is a neutron star that is, that is emitting, uh, radio waves or other, or other electromagnetic radiation.

Jocelyn: An electromagnet

David: From its polar cap due to the magnetic field at the magnetic poles. And if that magnetic pole is misaligned with the rotational axis, then you can get this lighthouse effect that Ben was describing earlier. And if that sweeping beam sort of passes, uh, such that it points at us during its, during its rotation, then, uh, we call that a pulsar.

Bethany: Okay.

Jocelyn: We don't think that every neutron star is a pulsar, and since the first neutron stars were detected as pulsars, and they were called pulsars because astronomers tend to be cautious about whatever the crazy astrophysics theory people are telling them. They're like, no, we're just gonna call this a pulsar and you can think that it's a neutron star, but we're not gonna be calling them that until we know for sure. By now, I think everyone's pretty happy saying that pulsars are neutron stars.

David: Yeah, and "pulsar" was actually coined because it's short for "pulsating star."

Bethany: Right. That makes sense.

Jocelyn: We also see neutron stars in other types of systems, like, there's some very nearby ones where we can actually measure their thermal emission. They tend to have some very faint pulsations because they're spinning, but they're not really, you know, detected as radio pulsars. And we also see some neutron stars in binary systems where the neutron star can be sucking matter off a big, main, regular star companion, and that can lead to bursts of, of x-rays and things.

David: And not just bursts, but you can also get, sort of, uh, steady x-rays from these sources.

Jocelyn: Right, right.

David: Um, just due to the fact that you're, you're—sort of, the gas is heating up as it spins down towards this really, really compact neutron star. So, remember that you have a lot of gravity going on here. What we said, a thousand, billion times the Earth's gravity, so as something falls down into this gravitational well, it gains a lot of kinetic energy, and when that gas collides with itself it can heat up and cause a lot of x-rays to be emitted.

Bethany: All right.

18:51

Jocelyn: So, so we see them in a few different ways, at least, but one of the main ways we detect neutron stars is as pulsed radiation in radio, but also in x-ray or gamma rays, or in gamma ray bursts, perhaps.

Ben: Do you know what gamma ray bursts are?

Bethany: No, I don't.

Ben: Okay, so—

Jocelyn: They're bursts of gamma rays!

Bethany: Well, I got that.

Bethany, Jocelyn, David: *laugh*

David: That are short!

Bethany: So, there are gamma rays and then they burst, is what you're saying. Okay, I've got it.

Jocelyn: Well, actually, you know the discovery of gamma ray bursts is kind of a funny story, too.

David: Right, so America had had these satellites that were up in space that, say, monitored for nuclear explosions for some reason.

Jocelyn: I don't know exactly why.

Bethany: During the Cold War, is that what you're saying?

David: *laughing* During the Cold War. Yeah, during the Cold War, America *happened* to have these satellites that were up in space that monitored for signs of nuclear explosions.

Bethany: Right.

Jocelyn: Which would be a burst of gamma rays.

David: Right. So, some of these satellites basically saw bursts of gamma rays coming at them.

Jocelyn: *All* the *time*!

Bethany: Oh, no.

David: But instead of coming from Earth they were actually coming from space, and rather than presuming that the Russians had, you know, started their nuclear testing in deep space, people looked for a more astrophysical explanation. And so, um, there are two types of gamma ray bursts: what are called long, soft gamma ray bursts, and what are called short, hard gamma ray bursts. So, long, soft gamma ray bursts are gamma ray bursts that last longer than a few seconds.

Bethany: Okay.

David: And they tend to have a much softer gamma ray, such as low energy gamma rays, whereas the short, hard bursts tend to have much harder x-ray spectrums, much more high energy x-rays and gamma rays, but they only last, you know, less than two seconds. Long gamma ray bursts are thought to originate from the collapse of massive stars directly into black holes, whereas short gamma ray bursts are thought to occur when two neutron stars merge, and when they merge, they sort of spiral in together due to the emission of gravitational waves and then they smack together, and when they smack together a black hole forms with a, uh, a ring of, uh, hot gas around it. And as that hot gas sort of flows on to the black hole, that can cause a big jet to occur, and if that jet's pointed at us, that's what we call a short gamma ray burst. Did that make any sense?

Bethany: It did make sense.

21:06

Jocelyn: Well, while we're talking about explosions in the sky, stellar explosions also have something to do about how, how these neutron stars get formed in the first place.

Ben: So, stars.

Bethany: Stars, yes.

Ben: They're held aloft like a hot air balloon.

Bethany: Mmhm.

Ben: So, like, hot air balloons are held aloft essentially by all of the energy on the inside pushing out.

Bethany: Right.

Ben: Right, and that's how they stay big and puffed up.

Bethany: Yes.

Ben: When you can't burn anything more on the inside, they start to kind of—shoof—collapse down on themselves.

Jocelyn: *laughs*

Ben: So, essentially, a similar thing is happening in a star. In the core of the star, Hydrogens fuses into Helium.

Bethany: That makes more sense.

Ben: Yeah! It makes lots of sense. Usually in the, in the main stage of growth, like, our Sun it's burning Hydrogen right now.

Bethany: Yeah.

Ben: And that keeps it aloft. And often what happens is when it runs out of Hydrogen, uh, the Hydrogen density drops low enough, the star changes the type of fuel it's burning and it enters something called the Red Giant phase. It starts burning Helium, and this makes the star puff out more. But eventually what happens is in the core it kind of runs out of different elements you can combine together to gain energy. Okay? So, eventually, once you reach iron, if you combine iron with anything to get a heavier element you need energy.

Bethany: Right.

Ben: So, you can't use this fusion reaction to fuel the puffing out of the star, and this causes core collapse. So, essentially what happens is this ball of iron-y matter at the middle of the Sun doesn't have enough energy to hold itself aloft anymore and it starts to collapse down under its own weight, and then there's a pressure barrier and that causes that, uh, the stuff to bounce. So, it collapses down on itself and then the surface bounces out, and this causes a shockwave to travel out through the rest of the star outside the core.

Bethany: Right.

Ben: And this shockwave is so energetic that it causes more fusion reactions, so all of the elements that are heavier than iron come from this process and it's so energetic that it blows off this outer envelope, and that's a supernova.

Bethany: Okay.

Ben: It's a bright light and you get lots of heavier elements and you get essentially a big cloud of gas and then this heavy, remaining core that lives at the center.

David: This is what was observed in the year 1054 by, uh, Asian astronomers.

23:23

Beth: Right, That Ben was talking about earlier.

Ben: Right.

David: That's right.

Ben: Um, so this core is in, it ends up being—if the star that's gone supernova is between certain masses, uh, if it's, if it's heavier than a certain limit, uh, the core will turn into a black hole.

Bethany: Right.

Ben: If it's lighter than something it'll turn into a neutr—or, um, a White Dwarf, won't it?

David: If a star—if a star is less than, um, less than, uh, 8 solar masses or so, um, it'll basically, uh, when it goes over the Red Giant phase it'll, sort of, push everything else off and then become a White Dwarf, um, and that's the eventual fate of our sun. If a star is above 20 solar masses, after the supernova what's left is a black hole.

Bethany: Right.

David: Um, if a star is between 8 and 20 solar masses, and that depends on sort of what the star's made out of and also how fast the star is spinning, but, uh, roughly between 8 to 20, um, it'll, uh, form a neutron star after the supernova.

Bethany: How common is that? Like, how common of a size range is that, the range of objects in the…

David: The majority of stars in the galaxy will form White Dwarfs but, um. Let's just say the majority form White Dwarfs.

Bethany: That makes sense, okay.

24:38

Jocelyn: Yeah, so David and I worked together on a paper recently which, which is kind of a cool bit of, of detail about neutron stars, so we should talk.

David: Right. So, uh, remember we talked earlier about short gamma ray bursts. So, short gamma ray bursts, uh, consist of two neutron stars merging, and so when they merge, uh, they spiral in towards one another and, uh, they some closer and closer together because they emit gravitational waves which carry off energy and angular momentum. Um, so when these guys, uh…

Jocelyn: So as, as they're, uh, as they're orbiting closer and closer together, they orbit quicker and quicker around each other so they start off kind of going around each other slowly and then as they tighten, the orbit tightens. They move closer towards each other, they go faster and faster and faster and they get closer and closer and closer together and eventually they're gonna crash together and that crash is going to lead to what we think is, uh, a cause of the short gamma ray burst.

David: Right. So, um, what—the paper that Joc and I recently wrote together, we, uh, we noticed that, um, as they're sort of spiralling close to each other—these are very, very dense objects and they basically gravitationally pull on each other as well, and they, um, they cause a tidal force on each other just like the Earth and the Moon sort of tidally pull at each other as well. Um, the tides occur with increasing frequency as these things orbit faster and faster and faster, and now it turns out that neutron stars have resonant frequencies, just like any other object. It has frequencies at which it naturally likes to, to oscillate at, just like wine glasses *wine glass chime* have natural frequencies that they like to oscillate at.

Jocelyn: How convenient that you had a wine glass ready for that!

David: How convenient! And you'll notice that if I drink some of the Two Buck Chuck, *wine glass chime* the frequency changes!

PAUSE

David: We can cut that out.

Jocelyn: No, no! Keep that in! It's very important because we can learn how much Two Buck Chuck is in each neutron star!

Bethany, David: *laugh*

26:39

David: So, each neutron star has its natural frequency, just like a wine glass, and if you're pulling at it with these tides *at* the resonant frequency, um, of these particular modes that Jocelyn and I found on this neutron star, then the neutron star crust, this solid, very, extremely tough crust, can shatter and cause a flare. And, um, just like we can learn a lot about what a wine glass is made of and the structure of a wine glass by what frequency an opera singer can sing to the wine glass and shatter it at, we can learn a lot about what the neutron star is made out of.

Jocelyn: *laughing* That's really how most wine glass attractions go.

David: That's true.

Jocelyn: you get a convenient opera singer, have them sing something.

Bethany: Now I can just picture you guys wearing those viking hats with the braids while you're writing your paper.

Jocelyn: We, we do that, usually.

Ben: Oh, I should use that, uh, that illustration for the thing with—

Jocelyn: Yeah.

David: Yeah, sure.

Ben: They had a mock-up illustration of an opera singer, uh, neutron star shattering and adjacent neutron star with singing.

Bethany: That's pretty cool.

Ben: Yeah, it's cool.

Bethany: Alright.

27:37

David: So, just like an opera singer can shatter a glass at a—when it's—if, uh, if she sings the right note, the neutron stars, when the tides hit the right frequency, they can cause the crust to shatter, and this shattering causes a flair, um, which, turns out, may be a good explanation for these particular—what are called "precursor flairs" before gamma ray bursts, where, a few seconds before the main gamma ray burst occurs, you see this, uh, very short flair.

Bethany: And so that's the crust of one shattering right before the, the stars themselves collide? Is that the idea, or?

David: That's the idea.

Bethany: Okay.

David: Yeah.

Bethany: Cool.

David: So, so it turns out that if we can figure out the timing and the frequencies at which these crusts shatter, we can learn a lot about the nuclear physics, um, of the neutron star.

Jocelyn: So, this is an example of one of the ways that we learn about all this crazy neutron star structure, is trying to explain little details of the astrophysical observations with models and then turning around and then using—saying, “well, what do these details mean about the model?” So, there’s all sorts of cool stuff that we see neutron stars do. We see their spin change as they’re, uh, the, the spin, the magnetic field of the neutron star is powering various radiation that’s taking energy away from it, and the speed of the spin decreases over time. So, you can talk about how that happens and how it’s explained by different properties of the neutron star.

David: There are neutron stars that have giant magnetic fields, *enormous* magnetic fields, and those can undergo certain flares and oscillations that we can learn a lot about the materials and how stuff behaves under strong magnetic fields that way.

29:22

Ben: Alright. Time to end it. Thank you, Jocelyn and thank you, Dave. You’ve pleased me. Your efforts have borne fruit, and that fruit is sweet. Here is some fruit, Jocelyn, for your good work on cores, here is a Granny Smith apple.

Jocelyn: Om nom nom om

Ben: And Dave, for your good work on crusts, here is a watermelon.

David: Arrgh arrr

Ben: Alright. I would like to thank—

Jocelyn: *laughing* What kind of eating was that, Dave? Sorry.

Ben: He was eating a watermelon.

David: Yeah.

Jocelyn: That was, like, choking on watermelon.

David: That’s ‘cos I didn’t have a knife, I had to break my way in.

Ben: Yeah, it was impressive.

Jocelyn: Good...good job. Wow.

David: Jaw strength, we call it jaw strength.

Ben: So, I'd like to thank my guest. Thank you, Bethany Murray, for coming on the show.

Bethany: No problem.

Ben: I hope you had fun.

Bethany: I had fun!

Ben: I hope you enjoyed interrupting nerds.

Bethany: Yeah!

Ben: Yyou asked really good questions. Everybody was impressed.

30:18

Ben: Okay, uh, so everybody, my tiphyter fans, you can email us: barn@titaniumphysics.com, or you can follow us on Twitter at @titaniumphysics. You can visit our website at www.titaniumphysics.com or look for us on Facebook. If you have a question you'd like my Titanium Physicists to address, email your questions to tiphyter@titaniumphysics.com. That's T-I-P-H-Y-T-E-R at titaniumphysics.com. That's the fan website. You guys, the fans, are tiphyters! And if you are physicists and you'd like to join my crew and be one of my Titanium Physicists, email physics@titaniumphysics.com, we are always recruiting. If you would like to leave a review on itunes, it would increase the traffic to the show and people will find it more easily. The Titanium Physicists Podcast is a member of Brachiolope Media. If you've enjoyed the show, you might also enjoy "Science, Sort Of" or "The Weekly Weinersmith." Check them out! The intro music is by Ted Leo and the Pharmacists and the end music is by John Vanderslice. Good day, my friends, and remember to keep science… in your hearts.

31:36

[Outro song; *Angela* by John Vanderslice]