Episode 75: The Undeniable Outward Push
Physicists: Dr. James Sylvester, Hannalore Gurling-Dunsmore

Transcribed by Denny Henke

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

1:44

Ben: It is important that you understand that nothing in this Universe is insignificant. There's no breed of object or thing which does not have the capacity to accomplish amazing feats. What's that? Did I hear you mention the humble photon. Did I just hear you tell me that photons have no weight and carry very little energy and the most they can do is shove an atom around but never shatter it? That they can move electrons around but they never lay a finger on the meat of the atom, it's dense impenetrable nucleus? Did I hear you mumble then about the pitiful neutrino? The byproduct of nuclear reactions but of almost no weight or significance, destined to pass through the Earth like a ghost and wander the Universe with almost no hope of even twisting the path of an electron or atom?

Well, let me tell you about how the largest stars in the Universe die. A star is a story which gravity tells matter. It's a story of thermodynamics. It's a story of progress. A cloud of gas up in space collapses on itself from the effects of its own gravity pulling itself in and as it does so it heats up and as it heats up it glows and as it glows it looses energy to outer space. There's never a moment of it's life when it has more energy than it did before it collapsed. The ratchet of thermodynamics means that it's always destined to collapse and never expand because it's always loosing energy out into space.

Now, the denser it gets the hotter it gets and atoms start to squish together. Hydrogen atoms become helium, helium becomes carbon, carbon becomes oxygen and oxygen becomes silicon and silicon becomes iron. And each step gives you a heavier element. Each step releases more energy which is also destined to radiate out into space. The bigger the star is the faster it all happens. Stars are stories that gravity tells matter. The story says that lighter elements become heavier elements. The story says that everything is going to end up in the middle, clumped together. The story says that it is all inevitable. That everything is going to join the middle and turn into iron and cool down.

But if things get hot enough this story always fails to unfold in this way. The outer part of the star will explode outward, emitting light and launching an envelope of gas into interstellar space. It's a famous event, you've heard of it. It's called a Type II supernova. So, who is responsible for this? Which character, which particle is responsible for overturning the inevitable crush? It's the humble photons and the pitiful neutrinos. At the core of the star the photons become so energetic that they shatter the nuclei in the iron core and dramatically change the politics of pressure and gases which dictated everything up to that point. And the neutrinos, the neutrinos are made in such flooding abundance that they push their way out, driving the explosion. So sure, we might think on our provincial planet, around our provincial star, that neutrinos and photons are inconsequential but remember that they are the key players in the most dramatic events in the Universe.

5:00

It's important that you understand that nothing in this Universe is insignificant. Today on the Titanium Physicists Podcast our topic is Type II supernova.

So, speaking of the inevitability of exciting events, there is a book coming out, *Soonish*, about technologies which are going to rock our world in the near future. The book was written by two friends and past guests of the show and I'm super excited to have 1/2 of them back. Today's guest is the co-author of the book called *Soonish* as well as the author and artist of the *Saturday Morning Breakfast Cereal* web comic. Welcome back to the show Zach Weinersmith!

Zach: Thank you.

Ben: So, Zach, today I have assembled two favorite Titanium Physicists, in a new and interesting combination. Arise Dr. James Sylvester!

James: RRRRRaaaaarrrgh.

Ben: Dr. James got his PhD from Queens University in Kingston Canada and he's currently a researcher in stellar astrophysics at Uppsala University in Sweden. And arise Hannalore Gurling-Dunsmore.

Hannalore: Rowrl.

Laughter

Ben: Hannalore got her masters degree from Caltech and she's currently a researcher at NASA's Jet Propulsion Laboratory and she's an expert in structure formation in space. Alright everybody, let's talk about big booms in the dark!

So, why don't we talk about these supernova things. Zach, do you know what a supernova is?

Zach: Ah, yes, but not substantially beyond what you said in your introduction so I'm, ah, I'm excited to learn more.

Ben: So, supernova are really, really, really, really bright things that happen in the night sky. And the interesting bit here is that they were cataloged before we had any idea of what they were. Essentially, ah, so, the famous jerk astrophysicist Fritz Zwicky and his collaborators, they were cataloging all these different, really, really bright temporary explosions.

Nova means new, so it's a new bright thing that wasn't before. Ah, they're essentially big explosions in space that don't last all that long but they are as bright as a galaxy. So, even if one happens in a far, far off galaxy we will still be able to see them. Um, and so they were cataloged before we had any idea of what they were. So, mostly when people talk about supernova they are talking about the thing we were talking about in the introduction. A star blowing up, right. But that's called a Type II supernova and the reason is, essentially, when they were cataloging the phenomena, they weren't listing them in any particular order. So, a Type I supernova is when there is a star and it has a companion star and if that companion star is a type called a white dwarf it won't be heavy or big enough to kind of explode but if it has a companion star sometimes a companion star kind of shoots gas or dust onto it and then as that white dwarf gets heavier and heavier and heavier sometimes it can go critical and blow up. So, that's a Type I supernova. The type we are talking about today, Type II comes about when ah, you have a star and it's really, really big and it reaches the end of its life and it explodes, okay?

Hannalore: You also can get that Type 1B and Type 1C. The B and C, indicate commonalities in spectral behavior, just for, like, people's personal edification I guess.

Ben: Long story short, the supernova's that we're used to talking about, you know, somebody will be on Star Trek and they'll be like there's a supernova happening nearby, that's usually Type II.

Zach: Yeah, so, if I were in Star Trek, Type II and Type I would both be super predictable, like, you would be able to time them, like, just by looking at the spectral analysis or something like that?

Hannalore: So, there's something called light curve, which is basically just a plot of luminosity coming from a star over a period of time. And Type 1As pretty much have identical light curves. And so they all behave very, very, very similarly. So, the difference between Type 1A and Type 1B and Type 1C, is when you look at the spectrum, not just the luminosity but the frequency which can tell you what's getting absorbed and what's not. And that can thus tell you what the composition of the star is, we have is in a Type 1A there is no hydrogen in the spectrum which tells us that the hydrogen envelope is gone. Which is why we think that they happen in binaries because in order to strip the hydrogen envelope rapidly enough to see them as often as we do, basically that needs to be getting stripped by a companion star rather than it just getting exhausted. Whereas a Type II has hydrogen in the spectrum and then within a Type 1B has no Balmer hydrogen lines and it also has pretty much no silicon lines but it does have strong helium lines. And then Type 1C don't have hydrogen, helium, or silicon.

Zach: So what causes the second star in the system to strip particular elements?

Hannalore: Gravity. Um, so, it's accretion.

Zach: Yeah, but, I mean like, how does it know to pick hydrogen and silicon, say, instead of…

Hannalore: Oh, of course. This is because hydrogen is the outermost shell of the star.

Zach: Just because it's so light?

Hannalore: Yeah. And it's also what a star starts off as.

10:00

So, let's go a little bit further back. So, there are gas giants and there are stars. And they both are gravitationally bound balls of gas in the night sky. The difference is that stars undergo fusion. And they start off as just hydrogen. Maybe a little bit of helium. But they basically just start off as hydrogen. And that hydrogen undergoes fusion. As its undergoing fusion it eventually, so just as burning a log will deposit ash, the hydrogen fusing will deposit an "ash" of helium and that creates this next shell within this star which is, you know, closer in because it needs to be in a region with more energy and is therefore, hotter in order to get that fusion. And so that's why. It's because the hydrogen is the outer shell both because it's the lightest and also because it was there first and everything else, in order to exist, has to be further in where it is hotter and more energetic.

Zach: So, you said in Type 1C you wouldn't see silicon in the spectrum, is that right? So, how would it get something heavy like silicon out?

Hannalore: The thing that's a little tough about 1Bs and 1Cs is they are a little bit harder to see. Like, for Type 1B and Type 1C, because those are less massive stars, so it just might never get hot enough to fuse down to silicon.

Zach: Oh, I see, so it never made the silicon in the first place, it's not that it got stripped.

Hannalore: Right.

Zach: So, with both Type I and Type II is it like you couldn't tell what was going on from a snapshot of the spectrum but if you had like, you know, a continuous sequence over some amount of time that you could tell what it was pretty readily?

Hannalore: If you got a snapshot of the spectrum and you knew at what temporal region in the light curve that that snapshot was from, yes, you could tell if it was Type 1A, Type 1B, Type 1C. But if someone just handed you a spectrum and said this came from a star at some point in its life cycle, it would depend on how pronounced the features are. Something that's just kind of neat just going back to what Ben was saying is, you know, we've seen Type II supernova throughout antiquity. They are actually recorded. And so it would have looked, basically like a new star appearing in the sky. You know, of course, at that time people took that sort of thing to be an omen. Now we take it to be, you know, the death throes of a star.

Zach: So, like, if you were there how long would the new star persist in the sky?

Hannalore: So, the light curves from a supernova really only last about a year. The peak of that lasts for about two months and then from there it drops pretty precipitously.

Zach: It's more linear. Like does it spike for two months and then slowly, it fades away quickly? I bet that would be really freaky, ah, if you didn't know what it was.

Hannalore: Oh, yeah, so many things in the sky were terrifying, I'm sure, at the time. And I think that's probably why they looked at them to be omens. I mean, think about the eclipse, that would be horrifying. Just for a few minutes, every, you know, generation or so the sun goes away.

Zach: Even today, like, it's hard to predict supernova Type II?

Hannalore: Yeah, so, so it depends on how detailed of a prediction you are making. For example, we're able to look at the spectrum of the star Betelgeuse in the Orion constellation and say that one should be going supernova pretty soon and we actually expect to see that happen within the next 5 to 10 decades, so, within the next 50 to 100 years we expect to see Betelgeuse go supernova.

Zach: Really?!? And it will just be gone.

Hannalore: Well, it won't be gone quite yet. We'll get a little bit. Um, so we can look at a spectrum and say yep, this star is going to go supernova sometime pretty soon. We can kind of give you an idea, is this star young, is this star middle-aged, is this star old? But we can't time it, we can't say and on this exact day at this time the flare should happen. So, I guess it depends on how precisely you mean by predict.

Zach: I mean, within the life of a star, getting it within a few decades is pretty tight it seems to me.

Hannalore: Well, I mean, so the reason why you can do that is because, actually the time frame of the end of the life of a star is actually super, super quick. So, um...

Ben: Ah, okay. Hydrogen burning lasts tens of millions of years. Helium burning lasts millions of years.

Hannalore: Carbon lasts about a thousand to 10,000 years. Neon lasts about a hundred to a thousand years. Oxygen is less than a year and silicon is days, that's it.

Ben: At this point in the game I think maybe we should back the truck up and set it up properly on the tracks of exactly how the inside of a star works.

James: So, as Ben already mentioned, ah, in his introductions stars have very different lives. Um, you have very small stars, very large stars. And typically I like to think of stars, they are sort of analogous to musicians. So, you can have very quiet, precise, classical music musician who will have a very calm life and who will probably live for quite a long time. But then you have these rock and roll stars that have very fast lives and they tend to die younger. And this is kind of what happens to stars.

15:01

You start off with the very small, cooler temperature stars and these are the stars that have very long, stable lifetimes. And then, if you look at the more massive stars, these are higher, also, in temperature. These have very short lives and also they tend to end more violently. So this is where the sort of analogy of musicians can come into play. So, if you look at the stars in reference to, for example, temperature and color, they sort of follow certain trends. So, if we talk about the more massive stars, these are the stars that have higher temperatures. And also, these are the stars that, generally, when you look at them, visually, they are bluer. So this is a very blue stars and then we have middling stars. So these stars that have temperatures around, ranging, just to give an example, 10,000 to 5,000 K. It's quite a long range there but it gives you an idea. And our star, the Sun, is sort of in the bottom of that range I mentioned. And this is quite a very small star. Not particularly massive but for us it's very lucky because it has a very long lifetime. It lasts for 10 billion years, well, that's the average lifetime. And so, this is great for life because, ah, if it was one of these rockstars as I've coined them then we probably wouldn't be here already because the star would have already blown up and done something quite nasty. And then when you get down to the cooler stars, these are the redder stars that have temperatures around 3,000 K. So these are stars that last for quite a long time and have very stable lives that end in a not particularly exciting way. One thing that I like to draw people's attention to, particularly when we look at the stars, is that I talk about the color. Now, people instinctively think that, why are the hotter stars blue? Because, you know, people maybe think that blue is a cooler temperature. And I usually get people to think about, ah, if they did experiments in high school with a bunson burner, I certainly remember, ah, my teacher telling me that the yellow flickering flame was the safer flame and the flame that was blue and violet was the hotter flame to avoid. So, that's always a way of linking the temperatures and the colors, blue stars are really hot, so yellow stars are sort of middle range and then we have some sort of redder in color stars which are the cooler, less massive stars. So, that's kind of how the stars are kind of thought about in a population sense and then the evolution of such stars can be quite distinctive. So, very small stars, nothing very violent happens, they end up in a state which we call a brown dwarf. Ah, slightly larger stars can become red dwarfs and in certain situations they can evolve into white dwarfs. And then we have medium sized stars and these evolve from yellow dwarfs into red giants and they can become planetary nebula in certain situations where you see these very interesting structures in space as gas is blown out from the star and they can end up in a white dwarf. And then when we get to the big stars, the rock and roll hero's that we're speaking about, then we start with these blue giant and as it evolves it can go to a red super giant and this can end up in a supernova as we're going to discuss in detail. And then as they evolve further we can either get neutron stars or a black hole, depending on the mass of the star in question. So, that's kind of how, very simplistically, how the stars differ in the sky. So, they're all different and they all lead different lives.

Hannalore: One of my favorite science facts is the reason why plants on Earth are green is our sun actually emits, most strongly, green light. And the thing is you might think, oh, hey, shouldn't plants be wanting to absorb that green light rather than reflect it to harness that energy for photosynthesis. But it turns out that the energy flux is so high that it would damage the cellular structures of plants. So, reflecting the green light is actually a way that plants protect themselves from the damage from that radiation because it's just got so much energy and so the absorption spectrum of chlorophyll has a strong peak in the blue light. Which that light is utilized for photosynthesis and then the red light actually also has a small peak and that's used for orientation of leaves. So…

Zach: That's awesome. I didn't know that.

Hannalore: Yeah! Science is cool.

Zach: This is totally not on topic but could you, like, make a super plant that can withstand all the energy and take all of it?

Hannalore: I mean, I'm sure that you could. I don't know how you would do that.

Zach: Like mutant chlorophyll…

Hannalore: As a result we can expect that plants on other planets would be different colors depending on what their stars emit most strongly. So, whenever people talk about colors of stars I always like that, because, now whenever I walk around and I see green plants which is not as common as you would think because I live in Southern California, but, you know, then you think about it and it's kind of a cool thing.

20:06

Ben: So, there was a, ah, who was it, was it Lord Kelvin who tried to calculate the age of the sun? There was a mystery about the age of the Universe and the sun. The presumption was that the reason that the reason the sun was hot, it was clearly not burning, like, it was clearly not burning wood. The sun is clearly not made of fire but it's really hot and so the question was, why is the sun so hot and one idea was that the sun was just hot because of thermal interactions. So, it started off as a big cloud of gas. It collapsed down but as things collapse down, you know, essentially everything is falling towards the middle, gas particles bump against each other. That turns into thermal vibrations, that turns into temperature, right. So this definitely would cause our collapsing ball off gas to get really hot and then if it was hot it would radiate energy out into space. And then the question was, how old is the sun if this is the process that is causing it to be hot. And the answer was that the age of the sun was way, way, way to small. Like, isotopes on the Earth suggest that the, ah...

Hannalore: It's the Kelvin Helmholtz, it's the Kelvin Helmholtz timescale and it's just basically the gravitational potential energy/luminosity and it should be about $3x10^7$ years.

Ben: Right. So, 10 million years, right. And that's no time at all cosmically. So, we knew that this couldn't be right because if this was the reason that the sun was puffy and bright, that the sun it would have exerted all this energy and would have collapsed smaller and been cooler and dimmer as a result. And so the question was, what's causing the sun to be bright? What's causing stars to puff up the way that they do? And the answer is, in the end, it had to be nuclear fusion. So, particles inside the sun colliding. Like, two hydrogen atoms has a higher mass than one helium atom but you need two protons to get together to make a helium atom and so $E=MC^2$. The difference in their masses as two hydrogen atoms become a helium atom, get's turned into energy, thermal energy photons. And so the release of energy from nuclear fusion is the reason our sun hasn't run out of heat.

Hannalore: Yeah. And that's on a nuclear time scale which is this energy released through fusion over luminosity. And that actually gets you to the right order of magnitude. Like, that symbol of the calculation gets you to the right order of magnitude of the age, like, how long our sun will live.

Ben: So, the interesting beast here is what's causing this nuclear fusion. You know, nuclear fusion isn't something we can achieve in a controlled way in any type of efficient way on Earth because it just requires immense temperatures, immense energies, immense pressures to overcome the electrostatic force and get two protons close enough together that they'll stick together. Using the strong force...

Hannalore: The big reason why we're struggling so much with getting fusion to work on Earth, actually, is that we can't confine the plasmas well enough. So, the hottest plasma's that we make are made in something called a tokamak. All you need to know about a tokamak is it is a certain geometry of this reactor. And the problem is is that we can't get the magnetic filed strong enough and fine tuned enough to keep the plasmas from running into the sides of the tokamak and cooling off. We can get the plasmas to a high enough energy momentarily. It's just that then they cool. So, this is actually one reason why room temperature and what we call high temperature superconductors, are super exciting is because that could eventually help us with getting fusion which, if we get fusion, tada, our energy problems are solved. Especially because fusion reactions actually don't produce the same kind of harmful byproducts as fission reactors. And actually, what's really cool, is you can line the walls of a functioning tokamak or functioning fusion reactor with the byproducts of fission and it would actually make the fission byproducts, essentially, harmless.

Zach: Yeah, actually for the book we wrote we actually did a fusion section so I'm more or less up on the depressing state of fusion research. It was the one section we had, because we were mostly doing like, emerging future stuff. Usually the people in these fields are kind of upbeat and/or crazy whereas in fusion, in fusion they are a little more staid and, like, pessimistic. Which is not surprising given that ITER is going to take, whatever it is, 20 or 30 years to build and like, maybe work.

Hannalore: It won't. Basically, like, the problem with ITER is that the simulations that we did for designing it are way, way too old and as we have improved our simulations all of them are basically showing that ITER is not going to work. ITER is going to be online pretty soon actually, I think within a decade or so. But, the thing is ITER has cost so much money that when it fails it is really going to be hard to get funding for as improved version.

25:05

This is why I got out of fusion, was like sitting at Oxford one summer and just listening to all of these people talk about all the ways ITER isn't going to work and I just was like, this is not a good career move, I feel like.

Zach: I kinda feel like researching soured me a little on just the general idea of international consortia for mega projects like NIF got built much more quickly. It was NIF so, like, whatever, but it got built quickly and way cheaper. And like, it failed faster and it seems like ITER is just a mess keeping funding together between however many nations it is.

Ben: So, I've got a question. Can they do that thing that LIGO did? They new LIGO wasn't going to work for the first ten years of it's operation, right?

Hannalore: The difference is that LIGO was always meant to be exploratory. Like, knowledge for knowledge sake. And ITER is, essentially, supposed to be an engineering project. The funding for ITER was given because we were supposed to be getting, like, a sustainable and eventually, cheap energy source.

Ben: So, they can't just go, well, you know, now advanced ITER is coming online and we fixed the things that won't work and in five years we're going to have it.

Hannalore: I mean, we can try, it's just a question of if we can convince the politicians because the problem is that we've been saying that we're 5, 10, 15 years away from fusion for a few decades now.

Zach: The really depressing part, to me, was like, even if ITER works great, what that means for the world is that there is a $30 billion type of reactor that you can build and $30 billion, for reference, is like, the cost of 15 conventional nuclear fission reactors. Like, even if it works, the capital expenditure math doesn't add up unless someone really fixed the cost problems.

Hannalore: I mean, a part of this also, is the fact that fission reactors are actually pretty safe if you let scientists design them. The problem with Fukushima was that they let business people make decisions on what the storm wall was going to be rather than listen to the scientists recommendation but…

Zach: Totally agree. Yeah. And can I say, for reference, like the upper limit case is that 1,500 people will experience premature death as a result of Fukushima which is like...

Hannalore: But, the word nuclear is scary. Nuclear is a scary word.

Zach: This suddenly became like, a political episode, ah, I assume this is all getting cut, right?

Hannalore: Every, every episode is a political episode. Science, unfortunately, is politicized.

Ben: The moral of the story is nuclear fusion is something that requires immense pressures, immense temperatures. It's really hard to do and confine. But, on the inside of a star, in the middle of the star where the pressure is really high and where it's really , really hot, nuclear fusion can happen. And so, the story of the stars that James was telling you where a star will puff up, turn into a red giant, or a star will puff up really big and turn into a red super giant and explode, what happens to a star is, essentially, dictated by what kind of fusion is happening in the core. Long story short, if your star isn't heavy enough you can't get any fusion in the core. In fact, our star is barely heavy enough to get fusion inside of it's core. Fusion happens in the core of our sun only be the virtue of quantum tunneling.

James: So, basically, we were talking about the giant stars. Right, so, for example, red giants. You start with a red giant that has enough heat to fuse helium into carbon so you get these two fusion processes occur in the core. And then basically what happens is, at some point, ah, the star runs out of helium so then it goes into a more complex situation. So, it starts to collapse and heat up and this causes the outer layers of the stars to expand and cool and you end up with basically these onion shells that we were talking about earlier. And so, in these shells you have, in what we now call a massive red supergiant, you have a hydrogen burning shell, a helium burning shell, a carbon burning shell, an oxygen burning shell, a neon burning shell, silicon burning shell and then an iron core. These supergiants have high enough pressure and temperatures that they can fuse these elements heavier, for example, than carbon and oxygen and this is where you have this sort of onion layer sort of structure going on. This is the stars that will eventually end up in the supernovas that we are discussing today.

Ben: Long story short, you end up with a temperature and pressure gradient inside these heavy stars and depending on what phase of its life that it's in, you're going to get nuclear fusion happening at different locations. So, at the very start, everything burns hydrogen in the middle and that energy is what holds the ball of gas aloft. If it starts to run out of hydrogen, the pressure and temperature of the gas in the middle can no longer hold the weight of the star above it and so it starts to collapse down.

30:01

And if it's heavy enough, if the star is big enough, um, the temperature an pressure in the middle can exceed the point where it can start burning helium. And this procedure happens over and over, depending on how massive the star is. So, it's possible for a heavier star to start to burn out all of the helium in it's core, because it's going to run out of helium in its core first. Because its core is where it's temperature and density are the highest. So, when it runs out of helium to burn in the middle of it, it's going to start collapsing down again. The pressure and density in the middle is going to increase, it's going to start burning, it will start combining carbon atoms, nitrogen atoms, oxygen atoms. And the idea here is that it is going to run out of fuel for this fusion in the middle parts first. And so what you have happen is essentially, one of these really, really big stars, you'll end up with two concentric shells. Outside of a certain radius it'll still be hydrogen burning but inside a certain radius it'll be helium burning and then when inside that radius, in the inner core, it runs out of helium to burn it will start burning heavier and heavier elements. Each stage of this procedure can only happen if the star is heavy enough for the pressure in the middle to exceed them as temperature and density if the star isn't heavy enough it just won't burn those heavier elements and it will just kind of settle down and keep on collapsing. And so these bigger stars, concentric down into the middle where it reaches iron. You know that thing I said before where if you combine two atoms of hydrogen, you end up with an atom of helium and the atom of helium has a lower mass than the hydrogen and so that difference in mass turns into energy. Once you reach iron that's no longer true. You can combine two iron atoms and the resulting atom that you get from that will be heavier than the two atoms that made it up. And so it's no longer energetically favorable, it no longer releases energy, this fusion procedure. And so these giant cores of stars stop burning once they reach iron and so you end up with a big ball of iron in the center of the star and then nuclear fusion in concentric circles as we get out to the farther radius. So, let's talk about how that goes wrong.

Hannalore: So, the first thing that I want to say is it might not be entirely obvious why we keep using a massive star synonymous with a hot star. In order to think about that, let's step back to something that I think a lot of people are familiar with, is the ideal gas law. And the ideal gas law is pressure x volume = some multiplicative constant x the number density x the temperature. And so, in a massive star the pressure is higher because there is more mass. This is just the pressure from the gravitational force of the star on itself which is holding the star together. And as a result, as that pressure increases so is the temperature going to increase. What temperature really is is the kinetic energy of the particles of matter. So, your electrons are bouncing around faster and faster, things are able to fuse. So this is why the mass of the star ends up translating to temperature. So, along similar lines, your iron core of a massive star, the reason why it doesn't contract immediately is because it's supported by what's called electron degeneracy pressure which comes from the Pauli exclusion principle which states that fermions, that is to say, particles with half integer spin, ah, cannot occupy the same region of space with the same energy level at the same time. Alright, that's pretty intuitive, I don't think anyone here is occupying the exact region of space at a given point of time as anything else. But, this is not some law that can't be broken. It's just something that, in most regimes, it's stronger than any force that's pushing things together but stars are really massive.

Ben: The way to think about this is, there's essentially a limit on how many electrons you can put in a box. Essentially on the inside of a star it's electrically neutral but it is a plasma. There's lots and lots and lots of electrons and they are running everywhere. But there's the same number of, kind of, positive charges from protons So, you're familiar with the Pauli exclusion principle? You learn it in high school when you're talking about, like, putting electrons on, like, atom diagrams, right. So, you draw the shells and you're like, every shell of this atom gets two electrons and you can't put anymore than two electrons on a particular shell because it violates this principle. So, essentially there is a limit on how many electrons we can stuff into this box at a certain pressure. The deal is that inside your stellar core only one electron can have each, kind of, defining, well, quantum number, defining its energy, right? Each additional electron you shove into there has to have a higher energy than the previous ones and you end up with an overall, kind of a pressure because you can't have any more low temperature electrons. All the low temperature electrons are already in there so the more electrons you stuff in there the denser it gets.

35:02

These electrons are going to have to have really high energy because all of the lower identities are taken and so they're going to kind of push back and so you have, you get a tremendous amount of pressure. And now is the photon thing. The idea here is that photons, particles of light, they don't usually, say, shatter nuclei. Like, you never hear of a light where, like, you shine light on a helium particle and it splits it into two hydrogen particles. But, it gets so hot that you get really, really high energy photons if the temperature reaches a certain point. And these photons are capable of smashing iron nuclei into pieces. And so, when they do that, you end up with a bunch of protons flying around. They're not iron anymore, they're just random protons. And in those high pressure situations those protons can get squished together with some of the free electrons to make neutrons which are, well, electrically neutral. But, the important thing is, these neutrons, they pull electrons out of circulation. And the problem was that these electrons were degenerate, it's called. Them, as a community, were what's holding up the center of the core. So, as soon as you reach that limit, suddenly the core loses a ton of its electrons and in doing so its pressure drops and the core can't hold itself up anymore and so it collapses.

Hannalore: And so this is the beginning of the intuitively titled core collapse process. So, we loose this electron degeneracy pressure and as a result we have nothing pushing back against that gravitational force of the core. And so it starts to contract and it keeps on contracting. The thing is if the inward pressure is so great that it overcomes the outward pressure of electron degeneracy there's not much that's going to stop it until you get to length scales of the nuclear force. So, all this matter is falling in, this happens over the course of a few milliseconds. And then we get to the regime of where the nuclear force which is usually attractive and it holds nuclei together, it becomes repulsive. Now, what's really, really cool about this is that we actually don't know a lot about the nuclear force in this regime. And a part of the reason is that the only place that this really happens that we know of is during core collapse. We can't replicate these conditions in a lab. At least, certainly not at this point. And so, we don't know much besides the fact that the nuclear force becomes repulsive. And this is one of the reasons why core collapse supernova are one of the most interesting laboratories in the universe. Is because it is this completely wild phenomena that is happening. So, the nuclear force actually starts to push back. You can think of it as essentially, the neutrons pushing against each other the same way that electron degeneracy pressure is the electrons pushing against each other. Again, I just want to really drive home, this is a lot of mass. I mean, that's how we're able to overcome the electron degeneracy pressure. And yet, the nuclear force pushes so hard against further compression that it is actually able to send the mass of the core back out with a ton of kinetic energy and this is what we're going to start calling the shock. So, you with me?

Zach: Me, yeah, yeah, yeah.

Hannalore: Yeah, cool, awesome. Okay, so, the shock is now moving outwards but the thing is is that stars are really big. And the thing that was really collapsing was this iron core and so the outer shells take a minute to realize, oh hey, wait, we can start moving inwards because we don't have that pressure pushing out against us. And you know, a part of that is because information can only travel any faster than the speed of sound in a plasma. So, the information that the outer boundary of the core has moved inward, that's not going to propagate to the outer shells of the star any faster than the speed of sound in a plasma. And the reason why it's the speed of sound is because of pressure waves and the speed of sound is how fast a pressure wave can move through a medium. So, what we have are the outer layers are still falling in and the now bounced core giving a shock that is moving out, right? At some point these are going to meet and because there is a lot of mass falling in that's going to have a lot of what we call ram pressure. And that ram pressure is enough that we stall that shock which again, you know, let's really thing about this. The shock has so much kinetic energy that it's able to overcome the electron degeneracy pressure to move outward. But that's how much pressure is coming in from the in-falling matter, is that it's able to stall that. Which is kind of wild I think. So, now we get this battle of the wills, right. And, this is where things take one of two paths. One, is that the in-falling matter has so much ram pressure that it overcomes that shock and it just piles on and it propagates all the way down to the core and eventually, and by eventually I mean within a few milliseconds, overcomes the Chandrasekhar limit, and so those give you a black hole without an explosion.

40:05

And those are called failed core collapse supernova. So, that's what happens when the shock fails to revive and fails to keep moving outwards. Sometimes though, the shock does revive. Now, how does this happen? Again, remember, we have a ton of kinetic energy coming with the shock from the bounced core, right. In order to stall that you need a lot of pressure from the in-falling matter. What's giving you all that pressure is super high density of matter. And because of that high density, where the shock is stalled actually becomes opaque to neutrinos. That is to say, neutrinos, which essentially have zero mass, they can't find their way through, they can't wiggle through little gaps in the matter. And so now, how I kind of visualize this is a little bit like putting a lid on a pot of boiling water. At first you're not going to hear anything, you're not going to see anything. It's just, the lid is going to get a little steamy. But, if you leave it on there and you keep that water boiling, that lid is going to start rattling, right? Because there's enough energy from that steam that's pressing up on that lid and it starts moving the lid around. So, this is what's happening. This is what's called the gain region. This is where the neutrinos are, essentially, boiling. Basically, ramming against the shock front and then going back and they are getting more and more and more energy. And eventually, if the ram pressure doesn't overcome the shock the neutrinos are what revive the shock. So, as the neutrinos gain more and more energy, just like the steam gains more energy as you leave the lid on the pot of boiling water. Eventually these neutrinos have enough energy that they are able to push back that shock, push that outwards and that's said to be the revival of he shock. And depending on how much energy those neutrinos have, you're going to get different observable phenomena. But, that's how you get a successful Type II supernova. And you're going to end up being left with a neutron star. That's what's going to happen with the core that didn't, you know, explode out.

Ben: Let's review what's going on. Essentially, we start out with a normal star. It's in equilibrium. Essentially, all the pressure at each point inside the star is supporting the weight of everything above it. Suddenly the core collapses, you get all these electrons being absorbed by all these protons that were knocked free by the really hot photons, the iron core collapses down. It looses electron degeneracy pressure but there's another type of pressure that can sustain it at a much smaller density so the core collapses down, becomes a really hard ball. The matter above it starts to flow inwards so it's gaining momentum as it falls inwards and then it hits the solidified core and it bounces outwards and this produces a shockwave that moves outwards. The shockwave can't just move outwards and blow the shell off the star because matter is still falling in. I want you to imagine, like, it's Black Friday, slowly coming up, right? Imagine we're at one of those big Black Friday sales. Imagine, like, we're in a cold place like Ontario or Michigan where all the malls have, like two sets of doors, like an airlock. An outer door and an inner door into the store. So, everybody is in the parking lot, there's a big crowd of people wanting to get into the store. The people closer to the door are more closely packed because they are all excited to get in. Farther out it's less closely packed. And then they open the outer doors and the people start to flow in. They're like "Yay, the store's open!" But the employees haven't unlocked the inner doors so the people flow into the airlock and hit the inner doors, they bounce off the doors. But there's still a crush of people that have heard that the store is open and have started filing in. So the people telling the people behind them, the word of mouth news that the store isn't open traveling outward, that's the shockwave. And so you end up with a shockwave moving out but it has to pass through this group of people that are moving inwards. There's an issue here where sometimes the shockwave can't travel out fast enough because the matter flowing inward is moving too quickly. There's a couple issues here like how the speed of a wave depends on the density. The more dense it is the slower the sound wave travels. So, what happens is, essentially, we end up with a shockwave front. All of the energy is building up in this one location where it is trying to move outwards but it can't because of the crush of matter moving inwards. Sometimes this crush of matter falling in wins and it drags the shockwave down into the middle, it's called a failed core collapse supernova. But the really exciting, the really bright ones, are when the shock wins. But what could cause the shock to move outwards fast enough with all this matter falling in trying to pass through it? And the answer is, it starts to cook. It, you know, a shockwave, it's a pressure wave and so the matter at the location of the shockwave is really, really, really dense and the density of matter is so high that neutrinos can't pass through. But inside that radius the density and the pressure and the temperature is so high that they are making neutrinos like gangbusters. They're making lots and lots and lots and lots and lots of neutrinos and these neutrinos just keep building up and building up and building up. And if they build up strong enough they can propel the shockwave out farther, faster, extra hard. It's possible for a star to loose up to 10% of it's core rest mass in neutrinos in that procedure.

45:00

So, we think that supernova are really bright in terms of luminosity but that's nothing compared to like the crazy neutrino flux that is required to blow the lid off the pot in Hannalore's expression. So, we have actually detected neutrinos at the same time as we've detected supernovas. In the 1987 supernova we had some neutrino detectors there...

Hannalore: I think it had to have been Kamiokande...

Ben: Yeah. We've detected neutrinos that were produced in this process and it's totally bonkers.

Hannalore: Something that's equally important that supernova do, and I would say, more exciting, is that, as we were talking earlier, we make all these heavy elements in the process of the star burning. And those elements still exist as the star collapses and explodes. And that's actually where we get the heavy elements that make up our bodies. Like, the calcium in our bones and the iron in our blood. It's like, we are literally made out of these elements that were produced in, in the process of getting to a supernova.

Ben: Ah, stellar fusion can only account for material up to iron, right?

Hannalore: Yeah.

Ben: And the fact that we have elements on the earth that are heavier than iron is because it was all formed in the shockwave of a supernova.

Hannalore: Yes. Everything that we get that's much heavier beyond iron, we have to get the process of the supernova. And actually, there's a couple of different processes that things can go through to drive that nucleosynthesis. One is the rapid process or R-process nucleosynthesis. And then there is the slow process nucleosynthesis and the P-process nucleosynthesis which is the, the p stands for proton. So, the rapid process is this process by which successive neutrinos are captured before the particle can beta-decay. So, basically the reason why it's called rapid is that it gains neutrons before it can fall apart. So, it has to happen pretty quickly. R-process is where a lot of really interesting, heavy elements come from. Because you're able to, basically, cram things together and make a bigger thing really fast and that happens pretty much just in supernova. So, besides the heavy elements that are made in these supernova, we also get compact objects, coming, ah, resulting from supernova. Ah, in particular, core collapse supernovas. So, if the explosion fails, if the supernova fails, you end up with a black hole. What happens is that you get all this matter piling on to what's left from the in-falling core. And if you get a high enough density of matter, especially in that small a space, it's going to collapse into a black hole. And that's how we think we get ah, what we call stellar mass black holes which are black holes that are black holes that are 10 to 100 solar masses. Any questions there?

Zach: About, no, that part makes sense. Yeah.

Hannalore: Okay, if the shock is successfully revived the core becomes what we call a proto-neutron star and as matter falls back on it, because not all the matter is going to get unbound by the explosion. This ends up becoming a neutron star. One thing that is really cool about neutron stars is that they are these big balls of super fluids. Which, generally speaking, we, we've only been able to make superfluids in the lab, generally at really low temperatures. Though we have recently made some pretty massive gains in what we call high temperature superfluids. So, that's something that's really wild about neutron stars is that they are really high temperature superfluids that come about from, like, this extreme high density that comes from a bunch of matter raining down on this bounced core. I don't know, like, do you have questions about...

Zach: Ah yeah, I was, ah, but the weirdest part was the, um, repulsive, strong nuclear force thing. You said that was not well understood, like, why are you sure it's the strong nuclear force doing it? Is that from models or...

Hannalore: Yeah, I mean, part of it is from models it also a part of it is the fact that there's not much else it could be at those length scales there's not much that it could be. Like, that's the regime of the strong force, the nuclear force. And that's empirical, like, that's just...

Zach: I see.

Hannalore: Well, it's what we got. We know that supernova happen...

Zach: Right. That's interesting.

Hannalore: ... and we know...

Ben: Yeah, one thing you can make an argument about is that the insides of these stars, when the core collapse starts, a lot of the protons in the system are going to get changed into neutrons. And so, its like, jeesh, how can the neutrons support themselves? Electrons can support each other, you know, they've got, you talk about cool-off affects and stuff like that, you can't, they'll push against each other. Neutrons are electrically neutral. And so if you've got a big ball, a big ball of neutron matter the only repulsive force you can think of, if they are all collapsing down on each other, are neutron degeneracy pressure.

50:05

And sure enough, I mean, you blow the outer parts off of a star and what's left behind is a neutron star. And we can see and observe neutron stars and get some sense of what they are made of and how they work, right? I mean, pulsars are just neutron stars. It's not the case that we've never seen the result of this collapse because one possible end state is it blows off the envelope and then we get to see whatever was in the middle of the star before it exploded.

Hannalore: Exactly. Basically we know that we start off with a star, we know approximately what stellar composition is when the star is burning. And then we know that explosions happen and we know what we're left with. From hydrodynamics we know a little bit of what's happening, you know, that causes the collapse and then what happens with the explosion, at least on a macroscopic scale. And so, as a result we can kind of deduce these are the only things that are left there, these are the only things that we have found and so as a result it has to be the nuclear force. So, it's a little bit of a process of deduction.

Zach: Interesting, so it's like, is it conceivable that there's something unthought of that's going on there or is this pretty well established?

Hannalore: It is possible, it's always possible that it's something just totally wild but the thing is is that the strong force, in a lot of its relevant regimes, has been pretty well tested and has obeyed the standard model pretty well. And so, if it were to be something totally different it would have to be something that would essentially reduce down to the strong force at slightly larger scales.

Zach: If it was something like, mysterious other force we would have found it in a particle collider or something?

Hannalore: Ah, yeah, it is very, very likely we would have found it in a collider or we would have seen some evidence of it. Well, it's totally possible, it's unlikely. And when it comes to cutting edge science that's really all we can ever say, right? Is, well, it's possible that it's something totally different but let's go ahead and if we're hearing hoofbeats, let's first assume that it's going to be horses and not zebras and certainly not unicorns.

Okay, so, another thing that's really, really cool about supernovas. Okay, so, alright, we get our small black holes, we get our neutron stars and we get our heavy elements from these Type II supernova. Another thing that we get are cosmic rays. And these cosmic rays are really just high energy particles streaming through space. We can actually detect them here on earth, we detect them with, we detect them with various experiments with like Super Kamiokande in Japan, assorted, certain neutrino detectors like Homestake which is in a mine. Actually a lot of these are located in mines but we...

Ben: Well, that was wonderful. Thank you James, thank you Hannalore. You've pleased me. Your efforts have born fruit and that fruit is sweet. This was fascinating so here is some fruit. Ah, James, you get the explodiest fruit, it's a popcorn.

James: Nice. Hmmm, tastey.

Ben: And Hannalore, you get the core collapsiest fruit, you get a soufflé.

Hannalore: That's not even fruit. That's a baked good.

Ben: Just eat it!

Hannalore: Nom, nom. Delicious.

Ben: Alright, I'd like to thank the guest of my show, Zach Wienersmith, thank you Zach!

Zach: Always a pleasure.

Ben: Alright, so go see Zach's webpage, the *Saturday Morning Breakfast Cereal* web comic and also you can buy his book on October 17th. It's called *Soonish*, it's about emergent technology and it's fascinating. Alright everybody, thank you very much!

Well, that was really fun. Well it's time for the announcements. First, again, please give us an iTunes review or, tell other people about us online. Why? Because people keep their deep love of physics secret and they want to know there is a show like ours online but they don't know that we exist and also, you know, having first hand testimony from people they know saying that the show is enjoyable might convince them that there is some fun to be had learning physics.

54:07

Thanks to the donations that we have received over the last few years I was able to hire a professional to redesign our website. It looks absolutely fantastic and it should work as well on your phones and tablets as it does on your computers. So, why don't you mosey on down, over to titaniumphysics.com and have a look. Ah, I need to rewrite some of the things on the website to fit the new style so I'd be happy to get your feedback about what you think could use a little bit of work.

On another note, we're still humbly soliciting your donations. Your donations go to paying our server fees and our project to transcribe all the episodes when they come out and buy everybody new microphones. I know I needed to replace my old microphone just this summer, aahoowwwhhh. Alright, so, if you'd like to you can send us one time donations through PayPal off of our website or you can go to our sweet Patreon site and give us a recurring $2 donation. This particular episode of the Titanium Physicists has been sponsored by a collection of generous people. I'd like to start by thanking the generosity of Preston Huft, Heather Richards, Albert Calumn, Sky Debry, Shiban Patel, Shumular Hymlick, for their donations. I'd also like to thank Sarah Stradler, Louise Pantalino, a guy named Ben, a Mr. Mathew Lombare, a fellow named Aioosh Singh, a David Murtle and Mr. Ryan Foster, Janetco Fifenberg, Steve Smetherst, Magnus Cristisen, Bart Gladys, and Mr. Stewart Pollack. Our emperor Courtney Brook Davis, Mr. David Lindells, Mr. Carl Lockhart, our eternal friend B.S. and Randy Dazel. A Miss Tina Roudio, the enigmatic Ryan, a gentleman named Crux, and Gabe and Evan Weans, David D and Dan Vale, a Mr. Alex, WTL, Mr. Per Proden, Andrew Wattington, Mr Jordan Young and John Bleasy. A Brittany Crooks, James

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

Hannalore: But, the thing is is that it’s really, really hard in the simulations to get neutrinos alone to get this explosion to revive. Because, again, neutrinos, do not have a lot of mass and they, you’re having to get a lot of energy. So something else that’s interesting is that, and that we’re starting to have the computing power to test in simulations, is non-symmetrical affects. Ah, so, it’s easiest to simulate something that’s basically symmetric because it’s basically one dimension, right? It’s just, you just have to worry about the radial position. But now we’re simulating fully 3D and so you can get these asymmetric affects. So, one example is called the standing accretion shock and stability, also known as SASSY. It’s thought that these kind of create a sloshing mechanism that can help with the revival of that shock. Sort of like if you were to then take that pot of boiling water and then grab the handles and kind shake it back and forth, that would start helping shake off the lid a little faster, right? And one reason why we think this sort of thing has to happen is because when we see these observations of neutron stars and a lot of these smaller stellar mass black holes is they actually have what we call momentum kick which is to say that there has been momentum imparted on these objects and if it were spherically symmetric that wouldn't happen. It would all balance out. But these are given an initial kick of momentum and from what we can tell things like SASSY are the most likely to impart that.