Episode 46: Burning Twice as Bright with Alasdair Stuart

Physicists: Ben Tippett, James Silvester and Vicky Scowcroft



The Titanium Physicists Podcast

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Transcribed by John Robinson

Ben: Oh, hello, old friend. It's good to see you. Let's talk about this word "fascination". It describes an unquenchable urge which compels our hearts to quest and be captivated. As long as there are elegant explanations to complicated phenomena, science will never lose its romance. Over the years I've traveled the world indulging in my fascination of physics and now I find that a new hunger has woken within me – a fiery need 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!

[1:47]

Ben: The most astounding thing about the universe is that we can understand it. Ancient astronomers noticed that the night sky was full of little points of light which marched across the sky every night. Most of them retained their position relative to one another as they marched across the sky over the course of the year. Now, given how they moved, ancient Greeks thought that they were little bits of ethereal fire mounted on a great celestial sphere which enclosed the earth and rotated around it. Finally, an explanation for what these little bright things are. They are stars! So, when somebody asks you to tell them about a specific star, you can only really tell them three things right off the bat: its position, its color, and how bright it is. So you can say that's a very bright blue star, or that's a very dim red star. Now, the marvelous thing about the 20st century is that astrophysicists figured out all about how stars work. I mean, even though we only really know two physical attributes about each star, we have millions of stars look at. And it turns out the stars only really have three things going on. They've got a mass, and they have an age, and they have a chemical composition. And those three things determined entirely how they look to us. So they're actually pretty simple objects. Well, figuring out their secrets required the knowledge and techniques of literally every branch of physics, from thermodynamics and gravity to quantum mechanics and particle physics. But yeah, physicists today have a pretty clear picture of how stars work. It's amazing. I'm amazed! Now, stars are these monstrous engines of destruction. They turn the light, pure and virginal gas from the Big Bang into heavier, useless, crummy elements.

Speaking of matters of crushing, I'm reminded of the *Pseudopod* podcast, a horror short story podcast were similar things are regularly explored. The host of said podcast is Alasdair Stuart, the gentleman blogger and essayist. Each horror story is bookended with one of Alasdair's essays, reminding us that the monsters are us. He's currently working on a shared world series of 15,000 word fantasy novel written between three authors. The part he's currently working on is a steampunk version of the end of the Avengers Assemble. Now, he's currently also writing the tenth Dr. Sourcebook for the Dr. Who role-playing game. Welcome back to the show, Alasdair Stuart!

Alasdair: Thank you for having me. How are you doing?

Ben: I am so great. Alastair, for you today, I've assembled two of my most powerful titanium physicists. Arise Dr. Vicky Scowcroft!

Vicki: Raaaar!

Ben: Dr. Vicky got her PhD. from Liverpool John Moores in the UK. She's currently a postdoc at Carnegie Observatories, where she works on the Carnegie Hubble program. She also has a knitting podcast called *One Starry Knit*, and we'll have a link to it on our web site if you want to find it. Now arise, Dr. James Sylvester!

James: Brk-ooock!

Ben: Dr. James got his doctorate from the Queens University in Kingston, Ontario, where he studied stellar magnetism. Until recently, James was a manager at the Scottish Dark Sky Observatory, and has a podcast called *Astrarium*, where he and David Warrington introduce us to astronomy. All right everybody, let's talk about Beyoncé. Alright, Alasdair. So I mentioned before that stars are really simple objects, and you might have trouble believing me about that because they seem crazy, right? The universe is full of them, and they're huge. I mean the Earth is a complicated enough thing, and its tiny compared to these big monster stars. So how do we know that these stars are actually pretty simple? It's a strange argument to make. And the idea is that, well ok. It's like I said before, each star that we look at has a color and a temperature. It doesn't really matter where we look in the sky. All stars kind of look, well, they don't look the same, but you're not going to look down in the southern hemisphere and see all green stars, and then the northern hemisphere you're only going to see yellow stars, right? I mean, the distribution of stars and their colors and stuff looks pretty uniform anywhere you look in the galaxies. So, the important thing is you look at a star, and when it's got a color and it's got a brightness. And the color is the important thing here. Your stove top, right? You turn on an element and it glows red, and that means that it's hot. But if it glowed blue or glowed white you would know that it was even hotter, right?

Alasdair: Mmm-Hmmm.

[6:05]

Ben: So there's a relationship between the temperature of an object and what color it glows. So right now, everything around us looks... I'm looking at a black telephone right now. It looks black. It's not glowing any particular color, but if I looked at it with like an infrared camera, I would see it glowing in the infrared. Any object that has a temperature will glow a certain color according to that temperature. So the deal is, each of these stars that we see in the sky has a color associated with it. Some of them are red color like... Betelgeuse is a red star. Some of them are white. The Sun is a white star, right? And there are blue stars out there. And each of these different colors correspond to a different surface temperature, right? So, a red star, its surface is a lower temperature than our white star, and a blue star is a hotter temperature than our white Sun. So the deal is that if you wanted to sort all these stars out, like I said, you know what a star's brightness is, and you know what temperature it has, based on the color. And so you can sort it. In essence, you can make a big diagram. You can draw two axis. Make the vertical axis the brightness and the horizontal axis the temperature or the color, and then you can just look at different stars and you can see where on the diagram they live. A bright red star will be in the upper right hand side of this diagram. A dimmer blue star will be in the bottom left hand corner of the diagram, and so on. So, you might imagine if stars were really, really complicated objects, if there were a whole bunch of crazy things going on inside them, there were a lot of diverse processes, what you would imagine is as you looked at all the different stars around you in the sky and put them on your diagram, your diagram would be blanketed with stars because there could be a star of each color and each brightness. But that's not really what happens when you do this population survey, and you throw them down on a diagram. What you see is they organize themselves into fairly specific rows and lines. This is the telltale sign that what's happening on the inside of stars actually are fairly simple process even though it's probably happening at a monster scale, its crazy large. We're dealing with crazy amounts of energy. The physical processes inside the star aren't really all that complicated, because if you did, you'd see a lot more diversity in this diagram. So, these diagrams are called H-R diagrams. H-R stands for Hertzsprung-Russell. It's illustrative right now to talk about where the star populations looks like on this diagram. So imagine that you have a place mat....

Alasdair: Ok.

Ben: You're going to eat dinner, and you've been given a lot of peas, and you don't like peas. So you're going to play with them. So imagine that you have a place mat in front of you. So the horizontal axis running along the edge of the table, that's going to be your red-blue axis. So to your left hand side, that's the blue color. Things to the right hand side, the further to the right it gets the more red color it gets.

Alasdair: Okey-dokey.

Ben: Now, vertically, the edge of your place mat closest to you is dim, and then the further up the place mat you go, the brighter the stars are going to correspond to. Ok?

Alasdair: Ok.

Ben: You are essentially going to look out in the night sky and put a pea down every time you see a star of a specific color and a specific brightness. So, what I want you to do is imagine that to have a spoon, and you're going to put the spoon diagonally from the red dim corner pointing at the bright blue corner. We call that the main sequence. So, you take a handful of peas, and now you pack a whole bunch of peas around that spoon. And then your mother comes in, and you say, "Screw off, I'm an adult! I can do what I want."

Alasdair: Ha ha ha ha.

Ben: So these correspond to fairly young stars. They're in their first phase of their life. They're not teenagers yet. And the deal is, when a star is born, when it collapses in from dust, when it's burning hydrogen as our Sun is, what it will do is it will line up along this line. And it's really interesting because it means that, you know, there's a clear relationship between the brightness and the temperature. In this case, the brighter it is at first, the bluer it would be. Ok. So, that's the main sequence. That's where your spoon is. I want you to take your knife now, and I want you to lay your knife horizontally along the top of your diagram. So, where your spoon ends horizontally.

Alasdair: Ok, I got it.

Ben: So now you're going to take another handful of peas and you're going to pack it along those.

Alasdair: Ok.

[10:25]

Ben: These represent the giant stars. They are really, really, really big, and they can come in an assortment of colors. Really bright blue stars... super giants. But then a lot of different stars like our Sun might one day, they enter a phase called the red giant phase where right now they seem to be, you know, normal size brightness, white color light. Eventually, our stars fuel will start burning a different thing, and it will puff up, it will get really big and bright. And so, the stuff on the right hand side of your knife, the peas over there, that's kind of the red giant area.

Alasdair: Ok, I got it.

Ben: Now, there are two other little populations of stars. You can see there are the white dwarves. Those live in the kind of blue dim side of things. So just take a handful of peas and put them kind of beneath your spoon, beneath that main sequence. So, to the left of it, somewhere. So there are some stars that are bluish colored but they are also fairly dim. And now there is going to be a packet of stars kind of to the right... Are there any other ones, Vicky?

Vicky: So you've got the giant branch coming off from the middle of the main sequence to the top right. And then the super giants are like the horizontal line at the top. So the Sun will become a red giant, and then the super giants are even bigger that, even brighter than that.

Ben: Oh, so you're saying that the red giants aren't at the end of the knife, they are under the knife.

Vicky: They are under the knife. They're right of the spoon.

Ben: There to the right of the spoon, but under the knife.

Vicky: Yes.

Ben: Their old, so they're getting plastic surgery.

Vicky:  Yeah.

Alasdair:  They're old, so they're under the knife?

Vicky:  They're the fork.  From the middle of the spoon, like going up towards the end of the knife that is not attached to the spoon.  Then that would be where the red giant bunch is.

Ben:  So, the deal is that any particular star will start off somewhere along the spoon, along the main sequence.  And then they will move, it will evolve, this H-R, this Hertzsprung-Russell diagram, to a different point to one of the other populations, depending on how big it started, and how old it is.

[12:35]

James:  I think it's worth pointing out that describing a stars life is a little bit like describing the transatlantic flight.  You have a lot of activity the first few parts of the journey, and then you have hours and hours and hours of nothing, and then you have a bit of excitement at the end.  And this is almost what's happening with these stars.  You have very active, quick processes, generally speaking, that happens during its formation.  And then the stars spends a lot of its life time on the main sequence in a very sort of stable state where nothing really changes.  And this is most of the stars life.  And then at the end, suddenly something interesting happens, and this varies depending on the size of the star.  And that's also a very short process.  So, though the main sequence part of the stars life is the longest, in essence the most boring part, and it's what's happening before and after that's different.  And as you say, it's the size it was in the first place that determines what form the exciting action takes.

Alasdair:  Right.

James:  And so talking about evolution, depending on the mass of the stars.  So very low mass stars, stars like the Sun or smaller, it's worth pointing out, I don't think we've really mentioned this yet, as are the Sun, is a relatively small star.  Actually, I think it's worth pointing out, actually, the interesting and important for life because the smaller stars live longer than the massive stars.  So massive stars are really like rock stars.  They have very short lives, and they die violently, where our star, the Sun, is actually very sort of calm.  It has a very measured life.  And this is good for us because if we were orbiting around a massive star, we wouldn't be here now.  So, it's plus for us sort of a sideline, but it kind of paints a picture that stars like the Sun are roughly speaking in the middle of this main sequence, and they are relatively calm. So a star like the Sun, its later stages, you'll get what becomes a red giant. So, in the case of the Sun, probably in about a billion years, the sun will start this process of slowly expanding. In fact, the Suns life is probably going to be for another four billion years, but as early as one billion years from now, they'll be some moderate level of expansion. And as it gets closer towards the end of its life, it really will puff up, and it will get so large in fact it will probably encompass the orbit of the Earth inside. So it goes from what it is now this massive giant which we call a red giant. So it puffs up really big for a time, and when it gets really close to the end of its life, this massive inflated red balloon, if you want to think of it like that, will suddenly just disappear back down, and we will end up with what's called a white dwarf which is sort of a very small object indeed. So that's what happens to a sun-like star, roughly speaking. Then, when we come to more massive stars, these processes get a bit more violent. So I think Vicki wants to talk about the more massive stars a little bit?

[15:25]

Vicky: Yeah. If you got like something that's much bigger than the Sun, then it's going to carry on up the main sequence, but it's going to do it much quicker. Like James was saying, it's going to evolve much quicker. But once it gets up the main sequence, everything is going to go faster. And it's going to burn all these elements, and it's going to burn more stuff and everything is going to be more violent. Eventually, it's going to run out of stuff to burn. It burns hydrogen, and then burns helium, and as it runs out of all these different elements to burn, it burns the next heavier thing. But eventually you get to like iron, and you can't do anything with that. That's like the heaviest thing it can do. So it has to stop. Then there's nothing left to do, and there's nothing to hold up the star anymore. Before, you had all this pressure from this star burning things to hold up the star and keep up the energy that was being pushed out with the thing that was holding up the star. That just basically switches off. So now the star would just collapse in on itself. So you've got this huge massive star and now all this stuff that was being held up is now collapsing in onto the center of the star. Once that collapses in, it causes this massive shockwave, which then blows off all this material, and that's a supernova. Then there is this giant explosion, and that's it. So if you're a big star, you're going to explode, which is kind of sad.

Ben: Let's take it back a little bit. So, the main idea here is depending on what its mass is, a star is going to evolve in a slightly different way. There are two things at play. The first thing is, the heavier the star is, the faster is going to burn through its fuel, and live its life, right?

Alasdair: Ok.

Ben: So, imagine your Hertzsprung-Russell diagram again. So your place mat, you've got a diagonal spoon covered in peas, and up above it, you've got a knife covered in peas... the super giants. And then you've got a pocket of peas over here... the red giant stars. And a couple of other pockets... Dead stars, stuff, ok? So the deal is, imagine that you had a population of stars that all formed at the same time. What those are going to look like is, they're going to look like a distribution of peas along the knife and along the spoon. And then starting from the very tip of the knife, the stars are going to burn out all of the hydrogen fuel, and start the next phase of their life. The moral of the story is they are going to strip away from the main sequence and the super giants, and move into the red giant phase along the spoon. So starting at the top left hand corner, you're going to take some peas off and as time goes on, you're going to take the peas and move them from the spoon over into the red giant pile. Then slowly, you see all of the stars stripping away from the main sequence as time goes on. The moral of the story is you can look to see a globular cluster, a population of a couple thousand stars that formed around the same time, and you can figure out how old that population of stars is by making one of these diagrams, and looking to see at what point along the spoon these pieces are being stripped off. The further along down this spoon you go, the older the group of stars must be. It's pretty clever.

Alasdair: Wow.

Ben: Yeah.

Alasdair: That's really cool.

Ben: I know, right? And you can say, "Hey, how old is that population of stars?" And you can be like, "Well, there's this many rock stars, and they're in old folks home." You can look at essentially how many have burnt out at a certain time, and that tells you how old the population is. So H-R diagrams are wonderful because on the one hand, they reassure us that stars are fairly simple objects, and there's kind of a life cycle to the stars. And then, the other thing they tell us is they kind of inform us about the different properties. It tells you how things change depend on mass. And so they allow us to come up with a pretty good picture of what's happening inside the star. And that itself is an amazing story. It's the story of attempting to hold back gravity. So, let's talk about exactly what happens in the life cycle of a specific star. Imagine you have a star, maybe a little bit heavier than the Sun. The Sun is a little bit light. Well, it's pretty light. In fact, it's glowing all the time. That was a pun.

[Laughter]

[19:23]

Ben: Usually, when we talk about stars, we talk about their masses in terms of how many times the mass of the Sun it is. So for instance, if a star is less than 10% of the mass of the

Sun, it won't be able to glow, essentially. It will just kind of collapse into a big, brown Jupiter-ey thing and float around in the heavens forever. So the deal is, imagine you have a great big cloud of gas, cloud of hydrogen, there's some helium mixed in, but a big cloud of gas in space. There's nothing around it. What will happen is the gas has a little bit of temperature. So the temperature causes kind of a pressure inside it because the gas is made out of little atoms. Temperature is just a reflection of how fast the atoms are moving inside of it. So they're all kind of bouncing around in a certain thing, they won't collapse down into something. It's kind of like if you want to have a party and too many people have their own ideas, you can't get them to settle down to go to Chuck E. Cheese's, right? But if that cloud is large enough or if the temperature is low enough, what will happen is the fingers of gravity will start to take effect, and the cloud will start collapsing down under its own weight around some central point. The question we always have to ask ourselves when we are talking about star evolution is what's keeping the gas from falling into the center? And at first, the answer is nothing. There is a little bit of thermal pressure but usually in these cases where it collapses down, the thermal pressure is insufficient to keep it puffed up. So it starts to collapse down under its own weight. It takes a while... collapse, collapse, collapse, collapse, collapse. And then it makes a ball of gas. And then the question is what keeps that from collapsing down any further? And the short answer is temperature does an OK job at first, but space is very dark and it's very cold and I mentioned before that anything with temperature is glowing. So anything with temperature is radiating photons, is radiating energy out into space. Over time, the ball of gas becomes less energetic and it collapses more and more and more and more and more.

Alasdair: Ok.

Ben: Now. There is a thing from quantum mechanics. Have you ever heard of the Pauli Exclusion Principle?

Alasdair: I have not.

[21:25]

Ben: Oh! The Pauli Exclusion Principle says that two quantum mechanical objects can't be identical. And so by identical we mean live around the same place, having the same momentum, having the same mass, the same particle type, having the same spin. There's a bunch of numbers we use to qualify a particle, and this rule says that electrons, each electron has to have its own set of numbers. And the deal is, as your cloud of gas gets smaller and smaller and smaller, if the gas isn't hot enough or if it doesn't have any energy, if it doesn't start burning hydrogen, what going to happen is, it's going to pack down so small that the repulsion of electrons from one another, quantum mechanically, is going to hold this thing aloft. And so, as the gas collapses, it can't collapse down to a point, because eventually this quantum mechanical effect kicks in, and it will just hold it aloft. And so you end up with a ball, a cold ball, sitting out in space.

Alasdair: Does it have a specific and internal structure, or is it just a sphere but below which it cannot get any smaller?

Ben: Yeah. It is kind of a sphere below which it can't get any smaller. It doesn't have a structure like a crystal, exactly. It doesn't have a lattice structure. But quantum mechanically, it has a structure. It's called electron degeneracy. Essentially, it's kind of like desks in a classroom. Each electron sits at each different quantum number. And so all of the quantum numbers up to a certain point are filled up. So there is some structure there, but it's not like it's a diamond.

Alasdair: Got it.

Ben: And if the cloud of gas isn't massive enough, this will be the end state. And equivalent structures are the end state of a bunch of different stars if they are not heavy enough to burn all the different possible things. So this is essentially the default. If it is not heavy enough, it just becomes a ball sitting in space not doing anything. But if the thing is heavy enough, something fantastic happen, because if it is heavy enough then as it shrinks down, then the pressure in the middle gets higher and higher fast enough that the temperature in the middle will reach 10,000,000 degrees Kelvin, and that's hot enough for hydrogen gas to fuse. There's a little bit of trivia on this. Hydrogen gas... I mean, you know what a hydrogen atom is, right?

Alasdair: Oh, yeah.

Ben: At these temperatures, the hydrogen electrons have slipped off. So they are just protons flying around. The deal is, there's two positive charges. Positive charges repel. It takes a crazy amount of energy to get these protons to stick together because of this static electric repulsion. But, this quantum mechanical effect called quantum tunnelling kicks in where the laws of nature says, essentially, they're a little bit leaky. They say, "Well, if the particles are moving fast enough but not quite fast enough to make these things merge, you know, quantum mechanics says that some of them will merge". So, anyway, the moral of the story is, they stick together and they merge into helium. The process is a little bit messy, but, you start out with hydrogen and you end up with helium-4, which is two protons, two neutrons. And the deal is, that there's a lot of energy that you can get from fusion. I mean, there's way more energy in fusing two hydrogen atoms together than, say, splitting a uranium atom. But the problem is that you need ridiculously high temperatures for this to happen. So in the center of the Sun, you have this big cloud of gas. It's been collapsing. The center gets hot enough for two hydrogen atoms to fuse, and they do, and they release energy. They released a photon. And that photon says, "Oh, I want to go out to space where it's cold and dark. I hate it here where is all cramped". And so it bounces its way out to the surface and then this pressure of all these migrating photons, as they move from the center of the star out into space, are essentially what holds the hydrogen atoms aloft. And it's what keeps our Sun from collapsing down into itself.

[25:01]

James: One thing that hasn't been mentioned, is that the different types of stars have different structures. So, if it's smaller than the Sun, actually very small stars, are completely convective. So that means if you were to travel through the star from the surface to the core, throughout, it would basically almost be analogous to a boiling pot of water throughout every single layer. But as you get to bigger stars, you only have convection in the core and then most of the stars is what's called radius. It's almost like you go from this boiling water scenario to something just, you know, photons streaming and radiating through. And then some stars have what's called a convective core with a bit of radiative envelope so the bit between the core and the surface and they'll have a little bit of convection on the surface. And in fact, that's what's happening in the Sun. It's not completely convective. It has a convective core, a radiative envelope, and then a bit of convection in the surface lies what we call the photosphere. And that's why when you see pictures of the Sun that has this sort of, almost much like a, it's a very orange-ey, looks like bubbled water. If you see these high res pictures of the Sun it almost looks like, you know, a boiling pot of water but its red/orange-ey liquid opposed to transparent. So, that means that you get different chemical signatures from different stars. So, a star like the Sun, all the elements that are made in the center of the Sun over time they present themselves on the surface, and you get this mix. You get this almost like homogenous mix of iron and other elements. But some stars, slightly larger mass stars, stars that are about two or three times the mass of the Sun, because there are no convection into the upper layers, you don't get this mixing effect. You actually get accumulation of certain elements into almost clouds. So you go from a situation with some stars where it's completely mixed and homogenous, two other stars where we actually see clouds of iron, clouds of silicon. So this gives us some sort of indication of the different processes that are happening in the various layers of these stars.

Ben: What impact does that have on the stellar weather?

James: Stellar weather. Well, that's a good question. You mean, stellar in terms of auroras and things like that? Yeah well, the stellar weather has really more to do with the magnetic field. That's a completely different story. But the magnetic fields do have more important things to do with stars. But actually, it has some effect in the Sun because you've got this convection going on, and any magnetic fields that come out of the surface, because they're almost in this boiling water situation, the magnetic field lines get twisted around. An analogy of this is if you can imagine taking an elastic band and holding it by the two ends. Then you start twisting the ends. After a time, you're going to get the elastic band winding up, and eventually it will snap. And this is what's happening in the Sun becomes the field lines are coming out of the surface, but because of the convection, it's almost being dragged, moved to some extent. Or at least there is some kind of effect happening there, and eventually this can fling off into space. The thing is, the weather is related to the magnetic field, and the convection and the magnetic field has sort of a ‘chicken and an egg’ scenario. In some stars where you don't have much of this convection up there in the atmosphere, so magnetic field domination helps freeze everything into these spots, whereas in the Sun, it's a different situation. And I should say that the chemical spots you see in the massive stars are different to Sun spots. Sun spots relate to an area of cooler temperature in the surface which is different from a chemical spot, which is a basically a cloud of a given chemical element.

Alasdair: Got it, thank you.

[28:37]

Ben: And the convection is actually related to a fantastic piece of trivia and is more complicated stars. You have to deal with the stars convection. Integrating convection into it answers a lot of questions, and so it’s really important. But if you imagine a star is just like this homogeneous ball of puffy gas where fusion is happening in the middle. And then you say, Ok, imagine that a photon gets released in the middle. The star is a big soup of protons and electrons and all of them have electric charges. An electric charge is, they really strongly interact with photons. And so this photon, every time it encounters an electron, or proton, it's going to get kicked in a different direction. So it's going to kind of move randomly. It can't make a straight line out of the Sun. So it bounces a little bit here and it bounces a little bit there and back and forth. Over time, it eventually migrates and statistically speaking ends up out of the Sun, and then it's like, "Phew! I can move out into space, Hoo-ray!" But, the amount of time it takes to do that is ridiculous. For our Sun, 50,000 years. The plasma is so opaque that it takes 50,000 years for a photon to make it from the inside of the Sun out into space. Even though, you know, it's less than, it's not like a light minute wide, the Sun. But, you know, it kicks the light around and does it forever. So, what happens in these stars is, you essentially get... Its millions of degrees inside and only thousands of degrees on the outside. So, essentially what happens is the water in the pot example, if you heat water too quickly, you get this gradient, this steep gradient of temperatures where it really hot on the bottom of the water, really cold on the top. Instead of saying, well, the temperature, these photons are just going to bounce, all the photons say, "Screw it. We're taking an elevator up". And they make a glob of really hot plasma that then rises through the Sun. But it's super tricky. So a magnetic field is generated when you have a charge that spins, right?

Alasdair: Mmm-hmmm.

Ben: So like electromagnets are generated by taking a coil of wire and passing a current through it. So there's a relationship between magnetic fields and circulating electric charges. And because the Sun is plasma, because it's made of a whole bunch of charged particles, it's a fluid that interacts with the magnetic field because these little electrons can go wherever they want. So they can spin, and they grab, they hold on to magnetic fields. So if you have one of these, you know there's a magnetic field passing through an electron down, and in the electron decides to take one of these convective elevators up, it's essentially grabbing the magnetic field and it pulls it off, and it twists it becomes the rotation of the Sun and stuff. So you end up with this big tangled up magnetic field inside the Sun. It's one of the harder fields of physics.

James: Wow!

Ben: Yeah. And you get that thing that James was talking about where essentially..... A sun spot is what happens when these magnetic fields gets so twisted around themselves, that whereas an elastic band would break, the magnetic field pinches off into a smaller little loop. And then that loop boils up to the surface, like a... I don't know, a bubble or piece of string. As it exits the Sun, the loop is always crossing the surface of the Sun in two spots. And those are the sun spots. As the magnetic field leaves the Sun, it creates one of these coronal mass ejections following the magnetic field.

Alasdair: I didn't know that. I had no idea that Sun spots were surface extrusion of an internal structure.

Ben: I know, right?

Alasdair: That blows my mind!

[32:03]

Ben: So, one last bit of thing inside the Sun. The fusion that's happening, it's happening at a fairly low rate. Quick side... One question is, hey, we know that particle colliders… We have the capacity to make bits of gas that are as hot as the center of the Sun. Why can't we fuse hydrogen together and essentially repeat what going on inside the Sun and harness it to make awesome fusion generators and clean energy forever, right? And the deal is that I mentioned before that need this quantum tunnelling effect inside the Sun. This temperature inside the Sun isn't hot enough for the particles to formally merge. They have to rely on the subtle quantum mechanical effect to happen. So the deal is that you need a much, much, much, much hotter temperature to get reaction rates that would be useful inside of a laboratory or inside of a power generator. So inside the Sun, this fusion is happening but at a fairly low rate. But the deal with the Sun is it's huge! So even though it is happening at a fairly low rate, it is generating enough energy that on the bulk it's causing this. But there's another much crazier piece of trivia. It was called the solar neutrino problem. Have you ever heard of this?

Alasdair: I have not.

Ben: Ok. So, Homestake mine, the Homestake experiment [sometimes referred to as the Davis experiment] I think it's called. So every time these hydrogen atoms fuse, they generate a neutrino. A neutrino is a sub nuclear particle. It's a tiny little particle. It's barely got a mass. It's traveling at almost the speed of light because it is so light and it barely interacts with anything. It interacts only through the weak nuclear force which is tiny, as the name suggests. And so, what happens is these neutrinos generated inside the middle of the Sun, they don't bounce off anything because they are so weakly interacting. So any time two hydrogens fuse, makes a neutrino, that neutrino bee lines it for outer space. We can measure these neutrinos. The measurements have to be really subtle. Measuring these neutrinos would do is give you a real time sense of how fast fusion is happening inside the middle of the Sun. Now, here's the crazy bit. They measured it in a mine in the United States, and the answer was one third the neutrino rate that they expected.

Alasdair: Really?

Ben: Yeah. And they didn't know why, and they thought that maybe one possible explanation was that fusion had stopped in the middle of the Sun, and the Sun was going out, but we haven't received the news yet, right? 50,000 years for a photon to emerge from the Sun? You know?

Alasdair: Of course.

Ben: So they thought maybe the Sun had gone out but we just hadn't gotten the news yet. Of course, the real answer is subtle. The Sun hasn't gone out. The deal is, neutrinos it turns out in a Canadian experiment at Queen's University in a mine in Sudbury, Ontario, Canada. They discovered that neutrinos change their type. So, we were looking for neutrinos of one type but there are two other types they could be. As the neutrino marches from the inside of the Sun out to our detectors, it mixes itself up and changes into different types of neutrinos. So the deal is, the reason we only saw a third of the reaction rate was because two thirds of the neutrinos had turned into other types that we couldn't detect.

Alasdair: So the good news is the world isn't ending, and the bad news is that neutrinos are card sharks, basically.

Ben: [laughter] Yeah, that's right.

Alasdair: Cool.

Ben: Ok. So that's, I mean, crazy business. We thought the Sun was going out. It's not. Vicky, it's your turn.

[35:32]

Vicky: Ok. So what we're talking about is fusion, right?

Alasdair: Uh-huh.

Vicky: So once you got, you started the process, when you've got your hydrogen fusing, you've got the quantum tunnelling going on, it's like "Yeah, I'm confused. I'm awkward". So that process releases some energy, so now you can make helium, which is the two protons and the two neutrons. That's making energy, but eventually you're going to run out of hydrogen. Your main sequence is all the time fusing hydrogen into helium, and that takes like 10 billion years for like a regular star like the Sun or something. So that's like, forever. But then, once you run out of hydrogen and that's when the interesting stuff starts to happen. Now you've got to start burning heavier stuff like helium. So at this point, we've got all this helium that you can burn. One of the first things that it can do is something called the triple-alpha process, where you've got three helium atoms, and you want to shove them together to make something else. So you start basically doing the same thing as you were doing with the hydrogen, where you're like forcing them together to just shoving them all together, to like quantum tunnelling, to like make the helium. But now you're doing the helium atoms to make heavier things like carbon. And this is going to make new things like carbon and then nitrogen and oxygen by like just shoving more and more helium atoms on top of each other. But there are two ways this can go. Like big stars, you can do this. It's going to be hot enough that you can do this. You can fuse your helium together. Eventually you will get heavier elements and you keep shoving them together and you'll burn through all of these. But I think the cool thing I think is actually in the smaller stars, where it's not hot enough to do that. So you've got all this helium and then eventually your hydrogen runs out, blah blah blah. Your helium isn't hot enough to start fusing your helium together. So once you've run out of hydrogen, your star starts to like collapse back in on itself a little bit. What that does is like increases the pressure on all the helium that's in the core of your star. Eventually, the pressure will get so big on the helium that it will crush all the helium atoms together so much that we're getting the exclusion principle coming back into play again. Exactly the same as Ben was talking about before, but now with helium. What that does is eventually it just sets all helium on fire, and that's called the helium flash. And that just like blow the helium up, like all of it together. It's like super, super quick. It's like a few seconds. In star terms, that's like ridiculous. Everything else in star terms happens on like years, and this is happening in a few seconds. And you don't even see it. If you look at the H-R diagram, you can see that these stars are like shifted in the H-R diagram because of the helium caught on fire. That only happens in small stars. So I think that's cool.

Alasdair: That's very cool.

Ben: One notable thing is that deal with these larger stars is that there's always a little bit more energy you can get by combining two elements into a heavier element until you reach iron. So, you smush some helium together to make a carbon. You don't get as much out of it as you did with hydrogen, but, it's happening a lot faster. The reaction rates are happening faster because smushing two hydrogen atoms takes a long time. You need to rely on this weird quantum mechanical thing. So, even though you don't get as much energy per reaction, the reaction rates are happening a lot faster. And so, in a helium burning star, it will release a whole bunch of energy, much more energy, say, per second, then a normal hydrogen burning star. And this will cause the star to change. What will happen is, suddenly the photons moving out from the center, they're will be a lot more energetic ones, and they'll puff out the star. They will push the gas out to a much wider size. James mentioned it earlier, our Sun will probably end up eating the earth. We call those red giants. We mentioned there's a pocket of red giants on the H-R diagram, and that's kind of the destiny of a lot of these heavier stars. They will burn helium and they puff up, and it gets really, really, really big and bright, but red colored because they're not hot but they're puffy, I guess. The moral of the story is they get big, and they get red, and then they burn out of helium and so they start smushing together. And so the core collapses, the pressure increases, and the story keeps going on. If the star is massive enough, it will end up burning, smushing together heavier elements, heavier elements, heavier elements, until all that's left in the middle of one of these stars is iron. You can't do anything with iron. It takes more energy to smush something into iron then gets released. Iron is the tipping point. So uranium is much heavier then iron, and that's why if you split a uranium atom, it releases energy. So for atoms lighter than iron, if you smudge them together, you release energy. You get it?

Alasdair: I get it.

Ben: Ok. So the question is, where did all the stuff on Earth that isn't made of iron come from? You've heard Neil deGrasse Tyson and Carl Sagan talk about how we are all made of star stuff?

Alasdair: Mmm-Hmm.

[40:43]

Ben: So what happens is we talked about supernovas before already, but essentially what happens is, if a star is sufficiently heavy and if it’s run out of other types of fuel, what will happen is as it collapses down on itself, it starts to make a neutron star or black hole.  That process releases a ton of energy all of a sudden.  And so you end up with a shockwave of energy moving out from the center.  There's a ton of neutrinos, a ton of photons, a ton of everything, just a shockwave of pressure moving out from the center that blows off the envelope of the star.  Which is what you see, that's the supernova, right?  It gets really, really bright all of a sudden.  But, in that moment, the pressure is so high in that shockwave, that that's when these elements fuses into heavier things, like uranium and metals heavier than iron.  So everything on earth that isn't hydrogen or helium came from the inside of a star that went supernova a long, long time ago.  But additionally, any element that is heavier than iron came about as a result of the shockwave from the supernova.

Alasdair:  I did not know that.

Ben:  So I mean it's all made out of the very last seconds, it's like an undergraduate student who like, does all their work the day before it's all due.

Vicky:  Early undergraduates do that, not grownups like us.

Alasdair:  Of course not.  There are a couple of things that I just want to make sure I've got clear in my mind.  There is a correlation between size and color, am I right?

Vicky:  Sort of.

James:  There's a correlation between temperature and color, and that kind of relates to size because if you have a given temperature, to sort of balance, you're going to be a different size.  To put it another way, you don't have two stars that have the same size, roughly speaking, and completely different temperatures...  Within reason, if we're talking about main sequence stars, for example.

Alasdair:  Got it.  Ok, that's really useful.  Let's talk briefly about binary and multiple star systems.  What impact does having a partner or multiple partners have on the internal way out of a star?

James:  That can have quite a fundamental effect on the tunnel way out of a star.  In a binary system, you can have a situation where one thing that happens you can have mass transfer, so that means material from one star goes to the other.  So basically if you have one star that's slightly larger, it could in a sense feed off the other star.

Alasdair:  I've seen diagrams of this, yeah.

[43:09]

James:  Also, other things happen, like for example usually stars are in binary systems.  If they start with different rotation rates, that means how fast they spin, within time they will match and synchronize.  So being in a binary system causes the two stars to have similar rotation rates which can have some sort of other effects on the star.  So being in a binary system does have quite a few effects on the star.

Vicky:  So what's interesting is that most stars are actually in binary systems, or more.  Yeah, most stars form in clusters.  Most of them are actually in binary systems.  Really quite weird to not be in one.  But not all of them are going to necessarily going to be in a system where they're so close that they're going to have like a dramatic effect on each other.  But when they do, it can be like super giant.  They could have mass transfer or just like one could completely engulf the other one.

Alastair:  You point that most stars are in binary systems.  I find that really interesting because when I was growing up there's a show, I'm sure, called Horizon.

Vicky:  Yeah.

Alastair:  Which I've always referred to Horizon as science tapas.  You would get kind of a 50 minute documentary about a thing.  In one week it would be trees, and the next week it'll be the space shuttle.  And I was this kind of weird, slightly apocalypse obsessed kid which says a lot about why I've ended up working in horror.  And I distinctly remember an episode of that which dealt with the Nemesis theory, the idea that the Sun has a dark twin.  At the time, I was 13, so at that time I was going, “I’m dead.  I’m dead at some point in the next ten years.  I might have sex by the time that happens.  I'm going to have to be Ok with that".  And obviously overtime, that's been completely disproven multiple different ways, but the thing which I find really interesting is now you've mentioned this thing how most stars are binary.  That puts the admittedly pretty wacky, because I think it was even referred to as the Death Star hypotheses at a couple of points.  That puts the fundamentally pretty wacky Nemesis hypothesis in a really interesting context.  That there was actually pretty solid science behind it, it was just wrong, you know?

Vicky:  Yeah, we just probably would have known about it if we were in a binary system.  The fact that it was like hiding that would be weird, yeah, a ninja star would have been weird.

Alastair:  But like I said, looking back at even age 13, I was going,"Yeeahh... maybe.  Hopefully not".

To Vicki:  But no.  Because stars tend to form in clusters.  It's not just like a cloud that collapses into one star.  They'll be a cloud and it will form a few stars.  And they might break of, and like, you'll get a few single stars. But you would tend to get a few stars together, so it's not rare for a star to be in a binary system.

[45:53]

Ben:  Ok.  So I've got some other fun trivia for you for this binary systems.  You've asked if they can alter each other's evolution.  We've mentioned accretion, right?  So you can have two stars, and the deal is, somewhere in between them is going to be kind of a point at which the gravity from one star is stronger than the gravity from the other star.  If you have gas that moves across that point from one star, like a red giant, then other star will start accreting gas from the red giant. The cool bit is that we mentioned that lots of these processes depend on mass, so there's like a cut-off mass for supernova to happen. There's a cut-off mass for certain types of hydrogen burning to happen, or helium burning to happen. The deal is, you can get one star that's just on the cusp of going supernova but it's not quite heavy enough. And then, the other star, big, it decides to puff up, start eating its helium, and then suddenly there's mass flowing from one star onto of the other star. The other star that didn't quite have enough mass to do the thing suddenly does, and it explodes! And that happens. Those are, what? Type 1A?

Vicky: Yeah. Those are like standard, because we know at the exact mass that happens at. We know how bright it looks to us. We know how bright it actually is, so we can tell how far away it is. So we know everything about that.

Ben: Because we know how bright they are. First of all, they're huge bright, so you can see them from half way across the universe. But because you know exactly how bright they're supposed to be, you can observe them and you can tell how dim they are, or you know what color they are coming in at. You can use that to figure out how far away they are from us, and astronomers use these particular types of stars to piece together the universe's expansion rate. They used it to piece together the history of the universe's expansion, and from those, we know that the universe is accelerating in its expansion.

Alasdair: Really?

Ben: Crazy business.

Vicky: So it's not just getting bigger, it's getting faster as it's getting bigger.

Ben: Yeah. And these binaries, this binary accretion thing is the reason we know.

Alasdair: Wow.

[laughter]

Ben: Well, that was fun. Thank you, James. Thank you, Vicky. Your efforts have borne fruit, and that fruit is sweet. Here is some fruit. James, you get a kiwi fruit.

James: Oh, yum!

Ben: And, Vicki, you get a jack fruit.

Vicky: Rawwyumm!

Ben: And I'd like to thank my guest Alasdair Stuart. Thank you, Alastair!

Alasdair: Thank you so much for having me on, guys. It has been brilliant.

Ben: That was super fun. Alright. Ok, listen Ti-Phi-ters. There's four things you need to know. Firstly, leave us an iTunes review. Whenever I feel sad, I go to iTunes to look at new reviews because it cheers me up. So you better do it, because your words, they're fueling me. Ok, Second. There's a podcast out called *Podiversity*, it's on the Android phone. It's a subscription for content-based app, so it's not free like the other ones, but, it's like Netflix but for podcasts. And they pay us! The more you listen to the show, the more they pay us. So it's nice to get paid a little bit for our efforts. Third, the T-shirts! We do sell T-shirts, and they're really nice. Chelsea Anderson from Calgary designed a lot of them, and they're wonderful. Go to the Ti-Phy website and buy yourself a sweet shirt. They're really high quality. They last forever. Bethany's had one for about three years and wears it like every day. Hey, you guys, nice shirts. Fourthly, if you want to contact us, you can send us an email. My address is barn@titaniumphysics.com I look forward to fan mail, and I forward people our fan mail. So if you want to tell James how lovely his voice sounds, send me a note, and I'll pass it on. Also, we're on Twitter and Tumblr and Facebook if you want to find us. Ok, so, that's is for the main part of our show. If you like listening to scientists talk about science in their own words, you might also want to listen to the other shows on the Brachiolope Media Network. I'm gonna rattle off the shows. There's *Astrarium*. Yeah, it's about astronomy. There's *Science… Sort Of* which is about news and culture and stuff… well, science. Yeah, it's fun. *Technically Speaking* is about engineering, *Collapsed Wavefunction* is about chemistry, and there's… uhhh… yeah… So, you guys, we need a biology show. Get on that. The intro song for today's show is by Ted Leo and the Pharmacists, and the end song is by John Vanderslice. Until next time my friends, good day, and remember to keep science in your hearts.