DJORGOVSKI: All right. Let's now talk how stars make energy. And they do it through fusion of lighter elements into heavier. That's mostly hydrogen to helium. This cartoon is actually what people aspire to do in the lab, to do controlled thermonuclear fusion in reactors like tokamaks or with lasers. We were still a little far away from that.

But stars know how to do it. And the ultimate physical reason why stars can shine is that nuclei of atoms have binding edge. Because there is a strong force that binds protons and neutrons together. And the difference between all those particles separately, and then bound together in a nucleus, corresponds to energy that can be taken away, if you can make nuclei.

So if you go from 4 hydrogens into helium, you just add up the mass. And you find out that there is a little bit of an excess. And so that corresponds to the change of energy of 27, almost 28 megaelectron volts per one of these fusions, or about 7 megaelectron volts per nucleon. And since the rest mass of a proton is a little shy of 1 gigaelectron volt, that means that 0.7% of the rest mass gets converted into energy during fusion of hydrogen into helium, mc squared.

So how does that happen? The dominant process is the chain of nuclear reactions called the proton-proton chain. And it begins, indeed, with two protons, which get captured together. And then one of them does beta decay, releasing charge in form of a positron. And there is anti-neutrino comes out-- I'm sorry, neutrino comes out. And then that positron then can annihilate with electron that was left over from these hydrogens and create gamma rays, which then get downgraded in energy to something different.

So that way you get deuterium. Then deuterium can create another hydrogen, another proton, and become helium-3 isotope, missing one neutron. Similar thing happens here. Some energy has been released. Now charge is conserved. So there is no neutrino emission.

And then, it turns out that two helium-3 nuclei can fuse much more easily than a hydrogen and helium-3. That makes the regular helium-4 and releases two extra protons that can participate in the third nuclear fusion again. And so that's sort of the basic fuse step reaction. People who try to do this in thermonuclear reactors on planet Earth actually bypass a lot of the hardest initial steps and try to fuse deuterium and tritium because that'll be the easiest part.

So in reality this is a little more complicated. You don't have to remember this. But I had to show you to show you what is the real chain of reactions. Sometimes other light nuclei, like lithium or beryllium, play the role of catalyzers. Just the chemical reactions can be catalyzed by some additional compound. So it can happen in thermonuclear reactions.

So you can fuse hydrogen to helium. Then you can fuse helium into heavier stuff, like carbon and oxygen and so on and so forth. And the question is, how far does this go?

Well, the answer is it will go as high as it's profitable to do in terms of energy. So it turns out if you plot the binding energy per unit nucleon for different nuclei, the number increases all the way up to iron, with iron 56. And then starts dropping. That means fusing things up to iron generates energy. Beyond that, you actually have to put in energy to generate heavier elements.

So what happens in stars, they create chemical elements all the way up to iron. And where do the heavier ones come from? They come from supernova explosions. That's the extra energy that you need where to fuse things all the way up to uranium. And so this is why nuclear fission is done with uranium and plutonium and heaviest elements you can find. Whereas nuclear fusion is most efficiently done with light nuclei.

But even for light nuclei, this is not an easy thing to do. And that is because protons are all charged positively. Electrons are irrelevant here. So if you have a nucleus-- it could be a single proton. It could be two in helium. It doesn't matter. Another proton;s coming in.

There is an electrostatic repulsive force. And if you were just to look at the electrostatic repulsive force, it would be a sort of hyperbola going up to infinity with particles at zero size. And most particles cannot come close enough for the nuclear forces that can grab them in. And then they're purely attractive. So once you get past that barrier, it's fine.

So if classical physics were working all the way down to the nuclear world, this will never happen. But there is a phenomenon of quantum tunneling that this is intrinsic to quantum physics. That sometimes particle can go through some barrier that normally wouldn't go. That can tunnel through walls, so to speak. This is a really tiny wall.

And there is a probability that can be computed how to do this. And it's highest for the highest energy particles. And so this very specifically quantum effect is what enables occasional proton to actually pass through this electrostatic barrier and fuse with whatever's inside the nucleus.

Now, that led to the concept of so-called Gamow peak. The theory of thermonuclear reactions in stars was worked out in 1940s, more or less, by Hans Bethe, George Gamow, their collaborators. And Gamow peak comes from competition of two different distributions. You need the fastest particles you can get. The highest energy particles you can get in a thermal distribution, the tail of the Maxwellian. Because those are the ones that can do anything.

The probability of them actually interacting for fusion increases dramatically with their energy. So those are two opposing trends. And you have to multiply the two. And it turns out when you multiply the two, there is a maximum where those two trends can intersect.

So there is a particular energy for a given plasma where particles are most likely to interact and fuse into something heavier. Now that also should be somewhere where there is available energy states for the product nuclei. That actually turns out to be important for some of the heavier elements.

So this is the mechanism. But quantitatively this happens very, very rarely. Nevertheless, there are so many particles there that even with a very low probability for any one of them doing it, there is still plenty of them fusing together.

So to recap this thermonuclear reactions, the burning of hydrogen and helium is the main source of energy in stars. And it's the only source of energy in stars for most of their life, also called Main Sequence of HR diagram, which we'll cover next time. And then heavier elements, fusion happens in advanced evolutionary states for stars that are sufficiently massive they can do this.

Now, solar luminosity, if you divide it by the yield of reactions, corresponds to turning 4.3 million tons of hydrogen into helium every second. And that's a lot of mc squared. This is why you get sunburned, even though you were an astronomical unit out. So that's impressive actually.

And proton-proton cycle that I described to you is the dominant, but not the only, way in which hydrogen can fuse in helium. There is a whole another set of nuclear reactions that involve carbon, nitrogen, and oxygen as catalyzers for nuclear reactions. And they can add additional hydrogen to helium production.

No matter what, all of these reactions are very steeply dependent on temperature because temperature is proportional to energy of particles. And probabilities of fusion or tunneling rise steeply with energy. So they're very, very sensitive to the temperature in stellar cores. And the density helps, of course. The higher the density, the more targets you have.

Now, by and large, more massive stars tend to achieve higher densities and temperatures in the middle. That's kind of intuitively clear. And because of that, it's the higher mass stars that can push fusion reactions beyond helium, all the way up to iron. And then they explode.

So this strong dependence of nuclear reactions on temperature is what actually establishes stability of stars. This is sort of the opposite of the core collapse effect that we discussed for collapsing protostars. So imagine you turn on the nuclear reactions, temperature goes up, pressure goes up, temperature goes up. Then core will expand. Because it expanded, the density drops. And temperature will drop. And fusion rate will go back down. And so there is a self-regulating cycle for a given star. Because of that feedback mechanism, stars exist for a long time and don't just explode. All right.