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ANNA FREBEL: Have you ever wondered how all the chemical elements are made? Then join me as we are lifting all these data secrets to understand the cosmic origin of the chemical elements. We talked a lot about the lighter elements that are made in fusion processes in the cores of stars. But what about all the other elements from the bottom half of the periodic table? We haven't really talked about those yet. Let's do that.

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What we need are so-called seed nuclei. We have an iron nucleus here. And if we are in a situation where there is a strong neutron flux available-- and we'll talk about where that happens in a sec-- then if we have little neutrons here, and this seed nucleus is getting bombarded with these neutrons, then it's going to swell and turn into a much larger nucleus that is radioactive and neutron rich. And it's an isotope. So it has lots of neutrons in it.

And what's happening, then, because this is radioactive, it doesn't like to stay in this way. It will, what we call, beta decay, which is just a fancy word of saying that all these neutrons here are being converted, or a good fraction of them, into protons. And so we end up with a stable element that's much larger than this original one, the iron, or it could also be a carbon atom.

So this is the basic idea of how all the other heavy elements are made. An example would be barium here or uranium. Uranium 238 is technically not a stable element, but its half-life is 4.7 billion years. So for us humans, that's pretty stable. But on cosmic timescales it is not. If we want to consider it a stable, it would be the heaviest element that we have on Earth that's long lived.

And so they're all made by this so-called neutron capture process, neutron capture process. Now there are a few details that we should consider, mostly that there are actually two different ways that this neutron capture process can happen. One is in a slow way, slow n-capture. And the other way is rapid. And that refers to how fast and over what timescale this neutron bombardment is occurring.

And in the case of the slow neutron capture, the timescale is about 10,000 years. And what happens is that in evolved red giant stars, evolved red giants, in the inner layers, in some of

the shell layers, where the nuclear fusion is going on, there are a secondary nucleus into this fusion processes operating, and as a result of that, free neutrons are produced. And so they provide a steady flux of neutrons that then get essentially shot onto these seed nuclei. And so over the timescale of something like 10,000 years, heavy elements are successively built up. A neutron is added. It turns into a radioactive isotope. It decays and then we have a steady one.

You add another neutron. It will decay again. And so you build up one by one by one, all the way up to lead. That's the heaviest stable, stable element, if you take away thorium and uranium, because they are radioactive, as I just mentioned.

Now in the case of the rapid neutron capture, that really requires much more energetic and extreme conditions. And what recent research has shown is that a rapid neutron flux only operates in two locations. One is perhaps in supernovae. When the iron core collapses at the end of a star's life, it actually implodes and forms a neutron star. So there's a really dense neutron star in the middle that's a compact remnant left over after the supernova.

And in the process of making this neutron star, there are, of course, lots of neutrons floating around, and they can provide this kind of flux, operating on a one to two second timescale. So huge neutron bombardment within a few seconds, and that can lead up to a very, very fast build up of a giant radioactive nuclei here, that then decays. So you have enough seed nuclei. All of them will do vroom and then slowly decay back to the different elements that make up the entire bottom of the periodic table.

Another option is an emerging neutron star. So if you take two of these neutron stars and you have them in a binary system where they orbit each other, and if this system eventually, or the two stars in the system eventually coalesce and merge, then you also have some kind of firework of neutrons. And that can also have this rapid neutron capture going on. And so we have to add here. So either in supernovae or the proton neutron star-- I'm going to abbreviate like that-- or in neutron star mergers.

So that are all the options. And what we now want to figure out, really, is how can we put all this theory to the test, right? How can we observe this? And that's why our old stars come back into play. Imagine that in the very beginning of the universe when the first stars emerged, and maybe the second generation of stars, so not too much of all the heavy elements was present at that time. And so let's say you have a neutron star merger go off at this very early time.

The rapid neutron capture process will occur. All these new heavy elements get spilled into the surrounding. And then you form a next generation star from this enriched material. And because the universe was not too much enriched in all the other elements, we have this opportunity to observe a clean nuclear synthesis process of this R process. We sometimes abbreviate it, rapid with R, so R process. R process.

And actually this here is S process. You could have guessed that. And so at the earliest times, it is possible to observe the signature of the R process, a clean signature, as well as the S process. That is not possible anymore today. The universe has experienced 13 billion years of chemical evolution. So it's a pretty messy place out there. And so if one more event goes off, that signature just gets diluted into whatever else is out there already. But at the earliest times, we have this chance to find these clean signatures.

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