Transcript from Epic of Evolution: Life, the Earth and the Cosmos (BEP 210A)
March 15, 2000 - Lecture by Claude Bernard

Any questions from last time? All right, let me continue. We talked about what happens with most stars. They go through a stage of hydrogen burning like the sun is doing now. When that's over their cores contract more, and helium burning starts. When the helium burning is taking place the outer layers are pushed out to a very large size. That's a red giant. And when the helium burning is finished the core collapses down again. For most stars it will continue collapsing until it reaches what's called the white dwarf stage, where the electrons are as tight together as they can be (each one filling about one wavelength). And that's as much as it can be compressed, and that's where it stops. And this is true for any star that has a mass up to about eight times the mass of the sun. Such a star will end its life as a white dwarf.

Now, if the mass is greater than eight times the mass of the sun, additional things can happen. When the helium burning is finished the core collapses as before, but if it has a bigger mass the core can get hot enough that new kinds of nuclear burning can take place. If the original star is less than eight times the mass of the sun it just can't get hot enough. With more than eight times the mass, the collapse after helium burning produces enough heat to start new stages. I'll put up a transparency of the various stages of burning.

[transparency 5] Okay, so we've gotten up to the first two stages (hydrogen and helium burning). If its mass is greater than eight times the mass of the sun, you can get the next stage, which is called carbon burning, and then a series of other stages (neon burning, oxygen burning). Each time, as the previous fuel is used up, the core compresses more and gets hotter, and a new kind of burning can begin. As you see in the last column in the table, the approximate ignition temperature for hydrogen burning is 1×10^7 degrees, a 1 with seven zeroes (10 million degrees). Helium burning is 1 with eight zeroes (100 million degrees). For carbon burning to take place you need 500 million degrees, and in most stars that never happens. They just turn into white dwarfs and nothing happens beyond helium burning. But if it's big enough you will get the next few stages. You can get carbon burning, neon burning and oxygen burning in a star that is eight times the mass of the sun. And if it starts out being 11 times the mass of the sun you can even go one further stage, which is called silicon burning. That's the last kind of burning that can take place, and I'll explain why. It's not obvious why this just couldn't go on forever if the star was heavy enough. But in fact the last kind of burning that can take place is silicon burning, which makes iron and nearby elements (for example, chromium, manganese, cobalt and nickel).

Okay, let me just say a little bit of the details just so you get a feel of what's going on in these kinds of burning. For example, in the very next stage, carbon burning, reactions occur that combine carbon in various ways. One example would be carbon 12 (^{12}C) plus another carbon 12 (^{12}C) making neon 20 (^{20}Ne) plus a helium 4 (^{4}He) nucleus. That's a standard kind of thing that can occur during the process of carbon burning: You make an element with a bigger nucleus (neon). Now we've already used up all previously existing helium when we made the carbon in the first place. But when carbon starts to burn you can make some new helium. Then the helium itself can also be recycled and combined with carbon that's already there to make oxygen. ($^{4}He + {}^{12}C$ makes ^{16}O.) So more oxygen gets made in this process also.

Another example in the carbon burning stage is carbon (^{12}C) plus carbon (^{12}C) makes magnesium 23 (^{23}Mg) plus a neutron. And this is a way that magnesium, which is found abundantly on Earth, can be created. But the process is especially interesting for a different reason: it is an example of way that a free neutron can be made. Free neutrons are useful for making bigger elements, because it's very easy to add a neutron to an existing nucleus. A neutron can be added to a nucleus without a Coulomb barrier because a neutron doesn't have any electric charge. So it's not repelled from the nucleus. It's only attracted by the Strong Force. So it's easy to add neutrons to existing nuclei to make bigger and bigger, heavier and heavier, nuclei. (There are many different reactions that make free neutrons in carbon burning and later stages; the one I just discussed is only one particular example.)

Another type of process that can occur in carbon burning and later stages involves photons. As the star gets hotter and hotter, photons of higher and higher energy are zipping around.
The photons can break up existing nuclei into smaller pieces, which then can recombine in new ways. It's a "mix and match" kind of process, but the general tendency is always towards bigger and bigger nuclei. Yes?

[Student: Is a proton missing in that reaction $^{12}C + ^{12}C$ makes ^{23}Mg + neutron? Each carbon has 12 protons?]

No, 12 is the number of protons *plus* neutrons, so together the two carbons have a total of 24 protons and neutrons. The magnesium has a total of 23 protons and neutrons, and here's the extra neutron. So the total number of protons and neutrons is 24 on both sides of the equation.

Now if you want to look at protons only, ^{12}C has 6 protons and ^{23}Mg has 12 protons. (Sometimes people show the number of protons also by writing them as $^{12}C_6$ and $^{23}Mg_{12}$.) So if you just want to compare the number of protons, you have 6 + 6 = 12 + 0, so that works.
Or if you want to compare neutrons only, you have 6 + 6 = 11 + 1, so that also works. (^{23}Mg has 12 protons and 11 neutrons, for a total of 23.) You had another question?

[Student: Yeah, I don't understand why the neutron comes off like that. Why is it "and an extra neutron"?]

Let me try to understand what your question is. Do you mean why is there a neutron around or why doesn't it just stick here and make a different isotope, ^{24}Mg, with no extra neutron flying off?

[Student: Why doesn't it just stick to the magnesium?]

Well, the two ^{12}C are colliding. The temperature's quite hot, and they're hitting each other pretty hard. When two cars collide, sometimes a piece of wreckage flies off. It depends on how they hit (head-on, side impact,…) and how hard they hit. With the two ^{12}C, it can happen that they just stick together and make something with a total of 24 protons and neutrons, but it can also happen that a piece of wreckage flies off. In the case I talked about, the extra neutron is just a piece of the wreckage. The only reason I emphasized that case is because the neutron can then hit something else and increase the size of that nucleus. And if you get enough of such events, you can build significantly bigger nuclei. The table [transparency #5] shows the main products of the nuclear reactions, but during this period some small amounts of still bigger nuclei are also made just by collisions (of the type described) with pieces of “wreckage.” If a free neutron is around and it happens to hit a big nucleus that was made previously, then it’ll make a still bigger nucleus. Small amounts of some very big nuclei are formed in this way.

Now, let me just emphasize one other point. Why do these new stages require higher and higher temperatures? Because in each new stage, the objects you’re combining have more and more protons in them. With carbon plus carbon, each one has six protons, so they repel each other a lot more than two helium nuclei, which in turn repelled each other a lot more than two single protons. In order to get over the Coulomb barrier it therefore takes a lot more energy than in previous cases. So the star has to be a lot hotter for the process to start. Each process can only take place when the temperature has increased enough above that needed for the previous process, which combined objects with less electric charge. Therefore stars only undergo one kind of nuclear burning at a time. It’s not enough for the next kind of burning and you’ve used up the fuel for the previous kind of burning. Mike?

[Michael: You mentioned previously that neutrons don’t last very long before decaying.]

Yes, a neutron by itself is unstable and will decay after an average of about 10 minutes. So if the free neutron doesn’t hit anything in roughly 10 minutes, it will decay and turn into a proton, an electron and a neutrino. But that’s very unlikely given how dense the core of a star is. The chances are this free neutron is going to hit something very soon. Okay, yeah?

[Student: That was going to be my question. Neutrons don’t last by themselves?]

They will last by themselves for a while but not forever. If you had a neutron in a little box sitting on your desk on average it would last about 10 minutes. That’s its lifetime.

[Student: Wasn’t it quicker than that?]

No, nucleosynthesis took place about 1 to 3 minutes after the Big Bang. At that point, very few of the neutrons that had been made earlier had already decayed. But it is clear that nucleosynthesis couldn’t have taken place, let’s say, 4 hours after the Big Bang because by that time essentially all the free neutrons were gone.

By the way, did people check their e-mail today? Did you get e-mail from me? Okay, cool. A few people sent me questions. I thought I might as well give the answers to everybody, so I tried sending e-mail to everybody in the class. If you didn’t get one please let me know.

So the basic pattern keeps repeating itself. You use up one kind of fuel. So there’s no more heat being produced in the core of the star. The pressure therefore decreases, and the star collapses because of gravity. The compression then produces heat, and it eventually gets hot enough that the next stage of burning begins.   If the star’s mass is between 8 and 11 M_O, the last stage that will happen is oxygen burning. After that you’ll have the same thing as before. It will collapse to a white dwarf. Although it will be a bigger white dwarf than before, it will still be held up by the pressure of electrons pushed up against each other. It never gets hot enough for the last stage (silicon burning) to take place.

But if the star is bigger than 11 times the mass of the sun then there is a last stage of burning, which combines silicon in various ways. It gets more and more complicated, with more and more possibilities, because we're talking about bigger and bigger things colliding. But the basic result of silicon burning is the production of iron and other nearby elements. The table [transparency #5] shows that these other elements include nickel and chromium and cobalt. Nickel and especially iron are very important constituents of the Earth, as Michael explained. Recall that the Earth's core is mainly iron, with some nickel.

Now, the question is, "why does it stop there (at silicon burning)? Why can't it just keep on going forever, each time making bigger and bigger nuclei?" We know that there are plenty of elements with nuclei bigger than that of iron: for example, tin, gold, lead or uranium (uranium is the biggest nucleus that occurs naturally on the Earth now). Why don't we get new stages of burning that make these nuclei, or even bigger ones? The reason is a very fundamental one about nuclei, and we already have the ingredients to explain it. It has to do with the competition between the Strong Force, which is binding protons and neutrons together in a nucleus, and the electromagnetic repulsion of the protons, which have positive charges. The Strong Force is stronger than electromagnetism so it tends to win, or at least it has won so far. But electromagnetism has the opposite advantage: it acts over a longer range.

Imagine a big nucleus with lots of protons and neutrons in it; iron, for example, has a total of 56 protons and neutrons. It looks like Figure 1A. Now, because I need to talk about protons and neutrons in a generic way, let me introduce a new term, "nucleon." A nucleon means either a proton or a neutron --- it doesn't matter which. The average nucleon in a big nucleus like Fig. 1A is completely surrounded by other nucleons.

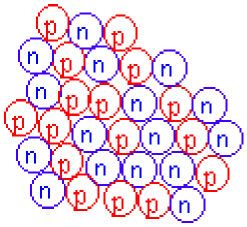

Figure 1A

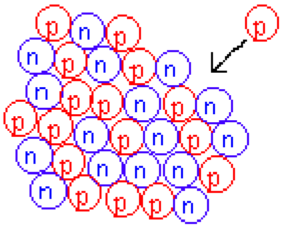

Figure 1B

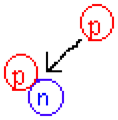

Figure 1C

Because the Strong Force is short range, it acts like "super glue" between nucleons: it holds them together tightly, but only if they are touching (or close to it). If two nucleons are far apart --- on opposite sides of a big nucleus, say --- the Strong Force doesn't result in any significant attraction between them. So when a nucleon is already completely surrounded by other nucleons, it's not possible to stick on a new nucleon in a way that would help the previous nucleons to stick together significantly more tightly. The new proton in Figure 1B won't make the nucleons on the left of the figure hold together any more strongly --- it doesn't increase the stability of the existing structure significantly.

Note that this is ***not*** true for a small nucleus where the average nucleon is not already surrounded by other nucleons. In Figure 1C the new proton will be able to stick to both of the previous nucleons, and thus will significantly increase the stability of the existing structure. But effects like that in Figure 1C get less and less important as you start talking about bigger and bigger nuclei, because most nucleons are already completely surrounded by other nucleons, and their part of the structure can't be made any stronger.

So when a nucleus is big, adding a new nucleon will ***not*** make it stick together (by the Strong Force) much better than it was already. But if the new particle is a proton, it will have an important electromagnetic effect on the existing nucleus: it will repel the preexisting protons. Since the electromagnetic force is long range, the repulsion does not just affect the nearby protons, it affects all of them. So it's actually counterproductive at a certain point to start adding more protons into the mix. The Strong Force will not hold the new nucleus together significantly more tightly, but the electromagnetic force will push it apart more. And what that ends up meaning is that the most stable nucleus is the nucleus of iron -- iron 56 (^{56}Fe) with 56 nucleons (26 protons and 30 neutrons). After that, adding extra protons tends to make it less stable. [Note: even adding just neutrons also makes a large nucleus less stable, but the reasons for this are more complicated --- involving quantum mechanics --- and I will not explain them.]

Now let's go back to our early picture of how two nuclei can join to make a bigger nucleus. The picture I drew looked like Figure 2 (this is the same as Figure 2 from the lecture of February 16.)

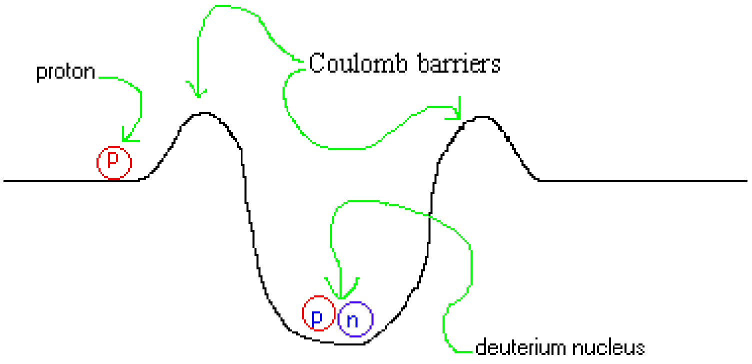

Figure 2

The picture in Figure 2 shows the process of combining a proton (hydrogen nucleus) with a deuterium nucleus to make helium 3 (^{3}He). The proton is attracted to the deuterium that's there already. If the proton could get into the "well," it would "fall down," and that energy (of falling) would be available to heat up things. In fact, this particular process (proton + deuterium) is a source of energy for the T-Tauri type of explosion. But of course there is a Coulomb barrier (due to the electromagnetic repulsion) in the way.

Now this same picture applies, with some minor variations, to all the reactions I was just showing you [transparency #5], which make all the nuclei up to iron 56 (^{56}Fe). Of course as the two nuclei that are combining get bigger, with more protons, the Coulomb barrier gets higher. But the basic shape of the picture applies to all of those.

What's different now? Suppose that, after we've made iron, we try to go on and combine it with another big nucleus to make something even bigger. For example, consider following reaction: iron 56 (^{56}Fe) plus chromium 52 (^{52}Cr) makes tin 108 (^{108}Sn). (Sn is the chemical symbol for tin.) Again, the details are not important but the picture will be. The picture in this case (Figure 3) looks very similar, but just not quite similar enough. There are still a Coulomb barrier and a dip or "well" in the middle associated with the attraction by the Strong Force. But for the reasons I just explained, the repulsion due to the electromagnetic force is now more important than the attraction. So the bottom of the well is now "above ground level."

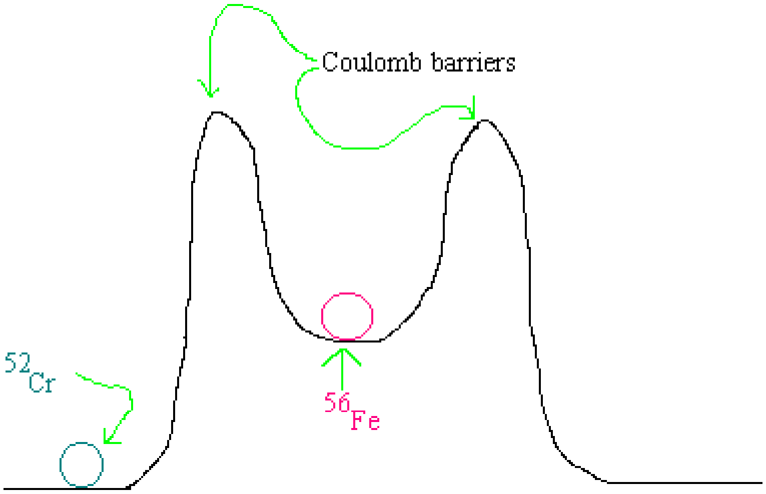

Figure 3

If the chromium gets over the Coulomb barrier, it can still combine with the iron and make tin. The tin would be stable because the pieces can't get back out of the well unless they're given enough energy to get back over the barrier. But notice that the total energy of the tin (that would be made if these two combined) would actually be greater than the energy of the chromium and the iron by themselves. This reaction absorbs energy. Since the bottom of the well is "above ground level," you have to supply a net amount of extra energy to "lift" the chromium up to its new higher resting-place.

In the reactions we've talked about previously, the Strong Interaction is so important that, once the incoming nucleus gets over the barrier, it falls down lower than it started (see Figure 2). So the incoming nucleus loses energy in the process, and that energy is released to the environment. Those reactions thus give off energy, which is where the star gets its energy to make heat and light. On the other hand, reactions that produce nuclei bigger than iron 56 (^{56}Fe) absorb energy (see Figure 3). So although such reactions can happen, they're not a way to produce energy.

They cannot power a star, or produce heat, or produce pressure to counteract gravity. Once you make iron 56, which is the most stable nucleus, there's no more fuel available for burning. And that's why the process stops with iron and elements close to iron. Questions?

While we're at it, let me talk about what would happen if you tried to join nuclei that are even bigger than the ones shown in Figure 3. For example, suppose I combine an element called krypton 92 (^{92}Kr) with one called barium 143 (^{143}Ba) to make uranium 235 (^{235}U). So we're talking about really big nuclei. What does that picture look like? Well, it's like Figure 3 but even more exaggerated (Figure 4). The electromagnetic repulsion is now so strong compared to the attraction by the Strong Force that there is just a very small indentation at the top.

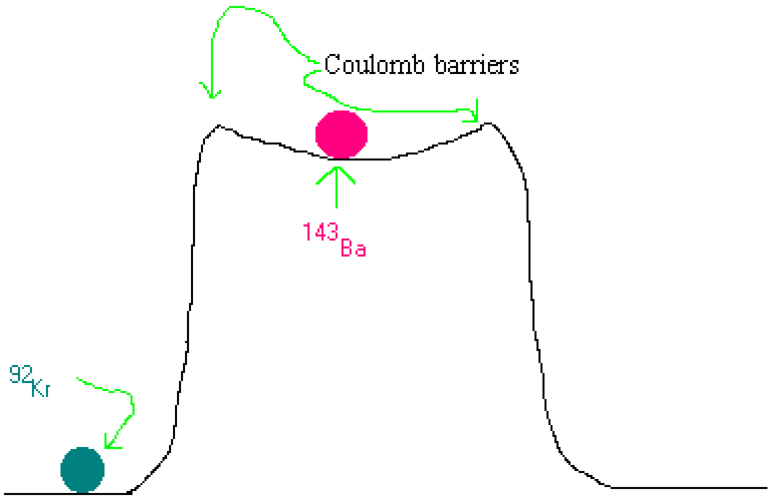

Figure 4

So if you started with barium nucleus and sent in a krypton nucleus, the krypton could, if it had just the right energy, get over the barrier and land in the indentation, combining with the barium to make uranium. But the indentation is so small that just by the natural jiggling of the protons and neutrons inside the nucleus, it is possible for the uranium nucleus to break apart again spontaneously. The new nucleus is not completely stable anymore --- the well at the top isn't quite deep enough because there is so much electromagnetic repulsion.

So uranium 235 (^{235}U) is not stable. It can decay spontaneously; we use the term "radioactive." Really big nuclei are radioactive for this reason, and in fact that's why nothing bigger than uranium exists naturally on the Earth anymore. Still bigger nuclei can exist. They have been made in the laboratory, for example, and (as we'll see) small amounts were made in massive stars. Such big nuclei also existed on the early Earth, which contained a lot of "junk" spewed out by previously existing stars. But really big nuclei are radioactive, so that by now anything bigger than uranium has completed decayed away on Earth.

When the nuclei decay, you get back out the energy stored. Because they are resting "high up" above "ground level," if the joined nuclei fall apart they release energy in "falling down."

That's why nuclei such as uranium can be used to generate energy, for example, in nuclear reactors or in "atomic" (fission) bombs. (The word "fission" means breaking apart.) In fact, the decay of radioactive elements is one of the ways that the early Earth was heated. And the still remaining radioactive elements, such as uranium, are responsible for the continuing "slow boil" of the Earth that Michael described.

[Student: I'm curious why is uranium still around. I assume it would have all decayed by now.]

Well, it's a question of how long it lives. Uranium decays spontaneously, but the "well" at the top of Fig. 4 is almost deep enough it make it stable. So the lifetime of uranium quite long. The uranium isotope I just mentioned, ^{235}U, lives on average 700 million years, so you are right that most (but not all!) of the ^{235}U has decayed by now. But there is another uranium isotope, ^{238}U, which lives 4.5 billion years on average. Since 4.5 billion years is about the age of the Earth, only about half of the originally existing ^{238}U has decayed by now. Nuclei that are even bigger than uranium decay more rapidly, because the "well" in Fig. 4 is even shallower. So by now we don't have anything bigger than uranium left.

Okay, let me show another table [transparency #6] to give you some idea of the times of these various stages. Recall that, to go through all the stages of burning, a star must be at least 11 times the mass of the sun. This table shows the times for a still larger star, 25 times the mass of the sun. As I have said before, such a star burns a lot faster than the sun, and lives for a lot shorter time than the sun. From the table, hydrogen burning takes 7 times 10^6 years, 7 million years. (Remember that our sun burns hydrogen for about 10 billion years.) Helium burning takes only 5 times 10^5 (500,000) years; carbon burning, 600 years; neon burning, 1 year; oxygen burning, 6 months; silicon burning, 1 day. These new reactions take place rapidly because the nuclei are at enormous temperatures. The nuclei are moving at very high velocity and are packed very close to one another because the core of a big star becomes extremely dense. So they hit into each other all the time and the reactions take place very, very fast. Austen?

[Student: What happens to the star after silicon burning?]

Ah, good question. I'll get to it. It's the big question because after silicon burning (which makes iron and nearby elements) there's no other way to produce energy by nuclear reactions. Any nuclear reactions that do take place absorb energy, rather than emit, energy. They don't produce heat, which would create pressure to oppose gravity. So something weird is going to happen.

In summary, when a star is 11 or more times the mass of the sun, the nuclear reactions will go all the way to the end --- i.e., they will make iron. After that, nuclear reactions can't produce energy, so what happens? Well, with no energy produced in the core, the star begins to collapse --- just as it did after each previous stage. Only this time, no matter how hot it gets, there are no new nuclear reactions to produce heat to oppose the collapse. So the star will soon reach the stage where the electrons are as close as they can be to each other (in other words, the white dwarf-type stage).

What happens after that depends on how much is left of the star. Of course, we started with a star with a mass at least 11 times the mass of the sun, but it has gone through at least one stage where it loses some mass: The red giant phase (during helium burning) pushes the outer layers away from the star. And as we saw in the slides last time, some of the stuff gets sent far away. So the total mass may now be less than 11 times the mass of the sun. But in most cases, the star will still be big enough that the pressure of electrons next to each other can't hold it up. If what's left when you get done with silicon burning is bigger than one and a half (actually1.4) times the mass of the sun, the white dwarf stage is not stable. The electrons' pressure pushing against each other doesn't hold the star up.

Now I said that the electrons can't be any closer than one wavelength to each other. How could the star possibly be compressed further? Well, as you compress it further, you get rid of the electrons! Then they're not there to push apart. And how do you get rid of them? The electrons are destroyed by a process we've seen before. As the pressure gets high enough the electrons start spending a significant amount of time very close to the protons. And then the Weak Interaction process of reverse neutron decay (electron plus proton makes a neutron and a neutrino) starts to occur. Recall that the Weak Force has a very short range so this process cannot take place until the electrons are literally pushed onto the protons. The process in symbols is e + p -> n + neutrino [the neutrino is sometimes symbolized by the Greek letter "nu"].

So the problem of the electrons holding up the star is solved by just getting rid of the electrons. They're combined with protons to make neutrons and neutrinos. In fact this process takes place very rapidly, in about 1 millisecond (a thousandth of a second). After the star is finished burning silicon, the star collapses, the electrons get pushed onto the protons, you make neutrons and neutrinos, and now the electrons aren't around to hold the thing up anymore. As I said last time, the electrons have a much bigger wavelength than protons or neutrons. So although the electrons might hold the star up at a reasonable size, once you get rid of the electrons the neutrons won't do anything until the star is much smaller. Neutrons can sit in a much smaller space since their wavelength is much smaller. So there's nothing to hold up the star and it keeps collapsing.

[Student: What was that process called again?]

This is reverse neutron decay, which we've talked about in other contexts. You make neutrons instead of getting rid of them. Hydrogen burning in the sun involves a very similar process (proton makes neutron + positron + neutrino) because a proton has to be turned into a neutron to allow four protons to make helium.

Now, I haven't talked much about neutrinos before. Let me just tell some of the most important properties of neutrinos. First of all, they interact with other particles only by the Weak Force and by gravity. Since those two forces are the weakest of the four, neutrinos interact very little with other particles. Second of all, neutrinos have very low mass, so they move almost at the speed of light. Why are these properties important? Because almost all the neutrinos will go streaming right out of the star at nearly the speed of light without hitting anything --- they interact so weakly with everything else. Thus the neutrinos that are made in reverse neutron decay don't help much to hold the core of the star up because they very rarely hit anything that's falling in. Most of them just go zooming right out.

To give you some idea how rarely neutrinos interact: billions of neutrinos go through our bodies every year. As I speak neutrinos are shooting right through my body and through your body, but they don't hit anything. They just go right on through because neutrinos don't have Strong Interactions and they don't have electromagnetic interactions --- just Weak Interactions (plus gravity, which is even weaker and therefore totally irrelevant). Every once in a while, about once a year, a neutrino will actually interact with something in your body and create a slight amount of damage to a protein or to a DNA molecule --- hopefully that gets repaired. The damage done by neutrinos is extremely small compared to other forms of naturally occurring radioactivity in the environment (e.g., radioactive elements in rocks, dental X-rays, cosmic rays --- the last of which you are exposed to particularly in air travel because you are not shielded by a lot of atmosphere). The effect of neutrinos is very small because almost all neutrinos just go right through us without interacting.

In fact, if you wanted to make yourself a shield to protect yourself from these neutrinos that are coming in all the time, what would you need? You'd need a wall of lead six light-years thick to cut out half the neutrinos! That'd only be half. If you wanted to cut it down to one eighth, you'd need a wall three times as thick. So obviously you can't protect yourself, but neither do you need to protect yourself. Neutrinos just go through us and most of them go right through the Earth too. If one's coming down here, the chances are very good that it will go right through the Earth and come out the other side. Every once in awhile, however, a neutrino will interact with something in the Earth.

Okay, so what do the neutrinos do in the collapse of a big star? Their greatest effect is just to take energy out from the star. A huge number of neutrinos are made. In fact, in the collapse about 10^{57} neutrinos are emitted (a 1 with 57 zeroes). Most of the time those neutrinos don't interact with anything on the way out. Thus the neutrinos are not useful for making more heat because almost all of them just stream right out of the star as the collapse occurs, carrying the energy away. Nothing is stopping the collapse.

[Student: How we can detect neutrinos if they don't interact?]

Well, I didn't say they don't neutrinos don't interact. I said they interact very, very rarely. They can be detected if you give them a big enough target and you wait long enough. We do have apparatuses that can detect neutrinos arriving at the Earth. Most of these detectors located deep (several miles) underground in, for example, abandoned salt mines. We set out a huge tank of water and wait. In a year you may get 5, 10, 20, 100 neutrino events --- were a neutrino hits one of the nuclei of the atoms in the water. The point is you have so many nuclei to hit in the big tank of water that eventually a few of them are indeed hit. You detect, however, only an extremely low fraction of the total number of neutrinos going through the tank of water. We put the tank underground to shield it from all kinds of other cosmic rays which are hitting the Earth all the time. On the surface you would just be swamped by all kinds of other stuff arriving and you would never be able to observe the neutrinos.

[Michael: Do neutrinos have a mass?]

Yes, we think so. Experiments done in the last couple of years seem to show that they have a mass. We can't say actually what the mass is, except that it's very small. The experimental situation however is not completely clear. But I think it's fair to say that it has been established that at least some types of neutrinos have mass. I haven't talked about this but there are at least three, maybe four, different kinds of neutrinos. We don't know for sure that they all have mass, but at least some of them have a (very small) mass.

Okay, so what happens to our collapsing star? It makes trillions and trillions of neutrinos. Most of these neutrinos just zoom out of the star, but every once in a while one of them will hit something in the star. And because there are so many neutrinos (10^{57}), the ones that do hit something are enough to blow the outer envelope of the star out in a big explosion. In the meantime, the core keeps collapsing down until finally the neutrons are right next to each other. Instead of electrons being right next to each other, which was the case for a white dwarf, you now have neutrons next to each other, and that is usually enough to stop the collapse. The core falls in, and then crashes when the neutrons hit each other. It's like jumping out of a 100-story building and falling freely until you hit the concrete. The "concrete" here is the neutrons hitting each other. They get close enough that they smash into each other.

When the neutrons hit each other, you get a bounce. And the bounce is a second, bigger explosion. If you dropped a ball off the Empire State Building it would bounce when it would hit. The same thing here: the outer part of the core bounces up after it hits, and that makes an enormous explosion. So we have a two-phase explosion here --- a big one from the neutrinos and then an even bigger one from the bounce when the neutrons hit each other. The two-phase explosion is what we call a supernova. It's what happens when a star is done all the burning it can. It collapses until the neutrons get right on top of each other. There is an incredible explosion from the bounce as well as from the neutrinos made during the collapse.

Those two explosions of a supernova spread a lot of the material of the star out into space. And that is how the heavy elements that have been made in the star get blown out and mixed with the interstellar gas and dust that is already there. The new interstellar mixture can condense later into new stars and planets. That is in fact how our solar system got all the heavy elements that are so important for the structure of the Earth and for life.

What's left after you blow out all the outer layers in a supernova is a core that is made entirely neutrons. It's called a "neutron star." If you thought a white dwarf was dense, you ain't seen nothin' yet. A white dwarf contains something like the mass of the sun compressed into a space the size of the Earth. A neutron star contains something like the mass of the sun compressed into a space the size of St. Louis (City). The density of a neutron star is about a billion tons per teaspoon. So a white dwarf seems like nothing now --- it only had 2.5 tons per teaspoon.

I'm almost done with stars, but I'll come back to them a little bit in the next set of lectures. Okay, let's look at some of the slides [slide 1]. These are the remnants of a supernova explosion in the Cygnus constellation. You can't actually see exactly where the explosion took place. The debris is heading out here to the right. It's hitting into some darker, cold gas and is streaming out past it. This is an explosion that took place about 15,000 years ago as observed by us. (If we were sitting on the Earth watching, the first signs of it would have been 15,000 years ago.) So this picture shows what the explosion looks like 15,000 later.

[slide 2] This is another supernova. It occurred in the constellation of the Crab. On the left is a ground-based picture of the explosion, and on the right is a Hubble picture of the center of the explosion. This explosion was first observed on Earth about 950 years ago and it was actually recorded by Chinese astronomers. I'll read you an astronomer's words from an original Chinese text. "'On a chichhou day [I don't know what that is] in the fifth month of the first year of the Chih-Ho reign period' [July, A.D. 1054], Yang Wei-Te, the Chief Computer of the Calendar [which is probably a counterpart to the modern British Astronomer Royal] addressed the Emperor in these deferential words: 'Prostrating myself before your majesty, I have observed the appearance of a guest-star [a supernova]. On the star there was a slightly iridescent yellow color.'" [I took the quotation from the book, Before the Beginning, by Martin Rees.] So this slide shows the remnant of a supernova explosion whose light first arrived at Earth 950 years ago. The actual explosion took place about 8,950 years ago, but because the location of the supernova is about 8,000 light-years from us, this light arrived only 950 years ago.

Let's just look briefly at the next two; I'll come back to them in my next set of lectures [slide 3]. This is another explosion. This star is called Eta Carinae, and this explosion took place 150 years ago. Of course, the picture is taken recently. This is the explosion as we see it now. The outer edges here are still going out at about a million miles an hour.

[slide 4] This shows a supernova explosion whose light first reached us in 1987. It's not in our galaxy but in a nearby galaxy in our local cluster. (The explosions in the previous 3 slides took place in our galaxy.) The thin rings you see are the outer edges of the explosion. The inner ring of gas was there before the explosion, but the explosion heated that up so it is also glowing.

Let me show you one more transparency and I'll let you go [transparency #7]. As I said, the explosion in slide 4 was observed on Earth in 1987. Here are two pictures of the sky, before the explosion and a few days after. You can see a new star, the supernova, in the upper right-hand corner. A supernova is about 100 billion times brighter than the sun but it only lasts a short time. We not only observed the light from the 1987 explosion, we also detected about 20 neutrinos: 20 out of the total of 10^{57} neutrinos emitted!

[end of lecture]