Transcript from Epic of Evolution: Life, the Earth and the Cosmos (BEP 210A)
February 16, 2000 - Lecture by Claude Bernard

Okay, let's get started. There's one thing I forgot to mention at the end of last time. I ranked the forces in order of strength, but I didn't make a quantitative comparison of the forces. Consider two protons right next to each other. The Strong Force between them is about 10^{38} times greater than the gravitational force. Remember that 10^{38} means a 1 with 38 zeroes. So in that sense, the Strong Force is enormously stronger than gravity. On the other hand, when you talk about huge conglomerations of things interacting over long distances, like a galaxy or like the solar system, the gravitational force is what is important. The Strong Force, which falls off very rapidly with distance, is totally negligible once the protons are a few diameters apart. One could say that the Strong Force is brawny but it doesn't have much endurance. It dies out quickly with distance.

We can also compare the Strong Force with the electromagnetic force. The electromagnetic force is roughly 100 times weaker if you compare them for two touching protons. But, again, the Strong Force falls off more rapidly with distance than the electromagnetic force. So if the protons are a significant distance apart, the electromagnetic force will be more important. For example, if the protons are at a distance 10 times their diameter, the electromagnetic force now would be about 10 times *stronger* than the String Force. These numbers are so enormous that I thought it would be worth mentioning. And it really is sort of amazing that gravity is so important, because it's so small on the scale of nearby particles interacting with each other. But once you talk about huge conglomerations of particles, for example a galaxy, gravity is the only relevant force. That is because gravity adds up (everything attracts everything else), and gravity has a long range.

Now, the last thing we were talking about is galaxy formation. The center of a galaxy will typically have such a big conglomeration of mass in the middle that it will turn into a black hole. And that black hole sucks in material from nearby. The gravitational forces are so strong that as the material falls in it heats up. The energy of each bit of falling material is turned into heat as it hits against other bits of stuff that are falling in. The result is enormous heating and therefore the emission a lot of electromagnetic radiation. So soon after a galaxy is formed, there will be an enormous amount of light coming from near the center. The light of course does not come from the exact center. The center is a black hole and nothing can get out of the black hole. But the stuff falling into the black hole gives out an enormous amount of light. This light is so bright that the region around the center of a young galaxy is brighter than an entire current galaxy with all its stars.

Such an object is called a quasar. The term comes from "quasi-stellar object." When they were first observed it was noticed that they were very small compared to an entire galaxy, yet the amount of light they were emitting was like the light of an entire galaxy. People didn't know what it was. They said, maybe this is some kind of weird star, and gave it the name quasi-stellar object. But now we know it doesn't really work like a star. It works by gravity pulling stuff in, which then emits lots of light. Let me show you a few slides here. [slide 1] The left one is taken from a ground based telescope of some distant galaxy. The right-hand picture (taken by the Hubble Space Telescope) is a blow-up of the tiny square in the middle of the ground-based picture. There is an enormous amount of light being emitted from the central region, which is a quasar or quasar-like object. The light is emitted because of the black hole in the center.

[slide 2] On the left is a picture from a ground-based telescope of the center of some very distant galaxy. And then here it is blown up (again a Hubble Space Telescope picture). It's not the greatest resolution but you can see the "accretion disk" around the central black hole. That's the area from which the black hole is sucking in matter. That matter then gives off light as its energy of falling is turned into heat. The process is very much like the one described in Michael's lectures about the heating up of the infant Earth as stuff fell into it. In the same way the stuff falling into the black hole heats up and gives off light. Question?

[Student: Last time you said that the quasar is the center of the galaxy and that it sucks in everything and it heats up and then it gives off light. But did you say that as it gets older it sucks in everything around it so there's less light?]

When it gets older it has already sucked in everything that's close by so there's nothing around to eat anymore. So the amount of light coming from the center decreases. It's like sticking a vacuum in the middle of a big pile of dust. Initially it's pulling in stuff from everywhere but eventually it's clean around there. All this stuff in the accretion disk here will be sucked into the black hole and then you won't get much light out of the center of the galaxy.

The next one [slide 3] shows various quasars far away. I don't want to give details about each one but it gives you some idea of very distant quasars. They are actually quite bright.

Now, as I said, the central black hole sucks in all the stuff, emits a lot of light. Then eventually in an older galaxy it's eaten up everything around so it's no longer so bright. One thing you notice if you're an astronomer and you go looking for quasars is that all the quasars are far away from us. Nobody's discovered a quasar close to us. Anybody know why that is? Yes, sir.

[Student: Because the galaxies [with quasars] aren't as old as the Earth?]

Yes, but why is that? Why should we be living in an old place of the universe, and out there it's young? Yes, sir.

[Student: Because the light takes so long to travel to us.]

That's it. Because the light takes so long to travel to us. When you look very far out, you're seeing the universe as it was earlier. Those are new galaxies that you see way out there. So probably all galaxies were quasars in their early stages. Around here, though, if you look to Andromeda it's only 2.5 million light-years away. You're seeing it as it was 2.5 million years ago. On the cosmological scale, that's pretty recent. It has long since ceased to be a quasar. But if you look out billions of light-years away then you're seeing the galaxies as they were billions of years ago, and many are still quasars. So looking distant is the same as looking back in time. And that's a key way that we learn about the Big Bang. The further we can look, the further back in time we observe. So you can look closer and closer to the Big Bang in time the further in distance we can observe. That's why astronomers keep pushing to build bigger and better telescopes. It's not just to find more of the same stuff. It's to look further back in time. Any other questions?

So now let's go back and just look at Andromeda [slide 4]. This is recent. This is close so it's about the same age as our galaxy. So kind of a normal galaxy as it would look today. You can see it's a standard spiral galaxy. It's a disk. It's in a plane like this and you're seeing it half edge on. It's called a spiral galaxy for the obvious reason. It has these spiral arms. And that's one thing I haven't explained yet about galaxies. I told why they make disks: that's the same reason --- having to do with angular momentum --- that the solar system formed as a disk and then congealed into planets. But why does a galaxy have these sorts of spiral arms? Why isn't it just a flat disk like a Frisbee? Why are there spaces in between the spiral arms?

Well, it's actually pretty easy to understand. Consider a galaxy that has just formed. Let's look at it down from the top so initially it would be rather disk-like, like a Frisbee. There would be a black hole in the center but the rest is sort of more or less like a uniform disk. Everything (gas and stars) is orbiting around the center. It's very much like an enormous superhighway with all this traffic going around. If you've ever been on an interstate with very heavy traffic you know that something interesting --- though not particularly pleasant --- happens. Even if there are no accidents and no breakdowns, you will find that every once in a while traffic comes to a stop or a crawl. You go for a while through the crawl, and then all of a sudden everybody's speeding up and you go faster for a while. Then you hit another jam. You can't figure out any reason for the jams. There's no accident; nothing's blocking the lanes.

Such intermittent traffic jams are called density waves of traffic. Dense places are followed by less dense places; it's a wavelike effect. You might wonder why everybody just doesn't go at 60 miles an hour 2 feet away from the car in front. Well, it's hard to keep your speed fixed exactly. Somebody's going to get a little too close and hit the brakes. When that person slows down, the person behind them is automatically going to get closer and also hit the brakes. So you're going to get a bunching of cars: a whole region where everybody's hit the brakes and cars are all bunched. And it's bound to happen if the traffic is heavy enough. Traffic engineers can actually predict how many cars per second per lane will result in this kind of traffic jam.

Now, it's similar, but not exactly the same, in a disk-like galaxy. Obviously there are no brakes on the stars going around. However, if by random processes a couple of stars or some gas happen to get unusually close to other stars or gas, that will produce a local increase in gravity. So other stars and gas will be attracted to that place. What you get then is stars and gas bunching in some places. The bunching is like a traffic jam. Then because of the rotation the bunchings get twisted up. So you end up with the spiral arms of a spiral galaxy.

Okay, so that's all I wanted to say about galaxy formation. Now, at the same time galaxies are forming, gas within the galaxy is contracting because of gravity and making "proto-stars" – stars in the early stage of formation – or pre-solar systems all over the place. And sometimes (as Michael explained) in those bunches of gas there'll also be smaller, little pieces bunching together, and those are planets. It may or may not happen. We don't really know what fraction of all stars have planets. They're hard to observe because the planets are dark and other stars are far away from us. So although we have observed some planets, we haven't yet seen anything that looks like Earth. We don't know how common planets like Earth are.

So gas is contracting into lumps the size of stars. As things push together, they heat up. This is sort of the reverse of the Big Bang. Remember in the initial Big Bang things are expanding and cooling. But now in various places we have the reverse process occurring --- things are being pulled in and heating up. Of course not everything is being pulled in to one place. There are just various little clusters here and there. On big scales things are pulled into galaxies and, on smaller scales, into proto-stars. As the gas gets pulled into a proto-star, it compresses and gets hotter and hotter. Things soon get so hot and violent that some parts of the gas bounce back out into space. The early phase of star formation is in fact very violent and turbulent. The stuff bouncing back into space makes a kind of slow-motion explosion. This explosive phase may last ten million years.

This slow explosion during the period of star formation is what is called a "T-Tauri phase" or "T-Tauri event." Michael mentioned the T-Tauri event in his history of our solar system. It is probably what caused the inner planets to lose most of their lighter, gaseous elements. The T-Tauri explosion blew away the gas from the inner planets. That is the reason the inner planets are primarily metal and rock, and only the outer planets, starting with Jupiter, are primarily gas. Yes?

[Student: Is the gas attracted to the gravity?]

Yes. The gravity of the planets is pulling in the gas. But the gas is light, so is not pulled very hard by the planets and the explosion can blow it away. The attraction of gravity for gas is also the reason why the star formed in the first place.

In the long-term (after, say, 20 million years or more), the violent bounces settle down, and the proto-star gets smooth and approximately spherical. The compression has, however, heated up the star tremendously, and you start getting nuclear reactions of a similar kind to those that happened early in the Big Bang: nuclear reactions creating bigger nuclei from smaller nuclei. The process is called nucleosynthesis.

In the Big Bang all that happens is protons and neutrons combine in various ways to make, primarily, helium, with a little bit of deuterium and a negligible amount of lithium. Now, what's left over from the Big Bang is contracting again, and you start to get similar kinds of nuclear reactions. Let me emphasize that I'm talking here about the kind of stars that formed first after the Big Bang ("first generation stars"). They therefore had to be made only out of what was left over from the Big Bang: about 75 percent ordinary hydrogen atoms (a single proton with a single electron going around it), about 25 percent helium (mainly ^{4}He, but also some ^{3}He), and about .01 percent deuterium (an isotope of hydrogen with 1 proton and 1 neutron in the nucleus). Yes?

[Ursula: You mean left over from right after the Big Bang? I thought it was too hot right after the Big Bang to do anything.]

Not immediately after Big Bang, but after nucleosynthesis, which occurs from about 1 minute to about 3 minutes after the Big Bang. The ratios of hydrogen, helium, and deuterium are fixed during this period of nucleosynthesis. At that point, we know how many protons we have, how many deuterium nuclei, and how many helium nuclei.

Now, let's look back at what happened in nucleosynthesis. I'll show you some of the reactions that occurred during Big Bang nucleosynthesis [transparency #3], and I want to point out the differences now. I don't expect you to memorize these reactions, but it's important to understand the key differences between what happens in nucleosynthesis and what happens in stars. In nucleosynthesis, protons and neutrons make deuterium. Then two deuterium nuclei make helium, and so forth. There's also another reaction that is less important in the Big Bang, but is important now. That reaction is proton plus deuterium makes ^{3}He + energy (in the form of a photon).

So these are the kind of reactions we had in the Big Bang, but there's one enormous difference now. In stars, we can't have this very first reaction (proton plus neutron makes deuterium). That's because there aren't any neutrons anymore. Any free neutrons have decayed. Remember that a free neutron will decay on average in approximately 10 minutes. So by the time a few hours have passed after the Big Bang, all the neutrons are gone. So in stars there are no neutrons to start this process out. The only thing you can do with these kinds of reactions is to use up the tiny amount of deuterium (.01 percent) that is there already. But you can't make any more deuterium by combining protons and neutrons, because there aren't any neutrons. Deuterium can still be made, but it requires a different kind of process, which is much slower. (I'll explain that reaction soon.)

So what does happen? Well, there is, as I said, a tiny amount of deuterium and the tiny amount of deuterium can react. So the first thing that happens is the existing deuterium is used up in two kinds of reactions: deuterium plus deuterium makes ^{3}He plus a neutron (the reaction pictured in transparency #3) and proton plus deuterium makes ^{3}He plus a photon (a gamma ray).
The second of these two reactions is more important because there isn't much deuterium around, so the chance of two deuterium nuclei hitting each other is very small. You have a better shot of taking one of the deuterium nuclei and hitting it with a proton. And what does this do? When proton plus deuterium makes helium and a gamma ray it liberates a lot of energy, which is carried primarily by the gamma ray. And the same is also true when deuterium meets deuterium. A lot of energy is released in the single neutron that's produced. These reactions very similar to the reactions that take place in what's called a "hydrogen" or "thermonuclear" bomb. I'll explain shortly what that means, why there's the word "thermo" in there. It's not a pleasant subject but it's important.

Now it needs to be hot for these reactions to occur in the first. It's not obvious why you need heat, and I will explain that shortly. The need for heat is indicated in the name "thermonuclear reaction." This kind of reaction only occurs when things get hot. Then you "burn" up the deuterium, and all the deuterium is gone and you can't continue in this way. You can't use up the protons, at least not in this way, because you can't make any more deuterium: there aren't any more neutrons. And you can't make any more deuterium in the way it was made in the Big

Bang, because there aren't any more neutrons. There is another way to make deuterium, however, which I will explain later.

Now, let me give a basic explanation of thermonuclear processes. This explanation applies not only to the proton + deuterium reaction when the star first forms, but also to the steady burning of the star later on. In addition, it applies to all kinds of late stages in stellar evolution. The basic idea explains why you need it to be hot and why it releases energy once you do get it hot enough to make the reaction go. Let me illustrate the idea for the most important initial reaction: proton plus deuterium makes helium plus gamma ray. And let's start with the most important force between protons and neutrons in nuclei: the Strong Force. That's what holds the nucleus together. But the Strong Force has a short range so it only is important when the protons and neutrons are very close to each other. So the proton is like a little ball rolling along on a surface and over here is a deuterium (a combination of a proton and a neutron) and it will attract the proton if the proton gets close enough. It's analogous to our ball (the proton) rolling along and having a big dip (or "well") in the surface by the deuterium [Figure #1].

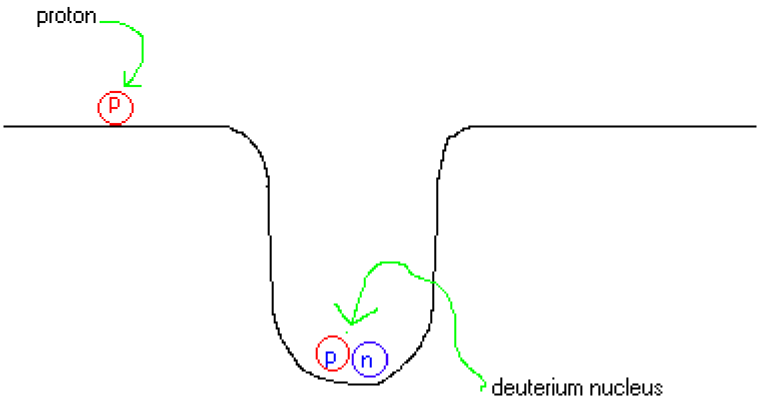

Figure #1. How a proton would "fall in" to a deuterium nucleus if only the Strong Force was active.

So if the ball rolls around out here, far away from the deuterium, it doesn't notice anything. But if it comes along and it gets close enough it would "fall in" the well, towards the deuterium. "Fall in" is metaphorical here. It's not falling in the sense of gravity, but it's being pulled toward the deuterium by the Strong Force. And if it falls in, it will land hard and emit energy. And the energy that it had because it was higher up and then fell down is the energy that gets emitted in the gamma ray. So that's the basic idea of why energy is emitted. It's because of the Strong Force, which wants to attract the proton toward the deuterium and stick them together.

Okay, that's the basic reason but it's not the whole story. To really understand it you also have to realize that there's another force involved here --- the next strongest force, electromagnetism. Electromagnetism is trying to prevent the proton from joining the deuterium. Remember, both the proton and the deuterium have a positive charge (deuterium contains a proton). So at the same time that the proton is being attracted to the deuterium because of the Strong Force it's being repelled from the deuterium because of the electromagnetic force. Including the electromagnetic force, the true picture looks like Figure #2.

There are two differences between Figures #1 and #2. First of all, the depth of the well is less in Figure #2, because the electromagnetic repulsion is countering some of the Strong Force attraction. But since the Strong Force is stronger than electromagnetism, it still wins, and there still is a well or dip close to the deuterium. The second difference is more important. Since the electromagnetic force has a longer range, it's what matters first when the proton starts to approach the deuterium. So because of the electromagnetic force, the "surface" in our analogy here actually has an upward bump, a "lip" around the well, which would tend to prevent the proton from approaching the deuterium.

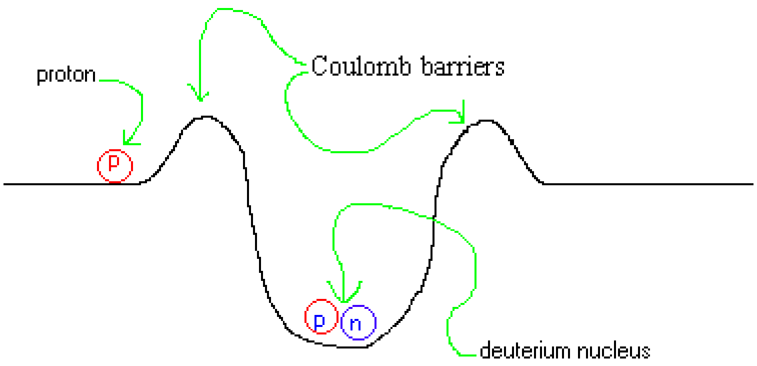

Figure #2. The interaction of a proton and a deuterium nucleus in the realistic case, with both the Strong Force and the electromagnetic force active.

As the proton starts to get close the first thing it feels is the electromagnetic repulsion because that is a long-range force. And if the proton doesn't have enough energy to get up and over the hill it will just "roll back" and never get to the deuterium. So no reaction will take place. On the other had, if the proton does have enough energy to get over the hill, the powerful, but short range, Strong Force will take over and pull the proton all the way in, joining it to the deuterium. Thus the deuterium is "protected" by the barrier around the hole. This barrier is due to the electromagnetic force and it's called the "Coulomb barrier." Coulomb was a physicist who described repulsion and attraction between electric charges. And that's exactly what creates the barrier: the repulsion between two positive charges.

So what’s the net result? The net result is that the proton can still end up falling in the well and releasing energy if it can get close enough, if it can get over the barrier. You may remember back to your childhood a toy where you roll little B-B’s around and you have to get the B-B’s into some tiny holes. The holes might have been in some picture, perhaps of a clown. And there are tiny holes in the clown’s hands and nose and eyes. You’re trying to roll the B-B’s into the holes, but there’s usually a little lip right around the hole so the B-B won’t go in if you roll it slowly. You have to give it enough velocity, enough energy, to get over the lip.

The same thing applies the proton and the deuterium: the proton needs enough energy to get over the lip and get inside. It will not happen if the proton doesn’t have enough energy. What does it mean to say that the protons on average have enough energy to get over the barrier, that they’re bouncing around fast enough? It means the protons have to be hot enough. Only when the temperature is hot enough will protons on the average have enough energy to get over the barrier and fall in the well and release energy. So in order to get energy out, you have to have enough energy in there to begin with. Just like it takes money to make money. Same deal. You have to have enough energy to get the process started. Then you can take extra energy out. When it actually falls in you get back not only the energy you had to begin with, but also some extra energy. But to make it work you have to have enough energy to begin with. So in fact the reaction of existing deuterium with protons in a young star only takes place when the central temperature reaches about a million degrees Kelvin, a million degrees above absolute zero. (What’s important for me is the temperature at the center. That’s where it gets hot first because it has the pressure of everything on top of it. Therefore the reactions will first occur at the center.)

I described the reaction of proton + deuterium in a lot of detail because the basic picture is the same for all the nuclear reactions I’m going to be talking about. You need some energy to get over the Coulomb barrier and then you fall in and you get energy out. The amounts of energy or the size of the Coulomb barrier might be different, but the same ideas hold for reactions such as deuterium + deuterium, or deuterium + ^{3}He, or deuterium plus tritium. These are the Big Bang reactions. In all those reactions, you have to have enough energy to start with to get over the barrier. And that’s one of the reasons nucleosynthesis stopped so soon in the Big Bang: as things cooled down, pretty soon the temperature was too low for things to get over the barrier and fall in.

Now let’s get back to the life history of a star. As a big glob of gas compresses because of its mutual gravitational attraction, the gas eventually gets hot enough so that processes like the one just described (proton + deuterium) occur. And once they start, they release energy and that creates extra pressure inside the star, which stops (for the moment) the compression. A significant amount of heat energy gets produced by the “burning” of deuterium to make helium, but the deuterium is quickly used up because there wasn’t much there to begin with. Remember, the Big Bang produces a fair amount of helium but only a small amount of deuterium, so the deuterium that a star starts off with disappears rapidly. The deuterium burning releases some energy, but then it’s over. Since we know that stars shine for a long time (for example, our sun has been shining for about 4.5 billion years) this burning of pre-existing deuterium can’t be what powers the sun – the sun just didn’t start out with enough deuterium.

We can't make more deuterium in the way it was done in the Big Bang, because – as I said before – now there are no free neutrons. Well, this "problem" is actually good for us. If there were lots of free neutrons around all the reactions would work rapidly, and it would all go up in a big bomb. We want a nice sun that stays lit for billions of years, so the Earth has a chance to form and cool off, and Ursula has a chance to make life. Okay, any questions?

So what can you do now? How can we get something that keeps going, despite the fact we have no free neutrons? Well, something can happen, but it requires a higher temperature than proton + deuterium reaction. That reaction occured at about a million degrees. But once the initial deuterium is used up, and there is no heat (and therefore no extra pressure) being created in the star, the star will start collapsing again. And as it collapses, it's going to get hotter and hotter, and it's going to pass a million degrees. Eventually it's going to get to about 10 million degrees, and then another process can occur. Remember that now all we have is protons and helium. We somehow have to be able to make deuterium out of just protons.

This is where the Weak Force comes into play. You first get the interaction of a proton with another proton. Now, there is no nucleus that's stable with just two protons in it; helium needs at least one neutron with the two protons (^{3}He) or two neutrons with the two protons (^{4}He). However, the two protons can come together for an instant, and then if you're extremely lucky while the two protons are very close, one of them can by the Weak Force turn into a neutron.

[Note: The reason there is no stable nucleus with just two protons is subtle and beyond the range of this course. However, I have added some comments about the point at the end of this lecture transcript. It is actually related to Michael's question of last time: "Why don't the neutrons inside a nucleus decay, as free neutrons do?"]

Now remember what the Weak Force does. The most well known Weak process is the decay of a neutron: neutron goes to proton plus electron plus antineutrino. I mentioned that last time. But if you have enough energy you can get a reverse process: proton goes to neutron plus positron plus neutrino. (The proton's positively charged so it has give off a positron, not an electron.) Now, normally this doesn't occur because the neutron has more mass than the proton does, so there's not enough energy for a proton to create a neutron plus other stuff. But here, if you could turn one proton into a neutron, you could make deuterium. And a proton and neutron combined into deuterium allow a lot of energy to be released --- it would be just like Figure #1 (but starting with a neutron, not a deuterium nucleus, at the bottom of the well.) And that energy release allows the proton to turn into a neutron. It's another example of reverse (or inverse) neutron decay. The proton can turn into a neutron. And you also have stuff that's left over (a positron and a neutrino), which carry most of the energy released by the process.

So two protons can make deuterium. But it requires a Weak Interaction, and, because it's weak, it's not very likely to occur. But every once in awhile two protons hit and before they can fall apart a Weak Interaction takes place and one of the protons turns into a neutron. So the net effect is p + p -> deuterium + positron + neutrino.

It's amazing. You need all four kinds of forces to make stars work: gravity to compress and heat the gas, electromagnetism to provide Coulomb barriers that prevent the processes from starting until the temperature is high enough, the Weak Force to make protons into neutrons (but do it slowly, so the sun or star can burn for a long time), and the Strong Force to bind protons and neutrons into nuclei and release the energy that powers the star (and make enough pressure to counter the gravitational compression). It sounds complicated, all these different forces. Why do we need them all? But we couldn't have a sun or stars if we didn't have all the forces.

Okay, now, there were a couple questions.

[Student: So, the neutron that's formed, is that also then able to be used?]

Yes the neutron is formed from one of the protons, but it immediately combines with the other proton to make deuterium. The net result is: p + p -> deuterium + positron + neutrino. Once the deuterium is formed, you're happy, you can just continue the kind of reactions we had before (e.g., proton + deuterium -> ^{3}He + gamma).

[Student: So then it just keeps going as cycle?]

It's not a cycle. Once you've made deuterium by the Weak Interactions these other reactions can now occur. I'll describe them more in a minute [or see, for example, transparency #3]. The end result is you have a bunch of helium. You're taking what was originally protons and ending up with ^{4}He. Since ^{4}He has two protons and two neutrons, clearly some of the protons have had to be converted to neutrons along the way. That requires the Weak Interactions. Okay? Did you still have a question?

[Student: I don't understand why this couldn't occur earlier. (For example, why couldn't it occur at the same time the original deuterium was burning.)]

Well, it's not hot enough for it to happen earlier. Because the Weak Interaction is so weak, the chance that a proton will turn into a neutron (after the proton gets over the Coulomb barrier) is very small. At a million degrees, the chance of getting over the barrier is itself rather small, and when that small probability is multiplied by the additional small probability of the proton turning into a neutron, the chances are minute that the process will take place. At about 10 million degrees, the chances of getting over the barrier is much greater, and so now – although it is still rare – you start getting a significant number of cases where the proton gets over the barrier ***and*** turns into a neutron. The fact that it is still fairly rare is important to us, because it is why the sun can live for so long. Yes, sir?

[Student: Is "reverse" neutron decay the same as "inverse" neutron decay?]

Yes, I'm using the two terms interchangeably. Reverse (or inverse) neutron decay is closely related to normal neutron decay, but the process goes backwards. You start with a proton and end up with a neutron. Like all these processes, it can go backwards or forwards, assuming you have enough energy to make it happen. It doesn't happen with just a single isolated proton because a single proton has less mass than a single neutron so you would be getting more mass (or energy) out than you started with, which is impossible. But it can happen if the proton is next to another proton when it tries, because then you can release some extra energy by forming deuterium.

It's complicated but this is the way our sun works. In fact, all run-of-the-mill stars are using the same process. Proton plus proton gives deuterium plus a positron plus a neutrino. The key thing to remember is that it requires a Weak Interaction. I'm not expecting you necessarily to remember the precise reaction. But it's important to know that it requires a Weak Interaction to covert protons into neutrons. It starts occurring when the central temperature is about 10 million degrees.

What happens after that? Well, then the deuterium that's made can combine easily with another proton in the same reaction we discussed earlier. Now that you've made deuterium, it's easy. You don't need any more Weak Interactions. You can get proton plus deuterium gives ^{3}He plus a gamma ray (a photon), so you start making ^{3}He. Then once you have a lot of ^{3}He, you can get the next reaction: ^{3}He plus ^{3}He makes ^{4}He plus two extra protons. And the net result is you've used up a bunch of protons and you've made ^{4}He.

Let's count the number of protons used to make ^{4}He. Well, the deuterium took two protons. Then the next reaction is proton plus deuterium makes ^{3}He. So a total of three protons went into the ^{3}He. So to make two ^{3}He you need six protons. Thus a total of six protons went into the reaction: ^{3}He plus ^{3}He makes ^{4}He plus two protons. And you get two protons back again to recycle at the end, so a total of four protons are used up to make ^{4}He. It makes sense: ^{4}He has two protons and two neutrons, and we use up four protons to make it. Along the way two of the four protons have been converted to neutrons by the Weak Force.

All right, so that chain of reactions, whose net effect is to turn four protons into ^{4}He + energy, is the principal source of the energy in the sun, or in other normal stars. (There are some additional minor processes but this reaction chain is the main source of energy.) And the key point to keep in mind is that one of the reactions in the chain requires the Weak Force. Because it requires a Weak Interaction the whole chain is slow. And because it's slow it allows the sun to live for a long time with a nice "warm" energy output. Of course, if you were close to the sun you wouldn't feel just nice and warm; you'd feel awfully hot. But where we are it's nice and warm. And the sun lasts for a long time at constant temperature – just warming us up! The lifetime of the sun is about 10 billion years. As Michael told you, the solar system is about 4.5 billion years old so the sun is just approaching middle age. And if my experience is any guide the sun is going to start forgetting things pretty soon... Any questions?

[Student: What happens to that positron?]

Well, soon or later it's going to hit an electron that's wandering around in the sun and the two will turn into some more energy. Positron plus electron makes two photons, i.e., electromagnetic radiation.

[end of lecture]

Here is the added note on why there is no stable nucleus with just two protons and no neutrons. (You are not expected to know this argument; I am just including it in case someone wants to learn more.)

As mentioned above, the reasoning is rather subtle. One issue is simply that the two protons repel by the electromagnetic force. However, because the Strong Force overwhelms the electromagnetic force at short distances, the electromagnetic force is really not an important part of the explanation of why two protons don't make a stable nucleus.

The explanation has to do with two features of quantum mechanics that are not intuitive. First of all, quantum mechanics says that any particle has an intrinsic "fuzziness" --- it's not really located in any one place but is spread out a bit. We actually say that particles have "wavelike" features. (I will talk a bit more about the "waviness" of particles later on in the course when I describe white dwarf stars and neutron stars.) Because of this spreading out, the two protons on average cannot be all that close to one another. This means that they can't take full advantage of the Strong Force of attraction between them, since the Strong Force is short range and they can't get really close.

Now a similar argument applies to the proton and the neutron in deuterium. It is the reason that the deuterium nucleus, though stable, is not bound very tightly together --- despite the fact that the Strong Force between the proton and the neutron would be enormous, if they could just get really close. But, compared to a proton and a neutron, two protons have to put up with an additional property of quantum mechanics, and it prevents them from binding together at all. The property is called the "Pauli exclusion principle." You may have heard about it if you took high school chemistry. The Pauli exclusion principle says that two of the same kind of particles can't be in the same "state" together. In chemistry this is the reason that, as you consider bigger and bigger atoms with more and more electrons, the new electrons have to go into new orbits with higher energies. The orbits are sometimes called "shells;" the shells have a limited number of states in them. The organization of the electrons into shells is what explains the Periodic Table --- new rows start when one shell is filled up and you have to start filling a new shell.

Now in our case the Pauli exclusion principle implies that, in a hypothetical nucleus made from two protons, both protons could not be in the same state. This means that one of them would have to have some additional energy. Combined with the fact that they cannot take full advantage of the Strong attraction (see above), the net effect is that the hypothetical nucleus made from two protons would need to have more energy than two separated protons. So the nucleus made from two protons is not stable --- it will immediately decay back into two protons + energy. In contrast, the deuterium nucleus is stable --- it has less energy than a separated proton and neutron, so it cannot decay into a proton and a neutron.

The above reasoning also explains the answer to Michael's question of Feb. 14: "Why is a neutron in a nucleus stable, while a free neutron is unstable and decays?" A free neutron decays because its mass (energy) is more than the mass (energy) of the proton and other decay products. But for a neutron in a nucleus, you must consider the energy of the entire system. For example, think about the neutron in a deuterium nucleus. If it were to turn into a proton, the new nucleus with two protons would immediately break apart into two separated protons + energy.

That additional energy is big enough so that the state of two separated protons + energy has *more* energy than a deuterium nucleus, even though the neutron in the deuterium has more mass (energy) than a proton. So the state of two separated protons + energy, which would result if the neutron in deuterium decayed, has *more* energy than the deuterium. Since you can't get more energy at the end than you had at the beginning, the neutron in deuterium can't decay!

Finally, I just want to note that, even though a nucleus with just two protons is unstable, if you add an additional neutron, you get a perfectly stable nucleus: ^{3}He. The reason is that the extra neutron increases the Strong Force enough to hold the nucleus together. Now the two protons have something else to hold onto by the Strong Force in addition to each other.