Transcript from Epic of Evolution: Life, the Earth and the Cosmos (BEP 210A)
January 28, 2000 - Lecture by Claude Bernard

Okay, let's get started. We've got 15 billion years to go through today so we've got to get going here. [I actually only got through 300,000 years... CB.] I hope you stuck with me last lecture when I introduced the particles and the radiation. It was a little bit technical and detailed, but I assure you from now on I'm not going to be throwing too many new characters in there, just saying how these characters act. So we started with a beach ball sized universe at some enormous temperature (3×10^{26} degrees). Despite the fact that it's enormously hot and very compressed, it's actually quite simple because it's completely uniform. It's in what we call equilibrium, homogeneous and at a uniform temperature. If you took any little part of it, it would be basically the same as any other little part, just lots of photons, lots of quarks, lots of antiquarks, lots of electrons, lots of antielectrons.

Now, when I talked about particles and antiparticles, I said they're equivalent and that's basically true. The forces we talked about, namely gravity, the electromagnetic force, and the strong force (which holds the quarks together into protons and neutrons and also holds protons and neutrons together in the nucleus), all treat particles and antiparticles completely symmetrically. They don't care whether something is a particle or antiparticle. For example, the electric force between a proton and an electron (which holds them together in atoms) is exactly the same force as the electric force between an antiproton and an antielectron. In a sense, it's like a mirror world. Aside from the fact that antiparticles have opposite charges to particles, they are identical as far as those three forces are concerned.

But actually there's one more force that physicists have identified. It's called the weak force. I'll talk about it more later on in the course. As its name suggests, it's a very weak effect. However the importance of the weak force for us is that it treats particles and antiparticles very slightly differently. There's a subtle difference in the forces it exerts on particles and antiparticles. And because of that, as the universe started to expand it developed a very slight difference in the number of quarks and in the number of antiquarks. In fact, for every approximately 30 million antiquarks there were 30 million plus one quarks. In other words, there were just slightly more quarks than antiquarks. I will talk more later about the process --- how this happened as the universe started to expand from the initial beach-ball size, but for the moment you'll need to accept the fact that the weak force generated a slight difference between the number of quarks and antiquarks. Yes.

[Student: Is that number now or when the Big Bang first happened?]

That's just after the time I'm starting, in other words, shortly after the universe was 30 centimeters in radius or like a beach ball. Precisely when it occurs is not that well known, and in fact, even the details of the mechanism is not that well known, but we do know that weak interactions have this property, that they treat particles and antiparticles slightly differently.

[Ursula: But does that mean that one quark was added or an antiquark went away? Are antiquarks actually disappearing or are quarks?]

Okay, I see what you're asking. What's happening is that a few extra quarks are being produced by decays of heavier particles. It's actually a very subtle problem. In fact when I started to prepare to teach this course, I started reading all these technical books, and this was the hardest thing to understand, how this could happen. And I think I finally did understand it, but it is very subtle. When the early universe was in equilibrium, completely smooth, the number of quarks and the number of antiquarks were equal. As it started to expand, it got "out of whack," because it started to cool rapidly and was not exactly in equilibrium anymore – some objects were cooler than others. In that period when it was "out of whack," the weak forces created, from the decays of heavier particles, a few additional quarks. The number was very small, but there were a few additional quarks compared to the number of antiquarks.

The same thing happened with electrons and antielectrons. The counting is a little bit different: for about every 90 million antielectrons (remember antielectrons have another name, they're also called positrons) there were 90 million plus one electrons. This is due to a similar mechanism: a few extra electrons getting created. It's only very slightly out of whack. As I said it's complicated, but we can understand that the weak force could do something like this because it treats particles and antiparticles differently.

Okay, so that's the situation shortly after 10^{-32} seconds. The name of this process is "baryogenesis." Remember that baryons are quarks and things made out of quarks, and because there is an excess of quarks produced, it's called baryogenesis. It could also be called "leptogenesis" (remember electrons are leptons) because an excess of electrons over antielectrons is produced. In fact, the latter term is sometimes used, but since the processes are similar and baryogenesis was investigated first by physicists, both processes are generally lumped under the heading "baryogenesis." It's the first big milestone after our starting point: the production of slightly more quarks than antiquarks and slightly more electrons then antielectrons. Yes, sir.

[Student: I still don't understand how we know all this stuff.]

Well, it's a long story. A lot of these things come from experiments done at high energy particle accelerators, for example, the one outside of Chicago called Fermilab. Physicists give very high energy to particles and smash them in to each other. The energies are high enough that the temperatures approximate those that occurred early in the Big Bang: extremely high temperatures. And you can learn the properties of these forces at very high energies or very high temperatures. So we understand the physics and therefore we can apply it to the Big Bang situation, which is similar. Although this temperature sounds fantastic, we know enough from experiments to have a pretty good idea what would go on such temperatures. Of course, as I said, I'm a little bit out on a limb in discussing this early part of the Big Bang, since some of the physics is a little bit more speculative than the physics which governs the later milestones. At those milestones, we really know everything quite well. Here, we have some good ideas, but the details are not definite. We know that the weak interactions treat quarks and antiquarks slightly differently, and we can understand how such differences could have caused baryogenesis, but the exact mechanisms are not completely determined.

All right, so this is my first milestone. I'm going to show a transparency that has the milestones on it. This is transparency #2, and is now on the course web page. The Big Bang is at the bottom of this transparency, and time flows upward. Here we are. The stuff down here at the beginning (before 10^{-32} seconds) is in the period where it's quite speculative, where we don't really know for sure. This transparency is from one of the books that I put on reserve [J. Silk, A Short History of the Universe, page 87]. And we're here, at baryon genesis or baryogenesis, at this temperature, and a radius of about 30 centimeters, and a very early time. And I'm going to talk about most of these milestones that occurred between then and where we are now, which comes at the top, where the radius is something like 40 billion light-years (a diameter of about 80 billion light-years).

Okay, so that was the first step. Now, the next big milestone for us occurs at about 10^{-5} seconds after the Big Bang. 10^{-5} is a hundred thousandth of a second. This time begins to seem a little bit more like the kind of thing we can comprehend, rather than 10^{-32} seconds, which is 1/100,000,000,000,000,000,000,000,000,000,000 of a second! At about 10^{-5} seconds, the temperature is now a cool 10^{13} degrees (a mere 10 trillion degrees), and the universe has now expanded quite a bit. Instead of being 30 centimeters, it's about a .002 = 2/1000 of a light-year across. That's approximately 100 times the distance from the Earth to the sun. So it's still a pretty small volume for the entire universe to be in, but compared to where we were a little while ago it's much bigger. Remember the distance to our nearest star aside from the sun is four light-years away and this is only .002 of a light-year, which is not really very far.

Okay, now what happened here? Well, at this point it's cooled down enough that quarks condense and make protons and neutrons. As I explained last time, as you heat things up you boil them out, you break them up. It's just like when we break up liquid water by boiling it and send the water molecules shooting off in every direction to make a gas. In the same way, when you heat a proton or neutron hot enough, you boil out the quarks. But the reverse happens also: if you cool the quarks down, they will condense into protons and neutrons. So one important thing that happens now is that protons and neutrons are formed for the first time. (Previously it was so hot that protons and neutrons could not exist --- their quarks would be immediately boiled out.) But of course there are also antiquarks, although very slightly fewer of them than of quarks. There are still plenty of antiquarks, and they will also condense into antiprotons and antineutrons. So now we've got protons and neutrons, and antiprotons and antineutrons. Of course we have slightly more protons and neutrons than we have antiprotons and antineutrons because we had slightly more quarks than antiquarks.

Another important thing happens about the same time. As these guys condense into protons and neutrons, it's also true now that things have cooled off enough so that the photons (the electromagnetic radiation) do not have enough energy anymore on average to create protons and antiprotons. If you recall, last time I said that if you took a proton and let it knock into an antiproton (p + p bar) they would make two very high energy photons called gamma rays. And the reverse can happen too. Two gamma rays can hit and make a proton and an antiproton. But remember, protons and antiprotons have mass. When photons make them it's because the energy of the photons goes into the mass of the protons. Mass and energy can be converted one into another; that's what Einstein said in the famous equation $E=mc^2$. So in the very early universe this is happening all the time -- quarks hitting antiquarks making photons and photons hitting each other making quarks and antiquarks. It's continually going back and forth.

But at the time 10^{-5} seconds, after the protons and antiprotons are made, the average photon has cooled off a lot. So the photons that are zooming around will on average not have enough energy when they hit to make a proton and an antiproton. Recall, because of the expansion of the universe, the photons are getting stretched out. They are getting longer in wavelength, which means lower frequency, which means lower energy. So these photons are getting cooler and cooler as the universe expands. At a certain point the average photon is just too cool, too low in energy, to make a proton-antiproton when it hits another photon. So we have a situation where protons and antiprotons --- whenever they meet --- annihilate each other, but they don't get recreated afterwards. They make two photons; those photons bounce around, lose any extra energy in hitting other particles, and get stretched out by the expansion of the universe. By the time two photons hit each other again, they don't have enough energy to make the proton-antiproton back again. Photons are no longer making protons and antiprotons or making neutrons and antineutrons.

The end result of this process of annihilation (protons--antiprotons and neutrons--antineutrons annihilating each other and not being recreated) is that most of the protons and all of the antiprotons will disappear. All the antiprotons will get annihilated with as many as protons as they can find, and there'll be a few protons left over. Same thing for neutrons: all the neutrons will annihilate with all the antineutrons they can find, but since there are a few more neutrons than antineutrons there'll be a few neutrons left over. So at the end of this period, we just have protons and neutrons. We don't have any more antiprotons and antineutrons. Yes?

[Student: What got the protons going in the first place? In other words, were did all this stuff come from?]

Well, before the time I started with (everything smashed into 30 centimeters at 3 x 10^{26} degrees), we don't really understand the physics well enough to say what there was. We have some ideas that are very vague, which perhaps could explain it. My last lecture is entitled "The Ultimate Free Lunch," is about an idea that all this could come out the vacuum, out of "nothing."   It's a very speculative idea of how that might happen; but the truth is we don't really know. What we do know is how much matter there is here now and how much energy there is in photons now, and we do know everything's moving apart. So we can turn the movie around and run it backwards, and we know it must have been in such-and-such situation at such-and-such time, until, when things were extremely hot, we run out of knowledge about what the physics was. So we don't know what came before that. But I can, for example, talk about what was going on in our "beach ball," because I can follow it backwards in time fairly well to that point, but not much before.

[Student: So in the beginning there were protons?]

As far back as I feel confident of, I can say "in the beginning there were photons and quarks and antiquarks and electrons and antielectrons." (For completeness, I should also tell you that there was also a lot of other junk, a whole zoo of particles that are not as important for us, so I haven't introduced them. The ones I talked about the main ones.) Yes?

[Student: If you said that protons and antiprotons make two gamma and the same thing with antineutrons and neutrons, if it's going from two gamma back, is there an equilibrium? I mean how does it know to make protons and antiprotons and not neutrons and antineutrons?]

Well, there's a certain probability when two photons hit to make proton-antiproton and another probability to make neutron-antineutron, and the net numbers will adjust themselves in equilibrium. For example, if at some time in equilibrium, there are too many neutrons and antineutrons and not enough protons and antiprotons, then what will happen is it will be more likely that neutrons and antineutrons hit each other and annihilate than that protons and antiprotons annihilate (because there are more neutron-antineutrons). And the photons that hit each other will continue to make the right proportion of neutron-antineutrons to proton-antiprotons. So the right proportions get restored. This is the idea of equilibrium. Equilibrium is what, for example, would happen if you put material in a container, where it can't expand, and kept at a fixed temperature. If one thing would get a little bit off it's proper amount, it would adjust itself. In equilibrium, if there are too many protons and antiprotons at some time they would annihilate with each other, make more photons and then some more neutrons-antineutrons would be made. The difference of course in the universe is that it's not in this nice box, staying at equilibrium. At the same time all this is happening the universe is expanding very rapidly, and so things change. As the universe cools, it's no longer possible to remake particle-antiparticle pairs, so when they annihilate they're gone. Only the leftover protons and the leftover neutrons, which have no antiparticles to annihilate with, are left.

[Student: I understand that in a closed container, you're going to have equilibrium. I was just wondering how it works in the universe.]

Well, it's tricky and it's hard to calculate, but we know how it works. It's a problem because the universe is not a closed container. It's expanding and cooling while all these processes are "trying" to take place. Sometimes, the processes would make something if the whole system were enclosed in a box, but in the Big Bang the particles get spread out too fast by the expansion so that the processes don't finish. We'll get to that kind of situation soon.

So we now have protons and neutrons and then a little while later --- at about 1 second after the Big Bang or after we started counting --- the same thing happens with electrons and antielectrons that just happened here. Remember, we have electrons, which have a negative charge, and positrons, which have a positive charge (e^+ and e^-). Electrons and positrons can make two photons and vice versa. But again, when the universe gets sufficiently cool, the process can't go backwards. The average pair of photons no longer has enough energy to make an electron and an antielectron. So what happens is that electrons and antielectrons annihilate and make photons but photons cease to make electrons and antielectrons. This happens a little bit later than proton-antiproton annihilation because ---as I said last time --- protons (and neutrons) have a lot more mass than electrons or antielectrons do. It takes a lot greater energy in the photons to make a proton-antiproton than it does to make an electron-antielectron. So as the universe cools the first thing that stops happening is making protons and antiprotons (or neutrons and antineutrons).

The photons don't have enough energy to make that much mass. Later on as it cools still further, the photons don't have enough energy to make the mass of electrons and antielectrons. So what happens now is electrons and antielectrons make photons, but not vice versa. This is the period shown as "electron-positron pairs annihilate" on transparency #2. This occurs at about 1 second after the Big Bang. The temperature is 10^{10} degrees, that's 10 billion degrees. And what is now our observable universe was then about 3 light-years in radius. So it's getting relatively big, but it's still very small compared to its radius now, which is something like 40 billion light-years.

Okay, so that was the next milestone. It's very much like the previous one. And again what happens after this is that all the positrons disappear and almost all the electrons disappear, but a few are left over. And now we have all the ingredients of ordinary atoms. We have protons, we have neutrons, and we have electrons. We don't have antiprotons, antineutrons or antielectrons left. They're not in atoms yet, but we do have protons, neutrons and electrons.

The next milestone is listed on the transparency as occurring at about 3 minutes, but really it takes place over a period roughly from around 1 minute to around 3 minutes. In this period protons and neutrons, when they hit each other, start making nuclei. They start sticking together and the temperature is low enough so that the nuclei don't get boiled apart anymore. So now we have what is called "nucleosynthesis" --- nuclei are made. The temperature is now only about a billion degrees. The radius of the universe is about 50 light-years. Of course it's changing during this whole period from 1 to 3 minutes; it's always expanding. 50 light-years is the average radius during this period.

So protons and neutrons can now hit each other and start making more complicated nuclei. And the temperature is low enough that once a nucleus is made it doesn't boil apart anymore. If it gets made it stays. Again, that's because the temperatures have decreased enough. Here [transparency #3 --- also on the web] are some of the processes that occur in this period of what's called nucleosynthesis. The very first thing that happens is that a proton may hit a neutron and make a deuterium nucleus. Remember, deuterium is heavy hydrogen. A deuterium nucleus has a single proton like all hydrogen does, but it has an extra neutron. This first process occurs when proton hits a neutron it makes a deuterium nucleus and emits an extra photon. And then two deuterium nuclei can hit each other and make helium-3 and a neutron. Don't worry about these particular processes. Just kind of try to get the idea that things are starting to stick together and making more complicated nuclei. Deuterium can hit deuterium and make tritium, which is extra-heavy hydrogen, which has one proton and two neutrons. They can make helium-3 which has two protons and one neutron. Deuterium can hit helium-3 and make helium-4 and a proton. Deuterium can hit tritium and make helium-4 and a neutron. These nuclei that are getting made now are relatively small but still more complicated than just a proton (the nucleus of a hydrogen atom). So we don't just have protons anymore. We have things like deuterium nuclei, helium-3 nuclei, and helium-4 nuclei. Even a little bit of lithium, which is the next heaviest element, gets made at this point.

To summarize this process of "Big Bang nucleosynthesis": Protons and neutrons come together and stick. They don't boil apart anymore because the temperature is cooler. So they condense, they stick together just as quarks stuck together to make the protons and neutrons themselves. Now, the interesting thing about this process is that this is about all that happens at this point.

Elements heavier than helium do not get made in any significant amount. A tiny bit of lithium is made, but nothing beyond that. In the early days of the Big Bang theory people said "well this *must* be how our elements got made." So they tried to figure out how the Big Bang could make all the elements that we see. For example, our bodies are made out of carbon and oxygen and nitrogen, etc., and the Earth has lots of iron and all kinds of other heavier elements. However, we now know that in the Big Bang this is all that happens. We make elements up to helium and a tiny bit of lithium and then it stops.

One reason Big Bang nucleosynthesis stops at helium is again because of the expansion of the universe. As everything continues to expand, it gets harder and harder for these small nuclei to hit each other and stick to make something bigger. Everything is spreading out and therefore becoming less dense. And as things get less and less dense the chances of them finding each other gets smaller and smaller. This is related to what created the protons and neutrons in the first place. Remember, it was because there was a slight imbalance between quarks and antiquarks, and therefore most of the original protons got annihilated and only a tiny excess remains. For that reason, the protons and neutrons that we have are actually rather rare compared to what there could have been. And that means even when we first have just protons and neutrons, they're very diffuse, very spread out. There isn't really that much matter because only a slight amount is left after the matter and antimatter annihilated. So it's pretty diffuse to begin with. And as the universe expands some more, the small nuclei that have been made are too spread out to continue to hit each other and make higher elements. So this is one reason the process stops now.

A second reason for the early end to nucleosynthesis is the cooling of the universe. You no longer have enough energy to get things close enough to stick. For example, suppose you wanted to make two helium nuclei hit each other and stick. Well, before they can hit and stick, they have to have enough energy to overcome the electrical repulsion between them. Recall that helium nuclei have positive charge: each of them has two protons. So if they happen to be coming closer together, they repel each other more and more. It's only if they actually have enough energy to hit each other that they can stick. When they hit, they stick because of the strong force, which is attractive, but before then they're repelling. So if they don't have enough energy because they're too cool, they'll have trouble sticking together.

Later in the course, I will go into some specific reasons why nucleosynthesis stops particularly with helium-4 and not some other small nucleus. But for now I'll just state the end result: the nuclei made in the Big Bang are deuterium, tritium (which quickly decays again since it's unstable), helium-3, helium-4, and a tiny amount of lithium. And of course, any protons that don't combine with any other protons or neutrons will just remain as ordinary hydrogen nuclei. And any neutrons that don't combine with other neutrons or protons will decay. (Remember that a neutron by itself is unstable.)

Knowing how fast the universe is expanding, and knowing how fast each of these nuclear processes take place, and knowing how dense the protons and neutrons were in the early universe, we can predict how much of these other elements get made during Big Bang nucleosynthesis. [transparency #4] This is a complicated graph but I just wanted to have you get the general idea here. The graph shows our predictions are of various amounts of different nuclei being produced. At the very top is a prediction of how much helium-4 would be produced assuming a certain amount of density of matter now. (Of course the density was a lot more then.) And we believe that the density now is just in this range, so that the amount of helium produced is in agreement with what's observed in the universe. The amount of helium-4 is in this horizontal range and the prediction says that if the current density is a certain amount, which is shown here as 3 in these units (i.e. 3 x 10^{-31} grams per cubic centimeter), then the right amount of helium-4 would have been produced. And the same is true of deuterium, helium-3 (although the observations aren't so good for helium-3), and even lithium, which is very rare. The predictions for all these nuclei are consistent if the density now is about 3 x 10^{-31} grams per cubic centimeter. And that density is consistent with the amount of matter left over from the period of baryogenesis. So everything fits together.

These predictions are for what's called the "primordial element production", or "primordial nucleosynthesis," or just "Big Bang nucleosynthesis." And that's what's made in the Big Bang: just these elements. So a question you might ask is "where do all the other elements come from?" We know that the Earth is made out of iron, oxygen, silicon, etc. And living creatures are made out of carbon, oxygen, nitrogen, etc. But the only nucleus more complicated than hydrogen that comes out of the Big Bang in significant numbers is helium. At the end of the period of Big Bang nucleosynthesis we have about 75 percent hydrogen and almost 25 percent helium (helium-4), instead of just having single protons (which as atoms would become hydrogen). So about a quarter of the mass that was in protons becomes helium nuclei in this period. And not much else happens. A tiny bit of lithium is way down here at one billionth of the amount of hydrogen, and helium is up there at almost 25 percent.

Now at present the ordinary matter in the universe is about 74 or 75 percent hydrogen, and about 23 percent helium. There is now a little bit (about 2 percent) of other, heavier elements (with more complicated nuclei), whose origin I haven't explained yet. This 2 percent includes all those important elements in the Earth and in living things. These were actually made in the interior of stars. The stars then exploded and sent the material back out into space; some of it then recondensed into new stars and planets --- for example, into our solar system. I will talk about how elements are made in stars in my next set of lectures.

All right, so that's nucleosynthesis. The next big milestone is called "matter domination." It's not really an event, but just a period when the balance between matter and radiation changes. At this time the photons have now cooled so much that more energy is in the form of mass of ordinary matter (protons and neutrons) than is in photons. Because protons and neutrons have a lot of mass they contain a lot of energy. (Electrons are much lighter and are relatively unimportant in this respect.) Previously, however, most of the energy was in photons. Remember that when particles and antiparticles annihilated earlier on they made lots of photons, and the photons didn't convert back into particles and antiparticles. So we ended the periods of annihilation with much more energy in photons than in matter. But at the period of matter domination, the photons have cooled enough (due to the expansion of the universe) that more energy is in matter than in photons. And I'll tell you why that's important in a second. It occurs at about 10,000 years. The radius of the universe is about 2 million light-years. It's still not the current distance to Andromeda (which is about 2.5 million light-years away if you recall), so the universe is big, but not that big. And the temperature is now 30,000 degrees.

The following line of reasoning shows why it's important when matter dominates photons. Photons move at the speed of light. Because they move very fast they create a lot of pressure as they bounce around: each time they hit something they push out. With all that outward pressure from photons, gravity is unable to pull the matter into big clumps. So galaxies and stars cannot form when most of the energy of the universe is in photons. As more and more of the energy is actually in matter, the photons become less and less important and the matter can start to clump together due to gravitational attraction. And that's the beginning of the things that will eventually become galaxies and stars. The matter is starting to clump because of gravity, and the photons no longer have the energy to push it apart. This is a gradual process, and nothing special happens exactly at the time of matter domination. But it's a milestone in the sense that a small amount of gravitational clumping of the seeds of galaxies and stars can now begin.

The next milestone takes this one step further. It's called the period of "decoupling." Decoupling occurred about 300,000 years after the Big Bang. The temperature is now only 5000 degrees. It was still warm by our standards but quite cool compared to what it was originally. The radius of the universe is about 15 million light-years. At decoupling, atoms were made. Now the temperature is so low that electrons aren't boiled off from the nuclei. Instead the electrons go into orbit around the nuclei and make ordinary atoms. So this is the first time that we actually have atoms. The temperature immediately before this time was so high that we just had separate electrons, protons and helium nuclei.

When atoms form, something else very important also happens. Remember that light is an electromagnetic wave. It has electrical properties. It interacts very strongly with objects that have electric charges, such as electrons or protons. But atoms are neutral. The negatively charged electrons are now very close to the positively charged protons, and the total charge is zero. As soon as you get neutral atoms and you don't have separate plus and minus charges, the photons don't interact very much with matter anymore. Since photons are electromagnetic, they interact very easily with single electrons or single protons or isolated nuclei, which have a positive charge. But once atoms are made, photons almost always go right on by without stopping, without hitting. To a very good approximation, photons don't even notice the matter anymore, and don't really do anything to the matter anymore. (It's like the end of a romance.) The photons just keep zooming around the universe. So the matter is totally free to clump without any interference from the photons. And the formation of structure, of proto-galaxies and proto-stars, therefore accelerates rapidly at the time of decoupling. And it's called decoupling because the photons are no longer coupled to the particles, to the electrons and the protons.

Decoupling has one final important effect. After decoupling, the photons have such a small probability of bouncing off an atom that most of them never hit anything again. So almost all of these photons that were present at the time of decoupling, 300,000 years after the Big Bang, are *still* zooming around the universe. They've just been moving in straight lines from then till now. And they are there today, those same photons. They haven't hit anything or been absorbed by anything in the almost 15 billion years since then. The only thing that's happened to them in that time is that they've cooled off, lost energy, because of the expansion of the universe. At the time of decoupling the average photon was visible, blue light. In the meantime nothing's happened to it, except that it's lost so much energy that it is now at much lower (microwave) frequency.

In fact, the microwave photons left over from the Big Bang (or more precisely, from the time of decoupling) have been observed. This is one of the most importance pieces of evidence for Big Bang picture. The leftover photons are called the “cosmic microwave background. They were first observed by accident in 1964. Two astronomers, Arno Penzias and Robert Wilson, were trying to look at some stars with a microwave telescope. They observed what looked like background noise coming from every direction, and it was the same in every direction. At first, they thought it was something wrong with their apparatus. In fact, they thought it was due to the pigeon droppings on the telescope. So they cleaned the telescope, but the “noise” was still there. And gradually people began to realize that this was the cosmic microwave background, left over from the Big Bang. Yes?

[Student: Did you say that photons slow down as the universe expands?]

They don’t slow down because photons are electromagnetic radiation and must always travel at the speed of light. But they do lose energy as the universe expands. Now when matter loses energy, it slows down. But photons can never go slower. The way they lose energy is their frequency decreases, but their speed doesn’t change.

[Student: Do we know what’s going to happen to them?]

Well, most of them are going to keep going along, continuing to lose energy as the universe expands. Now and then one of them interacts with something. The ones we see are of course the ones that interact with our apparatuses.

Since the universe at the time of decoupling was in pretty much equilibrium, we observe the same number and the same energy of photons coming from every direction to high degree of accuracy.

While you’re working on the questionnaires, I’ll just make some general announcements. The transcripts are gradually appearing on the Web. It’s slow because I talk fast and say a lot, so it takes a long time to edit. I will get the transcripts up on the Web as quickly as I can. I have also put up a list of things that I think are unclear or misleading in the Ferris book. For each chapter in Ferris there’s a link you can click on. There’s usually only about two or three things for a chapter and some of my corrections are kind of picky, but I just wanted you to have some place where all the facts are straight. I will also put questions emphasizing what I think was important on my lectures so you can have a way of reviewing and checking yourselves.