Transcript from Epic of Evolution: Life, the Earth and the Cosmos (BEP 210A)
March 13, 2000 - Lecture by Claude Bernard

Discussion About Midterm

Before I start lecturing I'll say a little bit about the midterm, which is coming up on Friday. There are short answers, which will require one to three sentences, depending on how you phrase things, and you will have a choice of 15 out of 18 of those. And then there are longer problems or discussions, which will require maybe a paragraph or two short paragraphs to answer, and there will be a choice of four out of six. And 6 and 18 are both divisible by three so you can assume that they come from the three basic areas that we've talked about. A couple of them may involve more than one area. Yeah?

[Student: How much should we focus on the readings and how much on lectures?]

Okay, maybe we should all answer that separately because we have different ideas. As far as my stuff goes, if you know what happened in lecture that's all you need to know. The scientific part of the reading, which was from Ferris' book, was to reinforce lecture or further explain the lectures. But if it's in Ferris and I didn't mention it, you're not responsible for it.

[Michael: It's the same for me. Everything will be from the lecture material and not from the other stuff.]

[Ursula: I will also just ask questions from the lecture. As of this morning the last few lectures that I gave before Break hadn't yet been put on the Web site. Have they come up yet? Has anybody looked? Okay, I gave them to him a long time ago but there was a power outage over the weekend and yada, yada so they should be up by tonight. I'm going to bug him.]

[Student: February 28th is there. That's what I just got.]

[Ursula: Yeah, but I mean the more recent ones. He has them, he just hasn't put them up, but it should be available soon. There will be questions on the reading on the final, so we're certainly interested in having you do it. But the midterm is just based on the lectures. Claude, you said there may be a question on two or more units, but in discussion section this morning somebody asked whether this was going to be the case, and I said I didn't think so, I thought that we were just going to be asking questions from our unit. Is that true?]

Well, I think that's basically true, but one short answer that I put on had some overlap with one of the other units. However, I did explicitly discuss that overlap it my lecture.

[Ursula: But in general just try to get the three strands separately, and don't feel like you're going to be asked for a lot of putting them together on the midterm. However, on the final we'll certainly be asking you to put things together --- in a way, that's the whole point of the course --- so it wouldn't hurt to start thinking about it.]

Yes?

[Student: A number of the transparencies don't load for some reason…]

I'm sorry, the transparencies or the lectures?

[Student: The transparencies.]

My transparencies work okay on my machines. You need to have Adobe Acrobat Reader…

[Michael: The problem may be with my transparencies. I'll check. They were working fine for me, but at one point there were some problems. I'll see if it's been fixed.]

Yes?

[Student: Will this week's lectures appear on the test?]

No. I will talk about new things this week. I may summarize in a few sentences what I said before, and what I said before is fair game, but anything new that I say today is not on the midterm. It could appear on the final but not on the midterm. So the midterm is all on the previous lectures, which are up or will be up very soon on the Web site. Hopefully the last couple will be put up today, they've already been sent. Did I see another question? Yeah?

Okay, other questions? The short answers are worth 4 points each and there are 15 so that's 60 points. And the long answers are worth 10 points each and you pick four out of six so that's the other 40 points, 100 points total. There was a question. Judy?

[Student: Yeah, could you give us an example of a type of short answer or a type of longer answer question that will be asked so I have an idea of like how much detail I need to go into in terms of studying or how much abstract thought you want us to have?]

You're interested in what answer I'd be looking for?

[Student: Well, what type of question and yes, what type answer you want.]

Most of my study questions on the web are like short answers questions. A few of them, especially those at the end of the sets, are more like long answer questions. For example, one of my questions asked about three different types of evidence for the Big Bang and the significance of each one. That is clearly a long answer type of question. A couple of my short answer questions were taken fairly literally from the study questions. The rest did not come directly from the study questions, but the study questions do emphasize most of what I consider important. Mark?

[Student: What about the readings? Like how much is going to be taken directly from the readings?]

I think we covered that one already. The quick answer is: nothing that's in the readings that's not in the lectures will be on the midterm. Okay, any other questions?

Lecture Begins

Okay, so let's go on with the physics. The very last thing I was talking about was what happens to a star after it exhausts its nuclear fuel for the first stage of burning, which is called "hydrogen burning." Hydrogen burning is the longest stage; it's the stage that the sun is in. The net process in hydrogen burning is the combining of four protons to make a helium nucleus (^{4}He). And that's where the energy for lighting the sun comes from. The helium nucleus has a mass that is less than the sum of the masses of the four protons that make it up. (Two of the protons get converted to neutrons somewhere along the line; that's an old story for us.) The difference in mass is turned into energy, and that's what gives the energy of the sun. That process continues for a long time. For a star like the sun it continues about 10 billion years. Because hydrogen burning is so slow, most stars that you see in the sky are in the hydrogen burning stage.

When all the protons are turned into helium, then the next stage starts, which I began to talk about last time. With the protons all gone, no energy is being produced in the core of the star. It gets cooler, and as it cools, the pressure decreases and it can't hold up the weight of all the material surrounding it anymore. The core collapses. And because of the collapse, it gets compressed and heats up again, and in fact it heats up hotter than it was before. And it's a little counterintuitive, but this same thing happens again and again. When you use up one kind of fuel the core of the star initially gets cooler, can't support the gravitational push in, collapses, gets compressed, and finally gets hotter. And in fact each time it's going to get hotter than where it left off the last time. Once it gets hot enough it can start a new phase of burning. The new phase of burning that takes place after hydrogen burning is called helium burning, and I discussed it last time. The net effect of helium burning is to take three helium 4 (^{4}He) nuclei --- recall that a helium 4 (^{4}He) nucleus has two protons and two neutrons in it --- and make carbon 12 (^{12}C), which has six protons and six neutrons. (Remember: the number next to the chemical symbol, in the upper left hand corner, tells you the total number of protons and neutrons.)

Just as energy is released in hydrogen burning because the mass of ^{4}He is slightly less than 4 times the mass of a proton, energy is released in helium burning because the mass of ^{12}C is slightly less than 3 times the mass of ^{4}He. I'll say a little bit more detail in a minute about this process.

An important feature of helium burning is that it requires a higher temperature to start than hydrogen burning did. And the reason involves the same ideas that explain why hydrogen burning requires a high temperature in the first place: you have to overcome the Coulomb barrier to get the protons close enough to each other so that the Strong Force can join them together. When they're far away they repel each other by the electromagnetic force. That's the Coulomb barrier. It's only when their energy is high enough (their temperature is high enough), that they can come close enough to join together and eventually make helium. The same issues apply here with helium. It's only when the helium nuclei have enough energy to overcome the Coulomb repulsion (the electromagnetic repulsion or the Coulomb barrier) that they can come close enough together that the Strong Force can join them together. Now a helium nucleus has more electric charge than a proton --- in fact, a helium nucleus has two protons and two neutrons so it has twice the charge of a single proton. And therefore two helium nuclei repel each other four times more than two protons. Each one has twice the charge as before so there's actually four times as much repulsion as there was for two protons. (I'm not going to ask you *how much* more the repulsion is, but it's important to know that it is *more* repulsion because the charge is bigger than it is in the case of hydrogen.) So they repel more with the electromagnetic force, and that means that it requires a higher temperature to get over the Coulomb barrier.

So when the hydrogen burning is taking place and the core of the star is at a mere 10 million degrees, no helium burning takes place. It's not hot enough for the helium nuclei to get together. They're repelled more than the hydrogen nuclei (protons). Later, when the hydrogen burning is finished and the core of the star collapses further and heats up to about 100 million degrees (about 10 times more), then helium burning starts. Once it does start, the star is again produces energy and therefore heat and light, and in fact you get out an enormous amount of energy. And as I said in my previous lecture, once the helium burning starts the core gets so hot that it blows the outer layers of the star out to an enormous size --- that makes a red giant. I showed you the example of Betelgeuse, which is a star in the constellation Orion. Let's look at the slide again [slide 1]. And Betelgeuse is the star up in the left corner of the constellation Orion. Remember I told you that the name comes from the Arabic but I couldn't find out what the Arabic word meant. Well, I finally found a dictionary that had it: the Arabic name is *Bet el geuse*, which means "Shoulder of the Giant." I guess in the Arabian countries they call the constellation the Giant, instead of Orion, the hunter. Betelgeuse is the shoulder of the giant. It's up in the upper left-hand corner. And here is the size of it compared to the Earth's orbit around the sun or the size of Jupiter's orbit --- so it's called a red giant for very good reason. It's an enormous star. The outer layers are pushed out very far.

Let's also take a look at the next one, which is also from last time [slide 2]. This actually shows the remains of the outer layer. In this case it blew out in two directions. This is called the "Hourglass Nebula" ("nebula" just means "cloud"). You can see the outer layer of the star, which has blown out to enormous size. What's left of the star is the tiny dot slightly off center in the blue. (When the helium burning stops, what's left of the star usually becomes a "white dwarf" --- see below.)

Okay, now, let me say a little bit more about the process of helium making carbon. It actually doesn't go in one stage. In the case of hydrogen burning, you didn't just have four protons hitting together all at once and making helium. It goes in stages of two protons hitting at a time because it's unlikely for four of them to come together all at once. It's much more likely that two of them will come together and they in turn will meet somebody else and so forth. And the same thing here -- it's not very likely that three heliums come together all at once. In fact, it goes in a two-stage process. First two helium nuclei come together and make a nucleus called beryllium 8 (^{8}Be). So we have ^{4}He + ^{4}He makes ^{8}Be. And again, the details are not important. I'm only really interested in the overall idea, but I do want to say a little about the details just to give you some feeling of how this goes. Now, beryllium 8 (^{8}Be) is actually not a stable nucleus. If it's left by itself it will soon decay back into helium plus helium. It's only if you're very lucky that the beryllium may be struck by another helium before it can decay. Then you can get carbon.

So helium burning is a two-step process, but the intermediate stage (^{8}Be) is unstable. You may know that there exists an element called beryllium which is perfectly stable, but that's beryllium 9 (^{9}Be). To be stable it needs an extra neutron to help glue things together. With just eight (four protons and four neutrons), it's not stable. And so if you're lucky and the beryllium is hit by a helium before it can fall apart again, then you can make carbon, which is stable. And the fact that there's no stable nucleus with a total of eight protons and neutrons is the final nail in the coffin of the Big Bang nucleosynthesis. We talked about nuclei being made in the Big Bang, but helium is to a very good approximation the biggest nucleus that gets made. To get further than helium you have to jump over beryllium --- because it's not stable --- and get all the way to carbon. And that means that once you make beryllium there has to be a good chance of it being hit by a helium nucleus before it falls apart again. And the early universe is just too spread out by the time of nucleosynthesis (1 to 3 minutes after the Big Bang) for there to be any appreciable chance for a ^{4}He to hit a ^{8}Be before it decays.

The fact that the particles are too spread out by the time of nucleosynthesis is largely because there were only slightly more quarks than antiquarks when the quarks got made in the first place. That means that most of the protons annihilated with antiprotons and most of the neutrons annihilated with antineutrons, and so what left was rather thin. Of course it wasn't thin by everyday standards. It was incredibly dense and hot, but compared to the centers of stars it was not very dense by that time. It was just not dense enough and hot enough for this process to continue to carbon. There weren't enough helium nuclei around. And, as I've mentioned before, there were also other problems --- it was cooling rapidly, and remember you need a very high temperature to have helium burning. So you only had a short period where you might have had a chance of making carbon, but in that short period it wasn't dense enough. So two helium nuclei may have collided and formed beryllium 8 (^{8}Be), but then it fell apart again before it had a chance to be hit by a third helium. That's why nucleosynthesis stopped in the early universe at helium (with just a tiny bit of lithium).

But a star, after it's done with hydrogen burning, can indeed make carbon this way. Because the center of the star is dense enough, there is some chance that a helium nucleus will hit a beryllium nucleus before it can decay. Actually again there is another detail that I don't expect you to remember but which is actually very interesting. The carbon that's made in this process is actually not a normal carbon 12 (^{12}C) nucleus, but what's called an excited state of a carbon 12 nucleus. We show an excited carbon 12 nucleus like this: $^{12}\text{C}^*$. Its protons and neutrons are jiggling around more than usual (which is what we mean by an "excited state"). Now there just happens to be an excited state of carbon 12 (^{12}C*) with energy very, very close to the total energy of the ^{8}Be and the ^{4}He. (By "total energy" I mean both the energy stored in their mass and any energy of motion they have due to their temperature.) The fact that there is a state of carbon 12 with energy very close the total energy of the ^{8}Be and the ^{4}He makes it possible for the reaction to proceed rapidly enough that a significant amount of carbon can be produced.

If there weren't an excited state of carbon right with the right energy, the energies wouldn't match up very well. That would have the effect of reducing the rate at which carbon would be made. And if the rate were smaller, then very little carbon would be produced in stars. And that would be a problem because we're made out of carbon. Stars burning helium are the only place that our carbon can be made. So if this excited state of carbon hadn't been there with just the right energy, stars wouldn't have made enough carbon, and creatures like us couldn't have evolved. I suppose there might have been other kinds of creatures, but life like that which exists on Earth couldn't have evolved --- it depends on there being enough carbon.

Later, after the excited state of carbon 12 ($^{12}C^*$) is made, the excited state just decays into a normal carbon 12 state (^{12}C) plus some photons, which carry away the extra energy. So you end up making ordinary carbon. But it needs this intermediate step --- like a landing on a staircase where you can catch your breath for a bit --- in order for this process to take place with a significant rate.

Once the carbon is made in these stars, you can also have a few further processes that are also very important to us: for example, a ^4He may join with the carbon that's been made and make oxygen 16 (^{16}O). And even the oxygen can combine with another helium that's there and make neon 20 (^{20}Ne). So in this stage of helium burning you make carbon, and you also make some oxygen and neon, and again it's kind of convenient. The process making oxygen is relatively slow because there isn't an excited state of oxygen that has just the right energy. That's also good because, if it were fast, it would use up all the carbon that was made. Carbon making is itself rather slow because when two helium nuclei make beryllium, usually the beryllium falls apart again before carbon can be made. Only once in awhile are you lucky enough that the beryllium gets hit by another helium before it can fall apart. So carbon production is slow. It's not slow because of a Weak Interaction, so it's not as slow as hydrogen burning, but it still is relatively slow. It's slow because most of the time it's a failure. You get to the first stage and it falls apart. It's like trying to make a very delicate house of cards. Most of the time you put the first cards on and before you can put the next cards on it collapses. So you do it again, and again. Finally, you happen to get it right.

On the other hand, making ^{16}O from ^{12}C and ^4He doesn't require an unstable intermediate step. So the process could have been quite fast, but it is slowed down to some extent because there's no excited state of oxygen that has just the right energy to allow it to go very easily. And that's also good because if there were an appropriate excited state of oxygen, the process would go so fast that it would use up all the carbon as soon as it got made. And although we like oxygen, we can make oxygen in lots of places in stars, but this is the only place where you make carbon. And if you use up all your carbon we can't exist.

[Student: Can you define an excited state?]

Yes. Normally the protons and neutrons are basically just sitting there in a nucleus. In an excited state, they have some extra energy vibrating and moving around each other. I'm not going into great detail about it, but it's interesting that there is this excited state because it's what allows the carbon-making process to happen fast enough for us to exist.

Let me read you an interesting quote here from a book called The Physics of Stars by A. G. Phillips. He says, "Small changes in the seemingly boring excited states of nuclei could have easily led to a solar system in which boredom would not be a problem, because nobody would be around to be bored." This fits into the idea of the Anthropic Principle that we've discussed in sections. Even if you don't like the Anthropic Principle, it is awe inspiring to realize that we couldn't be here if any of these details were a little bit different. Now, whether there could have been some other totally different form of life is something we don't have an answer to. Our kind of life is based on chemical reactions using carbon and many other elements. We don't know if it is possible for life to be made from other kinds of material and not require carbon or other elements heavier than helium. But at least to have the type of life we have on Earth, we need carbon and we need a lot of other elements, because that's where you get all the complexity that you need to have the genetic code and so forth. And for this, the "boring" details are crucial.

Learning about this has been kind of neat for me because I was trained as a particle physicist. We're interested in the smallest things (for example, quarks), and I always thought nuclear physics was boring. To me, a big nucleus like carbon was just a very large, complicated combination of lots of protons and neutrons --- something we know all about in principle, but too complex and too dependent on details to be well understood in practice. In nuclear physics, you have to make various kinds of models; you don't have the power to understand the details in the fundamental way that we do in particle physics. Particle physicists often look down upon nuclear physics and call it "unclear physics" because of the complexity that results when you combine so many simple objects. But by teaching this course I'm finding out some really neat things about nuclear physics. Details that might be boring in the abstract become fascinating when you realize that they're crucial to our existence. It makes it a lot more exciting to me --- I have a new appreciation for nuclear physics.

Okay, so helium burning goes on, but eventually the helium gets used up. What happens when it has all been made into carbon (and some oxygen and neon)? I'll talk first about what happens next in the most common situation, although there are other possibilities that are even more interesting, which we'll get to later. In the most common situation, what happens next is "not much." After the helium is used up, you start to have the same situation as before: There's no more energy produced in the core, it starts to collapse, and it gets hotter. But before it can get hot enough to start the next stage of nuclear burning (making yet bigger nuclei), it's held up by the electrons pushing against each other (I'll explain that in a minute), and it just stops. The electrons pushing against all the other electrons create a high pressure. When the electrons get very close to each other, the pressure gets large enough to stop the core from collapsing further. It doesn't collapse enough to get hot enough to start the next stage of burning. It does get quite condensed but just not hot enough to start the next stage.

Such a very condensed remnant after the helium burning is called a "white dwarf." And all a white dwarf does is sit there. It doesn't make any more energy. It just sits there and gradually cools off. And it emits light only because it's still warm from all the processes going on before. But there are no new nuclear processes making energy. It's just a hulk: electrons push against each other to hold it up against gravity and that's all. It takes a long time to cool off, however. It's very condensed so it has a very small surface area and that means that it can't lose heat easily. In fact, we don't think that any white dwarf that's been made since the Big Bang has had a chance to cool off enough that it would not be emitting light anymore. All the white dwarfs that have been made so far are all still glowing. It would take tens of billions of years for them to cool off enough to stop emitting light. But they gradually cool and gradually will stop glowing because no new energy is being released.

[Ursula: Am I right that that guy in the Hourglass Nebula . . .]

Yeah, in fact, I'm just going to show you that again. That one in the center there was a white dwarf. I'll also show you some other pictures of white dwarfs. Even with a telescope they don't look like much. They're just a small star, very condensed, gradually cooling but still emitting light because they're still quite hot. And eventually they'll just wink out when they get cool enough. Now, a white dwarf is so compressed that one teaspoon of white dwarf material would weigh 2.5 tons. So it is a very compressed thing. A typical white dwarf would be about the size of the Earth. To us the Earth is pretty big, but remember that the white dwarf starts out at roughly the size of the sun. Maybe half or three quarters of its mass has now been compressed into something the size of the Earth. (The rest --- from the outer layers --- was sprayed out when the star became a red giant.) Now the Earth is about a hundredth of the diameter of the sun and therefore has only one millionth of the volume of the sun. And so you have a mass that is roughly the mass of the sun compressed into a region that is a millionth of the volume of the sun. So it's very dense --- 2.5 tons to the teaspoon. Mark?

[Student: So is there no energy left in the white dwarf?]

Well, actually, there is energy left because there are further reactions that could in principle occur, using the previous end products (carbon, oxygen and neon) to combine into still bigger nuclei. But in a white dwarf, it just does not get hot enough for those reactions to start. Just like before: The reason it had to be hotter for helium burning than for hydrogen burning is that helium nuclei have a bigger charge, hence more Coulomb repulsion, hence require more heat to get over the barrier and fall in. These new nuclei have still bigger charges. Carbon has six protons in its nucleus and oxygen has eight, so for them to come together requires a much higher temperature. And a white dwarf stops condensing before it gets hot enough to start the new reactions. As I will explain in a few minutes, the pressure of electrons pushed tightly against each other is enough to prevent the white dwarf from collapsing enough to heat up and ignite. So there's still fuel there, but there's not a match hot enough to start it burning. Okay, is there another question? Yeah?

[Student: What percentage of the stars that we see are white dwarfs?]

I don't know the percentage offhand, but it's a small percentage. Most of the stars we see are actually in the very first stage (hydrogen burning). It's the slowest, longest phase. However, in some old regions, there are actually a significant number of white dwarfs. I'll show you a slide in just a second. Okay, Sam, then Judy, then there's a question over there, too. Okay?

[Student: I get it that our sun is still in this initial stage, but when it does go from this stage to the next stage would we see today it was this way and suddenly tomorrow it was that way?]

How quickly does the change from one stage to another take place? Again, I don't know all the numbers, but the answer is very quickly. In one case, which I'll talk about next lecture, I do remember how rapidly it changes between stages and it's quite fast: about a millisecond. The reason is that as soon as it runs out of fuel, it's going to start collapsing. And it doesn't take long for stuff to fall in, heat up and start the next stage. Judy?

[Student: Will all these processes eventually happen, if they have not already, to all stars? Is this is just a gradual aging process?]

That's right. The first stage (hydrogen burning) and the next stage (helium burning --- the red giant stage) will occur in all stars. The centers of most stars will then collapse into white dwarfs, and that will be the end of the story. Some stars, which are much more massive than the sun, have so much mass that they will get so compressed and heated that other stages of burning can occur before the electron pressure (that holds up white dwarfs) becomes significant. We'll get to that, but the answer to your question is that all stars will go through the first two stages, and most stars will end up as white dwarfs. Okay, Walter?

[Student: Yeah, my question was you said most stars in the sky are in the same stage as the sun. Do you mean now or when the light was originally emitted from the stars?]

That's a good question. I think it's true both now *and* when the light was emitted. In the meantime new stars have been made, but the stars spend so much time in the first stage that chances are very good that any star, no matter when it was made, will be in the first stage (hydrogen burning). If, for example, a star's mass is a bit less than that of the sun, then even if it was made soon after the Big Bang, it is still in the first stage, because that stage lasts so long for small or moderately small stars. Of course the bigger stars burn faster and they can be in new stages, but in the meantime new stars have been formed. So a large percentage of all stars are in the first stage whether we ask about what they are doing now, or what they were doing when the light was emitted.

Okay, let's look at a few slides again [slide 2]. So this one was a red giant and here are the outer layers, which were shot off into a kind of unusual pattern (this is the "Hourglass Nebula"). This red stuff is the remnant of the outer layers. The white dwarf that's left is just the little white dot slightly off-center, which I talked about before.

Now here is view of a group of rather old stars in our galaxy [slide 3]. (Such a group is called a "globular cluster" --- but the name will not be important for us). On the left is a view from the ground, and on the right is a picture taken by the Hubble Telescope. Blue circles have been drawn around the white dwarfs. Since this is an old region, there are actually a fair number of white dwarfs. As you can see, they're small and they don't emit much light. At least compared to other possible end stages that we'll discuss later, white dwarfs are rather ordinary and not all that interesting, since not much is happening. They're the rather boring end stage of most stars.

Okay, I promised I was going to explain how the electrons hold up a white dwarf. To do that I have to introduce a little bit more physics than I've discussed before. Earlier, we talked about electromagnetic waves. I first said that light is an electromagnetic wave (electric and magnetic fields making a wave). Then later I introduced the idea that light also behaves in many ways like a particle, called a photon. Actually light is both a wave and a particle. I never quite said how that could be --- it seems counterintuitive. But our modern view of light is that it can act like a wave in some circumstances and like a particle in other circumstances.

The idea that light can act both like a wave (electromagnetic wave) and like a particle (photon) comes from the branch of physics developed in the 20th century called "quantum mechanics." And it doesn't stop there. We normally think of electrons, protons and neutrons, as being particles --- acting like a little bullet or ball bearing. Quantum mechanics says that they also can act like waves. We're used to thinking of light as a wave, so it may have been surprising to hear me describe it as a particle, a photon. But the reverse is also true. Particles like electrons, protons and neutrons can also act --- depending on the circumstances --- like waves. That's the result of quantum mechanics, which is not something I can explain in detail at the level of this course. But it is a fact about how particles behave. And the particle and wave properties of electrons, say, are in fact very similar to those of photons.

So let me first review the basic properties of photons. A photon with a large energy has a high frequency, which in turn implies that it has a short wavelength. Those three things are related. Remember that there's an inverse relationship between frequency and wavelength. If an electromagnetic wave oscillates rapidly then, as it moves along, the regions of high and low electric field will be close together, so it will have a short wavelength. The same thing is true of electrons and other particles like protons and neutrons. When they have high energy, their corresponding wave will have a high frequency and a short wavelength. When they have less energy, their frequency will be lower and their wavelength will be longer.

Now, let's compare electrons with protons or neutrons. Electrons have a low mass. The mass of a proton or neutron is about 2,000 times the mass of an electron. But mass and energy are just two aspects of the same thing. The low mass of electrons means that they have low energy, whereas protons and neutrons have high energy. Following along with what we said about the corresponding waves, that means that electrons have low frequency and therefore large wavelength. And the protons and neutrons have high frequency, which means a small wavelength. Again it's a bit counterintuitive. Electrons, which are very light, actually have a big wavelength. The protons and neutrons are very heavy, therefore have more energy, and therefore have a higher frequency and a smaller wavelength.

Now, what's the relevance to us? Well, when you try to push particles close together, their wave nature takes over and prevents them from being pushed into a region smaller than their wavelength. So as you compress matter more and more, the electrons, with their large wavelength, limit how much compression you can have. Because protons and neutrons have a small wavelength, they fill only a small volume, and are not pushing against one another, even when the electrons are. So what holds up a white dwarf, and prevents it from collapsing, are the electrons pushing against one another.

As an aside, let me remark that the above discussion also explains why atoms have the structure that they do. Previously, I just presented the basic structure of an atom as a given: There is a nucleus with protons and neutrons very close together, surrounded by big a cloud of electrons. Now you could ask, "why are the electrons spread out in a big cloud?" Well, first of all, you may not think of an atom as being big, but I do. In fact, an atom is enormous compared to the size of its nucleus. Imagine that the nucleus of an atom were the size of a golf ball, then the electrons would be spread out over a radius of a mile and a half. So the nucleus is a tiny --- although very heavy --- part of the atom, and the electrons are spread out over a huge region. Why?   The large wavelength of electrons implies that they must spread out over a large region. The electrons are being attracted by the protons in the nucleus, but that attraction is unable to compress them into a region smaller than the size of their wavelength. So that's why an atom has the structure it does: big atom, small nucleus.

And this same effect is what holds a white dwarf up. After the star is done with helium burning, the core cools, loses pressure and starts to collapse. But eventually the electrons get pushed so close together that they're within one wavelength of each other, and then they can't get pushed any closer. So the star can't compress any further, at least as long as the electrons remain there, and you have a stable white dwarf. (As we'll see later, there is in fact a way for the star to continue to collapse by getting rid of the electrons.)

Now, any star that has a mass up to eight times the mass of the sun will end up this way. (Again, I'm not expecting you to remember this exact limit.) So even a pretty big star (up to $8M_O$) will become a white dwarf when it's done with helium burning. And it will also have big cloud around it of stuff that it threw off when it was a red giant. The next question is, "what happens if you start out with a star that has more than eight times the mass of the sun?"   I'll talk about it in detail next lecture, but the first answer is that a really big star can get hot enough to start new stages of burning.

[end of lecture]