Transcript from Epic of Evolution: Life, the Earth, and the Cosmos (BEP 210A)
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"When you have eliminated the impossible, whatever remains, *however improbable*, must be the truth" (Sherlock Holmes, in *The Sign of Four*, by Sir Arthur Conan Doyle)

Let me provide the stage for the story that I'm going to tell in my third of this course. We have, as our main player, the Earth. We have a lot of physical evidence right here for this part of the story. The Earth is a layered oblate spheroid. It is mostly like a ball, but it's not homogeneous. It's not all the same thing, so if you were to go down deep in the Earth, which none of us can ever do, you would go through a whole sequence of different layers. This tells very interesting things about how the Earth formed and how it works. And we'll get to that later on. I used the funny words "oblate spheroid." That's just a way of saying that it's flattened, and this should be no surprise to us now. We know that the Earth is rotating, so there is a merry-go-round effect. There is a centrifugal force that pulls you outward as you ride around a merry-go-round, and the same thing happens with the Earth. The equator has bulged out to the degree that if you are in Ecuador you are 22 kilometers (14 miles) further from the center of the Earth than if you go visit the South Pole. And that's not a lot, about one factor in 300, but it is exactly what we would expect for the Earth's rate of rotation in space. If the Earth were a big ball of water and you spun it at our rate of one revolution every 24 hours it would have this same change in height between the poles and the equator. And that says something very interesting, because you notice I just compared the Earth to a liquid. It turns out that the Earth actually behaves very much like a liquid over long periods of time. We'll get back to that. The average radius for the Earth is 6371 kilometers, though, of course, very few places on the Earth are actually 6371 kilometers from the center. But if you took the ball, the mass of the Earth, and tried to stuff it into a nice, round sphere, 6371 km is the radius that the sphere would have. And it's larger at the equator, smaller at the poles. The Earth has layering that begins far out beyond this radius. It has a magnetosphere: a large envelope around it that has a very strong noticeable magnetic field. This is interesting because not all planets have magnetic fields. Mars, right nearby, has almost no detectable magnetic field. This is kind of odd. And, of course, we have the atmosphere that contains the gas that we breathe, and this extends out to a radius of about almost 10,000 kilometers. Of course as you get further and further from the Earth the gas particles get fewer and fewer in between. The atmosphere provides causes a significant amount of pressure on top of us. In fact, the pressure that we feel from the air on top of us is the equivalent to about 10 meters (that's about 30 feet) of water. The pressure at the surface we call one "atmosphere" of pressure. So the air has some real weight, not a lot, but enough to be noticed. The hydrosphere contains the water of the Earth, and of course, most of it (98%) is in the oceans, though it is the other 2 percent that's most significant for us in terms of our groundwater and our rivers and streams and atmosphere. And I should add that if the oceans were totally flattened out across the whole land, you'd get a 2¼ kilometer thick ocean everywhere. It is interesting, geologically, that this is not the case. Of course, there is land and so the oceans actually get deeper in some places. And we have the biosphere that you'll begin to hear more about next week, and the biosphere extends from down in the Earth to high in the atmosphere. We find bacteria actually living within the pore spaces of rock down underneath us. Life extends from beneath the ocean seafloors up to land to the tops of mountains, where we've found bacteria living, and in the air --

spores and pollen. The biosphere is a pretty amazing envelope, extending around the whole globe. And then we get down to our crust, and you could think of this as light rock, and it's about 10 kilometers under oceans and about 40 kilometers under continents. Beneath the crust we have the mantle, and that goes down to a radius of 3,480 kilometers. The mantle is the largest part of the Earth. It consists of rock, so when we think of the bulk of the Earth, this is primarily rock, and I will talk more about this during my third week of lectures. Beneath the mantle we have the outer core, and it is pretty odd. The outer core extends from a radius or 3480 km down to a radius of 1,222 kilometers, and it is made of liquid iron. It is molten, with about the same consistency as water. And from 1,222 kilometers down to the center of the Earth we have the inner core, which is a frozen snowball of solid iron. If you look at the Earth by weight you get about 35 percent iron, and about 30 percent oxygen. We normally think of oxygen as something that we breathe, but in fact almost all of rock has oxygen as one of its main building blocks. Silicon comprises 15 percent of the total Earth, and in fact, silicon and oxygen combine to make up most of rock. If you have pure silicon and oxygen you get quartz, and quartz with various other sort of elements added or subtracted gives you most of the rock in the Earth. We will talk more about that later. Magnesium, which is the next major element, is 13 percent. Nickel, which is largely with the iron in the core, is 2.4 percent. And everything else is less than that, just a little bit. This is the bulk composition of the Earth, but remember: none of these elements were made in the Big Bang, as Claude mentioned last week. This is one of the major mind blowing concepts of this class: that a whole other star, maybe with its own solar system, maybe with planets that had life, had to die before our sun and its solar system could be formed. That's an important thing to remember. These formed not at the Big Bang but in the death of a star, and that is what our star formed from.

[If you make your list not by weight but by total numbers of atoms, would some of the Big Bang guys come in, like hydrogen?]

No, they play minor roles. Let's take a look just at the atmosphere, where we would expect to find hydrogen and helium. If I go by moles (which is an expression for the number of atoms), I find that nitrogen is 78.1 percent of the atmosphere, oxygen is 20.9 percent, argon is 0.93 percent, water vapor is 0.1 percent, and carbon dioxide is about 0.04 percent, but rising. We have been pumping a lot of carbon dioxide in the atmosphere, so this number has gone up. But you can see that it is still a tiny percentage. Almost all of our atmosphere is comprised of nitrogen and oxygen, so hydrogen and helium don't play a large role in the Earth.

To fill out our story in terms of temperature, the temperature is roughly 0 degrees Centigrade at the surface. Claude mentioned last week this is the same thing as 273 degrees Kelvin, as measured from absolute zero. The temperature goes to somewhere on the order of about 6,000 degrees Kelvin at the Earth's center, though this is a topic of "hot" debate in my field, as none of us can ever get anywhere near those depths. The pressure at the surface is one atmosphere, also called one "bar" (barometric unit), and the pressure goes to 3.64 megabars at the Earth's center. A megabar is a million bars.

[When you say pressure can you define that a little more? What does pressure on the surface mean?]

Okay, close your eyes. [Wysession pushes on the student's shoulder] What do you feel?

[Pressure]

Pressure. Okay, that's it. It feels like a weight. Imagine a column of air extending upward from your shoulder for 5,000 kilometers. That whole column of air rests on your shoulder and pushes down on it, applying pressure. Air is pretty light compared to other materials, so that it's not very much pressure. However, as you go down in the Earth, you can think about any point in the Earth as being underneath a column of rock as well as air, so you have a larger and larger force of pressure. By the time you're at the center of the Earth, you have rock all around you that is pressing in. This leads into what I was going to say next about the two major players in this story of the Earth, with one of them being gravity. It is gravity that applies this pressure. Gravity is another way of stating the "first law of geology", which is that rocks fall downhill. It sounds pretty simple, but this idea takes some complex forms in the way that gravity works. Gravity is a remarkably small force. Claude will talk more about the various different forces in the universe, and when you look at the magnitudes of these forces, gravity is almost trivially small; however, gravity acts upon all matter, which is not always the case. For instance, electromagnetic forces are much stronger, but unless you have something with an electric charge, it doesn't do much. For instance, apply a magnet on a piece of plastic: nothing happens. It doesn't do anything. But gravity is pulling everything in the universe together. There are forces of gravity pulling every one of you towards each other. Every object in the universe is exerting this force of gravity upon you. Now, it's small, and Einstein, who had many great quotes, said something to the effect that "Gravity cannot be responsible for the attraction that causes people to fall in love." It's a very, very small force, but taken over a planet's size, it's going to pull together all of this material of the Earth, and try to squeeze it in as tightly as possible. This causes tremendous pressures down deep in the Earth.

The second major player in this story is that of heat, and it takes many forms. Now, heat, as you know from physics, is interchangeable with work and other forms of energy. For instance, if I take this eraser and bang it on the table [bangs eraser on table as demo], what happens? I gave the eraser lot's energy and made it move fast. Where did that energy go? I put all this energy into the motion of the eraser, and then it hit the table and stopped. Well, you know from what Claude said last week that energy has to be conserved. What happened here is thatI just heated up all of the atoms on this part of the table and in the eraser. I gave them some additional energy. Those atoms are a little agitated and they are moving around faster, and that's where the energy went. I will do this again on Wednesday with a little added complexity when I incorporate gravitational potential energy. So heat and energy are really the same thing; however, energy tends to flow in a certain direction, and this is a principle we call entropy. It also goes under the less attractive name of the second law of thermodynamics, and it says that things tend to become disordered. They go from an ordered state to a disordered state. Let me bang the table one more time but let me first put a stack of poker chips on it. Okay, I've got a bunch of poker chips here, and let's see how many times I can bang the table before I knock it over. [repeated bangs] There it goes. Okay, how many times do you think it would take for me to hit the table and have those chips jump back up on that pile? It sounds like a ridiculous question, but it is actually very profound. No number of hits on that table is going to get all of those chips to suddenly fly up and stack back up in that pile again. Why is that? The reason is that our universe seems to have a direction to it. Time has a direction. It wouldn't make any sense for all of these chips to suddenly fly up and order themselves, but if you shake them they will fall apart. Things tend to go to states of disorder. It's not always a viable excuse for why your room might be messy, "Oh, Mom, it's entropy," but it's a real fact of our universe. However, we've got a battle between these two, gravity and entropy, because if everything were going to disordered states, then all the matter of the universe would just be dissipating outward. All the heat and matter would just dissipate and spread out, and everything would go to 0 degrees Kelvin and there would be nothing of any substance in this universe. But gravity battles this it all along, and Claude will talk more about this when he tells how galaxies form, and how stars form and they go into their initial sequence. So, this is the story within the Earth. All of the complex layering in the Earth was created by gravity pulling things together. And when you pull things together, you cause some interesting patterns to occur. Of course, it's more of a philosophical battle than a real battle per se, but entropy is pushing things to be disordered, and gravity is trying to put things into nice orderly balls. And I will take you through the creation of our solar system today and talk about how those orderly balls formed from what was initially a big ball of gas and dust.

Let me give you two quick warnings here. One is that earth science differs a little bit from some of the other sciences in that it's a little messy. You've probably heard over and over about the scientific method. You have a hypothesis, you design a test for that hypothesis, you make the test, you compare the output from that test to the predicted outputs from your hypothesis, you alter your test, you make a new test, etc. And geologists certainly do plenty of that. I'm not saying that that the scientific method isn't a major part of work within earth sciences, but there's another side to geology, and that is that sometimes geology is a little less of a scientific method and a little more of a Sherlock Holmes method. I remember one of the Sherlock Holmes stories where someone frantically rushes into Sherlock Holmes' office, asking for his help. The man is smoking a cigar, and his boots are muddy, but before he says anything, Holmes stops him tells the man what part of the city he lives in, where he's just come from, and what the problem is. The man is totally stunned. Holmes explains that the color of the mud on his boots is only seen in one part of town, and the mud is still slightly wet, so he must have just come from there. The cigar the man is smoking can only be bought at this one store in London, so he likely lives in that part of town. And so forth. From a few messy clues, Holmes was able to figure out a whole history of who this man was and where he had been over the course of the day. And geologists tend to be good at that, at determining histories of things from a few messy clues. For Holmes, it works because Holmes is an expert in mud and cigarettes and all sorts of other things. And geologists are able to determine the story of the history of Earth because they are experts in mud and all sorts of other things. So I'm going to ask you to take some of what I say -- in fact, most of it -- on faith. Obviously, every little bit of evidence that I put up here has a history, and I could go into how it was formed, how we learned it, who found it, and when. If you're interested, come up to me and ask me and I'm glad to tell you. Otherwise you're going to have to take it on faith that there are these Sherlock Holmes who have lived (or are still alive), who are experts on mud and various things, and who have put this story together.

Maybe we should do what Sherlock Holmes does and we should start with the clues that we have fror our solar system, and then we'll come back at the end and we'll see if the history that we can deduce fits these clues. As Sherlock Holmes said, once you eliminate the impossible, whatever remains, no matter how improbable, must be the truth, so we'll see if we can get there. First of all, we have a solar system that contains a sun and about a dozen discrete planets. When I say discrete, I mean that the planets aren't big fuzzy belts that wrap around the sun; they're little balls. But we have some exceptions to this because we have this belt of asteroids that exists between Mars and Jupiter. Where does that asteroid belt come from if all the rest of the planets are in little clumps? The inner planets are metal-rich and the outer planets are like the sun (they're gas-rich) and in between you get rock-rich material, like the Earth, which is mostly rock. If you look at the some of the inner planets, they are covered with craters. Look at the Moon, for example, or Mercury. Their surfaces are covered with what must have been the impacts of something. Something rained down upon them. But we don't see too much of this going on now. Despite all the Hollywood movies of asteroids hitting the Earth, it's just not happening much now, so something must have been different at some point in time. The planets go around the sun in the same plane. We call this the solar ecliptic. This is very interesting because the planets just aren't going around the sun every which way. They're all in pretty much the same level plane. That is not likely to happen by coincidence, and so we've got to be able to explain that. Secondly, the planets go in the same direction. It is not like some are going clockwise and some are going counterclockwise. They're all going the same way. I would say clockwise or counterclockwise, but it's meaningless depending upon from which side of the universe you happen to looking at our solar system. But they're all going in the same direction, and what is more, the planets are all revolving around the Sun in the same direction. But they also rotate on their own axes. The Earth spins around. That's why we have day and night. But we spin in the same direction that we're going around the sun, and that other planets spin, and go around the sun.

[Do they spin at different speeds?]

They all spin at very different speeds, and in fact, there are some interesting exceptions to this. Venus is almost not spinning at all, and Uranus seems like it's almost spinning on its side compared to the ecliptic, and Mercury is locked in a very unusual tidal rotation where it rotates three times for every two revolutions around the sun. And we call this being tidally locked, just the way the moon is tidally locked with the Earth. It revolves once every one rotation around the Earth so the same side of the moon always faces us. I'll talk a little bit more about the moon on Wednesday. So the rates of rotation do vary, and that also has to be explained by our final hypothesis.

The planetary orbits do not intersect each other, with one interesting exception. The orbits of Neptune and Pluto actually do cross each other. You probably learned the order of Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, Neptune, and Pluto. Well, sometimes it's Pluto and then Neptune. The orbit of Pluto actually comes inside of that of Neptune. Those two will eventually hit each other. The total mass of the planets is very small. In fact, it is almost exactly one millionth that of the sun. It's really trivial in terms of mass. The second thing is that there is very little "junk" floating around in the solar system. There's very little extra gas and dust. We get hit by some larger pieces of it every now and then, which we see as meteor streaks in the sky. We get some comets that come in from way out, a region called the Oort cloud, way far beyond the orbit of Pluto. This cloud contains little snowballs that are up to a few kilometers in size and sometimes whiz in towards the sun. Well, let's talk about how we can end up with a solar system like this. Let's start with a big cloud, though I do not have the imagination to conceive of how big this would initially be. Maybe cosmologists are good at understanding what it means to be billions of light-years across in distance, but that's pretty challenging for most people. Let's just say it was a large cloud of gas and dust that was off in a remote corner of the Milky Way, which is where we are. Not too close to the center, but not too close to the edge. Just right. We will see that there are a lot of things about the Earth that are "just right". Sort of like the middle path of the Buddha. By gas and dust, I mean molecules and groups of molecules, but if you are talking about certain atoms like hydrogen and helium, you often call them gas, and if they contain heavier atoms that would make up rock or metal, then we would call them dust. But imagine that this is very sparse. I mean, if you were actually flying through it in a Star Trek spaceship, you wouldn't even notice you were in this thing, it's so spread out. Now let's apply gravity to this, and we begin to pull it together. Two things are going to happen. One of them is what I call the spinning skater effect. I hate to do this because I'm always afraid I'm going to fall and hurt myself, but imagine that I was as graceful as Kurt Browning or Elvis Stojko, and doing a spin on the ice. Now, watch what's going to happen. I'm going to start spinning. I will start with my arms out, and then I'm going to pull my arms in. Okay, so I go like this [spins slowly] and then I pull my arms in, and I go around like this [spins much faster]. Good, I didn't hurt anybody. Why did I start to spin faster? I wasn't pushing off the ground. All I did was simply pull my arms in. Well, what happened was initially I gave myself some small amount of angular momentum and then when I pulled my arms in, and you can think of the cloud pulling in through gravity, that angular momentum was conserved. We often talk about the conservation of energy, but we also have a law of physics called the conservation of angular momentum. This basically says that the distance from the axis of rotation is inversely proportional to the speed at which something spins. If I move my arms closer to my body, I have to speed up to compensate for this. Now, I'm presuming that the cloud of gas and dust initially had some net rotation, even a tiny bit due to whatever stellar explosions began to push this cloud together. All I need is a tiny bit, however, because by the time I suck that cloud in to a very tiny space (our solar system) it's like the skater moving his arms in to one trillionth of an inch. The skater would go *really* fast if you could do that. Well, that's what happened here. I am going to cause the cloud to start to spin. This is going to do something very funny now, because I initially had a cloud that had gravity pushing on all sides. So I'm squeezing it together from gravity. But now I start to spin it, so I also am going to have a centrifugal force that's going to push it outward along the equator, and I'm going to end up with a disk shape (or you can think of it as like a fried egg shape). We call this an accretionary disk. It's dense in the middle because gravity's squeezing everything together, but perpendicular to the axis of rotation you're going to throw material outward. I call it the merry-go-round effect. The centrifugal force is going to balance off part of the force of gravity, so the cloud is still going to get squeezed in along the poles and you're still going to keep compacting what will become the sun, but you're also going to throw some stuff out the sides of this giant rotating Frisbee. The next thing that happens is that stuff starts to get lumpy. Initially you can think of the accretionary disk as being fairly smooth. One of the Calvino stories talks about this in a very elegant way. Initially you just had gas and dust, and if you went anywhere in any direction you wouldn't notice any objects. But gravity is still working, and we begin to have collisions between particles. Initially these particles are far apart enough that they don't bump into each other much, but when you begin squeezing them together, they begin to collide. There is a real thematic parallel here between what Claude just talked about last week concerning the nucleosynthesis of atomic particles. At some point, the particles begin to come together, and they stick. Claude was talking about quarks and atoms coming together to form more complex elements. I'm talking about the formation of planets, the seeds of planets. All throughout the disk, the dust began to glom together. We call these seeds of planets *planetesimals* (or baby planets), and there were probably thousands or ten thousands of these things early on. Their formation is a positive feedback process, because once you form a larger clump, it has a larger force of gravity that it exerts on nearby particles. The next time a particle comes by it is more likely to be grabbed by the planetesimal, or if it collides into the planetesimal it is more likely to stick onto it. Once you begin forming some of these planetesimals, they start growing. And they keep growing larger and larger, and they keep sweeping up material. You can imagine these things like shepherds, revolving around this rotating disk, sweeping up flocks of other little planetesimals, and growing larger and larger. They also begin to have enough of a gravitational pull that the larger ones perturb the orbits of smaller ones, making them fly off and collide into other planetesimals. This process goes on until no orbits cross. And this process will be complete when Neptune and Pluto hit each other. So it isn't fully done yet, but this is just a matter of time.

[If these planetesimals go along collecting a trail along the way wouldn't the inner core of the Earth be more than iron? Wouldn't it be other rocks as well?]

So what happened? The Earth isn't just a conglomeration of rock and metal, it is layered. The Earth is iron in the middle and rock on the outside. We'll get to that on Wednesday. It's a very good question. That's a very major question in the formation of the Earth.

[Do we have a sun yet or is this how our sun was formed as well?]

No, this is only the one millionth of the stuff that's in the solar system, but it's important to us because we live on a planet. Good question. What's going on here in the center? Okay, all this time, the sun is continuing to condense, but when it condenses it heats up. Think about the eraser slamming here on the table. Right at the center we've got all this energy coming in together. and at some point it gets to a temperature on the order 10,000 degrees, and it ignites. It begins to burn hydrogen to form helium. It begins to become a fusion reactor. This point has a name based on a star that we've seen. We call this the T-Tauri phase of a star, and at this time there is a huge explosion that can blow off up to 40 percent of the mass of the star outwards. So the T-Tauri phase is a rather mild name for a truly cataclysmic explosion. This explaosion sweeps away any remaining gas and dust. The stuff that hasn't quite attached to a planetesimal (any other gas and dust floating around) just gets blown the heck out of the solar system. Early atmospheres go as well. We have no idea what the early atmosphere of the Earth was like. The Earth had an atmosphere when it first formed, but that atmosphere was totally stripped away by this T-Tauri explosion. It just went blasting through the solar system, stripping away the surfaces of all the planets. Our atmosphere has entirely come about since then, largely through degassing of gases out of volcanoes, and with a lot of help from life. The oxygen in our atmosphere came as a result of one-celled plant life, which also kept the amount of carbon dioxide to a minimum. A little bit of added stuff comes from tiny comets continuously falling into the atmosphere. But our initial atmosphere was gone when our sun went into the T-Tauri phase. So we have an explanation that fits some of the muddy clues we see. The planets move in the same plane, they revolve around the sun in the same direction, and they rotate in the same direction. That's because they all formed out of this same rotating planetary disk. There are some funny exceptions though. Venus is barely rotating. Why? We think that it was due to a large collision right near the end of the age of planetesimals. This is called the Late Heavy Bombardment. The Late Heavy Bombardment was a period of time early on in our solar system when the last of the large planetesimals were colliding into each other. We see evidence of this on places like Mercury, where there are huge meteorite impacts. There is one crater on Mercury (the Caloris Basin) that's 1,300 kilometers across, and this was clearly the impact of something very large. We see that Venus is hardly rotating. Something probably hit it. One of the largest impacts I will talk about next class: the moon, our moon, was formed by an immense impact of one of these giant planetesimals with the early Earth. This impact threw out a huge amount of material that came together to form our moon. We didn't capture the moon -- the moon formed partly from us and partly from some other planetesimal that collided with us. And the funny exception to the discrete planets (the asteroids) is probably the shattered remains of an early planet that got blown apart. I have a rock here. This innocuous looking rock is actually a piece of a very famous meteorite called the Allende meteorite. It's interesting for a number of reasons. You can barely make out that it's got little white specks in here. It's not all the same color. This side is actually burned. This is from the fusing of rock as it flew through our atmosphere before it hit the ground. Inside, however, it contains little white specks, and these are carbonaceous chondrules. They contain organic molecules, the building blocks of life. We find them in the meteorites and asteroids, and we find them in interstellar dust. This was probably one of the earliest objects of our galaxy. This asteroid was probably part of a protoplanet that formed a thousand years or so after the formation of our solar system. This happened 4.56 billion years ago. This rock would have been in the interior of some other planet, like a Mars or Venus, but it got shattered and blown apart by a large impact. These asteroids now float around in the solar system, and occasionally gravity flings them out of orbit and they bump into us and other planets. This is how we know the age of our solar system. There are no rocks made on Earth that are this old. It is from arrivals from space like this that we get our date of 4.56 billion years ago. So just try to imagine what it was like in this early solar system. It was so hot near the sun, approaching 10,000 degrees, that lighter elements like gases and, to some degree, rock couldn't even condense in the formation of Mercury, which is mostly metal. It was just too hot in the inner solar system for small planets to hold on to gas particles. As you get to further planets like Mars, Earth and Venus, it was a bit cooler, so rock could be captured in a stable manner, as well as a little bit of gas. As you get farther from the sun, however, and you go to planets like Jupiter, Saturn, Uranus, and Neptune, they are almost like the sun. In fact, if Jupiter were 70 to 80 times larger than is, it would ignite and become its own star. It's actually very common for stars to exist in binary pairs of two stars that rotate around each other quite quickly. And Jupiter almost made it, but didn't quite end up with enough material. Its composition is mostly hydrogen with some helium, with a small core that also has rock and metal. And so it's very similar to that of a star. Here on Earth, however, we once again have the "just right" conditions. There is an interesting balance where we've got some iron, a goodly amount of rock, but were also able to hold on to a lot of our lighter elements like gases -- our nitrogen and oxygen and carbon. These are here because we're far enough from the sun that some of it could exist when the solar system was really hot early on. The next class will address the question that was asked about the Earth. I've left you now with a ball of rock that is the Earth, what we've got to do is take that ball and form a planet from it, and I'll do that on Wednesday.