Deep Time: Crash Course Astronomy #45

Crash Course: Astronomy
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===== Introduction (0:00) =====

Compared to human experience, the universe has been around a long time, nearly 14 billion years. That's a soul-crushingly long time. That's older than Earth, older than the Sun, older than well... everything... pretty much by definition. And yet, when you think about time itself, how long is 14 billion years, really? It seems like a long time to us now, but time keeps on slipping into the future, and every day the universe is a little bit older. I mean sure, duh, of course it is, but have you ever really thought about what that means?

Someday the universe will be 20 billion years old, 30, then 50 billion, 100 billion, a trillion, and even then the clock still ticks. Those numbers sound abstract, but those days will inevitably come. Time runs long. What will the universe look like in that far, far future? Different, it'll look different. We're about to go on a long journey, literally the longest possible. We're going to the end of the universe.

(Crash Course Intro)

First, a bit of a content warning. The stuff I'm going to show you today is incredibly interesting, incredibly cool, and well... maybe a wee bit distressing to some people. But I want to say that it's not all darkness and disillusion. Well to be honest, it's mostly darkness and disillusion, but there is some light, almost literally at the end of the long long tunnel.

===== Focus On: Scientific Notation (1:33) =====

I'm going to have to use some pretty big numbers in this episode, and by big, I mean BIG. Probably bigger than any numbers you've come across before. I'll have to use scientific notation, which is a shorthand way of expressing numbers using powers of 10. For example, the number 100 is equal to 10 times 10. So we say it's 10 squared, or 10 to the power of 2 (10^2). 1000 is 10 times 10 times 10 so it's 10 cubed or 10 to the third power (10^3). This might seem silly for smaller numbers, but it gets useful for much larger ones. A million is 10 to the sixth (10â•¶), a billion is 10 to the ninth (10â•¹), and so on. Mind you, every time the power, the exponent, goes up by one the actual number is 10 times bigger. So 10¹â•¸ isn't twice as big as 10â•¹, it's a billion times bigger.

===== The Five Ages of the Universe (2:20) =====

At different times in the life of the universe different objects dominate. For example, in the current universe now, you can make the case that stars are the dominant objects. They produce the most amount of energy. Before stars, something else was-- dispersed plasma, I suppose, generally speaking. Astronomers Fred Adams and Greg Laughlin looked at what will happen to the universe on very long time scales and divided it into five broad epics, then wrote about it in their book, *The Five Ages of the Universe*, which is a pretty good read. Their divisions aren't official in any way, but I think they did a good job given what we know, so let's use them.

===== Primordial Era (2:52) =====

First came the Primordial Era, which we already went over in the last episode. It's basically everything from the moment the universe Big Banged up to when the first stars formed about 400 million years later.

===== Stelliferous Era (3:02) =====

The second era is the one we live in now, where stars rule the night. This is the Stelliferous Era. We're about 13.4 billion years into it. But how long will it last? Or, to phrase it another way, when will the last star die? The lower the mass of a star the longer it will "live," steadily fusing hydrogen into helium at a very slow rate. Models indicate the lowest mass red dwarf can do this for about a trillion years. That is a long time. A red dwarf that formed when the universe was young would only now have used up about 1% of its hydrogen. It has about 99% of its life ahead of it. In human terms, they're still infants.

Right now galaxies are merrily churning away, converting nebular gas into stars, but eventually that gas will run out. Estimates vary, but star formation in most galaxies will start to peter out in a few billion years. Fewer stars will be born, and the ones already born will start to die off. Galaxy collisions and other events may trigger star formation after that, so maybe they'll extend things a bit, but even if it lasts another 50 billion years, or a hundred, it hardly matters. When the longest star sticks around for a trillion years, why quibble about a few billion here and there?

As this happens, galaxies will change color and fade. Most spiral galaxies have disks that are a vibrant blue in color-- the massive, hot, luminous stars dominating their emission-- but as these stars die and the fainter lower-mass stars take over, the galaxy will redden and dim. A few billion years after the nebular gas runs out, the only stars left will be those long-lived red dwarfs. In a trillion years, this is what awaits us. It may take longer. I've seen some calculations that show the very lowest mass stars might last 10 times that long. Whatever, I'm not going to worry too much about factors of 10 here or there. As the universe ages, those are essentially statistical fluctuations.

But when that does happen, when the last star dies, it means that the only objects left in the universe generating appreciable energy will be the corpses of stars: white dwarfs, neutron stars, and black holes. And to be fair, brown dwarfs as well-- those objects intermediate in mass between stars and planets. With the exception of black holes, those objects are supported by various forms of degeneracy pressure. That means in a few trillion years, it'll be the end of the Stelliferous Era and the start of the Degenerate Era.

===== Degenerate Era (5:15) =====

The universe will be dark-- dark to human eyes, at least, assuming we have eyes in a trillion years, or that we're even around. In the infrared, things are a bit brighter. Many of those objects will be glowing at those wavelengths since they'll be warm. Well... lukewarm. Neutron stars and white dwarfs are born very hot and fade over time. How long that takes depends on how massive they are and other factors, but it's safe to assume that they'll have cooled to room temperature at best in a few trillion years. And the deeper we get into the Degenerate Era, the cooler they'll be.

They'll have their moments though, because over trillions of years, binary white dwarf orbits will decay and the stars will merge and explode as supernovae. Binary neutron stars will merge and form

gamma ray bursts too, explosions so bright they'll outshine 1000 galaxies in this far-flung future. Briefly. These are short-lived events, and soon thereafter the universe will return to darkness.

Interestingly, brown dwarfs are a better bet as an energy source. Binary brown dwarfs could merge to form a relatively normal, if low mass, star that could shine for hundreds of billions of years. But again, time is long. After a quadrillion years, this too shall pass. Stars just ain't what they used to be. In fact, in the Degenerate Era, neither is the universe.

In our Dark Energy episode, I mentioned that as the universe expands, our view of it will shrink. At the same time, all the galaxies in the local group will collide and merge, forming one big elliptical galaxy. By deep into the Degenerate Era, all we'll be able to see is our own bloated, dark galaxy. The rest of the universe will be forever cut off from us. Not that there will be all that much to see anyway, and I hate to say this, but even that won't last.

Our models of how subatomic particles behave predicts that over very long periods of time, protons (the positively charged particles in the nuclei of atoms) will decay. The half-life of such an event is at least ten to the thirty-four (10^{34}) years, and it's almost certainly longer. But the Degenerate Era is longer yet. As protons decay one by one, matter itself will disintegrate. White dwarfs, neutron stars, brown dwarfs, planets, all of them will dissolve as their constituent protons decay.

There's an upside, kinda. Adam and Laughlin calculate that proton decay, which releases a tiny bit of energy, will cause white dwarfs to radiate heat with about the energy of 400 watts. Mind you, the microwave oven in my kitchen generates more power and it's a lot smaller that a white dwarf, but comparatively in ten to the thirty-eight (10^{38}) years, this will look like a bright star does to us now. By ten to the forty (10^{40}) or so years from now, even degenerate stars will be gone. The only big objects that will be left are black holes.

===== Black Hole Era (7:49) =====

Thus begins the Black Hole Era. Black holes don't generate a lot of energy unless they happen to suck down a large amount of material that can be torn apart and turned into an accretion disk. Otherwise, basically, they just sit there. However, there is a way black holes can make energy-- they evaporate. I know. Most people think that black holes can only eat stuff, and once it's in there, that's where it is forever. Oh but that's a pesky word, "forever." When you're talking 10 to the 50th (10^{50}), 10 to the 60th (10^{60}), 10 to the 90th (10^{90}) years, what does "forever" mean?

Back in the 1970s, physicist Stephen Hawking worked out the math of black holes combined with quantum mechanics and discovered that under some circumstances, they can emit particles. This is a very weak effect and has extraordinarily complicated physical mechanisms behind it. Check the doobly-doo for links that explain it. But the end result is that black holes can very slowly leak mass, and the more massive they are, the slower the leak. How slow? A black hole with three times the Sun's mass, the minimum size for one created in a supernova, will take about 10^{68} (10 to the 68th) years to evaporate. That's a ridiculously long time, but the universe can wait.

Even supermassive black holes in galactic centers evaporate. It takes them — get this — 10^{92} years. Ten to the 92nd power. That number is so huge, so colossally ridiculous, that I can't even come up with an analogy for it. It's a 1 followed by 92 zeroes. There aren't even that many subatomic particles in the entire Universe. See what I mean? Ridiculous. That's the length of time we're talking here. But it'll happen. Eventually.

As black holes lose mass they emit particles and energy faster, so each time one evaporates completely it'll emit a flare of light like a small bomb going off. During the Black Hole Era, that'll be the only source of energy in the Universe. Eventually, they'll all go away. And... that'll be it. There won't be anything else in the Universe except subatomic particles and photons, and they'll all be so low energy they might as well not exist. That'll happen pretty much by 1092 or 93 years from now.

===== Dark Era (9:54) =====

At this point, the Universe, it's safe to say, is dead. Kaput. Done. We have entered the ominously named Dark Era. It'll stretch to infinity, if time even has any meaning by then. That's awful. I mean, seriously, writing about this and talking about it is hard because it's not fun to think about this stuff. I mean, it IS, kinda, but when you internalize it it's bleak.

===== The Big Rip (10:18) =====

There IS another idea that would prevent this potentially eternal darkness from happening, but you won't like it much. Dark energy is pumping up the Universal expansion, causing it to accelerate. We don't know much about dark energy; we don't even know what it is. We do know that the cosmic horizon, how far out we can see into the Universe, is shrinking as the expansion accelerates.

One idea (among many) about dark energy is that its influence will get stronger and stronger. As it does, the horizon will shrink ever faster, closing in on us more and more rapidly. But that's not some illusion, it's a physical limit to the Universe, a stretching of spacetime. No force — not gravity or electromagnetism or anything — can cross it. It will be as if that part of the Universe across the horizon is ripped away from us, stretched beyond breaking.

Over time, according to this hypothesis, the cosmic horizon will eventually shrink until it's smaller than our galaxy, smaller than the nearest stars, smaller than the solar system, smaller than our planet… and it'll keep shrinking until it's smaller than a subatomic particle! When that happens it'll be as if the Universe is torn apart at the most fundamental quantum level. Astronomers call this the Big Rip.

We have no idea if it will actually happen or not, but if it does it'll be many billions of years from now, long after the Sun dies but long before the Dark Era. I'm not particularly comforted by this idea, but the good news is that this idea isn't really much more than conjecture. As we learn more about dark energy we'll learn more about its eventual influence on the fate of the cosmos. Yay?

===== Other Possibilities (11:48) =====

So. Is there any reprieve? Maybe. It's possible, though by no means proven, that our Universe is one of many Universes. A multiverse, if you will. Those other Universes may be ticking along just fine long after ours has wound down. Of course, we can't get to them, but still. Good on them.

And there's another idea. It's a little far-fetched, but not completely outside the realm of physics as we know it. We think of the vacuum of space as being devoid of energy, empty. But there's an idea in quantum mechanics that this might be an illusion. There might yet be a lower energy state we don't see. Think of it like a staircase. You've been standing on what you think is the bottom step, but then you find out you're actually one step up from that.

Our Universe may be narrowly balanced on this second-to-lowest step. It'll stay there, but if something bumps it, down it goes. It's possible that somewhere, out in the dark, dead Universe, for whatever reason, after a gazillion years, some small bit of space will quantumly jostled, and drop down to that next lower state, the true vacuum. What happens when it does? It'll bump the regions around it, and they'll drop. And so on, and so on.

Here's the weird part — well, it's all weird, but here's the really weird part: Inside this region, the laws of physics get rewritten. How? We don't know. As far as we know, we can't know what happens in there. But in a sense it will erase space and time inside it. Like, poof. Gone. Everything changes, at some fundamental level we can't even understand. This wave of destruction expands at the speed of light, engulfing all of what remains of the Universe. What is left behind in its wake is... something new. Something different. We literally can't know.

This idea actually gives me hope. Think of it as a cosmic reboot. The Universe has led a long, long life, and lingered an unimaginably slow death. This gives it a new lease, a chance to start over again. Maybe this is similar to how our Universe came into being in the first place, as a quantum fluctuation in some other Universe, budding off from there to create everything we know. Maybe this has happened before and will happen again. Over and again, an infinite number of times.

I have to say, I like this idea. If it's true — and we don't know, it's just conjecture at this point — but if it IS true, then it's not the death of our one Universe. It's the opportunity for the birth of an infinite number more. And that is perhaps the single most hopeful thing I know.

===== Recap (14:09) =====

Today you learned that our Universe's days are numbered. Stars will die out after a few trillion years, protons will decay and matter will dissolve after a thousand trillion trillion trillion years, black holes will evaporate after 1092 years, and then all will be dark. But there's hope that a new Universe will be born from it. There's always hope.

===== Credits (14:30) =====

Crash Course: Astronomy is produced in association with PBS Digital Studios. Head over there before the end of the universe to watch even more awesome videos. This episode was written by me, Phil Plait. The script was edited by Blake de Pastino, and our consultant is Dr. Michelle Thaller. It was directed by Nicholas Jenkins, edited by Nicole Sweeney, the sound designer is Michael Aranda, and the graphics team is Thought Café.

(Crash Course Outro)