Dark Energy, Cosmology part 2: Crash Course Astronomy #43

Crash Course: Astronomy
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Phil Plait: The previous episode of Crash Course: Astronomy was a bit of a brain-stretcher. We saw that the universe is expanding, space is expanding, and it's carrying galaxies along with it. That means it was denser in the past and at some point, 13.82 billion years ago to be fairly precise, all of space, time, matter, and energy was compressed into a single, infinitely dense point.

Astronomers call this "the singularity," which is as good a name as any. Something caused this singularity to suddenly let loose, expanding violently, cooling, and forming the universe we see today. Coming to grips with this idea took a while for astronomers, but nowadays, the current working model for how the universe started is with a big bang. All the galaxies we see are moving away from each other as space expands between them... that is, on large scales. Remember the ruler analogy where on small scales the expansion is small, and on bigger scales the expansion is faster. That's why distant galaxies appear to be rushing away from us faster.

On small scales, the expansion is small enough that gravity can overcome it. The Andromeda Galaxy, for example, is about 2.5 million light years away. That means it should be moving away from us at about 50 or so kilometers per second, but because of our mutual gravity, it's moving toward us. Its motion locally through space is more than enough to overcome the expansion of space between us.

It's like running up the down escalator; run fast enough and you can make it to the top. But every galaxy has gravity, and there are a lot of galaxies in the universe. That adds up, and should affect the expansion rate. It's a lot like the idea of escape velocity. Throw a rock hard enough, and even though gravity will slow it down, it will escape. But if you don't throw it fast enough it'll slow, stop, reverse course, and fall back down.

Astronomers fully expected to see this effect on the expansion of space. If you looked on the very largest of scales, you'd expect to see the universe slowing down, the gravity of the matter in the universe itself putting the brakes on the expansion. And with the discovery of dark matter, that meant the universe should be slowing down even more than we first thought. But when astronomers went looking for evidence of this, what they got instead was probably the single biggest shock in the history of astronomy.

(Crash Course intro)

In the 1990s, two teams of astronomers were using the world's biggest telescopes to peer as deeply as they could into the universe. They were looking for incredibly distant supernovae, and not just any kind, but special ones called type 1As. I talked about these before. They occur when a white dwarf increases in mass until electron degeneracy pressure can no longer sustain it against its own gravity. It collapses, undergoes a catastrophic wave of thermonuclear fusion, and explodes.

The beauty of these types of supernovae is that they all occur when the mass of the white dwarf gets to about 1.4 times the mass of the Sun. That's the magic number where pressure overcomes gravity and they go ka-blooey. That makes them good *standard candles* (objects whose intrinsic brightness, whose luminosity, is known). Knowing that, plus knowing how bright they appear to be in a telescope, lets you calculate their distances. Then those can be compared to the supernovae redshifts, which is a different way of getting their distance. This then tells you how fast the universe is expanding on really big scales.

But the results they got didn't make sense. Time and again, the supernovae were all fainter than they expected. It was as if the predictions based on the redshifts were underestimating the distances to the exploding stars. The astronomers did everything they could to see if maybe they had made a mistake somewhere, including making a literal list of things that could make stars look fainter: intergalactic dust, different chemical compositions for the stars that blew up, all kinds of things. But in the end, both teams independently came to the same conclusion; the supernovae were farther away than expected. And that meant something truly shocking. The expansion of the universe was accelerating.

Now remember, that's nuts! We were expecting the expansion of space to be slowing down due to the gravity of all the matter in the universe, but instead it was speeding up. It's hard to overstate how shocking this is. It's like tossing a rock in the air, and instead of it slowing down and falling back down into your hand, it shot upwards faster and faster, defying Earth's gravity. Of course, scientists were skeptical-- many still are-- but in the end, several other independent measurements have verified this result.

The universe is not only expanding, but that expansion is getting faster every day. What could possibly cause such a thing? To be flatly honest, we don't know... well, not exactly. But whatever it is acts like an energy suffusing space, pushing on the expansion, and we can't see it so it's invisible. We already have dark matter, so naturally this got tagged dark energy. It seems to be a property of space itself-- a tiny bit of energy in every single cubic centimeter of the universe. The amount per cc is incredibly small, but there are a lot of cubic centimeters in the universe-- it adds up, and we CAN add it up. Now that we have measurements of this, we can take an inventory of the universe. We can total all of the matter and energy there is, making a sort of "budget of stuff" in the cosmos. When we do, it looks like this. 95% of the universe is made of stuff we can't directly see. Normal matter is outnumbered 20 to 1. Maybe we should rethink calling it "normal."

So, if two-thirds of the cosmic budget is made up of dark energy, it must have some pretty big effects, right? Yeah, like changing the eventual fate of the entire universe. A big question, one of the biggest, is "Will the universe expand forever?" Well, astronomers have a framework to answer this question. We call it the geometry of the universe. Matter has gravity, and gravity bends space, so is there enough matter in the universe to stop the expansion? The geometry of the universe mathematically describes its overall curvature-- the shape of space-- on the largest scales of all.

To be clear, this concept is important to cosmologists, but it can be weird and confusing to someone who's just learning about all of this. Still, a lot of astronomy classes teach it, so I'm going to go over it very briefly, and if you want more information, we have links in the dooblydoo. The idea behind the geometry of the universe is that if there's enough matter, the cosmic expansion will slow, stop, and then everything will re-collapse-- a sort of big bang in reverse. If there's not enough matter, then the universe will expand forever. And in between the two, there's just enough matter that the expansion slows, but never quite reaches zero until an infinite amount of time in the future. Conceptually, it's a lot like escape velocity. It was once thought that the geometry of the universe, tied to the amount of matter in it, determined its destiny. But dark energy threw a monkey in the wrench for that, and geometry alone doesn't determine the eventual fate of the cosmos. We think there's enough dark energy in space to ensure the expansion will continue forever, despite the geometry. Dark energy is just too powerful, and will always drive the expansion of the universe ever faster. So for now, the answer as far as we can see is... yes, the universe will expand forever.

OK, there’s one more brain-melty thing we need to talk about. For this part you might want to sit down. Space itself is expanding. As light travels from one galaxy to the next, it fights that expansion, losing energy – just like you use up energy climbing a staircase.

When light loses energy its wavelength gets longer – that's what cosmological redshift is. The more distant the galaxy, the faster it recedes, and the more energy light loses as it travels to us. But wait. At some distance from us, space would be expanding so quickly that a galaxy in that part of the Universe would be moving away from us at the speed of light. Anything farther away would be swept away from us faster than light.

Now, before you start complaining, yes, this IS possible. The speed of light is the ultimate speed limit in the Universe – if you're traveling through space. But space itself is exempt from that rule; it can expand at whatever speed it wants. The matter in it – galaxies, stars, and such – is swept along with it, so they're not traveling so much through space as with it. When you solve the equations to calculate distance and redshift, the distance a galaxy would have to be from us to be moving away at the speed of light is about 13.8 billion light years.

Here's the fun thing: We can still see galaxies that far away. We can even see them farther than that. How? It's because that distance is how far the galaxy is from us now. When it emitted that light the Universe was much younger, smaller, and the galaxy closer to us. It would've been about 4.5 billion light years away at the time, and the light took over 9 billion years to get here. Back then, the space between us and the galaxy wasn't expanding as rapidly, so the light could keep pace.

Now, after all this time, the space between us and that galaxy means we're moving away from each other at lightspeed. But back then we were close enough to see each other. For that same reason we can see galaxies that are moving away from us faster than light, because when they emitted that light there was less space separating us. The most distant galaxies we see are now about 45 billion light years from us. We call this the radius of the observable Universe. It's essentially the cosmic horizon.

Mind you, the actual Universe may be far larger than this... who knows, maybe even infinite. But we can only see galaxies that are, by now, 45 billion light years away. That's our horizon. If space were simply expanding, the size of the observable Universe would expand as well. But we have dark energy, and space expands more rapidly every day. That means a truly distant galaxy's light is fighting more and more expansion all the time – it's like climbing an ever-steepening staircase.

Compared to a constant expansion, a galaxy in an accelerating Universe has to be closer for us to see it. It's losing energy faster. Worse, that fight gets harder every day. A galaxy just at the cosmic horizon, right on the edge of the observable Universe now might be visible, but in the future the space between us and it will have expanded even more. The light can't beat that expansion, and it'll never reach us. The galaxy, over time, disappears.

This has a weird and unnerving effect: The observable Universe is getting smaller. The cosmic horizon is approaching us. Eventually it'll be so close that every galaxy in the sky except our own will lie beyond it. At that point our own galactic gravity may overcome the expansion of space, so we'll remain intact, but the sky beyond will be black, the edge of the Universe hanging over us just a few hundred thousand light years away instead of tens of billions. It's the ultimate irony. The Universe itself is expanding, but we see less of it every day. So we'd better study it while we can; we may only have a few trillion more years left to figure this all out.

Today you learned that the majority of the Universe is made up of dark energy, a currently mysterious entity that pervades space. We don't know exactly what it is, but we can understand what it does – it accelerates the expansion of space. We think this means the Universe will expand forever, even as our view of it shrinks as space expands faster all the time.

Crash Course Astronomy is produced in association with PBS Digital Studios. Head over to their YouTube channel to catch even more awesome cool 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.