A Brief History of the Universe: Crash Course Astronomy #44

Crash Course: Astronomy
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Hey folks, Phil Plait here, and for the past few episodes I've been going over what we know about the structure, history, and evolution of the universe, and how we know it. Now it's time to put that into action. We can use this knowledge of physics, math, and astronomy to figure out what the universe was like in the past, going all the way back to literally the first moment it was born. So, here you go, a brief history of the universe. In the beginning there was nothing... then there was everything. Oh, you want more?

(Intro)

It may seem a little weird to suppose that we can understand how the universe got its start, but it's much like any other field of science; we have clues, observations, based on what we see going on now. Knowing the rules of physics, we can then run the clock backwards and see what things were like farther and farther into the past. For example, as I've talked about in the past couple of episodes, the universe is expanding. That means in the past it was denser, more crowded, and hotter. At some point it was hotter than the surface of a star, hotter than the core of a star, hotter than the heart of a supernova. And as we push the timer back even farther, we find temperatures and densities that make a supernova look chilly and positively rarefied.

A lot of what we know about the early universe comes from experiments done in giant particle colliders. When the cosmos was very young and very hot, particles were whizzing around at high speeds and slamming into each other, creating other subatomic particles in the process. That's exactly what colliders do. The higher energy we can give our colliders, the faster we can whack particles together, and the earlier the phase of the universe we can investigate. That's one of the main reasons why we keep making 'em bigger and more powerful-- to test our ideas of what the young cosmos was like.

So let's wind the clock back, looking around us, peering into the universe both near and far. What can we say about the beginning of everything?

When the universe got its start, it was unfathomably hot and dense. It was totally different than it is today because when you pump more energy into something, the way it behaves, even its fundamental physical nature changes. If you take a snowball and heat it up, it'll melt. We call that a phase change, or a change of state. Heat it more and it vaporizes, changing into a gas. It's still water, still composed of water molecules, but it looks and acts pretty differently, right? When you heat something up, what you're doing is giving it more energy. In a solid, this means the atoms wiggle around more and more until they break free of their restrictive bonds with each other, and the solid melts. The atoms are still bound by other forces, but if you heat them more, they break free of those too, and the liquid becomes a gas.

Heat them more, give them more energy, and the atoms whiz around faster and faster. Heat them to millions or billions of degrees, and the atoms themselves fall apart. They collide so violently, they can overcome the hugely strong forces holding their nuclei together, and you get a soup of subatomic particles-- electrons, neutrons, and protons. Heat them more, and even protons and neutrons will collide hard enough to shatter into their constituent subatomic particles, which are called quarks, and as far as we know, quarks and electrons are basic particles so they can't be subdivided any more. Maybe you can see where I'm going here.

As we wind the clock backwards, the universe gets denser and hotter. At some point in the past, it was so hot that atoms wouldn't have been able to hold on to their electrons. A little farther back, and it was so hot that nuclei couldn't stay together, and the universe was a small ultra-dense ball of energy mixed with neutrons, protons, and electrons. Go a wee bit farther back, and even that changes. Neutrons and protons couldn't form because the instant they did, they'd whack into each other hard enough to fall apart. The universe was a sea of electrons and quarks.

The cosmos was a bizarre, unfamiliar place back then. Even the basic forces we see today--gravity, electromagnetism, and the two nuclear forces responsible for holding atomic nuclei together, as well as letting them disintegrate in radioactive decay-- were all squeezed together into one unified super force. Like the snowball melting and vaporizing, each of these moments in the history of the universe was like a phase change. The very nature of reality was changing, its laws and behavior different.

At some point, we go so far back, so close to that first moment in time, that our laws of physics... well they don't break down so much as say, "Here be dragons." We just don't understand the rules well enough to be able to say anything about that first razor-thin slice of time. How far back are we talking here? If we call the instant of the Big Bang "time zero," then our physics cannot describe what happens in the first 10 to the -43 seconds. Now let me just say, only semi-sarcastically, that that's not so bad. The universe is 13.2 billion years old, so being able to go back to that first one ten-millionth of a trillionth of a trillionth of a trillionth of a second is a *massive* triumph of physics.

What happened after that fraction of a second is better understood. The universe expanded and cooled, the four forces went their separate ways, and the first basic subatomic particles were able to hold themselves together. This all happened in the very first second of the universe's existence. Three minutes later-- yes, *three* minutes-- the universe cooled enough that the subatomic particles could start to stick together. For the next 17 minutes, the universe did something remarkable; it made atoms. It was still ridiculously hot, like the core of a star, but it's at those temperatures that nuclear fusion can occur. For a few minutes the particles smashed together forming deuterium (an isotope of hydrogen), helium, and just a smattering of lithium. A little bit of beryllium was made as well, but it was radioactive and rapidly decayed into lithium.

Then at T plus 20 minutes, the universe cooled enough that fusion stopped. When it did, there was three times as much hydrogen as helium in the universe. This primordial ratio is still pretty much true today. When we measure the Sun's elemental abundance, we see it's roughly 75% hydrogen, 25% helium. At this point, the universe is still hotter than a star's surface, but it's also still expanding and cooling. As it does, structures start to form as the gravity of matter can overcome the tremendous heat. These will become the galaxies we see today. This is important, and a bit weird, so I'll get back to it in a minute.

The next big event happened when the universe was at the ripe old age of about 380,000 years. Up to this point, electrons couldn't bond with the atomic nuclei zipping around. Every time they did, it was so hot that random photons would blow them off again. The universe was ionized, but then, after 380 millennia, it had cooled enough that the electrons could combine with protons and helium nuclei, becoming stable neutral atoms for the very first time. We call this moment **recombination**. This was an important event.

Free electrons are really really good at absorbing photons, absorbing light. When the universe was still ionized, prior to recombination, it was opaque. A photon couldn't get very far before an electron sucked it up. But after recombination, the photons were free to fly. The universe became transparent. Why is this important? Because the light emitted at this time is what we see as the cosmic microwave background today. Those neutral atoms emitted light. They were as hot as a red dwarf star. Those photons have been traveling ever since, fighting the expansion of the universe,

redshifting into the microwave part of the spectrum, and seen today all over the sky.

That background glow predicted by the Big Bang model has been on its journey to earth for almost 13.8 billion years. This light is incredibly important because it tells us what the universe was like not long after it formed. For example, that light looks almost exactly the same everywhere you look in the sky. It looks smooth. That tells us that matter was very evenly distributed everywhere in the universe at that time, and also that all the matter had the same temperature. If there had been one spot that was denser, lumpier, then it would have been hotter, and we'd see that in the background radiation as a patch of bluer light. That's pretty weird.

When you look at the background radiation from opposite sides of the sky, you're seeing it coming from opposite ends of the universe. Even back then, those regions of the universe were separated by vast distances and had plenty of time to go their separate ways, change in different ways. They should look pretty different, but they don't. As telescopes got better, very tiny variations were found, but they were really teeny-- only a factor of 1 in 100,000. In other words, one part of the sky may look like it has a temperature of 2.72500 Kelvins, but another spot is at 2.72501. The universe had lumps, but they were far, far smaller than expected. Something must have happened in the universe to force it to be this smooth, even hundreds of thousands of years after the big bang.

This led theoretical physicist Alan Guth to propose a dramatic addition to the Big Bang model; at some point in the very early universe, the expansion suddenly accelerated *vastly*. For the tiniest fraction of a second space inflated hugely, far faster than the normal expansion, increasing in size by something like a hundred trillion trillion times. We call this super expansion **inflation**. It sounds a little arbitrary, but it actually has quite a bit of physical foundation now. In a sense, it's like one of the phase changes of the universe that happened in that first fraction of a second, dumping huge amounts of energy into the fabric of spacetime, causing it to swell enormously.

Inflation explains why the universe was so smooth at the time of recombination. Space expanded so rapidly that any lumps in it were smoothed out, like pulling on a bedsheet to flatten out the wrinkles. Inflation explains several other problems in cosmology as well, and although the details are still being hammered out, the basic idea is almost (pardon the expression) universally agreed upon by astronomers. The fluctuations we see in the background glow now were actually incredibly small perturbations in the fabric of space at the time of inflation, which got stretched by inflation to macroscopic size.

These denser spots were seeds, eventually growing even more, their gravity attracting flows of dark matter. Normal matter collected there too, condensing, eventually forming the first stars about 400 million years after the Big Bang. Eventually, those teeny little bumps from the beginning of the universe became galaxies and clusters of galaxies now tens of billions of light years away. Our own galaxy, our own piece of the universe started the same way, as a quantum fluctuation in space 13.8 billion years ago. Now look at us! How's that for an origin story?

There are still many unanswered questions in our understanding of cosmology. What's dark energy? What was the role of dark matter in the early universe? Where did the universe come from in the first place? Are there more universes out there? hidden away where we can't see them? If time and space started in the Big Bang, does it even make sense to ask what came before it? or is that like asking what's north of the North Pole?

We don't know the answers to these questions, and trust me, there are thousands more just like them, but here's the fun part: we might yet be able to answer them. After all, even asking if the universe had a beginning, let alone what happened between then and now, was nuts just a century or two ago. Now we have a decent handle on it, and our grip is getting better all the time. Science! Asking and answering the biggest questions of them all. I *love* this stuff.

===== Recap (11:22) =====

Today you learned that the timeline of the universe's history can be mapped using modern-day physics and astronomical observations. It started with the Big Bang when the universe was incredibly dense and hot. It expanded and cooled, going through multiple stages where different kinds of matter could form. It underwent a phenomenally rapid moment of expansion called inflation, which smoothed out much of the lumpiness in the matter. Normal matter formed atoms between three and twenty minutes after the bang, and the lumps left over from inflation formed the galaxies and larger structures we see today.

===== Credits (11:52) =====

Crash Course: Astronomy is produced in association with PBS Digital Studios. Head over to their YouTube channel to catch 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.