The Big Bang, Cosmology part 1: Crash Course Astronomy #42

Crash Course: Astronomy
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What is the nature of the Universe? How's that for a question? For a long time we humans had no idea what was going on in the Universe. To help, we made up stories to either help us explain what we saw, or to make us feel better about what we didn't understand. But then science came along, and we started to understand more. We could test our ideas, and as we got more confident in the process, our ideas grew. The field of cosmology was born, the study of the cosmos itself. And now, after centuries of speculation and just-so-stories, we're starting to get a grasp on the biggest ideas there are. What is the nature of the Universe? Let's find out.

(Crash Course intro)

By the turn of the 20th century, scientists knew the Earth was old. Darwin's Theory of Evolution strongly implied the Earth was at least millions of years old, and Lord Kelvin, a hugely respected physicist and engineer, confirmed the Earth was ancient, given that it must have cooled from an initially molten state. That takes a while, at least a million years. How old exactly, no one knew. As for the Universe itself, it logically must be as old or older than Earth.

A popular model for the Universe was that it was static: It is and always has been as we see it now, and in general hasn't changed. Stars may be born and they may die, but overall things pretty much stayed in balance. The Universe always existed, always will, always had galaxies in it, and so on. There are variations on this idea, but that's it in a nutshell, and it's what many astronomers believed.

This is important.

When we try to understand observations in astronomy, we fit them into a framework of understanding, things we think we already know. When something doesn't fit, it's a problem. Maybe the observation is wrong, or maybe we're misinterpreting it. Or maybe the framework is wrong! That's a big step to undertake, and needs proper contemplation and skepticism. Science is a tapestry, and when you yank at one thread, the whole thing may need reweaving. Sometimes – rarely, but sometimes – you have to yank that thread.

The thread that got pulled in this picture was first uncovered in 1912. That was when astronomer Vesto Slipher — who has the uncontested coolest name for an astronomer ever — started taking spectra of the so-called "spiral nebulae", hoping to get some insight on their characteristics (remember, this was before we understood what galaxies actually were).

It took him several years of observations, but by 1917 he had observed 25 of them, and he found something astonishing. When he examined their spectra, he saw that almost all of them were highly redshifted. In other words, it looked like most of these objects were rushing away from us at high speed, millions of kilometers per hour! What could that mean?

At this point, two different lines of work began to converge. One was by a Belgian theoretical physicist named Georges Lemaître. In the 1920s he had been studying Albert Einstein's work, the equations dealing with the behavior of the Universe as a whole. Einstein had concluded that the Universe was static, unchanging, but Lemaître disagreed. He found that an expanding or contracting Universe fit the equations better — and, given the redshifts observed by Slipher, he proposed the the Universe itself was getting bigger, which is why the galaxies appeared to be moving away from us. Another brilliant physicist, Alexander Friedmann, had also reached the same conclusion.

At the same time, astronomers were trying to determine the distances to the nebulae, now understood to be galaxies in their own right. As I mentioned in our first episode about galaxies, Edwin Hubble and his assistant Milton Humason were at the forefront of this. They observed variable stars in the Andromeda Galaxy that allowed them to get the distance to the galaxy. They then observed some of the same galaxies Slipher did, and measured their distances. When they compared distances to the redshifts Slipher observed, they found that the farther away the galaxy was, the faster it was moving away from us.

Let me repeat that, because it's kind of important: The farther away a galaxy was, the FASTER it appeared to recede from us.

Some other astronomers had also found similar results, but the work Hubble and Humason clinched it. We now know it to be true for every distant galaxy we observe: They are *all* redshifted, *all* heading away from us. And this ties into what Lemaître had concluded: the Universe is expanding. Wait, what? The Universe is getting bigger? How can that be? What does that even mean? There are lots of different ways of looking at this.

Lemaître himself suggested imagining the cosmic clock running backwards. Right now, as time inexorably marches on, all the galaxies in the sky are getting farther and farther away from us. But that means that in the past they were closer together. Run the clock back far enough, and they get closer and closer together until at some point in the past everything in the entire universe was crammed together into an über-dense…thing.

That is a really, really weird thought. It's hard to imagine everything in the whole cosmos – every star, nebula, galaxy; every atom, electron, and proton – all squeezed together into one infinitely dense blob. But that's what the observations are telling us. Lemaître called this a "primeval atom," or, more colorfully, the "cosmic egg." Fair enough.

But this has implications. If you squeeze all the energy everywhere into one place, that place is going to be HOT. When the Universe was a tiny dot it would've been unimaginably, hellishly hot. Then, for some reason, it suddenly expanded violently and started cooling. This sounds an awful lot like an explosion – BANG! - involving the entire Universe, which is big. What else would you call this but "the Big Bang"?

In fact, the term became popular when astronomer Fred Hoyle used it on a radio show, and later in a widely-read magazine article. Ironically, he meant it somewhat disparagingly, since he didn't think the Big Bang model was correct. To his, and many other astronomers', chagrin, the name stuck. I like it. It's not perfectly accurate, but it's succinct. Again, this is all pretty strange, and astronomers had a hard time accepting it. After all, it went against everything they thought was true at the time! In science, though, a hypothesis needs to make testable predictions before it can be taken seriously.

What predictions could the Big Bang model of the Universe make that we can observe today? The speed of light is fast: 300,000 kilometers per second, or about a billion kilometers per hour. Like I said, fast. But not infinitely fast. The Sun is 150 million kilometers away. It takes light about 8 minutes to reach the Earth, so in a sense you're seeing the Sun as it was 8 minutes ago. The nearest star system to us is Alpha Centauri, 4.3 light years away, so we see it as it was 4.3 years ago. The Andromeda galaxy is about 2.5 million light years away. The light we see from it now left that galaxy when Australopithecus walked the Earth.

The farther away something is, the farther in the past we see it. This is called the "lookback time", and it's a crucial tool for cosmology: By observing very distant objects, we can see the Universe when it was young!

You might think that we could see all the way back to the moment of the Big Bang, but there's a problem. At some point back in time, the Universe was so hot and dense that it was the same temperature as the surface of a star. It would've been very luminous, but also opaque! As it expanded, it cooled, and became transparent. If we look back far enough, that moment in time when it cleared up is as far back as we can see. What does that moment look like?

By looking at the physics of the Big Bang — the math that describes how matter, energy, space, and time behave — astronomers could predict when this moment happened in the lifetime of the Universe: a few hundred thousand years after the bang itself. Using the idea of lookback time, they could predict how far away it would be from us, and therefore calculate its redshift. Remember, redshift stretches the wavelength of light. The light the Universe emitted at the time would've been like a star, in the visible part of the electromagnetic spectrum, but the light that reaches us billions of years later — now — should be redshifted into microwave wavelengths.

In 1965, a pair of radio astronomers announced they had found a signal in their radio telescope that was like a background noise, coming from everywhere in the sky. They tried everything they could to explain it — including scraping out the bird poop inside their radio telescope, in case that might be causing it — but the only thing that made sense was that this was indeed the redshifted light from the early Universe. They had discovered the glow of the fireball leftover from the birth of the cosmos. Later, in the 1990s, satellite observations further refined the measurements of this cosmic microwave background, and now it's essentially confirmed. This glow was successfully predicted by the Big Bang model, and now we see it in exquisite detail. Its discovery was a huge step in cosmology.

The redshift of distant galaxies and the cosmic background are not the only confirmations we have that the Big Bang model is correct. For example, the model also makes predictions about the elements we see in the Universe. At first, when the Universe was dense and hot, only subatomic particles could exist. But as the Universe cooled, for a brief time, they could fuse and form heavier elements.

The Big Bang model predicts certain abundances of elements — ratios of them, compared to hydrogen — and that's just what we see in the Universe at large. Also, the size and shapes of large structures in the cosmos are in line with what a Big Bang model predicts. There's lots of other observational evidence as well. Pretty much every modern astronomer on Earth understands that the Big Bang model of how the Universe got its start is the correct one.

But what does it mean? I mean, physically? It's a very common misconception that the Big Bang was an explosion in space, with everything rushing away from some point. But that's not what's really happening. Remember, I've talked about space being a THING, in which matter and energy exist. Space can be warped, bent, by mass, creating what we think of as gravity. When we talk about the Universe expanding, we mean space itself is expanding, and when it does it carries galaxies along with it.

In a sense, it's like having a rubber ruler. When you pull on it, it gets longer, and the distance between the tick marks gets wider. When the ruler doubles in length, the tick marks that started out a millimeter apart are now TWO mm apart. But tick marks that were ten centimeters apart are now 20 cm apart!

In other words, the farther away a tick mark is, the faster it appears to move away. Sound familiar? That's just what galaxy redshifts are telling us. It also means that, really, the galaxies aren't actually doing any moving, it's that space between them is expanding. This may seem like a nit-picky semantic point, but it's physically true. The galaxies are, for all intents and purposes, standing still. The space in between them is where all the action is.

And it gets even weirder: This is true no matter where you are in the Universe. From any galaxy, it looks like all the others are rushing away from you. Look back at that ruler: No matter what tick mark you start with, when the ruler stretches, from that spot it looks like the tick marks are all moving away from you. This is what Einstein's equations showed, and what Lemaître saw in them. Space is expanding! But that means the Big Bang wasn't an explosion in some pre-existing space, it was the initial exploding expansion of space itself. The Universe isn't expanding into anything, because it's all there is. There's nothing outside the Universe for it to expand into. This also means the Universe has no center, no point of origin.

Imagine the ruler is now a circle, and the diameter is expanding. No tick mark is the actual center, yet no matter where you are, on the ruler, every tick mark appears to move away from you. In a similar way, every spot in the Universe appears like the center, which means none is. No place in the Universe is more special than any place else. We're all in this together.

It can be hard to grasp, and I'll admit we all have some difficulty with these concepts. But the math bears them out, and so do essentially all the observations we make of the distant Universe. And in all this weirdness, don't lose sight of the big picture: The Universe had a beginning. And we can see evidence of it!

Not only that, but by measuring how quickly it's expanding, we can use math to run the clock backwards and determine the age of the Universe. Currently, the best measurement we have of the age of the Universe is 13.82 billion years. Or perhaps I should say: 13.82 billion years! That's an amazing number. It's a long, long time — three times older than the Earth — but what gets me is that we can figure it out at all. Pretty smart, us apes.

Today you learned that distant galaxies show a redshift in their spectra, which means they're moving away from us. The Universe is expanding! This means it used to be hot and dense, then it started expanding and cooling. This model of the Universe's early behavior is called the Big Bang, and it was confirmed when the background radiation — the glow of the fireball — was detected in the 1960s. Other lines of evidence support it as well. Using this information, we have measured that the Universe is nearly 14 billion years old.

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.