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HOW WERE STARS FORMED?

David Christian explains how the first **stars** were formed. This two-part lecture begins by focusing on what the Universe was like in its first 200 million years of existence, a period in which there were no stars. It then takes up the process of star formation. **Gravity** is the key player in this part of the story, and gravity will also be critical to the formation of larger, more complex structures in the Universe such as **galaxies**, **clusters**, and **superclusters**. The **cosmic background radiation**, which provided important evidence for the story of the Big Bang, is also important here, offering evidence about the conditions that led to star formation. After reading the text below and watching the video, you should be able to explain the process of star formation and why star formation counts as the second major threshold in our story of big history.

Key questions

1 What made the formation of stars possible?

2 What evidence supports our understanding of star formation?

Transcript: Part 1

0:12-1:19

THE UNIVERSE BEFORE THE FIRST FORMATION OF STARS

We've all looked up at the stars at night and wondered about them. But, could you imagine what it would feel like if you looked up at the stars and you saw nothing? No stars at all? Well, that's what it was like for about 200 million years after the Big Bang. As the Universe expanded, it got colder and colder and darker and darker and, frankly, less and less like a place that might produce things like you and me. Astronomers call this part of the Universe's history the **Dark Ages**.

THE ASTRONOMICAL DARK AGES

During the Dark Ages, you had a lot of atoms flowing through space. About 75 percent of them were **hydrogen**, with one proton; about 25 percent, most of the rest, were **helium**, with two protons, and there was a tiny sprinkling of **beryllium**, of **lithium** — lithium's got three, beryllium's got four protons — and, finally, boron. There was also stuff that astronomers call **dark matter**, quite frankly because they don't understand what it is, but it doesn't seem to play much of a role in the story, so we're going to ignore it.

1:19-2:03

THE SIMPLICITY AND THE UNIFORMITY OF THE UNIVERSE DURING THE DARK AGES

The whole Universe was really very, very simple. We know this because of studies of the **cosmic background radiation**, that was released, you remember, about 380,000 years after the Big Bang. What that shows is that matter was distributed extremely evenly through the Universe. Everywhere you looked you seemed to have the same temperature, the same density, the same types of atoms. Really, everything was uniform. And that's a real problem. Because it seems as if the Universe was just too simple, too uniform, for anything interesting to happen. How could you produce you and me from such a Universe?

Well, we actually know how all of this happened, and the key players in all of this are stars. So what we are going to do in this unit is focus on how the first stars appeared.

2:03-2:46

THE GOLDILOCKS CONDITIONS FOR STAR FORMATION

We'll see throughout this course that more complex things seem to appear when you have just the right **Goldilocks Conditions** for their appearance. Not too hot. Not too cold. Not too big. Not too small. Not too close together. Not too far apart. You get the idea.

So, what were the perfect Goldilocks Conditions for creating just a bit more complexity in the early Universe? Well, it turns out that those conditions were scattered all through the Universe. The crucial things you needed were: first, lots of matter; secondly, gravity; and third, tiny differences in the distribution of that matter. And they were all there.

2:46-3:23

THE IMPORTANCE OF TEMPERATURE DIFFERENCES

Recent studies of the **cosmic background radiation**, using special satellites such as the WMAP satellite, have shown that, in fact, there were tiny differences in the temperature of the cosmic background radiation. Some regions, for example, were just a thousandth of a degree hotter than other regions. Now this was just enough for gravity to get to work, and what gravity could do was to magnify those differences and turn them into something much more interesting. And so this is what happened: gravity began to get to work on those differences, and eventually it created stars, something entirely new.

3:23-4:32

THE IMPORTANCE OF GRAVITY

So let's see how this works. **Gravity**, you'll remember, is one of the four fundamental forces, and it's the star of this part of the story. As Newton showed, gravity is more powerful where there is more stuff and when things are closer together. To give an example, the gravitational pull of the Earth is extremely powerful on you, but if you move away out into space, it suddenly gets much, much weaker.

GRAVITY CAN TURN MATTER INTO MORE COMPLEX THINGS

So now let's move back to the early Universe and think how this force might have worked. Remember that there are some areas that are just slightly hotter and slightly denser than others. In those areas gravity was just slightly more powerful. So what it did was clump those areas together. As they clumped together, they got denser, so the power of gravity increased and they began to clump even further together. Gravity increases, so the whole thing is clumping, a bit like a runaway train. And this gets faster and faster and faster. And now what happens is that in the center of each of those clouds of atoms, atoms begin to bang into each other really violently, and they begin to heat up, particularly at the center, where there are the most atoms.

Transcript: Part 2

4:36-5:41

CONDITIONS FOR THE FORMATION OF THE FIRST STARS

So far our story has been about a Universe that's cooling down; suddenly, we are talking about an area of the Universe that's beginning to heat up for the first time. Eventually the temperature reaches about **3,000 degrees**. Now that temperature should sound familiar. It's the temperature at which atoms can't hold together anymore, because protons can't hold on to electrons, so what happens is you recreate the sort of plasma that existed before the creation of the **cosmic background radiation**.

RISING TEMPERATURES CAUSE CONFUSION,

Now, the temperature in the cloud keeps rising until eventually it reaches **10 million degrees**. And something spectacular happens at that temperature: protons start banging together so violently that they overcome the repulsion of their positive charges, and they fuse together, and they are now held together by the "strong nuclear force." As that happens, there is a huge release of energy as some of their matter is turned into pure energy. This is very similar to what happens in an H-bomb.

5:41-6:37

THE CLOUD BECOMES A FURNACE

So now at the center of the cloud we have a sort of furnace that's pushing back against the force of gravity and that stabilizes the whole thing. And now what's happened is a star has lit up. And that star is going to shine for millions or billions of years.

THE SECOND THRESHOLD OF COMPLEXITY

We've now crossed our **second major threshold of complexity** in this course. From about 200 million years after the Big Bang, the Universe starts filling up with stars — billions and billions and billions of them.

And the Universe is now a much more interesting place. Instead of the sort of uniform mush that we saw before the appearance of the first stars, we now have a Universe that's filled with stars. It's not that it's just more interesting to look at, stars are much more important than that; our Universe is filled by these sort of glowing batteries that emanate light and heat. It's a much more interesting place.

6:37-7:49

STAR NURSERIES

In fact, astronomers can see stars still forming today; it's a process that's still going on today. They find them in **star nurseries**; they're some of the most beautiful places you can see in the heavens. And, in fact, it's worth going to the Hubble website or looking through a telescope at some of these star nurseries because they are amongst the most beautiful sights you can see in the sky.

STAR STRUCTURES GENERATE PHOTONS OF ENERGY AND LIGHT

Stars increase the complexity of the Universe in another way: they gave it new types of structure at many different scales – from the level of the **stars** themselves to **galaxies** to **superclusters**. So let me try to describe these structures one by one. Let's begin with the stars. **Stars** themselves have a very clear structure. At the center you've got protons that are at an extremely high temperature, as we've seen, and they're fusing to form helium nuclei. Just around the center, around the core, you have a sort of store of protons ready to be fused eventually when they sink down into the center. Now photons of energy and light from the center slowly work their way through the plasma, taking sometimes thousands of years, until eventually they reach the surface and they flash out into space.

7:49-8:55

STARS, GALAXIES, CLUSTERS & SUPERCLUSTERS

So stars have a lot of structure, but stars themselves are gathered together by gravity into much larger structures. We call these **galaxies**. Our **Milky Way** is our galaxy; it contains perhaps 100 billion, some say 200 billion, stars. It's absolutely huge! And there may be a 100 billion galaxies in the entire Universe.

But structures exist at even larger scales, too. Gravity gathers galaxies together into what are called **clusters**. Our local group is a cluster like that, and it contains about 30 galaxies, including **Andromeda** and the **Magellanic Clouds**, both of which you can see with the naked eye.

GRAVITY CANNOT HOLD MULTIPLE SUPERCLUSTERS TOGETHER

Gravity can even hold clusters together to form what are called **superclusters**. These scatter through the Universe in huge webs and chains. But beyond that gravity is too weak to hold [multiple] superclusters together. And it's beyond the level of superclusters that you begin to see finally what Hubble saw: you begin to see whole superclusters moving apart, and there, at that scale, you can see the expansion of the Universe.

8:55-9:43

Now, let's summarize. We'll see throughout this course that complexity builds on complexity. Now we've got stars, and stars are going to be key to later forms of complexity. Most of the Universe was then, and still is, cold, dark, empty, and, from our perspective, very, very boring indeed. But with stars you have something like campfires in Antarctica: lights that light up a cold Universe. And we'll see that from now on the Goldilocks Conditions for further complexity are to be found not throughout the whole Universe, but in galaxies, and above all around the stars, those cold campfires. That's where our story is going to go now.