DJORGOVSKI: Well let's go move back into the formation of the solar system. We went through the general picture of this last time, why this is a normal thing that will happen around most stars. And this is artist's conception-- which I think is completely fake, because Saturn already has these nice rings, and I think they're probably more later construction. But it's a pretty picture. It has a lot of comets you can see.

And just to freshen your memory, the idea is in protoplanetary disk, you start condensing pieces first from dust into pebbles, and so on. And what they're made of depends on where they form. Closer to the sun, they'll be mostly heavier elements. All the light stuff is getting pushed out. And so you tend to have different composition planetesimals. And then planetesimals get collected into plants.

So planets inherit chemical composition of the material they're built from, the planetesimals they're built from. And for some reason, planetesimals in the inner solar system were smaller. Those in outer regions could go grow bigger, probably because initially they had reasonably well-mixed dusty, kind of heavy element stuff with icy stuff, light elements.

But then you evaporate an blow away all the icy, refractory stuff. And so what's left is a smaller fraction of mass, because there is much less mass in heavier elements than there is in hydrogen and helium. In fact, it might be 1% or 2% of the total mass in the solar system is in form of elements heavier than hydrogen and helium. All right, so hydrogen and helium totally dominate. And yet in the inner solar system, they're just evaporated away.

So showing you pictures of some protoplanetary ring, or protostellar disks. Here is one around the star of Formalhaut. And people think this may be actually very similar to what our solar system looked like. This is picture with Hubble Space Telescope. The star itself is being blocked out.

And there probably are planetesimals forming right in there now, because all the infrared luminosity and properties are actually very convincing. And we've seen planets. We've actually taken pictures of some planets around some of nearby stars in the infrared. Here is one. And the way you can tell is it moves. So if you take pictures years apart, you can see it move along its orbit.

Now, a star moving itself relative to the background of stars. But these planets will move along with it, right? So they share a common proper motion with the star itself, but then move around the star ever so slightly. So there have been several of those seen by now.

So the consequences of all this is in the inner solar system, there wasn't much mass left, because all the lighter stuff was pushed out. And so whatever was formed was formed out of chemical elements-- silicon, oxygen, iron. Whereas in the outer solar system, there was still plenty of hydrogen-based compounds and carbohydrates left. And that's why first you can grow bigger planetesimals bigger planets. And their composition now is dominated by these lighter elements.

So the simple picture accounts for a lot of observed architecture of solar system. Now, not all planetary systems are like ours. And that presents some interesting questions. And I will talk about this next time.

So you put planets together. And there are still a lot of loose rocks flying around. So there is a period called the late heavy bombardment, which is when you already formed planets pretty much in their size and form that they are now, though still kind of settling in. And there are still a lot of planetesimals left. And those hit, generate deep impacts. You compute how much kinetic energy one of those things can have. And this would not be a good place to have life at the time.

But the icy ones also bring in water and lighter elements. So there is probably a dramatic case of this was the origin of our moon. For a long time, it wasn't clear, how did moon form. Now the prevailing theory is that around that time, there was a smaller protoplanet, about size of Mars, on a similar orbit which slammed into young Earth.

And if a 1-kilometer asteroid can cause a significant damage, you can imagine what two planets colliding can do. So essentially, the kinetic energy of this impact ejected a big chunk of the mantle of proto-Earth out in space. And then it cooled off, condensed, probably made a nice big set of rings around planet Earth-- just like Saturn's rings, but even more spectacular.

Then they started condensing. And eventually those circum-Earth planetesimals, if you will, formed the moon, which explains why the moon has the same composition as the outer regions of Earth, mantle and crust. It also helps explain why our rotation axis is tilted relative to the ecliptic. Because if this collision was slightly oblique, it's would have imparted angular momentum through grazing. And so the net angular momentum which might have been exactly orthogonal to the orbital plane could have tilted. And it also explains why the moon's orbit is tilted. Because moon's orbit tilts extra in addition to the Earth's ecliptic field by about plus or minus 5 degrees.

So this was done through computer simulations. There are always issues to improve things. But I think most people believe something like this probably happened. And then that continued.

Probably one of the better known ones was what happened to the dinosaurs. This is a nice artist's conception. We can think of it as Malibu for dinosaurs. And there they are, splashing in the water. And then there is this big fiery thing coming down.

We now think we have fossil crater of this. It's under the ocean. It's in the Bay of Mexico, off Yucatan. And it's called Chicxulub Crater, something like that. And so this is now generally accepted through a variety of geological evidence to have been cause of at least some mass extinctions in the, past which otherwise were very difficult to understand.

And then have continued. So here is a picture of the great crater in Arizona. And look, it missed these buildings on the left just by a little bit. And then the top picture is picture of fallen trees from Siberia, from Tunguska Event, a century ago. That is now believed to have been probably a cometary nucleus, because there was an obvious crater left.

And nevertheless, it was like an air burst of-- I forget how many tens of megatons worth of hydrogen bomb-- and the blast was heard around the world and so on. And had that happened over an inhabited part of Europe or North America, say, it would've been sort of like effect of nuclear war. Then more recently, a smaller cousin of it fell in Siberia, in Chelyabinsk. And you can see YouTube videos about it.

So these things happen all the time. Earth keeps accreting. Every meteor is a reminder that we're still collecting pieces of the protoplanetary disk. And there is some understanding what's their distribution, and the little ones happen all the time, and big ones happen less often. And like mass extinction-causing ones happen every few 10s or 100 million years. But they do happen, and you never know when.

All right. So when did this all happen? How do we know? We always say solar system is about 4.6 billion years old. Where is the clock? The clock is through radioactive dating. So some of the isotopes are unstable and they decay into something else. And you can measure their half-life time in the lab.

And so if you take a rock and measure the abundances of the progenitor isotope and a product isotope, you can figure out how many of these doubling times have elapsed to achieve that particular abundance ratio. And if you measure the half-time time in the lab, multiply the numbers, you get the age of the rock. So this was indeed done. And it's done independently in the oldest rocks on planet Earth, which I think come from Iceland. They've been dredged up by volcanoes. Lunar rocks, meteors, and they all come up with more or less similar number, about 4 and 1/2 billion years. It's actually more precise than this.

Now, in order to do this, you need an isotope with a half-life that's kind of comparable to the time scale you're measuring. Because if it's too short, there'll be nothing left of the progenitor nucleus by time you start measuring. If it's too long, well, it's hard to measure half-time time that's billions of years old in the lab during, say, work week. So you want to get something that's right in the middle.

And fortunately, there are plenty of these things. And so you can choose the right ones. A famous radioactive dating is with isotope of carbon, carbon-14. Its half-life time is in thousands of years. So this is well-suited to measure things over historical periods of thousands or tens of thousands of years in the past. This is how we do time scale of known history, of prehistory. But using things that are more like a billion years, or hundreds of millions of years, in half-life time, it can measure astronomical lifetimes.

Now this beautiful picture of how planets form and all this is not exactly complete. There is something in between planets and stars, and it's called brown dwarfs. Those are stars that didn't quite acquire enough mass to create enough temperature and pressure in the middle to ignite nuclear reactions to burn hydrogen into helium. It takes something like 8% of the solar mass minimum-- or 9%, something like that, depending on composition-- for stars to achieve conditions in the middle sufficiently to ignite nuclear reactions.

So there is this interim class of objects that are bigger than planets, and be tens of Jupiters in size or hundreds of Jupiters in size-- in mass, I should say-- but do not shine from nuclear reactions. Now, those have been discovered. The first one has been discovered at Palomar-- I forget, but about 20 years ago maybe, 30, 25 years ago. And now many, many more have been seen.

The way you find them now is through infrared sky surveys. And that's because these things are pretty cold. And they're cold because they do not thermonuclear reactions to generate luminosity like you would see in a normal star. Nevertheless, they do shine. And so where does that come from?

Well, that comes from so-called Kelvin-Helmholtz mechanism, which is essentially what I told you about how protostars shine. That there was a question of a protostellar cloud collapsing, releasing binding energy, but in this case you have a brown dwarf or a planet. It's composed as it is, but it's still settling. It has some finite temperature, in any case. A radius according to whatever the temperature is-- it could be hundreds of Kelvins or something.

And as it radiates energy, it has to shrink a little bit. Because it's shrunk, it has to convert this excess binding energy again in heat. And so as it shrinks as much as it can, it keeps radiating excess binding energy, typically coming out in infrared. Turns out, our Jupiter is like this. Jupiter is almost like a borderline brown dwarf.

It was realized very quickly in modern astronomical studies that Jupiter emits more radiation than the amount of light it intercepts from sun. And so the question is, where did that come from? And so this was understood to be to the source.

Actually, before we understood how stars shine, that there are thermonuclear reactions involved, this mechanism was believed to be the source of stellar luminosity. Now, if you do the numbers, how much binding energy is there in the sun, and measure solar luminosity, ask how long this is going to last, you come up with a number of 18 million years. So sometime in late 19th century or early 20th century, that's what people thought, that solar system is 18 million years old. That's how old the stars are.

And then after Rutherford and others discovered and measured radioactivity properly, people started finding rocks that are billions of years old. And so that was a problem. You can't have rocks that are older than the universe, right? But then as nuclear physics developed in the 1930s, '40s, '50s, it was already clear that you can do thermonuclear reactions. And temperature and density in stellar cores were already evaluated purely through classical physics arguments-- how much pressure do you generate by having so much mass, and so on.

And so those there was obviously plenty to actually do thermonuclear burning. But until that happened, this was thought to be the mechanism. So it actually is the mechanism how some things shine, but they're not stars. They're brown dwarfs or some really big planets, or protostars.