

NWX-NASA-JPL-AUDIO-CORE

Moderator: Anita Sohus
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Coordinator: Thank you all for standing by. At this time all participants will have open and interactive lines for the duration of today's conference. To avoid any background noise during the call please utilize the mute function on your phone or press star 6 to mute and unmute your lines.

This call is being recorded. If you have any objections please disconnect at this time.

You may begin when ready.

Jeffrey Nee: Hello everybody and welcome. I'm Jeffrey Nee from the Museum Alliance, the moderator for today's talk. All right. Well let's get going. So thank you all for joining us today and for anyone listening to the recording in the future thank you. We'll be talking today about the origin of the Moon.

As a final reminder do not put us on hold even if you have to step away because some phones play holding music which can disrupt the talk. Just be

sure your phone is on mute so that noises from your end don't disrupt the talk either.

So the slides for today's presentation can be found on the Museum Alliance site. If you have any problems email me at jnee@jpl.nasa.gov.

Our speaker today is Dr. Julien Salmon, a Research Scientist at the Southwest Research Institute in Boulder, Colorado. Dr. Salmon graduated from the French École des Mines de Saint-Etienne (forgive my French) where he was studying Image Processing along with other engineering related topics such as Energetics, Instrumentation and Solid Mechanics but also Human and Project Management.

Dr. Salmon then started a Ph.D. in Astrophysics at the University Paris 7 where he was working under the supervision of Dr. (Andre Brahic) and Dr. (Sebastian Charnoz). Dr. Salmon designed numerical models and hydrocodes to study the evolution of planetary rings and satellites. He found its main application in the viscous spreading of Saturn's rings and the formation of satellites by accretion of ring material.

Dr. Salmon's current activities at the Southwest Research Institute include modeling the dynamical evolution of disks around planets and the formation of satellites from accumulation of disk material in order to further understand the processes of planetary satellite formation, and in particular, the Earth's Moon and the satellites of Saturn and Mars.

He has indicated that he would actually prefer to take questions during the talk. So if there's something you don't understand or want repeated feel free to speak up.

Jeffrey Nee: Yes, just remember to re-mute yourself afterwards. It is my true pleasure to turn it over to Dr. Julien Salmon.

Julien Salmon: All right. Thank you very much. It's a pleasure to be here. The reason I ask to allow listeners to ask questions during the talk is that I took the liberty of making the presentation just a little bit technical so that you get an interesting level of detail. But it shouldn't be too complicated, but there may still be a couple of concepts that I do not explain sufficiently. So I want you to be able to ask about them so that you can understand the rest of the presentation better.

So we can right now go onto the next slide [Slide 2] where I just show you a nice picture of the people working here at Southwest Research Institute. As you can see we are in a delightful location, very close to the mountains. This is a picture that was taken, I think, two summers ago where we celebrated the 20 year [anniversary] of the Institute. Twenty years ago we started with three people. We now have about 80 persons, with some of the best scientists in planetary science, and I've been there myself for five years and really enjoying it.

So if you go to the next slide [Slide 3]. So the Moon is very particular because it's a very unique body in the Solar System. If we look at the terrestrial planets from Mercury to Mars it's pretty striking that there's a very small amount of satellites and the only large satellites we can find is around the Earth.

The Moon is really big. It's about 1% of the mass of the Earth, and in comparison the only other satellites we have are Phobos and Deimos around Mars, and the mass ratio of the satellites to the mass of the planet is much, much, much smaller, of an order of 10^{-8} . It's a million times smaller mass ratio than for the Earth-Moon system.

The Moon's density is about 3 - it's a density of about 3 [grams per cubic centimeter] which suggests that it has a very small iron core. And today the Moon orbits at about 60 times the radius of the Earth. That's the notation R_E , the physical radius of the Earth. But what we know is that it was initially much closer to the Earth and that it eventually moved away due to tidal interaction with the Earth.

Julien Salmon: So we're going to go to the next slide [Slide 4]. I'm going to start talking to you about the different theories that were suggested for the origin of the Moon. The first one is called the Fission Theory. The basic idea is that the Earth was rotating at some point so fast, that some of the material from the Earth was actually being ejected due to the centrifugal force. And that [theory says] basically the Earth rotated so fast, the material is pulled away from the Earth as you can see on that little cartoon. And that material that is pulled away eventually re-accretes to form the Moon.

The main problem with that scenario is that it's really not clear how you would create such a fast rotation state to begin with, and that particularly has issues with the overall angular momentum of the Earth-Moon system that is today much too low to be compatible with such a state initially.

So go to the next slide [Slide 5]. The second theory that was suggested is called Capture. The idea is that the Moon is a body that was wandering through the Solar System and passed close to the Earth and got captured by the Earth.

The problem we have with this scenario is the encounter velocity, meaning the velocity that the Moon has when it passes close to the Earth, is likely very high. And so you need to dissipate that velocity, dissipate the associated kinetic energy, so that the Moon can be actually bound into Earth's orbit. So to dissipate that energy you could do it maybe a little bit by tidal dissipation, using tidal forces from the Earth. But it's likely that the tides from the Earth are not strong enough to permit enough dissipation of energy.

Another possibility is that this capture happened when there was still a lot of gas around the Earth and as the Moon passes through this gas it's feeling a force that is slowing down its velocity and that could help capture the Moon around Earth's orbit. The problem is that if the gas lingers for a significant amount of time after the Moon is capture, the Moon's orbit keeps slowing down and it would drift inward and eventually collide with the Earth.

So it appears then a little unlikely that you would have this capture happen at the exact same sweet moment where there's still enough gas for the capture to happen but not too much that the Moon would eventually be lost. So that's why it seems to require a slightly unrealistic set of conditions.

[Slide 6] Finally another origin is called co-accretion. The idea is that the Earth and the Moon formed in the same location next to each other. The possibility is that as the Earth is forming, these small objects called

planetesimals that collided close to the Earth, inside what's called a Hill sphere, which is roughly a sphere of gravitational influence. And by having all these small bodies collide within Earth's gravitational influence you could form a disk from which the Moon accreted.

However this scenario implies that the Earth and the Moon essentially formed from the exact same material, but we have a problem with that, because the iron content of the Moon is much, much lower than the iron content of the Earth. So if they accreted from the same material, you would expect the iron content of the Earth and the Moon to be much more similar than it is today. So that's a compositional issue here.

So I'm going to the next slide here [Slide 7]. So in order to find some other ideas, what we can look into is planet formation. The little animation you have on the left panel is a result of a computer model that looks at how dust in orbit around the Sun interacts with each other with the effect of gravity. And we find that the gravity of the dust itself causes it to collect into larger clumps which eventually form what we call planetesimals, which are bodies that, you can compare to an asteroid or a comet. So fairly big, but not as big as a planet.

Eventually those planetesimals collide and they can form larger bodies. That's something we know from theories of planet formation, and over time they will grow into objects that are about the size of the Moon or about the size of Mars.

Jeffrey Nee: A quick question Dr. Salmon.

Julien Salmon: Yes.

Jeffrey Nee: Is this animation just a pure simulation or is it actually a model of the Solar System?

Julien Salmon: I'm sorry. Is it a pure simulation or what?

Jeffrey Nee: Of just particles or is it an actual model of the Solar System formation?

Julien Salmon: So this is just a simulation in which you put a number of dust particles - this is a computer model solely and you initially put thousands or tens of thousands of individual particles of dust in orbit around a central body, which in this case was the Sun. And as this dust orbits around the Sun it, you know, there's a difference. All the dust particles do not move all at the same velocity, and so they tend to collide into each other and they can stick together due to gravity.

Jeffrey Nee: Great. And is there a difference between the green and the blue at all?

Julien Salmon: So this is just the way the numerical model is performed, it would require way too much resolution to simulate all the particles around the Sun. So you only simulate a small patch which is represented by the green box. And the blue box that surrounds it are what we call boundary conditions where you just basically replicate what's going on at the other edge of the box. It's a symmetry process.

Jeffrey Nee: Great. Thank you.

(Jim Cassey): Dr. Salmon, this is (Jim Cassey) with SSA.

Julien Salmon: Yes.

(Jim Cassey): Are we effectively saying then, that an accretion disk of uniform particles of dust is essentially unstable?

Julien Salmon: Yes. If it's massive enough then it's going to be prone to what we call a self-gravity - gravitational instability - and eventually it's going to [collapse]. This self-gravity, which is the gravity of the particles that make up the disk, is going to cause them to form clumps, and then as these clumps collide with each other they can be disrupted and then re-accrete, et cetera. So it's an instability.

So if we move on to the next slide [Slide 8]. The theories of looking at how the planets form, from initially accumulation of small dust aggregates, all the way to accretion to collisions between large bodies, which are maybe the size of the Moon or the size of Mars, led us to imagine that the Earth may have been impacted towards the end of its formation, by an object about the size of Mars. And as this Mars-sized object collided with the Earth, it may have ejected material from the debris of the impact, but also ejection of material from the Earth itself. This material could have been placed into orbit and formed a disk, and the Moon could have formed by re-accumulation of that material in orbit around the Earth.

So we have a number of constraints for that scenario to work. And one of the most important one is the angular momentum of the Earth-Moon system. As you may know, the angular momentum of a closed system is a quantity that is completely conserved. You can transfer angular momentum from one part of

the system to the other, but the whole angular momentum, the whole system has to remain constant.

So because of that we think that the angular momentum of the Earth-Moon system that we have today was likely the same 4.5 billion years ago when that giant impact happened. We think that a little bit of angular momentum may have been drained due to interaction with the Sun but not in a significant way.

What we know also is that, as I said before, the Moon formed initially very close to the Earth, but eventually evolved away due to tidal interaction with the Earth. And so if we integrate its orbit backwards in time, we think that the Earth had an initial rotation that was about five hours instead of the 24 hours we have today.

Another constraint is that you need this impact to put enough material in orbit to produce a Moon-sized object. If you find an impact that only puts into orbit a tenth of the lunar mass, that's not going to be enough to form the Moon. And finally, we need to be able to explain the low lunar density and the small iron fraction in the Moon. So we need to form a disk that does not contain a lot of iron.

Man: Question.

Julien Salmon: Yes.

Man: About how old was the Earth when this happened?

Julien Salmon: So the question of the age of the Moon is still a matter of debate. But we think that the giant impact likely happened, if my memory serves me well, about 4.4 billion years ago. So this is very early in the history of the Solar System.

Man: Do we think this impact caused the 23-1/2-degree tilt of the Earth?

Julien Salmon: I'm not sure about that. That's not something I've looked into [in] detail. Frankly I don't know.

Man: Fair enough. Thank you.

Julien Salmon: Yes.

Man: Parenthetically though, I believe we can thank the Moon for keeping this 23-degree tilt.

Julien Salmon: Yes. So we know that the Moon is keeping the obliquity, which is the tilt that we're talking about. It's keeping that obliquity fairly low and we think that thanks to that the variation in temperatures over the Earth here have been kept pretty small which was favorable for development of complex life on Earth.

Okay so if we go to the next slide [Slide 9], I'm just going to show you a little bit how we think an impact can put material into orbit which we call orbital injection. So on this, you can look at this little cartoon and what we're saying is that basically upon the impact, the debris from the impactor and from the material that is impacted at the surface of the Earth, we see positive acceleration. So it's being ejected. However, following that positive

acceleration from the impact, the debris feels negative acceleration from Earth's gravity.

So if the total energy of the debris is positive then the debris would escape from the hyperbolic orbit. But if the total energy of the debris which is going to be the sum of that positive acceleration and negative acceleration from the Earth, if the energy is negative then the orbit of the debris is a close elliptical orbit that intersects the Earth so that the debris would eventually re-impact Earth.

So if we go on the next slide [Slide 10], one thing we have to consider is that because there's a lot of energy that is involved in the impact, you're going to have, for instance, vaporization of material. And with vaporization comes possible effects of pressure and particular pressure gradients. And the effect of this pressure gradient is to increase the energy and the angular momentum of the ejected material and that essentially lifts the periapsis of the orbit of the ejected material. And it lifts that periapsis above the surface, so that now the orbit of the ejected debris does not re-impact the Earth, but instead you get a full orbit around the Earth, and you can form a disk of material around the Earth using this process.

Man: So basically then, the aftermath of the explosion, to use another word, lifts the orbit into something that would be stable, yes?

Julien Salmon: Absolutely.

So going to the next slide [Slide 11], we're going to look into how we can model a giant impact in a computer. So on the left you have a very nice

painting from (J. Tucciarone) of a giant impact that could be similar to the one that may have formed the Moon. And on the right side you have - you may have to press Next to get to have the right panel appear. We have represented a numerical modeling of that type of impact in the computer.

Let's go to the next slide [Slide 12]. In this computer model what we do is that we describe the colliding planets by thousands, to maybe hundreds of thousands, to possibly millions of particles, and each particle is going to evolve due to several physical processes including gravity, but also a thermodynamical processes including heating, pressure, melting, and vaporization. And so in these computer models, we start with an initial condition of a number of particles representing each body and all these particles have a velocity and other properties. And then we have the objects collide and each particle is going to feel different processes, like gravity and others.

If we go to the next slide [Slide 13], we have here an animation of what I was telling you about. The color scale here represents the temperature of each particle. And you can see that the giant impact has heated the Earth quite significantly. But you can also see that there's a lot of particles that have been ejected into bound orbits. You have a couple of very large clumps that eventually are going to re-collide with the Earth and put additional small particles in a disk around the Earth.

So this is a simulation done by Robin Canup here at the Southwest Research Institute. She's one of the world experts on modeling those type of giant impacts using computer models.

All right so we go to the next slide [Slide 14], we get another animation in three dimensions so you can better see what's going on in the system. Again, the color scale here represents temperature with red being hotter than yellow, green and blue. And as you can see we eject material in all the dimensions but most of the material is in the equatorial plane of the planet, so that you indeed mostly eject material into a fairly slim disk around the planet.

Man: So in the latest animation we're kind of looking at it from a equatorial view, yes?

Julien Salmon: Yes. Yes it's from the side basically.

I mean, it's actually - let me - it's actually seen from the top mostly.

Man: May I ask a question?

Julien Salmon: Absolutely.

Man: In this particular simulation, if I understand it, it looks like the impactor and its plane as it was about to pass the Earth but didn't pass it, it collided with it was parallel to the plane of the Earth's rotation. Did you try 90 degrees out from the Earth's rotation and retrograde against the Earth's rotation and having findings from that?

Julien Salmon: Yes absolutely. So in this particular simulation we actually did not include the spin, like the proper rotation of each bodies. We assumed that they don't rotate. They have a spin of zero, basically. But Robin has performed an extensive study of looking at how considering rotation in the bodies prior to

the impact affect the outcomes. And it does have an impact on the type of disks you're going to form but it's not a dramatic impact. It gives you a little more leeway into the angular momentum of the system that you can play with. But overall all types of impact configurations lead to ejection of material with some configurations leading to more material being placed into orbit than others.

Julien Salmon: Okay so moving on to the next slide [Slide 15], we're going to here look at a similar simulation, but this time we're going to look at what is the fate of the iron that is initially located in the cores of the two impacting bodies. So in that animation the red particles are made of iron and the yellow particles in the mantles are made of silicate which is basically just rock. And if you start the animation by clicking on it, as you can see, again, the objects collide and the particles and material are pulled into orbit.

But if you look, eventually most of the red particles, that are the iron of the system, end up being located into the Earth and the final disk is composed mostly of yellow particles which represent silicate. So seeing that this particular type of impact is also a good way of putting only a little bit of iron into the disk and if the Moon accretes from an iron-poor disk then the resulting Moon will be also iron-poor.

Man: Question.

Julien Salmon: Yes.

Man: How well does this simulation predict the resulting densities? How closely does it get to the actual Moon's density?

Julien Salmon: It works pretty well. When you compute the fraction of iron in the disk it's a pretty good match with what we think the iron content of the Moon is.

So if we go to the next slide [Slide 16], what we show here on the left is a variation of the mass of the disk, so the mass that we put into orbit with the impact and the function of what we call the impact parameter. And you have on the right, a little schematic of what is the impact parameter which is basically the sin of the angle between the two colliding bodies.

The different colors represent different impact velocities but the general trend that is important here, is that we see that for an impact parameter b that is greater than about 0.7, which represents a fairly oblique impact, then we can put a significant amount of material [into orbit] with a total disk mass greater than 1 lunar mass. We can put quite a lot of mass into orbit using these impacts.

The next slide [Slide 17], we're now going to start thinking about how we form a disk - how we can form the Moon from a disk. A question that I've written is "How do the particles that make up the disk end up forming the Moon?"

So we're going to study this again using computer simulation, but instead of simulating the impact we will now look at what we call the protolunar disk. When we do that, we present that disk with a collection of a few thousand particles that you can see a schematic of on the little cartoon just below. So the large circle on the left of the schematic is the Earth, and you can see, on the right, all the particles from the disk that we're going to consider.

In this kind of simulation, we only consider gravitational interaction. We do not take into account physical processes such as thermodynamics, presence of vapor, or fragmentation between the colliding bodies. So this is just a gravitational study of how the particles in the disk will evolve.

The next slide [Slide 18]. So we show here the results of a sample lunar accretion simulation. The different panels represent the status of the system at different times of evolution. The bottom panel here shows a time of $1000 T_K$, where T_K is a measure of time, but to give you an idea, $1000 T_K$ is about 10 months. So the bottom panel here is a system after about a year.

This simulation has an initial disk mass of about 4 lunar masses, and you can see that, as the particles evolve, they can collide with each other. As they collide they can merge and grow into larger and larger bodies, so that after about a year, we're left with one massive body and only a couple of smaller particles. And in this particular run, we form a Moon that is just about the mass of the actual Moon. So the bottom line of this simulation is that we can indeed form a lunar mass object over a timescale of about a year.

Man: Can you comment? It looks like the difference between the initial mass and the final mass was 2.8 lunar masses. What was the fate of those?

Julien Salmon: Yes. So due to the interaction between all the bodies that make up the disk, you can have some scattering events happening, such that some objects are being thrown into the Earth for a significant part. But you can also have objects that are simply ejected from the system on hyperbolic orbits. So because of that, it's not a very, very efficient process because indeed you see

that you need a four lunar mass disk, in that particular case to form a full Moon. So you lose about two thirds of the mass of the disk either by material falling on the planet or being ejected from the system.

Okay so if we go to the next slide [Slide 19].

Julien Salmon: So we define the successful cases for giant impact models to be impacts that create a disk with an iron content smaller than 10%, that can form a satellite greater than a lunar mass, which is $M_S > M_L$, and a final lunar angular momentum, L_F , that is on the order of the current lunar angular momentum of the Earth-Moon system. We find that this works best for impactors that have about 10 to 20% the mass of the Earth. So that's about the size of Mars. And we find that the best case seem to require an oblique impact with an angle of about 35 to 50 degrees.

A problem with what I've presented you so far is that the mass that is placed into orbit by the impact is derived mostly from the impactor. We got a little bit of mass ejected from the Earth itself but mostly we [calculate] more than 60% of the disk is composed of material from the impactor.

This is an issue because we know, thanks to the lunar meteorites and all the samples we've brought back with the Apollo missions, that the Earth and Moon have nearly identical composition of multiple chemical elements. So this requires either that the impactor had the same composition as the target.

This can't be totally ruled out, but if that impactor somehow formed in a different part of the Solar System it's pretty likely that its composition is going to be reasonably different and it's unlikely that you would have a

composition that is so close to what we know of the Earth. So if that impactor didn't have the same composition as the Earth then we need to find another mechanism to explain the similarities in the chemical composition of the Earth and the Moon.

The next slide [Slide 20]. This picture here is a picture that I've designed from using actual input from my numerical simulations and this is a cartoon that represents what we think the Earth-Moon system looks [like] 4.5 billion years ago just after the impact. And the take home from this is that because there is so much energy that is delivered into the impact, there is a lot of material that is going to be in a liquid or vapor phase. So the protolunar disk is a very, very hot mixture, several thousands of Kelvin high, a very hot mixture of vapor and magma.

So the next slide [Slide 21]. This cartoon here is a schematic of the picture I've just showed you, where you have, on the left, the Earth just after the impact and, on the right, the protolunar disk. And basically the vapor component of the protolunar disk, we think, was connected with the atmosphere of the Earth.

And what we think may have happened is that, due to that connection of the vapor phases of the two, there may have been material exchanging between the Earth and the disk atmosphere. And then by subsequent cooling of that vapor into the disk you could evolve the composition of the disk as you progressively equilibrating the [disk] material with material from the Earth. And we think that that process may be capable of having a disk whose composition matches that of the Earth over a timescale of about 100 to 1000 years.

This is a great process, however, in the models that I've presented you in a couple of slides ago of the evolution of the protolunar disk, they show that the Moon formed from the disk in a timescale of about a year which is two or three orders of magnitude too short compared to what you need for this equilibration process to take place.

Next slide [Slide 22]. So what we took from this is that maybe our modeling of the protolunar disk that I've shown you before was maybe a little too simple. So there's an important physical parameter for the system called the Roche limit. And this Roche limit is a distance beyond which the bounding forces between two objects can overcome the disruptive tides from the planet. So basically if you're inside the Roche limit, and you have two objects colliding, even if they merge temporarily, the tides from the central body, from the Earth, is going to eventually shear apart that object so that you cannot grow large bodies inside the distance.

This is a distance that is material dependent, because obviously the internal structure of objects are going to depend on the material they're made of, so that it's going to be easier for objects made out of iron to stick together than it's going to be for objects made of, for instance, water ice.

So what we know is that inside the Roche limit the gravitational instabilities that we already saw in that first animation that I showed you, of dust forming aggregates, the gravitational instabilities, they tend to form clumps of material but because you're inside the Roche limit these clumps are immediately destroyed by tides from the Earth.

And [with] that process, because basically you're forming larger objects but immediately destroying them, you allow small objects to collide again, et cetera and et cetera. And through that process you're going to maintain a high rate of collision in the disk. If the objects were growing, you would have less and less objects, so less and less collisions. The collision rate would decrease. But if you are constantly destroying those large objects, you're maintaining a large number of small particles in the disk which can then collide over and over again.

So because all these collisions dissipate energy and release heat, a disk made out of particles was very rapidly vaporized. And that vaporized status cannot be represented by just a collection of condensed particles because you need to take into account some thermodynamical processes. So because of this consideration it is better - it is more appropriate to model the disk inside the Roche limit by a fluid and not by a collection of individual small objects. However outside the Roche limit, you do not have that process of clumps being destroyed by tides, because you're beyond the Roche limit, and so the disk can rapidly fragment and form independent bodies, so that outside of the Roche limit it is more appropriate to model the disk by a collection of individual particles.

Man: Are we saying then that inside the Roche limit there would be a considerable amount of material mixing?

Julien Salmon: Inside the Roche limit it would be what?

Man: There would be a considerable amount of material mixing?

Julien Salmon: Yes, potentially. Potentially, because it's going to be a very turbulent and very agitated system that's going to stir a lot of material, and you can have a lot of mixing, which is what we want for this equilibration process to take place.

Man: That's right because I see from the drawing from (Stevenson) 1987 you show a magma disk and a magma ocean. So then the material from the impactor and the proto-Earth would be fairly thoroughly mixed. So anything that makes orbit from that to form the Moon would then be identical with the stuff that remains on the Earth.

Julien Salmon: Yes. So that's the whole idea of this equilibration process. The problem that we're facing here is a problem of timescales because you need about 100 to 1000 years for this equilibration process to take place. But until recently our understanding of how the Moon formed from the disk was telling us that the Moon forms within a year. So you have 100 of - about 100 times too short a timescale for the equilibration to happen.

So if you go to the next slide [Slide 23], this is just to show you a different type of computer model that we have developed following those physical considerations that I've just told you about. So on this figure, again to the left, the big circle is the Earth, and then again we represent the material inside the Roche limit, which is represented by the vertical dashed line at about three Earth radii, we represent that material by a continuous fluid disk, and the material from the disk that is located outside this distance will instead use the same modeling of the previous models, which is just a collection of individual particles.

And so if you advance the slide you're going to have some annotations showing up. So again inside the rush limit a uniform fluid disk and beyond the rush limit individual particles.

And if you go then to the next slide [Slide 24] we're going to talk a little bit about what we call viscous spreading that was mentioned, I think, by Jeff in my introduction. Viscous spreading is a very, very important process for disks in general. That applies to the rings of Saturn, that applies to disk of gas and dust around the star in which planets can form. It applies to a lot of disk systems.

So basically, the idea is that there are physical and thermodynamical processes in the disk that are going to transport that quantity, angular momentum, and is going to transport that angular momentum from the inner to the outer regions of the disk. Again as I've mentioned, the angular momentum of a closed system has to be conserved but it can be redistributed between different parts of the system.

And so the rate of transport of this angular momentum can be modeled by a parameter that we call the viscosity. And because we have transfer of angular momentum from the inner to the outer region this is actually causing the disk to spread. So that's why we call it "viscous spreading". And this process can bring material beyond the Roche limit, as the disk spreads due to the viscosity, [bringing] material to larger and larger distances.

And even if you have a disk that is initially well confined inside the Roche limit eventually, through this viscous spreading, it's going to be able to bring material beyond the Roche limit. And at that point, the clumps that would

form from gravitational instabilities would be able to survive and form new moonlets at the edge of the disk.

So if you go to the next slide [Slide 25], there is another process that is important when you have objects orbiting a central body. This is what we call resonances. So the orbital period of a body around a central planet increases with distance. So for a given satellite position there are positions inside its orbit where particles would do exactly N orbit while the satellite does P orbits. So you have these N to P ratio in the orbital periods of the bodies that you can see here on the right cartoon that shows the evolution of Titan and Hyperion around Saturn. And so when you have this type of configuration you can have resonances between two satellites orbiting a central body.

But that can also happen when you look at the disk and the satellite because they're going to be positions in the disk where particles would do also exactly N orbit while the satellite does P orbit. This causes a transfer of angular momentum from the disk to the satellite and so the disk loses angular momentum and it contracts and the satellites gains angular momentum and its orbit expands and it moves away.

Man: So this is essentially a transfer of angular momentum outward then, yes?

Julien Salmon: Yes. Basically the viscous spreading is already transferring that angular momentum but it's going to oppose the perturbation from the satellite that is outside and that is causing a transfer of the angular momentum from the disk into the satellite.

Julien Salmon: So if we go to the next slide [Slide 26], I'm going to show you an animation of a typical simulation using that numerical model that we've put together that uses a hybrid modeling for the material inside or outside the Roche limit. This is a disk for which the mass inside the Roche limit - the mass of the disk is about 2 lunar masses - and in the other disk it's about .5 lunar masses. And it's a disk that is extended initially to about 6 Earth radii which is a typical type of disk we obtained from the impact simulations that I've shown you in the first part of this talk.

So if you press Next [Slide 27] you're going to see an animation start and now you can see very, very rapidly the individual particles located initially outside the Roche limit form a once large object into a timescale of less than a year which is what we saw in the particle-like simulation of the previous model.

As these large objects form it can confine the material inside the Roche limit by resonant interaction that I've shown you before. But eventually the disk is viscously spreading back to the Roche limit at which point new small moons can form at the edge of the disk and these small moons are going to be pushed by the disk due to resonant interaction as well, and again then collide with the proto-moon formed in the first phase to continue its accretion.

They can also, by the means of capture into resonances, serve as a transfer of angular momentum from the disk into the distance moon so that the orbit of the moon expands further away.

Yes let's go to the next slide [Slide 28]. So this is just a number of snapshots of that simulation that I've just showed you to better see what's going on over different timescales. So you can see on the third panel that shows the system

after about a year of evolution all the material initially located in the outer disk has accreted to form one large object that we're going to call the proto-moon. And that large object is interacting, with its resonances, with the disk located inside the Roche limit, and as I've said, the inner disk is being confined by that large object.

And you can see that it has contracted significantly inside the Roche limit again represented by the vertical dashed line at about 3 Earth radii. But eventually because this disk has a viscosity it spreads and it brings material back to the Roche limit when new small moons can form and they can then collide with the moon and continue accretion to continue growing the moon.

What we find with this system is that the delivery of material and the timescale for the moon to fully form depends on how efficiently the material inside the Roche limit is delivered. And so it is delivered to the Roche limit to continue the accretion of the moon. And so it depends on how strong the viscosity of the disk is. And because the physical processes that take place into the disk cause the viscosity that is fairly small, the time it takes for a disk to spread to the Roche limit is of the order of 100 years. So the material from the inner disk is progressively delivered through the Roche limit over a timescale of about 100 years.

And so if you go to the next slide [Slide 29], on that graphic what we show is, to the left, the mass of the largest body in the numerical simulation, and, to the right, which corresponds to the dashed line, we have represented the fraction of the mass of the moon that is composed of material originated from the disk located inside the Roche limit.

And so if you press Next you're going to have a couple of annotations come up on the graphic. And so in the first phase that last for about a year you create the material only in the other disk. As you can see the mass fracturing from the inner disk is zero.

Then in the second phase nothing happens. The mass of the moon remains constant. That's because in this initial phase the disk inside the Roche limit has been shoved back inside the Roche limit. And you need to wait over a few tens of years for that disk to spread back to the rush limit and start delivering material to continue the accretion of the moon, which happens in a third phase where you can see the mass of the moon growing only by accumulation of inner disk material, as you see the mass fraction from the inner disk progressively grows. And you can see that we continue accreting material from that inner disk over about 200 years.

So if you go to the next slide.

Man: Question.

Julien Salmon: Yes.

Man: It looks like the Moon achieved close to its final mass at about 100 years. And it looks like it winds up at about 6 Earth radii out which is about one tenth its current distance, correct?

Julien Salmon: Yes. Yes so the Moon finishes its accretion very close to the Earth and then is going to move away progressively due to tidal interaction with the Earth. And

that process is still going on today and is causing the Moon to move away from the Earth at a rate of about 3 centimeters per year.

Okay so if we go to the next slide [Slide 30] we can just do a small schematic of what the resulting Moon structure would be. And if you press Forward you're going to have again a number of cartoons progressively appear. So imagine that, from this accretion process, you accumulate all the material from the outer disk in the first phase and form a proto-moon. And then in your third phase, after the disk has spread back to the Roche limit, you're going to pile up, on top of that outer disk material, all the material from the inner disk.

And so we could imagine that the initial Moon structure would be very heterogeneous, with a core composed of the material from the outer disk, and a mantle composed from the material of the inner disk. A big question, though, is how much mixing you can have between those two layers. We know we're going to have some mixing because all this material is going to be molten. But how much mixing there was, we're not exactly sure.

So this could be an interesting way of explaining the lunar composition, because the material that is likely to be equilibrated is the material from that inner disk that is connected with the Earth through their atmospheres. And it seems to go in the right direction that the samples that we have come from the outer region of the Moon, which are more likely to be sampling that material from the inner disk that may have equilibrated with the Earth. So it's not unlikely that maybe if we had samples from the deep interior of the Moon we could find a chemical composition that is actually different from the Earth.

Man: Question.

Julien Salmon: Yes.

Man: About how deep would we have to go?

Julien Salmon: So in our best case scenario we have run dozens of these simulations, where we vary the initial parameters of the disk, meaning how much mass you have in the inner region or the outer region, how extended the disk is, et cetera. And in our best case scenario, we can form the Moon which contains about 60%, in mass, of material from the inner disk. That's our best case scenario. So 40% of its mass from the outer disk, 60% from the inner disk.

If you do a simple two-layer structure that would put this outer layer at a depth of about 500 kilometers which is where we think that the mare basalt, samples that we have from the Apollo missions, is this is what we think the samples may have formed. So it is possible that the mare basalt samples we have are still sampling that outer layer of material made from the inner disk.

Man: Question.

Julien Salmon: Mm-hm.

Man: Has any lunar seismology been helpful?

Julien Salmon: Yes. So I don't have all the figures in my head but I remember the conference that Maria Zuber, who was involved with the GRAIL mission, seems to see a dichotomy in the gravity field at depths of a few hundred kilometers. That may be, or may be not, could be a signature of that heterogeneous structure.

Man: So that figure of a few hundred kilometers is that consistent with your calculations?

Julien Salmon: Yes.

So if we go to the next slide [Slide 31], the summary of pretty much what I've just told you. I forgot that I had that slide here. So yes. So to sum up we find that with this more accurate modeling of the protolunar disk we find that the Moon forms over a timescale of about 200 years which is compatible with the time necessary for the composition of the disk to equilibrate with that of the Earth.

We find that the Moon forms over a three-step accretion process, with initial formation of the Moon core that accretes fast from outer disk material, for which very little to no equilibration is to be expected, but that the potentially equilibrated Earth-like material from the inner disk would be accreted last.

So again, with the big question of the amount of mixing you would have subsequently between those two layers, the results from the GRAIL mission have suggested that the interior of the Moon was cold. And so, there's some thermal consideration to be looked into here. But if you pile up hot material onto a cold core, maybe you will have only a small amount of mixing and you could preserve Earth-like material on top of the Moon. But that is really a question mark; we don't know very well as of today how much mixing occurred in the interior of the Moon just following its accretion.

And just to go to the last slide [Slide 32], in summary, so we find that a late giant impact on the Earth can form a disk with a low iron content, and that the Moon could form from the disk. We find that the compositional similarities between the Earth and the Moon can be explained with two possibilities: either the impactor was identical to the Earth which can't be ruled out, but it seems probably unlikely, or if the impactor was different but we allow the disk composition to evolve by mixing with the Earth's atmosphere. And we find that the Moon forms over a timescale of about 100 years at about a radius of 6 times the radius of the Earth, after which it progressively evolved away to its current position.

And with that I think that's all I have.

Man: Okay one more question. How much of this very remarkable hypothesis could have been formulated without the Apollo program?

Julien Salmon: I think the giant impact was very interesting from the beginning, that it was explaining the angular momentum of the Earth/Moon system because the Earth still has a fairly decent rotation. So it has - even if you just consider the angular momentum of the Earth/Moon system it's fairly substantial. If you compare it, for instance, to the angular momentum of Venus which is pretty much the same size as the Earth but it has barely any rotation and no satellites, the Earth/Moon system has significantly more angular momentum than Venus. And so having that giant impact delivering that angular momentum to the system is a good way of explaining that high angular momentum. And also it has outcome to be able to form to explain why the Moon has only a small amount of iron in its interior.

Now the question of the composition of the Earth and Moon was actually initially stipulated to be a problem for the giant impact because as I've said the early models of how the Moon forms, showed that the disk is made mostly from the impactor. And so we're like, if the impact forms a disk that is mostly from the impactor and the impactor is different from the Earth then the Moon should be different from the Earth.

So that was really brought up. The Apollo samples actually created a problem for the giant impact theories, and it's that equilibration process that was suggested, I think in 2007, that brought a new possibility, and kind of relieved some of the stress that was put against the giant impact theory.

So in that case we have - it's a case where we have so many constraints on the Moon that we have to come up with extremely sophisticated models to be able to replicate all of these constraint. And we're not yet entirely successful at doing it.

Man: Question. Can you hear us?

Julien Salmon: Yes.

Man: How have we disproven that the giant impact was not one impactor but more than one, two or three?

Julien Salmon: I don't think that's entirely disproven. We find for instance even with one giant impact, there are cases when you look at the accretion of the Moon from how the Moon forms from this disk, there are cases when you don't form one large moon but two maybe half-size moons. And there was a subsequent paper

by Robin Canup and some of the coauthors where they looked at the subsequent evolution of these two sub-moons as they tidally evolve away due to tidal interaction with the Earth, and they found that the two objects generally end up colliding with each other and forming one moon out of the two.

Now if you want to form the Moon from several impacts, I know this is something that is currently being studied and that has not yet been published. So this is something that people are investigating whether you can form the Moon from two subsequent impacts. I remember that something was mentioned about this at a “Origin of the Moon” meeting in London in 2013. I can’t remember who exactly made that comment, but that is likely to cause some problems in the composition of the exterior of the Moon because you would likely add core material on this outer layer of the Moon.

So I think, geochemically, it’s not favorable, but I think we can’t really be definite on this until we actually look at the feasibility of forming the Moon from two impacts. But I think there may be some problems - you may have some problems on what the expected composition of the Moon would be if it resulted from two or three or four large objects eventually merging together over timescales of maybe millions to tens of millions of years.

Jeffrey Nee: All right. Well thank you so much Dr. Salmon. This is so fascinating and it’s a really interesting hypothesis. One more question about the GRAIL mission: what exactly would we need for you to see how much mixing? For example do you really just need a core sample? Do you really need to just drill down there or is there some other way to get that data that you need?

Julien Salmon: So I think seismology would be a great way. I mean, sampling the interior of a large body is very difficult. It's impossible, I mean, with current technology, it's almost science fiction imagining drilling a hole in the Moon like hundreds of kilometers deep to bring back a sample from the deep interior. Maybe, you know, eventually we'll be able to do that, but that doesn't seem possible to be doing in the near future.

So another way of sampling the interior is using seismology. And we already have some data from the Apollo missions, but we now have detectors that are much more sensitive, able to sound the deeper interior much more accurately. So I think if we could put a current generation seismic instrument on top of the Moon, and do some new measurement, we may have some better insight on what the interior of the Moon looks like.

Jeffrey Nee: Great. Any last minute questions? We do want to be as respectful of everybody's time.

Man: What was the current rate of a lunar orbital rise - the speed at which the Moon is pulling away?

Julien Salmon: I think it's 3 centimeters per year. It's fairly small at the moment. It was much faster initially because the tidal effects strongly depends on the distance of the satellite to the planet. So the farther you are, the weaker the effect. So it's slowing down but it's still moving away a little bit. And eventually I don't know where exactly which timescale but probably in millions to hundreds of millions of years the Moon is going to escape the gravitational potential of the Earth.

Man: I've actually heard that it'll actually top out and then start coming back again.

Julien Salmon: How?

Man: That's a very interesting question. It might take some study to determine whether or not the Moon's orbit is actually hyperbolic.

Julien Salmon: Hm.

Man: Yes I didn't hear about it coming back. I just heard about it eventually stopping, come to an equilibrium at some point.

Man: That would be a possibility because if the Earth's rotation slows to the same period as the Moon's orbit then the Moon and the Earth become locked like Pluto and Charon.

Julien Salmon: A geosynchronous state. Yes that's right.

Julien Salmon: It's probably going to get locked at some point, yes.

Man: Yes, yes.

Julien Salmon: Yes that's right.

Jeffrey Nee: Okay. Well I think we won't spend too much longer. Dr. Salmon, any last minute thoughts or...

Woman: I have a question. This is (Adrian), a Solar System Ambassador. I'm wondering if - great presentation - Are there any efforts being made now or thought to apply this model to the other moons in our Solar System?

Julien Salmon: Yes. We're currently investigating, with Robin Canup, if it's possible to form Phobos and Deimos at Mars using the same idea, having a large impact onto Mars, eject material into orbit, and forming an extended disk. And we've done some work that we're hopefully going to put in a paper fairly soon, where we find that we could have that work to form Phobos and Deimos through a similar process.

Now I think that's all the research that's being really conducted at the moment. We think that also some of the satellites of Saturn are accumulated from material from the rings in a similar process. The origin of the rings of Saturn doesn't seem at the moment to be the result of a giant impact onto Saturn. It's more likely disruption by tides of an early satellite that drifted inward due to interaction with the gas that was around Saturn. And as that satellite drifted inward, eventually, it was destroyed by the tides on the planet and formed a massive ring system that we see today.

But, you know, that's something that we could also think about applying to exoplanets. We don't have at the moment any detection of satellites around exoplanets. But with the next generation of instruments that are going to be launched, I think, in the next couple of years we're going to have an even better detection limit and it's possible that first detection of satellites may happen in the next few years. And at that point if we start getting a little bit of constraint on that we can imagine doing the same thing to exoplanets and see if it works.

Woman: Great. Thank you.

Jeffrey Nee: All right. Thank you so much Dr. Salmon.

Julien Salmon: Well thank you for having me.

Jeffrey Nee: Yes it was very, very fascinating, and we're definitely going to have to have you come back when you publish that paper on Mars.

Julien Salmon: Yes. With pleasure.

Jeffrey Nee: All right. Thank you everybody for coming and for listening in. Don't forget our next telecon is on Thursday. And let's see. What is that one about? That one's about the...

Woman: Robotics?

Jeffrey Nee: That's the last one. Oh no, that was the robotics. Right (Kay)? I think that's it. Okay but all that information is on our Web site as usual. Again if you had technical problems with the movies or anything like that please email us and we'll get that squared away for you.

Dr. Salmon, any last second comments?

Julien Salmon: No just I encourage everybody that my email is at the end of the presentation. My phone number too. If you have any questions regarding this don't hesitate to contact me. I'll be happy to answer you.

Woman: Thanks.

Jeffrey Nee: Great. Thank you so much. Thanks everybody and have a wonderful day.

Woman: Thank you.

Julien Salmon: Thank you. Bye bye.

Woman: Bye.

Man: Thank you.

END