Student questions: SESE Exploration Fellow Colloquium

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"Stop hitting yourself! Puncturing the early lunar crust with returning debris"

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Could studying the craters on the moon be the helpful for your research?
Possibly, yes. One of our plans for continuing this work is to look at how the holes that get created 'heal' and whether there might be scars left from some of them that are visible on the Moon today.

How long did the simulation take using iSale for the 10 km diameter impactor?
That particular simulation took about a week. Some of our simulations took up to a month to complete, while others took only a few days, but a week was pretty typical.

In regards to In Hole Morphology what is more common on Earth -Partial or Complete Penetration?
How complex and different is the cooling of the moon compared with Earth's?
Why is there an over abundance of anorthite [on the Moon] compared to on earth?
I'll answer these questions together as the answers are related. Earth and the Moon are both likely to have had deep magma oceans after the Moon-forming impact, but they evolve quite differently.
One reason for this difference is that the chemical compositions of the magma oceans on Earth and on the Moon are slightly different. The material that forms the Moon spends a reasonable amount of time (most estimates are in the range of 1-100 years) spread out as small fragments in orbit around Earth. Just like the surface of Earth these fragments are hot and molten, but because they are small and have low gravity this allowed volatile elements and compounds, those with lower melting and boiling points, like water and sodium to escape. As a result the Moon has significantly less of these volatile elements and this changes the chemistry and influences which minerals form as the magma ocean cools.
Another important reason is simply that the Moon is smaller than Earth. This means that the pressures in the lunar magma ocean are much lower than in the magma ocean on Earth. The minerals that form are dependent on the pressure and temperature in the magma ocean, as well as the chemical composition of the magma and so this is another way in which the magma oceans on Earth and the Moon are different.
Both of these factors mean that the magma ocean on Earth produces much less anorthite than on the Moon so that Earth doesn't build up the same sort of insulating lid of flotation crust that the Moon does. This allows Earth to cool a lot faster than the Moon does.

When the moon had molten lava oceans and a thin crust, were plate tectonics possible?
That is a very interesting question, and one I have not really thought about before! The impacts would create weak spots in the crust though and the magma underneath would be convecting strongly. This might be able to produce something that looks like plate tectonics, but it would be very different to what we are used to on Earth today.

Is there any lunar debris from impact that is in the asteroid belt?
Almost certainly, yes, we just need to find it! (or identify it in our existing meteorite collections)

Is the relationship between the heating/cooling, the kinetic energy of the impacts and the openings for higher heat flux changing to exponential as impact levels change? Is the relationship still present or when did it end?
The relationship between heating and cooling doesn't really change with the impact level, that was one of the really interesting results, that the hole opening efficiency really just depends on the impact energy. The process of opening holes in the crust only applies while there is still a liquid magma ocean present underneath the crust, so that relationship would have ended when the last of the magma ocean solidified.

Based on your first gif of the debris field of the moon in relation to the other planet's orbits (Venus, Earth, and Mars) would this explain why we have lunar meteorites on earth and, if so, how similar are these meteorites to current lunar geology?
The existence of lunar meteorites is a similar phenomenon. A large impact onto the Moon can eject material from the surface and some of that material will eventually land on Earth as lunar meteorites. The rocks will have been subjected to large shocks, both when they were ejected from the Moon and when they landed on Earth, but other than that if we gather a significant number of different lunar meteorites we would expect them to be reasonably representative of lunar geology.

Based on the Hole Morphology, are impact craters this complex on all bodies (planets, moons, etc.), or more unique to the moon?
Impact craters have a lot of similarities across different bodies but there are some differences that depend on the surface gravity of the body being impacted, and on what materials the surface is made out of. The end result is that craters on the Moon look similar to craters on Mars for example, but not exactly the same.

I am an undergrad, and I am still getting to where I can begin to understand higher level topics like this. My question could be considered pretty low level, but what I am curious about is how trustworthy of a comparison is ice and water versus rock and magma, and how do we assume that the relationships would be similar?
That is a very important question. The main things we want to think about in comparing ice and water with rock and magma are the density, how strong the materials are, and viscosity (how runny the liquid is). Ice and water are about a factor of three less dense than rock and magma, so that is an important difference to consider. At the temperatures we are used to ice is quite a lot weaker than rock, but at the much colder temperatures in the outer Solar system in places like Europa and Enceladus ice is much tougher, more like how we are used to rocks behaving. We still need to think about that, but the difference is probably not as large as we are used to thinking about for ice and rock on Earth. The viscosity of the magma in the lunar magma ocean is actually expected to be quite similar to water, so that last one we probably don't need to worry about too much. Another important point is that in both cases you have a solid layer floating on a liquid layer. So there are differences, but there are similarities too.

Would waves form on the lunar magma ocean, and what effect would this have on the resulting modeling of heat transfer?
Ripples certainly form in the magma ocean after a penetrating impact, and these ripples do indeed play a role in the transfer of energy away from the impact site out into the magma ocean. Just like water in a pan, the magma is also convecting, and this is the biggest factor in determining heat transport in the magma ocean.

Has anyone done the same type of, or more advanced impact simulations for present day earth?
Yes, there has indeed been a lot of work simulating impacts onto Earth in the present day, or the relatively recent past. The impact that we believe resulted in the extinction of the dinosaurs, at Chicxulub in Mexico, is one such impact that has had a lot of modelling work devoted to it.

Does way the object and surface react change based on the material of the impactor and the impacted?
Yes, we expect some differences, but the similar behaviour of ice and water experiments compared to rock and magma simulations suggests that the outcome is not very sensitive to the materials of the impactor or impacted surface.

When was the last time the Moon had liquid magma still underneath its surface?
The date at which the last remains of the magma ocean solidified is somewhat debated, but it is somewhere between 50 and 200 million years after the formation of the Moon, about 4.3-4.4 billion years ago. Small pockets of liquid magma did still re-appear later on however, associated with volcanic activity, up to about 3 billion years ago.

What is the degree of mixing between the layers from a penetrating impact?
There is a reasonable amount of mixing. Something that we see quite a lot is that some of the crust from where the hole is created gets pushed down into the magma ocean where it would be melted and mixed back into the magma.

Could new minerals be generated from a penetrating impact?
Possibly. Something that we would like to investigate is how the introduction of material from the impactors into the magma ocean might alter the composition of the magma and adjust the mix of minerals that forms as it solidifies.

With increased interest in targeting space debris(like asteroids) for mining operations, where do those processes begin, i.e., do we look for mining practical sources at impact locations on planets and their satellites or the asteroids themselves?
Generally the impactor is broken up and dispersed over a fairly large area during an impact event. When Daniel Barringer first bought meteor crater he did so because he thought that if he dug down in the centre of the crater he would find the iron meteorite that had created it. Although some fragments have been found they amount to much less than the original mass of the meteor. So looking for the impactor is not likely to be useful. However, impact craters can excavate through a large amount of rock, so they could be useful mining locations if what you are looking for is normally buried a long way under the surface.

Will the Earth ever fully be engulfed by debris?
As time goes on the sources of impactors in the Solar system, like the asteroid belt and Kuiper belt, are slowly being depleted. Impact rates are much lower today than they were in the early Solar system. Very dramatic events like I was discussing really only took place in the very early history of the Solar system.

What was the debris made of during the Earth Mars collision?
The debris was made of a mixture of pieces of the proto-Earth and the Mars-sized impactor.

How thick was the flotation crust on the moon to cause its cooling rate to drop?
The flotation crust eventually becomes the crust of the Moon that we see today, which is about 50 km thick on average. That is the thickness that it reaches when the last of the magma ocean has solidified.

How large would an impactor have to have been in order to penetrate all the way through the Moon's anorthosite crust, and, assuming that the size of potential impactors followed some normal-like distribution, would there have been enough sufficiently large impacts to affect the cooling of the LMO to a significant degree?
How large the impactor needs to be to penetrate the crust depends how thick the crust is and how fast the impactor is moving. The crust starts off very thin, but by the time most of the magma ocean has solidified is nearly 50 km thick, so the size of impactor required to penetrate also changes quite a lot. A 10 km diameter impactor can penetrate 10 km thick crust even if it hits very slowly, but an impactor that is only 2 km across can penetrate if it hits quite fast. What matters is the kinetic energy, the 10 km impactor and the 2 km impactor can have the same energy if the smaller impactor moves faster. As I showed in my talk, early on the accretion rate is high enough that it is equivalent to a 10 km impactor hitting every year, so we can confidently expect this to be an important effect.

What benefits do you believe being an Exploration Fellow brings you?
There is nowhere else quite like SESE in terms of the mix people with different skills present in the same department. The work that I do really benefits from having that diversity of people to discuss ideas and work with.

Looking over your research, I was wondering why you think certain planet classes dominate in extrasolar systems?
That is a very good question and one many people, including myself, are spending a lot of time working on. There is no definitive answer yet, but there are a number of ideas

Are the graphs you showed only specific to the moon or they can be applied to other celestial bodies?
In what I showed I was referring everything to the Moon, but most of it also applies to other celestial bodies, albeit that there might be some differences, because for example other bodies have different surface gravity.

In my astrobiology classes, we have discussed different methods to investigate icy worlds like Enceladus. With current technology it seems near impossible to breach the kilometers of ice, do you see that your impact crater on-ice research could be applied in engineering techniques to assist in breaking the ice?
One of the most important things to know when designing a mission to go down through the ice on somewhere like Europa or Enceladus is how thick the ice shell is. Investigating impacts is an important tool for examing how thick the ice shell is.

With your model of the thin cap surface and the magma ocean, what do you think some of the larger bolides that created some of the massive craters on the moon would have done to such a fragile and molten surface?
There are quite a few craters on the surface of the Moon today that were created by impactors that would have been easily large enough to penetrate the crust during that early stage when the Moon still had a magma ocean. These craters formed after the magma ocean had completely solidified them otherwise the impact would have produced a hole, not a crater, but the existence of those large craters does tell us about the sizes of impactors that existed in the early Solar system.

Do you expect icy bodies like Europa or Ganymede to cool more quickly than the moon? What implications might that have for the development of complex chemistry?
Generally we expect smaller bodies to cool faster because the mass that contains the heat being lost shrinks faster than the surface area that the heat is being lost through. Ganymede is larger than the Moon, while Europa is smaller, so we would expect Europa to cool faster. However, the situation is complicated for Europa and Ganymede, as well as Io, because of the special resonance that exists between the orbits of the three moons. This resonance (for every 1 orbit of Ganymede, Europa orbits twice and Io four times), means that all three experience a lot of internal heating due to tides. The amount of tidal heating decreases as you move away from Jupiter, so that Io, the closest, is the most volanically active body in the Solar system, Europa, the middle one, has a thin ice shell and a relatively fresh, smooth surface with few craters, and Ganymede, the most distant, has a thicker ice shell with many more craters.