Student questions: Rebecca Fischer colloquium on “Core Formation on Earth and Mars”

1/20/21

Rebecca’s presentation mentions that there were two conditions of core formation from the Hf-W system namely, Re-equilibration (k ~ 1) and Core merging (k ~ 0). Do you know if there are considerations of other forms of Core merging where we have multiple impactors and a single target?
Complete re-equilibration ($k = 1$) and complete core merging ($k = 0$) are two endmembers; the actual extent of metal equilibration k was probably somewhere in between. It almost certainly varied from impact to impact, depending on things like the size of the impactor and the impact angle and velocity. For multiple impactors on a single target, there was probably a range of different k. In these types of models, at least thus far, we generally use one value of k for all impacts, because we don’t have a great understanding of exactly how it should vary. This can be thought of as some effective average value of k over a planet’s entire accretion history, but it is simplification.

If there are other possible considerations as such could we have a possibly different end member different from the established two-endmembers, with much more mantle.
I mostly discussed different extents of metal equilibration, but there can also be different extents of silicate equilibration. These two parameters trade off with each other. As with metal equilibration, the extent of silicate equilibration likely varied from impact to impact, but is simplified as a constant because it is poorly constrained.

Why study elements like Mg, Nb, Cr, Ta, and V?
In general, we run our core formation models for a wide range of different conditions, and look to see which do the best job of reproducing the (upper) mantle’s composition, which lets us put constraints on the conditions of core formation. This can be done with any elements – having more elements gives us more constraints. In general, we might prioritize including elements that meet these criteria: 1) Their abundance in the mantle (and in the meteorites we think best represent the bulk Earth composition) is well known; 2) Their metal–silicate partitioning behavior is well known, from experiments over a wide range of pressures and temperatures; and 3) Often, they are relevant to some important question in geochemistry. For these elements: Mg has been proposed to dissolve into the core during core formation, then exsolve, helping to drive the geodynamo; the Earth’s Nb/Ta ratio seems to be different from meteorites and we aren’t sure why, so we want to know how much of these elements could be hiding in the core; and the behaviors of V and Cr are thought to be particularly sensitive to changes in redox conditions, so they may provide better constraints than other elements on the early Earth’s redox.

Is the study of the Mars core based on anything from the Mars rovers or just from the meteorites?
Mostly meteorites, but the new rover that is part of the Mars 2020 mission is going to be drilling rock cores and leaving them for a future mission to pick up. Returned samples like that could be really helpful in better constraining the Martian mantle composition.

Why is nickel the second most common element in the earth's core?
Nickel is a fairly abundant element in the Solar System in general (it is very common in iron meteorites, for example), and almost all of the Earth's nickel is concentrated in the core.

I found the "non uniqueness" of the N body simulation outputting Earth's actual composition interesting. What could be done to parse out which configuration of CMB depth and k coefficient is "more likely to be correct" (or to show that one or another is definitely not possible")?
In part this is what led us to incorporate the Hf–W isotopes, which provide a better constraint than major/minor/trace elements alone. We are working on incorporating other isotopic systems with different behaviors that we hope will provide additional constraints. There are a bunch of other types of approaches that can get at these questions from different directions; for example, there are some really cool fluid dynamics experiments being done to constrain the extent of metal/silicate mixing (e.g., Deguen et al., 2011, 2014), and simulations of individual impacts to look at the extent and geometry of melting (e.g., Nakajima et al., 2020).

Does the difference of mass/volume between Earth and Mars have any bearing on the core mantle boundary? I thought it was interesting that they are so different, but the simulation yielded a similar CMB percentage (0.55-0.7?).
The difference in size means that Earth and Mars have very different core–mantle boundary pressures (and temperatures). Our results suggest that metal–silicate equilibration occurred as a similar *fractional* depth to the CMB on both planets, which might mean that they experienced similar fractions of mantle melting, but the *absolute* pressures are quite different.

If you are only comparing Earth and Mars Core structures and find similarities between those 2 planets. Can you more or less assume that other Terrestrial plant cores are also made similarly?
That is sort of a philosophical question. One can fit a line to two data points, but that doesn't mean it is a good idea. When we find similarities between Earth and Mars, I would say that it is *possible* that this could be true of all other terrestrial planets, and that might be an assumption to make as a starting point in the absence of any other information, but really we need more data before we can say that (returned samples from Mercury and Venus would be great!).

In your models of core formation you said it was important to match mantle conditions and compositions. Is it also important to match crust conditions and compositions?
Our models don't include the formation of the crust, only the separation between metal and silicate. Crust formation probably happened later in Earth's history

Are there planets that are layered with non-metallic cores?
In the inner Solar System, the terrestrial planets all have metallic cores (and my impression is that this seems to be true of most terrestrial exoplanets too). In the outer Solar System, conditions were more oxidized, so you might form differentiated bodies without metallic cores.

Why is there so much sulfur in Mars' core?
In general, there are higher abundances of more volatile elements (like S) farther away from the Sun. When the Solar System was forming, and solid material was condensing out of the nebular gas, there was a temperature gradient, with higher temperatures closer to the Sun. Volatile elements could mostly only condense farther from the Sun, where it was colder; closer to the Sun, they mostly stayed in the gas. Then that gas was lost from the Solar System before it fully condensed, which left this gradient in volatiles.

If Earth's components were oxidized like Mars' were at formation, how would that change Earth's core formation?
It would change the abundances of almost every element in the mantle and core. For example, the core would have more O and less Si. The mantle would have more Fe, Ni, Co. The core would also be smaller, and the mantle bigger.

You mentioned the use of 182 Tungsten to be able to tell when the core forms. What is the significance of knowing when the core formed?
Since core formation was happening at the same time at planet formation, it tells us how long planets took to form. It also tells us about the timing of Moon formation, since the Moon-forming impact probably happened at the end of Earth's growth.

Concerning the background information presented about Eath's trace elements, what is the basis for the discussion on whether to include H or not as part of the group of volatiles present in small quantities (C and S for instance) in the Earth's core?
There is a lot of disagreement over H's behavior at high pressures and temperatures, in particular in terms of its relative preference for being in the silicate versus metal. This is due to a wide range of experimental and analytical difficulties with H. For example, it is hard to study H in a diamond anvil cell, because it tends to diffuse into the diamonds and cause them to shatter, ending the experiment. It is also really hard to measure the abundance of H in a sample, especially with the really small samples we have to work with at high pressures; many techniques we normally use to measure composition don't work well on H due to its low mass.

She mentions that some of her research could be off depending on a measurement (sorry i forgot the specific name she mentioned) so how does her work get adjusted if that measurement is wrong, and how does the measurement get confirmed so she knows her research is correct?
I think this is referred to the fact that some of our constraints on Martian core formation come from S, and those numbers would be off if we are wrong about the degree of volatile depletion in bulk Mars. If that turns out to be the case, we would need to re-run our models with a different starting composition for the building blocks of Mars, and look to see if/how much that changes our findings about the conditions of Martian core formation. Better understanding of volatile depletion on Mars may come from new analyses of Martian meteorites, but would also likely benefit a lot from analyses of returned samples from Mars in the future.

Both you and Dr. Sharp mentioned that there are theories that Mars differentiated pretty quickly. I'm curious to hear more about this. Could you elaborate on it or point us towards a paper on the subject?
This is largely based on Hf–W isotopes and other isotopic systems that can used as chronometers of core formation. For example, see Dauphas and Pourmand (2011), Nature. But this also makes some intuitive sense: the Earth was built in part from Mars-sized bodies, so Mars-sized bodies must have formed first.

For the model of 100 bodies colliding into each other and forming planets similar to Earth, do the colors simply indicate the distance from the sun, or do they also indicate the composition of each?
They indicate initial distance from the Sun, but this is thought to be a proxy for composition, especially in terms of the abundances of volatiles like S, C, and water.

What is a focused ion beam and how does it work?
A focused ion beam (FIB) is a fancy instrument that is used for machining on the ~micron scale. It is usually part of a scanning electron microscope (SEM), which is used to view samples that are that small. It also usually has a micro-manipulator attached, so you can move around the samples. The FIB bombards the samples with a beam of gallium ions, which ablate away the sample material. We use the FIB to cut out slices in cross section through our tiny samples, so that we can perform chemical analyses on them.

What aspects of your research regarding core and mantle composition have been applied to the other terrestrial planets (Mercury and Venus)?
We haven't done much with Mercury or Venus yet simply because we don't know nearly as much about their compositions, but we are actively looking into ways to explore that.

Is there an estimate for the amount of Tungsten present in Earth's Core?
There is some disagreement over that number, because it depends on the amount of W in the mantle and in the bulk Earth, both of which are somewhat uncertain. McDonough (2003), Treatise on Geochemistry, puts it at 0.47 ppm, for example.

How do Diamond Anvil Cells function?
They consist of two halves, a piston and a cylinder. We mount a diamond on each half. These are high quality single crystal diamonds, similar to those used in jewelry, but a bit smaller (about a quarter of a carat each) and instead of coming to a point on the back, the tip is polished off to make a small surface, usually a few hundred microns across, called a culet. The culets of the two diamonds are carefully aligned with each other (if they aren't well-aligned, they can break at high pressures). Between the culets, we put a gasket, which is a piece of metal (usually steel of Re) with a tiny hole drilled in the center (on the order of 100 μm across) for the sample. We put the gasket on one diamond, and carefully load our sample into the gasket hole, by hand, under a microscope. For high temperature experiments, we have to put some insulating material between the sample and the diamonds. We also often have to include some material that serves as a pressure standard, so we can determine the pressure. When the sample is loaded, we close the cell, putting the piston into the cylinder. There are four screws that pull the piston and cylinder together, which we turn by hand. We can reach such high pressures (pressures of Earth's core,

several million atmospheres) with these modest forces because pressure = force/area, and our area (the culet) is really small. The diamond cell is small enough to fit in the palm of your hand, portable, and can hold the sample at these pressures indefinitely. Since the diamonds are transparent, we can also shine lasers through them, to heat up the sample or for spectroscopy.

If Earth's core ended up being comprised of only iron, how would that affect the magnetic field?
It is thought that about half of the energy that goes into driving the dynamo today comes from the light elements impurities in the core (with the other half being thermal convection): as the inner core crystallizes, they are preferentially excluded, and rise buoyantly in the outer core, contributing to convection. If the core were pure iron, that energy source would be missing, making it harder to drive a dynamo. But, there is a lot of evidence that the Earth has a magnetic field before it had an inner core, though that may have been related to these kinds of impurities as well.

You mentioned that even though there is a very small weight percent of carbon in the Earth's core that it represents a large percentage of the total carbon on/in the Earth and that this has interesting implications. What are those implications?
One application is in understanding what the Earth is made of, and when and from where it got its carbon. Different types of meteorites have different volatile element ratios (like C/S, C/H, and C/N). If we understand what these ratios are for the bulk Earth, we can use them as a sort of fingerprint to assess what meteorite type(s) are the best match to Earth’s building blocks, and this depends strongly on how much of these elements are in the core. Also, understanding the core abundances of these elements helps us understand whether the amounts we see in the mantle can be explained solely through core formation (we found that they can for C) or whether they must have been accreted later, such as in the late veneer (which can’t be ruled out at this stage, but is not strictly required for C).

How did you determine the main factors, like the equilibrium factor(k) and formation timing, to consider when creating your models?
We don’t have a good understanding of the real value of *k*, so we varied it over the full range of possible values (0.05–1) to see which gave us the best match to the Earth’s mantle composition. The formation timescales are not a parameter that we set, they come from the *N*-body simulations of planetary accretion. It is important to note though that different accretion scenarios (which differ primarily in terms of the orbits and migration of Jupiter and Saturn, as well as whether the terrestrial planets accreted from planetesimals and planetary embryos or from pebbles) produce rather different timescales for terrestrial planet growth. We have been exploring this by testing a variety of different accretion scenarios, though we haven’t tried pebble accretion yet (which forms planets really fast).

What is pebble accretion and how many planets do you suppose have been formed by this?
Pebble accretion is the idea that planets in the inner and outer Solar System may have formed mostly from the accretion of cm- to m-sized objects called “pebbles”, as opposed to planetesimals (10s–100s of km) and planetary embryos (Moon- to Mars-sized) as conventionally thought. See, for example, Levison et al. (2015), Nature, and Levison et al. (2015), PNAS. It is difficult to know how many planets formed this way; it is one of several competing hypotheses.

Was there a particular situation or result that first started you on exploring the earths and mars core and what was it?
I got my start doing measurements of phase relations and densities of iron-rich alloys to compare to seismic data on Earth’s core, motivated by the observation that the core is less dense than pure iron. In that work, we were able to put some upper bounds on the amounts of Si and O in Earth’s core, but not actual estimates. This led me to start thinking about core formation, to try to understand how the Si and O could have gotten into the core in the first place as a different type of approach. I started working on Mars when I learned about NASA’s InSight mission, which is currently operating a seismometer on Mars that we hope will tell us something about its core.