Student questions: SESE Graduate Students Colloquium

3/3/21

John Morgan Christoph: "Space Weathering on Metallic Asteroids: Insights from Laboratory Experiments"

Why is sulfur preferentially depleted by space weathering, and do any other important trace elements do the same?
This is an excellent question, and indeed my coauthors and I devote a large section of our upcoming paper on this project answering it in as much detail as we can. A short answer is that in any ion irradiation, atoms which are lighter, have lower surface binding energy, have higher diffusion coefficients, or are more abundant on the surface will preferentially be removed. In a planetary science context, this means oxygen is also often preferentially removed from silicate minerals on surfaces such as the Moon.

What are the primary "other ions" in the solar wind aside from the big two (H+ and He+)?
The trace ions in solar wind are generally the same as those found in the solar corona: C, N, O, Mg, Si, Fe, etc. These are the same elements in approximately the same ratios that we refer to as a "chondritic" composition, i.e. the relative abundances of elements in the protoplanetary disk from which the Sun, planets, and other objects in the Solar System accreted.

Many times simulations were mentioned, what was used to run these simulations?
The simulations I mentioned used a piece of software called SDTrimSP, which kinematically simulates the collisions between ions and the atomic structure of an irradiated surface. In terms of hardware, we ran these simulations on a supercomputer cluster at the University of Virginia, and if you're interested in additional details I'm happy to put you in touch with my collaborators there.

Where can we learn more about the Psyche mission, its goals and progress, and such?
So many places! If you haven't heard anything about it, ASU and JPL both maintain websites for the mission which post regular updates (psyche.asu.edu) (jpl.nasa.gov/missions/psyche). For more technical detail, I recommend starting with the following paper published by our mission team: Elkins-Tanton, L.T. et al. (2020) Observations, Meteorites, and Models: A Preflight Assessment of the Composition and Formation of (16) Psyche, *Journal of Geophysical Research: Planets 125*, e2019JE006296. https://doi.org/10.1029/2019JE006296

What are the implications of the altering of the microstructure of metals due to space weathering in terms of the Psyche/the Psyche mission?
The microstructural aspects of space weathering are important in their own right because they provide evidence that can help us determine which specific mechanisms are responsible for different aspects of the weathering process. In terms of the Psyche mission, the microstructural changes we observe in weathered sulfides are relevant because they may also occur in metals like kamacite and taenite. If the changes we see in reflectance spectra of space-weathered materials are in part due to the altered microstructure as well as the altered surface composition, then there's a possibility that a weathered metal surface on Psyche might not have identical spectra to un-weathered surfaces of iron meteorites measured in the lab.

Can you explain how ground-based data tells us that Psyche is metallic?
There are several lines of evidence suggesting Psyche has a metallic composition: high reflectivity to radar, low reflectivity and few absorption features in visible to near-infrared light, and a relatively high bulk density as measured by how its gravity purturbs the orbits of asteroids that pass it within a few hundred thousand km. The full details can be found in this paper by our mission team, which revies the current state of observations of Psyche: Elkins-Tanton, L.T. et al. (2020) Observations, Meteorites, and Models: A Preflight Assessment of the Composition and Formation of (16) Psyche, *Journal of Geophysical Research: Planets 125*, e2019JE006296. https://doi.org/10.1029/2019JE006296

Does the solar wind affect Troilite at the molecular level in a way that it changes its crystal structure?
Fantastic question! Short answer: yes, in **many** different ways. Longer answer: one of the things many researchers have found independently is that in the region that solar wind ions can penetrate, the troilite can become amorphous as it loses its sulfur. There are some amazing transmission electron microscopy images showing this layer in troilite grains returned from asteroid Itokawa in one of the papers I cited in my talk: Matsumoto, T. et al. (2020) Iron whiskers on asteroid Itokawa indicate sulfide destruction by space weathering, *Nature Communications* https://doi.org/10.1038/s41467-020-14758-3

How do weathered asteroids affect the possibility of damaging the equipment that is being used
The space weathering processes that I'm studying occur over long enough time scales (thousands of years) that they likely will not damage any of the instruments used by the Psyche mission. That said, there are more energetic types of radiation, like cosmic rays, which *can* damage spacecraft instruments. The team at the Johns Hopkins Applied Physics Lab building the Gamma Ray and Neutron Spectrometer for the Psyche Mission has been particularly focused on that problem, since their instrument is specifically going to be measuring how those more energetic types of radiation modify Psyche's surface. If you'd like to know more, they've published several good papers and conference abstracts discussing it in more detail.

Are planets and moons also effected by space weathering?
Yes! A variety of space weathering mechanisms have been invoked to explain the abundance of alkali metals on Mercury, Europa's oxygen ionosphere, and the loss of Mars's atmosphere over time. In fact, the exact process of solar wind ion irradiation was first proposed way back in the 1950s to explain why older surfaces on the Moon appeared darker than younger ones: Gold, T. (1955) The lunar surface, Royal Astronomical Society v. 115, p. 585-604

Is it possible for the data in the figure of Intensity and Binding energy to be represented in some sort of phase diagram to represent the differing compositions?
So the plot of X-ray count vs. binding energy is a spectrum plot rather than a phase diagram. That said, you maybe could use the information contained within the multiplet peaks in the spectrum to plot the compositions of the various layers on something like a ternary phase diagram, and maybe even include a set of vectors to show how that composition changes over the course of the irradiation, similar to how magma cooling is shown in igneous petroloy. The main reason we haven't made such a phase diagram is that apart from the chemical composition, we don't actually know what "phase" the weathered material in our own experiments is, i.e. whether it's a continuous amorphous layer or a mixture of discreet particles. To find out, we'll need to do some additional microscopy.

What do you think is causing the nanoparticles to form?
At the most basic level, as sulfur atoms are removed, the iron atoms that had been bonded to them are chemically reduced from the +2 oxidation state to the +0 oxidation state. In an idealized model, these reduced iron atoms are distributed more-or-less uniformly throughout the altered region. However, because the troilite has a non-zero temperature, those reduced iron atoms are able to diffuse through the crystal lattice until they come into contact with each other; at which point it's energetically preferable for them to form metallic bonds with one another. As more and more of these reduced iron atoms come togeher, they form nanoparticles. Based on my own work and that done by other researchers, we currently think that adding more heat to increase the diffusion rate is necessary to grow these particles from nanometer-scale to micrometer-scale, like we've obesrved in returned samples.

Could the amount of weathering on an asteroid affect and create difficult environments for devices and equipment brought to the asteroid?
The weathering itself won't affect the operation of any of the instruments on the Pysche mission. What it could affect is what those instruments measure. If there's a body of troilite on Psyche's surface, we may observe a different spectrum with our visible and near-infrared filters on the Imaging System, or if the weathering is extensive enough we may observe a different sulfur abundance with the gamma ray & neutron spectrometer.

How do the iron atoms find themselves bonding with one vs two sulfurs?
I may have stated this too simply in the presentation. All of the iron and sulfur atoms in the troilite are bonded to each other in a repeated crystal structure, so every iron atom will actually be bound to more than 1 or 2 sulfur atoms, even though there's a 1:1 sulfur-to-iron ratio in the unmodified bulk troilite. What the Fe(IV) peak in the XPS spectrum is really showing is iron atoms which have hybridized electron orbitals with twice as many electrons as the Fe(II) ions in the normal troilite structure. This most likely occurs at the interface between the surface oxide layer and the bulk troilite, or as a result of incident ions partially amorphizing the troilite crystal structure.

Why does the adding of helium change the picture/structure?
Hydrogen and helium ions interact differently with the surfaces of planetary bodies. Firstly, they have different atomic masses, which means they'll penetrate the surface to different depths and thus alter different regions. Secondly, they produce different sputtering yields when they collide with the surface, which means that they'll remove atoms at different rates. Finally, the hydrogen ions are in a different oxidation state than the helium ions, which makes hydrogen slightly better at chemically reducing the surfaces, though that's less relevant for sulfides like troilite than it is for forming hydroxyl within the structure of oxygen-bearing minerals like silicates on the Moon. The reason we specifically used both ions in our experiments is that a lot of previous experiments have only simulated helium ion irradiation, and assumed hydrogen ion irradiation would be similar; we found that to not necessarily be the case.

Does the solar wind weathering that leads to sulfur depletion and darkening/reddening of Troilite operate in a similar way to the processes that produce 'desert varnish' weathering on rocks here on Earth?
Short answer: not really. Longer answer: If what I remember from my undergraduate field courses is still true, the exact mechanism that produces desert varnish is still uncertain, and that's also the case for our current state of knowledge of space weathering. In terms of the results, to the extent that desert varnish has any commonality with space weathering, it's that they both involve chemical and physical change on the surface layer of the exposed material. Beyond that, they're very different processes, most especially in that space weathering tends to chemically reduce surfaces, while desert varnish tends to oxidize them.