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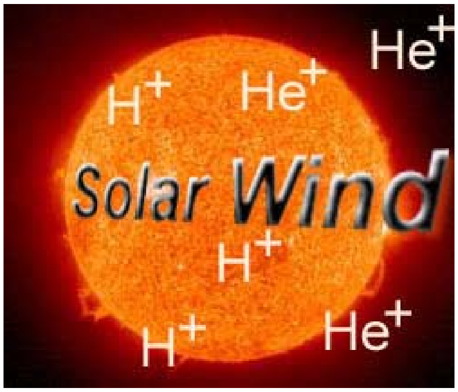

Hot Idea August 10, 2009

Space Weathering Agent: Solar Wind

--- Bombardment of helium ions on olivine in the laboratory simulates space weathering of asteroids and other airless bodies.

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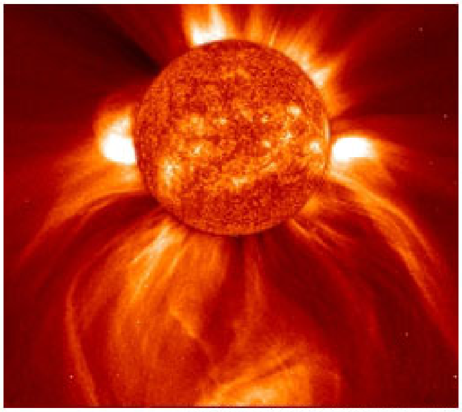
In the vacuum of space, the interactions of energetic particles with the surfaces of airless planetary bodies cause radiation damage, chemical changes, optical changes, erosional sputtering and heat. This is an essential part of the process called space weathering. A group at the Laboratory for Atomic and Surface Physics at the University of Virginia specialize in experiments, among other things, where they bombard surfaces with charged particles to see what happens. Recent work by Mark Loeffler, Cathy Dukes, and Raúl Baragiola focused on what happens to olivine mineral grains when they are irradiated by helium ions to better understand the effects of solar wind on the surface composition and, therefore, appearance of asteroids. Their experiments were the first to measure chemical and reflectance changes in olivine before and after irradiation while still under vacuum conditions. The resulting changes in the reflectance spectra of olivine slabs and powders are directly correlated with the formation of metallic iron in the very outer surface of the mineral grains.

Reference:

- Loeffler, M. J., Dukes, C. A., and Baragiola, R. A. (2009) Irradiation of Olivine by 4 keV He^+: Simulation of Space Weathering by the Solar Wind. *Journal of Geophysical Research*, v. 114(E03003), doi:10.1029/2008JE003249,2009.

Sun's Coronal Mass Ejection



SOHO/LASCO (ESA & NASA)

Solar Wind (Everywhere All the Time)

Our star, the Sun, our source of sunlight, is a hot ball of gas made mostly of hydrogen. The Sun's gas is so hot that most of it is really a fourth state of matter called plasma. Streams of plasma --charged particles--ejected in all directions from the hot outer atmosphere (corona) of the Sun are known collectively as the solar wind. The composition of the solar wind is approximately 95% ionized hydrogen, 4% helium, and 1% minor ions, which are mostly carbon, nitrogen, oxygen, neon, magnesium, silicon and iron. The solar wind is always flowing throughout our Solar System, blowing comet tails away from the Sun's direction, shaping the magnetic fields around the planets (including Earth's), disrupting human satellite communications and electrical power systems, and bombarding all surfaces that lack protective magnetic fields or atmospheres. It's the last point that we'll delve into here. Solar wind bombardment causes critical changes in the chemistry and optical properties of the surfaces of airless planetary bodies through irradiation, ion implantation, and sputtering. Solar wind is a dominant space weathering agent.

This image composite shows a spreading coronal mass ejection, blasting clouds of hot plasma from the Sun's corona. Click for more information. Image was taken by the SOHO LASCO and EIT instruments in 2002, courtesy of SOHO/LASCO/EIT consortia. SOHO is a project of international cooperation between ESA and NASA. LASCO is the Large Angle and Spectrometric Coronagraph, EIT is the

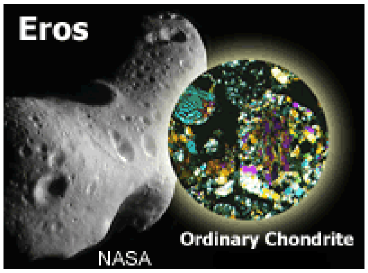
Extreme Ultraviolet Imaging Telescope, two of 12 instruments on-board SOHO.

Why Things Don't Always Look Like We Thought They Would

The way light reflects off the minerals in a rock depends on grain size, temperature, sun angle, and the extent of space weathering. The most important space weathering agents affecting airless planetary bodies are solar wind hydrogen and helium ions, along with micrometeorites. This concept began in the early 1970s when cosmochemists had their first opportunities to see the effects of space weathering on the lunar rock and regolith samples returned by the Apollo astronauts. Through the pioneering work of Bruce Hapke (Emeritis Professor at University of Pittsburgh) and others we learned a lot about what happens to the materials on the Moon's surface exposed to the solar wind and micrometeorite impacts (see **PSRD** article: New Mineral Proves an Old Idea about Space Weathering): chemical alterations caused by broken molecular bonds, synthesis of new molecules, changes in elemental compositions caused by ion implantation and preferential sputtering, creation of vapor during impact bombardment and the subsequent deposition of glassy, iron-bearing patinas and iron-bearing condensates. In addition, micrometeorite bombardment mixes the regolith by bringing subsurface particles up to the surface and changes the particle size distribution by breaking them into smaller pieces or by creating glassy agglutinates through shock-induced melting and rebonding. These things cause changes in the optical properties of surface materials in the visible and near infrared wavelengths, and complicate any interpretations we try to make about their original properties.

Implications for Asteroids

Scientists are especially interested in applying what they know about space weathering to asteroids. The ongoing research to understand the processes and timescales of space weathering on asteroids will lead to better interpretations of their reflectance spectra obtained remotely. Though these days the phrase "remote" is moving closer to the target as Earth-based telescopic spectra are enhanced by satellite fly-bys and touchdowns. A robotic spacecraft is even making its way back to Earth right now with samples collected from a near-Earth asteroid (see below).



S-type asteroid 951 Gaspra, orbits the Sun near the inner edge of the main asteroid belt. Earth-based telescopic spectra first showed it to be olivine-rich. This was confirmed by near-infrared reflectance spectra obtained during a flyby in 1991 by NASA's Galileo spacecraft as it passed through the main belt on the way to Jupiter.

The Near Earth Asteroid Rendezvous (NEAR) mission to asteroid 433 Eros, launched by NASA in February 1996, gave scientists the first opportunity to study in detail the effects of space weathering on the surface of an airless body near Earth other than the Moon. The mission included a soft landing of the NEAR- Shoemaker spacecraft and helped to document the heavily-modified surface of Eros. Studies using the spacecraft's X-ray spectrometer (XRS) and MultiSpectral Imager (MSI) show that this S-type asteroid experienced minimal heating and has major-element composition and mineralogy similar to ordinary chondrite meteorites with the exception of a low abundance of sulfur, attributed to space weathering.

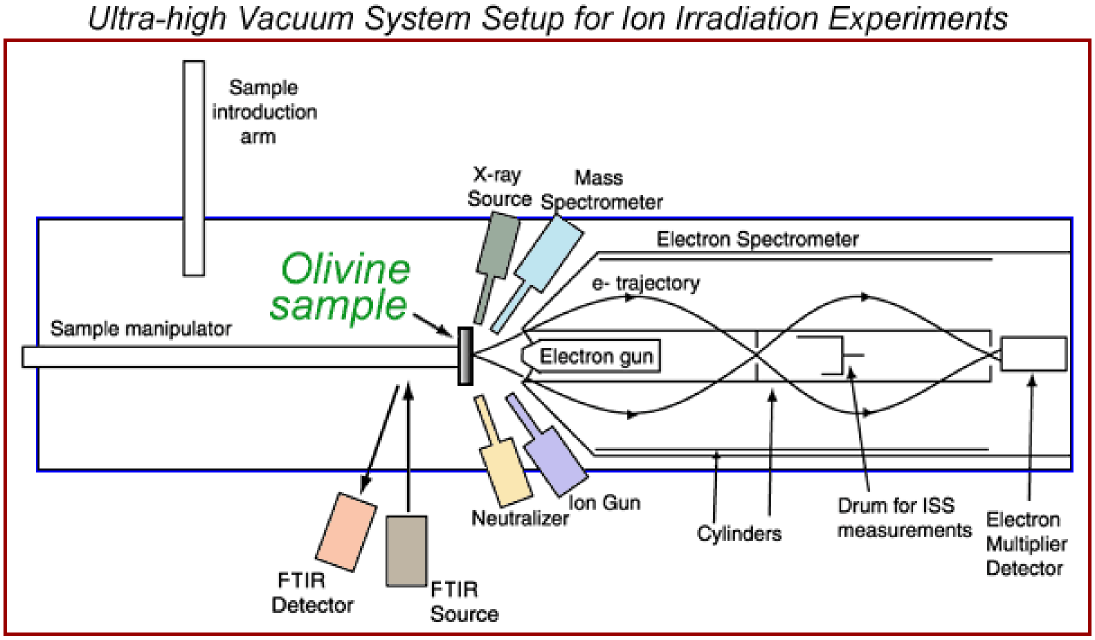
The Hayabusa spacecraft, launched in 2003 by the Japan Aerospace Exploration Agency, landed successfully on near-Earth, S-type asteroid, 25143 Itokawa in 2005. In 2007 Hayabusa began the journey back with its cargo of regolith samples for a return to Earth in June, 2010.

Asteroid 2867 Steins in the main belt was imaged in September, 2008 during the closest approach of the European Space Agency's Rosetta spacecraft. This E-type asteroid was the first target of Rosetta, which is on a 10-year journey to rendezvous and land on a comet.

Experiments with Helium Ions

Laboratory simulations allow researchers to study the fine details of the causes and effects of space weathering. Some experiments have used the energy of tightly focused, pulsed laser beams to simulate micrometeorite bombardment. Other experiments have simulated solar wind ion irradiation with 1 keV H (hydrogen) and 4 keV He (helium). Following on the success of their own previous experiments and those by others using ion irradiation at different fluences (ions per unit area) on different targets, Mark Loeffler and colleagues chose to work expressly on the common mineral olivine (Mg_2SiO_4 to Fe_2SiO_4), irradiated with 4 keV He^+ ions, and monitored with spectrometers to verify the changes in the mineral seen in the visible and near infrared wavelengths.

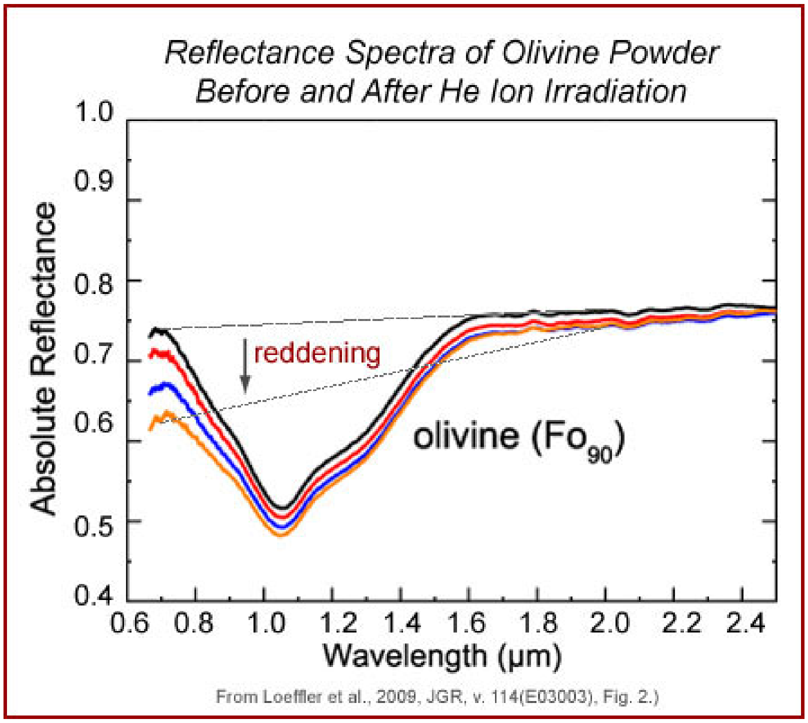
Reproducing the space environment in the laboratory requires an ultra-high vacuum chamber. Within that chamber Loeffler and coauthors performed experiments on a flat, solid piece of olivine and on olivine powder. These samples were mounted on a copper holder and transferred into the vacuum chamber with a base pressure between 5 and 10×10^{-10} Torr (equivalent to about one trillionth of the pressure at the surface of the Earth). During irradiation by the ion gun the chamber pressure remained in the mid 10^{-8} Torr range. Four keV He ions (simulating the solar wind) were rastered uniformly over the sample surface then subsequently analyzed using X-ray photoelectron spectroscopy (XPS) to measure the buildup of metallic iron and other chemical information and a Fourier Transform Infrared Spectrometer (FTIR) to measure changes in the near-infrared reflectance of the olivine. Analyses were performed before and after irradiation all under vacuum. Survey spectra were measured in about five minutes and more detailed spectra took about one hour. The experimental set up is shown in the drawing below.



(From Loeffler *et al.* (2009) *JGR*, v. 114(E03003), Fig. 1.)

Schematic drawing of the ultra-high vacuum system setup for the helium ion irradiation experiments on olivine performed by Loeffler and colleagues.

Olivine is a solid solution series ranging from the magnesium end-member called forsterite, Mg_2SiO_4 (Fo_{100}) to the iron end-member, fayalite, Fe_2SiO_4 (Fo_0). The Fo value is a convenient shorthand for describing olivine composition. Fo = mol%Mg / (mol%Mg + mol%Fe) x 100. The plot below shows four spectra obtained by Loeffler and coauthors for olivine (Fo_{90}) powder. The powder had particle sizes < 45 µm. The four spectra are similar in shape and show no change in the position of the 1 µm absorption band (no change in mineralogy). A clear change in spectral slope occurs for different fluences of ion irradiation. The steepening of the slope at these wavelengths is termed reddening.



From Loeffler et al., 2009, JGR, v. 114(E03003), Fig. 2.)

This plot of experimental data shows the diagnostic 1 µm absorption band for olivine. The olivine powder had a composition of Fo_{90} and particle sizes < 45 µm. The top, black curve shows the reflectance spectrum for olivine powder before ion irradiation. The lower three spectra show reflectance after irradiation by 4 keV He^+ at increasing fluences (10^{17} ions/cm^2): 1.5 (red), 5.3 (blue), and 25 (gold). The dashed grey line shows the slope of the spectrum of olivine between 0.7 and 2.0 µm before irradiation. The dotted grey line shows the slope of the spectrum of olivine after irradiation to 25 x 10^{17} ions/cm^2. This change in steepness of the spectral slope is referred to as spectral reddening.

In addition to the reddening of the spectral slope, Loeffler and colleagues confirmed other effects caused by He^+ irradiation.
They found:

- spectral reddening
- slight darkening (reduced albedo) of the olivine samples
- attenuation of the 1 µm absorption band (as the sample is irradiated, the area of the 1 µm absorption band decreases)
- formation of metallic iron in the sample

These results are in agreement with previous experiments and are attributed to the removal of surface ferric iron (Fe^{3+}) and reduction to Fe^{2+} and Fe^0 because of the preferential loss of oxygen from the surface due to breaking of the Fe-O bonds during sputtering. The spectral reddening is correlated with an increase of metallic iron in the sample, specifically with the formation of metallic iron in the outer 50-80 Å of the mineral surface. And what's intriguing is that Loeffler and colleagues also found the rate of metallization (F^0) in the < 45 µm-sized powder sample is about two times slower than the rate on the flat, solid piece of olivine. They suggest this is due to redeposition of about two thirds of the sputtered (and oxidized) material back onto the particles.

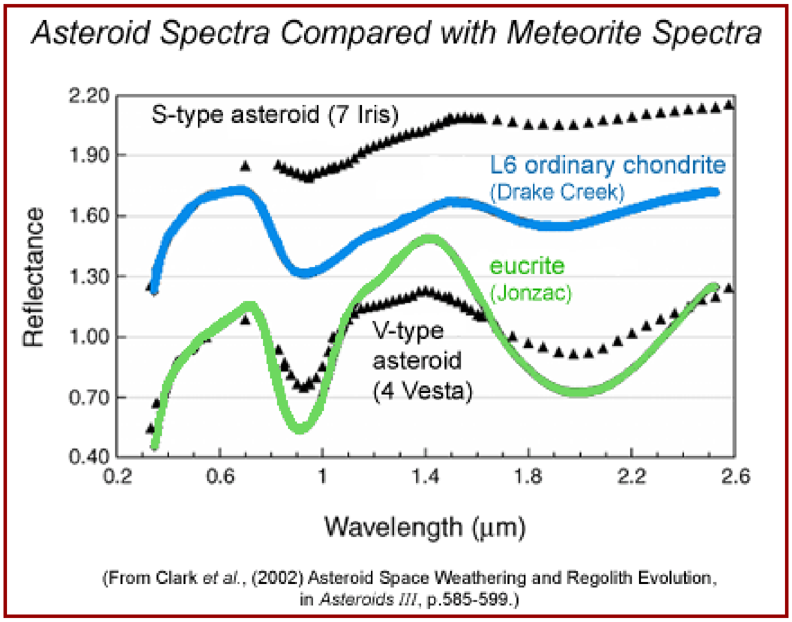
That metallization happens at all on flat, solid pieces of olivine has not been observed in all previous experiments. A common thought is that irradiating a smooth surface has no effect on the mineral's optical properties and that metallic iron forms as impact-induced vapor-phase depositions in glassy rims on the mineral grains or as iron silicide condensates. But Loeffler, Dukes, and Baragiola make the case that metallic iron is created in a flat solid piece of olivine where redeposition is negligible, as determined by their XPS measurements of Fe^{3+}, Fe^{2+}, and Fe^0, independent of infrared spectroscopy.

Interestingly, when Loeffler and colleagues finished the He^+ irradiation, they removed an olivine sample from the vacuum and exposed it to the atmosphere and remeasured. The near-infrared reflectance did not change, but the amount of metallic iron on the surface decreased significantly because of reoxidation. This illustrates the how chemically reactive the irradiated surfaces are. In previous work with E. Cantando (Laboratory for Atomic and Surface Physics, University of Virginia), the team noticed that irradiated olivine surfaces, removed from vacuum, were extremely reactive to humidity or immersion in water. This led to loss of magnesium from the outer 15 nanometers. These observations show the importance of proper handling of returned extraterrestrial samples and laboratory irradiated materials to prevent unwanted modification before analysis.

Finally, the effects of metallic iron particles on a mineral's reflectance spectra depends on the size of the iron particles. Smaller iron particles produce spectral reddening and larger particles cause darkening. Looking at their experimental results, spectral reddening but only slight darkening of the olivine samples, lead Loeffler and coauthors to conclude that the metallic iron formed in their experiments is in very small precipitates, perhaps less than 15 nanometers. Bruce Hapke's 2001 space weathering model shows that the addition of as little as 0.025% of sub-microscopic iron can alter the spectrum of a crushed ordinary chondrite meteorite so that it strongly resembles that of an S-type asteroid.

Matchmaking Asteroids to Meteorites

Cosmochemists, of course, compare reflectance spectra of asteroids to reflectance spectra of meteorites obtained in the laboratory in an attempt to determine where a meteorite came from, its parent body. It's a difficult job and the comparisons are never perfect, thanks in part to space weathering agents. (See, for example, **PSRD** articles: The Composition of Asteroid 433 Eros and The Complicated Geologic History of Asteroid 4 Vesta), and the plot shown below).



(From Clark *et al.*, (2002) Asteroid Space Weathering and Regolith Evolution, in *Asteroids III*, p.585-599.)

This plot shows two examples of a reflectance spectrum of an asteroid matched with a reflectance spectrum of a meteorite. The plot is taken from a chapter on asteroid space weathering and regolith evolution in the excellent publication, *Asteroids III* (see Reference list). The asteroid spectra are displayed in black and meteorites are displayed in blue or green. The top pair is offset vertically by 0.7 for clarity and show S-type asteroid 7 Iris with the L6 ordinary chondrite Drake Creek. Although both objects have approximately the same mineralogy as shown by their absorption bands, the spectra of the asteroid is reddened by 30% and the absorption band is weaker relative to the meteorite. The bottom pair of asteroid

> 4 Vesta and eucrite Jonzac also show similar mineralogy, but the band depth of the asteroid is reduced by 40% relative to its analog meteorite. The mismatches in the spectra have been explained by space weathering processes affecting the surfaces of the asteroids, altering them from their original spectral properties, as supported by laboratory experiments like those carried out by Loeffler, Dukes, and Baragiola.

Scientists have different working hypotheses and are still debating the time scales of space weathering and which space weathering agents, solar wind ions or micrometeorites, are more effective in different regions in space. Loeffler and coauthors suggest He^+ irradiation causes spectral reddening of olivine faster than by micrometeorite bombardment. Yet the laboratory results also seem to indicate different space weathering mechanisms lead to similar final effects on the reflectance of olivine. As is common in science, answers lead to more questions. And so the discoveries will continue in the laboratories and with data returned by spacecraft, helping the asteroid/meteorite matchmakers do their work, and keeping our interest in space weathering stirred for quite a while to come.

Additional Resources

LINKS OPEN IN A NEW WINDOW.

- Cantando, E. D., Dukes, C. A., Loeffler, M. J., and Baragiola, R. A. (2008) Aqueous Depletion of Mg from Olivine Surfaces Enhanced by Ion Irradiation. *Journal of Geophysical Research*, v. 113(E09011), doi:10.1029/2008JE003119,2008.
- Clark, B. E., Hapke, B., Pieters, C., and Britt, D. (2002) Asteroid Space Weathering and Regolith Evolution, in *Asteroids III*, edited by W. F. Bottke Jr., A. Cellino, P. Paolicchi, and R. P. Binzel, University of Arizona Press, Tucson, Arizona, p. 585-599.
- Dukes, C. A., Baragiola, R. A., and McFadden, L. A. (1999) Surface Modification of Olivine by H^+ and He^+ Bombardment. *Journal of Geophysical Research*, v. 104(E1), p. 1865-1872.
- Hapke, B. (2001) Space Weathering from Mercury to the Asteroid Belt. *Journal of Geophysical Research*, v. 106(E5), p. 10,039-10,073.
- Galileo mission homepage.
- Hayabusa mission homepage.
- Hiroi, T., Abe, M., Kitazato, K., Abe, S., Clark, B. E., Sasaki, S., Ishiguro, M. and Barnouin-Jha, O. S. (2006) Developing Space Weathering on the Asteroid 25143 Itokawa. *Nature*, v. 443, p. 56-58.
- Laboratory for Atomic and Surface Physics, University of Virginia.
- Loeffler, M. J., Dukes, C. A., and Baragiola, R. A. (2009) Irradiation of Olivine by 4 keV He^+: Simulation of Space Weathering by the Solar Wind. *Journal of Geophysical Research*, v. 114(E03003), doi:10.1029/2008JE003249,2009.
- Martel, L. M. V. (2004) New Mineral Proves an Old Idea about Space Weathering. *Planetary Science Research Discoveries*. http://www.psrd.hawaii.edu/July04/newMineral.html.
- NEAR mission homepage.
- Rosetta mission homepage.
- Solar and Heliospheric Observatory (SOHO) homepage, an ESA/NASA international project to study the Sun from its deep core to the outer corona and the solar wind.
- Taylor, G. J. (2002) The Composition of Asteroid 433 Eros. *Planetary Science Research Discoveries*. http://www.psrd.hawaii.edu/Feb02/eros.html.
- Taylor, G. J. (2009) The Complicated Geologic History of Asteroid 4 Vesta. *Planetary Science Research Discoveries*. http://www.psrd.hawaii.edu/June09/Vesta.granite-like.html.

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