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Space weathering on Mercury

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Abstract

Space weathering is a process where formation of nanophase iron particles causes darkening of overall reflectance, spectral reddening, and weakening of absorption bands on atmosphereless bodies such as the moon and asteroids. Using pulse laser irradiation, formation of nanophase iron particles by micrometeorite impact heating is simulated. Although Mercurian surface is poor in iron and rich in anorthite, microscopic process of nanophase iron particle formation can take place on Mercury. On the other hand, growth of nanophase iron particles through Ostwald ripening or repetitive dust impacts would moderate the weathering degree. Future MESSENGER and BepiColombo mission will unveil space weathering on Mercury through multispectral imaging observations.

1. Introduction

Space weathering is a proposed process to explain spectral mismatch between lunar soils and rocks, and between asteroids (S-type) and ordinary chondrites. Most of lunar surface and asteroidal surface exhibit darkening of overall reflectance, spectral reddening (darkening of UV–Vis relative to IR), and weakening of absorption bands. Recent asteroid observations strongly support that space weathering occurred not only on the moon but also on asteroids. Galileo observation of the S-asteroid Ida revealed that fresh craters and ejecta show weaker reddening which would suggest subsurface composition is like ordinary chondrites (Chapman, 1996). Many small asteroids have reflectance spectra between ordinary chondrites and S-asteroids (Binzel et al., 1996). Moreover, observation of the S-asteroid Eros by NEAR X-ray spectrometer showed that elemental composition of Eros is close to that of ordinary chondrites (Trombka et al., 2000). Mercury is also an atmosphereless body, which may experience space weathering on the surface.

In the space weathering process, impacts of high-velocity dust particle as well as solar wind – cosmic ray irradiation should change the optical properties of the uppermost regolith surface of atmosphereless bodies. Although Hapke et al. (1975) proposed that formation of iron particles with sizes from a few to tens nanometers should be responsible for the optical property changes, impact-induced formation of glassy materials had been considered as a primary cause for space weathering. Keller and McKay (1993, 1997) found nanophase iron particles within amorphous rims of lunar soil grains. Hapke (2001) showed theoretically that presence of nanophase iron particles should cause optical changes typical of space weathering.

To simulate space weathering, various heating experiments have been performed. Clark et al. (1992) observed spectral changes after the melting of meteorite samples by a fusion furnace but the changes were due to glass formation. Moroz et al. (1996) observed changes of silicate reflectance using a pulse laser as a heating device to simulate micrometeorite heating. However, the laser pulse duration was 0.1–1 μs, which was still 1000 times longer than the actual timescale of micrometeorite impacts. Their laser-irradiated samples were molten and the spectral change should be due to glass formation. Thus, we perform nanosecond pulse laser irradiation simulating dust impact heating (Yamada et al., 1999; Hiroi and Sasaki, 2001; Sasaki et al., 2002; Hiroi et al., 2001). We irradiated pellet samples of olivine and pyroxene with a pulse laser beam (1.064 nm) under a

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vacuum at 10^5 torr. Scanning is performed using an automatic X–Y stage. The pulse duration was 6–8 ns which is comparable to the timescale of impacts of interplanetary dust particles. Nanosecond pulse laser has been used to simulate high velocity impact of dust particles in physical studies (Kissel and Krueger, 1987).

2. Results of space weathering simulation

After pulse laser irradiation simulating space weathering, we observed the change of reflectance – darkening and reddening – of olivine and pyroxene samples (Yamada et al., 1999; Hiroi and Sasaki, 2001; Hiroi et al., 2001). One scanning irradiation of 30 mJ pulse laser produced at most 50% reduction of reflectance of San Carlos Olivine (8.97 wt% FeO) and at most 16% reduction of reflectance of Bamble Enstatite (9.88 wt% FeO). Moreover, TEM study of laser-irradiated samples revealed that the optical changes are really caused by formation of nanophase iron particles within vapor-deposited rims of irradiated grains (Sasaki et al., 2001). Previous simulation experiments did not confirm the formation of nanophase particles and spectral changes such as darkening and weakening of absorption bands could be explained by molten glass formation. A typical example of nanophase iron particles in our experiments is shown in Fig. 1. The occurrence of nanophase iron particles is very similar to that observed in lunar soils (Keller and McKay, 1997; Pieters et al., 2000). And ESR (electron spin resonance) study revealed that weathering degree is controlled by the amount of produced nanophase iron particles (Kurahashi et al., 2002).

Originally solar wind irradiation was considered to be responsible for formation of nanophase iron, because ion sputtering processes should alter the surface and implanted hydrogen could reduce ferrous iron. The laser irradiation study showed that hydrogen is not necessary for the formation of nanophase iron particles causing spectral changes (Sasaki et al., 2001). Space weathering is caused by nanophase iron particles formed through vapor deposition during high velocity impacts of dust particles and it does not require solar wind implantation.

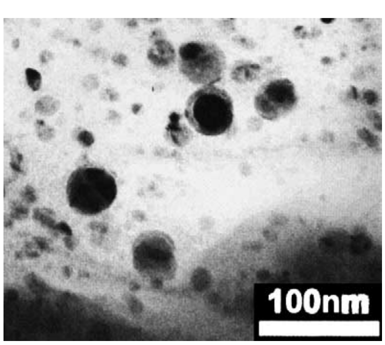

Fig. 1. Nanophase metallic iron particles within amorphous rim of laser-irradiated olivine (Sasaki et al., 2001). Although most of particles are from several to 20 nm in diameter, some particles have diameter as large as 50 nm and shell-like structure, which suggests particle growth through multiple laser irradiation.

3. Space weathering on Mercury?

Mercury is also an atmosphereless body covered with silicate regolith like the moon and asteroids. Mercurian magnetic field would decrease the solar wind irradiation to be hundredth of that on the moon, and solar wind irradiation would not be the main cause of space weathering on Mercury. Since Mercury is much closer to the sun, dust flux on its surface is about 10 times as high as that on the lunar surface (dust flux being proportional to a^{-2}: a being heliocentric distance). Impact velocity (proportional to $a^{-0.5}$) of dust particles is about twice as high as that on the lunar surface. Keplerian dust particles have relative velocity in the order of $(e, i)v_k$ (e and i being eccentricity and inclination, respectively) and as small as several km/s. On Mercury, dust particles from the sun, so-called β meteoroids, would be the most significant dust source causing the space weathering, because their impact velocity on the surface is in the order of Keplerian velocity v_k – 50 km/s. In calculating the Mercurian atmosphere production flux, Cintala (1992) estimated vapor formation by dust impacts is 20 times as much as that on the lunar surface. Mercurian surface would have been more weathered than that of the moon and asteroids.

Mariner 10 revealed on Mercury that there are fresh craters with bright ray of ejecta. Fig. 2 shows Degas crater, which has bright rays extending on the surrounding terrain. Presence of rayed craters suggests that space weathering is ongoing on Mercurian surface but also space weathering is not so intensive to darken the surface rapidly. Fig. 3 shows that some small craters have bright ejecta but the others do not, which would also indicate space weathering. The small craters with bright ejecta should be relatively new. Robinson and Lucey (1997) re-examined Mariner 10 data of two wavelengths: 355 nm (UV) and 575 nm (orange). They examined the region involving Kuiper–Murasaki Crater, which is apparently brighter than surrounding regions. Kuiper–Murasaki Crater shows lower weathering degree (or lower Fe) and has also less opaque minerals.

From ground observations (VIS-NIR), Mercurian surface should have basically reddened spectrum and 1 μm absorption band would be unclear. Recent CCD imaging of 200 km resolution over 550–940 nm shows that surface reflectance contrast of Mercury is 25–35% except brighter Kuiper region (Warell and Limaye, 2001). From microwave reflection data, Fe abundance in regolith would be a few 10% of lunar values. Mid-IR

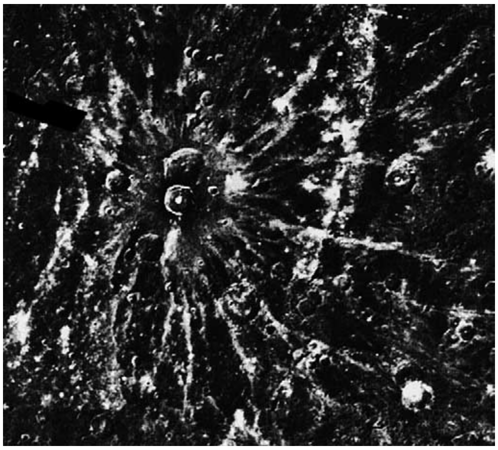

Fig. 2. Rayed crater Degas (45 km in diameter). The rays are formed of sprayed impact ejecta, which cover surrounding surface. Since bright rays should be less weathered, rayed craters are considered relatively young.

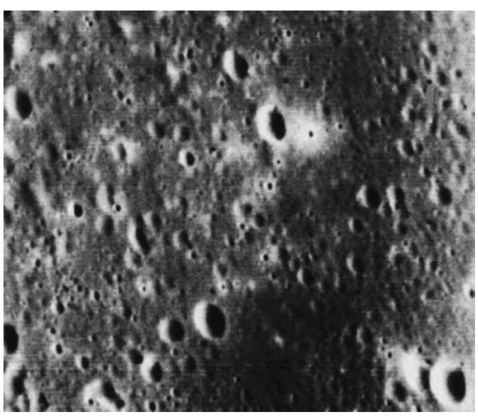

Fig. 3. Small craters with bright ejecta on one of highest-resolution images on Mercury taken by Mariner 10 (PIA02961). Image width is 25 km and height is 20 km.

observation (7.5–13.5 μm) showed that spectrum of some part is similar to anorthite–pyroxene mixed breccia (Sprague et al., 1997). Both lower Fe and anorthite-rich crust model would suggest compositionally less weathering. This compositional effect may have moderated the weathering degree.

4. Discussion

In simulation experiments using pulse laser, we confirmed significant spectral changes on olivine and pyroxene samples with 8–10 wt% FeO, which is lower than FeO content of surface lunar regolith. Extrapolation of FeO content suggests that observable spectral reddening can be produced even at lower 3–5 wt% FeO. We preliminary irradiated pulse laser beams on nearly pure anorthite with little Fe content. Change of reflectance is less than 10% in VIS-NIR region after five irradiation scans of 30 mJ pulse laser. However, anorthite grains can be covered with nanophase iron from other minerals such as olivine and pyroxene containing FeO. This should cause darkening and reddening of overall reflectance. In reality, such anorthite grains coated with a rim containing nanophase iron were observed in lunar soils (Keller and McKay, 1997). Although Mercurian surface is poor in iron and rich in anorthite, nanophase iron particles causing space weathering could be formed. This is compatible with a recent observation study: Comparing spectral observation (400–670 and 520–970 nm) of Mercury with observation of the moon, Blewett and Warell (2003) concluded that Mercury must be extremely low in spectrally neutral opaque phases and in ferrous iron while nanophase iron particles must be abundant as a reddening agent.

There is a possibility that increase in the size of nanophase iron particles should affect space weathering. Noble and Pieters (2001) suggested the possibility that size of nanophase iron particles should increase by Ostwald ripening under high temperature of several 100 °C. They predicted latitude dependency of the space weathering degree: less optical change at lower latitude where the surface temperature in daytime is higher. But Ostwald ripening is not the only cause of the growth of nanophase iron particles. Our experiments of nanosecond pulse laser irradiation showed apparent growth of nanophase iron particles after repetitive irradiation (Fig. 1). Repetitive heating will re-evaporate the amorphous layers containing nanophase iron. But if preexisted nanophase iron particles are not evaporated, they will grow during recondensation of vapor. The repetitive heating by high velocity dust impacts will cause the saturation of space weathering, which is also suggested by results of ESR measurement (Kurahashi et al., 2002).

5. Space weathering on Mercury – future

In the next decade, MESSENGER and BepiColombo missions will unveil various characteristics of Mercury (Solomon et al., 2001; Anselmi and Scoon, 2001). Both missions will perform multispectral observation of whole surface of Mercury. Also an X-ray spectrometer will confirm chemical compositions including iron contents of Mercurian surface. Recently, we confirmed experimentally that space weathering should decrease EUV (50–100 nm) reflectance significantly. This is compatible with EUV observation of lunar surface, where albedo variation could be ascribed to the weathering degree (Shiomi et al., 2001). Therefore, ultraviolet observation of Mercurian surface (by BepiColombo UVS) is another key to discuss space weathering. From MESSENGER and BepiColombo data, we will examine large- and small-scale differences of surface mineral composition and the space weathering degree. If the weathering degree is relatively small at lower latitude, growth hypothesis of nanophase iron would be probable.

Also, more laboratory experiments are necessary to simulate Mercurian space weathering. Especially weathering simulations of anorthite–pyroxene mixture or anorthite–olivine mixture are important to know whether anorthite spectrum can be darkened and reddened. Moreover, simulation for various iron contents of silicate minerals should be performed.

Acknowledgements

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