Earth Moon Planet (2009) 105:249–255
DOI 10.1007/s11038-009-9340-9

Space Weathering of Small Solar System Bodies

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Received: 28 December 2008 / Accepted: 5 April 2009 / Published online: 31 July 2009

Abstract Micrometeorite bombardment and irradiation by solar wind and cosmic ions cause variations in the optical properties of the small Solar System bodies surface materials. These space weathering processes are reasonably well understood for the Moon and S-type asteroids. The research is based on laboratory experiments performed by several groups on meteorites and minor bodies surface analogues, whose results have been applied to the spectral modeling and interpretation of observations from large surveys and space missions. Recent results from young asteroidal families, and the relation between spectral slopes and dynamical properties, have stressed the role of the solar wind exposure timescale. Space weathering processes remain poorly investigated in the case of other types of asteroids, and they are still unclear in the case of outer Solar System bodies, due to a strong dependence of the weathering process on the original composition.

Keywords Asteroid surfaces · Spectroscopy · Experimental techniques · Radiation chemistry · Meteorites

1 Introduction

Small Solar System bodies (SSSBs) currently include the classical asteroids (except for Ceres), most Trans-Neptunian Objects (TNOs), the centaurs, comets, and other small bodies. Many of these bodies are not (or are weakly) protected by an atmosphere or a magnetic field, so that their surfaces are exposed to the bombardment by micro-meteorites, solar wind ions, and cosmic ions. Irradiation by cosmic and solar wind ions and bombardment by interplanetary dust are believed to induce space weathering (SW), i.e., time-related processes able to change progressively the solar reflectance spectra of airless surfaces. These two mechanisms are believed to be active, with different intensity and

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effects, on a large distance scale, from Mercury (Killen et al. 2001) to the Kuiper Belt (Brunetto et al. 2006).

SW was initially studied for the Moon, since lunar soils returned from Apollo missions have optical properties that differ significantly from those of pristine lunar rocks (Conel and Nash 1970). Some authors (Cassidy and Hapke 1975) suggested the presence of metallic iron particle coatings on lunar soils; these coatings should be produced by deposition of atoms sputtered by solar wind particles and deposition of gaseous species produced by micrometeoritic impacts. Analyses of the SW products of lunar soils later demonstrated that nanophase reduced iron is produced on the surface of grains by a combination of vapor deposition and irradiation effects (Pieters et al. 2000).

It has been suggested that SW can be responsible for the puzzling and significant mismatch between the visible and near infrared (VNIR) spectra of the most populous class of meteorites (ordinary chondrites, OC) and the surface spectra of S-type NEOs (Near Earth Objects) and MBAs (Main Belt Asteroids), their presumed asteroidal parent bodies (Gaffey and Gilbert 1998). Such long debated OC-paradox (the discrepancy between the abundance of OCs and the rarity of similar assemblages in the main belt) seems to have been solved thanks to several laboratory experiments that simulate SW.

In this paper I will briefly summarize experimental results on silicates (Sect. 2) and some applications to the spectral modeling of asteroids (Sect. 3). In Sect. 4 I will identify some important asteroidal general trends deduced from observations. The case of outer Solar System bodies will be briefly discussed in Sect. 5.

2 Laboratory Experiments on Silicates

SW processes cause variations in the optical properties of airless bodies surface materials. Thus the interpretation of SSSB observations requires the knowledge of mechanisms determining their surface evolution. Experimental studies are fundamental to achieve this goal. In the laboratory it is possible to simulate SW processes on relevant materials (analogues), such as silicates, ices, and carbons, and in a few cases on materials directly coming from space, i.e. meteorites, interplanetary dust particles IDPs, and grains collected on Earth or from sample return missions. Solar wind and cosmic ion irradiation can be correctly simulated by keV–MeV ion irradiation, while micro-meteorite bombardment can be simulated by impact experiments. For instance, quartz micro-spheres impacts on meteorites can be performed to simulate the sculpting of airless bodies by low-energy dust bombardment (Moretti et al. 2006).

The importance of simulating solar wind irradiation in studying the optical properties of airless body surfaces has been known since a long time (Cassidy and Hapke 1975). A number of laboratory experimentalists have tried to simulate the effects of SW on asteroid material analogues. Ion irradiation of silicate samples has been performed using H^+ and He^+ ions at keV energies (Hapke 1973). Spectral darkening and reddening were observed. A principal factor in producing these spectral changes is thought to be the sputtering of iron from iron-bearing silicates due to ion irradiation and the deposition of nanophase neutral Fe on adjacent grains (Hapke 2001). Dukes et al. (1999) irradiated olivines and did not find significant spectral change. Yamada et al. (1999) performed high energy (MeV) proton implantation, producing only small changes in the spectra. Reddening and darkening of ordinary chondrite and silicate analogues were observed when using heavy ions at keV energies (Strazzulla et al. 2005; Brunetto and Strazzulla 2005). An example is given in Fig. 1.

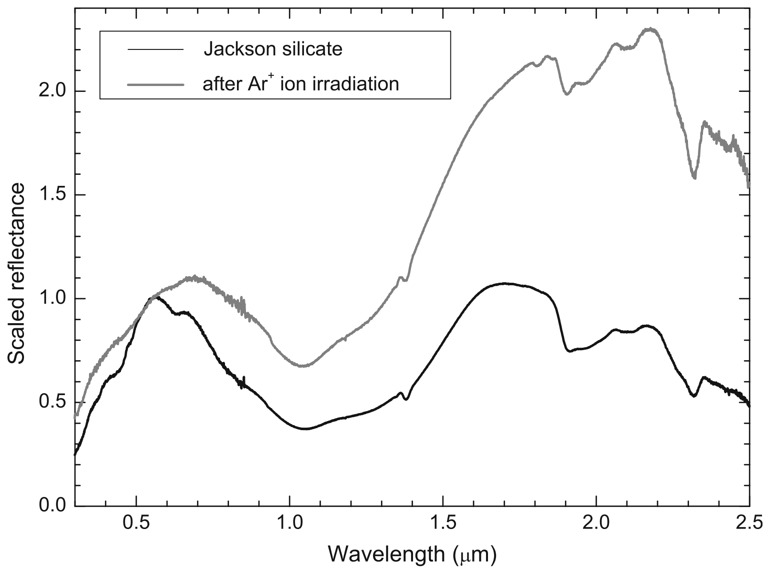

Fig. 1 Ion irradiation of Jackson silicates (Brunetto and Strazzulla 2005) using 10^{17} Ar^{+}/cm^{2}, energy of 200 keV, performed in the Catania LASp laboratory. Spectra are scaled to unity at 0.55 μm

Comparing laboratory spectra of irradiated samples with observations of silicate-rich asteroids, and scaling the fluences and doses used in the laboratory to the fluxes of the solar wind ions, the timescales for this process can be estimated in the order of 10^{4}–10^{6} years in the inner Solar System. Such high efficiency of ion-induced SW indicates the presence of rejuvenating processes able to partially resurface the asteroid and thus counterbalance the reddening effect. In this respect, it should be stressed that the surface layer weathered by the solar wind is most probably less than few micrometers thick, so that even collisions with mm-sized impactors can efficiently remove it or remix it with more pristine materials.

Several authors assume that micro-meteorite bombardment can be simulated by pulsed laser irradiation. It should be noted that, while ion irradiation and impact experiments are a direct reproduction of the studied astrophysical process, laser irradiation presents analogies with micro-meteorite bombardment and cannot be considered an exhaustive simulation. Simulations by laser irradiation are based on the use of nanosecond pulses, in order to reproduce the duration of the vaporization process induced by micrometeorite impacts. A 6–8 ns pulsed Nd-YAG laser (1,064 nm) was used in a number of experiments performed in Japan (Yamada et al. 1999; Sasaki et al. 2001) on pellets of pressed silicate powder, inducing vaporization and redeposition processes. This was supposed to well simulate dust impact on asteroidal surfaces. Such experiments showed progressive (increasing the shot number) darkening and reddening of the VNIR silicate spectra, whose comparison with asteroid spectra led to a time-scale for this process (in the near-Earth space) of about 10^{8} years. They attributed the observed spectral weathering to formation of coating enriched in vapor-deposited nanophase iron (Sasaki et al. 2001).

Irradiation of silicate samples with an UV excimer laser, below and above ablation threshold, confirmed and extended those results (Brunetto et al. 2006); it was found that the most efficient experimental conditions to redden the reflectance spectra are obtained performing congruent (stoichiometric) laser ablation, i.e., using an UV laser with fluence above the ablation threshold. An increase in magnetic susceptibility on laser ablated orthopyroxene of more than a factor 3 was observed (Brunetto et al. 2007). Other experiments (Bentley 2005) showed that magnetic susceptibility increases on laser irradiated olivine. Studying redeposition of impact-ejecta on mineral surfaces (Loeffler et al. 2008), it was found that darkening and reddening occur when the deposit is olivine (i.e. a mixture of Mg-rich forsterite and Fe-rich fayalite) but not if it is pure forsterite, and in situ X-ray Photoemission Spectroscopy (XPS) measurements revealed that the olivine deposits are reduced, with about 50% of the iron becoming metallic. These experimental results stress the role of the formation of small metallic iron inclusions in silicates weathered by micrometeorite bombardment.

3 Spectral Modeling

Spectral models are a powerful tool to estimate asteroidal surface compositions. However, without a solid understanding of SW, it is not possible to discriminate between slopes and band depths due to SW and those due to composition (Gaffey 2008), and unfortunately the nature of the various types of SW on asteroids is not yet fully understood. Nonetheless, a number of models have been developed to include the SW effects in the scattering models.

The Hapke's SW model is based on the Maxwell-Garnett effective medium theory, to calculate the absorption coefficient of a silicate host medium containing inclusions of small metallic iron spheres (Hapke 2001). It has been recently applied to spectra of asteroid (25143) Itokawa collected by the Hayabusa spacecraft (Hiroi et al. 2006). Application of the Hapke's SW model to asteroid (1951) Lick, yields a composition rich in olivine with high Mg number and a volume fraction of metallic inclusions similar to what observed experimentally after UV laser ablation of Mg-rich olivine (Brunetto et al. 2007). This implies that the surface of Lick is extremely weathered, indicating a saturation regime similar to what observed in the laboratory. Alternatively, it is possible to estimate effective optical constants of weathered silicates in the laboratory, and insert them in a scattering model (Brunetto et al. 2007). Other possibilities include the so-called iso-grain model (Hiroi and Pieters 1994; Hiroi and Sasaki 2001).

It was found (Brunetto et al. 2006) that computing the ratio between spectra of weathered and unweathered materials, the contribution of silicate bands almost disappears, and a continuum curve is left. This is parameterized by a coefficient related to the SW exposure time. Application of this model to asteroid 832 Karin showed that the irradiation timescales estimated for this body are in agreement with the age of the impact that rejuvenated the surface about 5.8×10^6 years ago (Brunetto et al. 2006).

4 General Trends and Space Missions

Thanks to the high number of observations obtained in the past decades, a few general SW spectral trends for asteroids can be established. Here I report some of them. These general trends are in agreement with laboratory results mentioned above.

a. By analyzing the VNIR spectra of a large sample of OCs, MBAs, and NEOs, it was found a similar mineralogy between most asteroids and meteorites, but different distributions of spectral slopes (Marchi et al. 2005). This was interpreted as a SW effect induced by solar wind ion irradiation.

b. Studying the slope-diameter correlation for NEOs, it was observed a size-dependent transition from ordinary chondrite-like (Q-type) objects to S-type asteroids over the size range of 0.1–5 km (Binzel et al. 2004). This indicates a competition between SW and rejuvenating processes.
c. A correlation was found between the visible spectral slope of asteroids and the exposure to solar wind (Marchi et al. 2006a, b; Paolicchi et al. 2007). This proves that solar ion flux is a relevant source of the asteroidal SW.
d. The color of asteroid families becomes redder with increasing dynamical age (Willman et al. 2008). A determination of the SW rate using spectra of young asteroid families (e.g. the Iannini family and the Karin family) yielded values close to what estimated by experimentalists.
e. SW produces a bluing of the spectrum at near-UV wavelengths, in contrast to the reddening in the VNIR, and such UV bluing occurs with a lower amount of weathering than the VNIR reddening (Hendrix and Vilas 2006). This implies that the UV range is highly promising to better constrain the SW timescale.

Generally speaking, results from space missions confirmed that SW plays a major role in determining the surface spectra of asteroids. However, peculiar behaviors seem to be present. The Galileo mission revealed that 243 Ida presents significant spectral variations, but little albedo variations (Chapman 1996), whereas the NEAR mission at 433 Eros detected large albedo variations (many in topographic locations where different degrees of SW would be expected) with little slope variations (Clark et al. 2001). More recently, the Hayabusa mission detected regions with different maturity on near-Earth asteroid 25143 Itokawa and drew a map of the degree of SW; removing the SW contribution through spectral models, it was found that the composition is similar to that of LL meteorites (Hiroi et al. 2006).

Although these missions clearly showed the presence of SW through indirect spectral effects, a direct detection of asteroidal SW is still missing. This could be possible thanks to a sample return mission (e.g. Hayabusa). In perspective, one should consider the possibility of including a magnetic susceptibility sensor on future planetary landers, that would be able to detect the formation of metallic iron (Rochette et al. 2004; Bentley 2005).

It should be mentioned that the Rosetta spacecraft has recently performed a flyby of asteroid 2867 Steins, and will flyby asteroid 21 Lutetia in 2010. Unfortunately, there is a lack of laboratory SW simulations on meteorites relevant to these asteroids. Carbonaceous chondrites should redden if the silicate component prevails (Lazzarin et al. 2006) and should flatten if the organic component prevails (Moroz et al. 2004). Ongoing studies indicate that asteroid Lutetia can be associated with enstatite chondrites, and that SW of these meteorites produces little spectral variations (Vernazza et al. 2009). Future SW experiments should concentrate on meteorites other than OCs.

5 Outer Solar System

Outer SSSBs are characterized by the presence of ices and organics on their surface. It is known since a long time that SW effects on simple C-bearing ices can produce organic residues that have VNIR properties able to explain the dark albedos and red to neutral colors observed on SSSBs (Andronico et al. 1987). Due to a lack of adequate optical constants, tholins (Khare et al. 1984) are commonly used in the SSSB spectral models as representative of a very broad class of complex organic solids produced by energy deposition in gases and ices having compositions of planetary relevance.

Natural bitumens (e.g. asphaltite, kerite) appear to be reasonably good reference analogs for refractory extraterrestrial organic matter, in terms of spectral properties and chemical structure, especially for TNOs and comets. Their VNIR spectra flatten after ion irradiation (Moroz et al. 2004). The same weathering process on originally low absorbing ices induces color variations that can reproduce the observed spectral variety of outer Solar System objects. This has been proven irradiating CH_4, CH_3OH, and C_6H_6 (Brunetto et al. 2006). The obtained organic refractories are generally characterized by low albedo and red spectral slope. Thus, the SW color trend is not yet well established, due to a strong dependence on the unknown original composition. Other SW effects on ices include an ion-induced surface chemistry with formation of new molecules (e.g. Strazzulla et al. 1991; Moore et al. 2003; Brunetto et al. 2005), and amorphization of water ice (Mastrapa and Brown 2006). If the surfaces are heavily irradiated, a crust may be produced that can easily mask the presence of volatiles (Strazzulla et al. 1991; Brunetto and Roush 2008). However, this process can be efficient only for bodies in the Scattered Disk or in the Oort Cloud, but not for bodies orbiting at about 40 AU, as can be deduced from estimates of the dose accumulated by surface layers (Cooper et al. 2003; Strazzulla et al. 2003).

Finally, thanks to the Raman analysis of collected extraterrestrial carbons (e.g. Busemann et al. 2007, and references therein), in particular meteorites, IDPs, and comet Wild 2 grains from the Stardust mission, it has been suggested that that primitive organic matter has experienced irradiation induced amorphization prior to the accretion of the parent bodies, emphasizing the important role played by early solar nebula processing (Brunetto et al. 2009). The strong particle and photon radiation emissions of the early Sun may have had major influences on processing of material during the accretion phase, and more specifically on the carbon chemistry. Eventually, we wish to be able to disentangle recent SW effects from SW that took place in the early solar nebula.

6 Conclusions

SW processes are reasonably well understood for the Moon and S-type asteroids. The timescale measured in space are approaching what estimated in the laboratory, but the UV range is highly promising for future observations to better constrain the SW timescale. Hot topics in the SW investigation include: analysis of young families; relation with exposure and dynamics; spectral variation on the same body. A lack of laboratory SW experiments on meteorites other than OCs (e.g. ECs, aubrites, CCs, etc.) needs to be addressed, in particular for the interpretation of data from space missions. Sample return missions shall give use the possibility of a direct measure of a weathered asteroidal sample. Finally, SW processes in the outer Solar System are still unclear, due to a strong dependence on the original composition.

Acknowledgements The author warmly thanks the LASp team at INAF–Osservatorio Astrofisico di Catania (Italy) and the “Astrochimie et Origines” team at IAS–Orsay (France) for useful discussions. The author acknowledges support from the French “Agence Nationale de la Recherche” (contract ANR-05-BLAN-0148-02).

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