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Space weathering: from laboratory to observations

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Abstract. An ongoing research program in our laboratories is focusing on the effects of laser ablation and ion irradiation on silicates, meteorites, and ices, as a simulation of space weathering on Solar System minor bodies (asteroids, Trans-Neptunian Objects, etc.). Spectroscopic results show a general reddening and darkening of the various materials in the 0.3-2.7 μm range. Laboratory data are then compared with observations, through spectral characterization and scattering models, indicating that space weathering is a very efficient process both in the inner and outer Solar System. In particular, we demonstrated that the majority of TNOs and Centaurs can develop an organic crust mantle produced after irradiation of simple C-bearing molecules. Another relevant result is that the exposure to surface space weathering of asteroid 832 Karin, as calculated from our experiments and models, is in agreement with a dynamical time-scale, i.e. the age of the corresponding Karin family.

Key words. Solar System: Minor planets, asteroids – Solar System: Kuiper Belt - Comets: general – Methods: laboratory – Molecular processes

1. Introduction

Irradiation by cosmic and solar wind ions, and bombardment by interplanetary dust particles (micro-meteorites), induces relevant surface modifications on airless bodies of the Solar System.

Such alteration processes, known as space weathering, affect the spectral properties of silicate-rich objects, inducing progressive darkening and reddening of the asteroids reflectance spectra (Hapke 2001; Marchi et al. 2005).

Also minor bodies in the outer Solar System show the effects of space weathering: a great variety of spectral colors is observed for Trans-Neptunian Objects (TNOs) and Centaurs (Doressoundiram et al. 2002), and this can be only partially explained by a different composition.

In our laboratories in Lecce and in Catania, we perform laser ablation and ion irradiation experiments on silicates, meteorites, and ices, as a simulation of space weathering on Solar System minor bodies (asteroids, TNOs, etc.). Weathering effects are studied through reflectance and transmittance spectroscopy, usually in the 0.3-2.7 μm range. Details of the

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experimental setup can be found elsewhere (Brunetto & Strazzulla 2005; Brunetto et al. 2006a). Laboratory data are then compared with observations, through spectral and scattering models.

Here we present a few results of our ongoing research program.

2. Inner Solar System

Many asteroids in the inner Solar System show high silicate content (Marchi et al. 2005). We conducted micro-meteorite bombardment simulations using a nanosecond pulsed UV ablating laser on silicate targets (Brunetto et al. 2006a). Such simulations show spectral reddening and darkening (UV-vis-NIR range), and indicate that the weathering timescale for micro-meteorite bombardment in the near-Earth space is about 10^8 years.

We also simulated solar wind heavy-ion irradiation on asteroids: we irradiated ordinary chondrite Epinal (H5), which is a good analogue for silicate-rich asteroids, with Ar^{++} (60 keV), producing strong reddening and darkening. Comparing spectra of irradiated samples of Epinal with those of some silicate-rich NEOs, the timescales for this process were estimated to be in the order of $10^4 - 10^6$ years at 1 AU from the Sun (Strazzulla et al. 2005).

Performing irradiation experiments with different ion species (H, He, N, Ar, etc.) and energies (30-400 keV), we investigated the physical mechanism producing weathering effects. We obtained that the increasing of the spectral slope of the continuum above the 1-micron silicate band is strongly related with the number of displacements caused by colliding ions inside the sample, i.e., the elastic collisions with the target nuclei (Brunetto & Strazzulla 2005).

This is very similar to what has been observed in amorphization of other materials relevant for Astrophysics (namely forsterite, graphite, and diamond) after ion irradiation experiments (Brunetto et al. 2005a). This suggests that asteroidal weathering is more connected with a physical damage process, rather than chemical.

In Fig. 1 we show a typical weathering experiment on Fe-poor San Carlos olivine. The effects of space weathering can be easily described by an exponential continuum. Indeed, if we compute the ratio between spectra of irradiated and unirradiated samples, the contribution of silicate bands almost disappear, and a continuum curve is left, with decreasing intensity moving from the NIR to the UV spectral range. This space weathering process does not significantly affect the position or relative intensities (areas) of the mafic silicate absorption features (lower panel in Fig. 1). We model the weathering continuum by fitting with an exponential curve given by $Ratio = W(\lambda) = Kexp(C_S/\lambda)$, where λ is the wavelength, K is a scale factor that change according to the normalization of the spectra, and the parameter C_S rules the strength of the exponential curve, i.e. it is a measure of the effects of space weathering. The quantity $W(\lambda)$ is what we call weathering function.

The C_S parameter is strongly related with the number of displacements per unit area (damage parameter), and it becomes more negative as the space weathering effect increases (Brunetto et al. 2006b). In Fig. 2 we show the experimental damage curve and its application to asteroid 832 Karin. Using our weathering function in conjunction with the Shkuratov scattering model (Shkuratov et al. 1999), we fitted the observed reflectance spectra of asteroid 832 Karin, and estimated that Karin's surface accumulated about 8×10^{18} displacements per unit area (Brunetto et al. 2006b). This would correspond to an exposure of about 2×10^6 years at 2.9 AU from the Sun (about Karin's semi-major axis).

This result for the exposure to surface space weathering of asteroid 832 Karin is in good agreement with a dynamical time-scale, i.e. the age of the corresponding Karin family. Indeed, a disruptive impact rejuvenated Karin's surface 5.8×10^6 years ago, originating the Karin family (Nesvorný et al. 2002). This scenario is coherent with the model of a very efficient space weathering process caused by solar wind ions; it has also been confirmed by recent discovery of an increasing trend for the visible spectral slope of Main Belt aster-

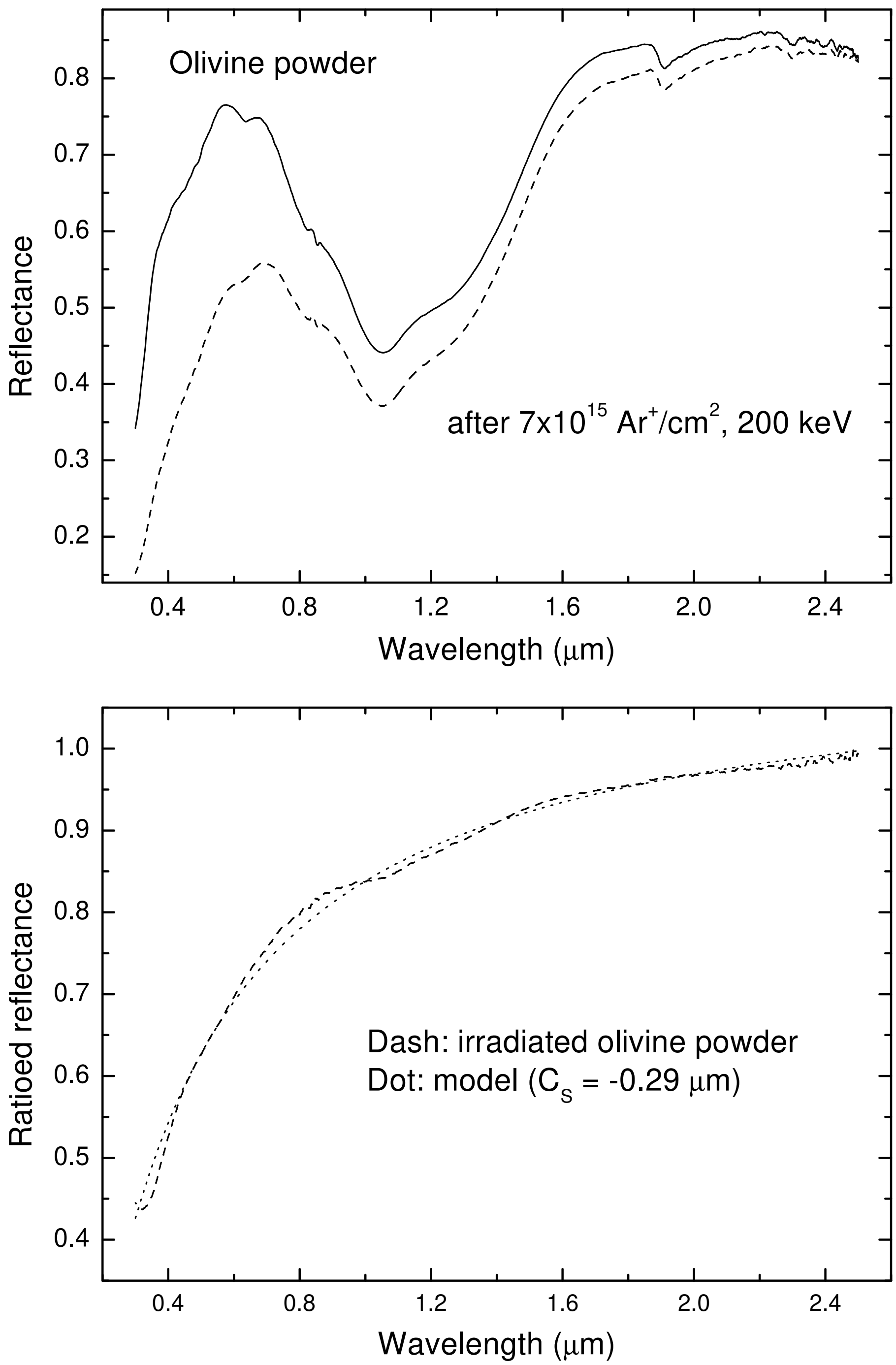

Fig. 1. Upper panel: reflectance spectra of powdered San Carlos olivine, before (solid) and after (dashed) ion irradiation. Lower panel: ratio plot of the spectra shown in the upper panel; the dotted curve represents the model obtained using the weathering function $W(\lambda)$.

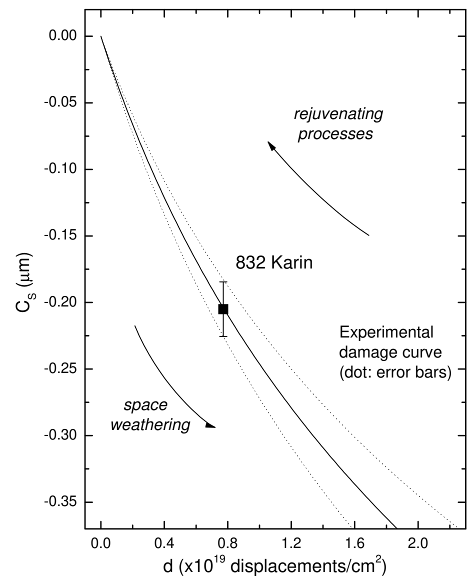

Fig. 2. The C_S parameter as a function of a damage parameter (displacements per unit area), as calibrated from ion irradiation experiments. The corresponding value for asteroid 832 Karin is also included, as derived from model of the continuum using the weathering function.

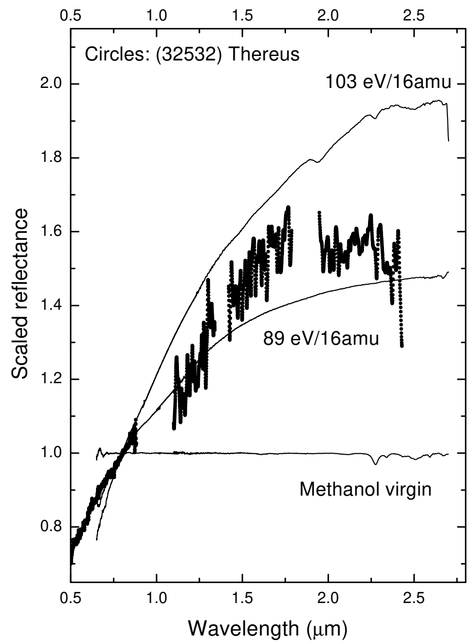

Fig. 3. Scaled (0.8 μm) reflectance spectra of methanol ice (T = 77 K), before and after ion irradiation (doses indicated), qualitatively compared with the spectrum of Centaur (32532) Thereus.

oids as a function of exposure to solar wind ions (Lazzarin et al. 2006).

3. Outer Solar System

Methane and methanol are simple molecules relevant for the composition and chemistry of TNOs and Centaurs. For instance, methane (CH_4) ice is present on Pluto (Owen et al. 1993), and on TNO 2005 FY_9 (Licandro et al. 2006); methanol (CH_3OH) ice has been possibly identified on Centaur Pholus (Cruikshank et al. 1998).

As simulated by laboratory experiments, simple frozen molecules are destroyed by energetic particles and by UV photons, with consequent modification of their band intensities and formation of other molecules (Brunetto et al. 2005b). Furthermore, when carbon is present, an organic residue is synthesized that may produce a crust of refractory material, as in the case of comets in the Oort cloud (Strazzulla et al. 1991).

Using 200–400 keV ions, we performed irradiation experiments of frozen (16–80 K) methanol, methane, and benzene (as a template for aromatic compounds), monitored by vis–NIR (0.65-2.7 μm) reflectance spectroscopy. The aim was to compare the induced color variations with the observed spectra of some Centaurs and TNOs.

In Fig. 3 we show scaled reflectance spectra of methanol ice (T = 77 K) before and after ion irradiation, compared with the spectrum of Centaur (32532) Thereus. The spectral slope of Thereus is compatible with the presence of an irradiation mantle on its surface (Brunetto et al. 2006c).

Similar results are obtained for a relevant number of TNOs and Centaurs, showing that about 70% of the observed objects have spectral slope well reproduced by irradiation of methanol, methane, and benzene (Brunetto et al. 2006c). So, the surface colors of these objects are compatible with the presence of a refractory organic crust developed after prolonged irradiation by cosmic ions.

4. Conclusions

Our comparison between laboratory experiments and astronomical observations indicates that space weathering is a very efficient process. In the outer Solar System, in particular, the majority of TNOs and Centaurs can develop an organic crust mantle produced after ion irradiation of simple C-bearing molecules.

Regarding the inner Solar System, the spectral slope of asteroids increase as a function of exposure to solar wind ions: a relevant case is given by asteroid 832 Karin, whose exposure to surface space weathering, as calculated from our experiments and models, is in agreement with a dynamical time-scale, i.e. the age of the corresponding Karin family.

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