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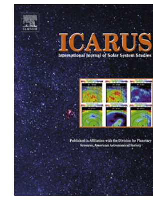

Near-ultraviolet bluing after space weathering of silicates and meteorites

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ABSTRACT

Asteroid surface space weathering has been investigated both observationally and experimentally, mostly focusing on the effects on the visible–near infrared (VNIR, 0.4–2.5 μm) spectral range. Here we present laboratory near-ultraviolet (NUV, 200–400 nm) reflectance spectra of ion irradiated (30–400 keV) silicates and meteorites as a simulation of solar wind ion irradiation. These results show that the induced alteration can reproduce the spread observed in the VNIR vs. NUV slope diagram for S-type asteroids. In particular, the well-known spectral reddening effect induced in the VNIR range is accompanied by a less known but stronger bluing effect at NUV wavelengths. Such trend was previously identified by Hendrix and Vilas (Hendrix, A.R., Vilas, F. [2006]. Astron. J., 132, 1396–1404) but only based on the comparison between observations and laboratory spectra of lunar materials. We attribute the NUV bluing, analogously to the VNIR reddening, to the formation of iron nanoparticles accompanied by structural modifications (amorphization) of surface silicates. We expect the evidence of weathering processes in the NUV part of spectra before these effects become observable at longer wavelengths, thus searching for the space weathering effects in the NUV range would allow establishing the extent of space weathering for very young asteroidal families.

It will be important to include in future studies the NUV range both in the observations of specific classes of objects (e.g., the Vestoids) and in the laboratory spectra of meteorites and terrestrial analogues before and after space weather processing.

1. Introduction

Asteroid surfaces are continuously altered by solar and cosmic ion irradiation, and micrometeorites. These processes are commonly known as space weathering. As a consequence of the chemical–physical alterations induced by space weathering, optical properties of asteroid surfaces may change, thus affecting the interpretation of their spectral properties and the efforts to establishing a solid meteorites–asteroids link (Hapke, 2001; Clark et al., 2002; Brunetto et al., in press). Direct evidence of the effect of these processes have been recently provided by the laboratory analyses of particles returned from Asteroid 25143 Itokawa by the Hayabusa mission (see e.g., Noguchi et al., 2014 and references therein).

Spectroscopically, asteroid space weathering has been mainly studied at visible–near infrared (VNIR, 0.4–2.5 μm) wavelengths. In this spectral range, S-type asteroids are generally spectrally redder (and darker) than ordinary chondrite (OC) meteorites (the so called OCs paradox), even though on the basis of mineralogical interpretation of NIR spectra a fraction of S-type asteroids have mineralogies (in terms of olivine and orthopyroxene percentage) compatible with OC meteorites (Gaffey et al., 1993; Vernazza et al., 2007). The opposite trend seems to take place at near-ultraviolet (NUV, 200–400 nm) wavelengths (a spectral range only occasionally considered): some observational evidence indicates that space weathering of rocky objects in the Solar System such as S-type asteroids, induces a bluing (relative increasing of reflectance at lower wavelength) of the spectrum (Hendrix and Vilas, 2006; Vilas et al., 2015), in contrast with the reddening (lowering of reflectance at lower wavelength) observed at visible–near-IR wavelengths (see e.g., Brunetto et al., in press and references therein).

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A number of experimental studies have focused on the spectral alteration induced by irradiating OC meteorites and terrestrial silicates using the two main agents of space weathering of asteroids, namely energetic ions – to simulate the effects of solar wind and cosmic rays, and laser pulses to simulate micrometeorite bombardment. Solar wind is an expanding flux of fully ionized plasma that reaches at distances greater than a few solar radii an expansion speed about 400 km s^{-1} corresponding to an energy of ≈1 keV/u (slow solar wind, see e.g., Gosling, 2007). Energetic ions interact with the atoms in the solid material through elastic (nuclear) and inelastic (electronic) collisions. The aim of laboratory experiments is to mimic the energy transfer distribution of the solar wind ions. Ions of high energy are used in experiments and the results are interpreted on the basis of the physical mechanism that is causing the observed spectral effects (for details see e.g., Kanuchova et al., 2010).

Solar wind was found to be the main source of rapid weathering (Vernazza et al., 2009), as the effects caused by ion bombardments (deposited energy on the grain surface may induce sputtering or structural and chemical changes) saturate between 10^4 and 10^6 years (Hapke, 2001; Strazzulla et al., 2005; Loeffler et al., 2009). Micrometeorite impacts, that can vaporize some of the asteroid regolith grains, alter the surface of asteroids at slower rates – the saturation is supposed to be achieved on the scale of 10^8 years (Sasaki et al., 2001; Brunetto et al., 2006). The nanosecond-pulsed laser at fluences higher than the ablation threshold was found to be a good analog for micrometeorites impacts (e.g., Brunetto et al., 2006; Sasaki et al., 2001). The general trend of space weathering of silicates – VIS–NIR darkening (lowering of reflectance) and reddening (causing a slope change) of their spectra, is similar for both types of experiments.

The state of the art on the laboratory results has been recently reviewed (Bennett et al., 2013; Domingue et al., 2014; Brunetto et al., in press). Just as an example: the paradox of OCs has been virtually resolved demonstrating that ion irradiation of OCs causes a spectral reddening that reproduces all the range of the VNIR slopes observed for S-type asteroids (Strazzulla et al., 2005).

The results of ion and laser irradiation experiments are, besides other applications, used to estimate timescales for which spectral alterations observed in laboratory may occur in the space environment. Alternatively, to estimate the rate of space weathering processes in the Solar System, asteroidal families (i.e., groups of fragments of one larger parent body) can be used. The objective is to find a correlation between the dynamical age of families and the observed characteristics of their members, with resurfacing processes taken into account. Due to the precision limits of dynamical methods, spectral characterization of families younger than app. 10 Ma is highly important. As NUV bluing occurs with a lower amount of weathering than the VIS–NIR reddening (Hendrix and Vilas, 2006), the study of space weathering processes in this spectral region is very substantial.

However, the laboratory experimental evidence of the NUV bluing in processed meteorites or terrestrial samples is still limited. Here we present the experimental results obtained by ion bombardment at the Laboratory for Experimental Astrophysics (LASp – Laboratorio di Astrofisica Sperimentale) in Catania (Italy) and by the laser irradiation at the University of Lecce (Italy). We also present analysis of several laser irradiation experiments of meteorites published in the RELAB database (Pieters and Hiroi, 2004). Some experiments from LASp are new, while others have been already published (mostly to support the VNIR reddening) and are here reviewed focusing on the NUV part of the spectrum.

2. Experiments

Samples of different materials – meteorites and terrestrial silicates – have been irradiated with different ions at room temperature, inside a stainless steel vacuum chamber ($P < 10^{-7}$ mbar), faced to different spectrometers. After irradiation samples have been removed from the vacuum chamber and further spectral analysis has been obtained ex-situ in a wider spectral range (see e.g., Strazzulla et al., 2005; Fulvio et al., 2012). In this paper we also consider the results obtained after pulsed laser irradiation of silicate samples (Brunetto et al., 2006).

The spectrometers that have been used at the LASp-Catania and at the University of Lecce (Italy) to obtain the spectra showed in this paper are:

- FTIR Bruker Equinox 55, here used in reflectance mode in the spectral range 0.7–2.67 μm.
- NUV–VNIR Spectrophotometer Perkin–Elmer Lambda 19 (0.2–2.5 μm).
- NUV–VIR Spectrophotometer Perkin–Elmer Lambda 900 (0.25–2.5 μm).

The sample considered in each ion irradiation experiment is mounted at the center of the vacuum chamber, held vertically by a metallic sample holder. Samples are irradiated with different ions produced by a Danfysik (1080–200) ion implanter. Ions with an energy from 30 up to 200 keV (400 keV for double ionization) can be obtained. The ion beam passes through a sweeping system, producing a uniform coverage over an area of about 4 cm^2, thus irradiating the whole surface of the sample. The ion currents are below a few micro-ampere to avoid macroscopic heating. The ions impinge the surface of the sample at an angle of 45°. A light beam (from a tungsten lamp) impinges the sample orthogonally (see Fig. 1) and the diffuse bi-directional reflected light is detected at an angle of 45° by the FTIR Bruker Equinox 55 spectrometer. In this way we can obtain reflectance spectra during irradiation (stopped when spectra are obtained) and without tilting the sample (e.g., Brunetto and Strazzulla, 2005). After irradiation, samples are extracted from the vacuum chamber and directly placed onto the

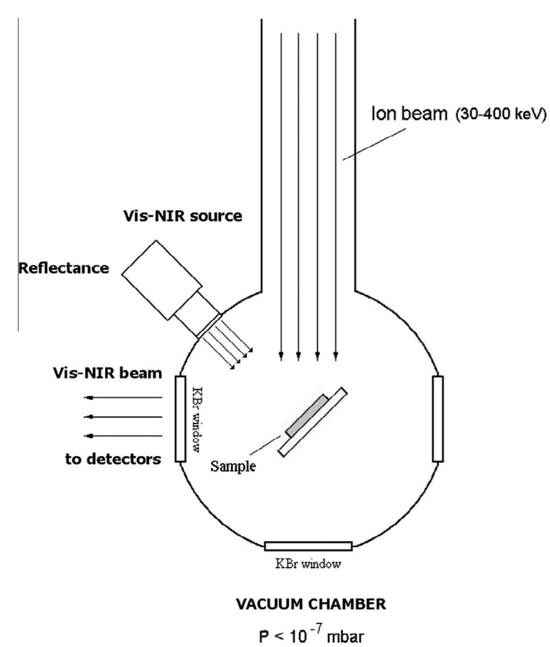

Fig. 1. A scheme of the vacuum chamber: bulk silicates are in contact with the sample holder (at room temperature); the chamber is interfaced to an ion implanter; bi-directional reflectance spectra are acquired using a tungsten lamp source, put perpendicularly to the sample surface; in situ spectra can be obtained before, during and after irradiation, without tilting the sample (from Brunetto and Strazzulla (2005)).