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Space weathering on minor bodies induced by ion irradiation: some experimental results

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Abstract. Some ion irradiation experiments are here performed to simulate space weathering on minor bodies of the Solar System. Ion irradiation of frozen (16 and 77 K) methanol (CH_3OH) with 30 keV He^+ and 200 keV H^+ ions induces the formation of CO and CH_4, and a strong decrease of the intensity of the methanol band at about 2.34 μm in comparison with that at 2.27 μm. These results are discussed in view of their relevance for icy objects in the outer Solar System (namely comets, Centaurs, and Kuiper belt objects) where CH_3OH has been observed or suggested to be present. We describe also an ion irradiation experiment of Epinal (H5), an ordinary chondrite meteorite, with 60 keV Ar^{++} ions, simulating solar wind heavy particle irradiation. Reflectance spectra (0.3-2.67 μm) of increasingly weathered Epinal exhibit a progressive reddening that is similar to the spread of spectra observed for S-type near-Earth asteroids. The timescales for inducing the same effects in space as those obtained in laboratory are estimated to be 10^4-10^6 yr; irradiation by heavy ions may be a very efficient weathering process of NEOs.

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

1. Introduction

Irradiation by cosmic ions and bombardment by interplanetary dust are processes believed to induce space weathering, i.e., time-related processes able to change progressively the solar reflectance spectra of airless planetary surfaces.

Space weathering was studied by Pieters et al. (1993) on lunar soil and proposed by Chapman (1996) to explain the surface variations of Asteroid 243 Ida measured by the Galileo spacecraft. According to this description, space weathering produces a progressive change in the surface color of an atmosphereless body which grows darker in time, while its reflectance spectrum becomes redder.

Space weathering processes should explain the spectral diversity among objects of the same population, e.g., main-belt asteroids belonging to dynamical families, near-Earth objects (NEOs), trans-neptunian objects (TNOs) and Centaurs.

In the Laboratory of Experimental Astrophysics in Catania, we are performing ion irradiation experiments of ices (CH_3OH, CH_4), silicates (olivine, pyroxene), carbonaceous materials (bitumens) and meteorites

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(Epinal, Murchison, Tagish Lake) to simulate the effects of space weathering on minor bodies of the Solar System. In these experiments we use different ions (H^+, He^+, O^+, Ar^+, Ar^{++}, etc.) having different energies (30-400 keV) to study the changes induced on reflectance spectra.

It has been shown that ion irradiation of asphaltite (bitumen) causes a flattening of the reflectance spectra that can explain the diversity in spectral slope among Kuiper Belt Objects (KBOs) (Moroz et al. 2004). Here we review some results regarding ion irradiation of frozen (16 and 77 K) methanol (CH_3OH) and water-methanol (1:1) mixtures, and of Epinal (H5), an ordinary chondrite meteorite. With our experimental setup we can collect reflectance spectra of both rocky or icy samples (16-300 K) placed inside a high vacuum chamber, before, during and after irradiation. Experimental details are described elsewhere (Strazzulla et al. 2001).

2. Irradiation of methanol

Methanol has been suggested to be present in comets, where its abundance has been estimated to be on the order of few percent with respect to the dominant water ice (Mumma et al., 1993), and varies among different comets, some appearing to be CH_3OH rich.

Methanol has been tentatively identified also on Centaur 5145 Pholus: Cruikshank et al. (1998) observed the methanol band around 2.27 μm, although the band around 2.34 μm has not been observed, and modeled near-IR (NIR) spectra with a multicomponent ensemble containing both refractories (silicates and carbons) and ices (water and methanol). The abundance of methanol would be comparable to that of water ice.

Both in the case of comets and of Pholus, methanol could be subjected to ion bombardment from different cosmic ion populations in the various stages of evolution (pre-solar dust in the interstellar medium, pre-solar nebula, comet or solid object in the outer Solar System; e.g., Strazzulla, 1997).

We have investigated the effects induced by ion irradiation on frozen methanol at two different temperatures (16 and 77 K). In Fig. 1 we report the reflectance spectra of virgin and irradiated CH_3OH at T = 16 K and T = 77 K. Three irradiation steps with 200 keV H^+ ions are shown, up to a fluence of 5×10^{14} H^+ cm^{-2} (11 eV/16 amu, amu = atomic mass unit). The thickness of the film was about 1 μm, so that the ion beam irradiated the whole sample thickness: the penetration depth of 200 keV H^+ ions in a CH_3OH film is indeed about 2.2 μm, as estimated using the SRIM code (at http://www.SRIM.org/, Ziegler et al., 1985).

Virgin methanol is a simple alcohol and its spectrum, in the studied spectral range, exhibits two bands at 2.27 and 2.34 μm attributed to the combinations of the C-H asymmetric stretching and deformation modes and to the combinations of the C-H symmetric stretching and deformation modes respectively (Cruikshank et al., 1998).

After irradiation the spectrum of methanol changes dramatically. New bands appear at 2.33, 2.35, and 2.38 μm that we attribute to CH_4, CO, and CH_4, respectively (Brunetto et al., 2005). The amount of newly formed CO and CH_4, at the investigated doses, is estimated to be about 0.1 with respect to methanol abundance. Moreover the intensity of the CH_3OH band at 2.34 μm decreases more strongly than that of the 2.27 μm feature. At the high doses the band at 2.34 μm almost disappears. In both of the experiments (16 and 77 K) it is also apparent a reddening of the spectra, together with a (not shown) darkening. We have also verified that the results here presented are still valid when mixtures water-methanol are considered, irradiated with 30 keV He^+ (Brunetto et al., 2005).

For ion fluences higher than 10^{15} H^+ cm^{-2} the newly formed molecules are in turns destroyed; ion irradiation induces a progressive carbonization of the target, and the irradiated icy sample evolves towards a complex carbonaceous refractory structure. This organic residue, that we refer to as IPHAC (Ion Produced Hydrogenated Amorphous Carbon), is stable upon thermal annealing to room temperature.

Ions colliding with molecular solids cause the rupture of chemical bonds. The recombina-

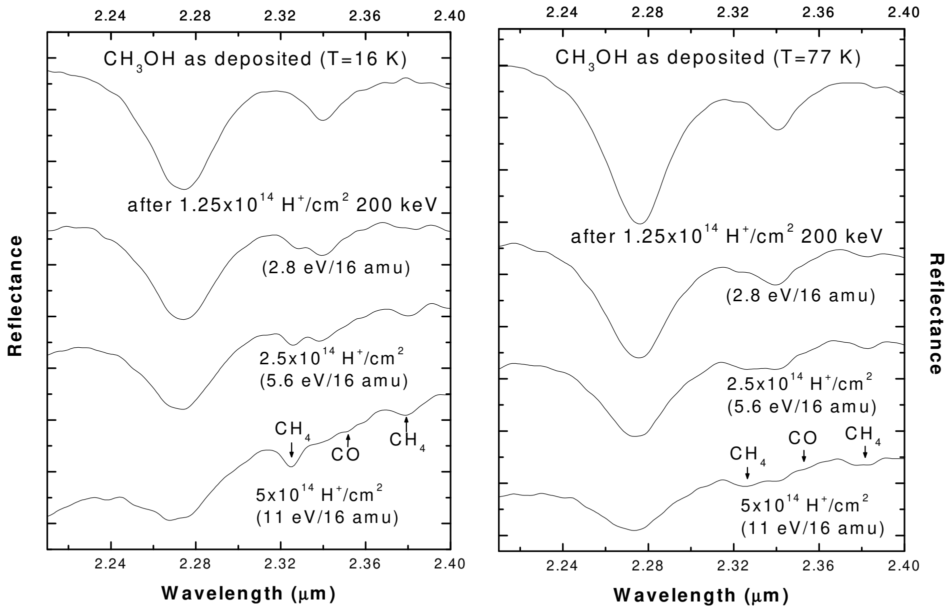

Fig. 1. NIR reflectance spectra (2.2-2.4 μm) of ion irradiated methanol at T = 16 K (left) and T = 77 K (right), offset for clarity. The methanol bands decrease, in particular that at 2.34 μm; bands appear from newly formed CO and CH_4. The spectrum gets redder as the ion fluence increases.

tion of fragments produces newly synthesized molecules as well as an alteration of the structure of the sample (radiation damage and/or amorphization). Because both the profile and the intensity of the IR bands depend on the chemical composition of the bulk matrix and on its structure, it is not surprising that the relative intensities of different bands of the same species vary. In particular, as observed in the present case for the CH_3OH bands, the symmetric modes are weakened with respect to the asymmetric modes.

Our results can be a case for some small bodies in the outer Solar System, such as Pholus: its surface could in fact have been exposed for a long time to ion irradiation at the various stages of its evolution. Let us consider, as an example, only the post accretion irradiation by galactic cosmic rays. Cruikshank et al. (1998) quote that the upper 10 m of the surface (depending on density) accumulated a dose of 1.3×10^{12} ergs cm^{-3} that, for a mean molecular weight of 16 and a density of 0.5 g cm^{-3}, corresponds to about 40 eV/16 amu, i.e., on the order of magnitude that we used in our experiments.

The temperature of Pholus surface is estimated to vary between 40 and 90 K. Our experiments indicate that for different ions (H^+, He^+), in a wide range of energy of the incoming ions (30-200 keV), and temperature (16-77 K), the intensity of the methanol band at 2.34 μm strongly decreases with respect to the one at 2.27 μm. Pholus surface could then be rich of processed materials, and the fact that the band at 2.34 μm was not observed could be indicative of ion irradiation processes.

Laboratory experiments on methanol are also valuable to simulate variations in the slopes of the VIS-NIR spectra that are observed to occur in the small bodies of the outer Solar System. Indeed, the existing observational data of these colors (spectral slopes) show a continuous spread of objects with colors from very red (as it is the case for Pholus) to essentially dark (e.g., Barucci et al., 2001, and references therein).

Laboratory results indicate that whatever is the irradiated hydrocarbon, it is converted to a refractory, insoluble residue (e.g., Strazzulla and Johnson, 1991; Strazzulla, 1997). The slope of the reflectance spectra of such a residue changes with ion fluence.

Natural solid bitumens are possible analogs for cometary and asteroid organics (Moroz et al., 1998); laboratory experiments (Moroz et al., 2004) show that ion irradiation of bitumens neutralizes the spectral slopes (0.3-2.5 μm) of these red organic solids. On the other hand, in the experiments here reported (2.2-2.4 μm), the reflectance spectrum of methanol, which is flat and bright at the beginning, gets redder after ion irradiation (Fig. 1).

Work is in progress in our laboratory to study, by in-situ reflectance spectroscopy, the ion induced evolution in the colors of different samples, including deposited ices such as methanol, that are relevant to the surface properties of distant objects in the Solar System.

3. Irradiation of Epinal meteorite

Ordinary chondrites have spectral properties that are near the lowest limit (least reddened spectra) of the range of variation of the spectral slopes of NEOs, while the upper region better represents the spectra of the S-type main-belt asteroids (Binzel et al. 1996, 2004).

It is largely believed that the diversity in the spectra of NEOs and S-type asteroids are due to time dependent surface weathering processes. In this scenario, NEOs with spectra similar to those of S-type main-belt asteroids would be those with older surfaces, while objects most closely resembling ordinary chondrite meteorites would have the youngest surfaces probably rejuvenated by collisions.

A limited number of laboratory experiments have been performed to simulate space weathering effects by solar wind on silicate materials. Experiments made by pulse (6-8 ns) laser irradiation of olivine, assuming to simulate micrometeorite bombardment, evidenced darkening and reddening of the reflectance spectrum over 0.25-2.5 μm wavelengths (Yamada et al. 1999; Sasaki et al. 2001).

Here we present results obtained by ion irradiaton of Epinal, an ordinary chondrite (H5) meteorite, kindly provided by the Specola Vaticana Observatory.

Bulk samples (surface area of about 2 cm^2) of the Epinal meteorite were irradiated with heavy ions, namely 60 keV Ar^{++}, simulating solar wind heavy particle irradiation. Spectra taken at increasing ion fluences are shown in Fig. 2 (left panel).

The spectrum of Epinal exhibits the two bands at 1 (band I) and 2 (band II) μm which are typical of ordinary chondrites. The band at 1 μm is due to the presence of ferrous iron in both olivines and pyroxenes. The band at about 2 μm is attributed to pyroxenes (Adams 1975).

Irradiation of the external layers (the penetration depth of 60 keV Ar^{++} ions in the meteorite sample is about 500 angstroms) of Epinal produces a progressive darkening and changes in the slope of the spectra. The spectral slope across band I increases dramatically, while the depths of both band I and band II become weaker.

We performed some experiments with H^+ ions (30 keV) that produced modest differences in the spectra. 30 keV protons deposit their energy in the target mainly through ionizations and excitations (inelastic scattering). 60 keV Ar^{++} ions mainly interact with target nuclei through elastic collisions. Thus, our results suggest that spectral alteration is produced because the displacements of the nuclei of the target.

In the right panel of Fig. 2 the initial spectrum of Epinal and that obtained at the highest ion fluence are shown normalized to unity at 0.7 μm. Figure 2 shows also a comparison between laboratory spectra of Epinal and those of three S-type NEOs: 25143 Itokawa (1998 SF36), 1916 Boreas (1953 RA), and 19356 (1997 GH3). All spectra are normalized to 1 at 0.7 μm.

Asteroid 1997 GH3 exhibits the flattest spectrum, i.e., it is representative of less al-

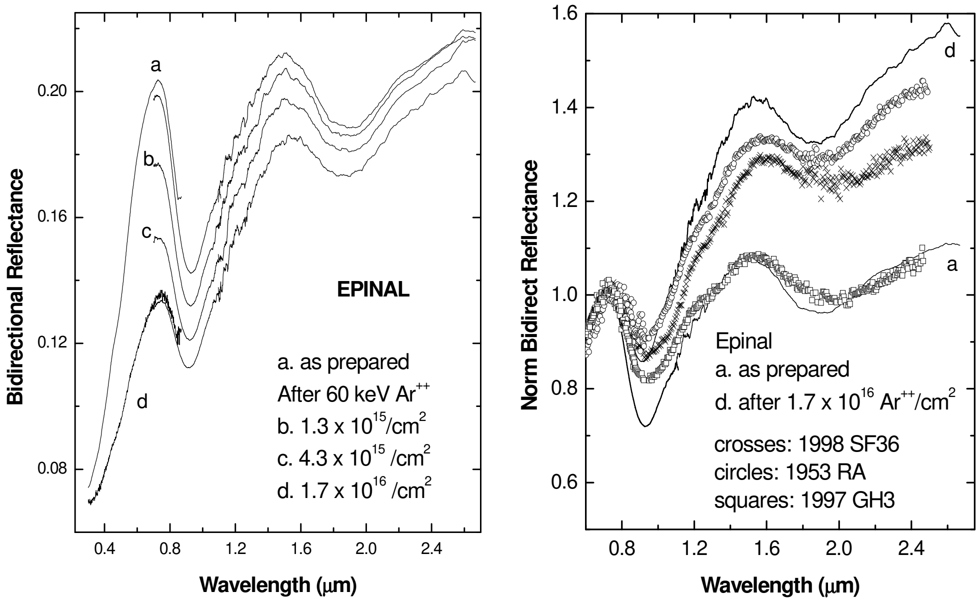

Fig. 2. Left: UV-Vis-NIR (0.3-2.67 μm) reflectance spectra of the ordinary chondrite meteorite Epinal before irradiation and after three different ion fluences (60 keV Ar^{++}). Spectra in the range 0.7-1.11 and 1.1-2.67 μm have been collected in situ (high vacuum). Spectra in the range 0.3-0.85 μm have been collected ex situ (at atmospheric pressure). Right: the initial reflectance spectrum of Epinal and that obtained at the highest ion fluence are shown normalized to 1 at 0.7 μm. The normalized observed spectra of three NEOs are also shown for comparison.

tered objects (or of a surface rejuvenated by a recent collision). Its spectrum is close to that of unprocessed Epinal, but as evidenced by the less intense band I, the asteroid has a lower content of olivine with respect to the meteorite. Asteroids 1916 Boreas and 25143 Itokawa have altered surfaces but their spectra are within the range of variations observed in the laboratory after ion irradiation of Epinal.

From the normalized spectra of Epinal and of 13 NEOs (10 Amors and 3 Apollos) we have calculated the spectral slopes between about 0.7 and 1.55 μm as the slope of a linear continuum across band I (Strazzulla et al., 2005), and clearly demonstrated that, though showing a different depth for band I, irradiated Epinal well reproduces the whole spread of spectral slopes observed for those 13 S-type NEOs.

Solar wind particles dominate the ion population in the near-Earth region. Solar wind ions have an energy of about 1 keV amu^{-1}. The flux of Ar ions (36 keV) in the solar wind has been measured to be $4{\times}10^2$ ions cm^{-2} sec^{-1} (Jull et al., 1980) at 1 AU (AU = Astronomical Unit) and decreases as the square of the distance from the Sun. The maximum fluence of Ar^{++} ions we used in the experiments is $1.7{\times}10^{16}$ ions cm^{-2}. This, in the near-Earth region, corresponds to an irradiation time of about $1.3{\times}10^6$ yr. However a wide range of the solar wind ions (beyond Ar) may contribute as well to alter the surfaces; thus we estimate that the timescale for the weathering of NEOs surfaces is on the order of 10^4-10^6 yr. This is by far more efficient than the effect due to the micrometeoritic impact simulated in the laboratory by pulsed laser irradiation (Yamada et al., 1999; Sasaki et al., 2001). Thus ion irradiation may be able to alter the surfaces of NEOs and reproduce the whole range of observed spectra on short time scales. This implies that either the surfaces exhibiting the flattest (least reddened) spectra belong to objects recently injected in the near Earth orbit or they have been recently rejuvenated "fresh" surfaces.

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