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Simulation of low-velocity bombardment of asteroid surfaces: regolith formation and reddening of the spectra *(Research Note)*

P. F. Moretti[1,2], A. Maras[2], F. Somma[3], and P. Aloe[3]

[1] I.T.I.S. G. Galilei, via Ponchielli, Latina 04100, Italy
e-mail: pierfrancesco.moretti@uniroma1.it
[2] Department of Earth Sciences University of Rome La Sapienza, P.le A. Moro 2, 00185 Rome, Italy
[3] Physics Department, University of Rome Tre, via della Vasca Navale 84, 00100 Rome, Italy

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ABSTRACT

Aims. The association of the most abundant population of meteorites, the ordinary chondrites, and the S-type asteroids through the comparison of their reflected spectra in the visible and near infrared spectrum, is still widely debated. Many asteroids show reddened spectra. To date, this reddening has been attributed to the presence of metallic nanoparticles, produced by the vaporization of Fe-bearing silicates or by a shock-induced phase transformation of metallic Fe-Ni alloys. Both the mechanisms are suggested to be related to impacts on asteroid surfaces. We show how sculpting by low-energy impacts can play an important role in the reddening of asteroid surfaces.

Methods. We used quartz micro-spheres impacting on ordinary chondrites to simulate the sculpting of airless bodies due to the low-energy bombardment of micro-meteoroids.

Results. The bombarded surfaces show that metals in ordinary chondrites maintain their dimensions while silicates are comminuted. Moreover, the spectra of the simulated surface are redder than traditional powdered meteorites.

Key words. minor planets, asteroids

1. Introduction

The most abundant class of meteorites, the ordinary chondrites (OC), has been associated with the S-type class of asteroids, whose reflected spectra in the visible and near infrared range (VIS-NIR) are often redder than those of powdered OC (Gaffey 1976; Gaffey et al. 1993; Britt et al. 1992; Cloutis et al. 1990).

First observed in lunar soils (Mc Cord & Adams 1973; Morris 1980), this reddening has been attributed to the presence of metallic nano-particles (Pieters et al. 2000; Noble et al. 2004). These nano-particles have been demonstrated to be produced in terrestrial analogs of the OC main constituents (olivine and pyroxene) by the vaporization of Fe-bearing silicates (Sasaki et al. 2001). Recently, it has been shown that an Fe-Ni phase, named martensite and often reported in OCs, reddens VIS-NIR spectra (Moretti et al. 2005). Martensite is well known in metallurgy as the hardest phase in metal alloys and is a nanostructured phase (Hoffmann et al. 1993; Shimojo et al. 2001).

"Nanostructured materials" are a broad class of materials with microstructures modulated in zero to three dimensions on length scales less than 100 nm. These materials are atoms arranged in nano-sized clusters, which become the constituent grains or building blocks of the material. Conventional materials have grains sizes ranging from microns to several millimeters and contain several billion atoms each. Nanometer sized grains contain only about a thousand atoms each. As the grain size decreases, there is a significant increase in the volume fraction of grain boundaries or interfaces. This characteristic strongly influences the chemical and physical properties of the material, including hardness.

Martensite can be produced by shock-induced processes (Levitas et al. 1998; Kadau et al. 2002) and, in particular, has been demonstrated to be produced with some industrial surface mechanical treatments (Tao et al. 2002; Zhang et al. 2003; Umemoto et al. 2003; Umemoto et al. 2004). Different treatments are used to harden steels through their surface plastic deformation. One of these is air blast shot-peening treatment, consisting of impacting the steel surface with micro-spheres at velocities of the order of several m/s (Umemoto et al. 2004). Similar impacts occur on asteroid surfaces.

Collisions in space are mainly due to dust from the local interstellar cloud and the material created by impacts within the asteroid belt. Interstellar dust has impact velocities around 25 $\mathrm{km\,s^{-1}}$ and a grain dimension distribution that peaks around 1 μm (Grun et al. 1995; Landgraf et al. 2000). Impacts with resident dust occur at much lower velocities (below 2 $\mathrm{km\,s^{-1}}$) and can involve much larger grains (Liou & Dermott 1994).

Remote observations have claimed the presence of regolith with grain sizes between 30 and 300 μm on asteroid surfaces (Chapman et al. 1975; Dolfus et al. 1989). The production of these grains should be mainly related to low quantum momentum impacts, since the gravity of small bodies would not preserve the regolith from escaping the surface. The regolith grain size distribution on the surface is still a controversial problem because different mechanisms can cause the coarser or the finer material to be segregated (Rosato et al. 1987; Robinson et al. 2001), while catastrophic events are assumed to refresh any regolith transformation.

High velocity collisions have been simulated (Davis & Ryan 1990; Hartmann 1985; Karawami et al. 1983) mainly to define

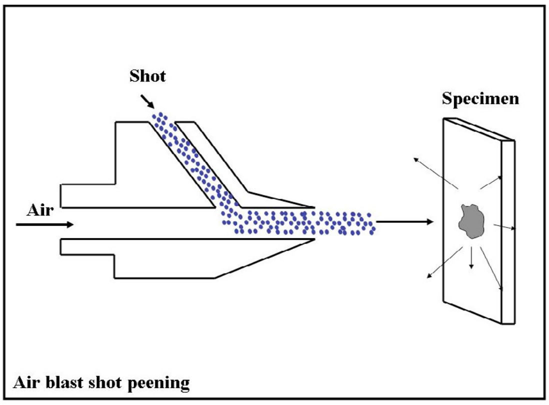

Fig. 1. A sketch of the shot-peening treatment used to simulate the bombardment of micro-meteoroids on asteroid surfaces. One hundred micron diameter quartz spheres were pneumatically propelled to impact onto 5 mm thick sections of ordinary chondrites. The air pressure controls the mean impact velocity on the target between 12.5 and 25.0 m/s.

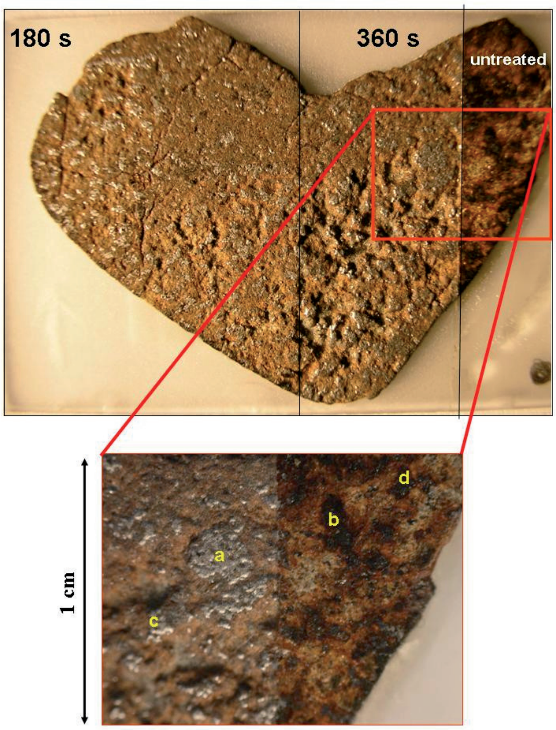

Fig. 2. Images of a shot-peened H6 S2 W1 ordinary chondrite (visible light source at 30 degrees from the vertical). The sample was first polished with a 1 μm diamond paste (untreated region) before shot-peening with 100 μm quartz spheres at 15 m/s impact velocity for 180 s and 360 s. In the bottom frame, a close up image showing the difference between the untreated and the 360 s shot-peening regions. Metallic zones have not been fragmented by the collisions, while craters formed in the stony, more brittle regions. Some of the metallic zones are marked as a, b, c and d: they appear dark in the polished and untreated region since the light reflected by their surface is not along the vertical. The metallic zones can instead appear brighter in the bombarded region, depending on the deformation of their surface.

some parameters in the scaling laws for cratering processes and phase transformations, but experiments have recently been developed involving low velocity collisions in zero-gravity conditions (Colwell 2003). In low velocity impacts, the cratering process is mainly determined by the ratio between the target mechanical strength and the gravitational energy density of the mass removed in the crater (Housen 2003). This simplistic picture has been modified as the propagation of the impact, which can alter the mechanical properties of the materials, and the porosity and cohesion of the target, also play important roles (Housen 2003; Nolan et al. 1996). Nevertheless, in small scale events such as those involved in the sculpting of airless bodies due to the bombardment of micro meteoroids, the cratering can be considered as mainly determined by the crushing strength of the target. We simulated the sculpting of airless bodies due to the low-energy bombardment of micro-meteoroids on samples of ordinary chondrites. We used 100 μm diameter quartz spheres impacting at velocities of the order of 10 m/s, whose kinetic energy corresponds to collisions with 5 μm particles at 1 km s^{-1}.

We discuss the regolith formation and, in particular, the consequences of our results in the theoretical models and observations of asteroid VIS-NIR reflected spectra.

2. Observations

The principal constituents of OC are olivine and pyroxene, with a maximum 16% of metallic Fe-Ni phases in the H type (Jarosewich 1990). Ordinary chondrites typically show Fe-Ni regions with dimensions on the order of hundreds of microns, while the stony regions can widely vary in their dimensions. Only the so-called dark ordinary chondrites show sub-micron metallic regions (Britt & Pieters 1994). We used three OC (classified respectively as LL6 S2 W3, L/LL7 S2 W2 and H6 S2 W1) to produce 5 mm thick sections which were exposed to a continuous shot-peening treatment in order to simulate the bombardment of micro-meteoroids. This thickness permits the use of standard machines for polishing the surfaces and reveal the metallic regions with optical microscopy in reflected light. We used a commercial air-blast shot-peening machine to simulate the bombardment of micro meteoroids (see Fig. 1). "Shot peening" is the process of cold working or hammering the surface of a material with small spheres of steel, ceramic or glass media pneumatically propelled, where the pressure of the air controls the mean impact velocity on the target. The shot particles create a series of overlapping dimples on the material's surface which places the upper layers of the material into compression.

In our case, we utilized quartz micro-spheres of 100 μm diameter, with impact velocities from 12.5 to 25 m/s, and exposure times from 60 to 360 s. Much longer exposure times reduce the thickness of our sections leading to a final break.

The shot peening machine provided a flux of $\simeq 3\times10^7$ s^{-1} m^{-2} for the 100 μm diameter spheres. The analysis of the surfaces after the shot peening treatment suggests that the area of the target involved by the single impact is $\simeq 10$ μm diameter, and consequently we obtain a flux on the target of approximately 3×10^5 s^{-1} m^{-2}.

Since the flux for the 1 μm diameter meteoroids around 1 AU is $\simeq 10^4$ s^{-1} m^{-2} (Grun et al. 1995), we suggest that an OC parent body surface, after a 10^7 year exposure to micro meteoroid bombardment, should look like the OCs that we simulated with a 360 s shot peening.

A typical example of the result of our simulation is shown in Figs. 2 and 3: the quartz micro-spheres have created craters corresponding to the more brittle or fragmented crystals, while the metallic regions have been largely preserved in their shape but deformed in their roughness. A detail of the surface before and after the shot-peening is shown in Fig. 3, where the selective

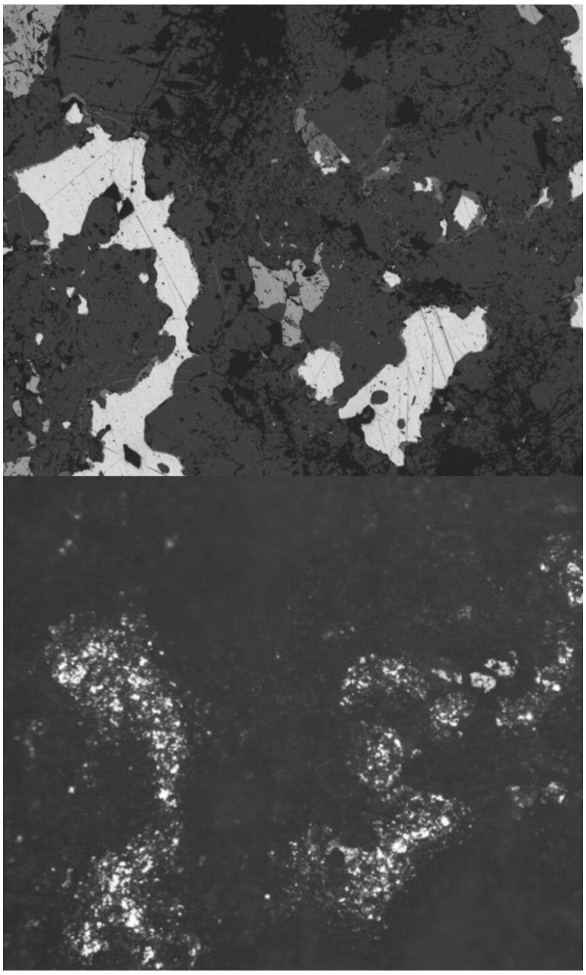

Fig. 3. *Top*: a photomicrograph from the thick section of the ordinary chondrite imaged in Fig. 1 (in reflected light optical microscopy), before the shot-peening treatment. The thin section was polished with a 1 μm diamond paste. The horizontal field of view is approximately 1.5 mm. Light regions are the metallic zones. *Bottom*: the same region after shot-peening with 100 μm quartz spheres for 180 s at 15 m/s impact velocity. The metals are mainly preserved in their dimension and shape, while in the silicate regions, a pronounced cratering occurred.

cratering process is evident. The expected resistance to comminution of metallic grains was previously reported for high velocity impact experiments, using millimeter sized aluminum spheres at 2 km s^{-1} (Cintala et al. 2004).

Due to the limitations of our experimental setup, the debris created by the bombardment is mainly lost. Nevertheless, we expect that on asteroids surfaces the eroded fragments from the metallic peaks should accumulate in the valleys, where a mixture of coarse metals and finer silicates should exist.

We powdered the OCs to a grain size of approx. 100 μm and removed the largest metallic pieces. We then reduced the grain size to approx. 30 μm and placed this final powder in the craters we obtained with the shot-peening treatment (see Fig. 4). With this procedure, we cannot exclude the presence of small metallic grains in the craters.

We then obtained spectra of the shot-peened surface filled with this powder and the spectrum of a powder with the same grain size (approx. 30 μm) for all the constituents (that is, the powder traditionally used for comparison with asteroid observations). The sample preparation we showed is different from a powder simply made of coarse metallic and finer silicate grains.

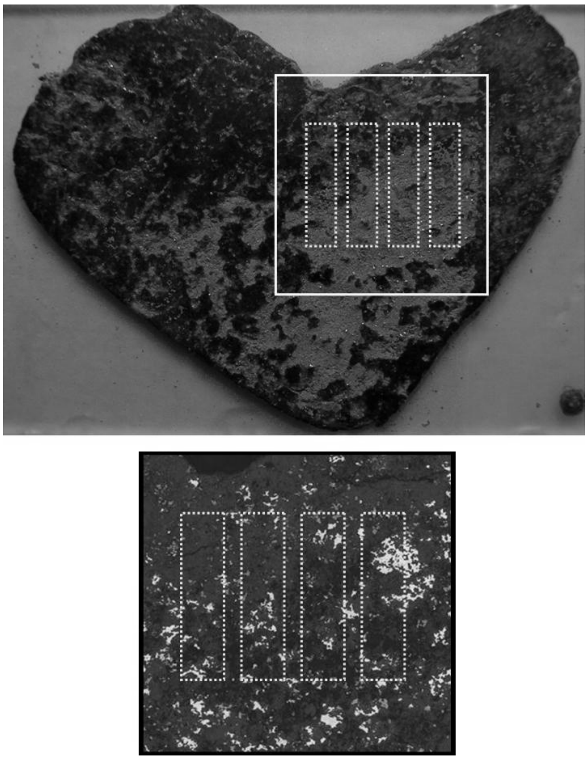

Fig. 4. *Top*: the same thick section shown in Fig. 1, where the craters obtained with the shot-peening treatment were filled with a 30 μm grain size powder obtained from the same OC (see text). The white frame indicates the region imaged below. *Bottom*: a composition of photomicrographs in reflected light of the polished section, before the shot-peening treatment. Metallic zones appear white. The dashed rectangles represent the 2×8 mm^2 areas whose spectra are shown in Fig. 5.

In fact, in our case the metallic peaks are not covered by the finer silicate powder and their reflectivity is not reduced dramatically.

We used a Perkin Elmer 900 spectro-photometer with an integrating sphere. The spectra of our simulated surface + powder are always redder than those from the powder alone (see Fig. 5). This is mainly due to the larger contribution of the redder specular reflectivity of the metallic zones with respect to the rest (Britt & Pieters 1988; Clark et al. 2001). A greater spectral contribution from metallic regions has been proposed to reproduce the S-type asteroid VIS-NIR spectra using mixtures of stony and iron meteorites (Hiroi et al. 1993), but this has never been observed in standard OC powdered samples. In our experiment, the spectra shown in Fig. 5 were obtained from areas of the shot-peened H ordinary chondrite whose coverage of the metallic peaks was estimated to be between 15 and 20%.

3. Conclusions

A simulation of low velocity bombardment on asteroid surfaces has been performed using a commercial air-blast shot-peening machine with quartz micro-spheres impacting on ordinary chondrites. The experiment demonstrated that metal phases, usually more compact than the brittle and fragmented crystals of silicates, are preserved in their size.

Even if our experiment is limited to the low-velocity regime of the collisions occurring on the surfaces of asteroids, we expect regoliths on the surfaces of their parent bodies, as well as that returned by future sample return missions, to show different

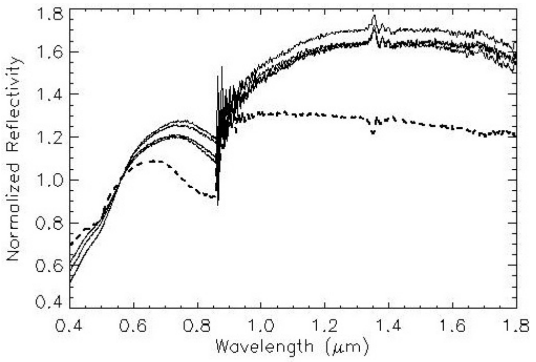

Fig. 5. Reflected spectrum of the powder alone (approx. 30 μm grain size, dashed line) obtained from the ordinary chondrite H6 S2 W1 shown in Figs. 2–4 and spectra from 2×8 mm^2 regions of the 360 s bombarded surface whose craters were filled with an powder (continuous lines, see also Fig. 4). Spectra were obtained with a Perkin-Elmer spectrometer with an integrating sphere and normalized to 0.56 μm.

grain sizes for the different phases. The importance of the different textural roughness for different components in the spectral reflectance has been previously shown using a Martian crater-like regolith target (Cord et al. 2005).

The results we showed also suggest the need for a revision of the state-of-the-art models of the spectra of mineral mixtures, such as those used to interpret the case of the NEAR mission (Britt & Pieters 1988; Clark et al. 2001; Nittler et al. 2001; Hapke 2001), where all the mineral constituents have the same grain size.

We also showed that the VIS-NIR spectra using the cratered surface filled with the powdered bulk are redder than the powdered bulk alone. This result, due to the contribution of the specular reflectivity of coarse metallic grains, could act as an unexpected mechanism in the reddening of the spectra of the ordinary chondrite parent bodies.

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