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SPACE WEATHERING IN THE MAIN ASTEROID BELT: THE BIG PICTURE

M. Lazzarin,[1] S. Marchi,[1] L. V. Moroz,[2] R. Brunetto,[3,4] S. Magrin,[1] P. Paolicchi,[5] and G. Strazzulla[3]

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ABSTRACT

The optical properties of silicate-rich asteroidal surfaces (namely, S-complex asteroids) evolve over time under the influence of several processes, known as "space weathering" (SW), and are amply analyzed in laboratory experiments. A first estimate of the spectral reddening rate, due to SW, on family S-type main-belt asteroids (MBAs; Jedicke et al.) has been confirmed and generalized, using a different approach, which also provided us with clues about the relative relevance of the various SW processes (Marchi et al.). However, in the main belt, the S complex accounts for about 40% of the listed bodies, and even less in terms of mass. Most of the remaining main-belt population is composed of spectrally featureless asteroids (i.e., with nonsilicate-dominated spectra) and can be divided into two main groups: the C complex and the X complex; the three complexes comprise up to more than 90% of the MBAs. The question as to whether SW has general observable consequences for the whole main belt is still open. In this work we show, on the basis of a wide statistical analysis, that the spectral trends due to SW are similar for the three major complexes. We have also been able to identify some underlying relevant physical processes. Our observational findings, and the related clues, are also supported by new experimental results, which are also summarized here. The resulting scenario has several important implications for the formation of evolutionary models of the main asteroid belt as well as for the existing taxonomical classification.

Subject headings: minor planets, asteroids — solar system: general

1. INTRODUCTION

S-complex asteroids are composed mainly of mafic silicates—olivine and pyroxene—and possibly some spectrally featureless phases such as plagioclase, FeNi metal, and sulfides (Gaffey et al. 1993). For what concerns SW, laboratory experiments demonstrated that their analog materials redden under both ion bombardment (Strazzulla et al. 2005; Brunetto & Strazzulla 2005) and laser irradiation (Moroz et al. 1996; Yamada et al. 1999; Brunetto et al. 2006); the latter simulates micrometeorite impacts. Thus, the spectral "slope" increases with SW. The experiments shed light on the physical processes involved: micrometeorite impacts and solar ion bombardment darken silicates and silicate-rich meteorites and also introduce positive spectral slopes (reddening) in the visible and near-infrared spectral ranges. The reddening due to micrometeorite impacts and low-energy light ions (e.g., H^+) appears to be related to the formation of nanophase metallic iron particles (SMFe; Hapke 2001; Sasaki et al. 2001), while the reddening induced by irradiation with heavy ions (e.g., N^+ and Ar^+) strongly correlates with the number of atomic displacements caused by elastic collisions in the target (Brunetto & Strazzulla 2005). The micrometeorite impacts may be important contributors to the reddening observed in the lunar samples (Hapke 2001); however, note that the different space environments and surface mineralogy between the lunar samples and the MBAs do not allow for a direct extension of this statement to MBAs. In fact, the SW on S-complex asteroids seems to be more related to solar ion flux rather than to micrometeorite bombardment (Marchi et al. 2006). Consistently, Brunetto & Strazzulla (2005) suggested that, in terms of the astrophysical timescale, solar wind ions (both light and heavy) are more efficient than micrometeorites.

In comparison to the S complex, our understanding of C and X complexes (together more than half of the spectrally classified asteroids) is by far less satisfactory, and their mineralogical assessment is not fully established. C and X complexes are characterized by having mostly featureless visible spectra, but with different slopes: from bluish to slightly red for the C-complex asteroids and from slightly red to moderately red for the X-complex asteroids. Due to their featureless visible spectra, the only clues to their composition can be found with the help of NIR observations and with the use of meteoritic—assumed—counterparts.

Carbonaceous chondrites (CCs) have been suggested as possible fragments of some C-complex asteroids on the basis of their spectral match and low albedo (∼0.07; Johnson & Fanale 1973). Although CC meteorites are dominated by silicates (anhydrous and/or hydrated) by mass, their optical properties are dominated by fine-grained opaque phases (e.g., sulfides) and organics. The response of the latter phases to SW may be different from that of silicates (see below); thus, it is not obvious how CCs (and C-complex asteroids) would behave under SW.

The situation is even more complicated for the X-complex asteroids. Good spectral matches have been found with different meteorite clans like enstatite chondrites (E chondrites), aubrites, and irons (Burbine et al. 2002; Lazzarin et al. 2005; Lazzarin et al. 2004). Thus, the possible composition should range from Fe-free low-Ca pyroxene, enstatite, metal, and sulfides (E chondrites and aubrites) to FeNi metal for the irons. This is also confirmed by the wide albedo range observed. Due to recent observational work (Hardersen et al. 2005), features

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[1] Dipartimento di Astronomia, Università di Padova, vicolo dell'Osservatorio 2, 35122 Padova, Italy; lazzarin@pd.astro.it, marchi@pd.astro.it, s.magrin@pd.astro.it.

[2] Institute of Planetology, University of Münster, Wilhelm-Klemm Strasse 10, D-48149 Münster, Germany; and Institute of Planetary Research, German Aerospace Center, Rutherfordstrasse 2, D-12489 Berlin, Germany; Ljuba.Moroz@dlr.de.

[3] INAF–Osservatorio Astrofisico di Catania, via S. Sofia 78, I-95123 Catania, Italy; rbrunetto@oact.inaf.it, gianni@oact.inaf.it.

[4] Dipartimento di Fisica, Università di Lecce, via Arnesano, I-73100 Lecce, Italy.

[5] Dipartimento di Fisica, Università di Pisa, largo Pontecorvo 3, 56127 Pisa, Italy; paolicchi@df.unipi.it.

at 0.9 and 2 μm have been detected in the spectra of some moderate-albedo X-complex asteroids (i.e., M-type asteroids), and they have been assigned to mafic silicates (low-Fe, low-Ca pyroxene). These findings might favor a mantle-core origin, ruling out the link with undifferentiated E chondrites. However, absorption features at 3 μm have been detected and interpreted as being due to phyllosilicates (hydrated silicates), and this is inconsistent with the high-temperature scenario for a differentiated parent body (Clark et al. 2004; Lagerkvist et al. 2005).

Also, the experimental background of SW effects on terrestrial and meteoritic analogs relevant for C and X complexes is not well established, basically due to a lack of experimental work. The first experiments conducted on natural complex hydrocarbon materials (asphaltite and kerite) showed that materials become less red (the slope decreases) and less dark after irradiation with low-energy ions (Moroz et al. 2004a), suggesting a similar SW trend for organic-rich objects, opposite to that defined for silicates. Laser irradiation of a mineral mixture containing 5 percent by weight (wt.%) kerite mixed with hydrated and anhydrous silicates, metal, and calcite showed a slope decrease and darkening (Hiroi et al. 2003). The same effect was observed after laser irradiation of a unique reddish CC Tagish Lake (Hiroi et al. 2004) containing only 2.5 wt.% of organic material. However, no ion irradiation (presumably the dominant SW process for asteroids; Marchi et al. 2006) experiments have been performed on Tagish Lake, organic-poor mineral mixtures or on pure hydrated silicates and sulfides, the latter being the main darkening agents in primitive CC meteorites. The relative abundances of organics compared to silicates and other constituents, the carbonization degree of organics, as well as the texture of constituents may define which particular SW trend (increase or decrease of the slope) would dominate. Observations of the slope-diameter anticorrelation for dark Cybele and Hilda outer belt asteroids might suggest the dominance of the organic-like SW trend on these distant (3.3–4 AU) objects (Lagerkvist et al. 2005).

As for the bright X-complex analog materials, no experiments have been performed yet.

2. SPECTRAL TRENDS IN THE MAIN BELT AND NEW EXPERIMENTAL WORKS

With the aid of the method used for the S complex (Marchi et al. 2006), it is possible to obtain some relevant observational results concerning the above-mentioned problems. We used the largest existing MBA spectroscopic database, consisting of 559 S-complex, 418 C-complex, and 250 X-complex MBAs from the second phase of the Small Main-Belt Asteroid Spectroscopic Survey (SMASSII; Bus & Binzel 2002). The model takes as input a state-of-the-art estimate (Bottke et al. 2005) of the mean collisional age of the asteroids as a function of their size. Combining the ages with the asteroid's orbital configuration (namely, the semimajor axis and eccentricity), we obtain a parameter proportional to the exposure of the ion flux from the Sun. With respect to the previous model (see Marchi et al. 2006 for a detailed explanation of the definition of exposure), we improve the age estimates for the members of dynamical families, which can be set, if less than the collisional age, equal to the age of the family (we used the recent and reliable estimates of Nesvorný et al. 2006). We also improve the exposure estimate by using the more stable proper elements (Knežević & Milani 2003) instead of the osculating elements. We use the spectral slopes between 0.52 and 0.92 μm to characterize the degree of SW. Figure 1 shows the slope-exposure distribution for the three major complexes. The most striking result is that for all the complexes, the trends are very clear and statistically significant (the two-tailed probability, P, is <0.01%, ∼0.7%, and ∼0.8%, for the S, X, and C complexes, respectively). The trends are, respectively, (24.9 ± 4.6), (14.6 ± 3.2), and (8.8 ± 5.4) × 10^{-5} $\mu\mathrm{m}^{-1}$ Myr^{-1} AU^{2}. Despite these significant statistical trends, spectral slopes of individual objects exhibit a strong scatter. This is certainly due to several parameters, like differences in composition, surface roughness/texture, and inaccurate age determination; we use a mean value and neglect possible dynamical corrections. Nevertheless, the quality of the results, in statistical terms, is also supported by the overall agreement of the linear fits with the average curves. Notice that the trend we find for the S complex is slightly reduced compared to that previously found (Marchi et al. 2006). Notice also that the trend we find for the C complex seems to be opposite to the only one available in the literature for family C-complex asteroids (Nesvorný et al. 2005). In order to understand the trend obtained by Nesvorný et al. (2005) using photometric rather than spectroscopic data, we selected the C-complex family members present in our database. Within the uncertainties due to the small number of objects, we obtain that slope anticorrelates with exposure (and age), in agreement with Nesvorný et al. (2005). The discrepancy between this trend, effective only for family members, and the general, opposite, one is unclear, and it is probably due to some "sampling" effect: the listed families may not be representative of the average composition of the whole C-complex population of the main belt. The anticorrelation of family members is mainly due to five families (24 Themis, 490 Veritas, 668 Dora, 1128 Astrid, and 1726 Hoffmeister) located beyond 2.78 AU, where the abundance of organics (or other nonsilicate components) might be higher than in the inner part of the main belt. Indeed, it has been suggested that the slope-age anticorrelation within C-complex families may be due to an organic-like SW trend

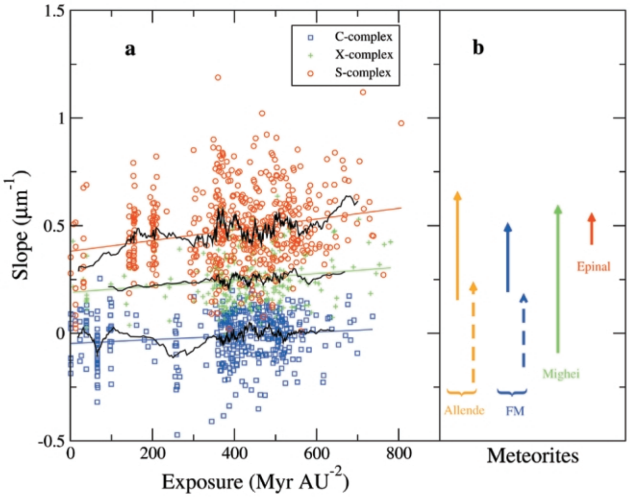

FIG. 1.—Spectral trends for MBAs and their comparison with laboratory experiments. (*a*) Slope-exposure trends for the three major complexes of the main belt. Average curves (20 points) are also shown (see text for further details). (*b*) The arrows indicate the results of the first ion-bombardment experiments performed on CC meteorites (namely, Allende and Frontier Mountain [FM] 95002); the solid arrows are for powders, while the dashed ones are for pressed samples. The results of the laser irradiation of the Mighei meteorite (dust sample) are also shown. For comparison, ion bombardment on a slab of Epinal meteorite (OC) is overplotted (for experimental details, see Fig. 2). In all cases, the arrow's starting point corresponds to the slope of the untreated samples, while the end of the arrow corresponds to the irradiated ones.

(Moroz et al. 2006). Our conclusion is also supported by the discovery of two active Themis family asteroids (Hsieh & Jewitt 2006), which are certainly compositionally very different from the usual C-complex asteroids; it is possible that a relevant part of the Themis family itself has similar peculiar properties.

Although the general trends are similar, it must also be noted that the reddening rates decrease, passing from the S complex to the X complex to C complex. This may be related to an increasing content or decreasing grain size of nonsilicate components.

This new observational scenario can also be supported by new laboratory experiments, which are briefly reported here. We performed ion-bombardment experiments on two CCs, namely, CV3 Allende and CO3 Frontier Mountain 95002. Results and experimental details are presented in Figure 2. Both meteorites redden under ion fluence irrespective of the sample preparation (powder vs. pressed pellet). A similar spectral effect (see Fig. 2) is observed after laser irradiation of the CM2 chondrite Mighei (Moroz et al. 2004b).

Similar considerations may hold for X-complex asteroids, but so far no experiments have been performed on possible analogs, such as aubrites, E chondrites, or irons.

For a better comparison, Figure 1*b* also shows the reddening rate of these experiments and the ion-irradiated H5 ordinary chondrite (OC) Epinal (Strazzulla et al. 2005). Notice that the arrow lengths do not quantify the absolute degree of reddening; they simply reflect the experimental conditions and cannot be used for a quantitative comparison.

3. CONCLUSION: THE BIG PICTURE

We have shown that a statistically significant slope-exposure correlation holds for all the major MBA complexes and that this result may be understood consistently in terms of the new experimental data. There are a few major implications for asteroid science. First, it entails that the response to SW of (nearly) all kinds of asteroids between 2 and 3.3 AU (where most of the asteroids in our sample are located) be silicate-like. This limit corresponds to the farthest distance where the Sun-related alteration effects have been measured so far. Moreover, the existence of a reddening trend for the C complex might define an upper limit (of a few percent) to the content of organics within this region. The new SW simulation experiments on CCs confirm the general robustness of our scenario. In addition, the existence of slope-exposure trends indicates to us a Sun-related origin of the asteroidal SW, at least in this region.

The low content of organics that we are suggesting may be explained either in terms of their low original abundance in the part of the Solar Nebula from which MBAs originate or as being due to a significant contamination by inorganic materials, probably injected from the terrestrial region (e.g., within the outward migration model recently proposed Bottke et al. 2006). The existence of a slope-exposure anticorrelation among C-complex families may also be due to the existence of bodies with a different composition (as a result of the compositional gradient in the Solar Nebula or due to interlopers from the outer solar system), perhaps with higher contents of surface organics. The case of the active Themis member asteroids may support this conclusion.

Concerning the moderate- to high-albedo part of the X complex, if the SW-induced reddening is related to any change in the chemical state of Fe (e.g., SMFe formation), then E chondrites and aubrites containing only Fe-free silicates cannot be dominant components of the complex. However, additional SW experiments on pure Fe-free silicate targets are required. Finally, the emergence of similar reddening trends for C and X complexes may cause a severe ambiguity between the two complexes since reddened (exposed to SW) C-complex asteroids can be spectrally very similar to fresh X-complex asteroids, as shown by our new ion-bombardment experiments. It is also possible that space-weathered C-complex asteroids may be confused with low-albedo X-complex asteroids. On the basis of the available albedo data, this ambiguity might affect a large fraction—of about 50%—of X-complex asteroids.

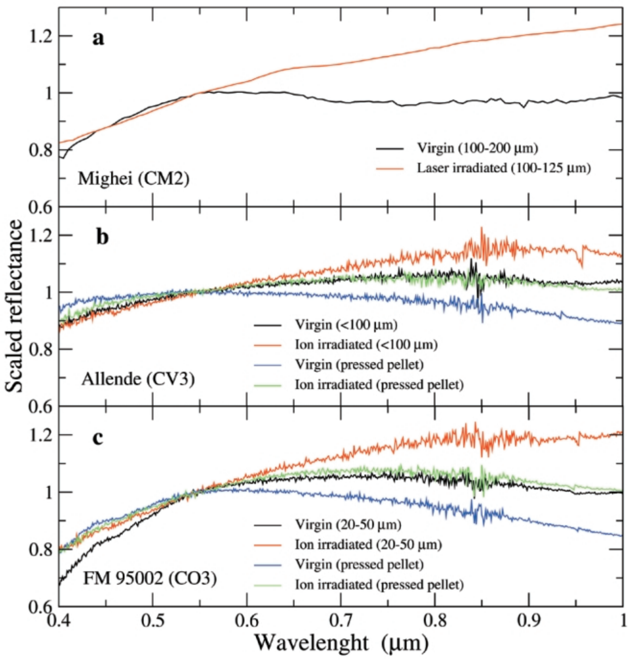

FIG. 2.—Reflectance spectra of three CC meteorites before and after laser and ion irradiation. (*a*) Laser irradiation experiments on CM2 Mighei samples (Moroz et al. 2004b; Shingareva et al. 2004) have been performed under a vacuum of $\sim 10^{-4}$ Hg using an ND-YAG multiple-pulse laser with a pulse frequency of 30–40 kHz and pulse duration of 0.5–1 μs. Bidirectional ($i = 30°$, $e = 0°$) reflectance spectra of nonirradiated and laser-irradiated Mighei coarse powders shown in the upper panel were acquired at the NASA-supported RELAB facility. (*b*) We performed ion-bombardment experiments and in situ spectral reflectance measurements of powdered meteorites and pressed powders in a vacuum chamber (pressure below 10^{-7} mbar) facing an FTIR spectrometer (Bruker Equinox 55) and interfaced to an ion implanter, Danfysik 1080-200. The ion beam produces a circular (about 4 cm^2) spot on the targets. We used fluences up to 9.4×10^{15} Ar^{++} cm^{-2} (energy of 400 keV) and currents below 1 μA cm^{-2}. In our setup, we can acquire in situ bidirectional reflectance spectra ($i = 0°$, $e = 45°$) and ex situ hemispherical reflectance spectra (see Brunetto & Strazzulla 2005 for details). Shown here are the ex situ spectra, but in situ spectra show strong reddening after ion irradiation as well. Note the significant difference in spectral slopes between powders (grain sizes are reported for each sample) and pressed samples; variations in surface roughness/texture may contribute to the scatter in spectral slopes, typical of all main-belt complexes (see text). All spectra are scaled to 1 at 0.55 μm.

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