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Collisional evolution and reddening of asteroid surfaces – I. The problem of conflicting time-scales and the role of size-dependent effects

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ABSTRACT

Space weathering is the generic term used for processes that modify the optical properties of surfaces of atmosphereless rocky bodies under exposure to the space environment. The general agreement about the relevance of the effects of space weathering on the spectral properties of S-complex asteroids fails when some basic quantitative estimates are attempted. In particular, there is severe disagreement regarding the typical time-scales for significant spectral reddening to occur, ranging from 1 Myr to 1 Gyr.

Generally speaking, the spectral reddening of an individual object can be considered as the sum of three terms, one (which is relevant for statistical analyses) depending on the exposure of the object to space weathering during its lifetime, a second one due to the original surface composition, and a third one (a noise term) due to the combination of poorly constrained effects (e.g. structure and texture of the surface).

The surface of an asteroid is usually covered by regolith, and its presence and properties presumably play a critical role in the weathering processes. In this paper, we discuss the role played by collisional evolution in affecting the spectral properties of asteroids and refreshing the surfaces due to the formation of ejecta, and the necessity of a simultaneous modelling of collisions and weathering processes. We introduce a new idea, based on the possibility of a sort of saturation of the refreshing process whenever a massive re-accumulation of the impact ejecta takes place. In this case, a dependence of the overall reddening on the asteroid size should naturally come out. We show that this conclusion is indeed supported by available main belt asteroid spectroscopic data.

Key words: meteorites, meteors, meteoroids – minor planets, asteroids: general.

1 INTRODUCTION

The spectral reddening of asteroidal surfaces is of fundamental importance to understanding the spectral properties derived from remote observations of asteroids and for making a reliable comparison with the corresponding laboratory meteorite data. The process of spectral reddening for S-complex asteroids has been recognized for a long time (Chapman & Salisbury 1973; Gaffey et al. 1993), and it has been attributed to the alteration of surface optical properties under exposure to the space environment. More recently, several contributions from laboratory experiments (Hiroi & Sasaki 2001; Strazzulla et al. 2005), in addition to dedicated asteroid observations and modelling, have disclosed several intriguing aspects of the reddening processes (Jedicke et al. 2004; Marchi et al. 2006a, hereinafter P1; Paolicchi et al. 2007). It has also been shown that, to some extent, the overall results obtained from S-complex asteroids may play a non-negligible role also for other main taxonomic complexes and spectral types (Lazzarin et al. 2006; Marchi et al. 2010).

On the basis of a statistical analysis of a large sample of visible spectra of S-complex asteroids (P1), it has been suggested that the solar wind is the dominant cause of the reddening. This conclusion was based on the significant dependence of the spectral slope on the exposure (E) to the solar wind, namely the integrated ion flux that an asteroid received from the Sun during its past evolution. This analysis is based on a large sample of both near-Earth asteroids (NEAs) and main belt asteroids (MBAs). In a series of papers (Marchi et al. 2006b; Paolicchi et al. 2007), additional details of the process were determined, and an estimate of the reddening time-scale was given. It was found that 80 per cent of the slope reddening is reached after about 200 Myr at 1 au, or 800 Myr at 2 au (Paolicchi et al. 2007). In general, the derived correlation between the slope and the asteroid age, the latter estimated by the collisional lifetime, requires that the

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time-derivative exhibits an exponential decay: a fast initial reddening (leading to almost 50 per cent of the final reddening in a few tens of Myr) is followed by a slower increase, asymptotically pointing to saturation. Note, however, that the estimated reddening time-scale due to heavy ion bombardment is of the order of 0.01–1 Myr at 1 au (Strazzulla et al. 2005).

A recent analysis based on S-complex MBA families (Vernazza et al. 2009, hereinafter P2) claims that the solar wind is the dominant cause of the reddening. This conclusion was derived on the basis of the fast reddening time-scale (∼1 Myr) observed for two young asteroid families. Moreover, a slower residual reddening is present in their data for older families. Although P2 agrees with what has already been found by P1 about the solar wind driven space weathering, the derived time-scales differ by orders of magnitude.

To make the story more complicated, a recent analysis (Willman et al. 2010) suggests that space weathering time-scales may be very large (of the order of 10^2–10^3 Myr for MBAs), claiming agreement with a different series of laboratory experiments which assume that micrometeorite bombardment is the dominant weathering process (Willman et al. 2010, and references therein). While the time-scales found by Willman et al. are in partial agreement with some P1 results, the physical process that is the claimed cause of the reddening is completely different.

A recent comprehensive review by Gaffey (2010) points out that the consequences of space weathering may vary strongly among bodies, due, possibly, both to different physical processes and to different properties of the affected surfaces. For instance, it has been found that the space weathering of lunar regolith is likely due to the formation of nanophase iron particles (Pieters et al. 2000) produced by the vaporization of surface particles by microimpacts. It is noteworthy to recall that lunar-ray craters (e.g. Tycho and Copernicus) show a moderate reddening even if their estimated age (or the corresponding exposure to the Sun) is relatively large, of the order of hundreds of Myr (Stoffler & Ryder 2011). Microimpact vaporization, however, might have nothing to do with the reddening of asteroids, perhaps due to much lower mean impact speeds in the main belt (5 $\mathrm{km\,s^{-1}}$) compared to that on the Moon (18 $\mathrm{km\,s^{-1}}$). Moreover, even if we decide to restrict our analysis to the asteroids, severe differences come out in the weathering properties of objects that should be – in principle – rather similar (e.g. Eros and Ida). According to the conclusions of Gaffey (2010), it is not easy, and probably potentially misleading, to define a simple – uniparametric – asteroid weathering scenario.

On the other hand, both the solar wind and micrometeorite bombardment weathering processes coexist for all asteroids, even if their relative efficiency may vary depending on the heliocentric distance. The different effects of space weathering should be foremost dependent on the different properties of the impacted surfaces (composition, texture, presence of regolith, etc.). Unless we are able to find a well-defined selection criterion, which divides the asteroids into different groups, with different values of all the variables affecting the individual reaction of the bodies to the space environment, the weathering properties of *individual* bodies are difficult to assess, but the possibility of a statistical analysis and the search for a unitary statistical model remain open.

In this series of papers, we discuss the role of mini- and micro-collisions, as a potential solution to the two-time-scale conundrum (as already suggested, at a very qualitative level, in Paolicchi et al. 2009).

The role of gardening in affecting weathering properties has been discussed in the literature (see, for instance, Gil-Hutton 2002), and a quantitative model has been introduced by Willman et al. (2008, 2010). However, their models, based on some ad hoc assumptions (discussed later), seem to be not capable of fitting together the properties of the asteroids with those of ordinary chondrites (OCs). In a recent improvement (Willman & Jedicke 2011), the fit with ordinary chondrites could be attained, but the reddened surfaces of young asteroid families do not fit with the inferred space-weathering time-scale.

Note that, however, not all S-type asteroids are expected to be genetically linked to ordinary chondrites. Indeed, several observed S-types have inferred compositions incompatible with ordinary chondrites (Gaffey et al. 1993; Marchi et al. 2005), while laboratory analysis shows that ordinary chondrites may have originated from a comparatively small number of parent bodies (Burbine et al. 2002). Therefore, we caution that the average unweathered spectral slope of S-types may be different from that of ordinary chondrites.

Apart from the technical details, the essence of the problem can be qualitatively sketched in the following way. We have, on the one hand, some evidence for a short (∼1 Myr) time-scale for substantial reddening: experiments on ion implantation and the observed reddening of some of the youngest asteroid family members. On the other hand, we have also hints for a longer time-scale (∼10^2–10^3 Myr), both from micrometeorite bombardment experiments and from a significant continuation of the reddening of old asteroids. However, at a microphysical scale, both processes must be present simultaneously. Thus, if the short time-scale holds, there is no conflict, while, in the opposite case, one should understand why the faster process does not work. Moreover, if we introduce a de-weathering effect due to collisions, we can have two extreme cases: if the collisional time-scale is far shorter than that of the weathering, no significant reddening can happen at all; if it is far longer, the collisions do not affect the reddening much. Thus the role of collisions, within this scheme, may be relevant only if the gardening has a time-scale comparable to that of the weathering; this may be the case, as suggested by Willman et al. (2010), but this is not enough to solve the two-time-scale conundrum.

Thus the solution may require an additional effect to be considered. In our model, this effect is connected to the *saturation* of the spectral properties, which can take place even in the presence of frequent gardening of the surface, due to the re-accumulation of the ejecta created by an impact; this re-accumulation can partially cover the surface with already reddened layers. The relevance of the re-accumulation may differ in importance, depending on the target's size: thus, a different behaviour for small versus large objects has to be expected.

In this paper, we show new observational results in support of the above mechanism. Detailed numerical simulations of the regolith evolution and impact processes are deferred to the next paper of this series.

2 CONFLICTING TIME-SCALES

2.1 The 'short-time' camp and the problem of NEAs

The most explicit statement of a fast reddening of S-complex asteroids is presented in P2, where the analysis is restricted to a set of MBAs, namely members of dynamical families. The reddening time-scale is obtained, in P2, by the correlation of the spectral slope of asteroids (corrected to eliminate compositional effects) and their family age. The time-scale for most of the reddening to occur is obtained using data concerning two young MBA families (namely, Datura and Lucascavin) and it is of the order of 1 Myr. This value is consistent with the estimates from ion bombardment laboratory

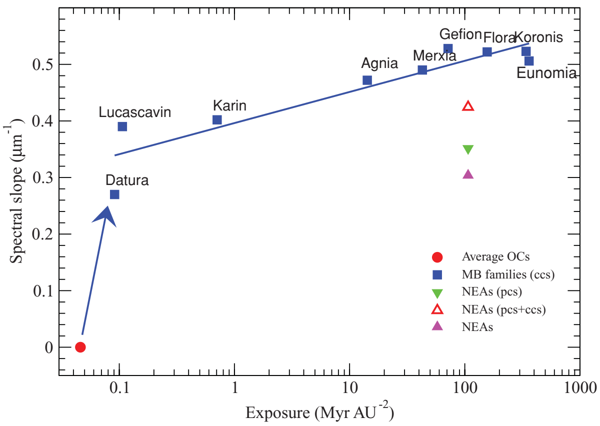

Figure 1. A slope–exposure relation corrected for chemical composition, based on the data of Vernazza et al. (2009). Average NEA data points are also included (triangles), represented with their nominal age as estimated in Marchi et al. (2006a,b) and Paolicchi et al. (2007). The three points correspond to the nominal mean slope, to the same data corrected for the perihelion term (labelled as 'pcs'), and also to a further compositional correction due to the different mean values of the olivine–pyroxene parameter between MBAs and NEAs (labelled as 'pcs + ccs'). See text for further details.

experiments (Strazzulla et al. 2005); therefore, the authors of P2 claim that the reddening of young asteroid families is due to the solar wind. However, they also find a slower further increase in the spectral slope, which, according to the authors, might be due to different physical processes. Note that the observed initial fast reddening is based on the assumption that the unweathered slopes of the S-type Datura and Lucascavin families are the same as that observed in ordinary chondrites. Otherwise, the resulting reddening time dependence may be different, even showing no intrinsic evidence of a double time-scale. However, the existence of a fast-reddening process and the observed peculiar properties of Q-type NEAs (Marchi et al. 2006b; Binzel et al. 2010) do not support this extreme possibility.

The reddening, if mainly caused by the Sun, has to be related to the exposure E to the solar wind, as defined in P1:

$$E \simeq \frac{1}{a^2(1-e^2)^{1/2}}\,(\mathrm{age}).$$

For the data sample used in P2, the slope–age and slope–E plots are similar, since the range of heliocentric distances is rather narrow (2.23–2.87 au). The slope–E relation, obtained from the same data as used by P2, is represented in Fig. 1. In the same plot, we also report the average data point from the NEA data set of Paolicchi et al. (2007). For a more detailed comparison between NEAs and MBAs, we correct the average NEA data point for surface composition and perihelion de-reddening effects due to close encounters with terrestrial planets. For the composition effect, a mean relative abundance of olivine and pyroxene, $ol/(ol + opx) \sim 0.7$, was estimated for NEAs (Vernazza et al. 2008). Thus, using the formula given in P2 to correct the slope for a different composition, the mean spectral slope of NEAs has to be slightly increased by $+0.07\ \mu\mathrm{m}^{-1}$ (Fig. 1). This data point was further corrected in order to take into account the perihelion de-reddening correction, as introduced in Paolicchi et al. (2007).

We see that, in all cases, the NEA data points are too low compared to MBAs for a similar exposure. On the other hand, the average NEA slope is similar to those of the Datura and Lucascavin families, thus implying a similar exposure. Due to the different heliocentric distance, this exposure corresponds to a typical age of the order of 0.1 Myr for NEAs.[1]

This time-scale is very short compared to all the relevant evolutionary time-scales concerning NEAs:

(i) their average ages (or collisional lifetimes) taking into account also the time passed in the main belt (the latter may exceed the dynamical lifetime of a typical NEA and have a dominant role in determining the reddening; see P1);
(ii) their typical lifetimes as NEAs;
(iii) the time-interval between significant de-weathering close encounters (Marchi et al. 2006b; Binzel et al. 2010).

In other words, the NEAs should be almost completely reddened, a conclusion that is in stark contradiction to observations.

A drastic solution to the problem assumes that the short time-scale for reddening estimated by P2 is a fluke, and the correct time-scale is of the order of hundreds of Myr. In this case, the NEA problem would be solved; however, to match ordinary chondrites and young family objects is far less easy. In fact, the typical slope of the youngest known asteroids is, for the most part, significantly redder than that of the ordinary chondrites.

It is also possible to suggest that the time-scale estimated in P2, and based only on a couple of observational points, is underestimated by, say, one order of magnitude. In this case, the de-weathering effect due to close planetary passes (Marchi et al. 2006b; Binzel et al. 2010) might do the job. This possibility should be enforced by weakening, as discussed before, the link between the slopes of ordinary chondrites and unweathered S-types.

Another, and more intriguing, possibility will be discussed in greater detail below, namely that the main difference between NEAs and MBAs should be the *size*: most NEAs are small and, if the gardening refreshing is rather fast but can be significantly weakened by the self-re-accumulation of the ejecta, then small bodies cannot become too red. See Section 3 for further discussion.

2.2 The 'long-time' camp

The long-time camp is mainly represented by Willman et al. (2008, 2010). Their time-scales are of the order of several hundreds of Myr, and a different laboratory counterpart (namely micrometeorite impacts) is suggested (Hiroi & Sasaki 2001). The long-time camp is partially supported also by the results of our group (P1). We have found that a residual reddening (20 per cent) takes place over very long ages, even of the order of 1 Gyr. However, in our model, most of the reddening takes place in the first period, according to the analysis and plots presented in Paolicchi et al. (2007).

Moreover, there is evidence for a fast reddening of some young objects (such as those of the Karin family), in substantial agreement with the short-time-camp suggestions (Paolicchi et al. 2007). Finally, the apparent Sun dependence of the weathering (the slope is more strongly dependent on the exposure than on the age: P1) strongly supports the dominance of the solar wind driven ion-implantation processes, even if it cannot be considered as final, unequivocal proof: in fact, the micrometeoritic bombardment may also depend on the distance from the Sun (Cintala 1992), as claimed by Willman et al. (2010). Note, also, that the total fluxes used in

[1] A similar conclusion is also obtained by rescaling the difference in exposure between the young MBA families and a typical NEA ($a \sim 1.5$ au; $e \sim 0.4$). The reddening time-scale of 1 Myr suggested by P2 becomes 0.1–0.2 Myr for a typical NEA.

experiments are tuned to those expected to come from the Sun, even if the laboratory rate of ion bombardment is, obviously, far larger. Thus, if the ion-implantation process is not the main cause of weathering, one should find a theoretical explanation of it.

In summary, we are facing a process characterized by two reddening time-scales: the former, of the order of a few Myr (or even less), is characterized by significant reddening of several young (and typically small) objects; the latter, of the order of 10^2–10^3 Myr, is characterized by a further reddening, towards saturation of the effect. While there is no reason to suggest that two different microphysical effects are at work (why is the faster one not able to redden after the first few Myr?), the possibility of a complex process, in which weathering and de-weathering effects are simultaneously active, seems to deserve serious scrutiny.

3 GARDENING VERSUS WEATHERING: THE MODEL

The time-scale of collisional gardening is not easy to compute, since it depends on several (partially unknown) parameters. This is also the basic reason for the forthcoming numerical simulations (see Section 5). Recent estimates, presented in the literature, differ by several orders of magnitude (Melita, Strazzulla & Bar-Nun 2009; Willman et al. 2010) and it is not easy to solve the apparent discrepancies. In this section, rather than presenting a new computation, we identify the main parameters of the problem. Essentially, the basic questions are as follows.

(i) *Question 1.* For a given asteroid size, what is the ratio between the collisional disruption time-scale (t_{cd}) and the global resurfacing time-scale – not automatically entailing a general spectral refreshing (see later in the text) – due to an individual impact (t_{gr})?

(ii) *Question 2.* Given the size distribution of the projectiles, what is the gardening time-scale (t_{ga}) due to all projectiles? The result is obtained by integrating between a maximum projectile size (D_{max}) and a minimum size (D_{min}). When is the integral dominated by the value of D_{min}?

(iii) *Question 3.* What is the minimum impactor size to be considered?

(iv) *Question 4.* If a crater is formed on a reddened region, what is the fraction of the ejecta which, refalling on to the asteroid surface, gives rise to a – partially or completely – reddened surface? This possibility has not been taken into account in previous computations. The relevance of the effect depends, obviously, on the size of the asteroid, thus introducing differences between small and large objects.

Let us consider *Question 1* first. According to the analysis presented in Willman et al. (2010) and Melita et al. (2009), the size of the resurfaced region (d_{res}) is roughly proportional to that of the impacting projectile (D), namely $d_{res} \simeq \alpha D$. Thus, the resurfaced area is α^2 times larger than the projectile cross-section. The value of α depends on various parameters, but the linear relation seems rather reasonable and robust for the typical conditions of asteroidal impacts: in fact, the size of the resurfaced region is proportional to the size of the crater (Melosh 1989), and the latter is proportional to that of the projectile (at least in the strength regime; Melosh 1989). Thus, we can adopt this as a basic rule. Consequently, it is also possible to discuss the first question: a global resurfacing follows from the impact of a projectile whose size is about $2/\alpha$ times that of the target (the factor 2 comes out from the factor 4 relating the surface of a sphere and the area of a circle with the same radius).

The value of α is not easy to estimate. According to Willman et al. (2010), and references therein, the size of the crater $d_{cra} \simeq 13D$, and the size of the resurfaced region is about 2.3 times larger than the crater size. The mean size of the resurfaced region is thus about 30 times that of the projectile (or, in terms of the area versus cross-section of the projectile, we have a factor around 10^3). However, the size of the crater might be larger: for instance, the scaling laws suggest a value approximately twice as large; moreover, the *Deep Impact* experiment (Richardson et al. 2007) suggests a transient crater, say, more than 100 times larger than the projectile. On the other hand, to compute the ratio between the resurfaced area and the crater area is even more difficult: the estimates might be a factor of $\simeq 5$ (Willman et al. 2010), or of $\simeq 25$ (Melita et al. 2009), which is intermediate between those suggested by Gil-Hutton (2002), according to which the ratio between the sizes (to be squared to convert to areas) is between 2 and 10. The above uncertainties, all together, may affect the value of α, increasing it from a minimum value of about 30 (see above), by even more than an order of magnitude, consequently strongly decreasing the gardening time-scale.

Therefore, the minimum projectile-to-target mass ratio causing a complete gardening is $\simeq 3 \times 10^{-5}$ in the conservative case, while going down to 10^{-8} in the extreme opposite case; the former value is, according to current collisional theories (Bottke et al. 2005; Holsapple 2009), smaller than that causing a catastrophic disruption but larger than that causing a complete shattering of the target (Willman et al. 2010). If, as usual, the size distribution is a monotonic decreasing function of size, it entails $t_{gr} < t_{cd}$ (maybe $t_{gr} \ll t_{cd}$). Moreover, especially when considering large targets, the role of gravity has to be taken into account.

Note that in order to evaluate the global effects of collisions, it may also be important to consider the so-called 'global-jolt', namely regolith displacement over the entire target surface due to impact-generated seismic waves. These effects can be estimated according to O'Brien, Greenberg & Richardson (2006) by the following equation:

$$D^*(g/g_t) \propto (d_t^5/v^2)^{1/3}, \tag{1}$$

where D^* is the size of the projectile producing, as a consequence of the impact, an acceleration g (in units of the acceleration due to gravity g_t) to all surface particles, and is a function of the target diameter d_t and of the impact speed v. Assuming that similar consequences follow from a similar value of g/g_t, the above formula indicates that the size of a projectile able to produce global-jolt scales as $d_t^{5/3}$. Therefore, for the same impact speed, smaller asteroids are affected by progressively smaller impactors than larger ones.

Previous arguments showed that the physics of the impact processes plays a major role in understanding the collisional disruption rate and the rate of global resurfacing. Since the outcome of a collision depends on the physical properties of the target, maybe a single recipe for all asteroids does not hold. More likely, small rubble-pile asteroids will have a different response compared to large rubble piles or monoliths.

The answer to *Question 2* requires the choice of an asteroid size–frequency distribution. The problem is not simple and will not be discussed in detail here. However, we can take a simple power law, such as the traditional 'Dohnanyi slope' (Dohnanyi 1969), obtained by simplified assumptions regarding a stationary collisional cascade:

$$\mathrm{d}N = A m^{-q} \mathrm{d}m = A' D^{-q'} \mathrm{d}D, \tag{2}$$

where A and A' are constant quantities and m is the mass. In general $q' = 3q - 2$; for the Donhanyi slope $q = 11/6$, $q' = 7/2$. If we combine this assumption with the above-quoted ansatz $d_{\rm res} = \alpha D$ [and thus $S_{\rm res} = (\pi/4)\alpha^2 D^2$, $S_{\rm res}$ is the resurfaced surface], then we obtain the relation

$$\mathrm{d}S_{\rm res} = S_{\rm res}(D)\,\mathrm{d}N \propto D^{-3q+4}\,\mathrm{d}D. \quad (3)$$

The integral has to be performed between a maximum size $D_{\rm max}$ of the order of that causing the collisional disruption (with a corresponding time-scale $t_{\rm coll}$), or, better, of the order of the projectile size that causes global resurfacing $D_{\rm gr}$, and a minimum $D_{\rm min}$ to be defined. With the above assumptions, we obtain something proportional to $D_{\rm min}^{-3q+5} - D_{\rm gr}^{-3q+5}$. If so, whenever $q > 5/3$ (or, equivalently, whenever the differential size distribution has an exponent steeper than -3), the small impacts dominate the time-scale:

$$t_{\rm ga} \simeq t_{\rm gr}(D_{\rm gr}/D_{\rm min})^{3q-5} < t_{\rm coll}(D_{\rm max}/D_{\rm min})^{3q-5}. \quad (4)$$

Assuming a Donhanyi slope ($3q - 5 = 1/2$), for an asteroid of size a few km, which should be disrupted by an $\simeq$km-sized projectile, the gardening time is of the order of $t_{\rm gr}/20$ (or less) if the minimum useful size of the impactor to cause damage is assumed of the order of a few metres (as in Willman et al. 2010), while decreasing below $10^{-3}t_{\rm coll}$ assuming $D_{\rm min} \simeq 1$ mm (as in Melita et al. 2009). The values can change also assuming a different size distribution or altering other parameters of the model.

Fig. 2 compares the analytic distribution with that of MBAs derived by a collisional evolution model (Bottke et al. 2005). The plot also shows the MBA size distribution derived by Subaru observations (Yoshida & Nakamura 2007), which is valid down to ∼1 km. All distributions are normalized at 5 km. The plot shows that the Dohnanyi slope is a good approximation of the MBA size–frequency distribution for the purpose of this work, although there may be significant local slope variations.

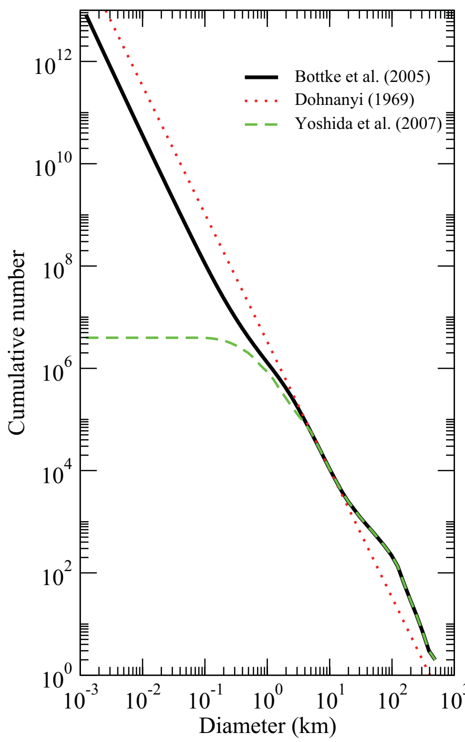

Figure 2. MBA cumulative size–frequency distributions according to the Bottke et al. (2005) model (solid black), to Subaru observations (green, significant only for bodies larger than 1 km, Yoshida & Nakamura 2007) and to the analytic Donhanyi relation (red). All curves are normalized at 5 km.

The discussion above shows that gardening is usually dominated by small impacts and that the estimate of the minimum impactor size causing resurfacing (*Question 3*) is crucial for estimating the gardening time-scale.

The last question of the list (*Question 4*), however, may affect the above conclusions. In the case of an impact followed by the recapture of all the ejected fragments, one may imagine that a non-negligible fraction of the fragments (σ) will show an already-reddened surface. This fraction should be particularly large in the limit of a very small crater. We assume that a newly formed crater excavates material from pre-existing ejecta layers. This material will be mixed up and then spread around to form a new ejecta blanket. Let β be the volume ratio of reddened particles to non-reddened particles present in the ejected material ($\beta = 0$ and 1 for non-reddened and totally reddened particles, respectively). Thus, the resulting fraction of reddened particles exposed in the new ejecta blanket is $\sigma = 0.5\beta$, assuming that half of the particles should fall showing the reddened surface.

If we neglect this effect, the maximum attainable spectral slope, due to the combined effect of weathering (with a time-scale of $t_{\rm sw}$) and collisions, should be a function of $t_{\rm sw}/t_{\rm ga}$ (Willman et al. 2008, 2010). A similar analytic toy model is discussed in Paolicchi et al. (2009). Conversely, if we take it into account, one can imagine a progressive slope saturation, with a time-scale of the order of $t_{\rm ga}/\sigma$. However, in the meantime, larger impacts take place, affecting deeper – and fresher – regions; the resurfacing causes a partial refreshing (the fraction is related to the fraction of deep, unweathered ejecta) and the slope does not completely saturate. After a longer time, these layers also become completely or extensively reddened, and the saturation is limited only from the consequences of even larger – and rarer – events. Thus, the slope saturation may take an asymptotic behaviour; one can guess that the final time-scale to approach the slope saturation may be of the order of $t_{\rm cd}$ (Paolicchi et al. 2009). In principle, one might suggest that the reddest asteroids should be those whose typical age (or lifetime) is close to the age of the Solar system. Smaller asteroids should be bluer – for the reasons discussed above – than intermediate-sized bodies; the same holds true for the larger bodies being farther from the asymptotic saturation. In the next section, we compare our ideas with observations.

4 COMPARISON WITH THE OBSERVATIONS

The discussion presented in the previous section is rather challenging. Some suggestions may be verified only with the aid of a detailed model of surface evolution, requiring numerical simulations. In this section, we introduce some observational data that seem to support our ideas.

One of the most interesting points in our model is, certainly, the different behaviour between small and large asteroids. For the former, gardening is more effective, since the re-accumulation of partially reddened ejecta is absent or strongly reduced. If the asteroids are a little bit larger, gardening is less effective, and the surface, for a given exposure, might be redder. This trend should continue as far as the asteroid size increases, reaching a plateau when the re-accumulation becomes massive or almost total. The value of the corresponding size depends on the physics of collisional processes; it has certainly to be within the one to tens of km size range, since

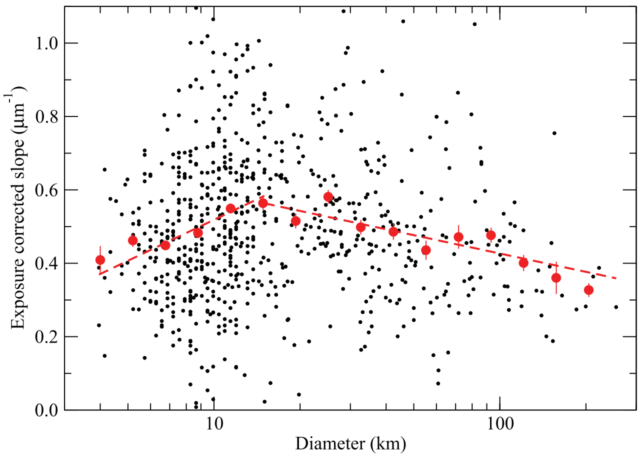

Figure 3. The exposure-corrected slope for the S-complex MBAs as a function of size. The sample is limited and incomplete at the small-size end, due to observational biases. The red dots indicate average slope values for binned intervals of asteroid sizes. A best fit has been performed with a linear trend increasing up to 20 km and a following decrease. Both trends are statistically significant. See text for discussion.

re-accumulation requires the typical speeds of the ejecta to be smaller than the escape speed.

For larger bodies, as a first approximation, we imagine the spectral slope to remain close to the plateau value, but, if the arguments presented at the end of the last section are valid, the complete 'slope saturation' is reached in a time which is of the order of the collisional lifetime. Thus, if the lifetime is larger than the possible age of the body (which cannot exceed the age of the Solar system), the slope might be slightly under the saturation value. The transition is for bodies of the order of a few tens of kilometres (see, for instance, Bottke et al. 2005). In Fig. 3, we show the exposure-corrected slope as a function of size for MBAs. The exposure-corrected slope is computed by multiplying the observed slope of a particular object by the ratio between its estimated exposure (function of the orbital parameters and of the age) and the mean (among all asteroids) exposure. Thus, the obtained exposure-corrected slopes are scattered around an average value with no correlation with the asteroid sizes. We find a statistically significant increase up to around 15 km (two-tailed probability of 2.2×10^{-11}), followed by a significant decrease beyond 15 km (two-tailed probability of 3.5×10^{-9}). Note that the exposure, used to obtain the data represented in the figure, assumes constant orbital elements (a, e) and an age computed according to the prescriptions of P1 (applied to all objects, regardless of their family membership). However, for family asteroids, a different age estimate, obtained from the analysis of the overall properties of the related family, can be obtained. We verified that the quality of the trend is not affected by the definition of the age. With all the uncertainties in the model, Fig. 3 supports our ideas.

5 NUMERICAL SIMULATIONS

As discussed in the previous sections, the basic problem to be solved for a reliable assessment (or falsification) of the ideas sketched above, and partially supported by observational evidence, is to understand what happens when a crater is formed on the surface of an asteroid. In particular, the critical issues are as follows.

(i) *Issue 1.* What happens when the projectile impacts on to a fractured (regolith, imbricated) surface and the size of the projectile is smaller than or comparable to that of the surface components? (This projectile size is represented by $D_{\min}$ in Section 3.)

(ii) *Issue 2.* What is the size and velocity distribution of the ejecta (and, possibly, the size–velocity relation)? In other words, given the size of the target, how many – and which – ejecta will fall again on to the target, and where (within the crater, close to the crater, everywhere on the surface)?

(iii) *Issue 3.* Is there any effect due to the rotational properties of the ejecta? In other words, do they, re-falling, show approximately the same external surface in about 50 per cent of the cases (consistent with common sense), or is there some subtle reason for a different value?

Handling of these problems, with the use of numerical simulations, might be successful, as indirectly shown by the possibility of explaining some observed features of Eros in terms of a dynamical model of crater ejecta (Durda 2009).

Direct simulation of regolith dynamics is becoming more feasible with advances in computer speed and numerical algorithms. Sánchez & Scheeres (2011) and Richardson et al. (2011) have begun development of discrete element methods tailored for the low-gravity environment of small asteroids. Key advances include efficient collision handling, proper accounting of surface friction, and implementation of weak non-gravitational forces that may play a critical role in the evolution of surface regolith.

Many parameters are uncertain, even if critical information and constraints may come out from the analysis of space missions (see, for instance, Richardson et al. 2007). However, new interest in sample return from and possible human exploration of small asteroids is spurring development of laboratory and computer experiments that may ultimately shed light on the weathering processes being discussed here.

We will devote a forthcoming paper to the implementation of the required numerical simulations and to the discussion of the results. Simulations being developed will allow a portion of the granular surface of an asteroid to be modelled as a collection of discrete, possibly non-spherical particles in resting contact. Impacts and/or seismic shaking of the region will be simulated to determine the extent of ejecta redistribution and overturning as a function of impactor size, speed and incidence angle.

6 CONCLUSIONS AND FUTURE WORK

The purpose of this series of papers is to establish a complete model of the space-weathering processes for S-complex asteroids, in terms of a balance between the reddening due to weathering and the refreshment of the surface due to collisional processes, introducing also the possibility of a reduced refreshment arising from the re-accumulation of collisional ejecta. In this paper, we have outlined the general features of the scenario and the most relevant uncertainties of the theory. In spite of these uncertainties, we have suggested a way to overcome the apparent conundrum of the relevant time-scales coming out from the data. The suggested explanation is also – at least qualitatively – supported by a particular analysis of the data. However, the overall complexity of the impact/cratering/ejection/re-accumulation processes requires a more detailed analysis in terms of numerical simulations, which we intend to perform.

The realistic goal of this future study is a more quantitative estimate of the involved time-scales, allowing a better general model and a more detailed statistical analysis of the data. However, we guess that the detailed interactions between external disturbances and the surface properties of any individual asteroid may lead to a wide spread of results. Their interpretation, and the related possibility of deriving some relevant surface properties for a given object, requires very sophisticated modelling. In this sense, the verification or falsification of the suggestions presented in the last section may be of some preliminary use.

Finally, we remark that a reliable model of space weathering of asteroids is not only interesting per se, but also represents a fundamental step to understanding the overall surface evolution of asteroids, including collisions, thus cratering and erosion, formation of regolith layers, etc.

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