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Space weathering (and de–weathering) of asteroids

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Abstract. The main features of the space weathering of asteroids, in particular those pertaining to the S–complex, have been analyzed and understood. However, several relevant problems remain open. In particular there are contrasting evidences for a fast reddening (timescale of the order of $10^6 yr$) and for a much slower process, by, at least, two orders of magnitude. After reviewing the status of the art and the various suggested solutions, the paper focuses on the possible de–weathering effects due to collisions: a problem which will deserve a quantitative analysis in the next future.

Key words. Asteroids – space weathering – collisions – close encounters

1. Introduction

The changes in the reflection spectra of the asteroids are among the most interesting effects of the "space weathering" processes, which affect the surface properties of several bodies of the Solar System. According to the literature, there are two main causes of space weathering affecting the asteroids: ion implantation processes (Strazzulla et al. 2005) and micrometeorite bombardment (Sasaki et al. 2001). The reddening of the surface is the main and most general observable consequence of space weathering of asteroids. The reddening is more significant for the S–complex asteroids, but a weaker effect can be found also in the C and X–complexes (Lazzarin et al. 2006).

If the weathering processes are directly –or indirectly– solar based, the reddening is faster for bodies which orbit closer to the Sun. The correct physical relation has to be a **slope–exposure** one, where the exposure is defined as proportional to: $\int_{t_0}^{t} r(t)^{-2}\, dt$ and the integration of the inverse squared distance from the Sun is carried along the age of the body, while the slope refers to the dependence of the reflectivity on the wavelength: an increase in the slope means a larger reflectivity for larger wavelengths, and thus a "redder" colour of the body. The real age of an asteroid is –generally– unknown, but an estimate can be carried (Marchi et al. 2006) in terms of its average collisional lifetime (Bottke et al. 2005). On the other hand, the ages of some dynamical families can be guessed, analyzing the overall properties of the family (Nesvorny et al. 2005); thus, if a body is a family member, a further, independent, estimate of the age can be obtained. Note that individual fragments may be younger than family age if collisional evolution takes place. Note also that the two estimates are based on different assumptions: according to the former one the body is simply an average asteroid of a given size, while the latter selects it as the outcome of a major catastrophic event. Accordingly, the estimated ages can be expected to be – and are– different: the "family–ages" are sistematically smaller.

The spectral properties of the asteroids can also be affected by their individual properties (e.g. composition) or history. We will discuss some new ideas later. For the moment, let's recall the –already established– effect of planetary close encounters (Marchi et al. 2006; Binzel et al. 2010): the planetary tides can mix the debris and regolith close to the surface, thus causing a partial refreshing. The above considerations and assumptions define a general scenario; as a result, we can obtain a best–fit slope–exposure relation (Paolicchi et al. 2007) for S–complex asteroids.

Also the compositional differences within the S-complex can be effective. The effects of the composition (especially the ratio olivine/pyroxene) have been discussed by Vernazza et al. (2009); the Authors derive a chemically–debiased slope–age relation. The same can be converted into a slope–exposure relation (Marchi et al. 2012). For a given age, or exposure, the resulting spectral slope of an asteroid can be larger or smaller depending also on the composition. In principle, one can assume that the average slope–exposure relation has to be corrected, for every asteroid, by a "compositional term" plus a "noise" (depending on the individual formation and collisional history). If so, one might also obtain indirect hints on the composition of those objects which are distinctly above –or below– the average curve (see the figure). This point will be addressed in a future analysis.

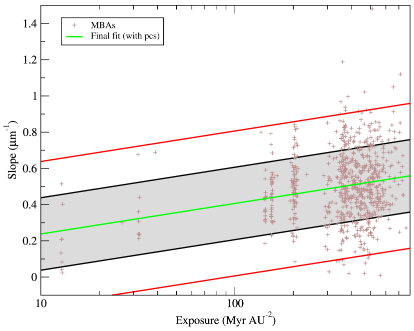

Fig. 1. The slope–exposure relation (obtained taking into account all asteroids, and taking also into account the "perihelion correction" for NEAs Paolicchi et al. 2007) is represented together with the correponing values for MB asteroids. If we assume that the individual deviations from the average are due to a "noise" term (uncertainties in age, collisional history and all that) plus a correction due to the chemical composition (Vernazza et al. 2009), one can obtain indirect hints on the chemical composition of a few asteroids, which are significantly above or below the curve.

2. The two timescales

In spite of the relevant success of general ideas concerning space weathering of the asteroids, several aspects are poorly understood, and significant problems are still open. Among them, the ambiguity concerning the typical timescales is probably the most intriguing. We summarize here the analysis discussed in Marchi et al. (2012).

We have evidence for a short timescale ($1 Myr$) reddening from a series of laboratory experiments (Strazzulla et al. 2005), based on the ion implantation process, and from the substantial reddening of members of some very young families (Vernazza et al. 2009). However, a completely different timescale (two orders of magnitude larger) comes out from other sets of experiments (Sasaki et al. 2001) (assuming micrometeritic bombardments as the source of the weathering) and from the continued reddening with increasing age, as results from the general statistical analysis of Main Belt asteroids, and from the slope–exposure relation discussed above. The best–fit relation (the slope increases linearly with the logarithm of the exposure) entails a slowing down of the reddening with time, but not an early *saturation*. The two basic physical processes should coexist; thus, from the point of view of the microphysical interpretation, the "characteristic time" should be the shorter one, and the reddening should *saturate* after a time of the same order of magnitude. If so, what is the origin of the very late reddening we find in the data?

The role of collisions in affecting the spectral properties has been discussed by various Authors in the last years (Paolicchi et al. 2009; Willman & Jedicke 2011; Marchi et al. 2012). The basic underlying process is the "gardening" of the surface due to collisions, and the resulting displacement of debris and regolith. Consequently, fresh material comes to the surface, replacing the old, reddened one: thus a general *de–weathering* effect can be envisaged.

However, a quantitative assessment of the effect is rather difficult. According to some Authors (Willman & Jedicke 2011) the gardening timescale is of the order of hundreds *My*, thus significant effects can be present only if the weathering timescale is of the same order. The non–saturation of the slope due to collisions depends on the ratio between the two timescales, and is appreciable only if the former is not by far larger than the latter. Thus a relevant effect of the gardening should be inconsistent with a fast reddening (such as the one resulting from the implantation processes).

However, according to a different analysis (Marchi et al. 2012), the gardening timescale may be shorter. Moreover (Paolicchi et al. 2009; Marchi et al. 2012) the partial or total reaccumulation of the ejecta created by a collision may cause a further effect. The ejecta which were originally on the surface exhibit a reddened side; thus the refreshing effect of a collision is reduced. After some collisional events most of the fragments have passed some time on the surface, thus the surface is asymptotically reddened; however, when a particularly intense collision takes place, also deeply buried –and thus spectroscopically fresh– fragments become ejecta: a complete "saturation" of the slope is obtained only after a full cycle of collisional evolution; thus while a partial reddening can be quick, the further reddening has to be slow, presumably with a timescale close to collisional lifetime. Unfortunately, a quantitative modelling of this effect is extremely difficult; for the moment we have only a few data indirectly supporting the idea (Marchi et al. 2012); a more systematic analysis is required, maybe with the use of discrete element methods tailored for the low-gravity environment of small asteroids (Sanchez & Scheeres 2011; Richardson et al. 2011).

To complete the overview, we recall the that a very recent analysis (Pieters et al. 2012) of data –obtained from space– concerning Vesta, has shown complex and unexpected features: the refreshing of the surface due to impact cratering has not always the same spectroscopical consequences: some "refreshed" regions are bluer, some others are redder than the average. The result may be related to the complex chemical composition of Vesta: presumably different materials, with different spectroscopical properties, are present on the surface; small collisions are mixing the regolith, thus affecting the local spectral properties. More in general, we have to remark, as already pointed out (Gaffey 2010), that the "unidimensional" model of space weathering, barely based on the slope–exposure relation, is only a simplified first–order model of the real process.

3. Conclusions

In the last decade some previous hard problems have been probably solved, at least from a general point of view: the ordinary chondrite paradox, a "hit" of the asteroid science in the 90's, seems to have been solved, and other pieces of the jigsaw are in place. Some general ideas on how the spectral properties evolve with time have been defined. However, as it usually happens in science, the flow of new data can be helpful to solve an old problem, but, at the same time, new puzzling features come into evidence. The dependence of the space weathering on a few parameters, such as the chemical composition, is not surprising. Moreover, it seems that a good model strongly requires a simultaneous analysis of weathering, collisions (at all scales) and close encounters. The final observable results may depend critically on the details of the model.

A very refined integrated evolutionary model is probably required to fully understand the variation of spectral properties with time. The most relevant difficulties are presumably related to the detailed analysis of the surface evolution due to collisions, at all scales. Some modelling might be attempted by means of numerical simulations (Richardson et al. 2013).

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