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Space weathering and tidal effects among near-Earth objects

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Abstract. The effect of the space weathering on the spectral properties of the S–complex asteroids (both Main Belt bodies and near–Earth asteroids) has been widely discussed in recent times. It has also shown that the evolution of spectral properties of planet–crossing bodies, and in particular of near–Earth asteroids (NEAs), is also affected by other physical processes, such as tidal resurfacing due to close encounters with planetary bodies. In this paper we show how to combine previous analyses with the purpose of obtaining a global model for NEAs space weathering.

Keywords. asteroid, surfaces; asteroid, spectra; space weathering

1. Introduction

The action of the space environment on optical properties of asteroid surfaces has been put into evidence in several recent papers (Hapke 2001; Hiroi & Sasaki 2001; Clark *et al.* 2002; Chapman 2004). In particular, the analysis of the so–called *space weathering* has been thorough and systematic for what concerns the S–complex asteroids: older asteroids are expected to be redder and darker. After the work of Binzel *et al.* (2004) devoted to NEAs, a colour–age relation has been suggested within an analysis devoted to Main Belt family asteroids (Jedicke *et al.* 2004; Nesvorný *et al.* 2005). More recently, a general relation has been shown to hold for all S–complex asteroids (Marchi *et al.* 2006a, hereinafter Paper I). It has been also shown that the most significant parameter to be correlated with the colour change (in technical terms, the observed visible spectral slope) is not simply the diameter (as shown in Binzel *et al.* 2004) nor the age (as in Jedicke *et al.* 2004) but rather a combination of age and orbital parameters, namely the *exposure* defined as

$$Exposure = \int \frac{dt}{r(t)^2} \simeq \frac{age}{a^2\sqrt{1-e^2}}$$

i.e. the age times the inverse squared mean distance from the Sun (function of the semi–major axis, a, and of the eccentricity, e). The relevance of the exposure parameter entails the dominance, at least for distances smaller than about 3–4 AU, of space weathering effects connected to the Sun (such as, for instance, the ion bombardment; see also Lazzarin *et al.* 2006 and Marchi *et al.* 2005).

In a following paper (Marchi *et al.* 2006b, hereinafter Paper II) a relation has been evidenced to hold for NEAs and Mars crossers (MCs), involving the perihelion distance and the spectral slope. The underlying idea is that a smaller perihelion distance increases the probability of having undergone a recent close encounter with one of the inner planets (Nesvorný *et al.* 2005). The tidal effects of a deep encounter might severely affect the surface, introducing, among the others, a sort of *de–weathering*, i.e. a rejuvenation of the asteroidal surface. In reality the weathering and the de–weathering effects act simultaneously on the asteroids, but the range of application of the tidal–triggered de–weathering is essentially limited to the inner bodies.

In this preliminary paper we try to combine the analyses introduced in Papers I and II. We will use an updated database and updated age estimates. The details of these improvements are presented in Paolicchi *et al.* (2006).

2. Summary of updates

We closely follow the methodology presented in Paper I. In particular the basic method to estimate the ages is the same, taking into account the collisional lifetime only for what concerns Main Belt asteroids (and MCs) and adding a correction due to Yarkovsky effect for the age computation of NEOs. However we use here a larger database and introduce several relevant corrections:

(*a*) The formation of a family is assumed to come from a violent collisional process (Zappalà *et al.* 2002), usually catastrophically breaking both projectile and target involved in the impact, sometimes (for instance, in the case of Vesta family) only creating a large crater on the –massive– target body. In all cases the process converts internal parts of the parent body into surface regions of the resulting fragments. Also the –space weathered– surface of the parent body is presumably deeply shaken, and thus it may appear as rejuvenated when observed as surface of the largest remnant. Thus the age of the family is an upper limit to the age of its members; this value has thus to be used also to constrain the time a family asteroid has been exposed to space–weathering. We have used the new estimates of family ages summarized in Nesvorný *et al.* (2006).

(*b*) We used the proper orbital elements, when available, instead of the osculating orbital elements: they are more stable over time and hence more meaningful for estimating the exposure.

(*c*) The ages of MCs, computed with the same method as the other Main Belt asteroids (MBAs), may have been overestimated: they are in a region subject to fast dynamical processes. Thus their ages should be, in mean, smaller than those of MBAs of similar size. Moreover, the relevance of the –relatively– young (Nesvorný *et al.* 2006) Flora cluster in this region may affect their age. In agreement with these theoretical considerations, we find that MCs slopes are, on average, lesser than MBAs slopes. A first order estimate of the age correction might be introduced assuming that the smaller mean spectral slope of MCs compared to slopes of Main Belt asteroids is fully due to their typical smaller age. The mean slope of MCs is $\simeq 0.447\ \mu\mathrm{m}^{-1}$, compared to the MBAs value of $\simeq 0.503\ \mu\mathrm{m}^{-1}$. Therefore we estimate that the age of MCs has to be reduced by a factor of $\simeq 0.3$. This point is discussed in detail in Paolicchi *et al.* (2006).

(*d*) Here, we use an updated database, including also the new spectroscopic data obtained by S^3OS^2 survey (about 190 objects were not present in previous works; Lazzaro *et al.* 2004) for a grand total of 1026 S–complex asteroids, most of which are from SMASSII.

3. The new slope–exposure relation

We are now ready to include all S–complex asteroids (NEOs, MCs and MBAs) in a unique plot (Fig. 1). We can also try to plot a best fit curve. We overplot a linear fit, as we did in the previous analysis (Paper I). The linear fit, represented in the figure, is highly significant. However, taking into account some general physical considerations (see later) and the fit presented by Nesvorný *et al.* (2005) for what concerns family asteroids, we decided to look also for a logarithmic slope–exposure one. The best fit curve is represented in the figure. It corresponds to a correlation coefficient equal to 0.375. In terms of the RMS deviation of the data from the fit we pass from a value $RMS = 0.221$ (linear fit) to a value $RMS = 0.205$ (dashed line logarithmic fit; note that the number of parameters is the same in the two cases). Thus, combining the physical suggestions and this –moderate– statistical improvement, we decided to go on with the logarithmic fit. In the figure we also show the finally corrected logarithmic fit (see next section for details on the correction).

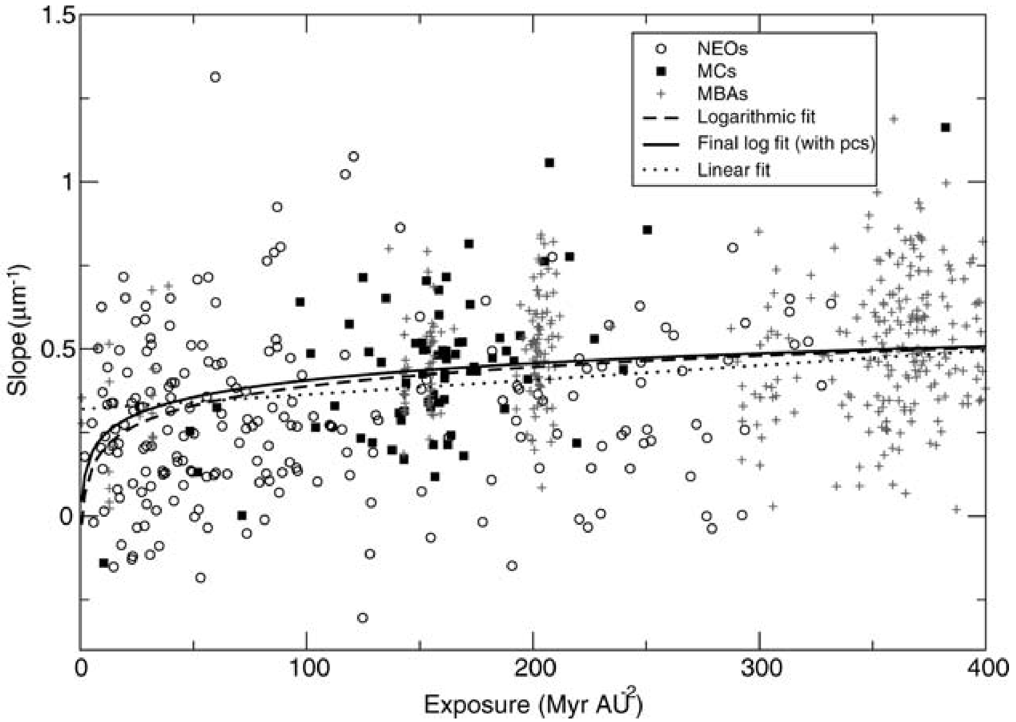

Figure 1. The slope–exposure plot including part of MBAs, MCs and NEOs. The figure has been limited to an exposure value of 400 My AU^{-2} to give a better representation of the NEO region. A linear fit (obtained for all bodies) is plotted (dotted line). A logarithmic plot, more meaningful (see the text for discussion), is also represented (dashed line). The solid–line curve represent the final corrected logarithmic plot (see text).

4. The slope vs. perihelion correction

According to Paper II, there is a significant evidence for the existence of a slope–perihelion correlation, in the range of NEOs and MCs. It should be taken into account, not to mix different effects. In order to do so, we represent the exposure corrected slope (ECS) vs. perihelion for all asteroids in our sample. The ECS has been computed (see

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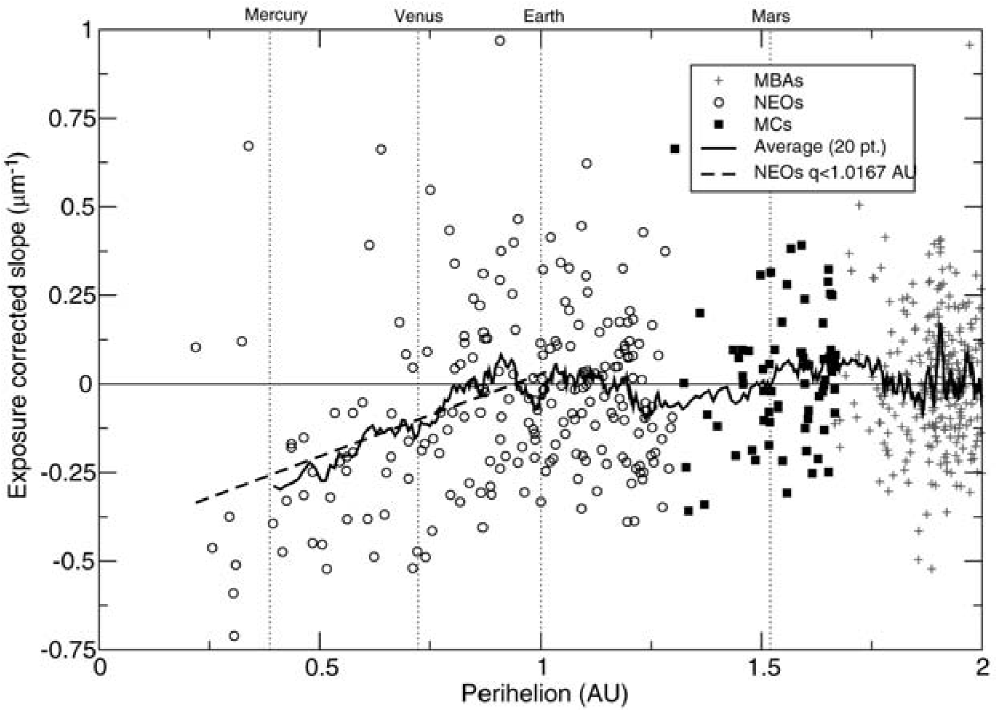

Figure 2. Using the logarithmic fit presented in the Fig. 1, we have corrected the observed slope. We plot the residual slope value (i.e. the difference between the real and the fit values) as function of the perihelion (limited to 2 AU). The existence of a significant relation between the residual slope and the perihelion is apparent at least for a semi–major axis smaller than about 1 AU.

above) subtracting from the actual spectral slope the mean slope obtained from the best fit curve of Fig. 1 and corresponding to the same exposure. The plot is represented in Fig. 2.

As we can see, there is a systematic and significant residual deviation for perihelia smaller than –about– 1 AU. The figure reproduces the slope–perihelion *real* relation, and should be seen as an improved version of Fig. 1, Paper II. No significant deviation is present for perihelia larger than Mars semi–major axis. The intermediate region is somehow less clear, but the presence of a correlation is not evident. Thus we conclude that the slope–perihelion relation is robust within distances smaller than 1.016 AU (namely Earth's aphelion). The relation is such as

$$slope = -0.44 + 0.47 \cdot q$$

and can be used to introduce a perihelion correction to the slope exposure relation. The simplest way to do it is simply to compute the perihelion corrected slope (PCS), by subtracting the perihelion correction (if applicable) from the observed slope. The result is represented in Fig. 1, and corresponds to a relation such as:

$$PCS = 0.07 + 0.17 \cdot \log(exposure).$$

The variance is slightly smaller than that obtained above ($RMS = 0.200$). The exposure range is from about 0.7 to 800 My AU^{-2}. At 1 AU this corresponds to an excursion from 0.7 My to 800 My; or 2.8 My to 3.2 Gy at 2 AU.

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In this range of exposure, PCS varies from 0.044 $\mu\mathrm{m}^{-1}$ to 0.559 $\mu\mathrm{m}^{-1}$, namely it increases by more than one order of magnitude. Notice that the reddening is very steep at the beginning, and that, for instance, the 80% of the excursion is reached at about 200 My at 1 AU; or 800 My at 2 AU.

5. Discussion

The fit obtained in the previous Section is not the only possible one, but is fully representative of the two major features of the data: the steep increase in the slopes for very short exposures, and the nearly–saturated trend for large exposures. Both features are qualitatively observed also in laboratory experiments. On the other hand, the log–fit cannot be significant (due to its divergent behavior at the $t = 0$ limit) to reproduce the very beginning of the slope–exposure relation, in particular for exposure ~ 0. Apart the mathematical difficulties, maybe a physical problem remains open. The astronomical space weathering (for what comes out from the observations) seems a bit slower than one might expect on the basis of laboratory experiments: in particular one should expect a faster saturation.

The most immediate suggestion may be to invoke the regolith mixing. In analogy with what observed on the Moon, regolith evolution is a complex process, which involves gardening (stirring of grains by micrometeorites), erosion (from impacts and solar wind sputtering), maturation (exposure on the bare lunar surface to solar winds ions and micrometeorite impacts) and comminution of coarse grains into finer grains, blanket deposition of coarse-grained layers, and other processes. As a result, the degree of maturation of the regolith varies with depth, and reaches depths by far exceeding the tens of nanometers attained in laboratory experiments. Therefore the observed discrepancy would be the result of the reddening and the mixing of the upper layer due to meteoritic impacts (see Paolicchi *et al.* 2006 for a thorough discussion). Unfortunately, the verification or falsification of a such a possibility is presently out of reach, due to the lacking of detailed knowledge of regolith properties on asteroids.

6. Conclusions

The combination of the slope–exposure and slope–perihelion relations presented in Paper I and II has been performed, also with the use of new data and of an improved analysis of the age of MBAs and MCs. The presented final slope–exposure relation qualitatively confirms the results, and the underlying physical ideas, discussed in the previous papers. However, the slope–exposure relation is less steep than previously discussed, and may be properly fitted with a logarithmic relation. Moreover, we find again a perihelion effect which is safely identified below the Earth's aphelion. As a side result, we have found that the MCs are presumably –in mean– younger by about a factor 3 than their MB siblings of the same size.

However, the space weathering timescale that we obtain from our observational sample are systematically larger than one might expect, on the basis of laboratory experiments, even if a progressive saturation has to be taken into account. A complex asteroidal regolith evolution, as found for the Moon, might be invoked to solve the discrepancy.

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