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A GENERAL SPECTRAL SLOPE–EXPOSURE RELATION FOR S-TYPE MAIN BELT AND NEAR-EARTH ASTEROIDS

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ABSTRACT

We present a general and significant relation between the spectral slope of silicate-rich asteroids (both main-belt and near-Earth asteroids) and the *exposure* to space weathering, computed taking into account the age and the distance from the Sun. We find strong evidence for the existence of a slope-distance relation that may identify the dominant space-weathering processes as Sun-related. In turn, the age estimates depend on various parameters and in particular on the effectiveness of the Yarkovsky-driven orbital mobility. We show that values of the parameters of the Yarkovsky effect consistent with recent experimental measurements can lead to a unique slope-age relation for main-belt and near-Earth asteroids.

Key words: minor planets, asteroids — solar system: general

1. INTRODUCTION

The space environment acts on the optical properties of silicate-rich asteroid surfaces: older asteroids are expected to be generally redder and darker than their younger siblings (Hapke et al. 1975; Hapke 2001; Pieters et al. 2000; Chapman 2004). Recently, an analysis limited to main-belt asteroid (MBA) families (Jedicke et al. 2004; Nesvorný et al. 2005) has evidenced a color-age relation. Also, the size–spectral slope relation suggested to hold for near-Earth asteroids (NEAs; Binzel et al. 2004) can be qualitatively included in the same scenario (larger asteroids are—in mean—older). These results show the relevance of space-weathering (SW) processes. The intensity and the properties of SW depend mainly on the age of the body but also on the relative importance of the various involved physical processes (such as, for instance, micrometeorite impacts and ion bombardment), some of them related to the distance from the Sun.

Silicate-rich asteroids (namely, those belonging to the S-complex; Bus 1999) are of particular interest for SW studies, being a representative and rather homogeneous sample of objects. Moreover, laboratory experiments have simulated SW processes on silicate samples (Moroz et al. 1996; Yamada et al. 1999; Strazzulla et al. 2005). According to both experimental and observational investigations, it is now widely accepted that SW can be quantitatively estimated in terms of the spectral slope (Pieters et al. 2000). In the present work, slopes have been derived from high-quality visible (0.52–0.92 μm) Small Main-Belt Asteroid Spectroscopic Survey (SMASSII) data (Bus 1999), which represent the baseline for the definition of the S-complex (and, more generally, for a feature-based taxonomy). From SMASSII we selected 559 MBAs belonging to the S-complex. Spectra of 170 NEAs have been taken from the SMASS Near-Earth Object survey (Binzel et al. 2004), while another 44 come from the Spectroscopic Investigation of Near Earth Objects survey (Lazzarin et al. 2004, 2005). In the following sections we describe our approach to the complex problem of SW by a new method that takes into account the ages of individual asteroids and their distances from the Sun.

2. A GENERAL APPROACH TO SW

A complete analysis of SW would require the knowledge of all the relevant parameters. Owing to the "progressive" nature of SW, the age of the body is the most important one. Other parameters follow from the properties of the physical processes (micrometeorite impact, ion bombardment, sputtering, etc.). Some of these processes depend on the distance from the Sun, which may be an important parameter of SW whenever the related processes are important.

2.1. *Age Estimate*

The age of MBAs can be constrained by the age of the belt and by collisional times. It depends on the assumed physical modeling of collisions between asteroids and on the overall evolution of the belt population with time. We adopted an estimate of the collisional lifetime as a function of the size, derived from Bottke et al. (2005), which seems to be consistent with the most commonly accepted ideas on the subject. The adopted lifetime-size relation is also represented in Figure 1. In general, the probability that a body created at a time t (the time is counted backward, so that $t = 0$ means the present epoch) survived catastrophic collisions until now is $e^{-t/\tau_{\rm coll}}$. The present population can be obtained by integrating this probability, multiplied by the past collisional creation rate, both functions of t. The mean age $T_{\rm MB}$ can be obtained by multiplying the same integrand by t and dividing by the population integral. According to Bottke et al. (2005), the asteroid population did not undergo a dramatic evolution during the last 4 Gyr (after the end of the "late heavy bombardment," $t_{\rm LHB}$); consequently, we can approximately factor out the number of bodies created per unit time in both the population

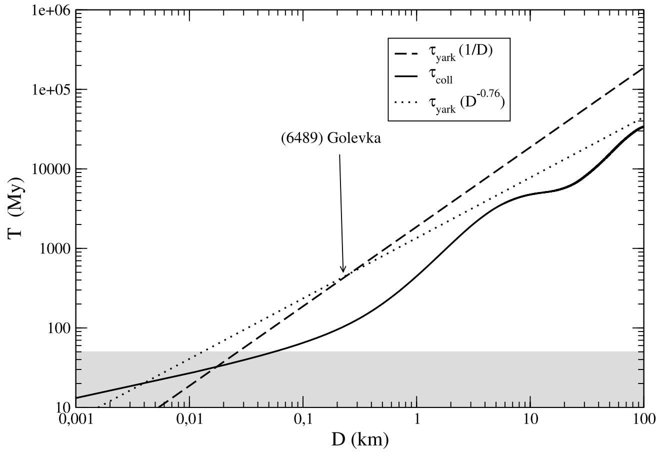

FIG. 1.—Collisional lifetime (according to Bottke et al. 2005; *solid curve*) and the Yarkovsky times (two cases, both fitting the observations; see text) as functions of size. The shaded region in the bottom of the figure represents a rough upper estimate of the lifetimes of NEAs after their injection into the "channels." Thus, the age estimates concerning the size ranges, for which the collisional and Yarkovsky times are within this region, might be unreliable. However, this happens for objects smaller than a few tens of meters, which are not present in our spectroscopic database.

and the age integrals. After that, the population integrand is essentially $e^{-t/\tau_{\rm coll}}$. The integral is smaller than unity, since the maximum past time is finite (we used 4 Gyr), and is equal to $1 - e^{-t_{\rm LHB}/\tau_{\rm coll}}$. We have to add the contribution of primordial MBAs, i.e., those that survived the long period of time between the end of the LHB and the present epoch. They affect both the population integral and the mean age estimates. Since an explicit estimate of this fraction, consistent with the same physical hypotheses that we adopted to compute the collisional lifetime, is currently not available from the literature, we adopted a simplified correction, adding a fraction $e^{-t_{\rm LHB}/\tau_{\rm coll}}$ of bodies of age $t_{\rm LHB} \simeq 4$ Gyr. This estimate is qualitatively consistent with the statement by Bottke et al. (2005), according to which bodies larger than about 100 km are mostly primordial: their collisional lifetimes, as shown by Figure 1, exceed $t_{\rm LHB}$. Finally, the mean age for MBAs can be estimated with the equation

$$T_{\rm MB} \simeq \tau_{\rm coll}\left[1 - \left(1 + \frac{t_{\rm LHB}}{\tau_{\rm coll}}\right)e^{-t_{\rm LHB}/\tau_{\rm coll}}\right] + t_{\rm LHB}e^{-t_{\rm LHB}/\tau_{\rm coll}}.$$

The age estimate of NEAs is by far more difficult owing to their rapid, often chaotic, orbital evolution. We assumed that none of them are primordial and that their lifetime in the main belt has been limited by the "Yarkovsky time" $\tau_{\rm Yark}$, defined as the time that an asteroid requires to change its semimajor axis by 0.5 AU. This last value estimates the mean distance between a random original orbit in the belt and the closest resonant or dynamically unstable region. A more refined analysis might correct this rough estimate, but by a factor not too different from unity: thus, by far, within the existing uncertainties on the parameters of the Yarkovsky effect. In Figure 1 we report the behavior of the Yarkovsky time as a function of the size, in two cases. We assume that it is consistent with the only existing observational value (Chesley et al. 2003) and that it depends on the size D, either as $1/D$ (consistent with simple theoretical arguments, e.g., see Farinella & Vokrouhlicky 1999) or according to the smoother size dependence discussed by Penco et al. (2004) as a consequence of the numerical data presented by Spitale & Greenberg (2001). In our computations we used both assumptions and performed additional tests. However, we obtained our best results (in terms of the uniqueness of the relations for NEAs and MBAs) in the former case, which has been adopted in the final plots (see the following discussion). In general, $\tau_{\rm Yark}$ is larger—but not much larger—than $\tau_{\rm coll}$ but is usually far smaller than $t_{\rm LHB}$; it is enough to cut the ages of NEAs, which are systematically younger than MBAs of the same size. We assume that no original body has been delivered into the present NEA region; for this to happen, a very fine tuning of its semimajor axis mobility should be required. According to all these considerations, the mean NEA age can be estimated as

$$T_{\rm NEA} \simeq \frac{\tau_{\rm coll}\left[1 - (1 + \tau_{\rm Yark}/\tau_{\rm coll})e^{-\tau_{\rm Yark}/\tau_{\rm coll}}\right]}{1 - e^{-\tau_{\rm Yark}/\tau_{\rm coll}}}.$$

We remark that the age estimates (for both MBAs and NEAs) are intrinsically statistical and do not apply to individual bodies.

2.2. *Exposure Estimate*

In order to estimate the amount of solar radiation that a body receives along its orbit (i.e., what we call "exposure"), the following integral has to be evaluated:

$$\text{exposure} = \alpha \int \frac{1}{r(t)^2}\,dt,$$

where $r(t)$ is the Sun-asteroid distance as a function of time t and α is a constant. Since the angular momentum is conserved, the above integral can be simply written as

$$\text{exposure} = \alpha f(t)/l,$$

where l and f are the angular momentum per unit mass and the true anomaly. According to the above equation, the exposure grows linearly with t, with an additional periodic term depending on the eccentricity. Averaging over a period P, and thus eliminating the periodic term, we can define the mean exposure per unit time:

$$\text{exposure} = \langle\text{exposure}\rangle t = \frac{1}{P}\left[\oint \alpha\, f(t)/l\right] t.$$

Finally, in terms of a new constant α_1 we obtain

$$\text{exposure} = \alpha_1[\Phi(a,\ e) \times \text{age}],$$

where

$$\Phi(a,\ e) = \frac{1}{a^2\sqrt{1 - e^2}}$$

(a is the semimajor axis and e is the eccentricity). The quantity Φ is essentially proportional to the mean energy flux received from the Sun during one orbit, per unit time, and thus accounts for the Sun-asteroid distance effect. Note that the equation above does not take into account the orbital evolution of asteroids with time.

3. RESULTS AND DISCUSSION

The slope-age plot is shown in Figure 2. Asteroids show a wide spread in slope, likely due to compositional variations within the S-complex (Bus 1999) and also to their different distances from the Sun and to the difference between the "mean" computed ages and the real individual ones. However, the mean slope increases with the age, and a unique slope-age correlation holds for NEAs and MBAs younger than 2.7 Gyr. The correlation is statistically significant: for NEAs the two-tailed probability (P) for the linear

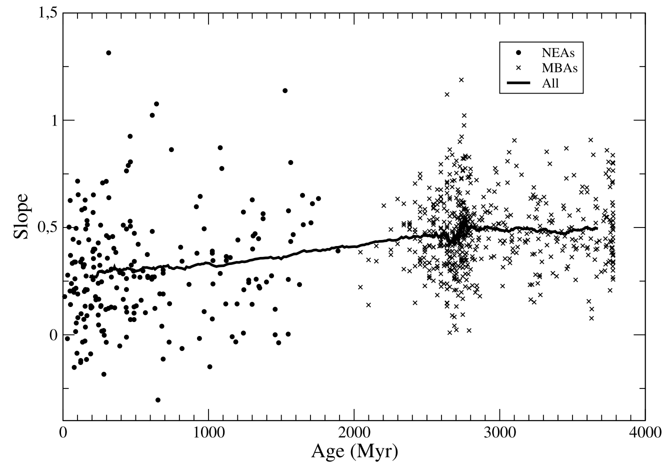

FIG. 2.—Slope-age relationship for NEAs and MBAs. The solid curve corresponds to a running-box average (100 points) of the data. The figure shows a clear, statistically significant, increasing trend for NEAs. The NEA rate is $(8.3 \pm 3.5) \times 10^{-5}$ μm^{-1} Myr^{-1}. This rate is slightly reduced for young MBAs (i.e., <2.7 Gyr), and after a "knee" at 2.7 Gyr, the MBA slope becomes almost flat.

correlation is 2%, while for NEAs and MBAs younger than 2.7 Gyr it is less than 0.1%. We note that a linear correlation is considered significant whenever $P < 5\%$.

For estimated ages larger than about 2.7 Gyr, the slope becomes almost constant. This result may be due to a sort of age saturation, consistent with recent outcomes from laboratory experiments (e.g., see Brunetto & Strazzulla 2005). However, the SW also depends on other parameters; therefore, it is not easy to draw firm conclusions on this point (see also the following discussion).

Note that the possibility of joining together NEAs and MBAs with a unique relation is critically dependent on the assumed lifetimes, and in particular on the adopted values of $\tau_{\rm Yark}$. For instance, with larger values of $\tau_{\rm Yark}$ (i.e., with a less effective semimajor axis mobility) the NEA slope-age curve should have been systematically moved down. Since we expect no systematical difference between NEAs and MBAs of similar age—apart from, perhaps, a small selection effect due to the origin of NEAs, more frequently in the inner belt—the parameters of the Yarkovsky effect are constrained within a given range in order to ensure a reasonable continuity from NEAs to MBAs. The present fit has been achieved assuming a scaling of the Yarkovsky effect with the size as $\sim(1/D)$ and a mobility of 40 km yr^{-1} (for 1 m bodies), in fair agreement with experimental values (Chesley et al. 2003).

Note also that our slope-age relation is consistent with the NEA slope-size relation found by Binzel et al. (2004). However, the correlation we find is statistically more significant (P for the slope-size relation is only 7%).

Among the several processes leading to SW, two have been suggested to dominate: ion bombardment (Strazzulla et al. 2005; Brunetto & Strazzulla 2005) and micrometeorite impacts (Moroz et al. 1996; Yamada et al. 1999). Ion bombardment (like other less relevant processes) is due to the Sun and thus depends on the Sun-body distance. Other processes (such as micrometeorite impacts) do not. Recent experimental work seems to suggest a predominant role for the ion contribution (Strazzulla et al. 2005), at least at the Sun-Earth distance. The dependence of the slope on the Sun distance may allow one to evaluate the relative importance of these effects at different distances.

Following the discussion above, the estimate of the mean distance of an MBA from the Sun can be easily performed in terms of the parameter $\Phi(a, e)$. The same analysis can be extended to

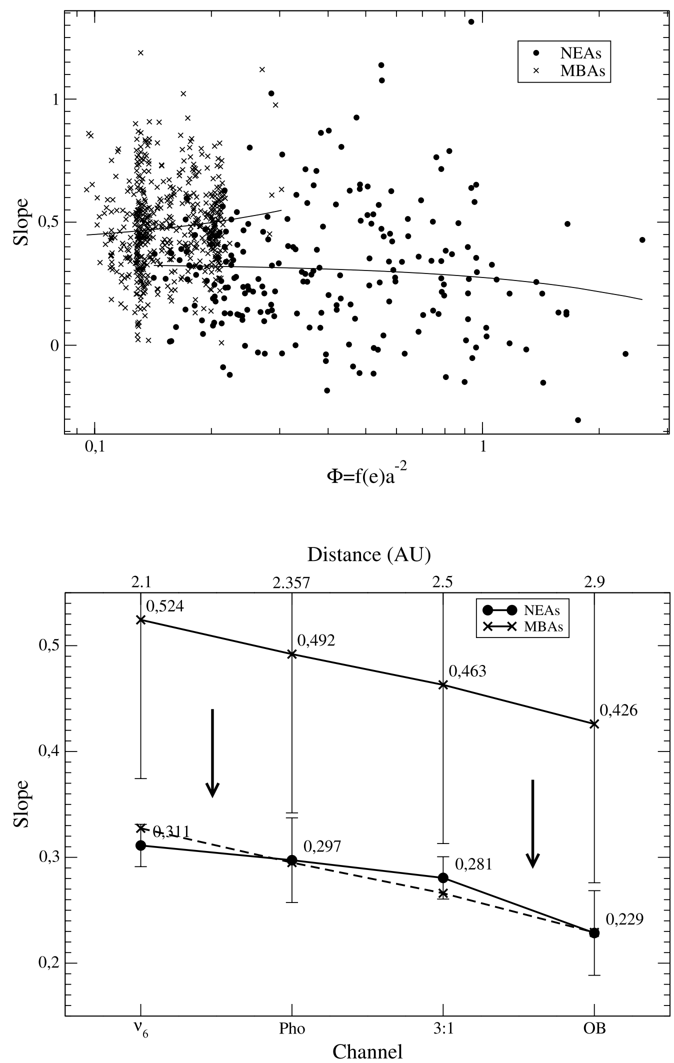

FIG. 3.—*Top*: Slope-Φ relationship for MBAs and NEAs. The solid curves represent the linear regressions of the data (note the logarithmic scale). The slopes of the MBAs show a significant positive correlation with Φ (P is about 2%). The same correlation does not hold for NEAs, which indeed show a smooth negative trend (see text). *Bottom*: Mean slope distribution of NEAs as a function of the four "narrow" channels of origin, compared to the behavior of MBAs, at the same distances. The channels are the resonances ν_6 and 3 : 1, the Phocaea region (Pho), and the outer belt (OB). Note that the effective NEA channel distances should be corrected, taking into account possible selection effects; for example, most of the bodies that passed through ν_6 should have come from a larger original distance (La Spina et al. 2004). Perhaps this correction will improve the fit between MBAs and NEAs.

NEAs, using their present orbits. The results are summarized by Figure 3 (*top*) and show a slope-distance anticorrelation for MBAs, while NEAs behave in the opposite way. However, we have to recall that the present orbital status of a NEA has a typical lifetime of a few million years (Morbidelli et al. 2002), and the previous transition stage (within resonances or due to close encounters with Mars) is even shorter (Gladman et al. 1997). Thus, the reddening of a NEA should be mainly due to its past life within the main belt and, in particular, to its mean distance from the Sun as a MBA. We have no direct information, but we can estimate the probability, for each NEA, of having been injected while passing through one of the seven main channels (Morbidelli et al. 2002). Some of them are "narrow," i.e., allowing the identification of the region of the belt from which the asteroid has been extracted: the secular resonance ν_6 ($\sim$2.1 AU), the Phocaea region ($\sim$2.375 AU), the mean-motion resonance 3 : 1 ($\sim$2.5 AU), and

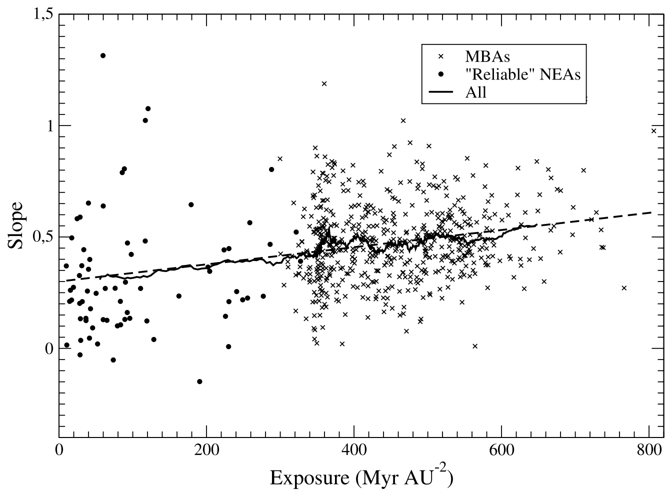

FIG. 4.—General slope-exposure relationship for "reliable" NEAs and MBAs. Only NEAs having a total probability of origin from ν_6, Pho, 3 : 1, and OB exceeding 75% have been considered as reliably distance-assessed (only in this case can the estimate of Φ be considered as accurate enough). The solid curve corresponds to a running-box average (50 points) of the data, putting together NEAs and MBAs. The curve can be approximately fitted with a line (*dashed line*). The *P* of the linear fit is less than 0.1%, supporting a full statistical significance.

the outer belt (~2.9 AU). Thus, we can define a "mean channel original distance" by weighting the distances of the narrow channels with the related probabilities (and taking into account only these channels). The results are shown in Figure 3 (*bottom*). NEA slopes are anticorrelated with the channel distance, with a best-fit slope-distance relation that is almost parallel to the corresponding one obtained for MBAs (the slope offset is obviously due to the different mean ages). The presence of a slope-distance correlation entails that SW is mainly due to Sun-related effects (presumably to the ion bombardment).

Finally, we can put together age and distance estimates in order to obtain a slope-exposure plot (Fig. 4), where the exposure is defined by the product of Φ and the age, as described above. A unique (for NEAs and MBAs), approximately linear fit comes out, with an angular coefficient of $3.8543 \times 10^{-4}\ \mu\mathrm{m}^{-1}\ \mathrm{Myr}^{-1}\ \mathrm{AU}^2$. The *P* of the linear fit is less than 0.1%, supporting a full statistical significance.

Note that the slope-exposure plot does not exhibit the knee shown by the slope-age relationship at 2.7 Gyr. This supports the idea that it was indeed not physically significant. Note also that, as expected, the dispersion around the mean curve is smaller than in the slope-age plot due to the elimination of the distance effect.

In spite of the strong statistical significance resulting from the standard mathematical tests, one might argue against the significance of the obtained correlations due to the large scatter of data, the presence of different parameters, for instance, the typical collisional and Yarkovsky times and the age of the LHB, and several simplifying assumptions. However, some additional considerations can support the validity of the present results and their robustness to future improvements of knowledge, data, and methods. First, we have to remark that the linear best-fit (represented in Fig. 4) almost overlaps the running-box average curve. This seems to support the significance of the data. Second, and more generally, we did several tests, using partial samples (i.e., only NEAs, only NEAs whose original channels were defined well enough, and only MBAs). We also tried to plot the data with different methods to estimate the age, neglecting—or exaggerating—the Yarkovsky effect, and so on. We have found similar and significant trends in all cases. The only relevant difference concerns the uniqueness of the relation for NEAs and MBAs. As already discussed, the curves are the same only with given assumptions about the Yarkovsky-effect parameters. We tested various values of the Yarkovsky parameters, finding a good overlap for values consistent with the most recent theoretical and observational results. At the present status of the art, we can consider this fit as a further support to the reliability of both Yarkovsky-effect models and our results.

4. CONCLUSIONS

In spite of a few simplifying assumptions and their intrinsic uncertainties, we have found a significant relation between asteroid spectral slopes and their past evolution (and thus their cumulative SW), providing a unique and general slope-exposure plot, valid for the whole S-complex. Most notably, the use of both NEAs and MBAs has allowed us to obtain a general description of the SW in the range of 10 Myr–3.7 Gyr. Moreover, by using NEAs we were able to link their reddening with their past evolution into the main belt.

In doing so, we find important constraints on several physical processes, such as the efficiency of the NEA Yarkovsky delivery and the dominance of Sun-related effects among SW processes. Indirectly, our results also support the existing reconstructions of the past dynamical evolution of NEAs.

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