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Solar wind as the origin of rapid reddening of asteroid surfaces

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A comparison of the laboratory reflectance spectra of meteorites with observations of asteroids revealed that the latter are much 'redder', with the spectral difference explained by 'space weathering'[1,2], though the actual processes and timescales involved have remained controversial[3,4]. A recent study[5] of young asteroid families concluded that they suffered only minimal space weathering. Here we report additional observations of those families, revealing that space weathering must be a very rapid process—the final colour of a silicate-rich asteroid is acquired shortly after its 'birth' (within 10^6 years of undergoing a catastrophic collision). This rapid timescale favours solar wind implantation as the main mechanism of space weathering, as laboratory experiments have shown that it is the most rapid of several competing processes. We further demonstrate the necessity to take account of composition when evaluating weathering effectiveness, as both laboratory and asteroid data show an apparent dependence of weathering on olivine abundance. The rapid colour change that we find implies that colour trends seen among asteroids are most probably due to compositional or surface-particle-size properties, rather than to different relative ages. Apparently fresh surfaces most frequently seen among small near-Earth asteroids may be the result of tidal shaking that rejuvenates their surfaces during planetary encounters[6,7].

The opportunity to measure the surface properties of asteroids formed in the past 1 Myr has only recently been realized, with the identification[8] of four asteroid families that were formed by collisions occurring in the past 1 Myr. They are the most recent asteroid break-ups yet discovered in the main belt. Astronomical observations of their family members can be used to better understand surface-ageing processes and determine their surface alteration rate. These so-called space weathering processes redden and darken the initially ordinary-chondrite-like (Q-type[9]) spectrum of a fresh asteroid surface, transforming its appearance to that of an S-type asteroid spectrum[2,10,11]. *In situ* measurements on board the NEAR and Hayabusa spacecrafts have provided direct evidence for such weathering[12,13]. However, the identification of the main weathering agent, as well as the weathering rate, remains to be accomplished. Laboratory experiments performed on ordinary chondrites and their main constituents (olivine, orthopyroxene) simulating two different processes, solar wind implantation and micrometeorite bombardment, suggest two very different timescales: a short weathering timescale of 10^4–10^6 years for solar wind irradiation[14,15] and a 10^8–10^9 year timescale for micrometeorite impacts[16]. The 10^6-year age of the youngest known families provides a direct test to distinguish between these two processes and their very different timescales.

To explore the colours and the mineralogical composition of presumably very young surfaces of small asteroids within the most recently formed families, we used four telescopes, namely the NTT (New Technology Telescope; La Silla Observatory, Chile), the VLT (Very Large Telescope; Paranal Observatory, Chile), the TNG (Telescopio Nazionale Galileo; La Palma, Spain) and the IRTF (Infrared Telescope Facility; Mauna Kea, Hawaii). We obtained data for two families (Datura and Lucascavin cluster), which are both S-type[5]. As a comparison to completely 'fresh' surfaces, we use laboratory spectra of similar silicate-rich ordinary chondrite meteorites catalogued in the RELAB database (http://www.planetary.brown.edu/relab/). For 'old surfaces' we use similarly measured spectral properties of seven older S-type families. For older families, the visible wavelength portion of their spectra and some near-infrared spectra were available from previously published studies[17–20], while the remaining near-infrared portions were acquired with the IRTF.

Space weathering processes primarily affect the spectral slope of silicate-rich asteroids[21]. Thus for comparison, we calculate spectral slopes over the 0.52–0.92 μm wavelength range as the slope of a best-fit line, forced to have the value of unity at 0.55 μm. In Fig. 1 we show the mean slope of each family (with its 1σ deviation) versus the age of the family. We find that the two youngest families (Datura and

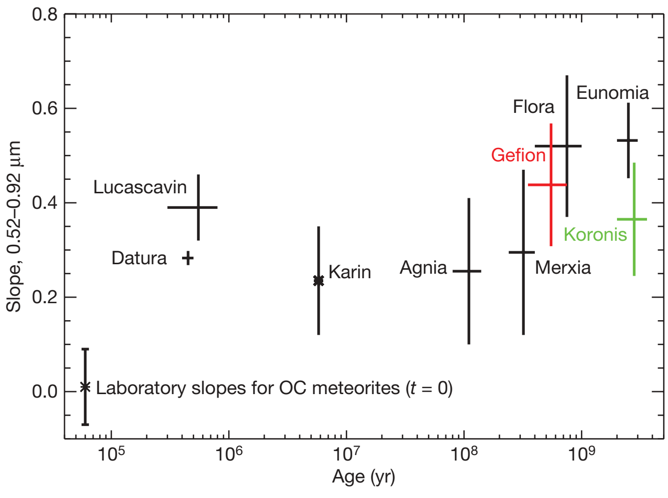

Figure 1 | The relationship between the spectral slope (visible wavelengths) of S-type asteroid families and their ages, as observed. We show the mean slopes for both ordinary chondrite (OC) meteorites and S-type asteroid families. Laboratory spectra for OC meteorites form the baseline assumption for fresh ($t = 0$ yr) 'unweathered' asteroid surfaces[2,9]. We place the slope domain for OC meteorites at $t = 4.6 \times 10^4$ yr because we want to zoom into the 10^4–10^9 yr window and therefore we can not show $t = 0$ yr. The slopes and names for the old families lie very close to each other. We therefore use colours to guide the eye of the reader. Error bars, 1σ.

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Lucascavin, age $\sim 10^5$ years) have higher average slopes than the Agnia family (age $\sim 10^8$ years), while the very young Lucascavin cluster (5.5×10^5 years) appears to be even redder than the oldest family from our sample (Koronis family, age $\sim 2 \times 10^9$ years). Our results showing weathered surfaces for even the 'youngest' asteroids have two new implications: (1) space weathering processes are extremely rapid, occurring within 10^6 years; (2) space weathering processes are so rapid, that as yet, a colour–age relationship cannot be determined[3,4].

Among the two competing space weathering processes (solar wind ion irradiation or micrometeorite bombardment), such rapid alteration is consistent only with solar wind bombardment, whose weathering timescale[14,15] (10^4–10^6 years) matches well the youngest ages known for the Datura and Lucascavin clusters. While Datura's and Lucascavin's red spectral slopes can be accounted for by a fast acting solar wind effect, it is puzzling how both of these young families could display spectral slopes as red as (or more red than) significantly older families. Composition may play a central role. Laboratory experiments have shown that olivine is more sensitive to space weathering effects than orthopyroxene[22,23] (this is true for both ion irradiation and micrometeorite bombardment, see Supplementary Information). To test this olivine dependence of weathering for real asteroid spectra, we chose a sample of 30 S- and A-type main-belt asteroids. A-types are almost exclusively made of olivine and S-types are composed of a mixture of both olivine and pyroxene[24]. In our sample, we excluded (1) asteroids belonging to well-known families to avoid a bias due to their age, and (2) near-Earth asteroids (NEAs) because many of the latter objects look very fresh, which contrasts with the colour distribution observed within the main belt. Specific explanations (size, planetary encounters) may exist for this discrepancy[6,7,25].

To infer the olivine-pyroxene composition of S-type asteroids, we applied a radiative transfer model[26] using three end-member minerals, namely olivine, orthopyroxene and clinopyroxene, and selected the inferred abundances for the two main minerals. The composition was measured quantitatively by the ratio ol/(ol+opx), where ol is olivine and opx is orthopyroxene. To account for spectral reddening (if present) due to space weathering processes, we used a space weathering model[27]. We show the distribution of spectral slopes versus compositions for our main-belt sample in Fig. 2. A high spectral slope for the most olivine-rich asteroids has long been recognized[28]. Here we see that the trend for increasing spectral slopes with increasing olivine abundance is followed for intermediate olivine abundances. For S-type asteroids, we observe a linear relation between slope and composition with a correlation coefficient of ~ 0.62 (with $N = 25$), a 99.8% confidence level that this correlation is not random. (Including the A-types further increases the correlation coefficient to 0.89.) Using the slope over the full visible–near-infrared range (0.45–2.45 μm) for our S-type sample ($N = 25$) further increases the correlation coefficient to ~ 0.75, a 99.95% confidence level that this correlation is not random. This correlation demonstrates that composition is a key factor when evaluating the overall effectiveness of the space weathering process, as composition can vary the outcome of a space weathered slope value by almost a factor of 2.

To test whether composition plays a role in the slope distribution shown in Fig. 1, we examine the composition of the low slope ('less red') families (Agnia, Merxia, Koronis and Karin) relative to the composition of the high slope ('red') families (Datura considering its young age, Flora and Eunomia). We find that the 'less red' families are less olivine-rich ($ol/(ol+opx) \le 0.6$) than the 'red' families ($ol/(ol+opx) \ge 0.78$). Thus a more accurate comparison between weathered spectral slope and surface age requires a correction for composition. To perform this correction, we chose the composition of the Flora family ($ol/(ol+opx) = 0.78$) as a reference composition. To estimate the slope deficit or excess for each family versus the slope of the Flora family, we fitted the slopes of our S-type sample (over the 0.52–0.92 μm range, as used in Fig. 1) by a straight line (see Supplementary Fig. 5). This line gave us the mean slope for a given composition. To correct the slope distribution for composition (Fig. 3), we calculated the slope deficit or excess for all families and shifted (up or down) their mean slope values by the calculated amount (see Supplementary Information for a more detailed explanation of our method for applying the correction). Figure 3 shows the mean slope of each family with its 1σ deviation after correction for composition versus the age of the family.

On these basis of these results for composition-corrected spectral slope versus age (Fig. 3), it appears that space weathering causes spectral slope to increase rapidly for the first $\sim 10^6$ years; the increase

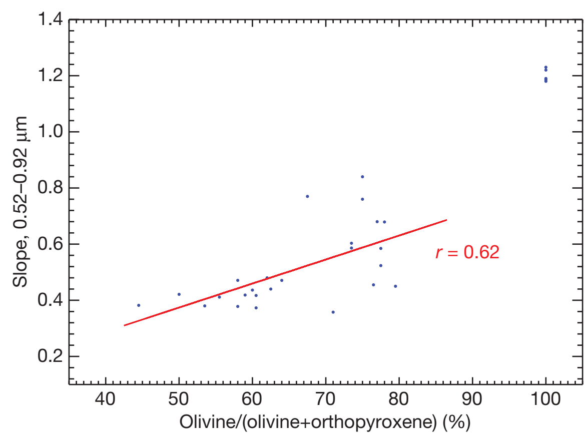

Figure 2 | The relationship between the slope of S- and A-type asteroids and their composition. For S-type asteroids (that is, ol/(ol+opx) = 45–80%), we observe a linear relation between the slope and composition with a correlation coefficient of $r \approx 0.62$ ($N = 25$), a 99.8% confidence level that this correlation is not random. Adding the A-types (5 objects; ol/(ol+opx) = 100%) further increases the correlation coefficient to 0.89. The A-type asteroids require a correction that increases their slope by 0.3 (see Supplementary Information).

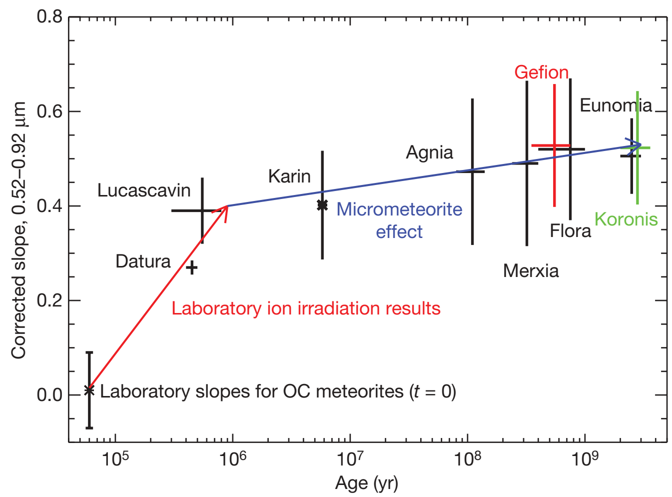

Figure 3 | The relationship between the spectral slope (visible wavelengths) of S-type asteroid families and their ages, after being corrected for composition. The red and blue arrows stress two different slope regimes that become apparent from our results (these arrows are not a fit of the data points). First, the slope of an unweathered surface (at exposure time $t = 0$) starts in the middle of the slope domain of OC meteorites and reaches the 0.4 slope value of the Lucascavin family in less than 0.5 Myr. This represents a slope variation of ~ 0.4 in just ~ 0.5 Myr (red arrow), which is consistent with the very rapid reddening trend observed during laboratory ion irradiation experiments[14,23]. Such a rapid trend appears to be required within the first $\sim 10^6$ yr for newly formed asteroid families. Second, the slope evolution over the interval $t = 0.5$–5 Myr to $t = 2{,}500$ Myr appears more gradual (blue line). Gradual weathering processes such as micrometeorite impacts[16,22] may account for the continuing slope increase throughout the following 2×10^9 yr. Error bars, 1σ.

then continues much more gradually throughout the following 2×10^9 years. Physically, an initially steep evolution that levels off within a short timescale ($\sim 10^6$ years) is in agreement with the saturation timescale of a surface undergoing ion implantation[29]. The subsequent and more gradual slope evolution (seen beyond 10^6 years) may be evidence of other effects, such as (1) micrometeorite (dust) impact effects, which are known to be a slow process, and (2) a global maturation of the regolith, including 'gardening' (evolution of surface particle sizes and exposure depth by bombardment) and reddening of freshly exposed regolith via both ion implantation and dust impacts. Comparing the mean spectral slope values of the very young Lucascavin and Karin families ($\sim$0.4) with the mean spectral slope of the oldest families (0.5–0.55), it appears that $\sim$80% of the slope alteration (colouring) of a silicate-rich asteroid is acquired within the first million years.

It is important to note that apparently 'fresh' (that is, unreddened) surfaces are abundant[25] ($\sim$10% of all asteroids) among the smallest ($\sim$1 km) asteroids observable in proximity to Earth. These fresh kilometre-sized and larger Q-type NEAs have collisional lifetimes[30] greater than 100 Myr and dynamical lifetimes greater than 2 Myr—timescales fully adequate for ion implantation to modify their surfaces from 'fresh' (Q-type) reflectances to 'weathered' (S-type) reflectances. Thus two implications of a fast space weathering timescale are that (1) Q-type NEAs must retain their freshness by frequent rejuvenation of their surfaces, and (2) collisions cannot be the main mechanism responsible for the high fraction of Q-types among NEAs. Planetary encounters may be the responsible process, where tidal shaking[6,7] frequently exposes fresh unaltered material. This hypothesis could be tested by looking at the spectral colours of small main-belt asteroids compared to those of NEAs; if the planetary encounter scenario is correct, then at comparable sizes, Q-type main-belt asteroids should be substantially rarer than NEAs of the same type.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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