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Space weathering, reddening and gardening of asteroids: A complex problem

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Abstract

The association of ordinary chondrites and their parent bodies through their visible and near infrared spectra is still a debate. In fact, many asteroids show reddened spectra, while the ordinary chondrites do not.

In the framework of the space weathering of asteroid surfaces, the interpretation of the reddening, darkening, and depletion of band depths is not as simple as previously described.

We present a summary of the recent results in the study of the reddening of the spectra. To date, different mechanisms have been proposed to explain some properties of spectra, but a complete scenario capable of reproducing the whole set of observations is still missing.

Keywords: Asteroids; Observations; Space weather

1. Introduction

The most abundant class of meteorites, the ordinary chondrites (OCs), has been associated to the S-type asteroids (Gaffey, 1976; Cloutis et al., 1990) by the comparison of the reflected spectra in the visible and near infrared range (VIS–NIR), but many asteroids show reddened spectra (Gaffey, 1976; Britt et al., 1992a; Gaffey et al., 1993).

The reddening, the darkening and the depletion of the band depths are usually interpreted as the main consequence of the space weathering (SW) of asteroid surfaces.

The SW was first observed in lunar soils (Mc Cord and Adams, 1973) and demonstrated to be caused by the presence of metallic nanoparticles (Pieters et al., 2000).

The formation of metallic nanoparticles (hereafter npFe) was investigated by laser irradiation experiments, where the impulsed energy driven by a laser was used to simulate the bombardment in space by the micro-meteroids (Yamada et al., 1999; Kurahashi et al., 2002; Sasaki et al., 2001; Sasaki et al., 2006a).

These experiments were performed on terrestrial Fe-bearing silicates (Sasaki et al., 2001; Kurahashi et al., 2002), that are the major constituents of the OCs, and on OCs directly (Sasaki et al., 2006a).

The experiment on the silicates showed that the npFe condensed after a vaporization process.

Though the laser experiments show an unambiguous reddening of the spectrum and a depletion of the band depths after the irradiation, the problem of the SW seems not to be solved. In fact, the close-up observations of the Psyche crater on Eros showed bright features but redder than the powdered OCs (Murchie et al., 2002), suggesting an alternative mechanism capable of reddening but not to darken (Clark et al., 2001).

Moreover, the recent results in ion irradiation experiments and the statistical distribution of the reddenings through the solar system (Lazzarin et al., 2006), suggest

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that the solar irradiation and not the micro meteoroids bombardment can play the dominant role in the main scenario.

We report other phenomena, alternative to the ion irradiation or vaporization of Fe-bearing silicates, which can be invoked to explain the reddening of the asteroid VIS–NIR spectra.

We then discuss the problem of the time scales of SW suggested by the experiments, whose values are singularly much shorter than those observed in the asteroid reddened spectra population.

2. The reddening of the VIS–NIR spectra

2.1. The shock-induced phase transformation of metals alloys in OCs

Metallic nano-particles have been demonstrated to redden the VIS–NIR spectrum independently of their formation mechanism (Noble et al., 2003). Sparse metallic nano-particles were observed in Fe–Ni region of the OC but never associated to the reddening of the spectra (Leroux et al., 2000).

Moretti et al. (2005) identified the martensite (a shock-induced phase in Fe–Ni alloys) as a nano-phase structure also in OCs and showed that the spectra where martensite was more abundant were redder than elsewhere.

Martensite has a large reflectivity and, for this reason, the shock-induced transformation of Fe–Ni alloys can be invoked to explain the Psyche crater dilemma.

2.2. The contribution of metals in sculpted surfaces

The sculpting of airless bodies due to the low-energy bombardment of micro meteoroids on samples of ordinary chondrites have been simulated and showed in Moretti et al. (2006). One hundred micron diameter quartz spheres were used to impact the surface of OCs at velocities of the order of 10 m/s. The micro-spheres created craters in correspondence of the more brittle or fragmented crystals, while the metallic regions were largely preserved in their dimension even if deformed in their roughness. This selective erosion, consisting of a preferential silicate removal and metal particles in relief, resulted in a larger contribution of the specular reflectance from the metallic regions.

The spectra from the sculpted surfaces are redder than those obtained from the powdered samples. A greater spectral contribution from metallic regions was already proposed to reproduce the S-type asteroid VIS–NIR spectra using mixtures of stony and iron meteorites (Hiroi et al., 1993), but this was never observed in standard OC powdered samples.

Moreover, the results showed in Moretti et al. (2006) suggest the need for a revision of the state-of-the-art models of the spectra of mineral mixtures, where all the mineral constituents have the same grain size.

2.3. Other mechanisms

Some minerals, observed or compatible with the formation of OCs, show VIS-NIR spectra with a positive slope (that is, their presence can largely redden an average spectrum).

Troilite is very abundant in metallic meteorites and also in OCs is not negligible (about 6%, Britt et al., 1992b).

The spectrum of troilite (see Britt et al., 1992b) is redder than many of the principal constituents of the OCs. Nevertheless, troilite is thought to be depleted by impacts on asteroid surfaces due its low vaporization energy (Killen, 2003).

Shock melts have been reported in OCs. Impacts in chondritic parent bodies can significantly change the olivine/pyroxene (ol/pyx) modal ratio (Folco et al., 2004, 2005; Grier et al., 2004).

The ol/pyx values are very different for H, L and LL OCs (McSween et al., 1991).

Nevertheless, the spectra analysis can lead a H-chondrite to be identified as an L-chondrite. Gaffey et al. (1993) showed that when the band center (near 1 μm) is plotted versus band area ratio (ratio of areas of the 1 and 2 μm bands), the ordinary chondrite meteorites cluster in a specific part of the space. Gaffey and Gilbert (1998) refined this diagram to allow for specific types of OC meteorites to be distinguished. But when placed on such a diagram, impact melts from H-chondrites move to the LL region (Grier et al., 2004). When applying this method to the interpretation of asteroid spectra, differing amounts of melts on asteroid surfaces may skew the results.

The VIS–NIR spectra from impact melts are redder than those of the un-impacted regions.

3. Conclusions

Different phenomena can redden the VIS-NIR spectra of asteroid surfaces.

Many of these are related to impact events.

Laser experiments are believed to simulate the heat transfer involved in the impacts and low velocity impact experiments can show a reasonable trait of the sculpted surfaces. Nevertheless, we suspect that these experiments can not reproduce the space environment, when threshold phenomena are involved and where impacts are very rare.

In Table 1 we report the slope and the reflectance for different mechanisms.

The slopes have been computed using a linear fit of the reflectance spectra between 400 and 1800 nm.

We remind that the VIS–NIR spectra have been usually, and then historically, acquired between 400 and 2500 nm. The normalization of the spectra for the OCs and S-type asteroids was also historically performed at 560 nm, far from the possible influence of the silicatic 1000 nm band and the Fe bands in the UV range. We then stress the importance of comparing the slopes of the spectra in the same spectral range or, in the case the data do not permit

Table 1
A summary of the mechanisms capable to redden the VIS–NIR spectra on asteroid surfaces

Mechanism and technique	References	Spectral slope (μm^{-1})	Reflectivity at 0.55 μm
Added metallic nanoparticles (gel)	Noble et al. (2003, 2004)	0.8 max	0 0.6 (0.3 at the maximum slope)
Vaporization of Fe-bearing silicates (identification of metallic nanoparticles – laser irradiation on terrestrial samples)	Yamada et al. (1999, 2001); Kurahashi et al. (2002); Brunetto et al. (2006)	1.4 max	0.3 (*bulk*)
Vaporization of Fe-bearing silicates or impact melts (laser irradiation on ordinary chondrites)	Sasaki et al. (2006a,b)	<0.4	0.15 (*bulk*)
	Starukhina (2006)		
Shock-induced transformation of Fe–Ni alloys (identification of metallic nanoparticles on ordinary chondrites)	Moretti et al. (2005)	1.5 max	0.15 average
			0.6 in metallic regions
Specular reflectivity of metals (low velocity impacts on ordinary chondrites)	Hiroi et al. (1993)	1.0	0.4 (Mundrabilla)
	Moretti et al. (2006)	0.8	0.15
Troilite	Britt et al. (1992b)	0.6	0.07
Pirite	UGCS archive	1.3	0.06
Goethite	UGCS archive	1.3	0.25
Impact melts	Grier et al. (2004)	0.2	0.1
	Folco et al. (2005)	0.2	0.1
Ion deposition (irradiation on ordinary chondrites)	Strazzulla et al. (2005)	0.7 max	0.15 (*bulk*)
Ion deposition (irradiation on silicates)	Brunetto and Strazzulla (2005)	0.7 max	0.3 (*bulk*)

Spectral slopes have been computed using a linear fit between 0.4 and 1.8 μm. The error on the single slope is of the order of 20%.
Spectral slopes for ordinary chondrites are typically $0.1\mu m^{-1}$ (for H) and $0.2\ \mu m^{-1}$ (for both L and LL), with a reflectivity at 0.55 μm of the order of 0.25. S-type asteroids which are considered as reddened show a spectral slope of the order of $0.7\ \mu m^{-1}$. We remark that reflectivity strongly depends on grain size, texture and phase angle.

this homogeneous comparison, the normalization should have a physical explanation or the results demonstrated to be independent of it. From Table 1, it can be seen that some mechanisms are more efficient in the reddening of the spectrum and that, the use of the sole slope as a probe of the space weathering can not discriminate between the proposed mechanisms.

A broad survey of asteroid spectra, comprising S, C and X asteroids, recently showed that the reddening seems to be well correlated to both the age and the distance from the Sun (Lazzarin et al., 2006). This new result suggest the solar distance plays an important role in the alteration of the spectrum, making the solar wind, that is the ion irradiation, to dominate the effect on the surface. Though this phenomenon seems to be the best candidate to describe the average distribution of the spectral slopes, some observational evidences can not be interpreted by this mechanism, like the Psyche crater on Eros (Clark et al., 2001).

We then suggest that the study of the reddening, and of the SW in general, should be focused nowadays on interpreting the unexplained details which demonstrate our interpretation of the spectra can be misleading or incomplete and which can indeed provide clues on the general description.

It has been demonstrated that the slope of the asteroid spectra, that is a probe of their surface alteration, is related to their age via an exponential Kohlrausch–Williams–Watt (KWW) behaviour (Jedicke et al., 2004). This behaviour, with a time scale of the order of 10^{10} years, is much longer than any of the time scales proposed by all the experiments (10^8 for Sasaki et al., 2001, approximately 10^5 for Moretti et al., 2005, from 10^4 to 10^6 for Strazzulla et al., 2005).

The KWW behaviour reveals a non independent cooperation between different mechanisms (Careri and Consolini, 2000). This implies that the gardening or refreshing of the surface is not independent from the phenomenon responsible for the reddening. The presence of different altered surfaces on the same body (the Karin asteroid) suggests that impacts can be a plausible candidate for the differences in the space weathering effects (Sasaki et al., 2005), but cratering and sculpting processes (that is low or high energy regimes) are still not investigated in detail.

In summary, recent observations have demonstrated that the space weathering is not a simple process. After the Psyche dilemma on the Eros surface, we now deal with the recent observations of the surface of the asteroid Itokawa, where decimetre scale bright spots have been revealed but whose interpretation is still missing.

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