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Physical and spectral properties of the Chelyabinsk ordinary chondrite: Support information for future impact deflection missions to asteroids.

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Abstract

Asteroids of the near-Earth population experience collisions that disrupte them, producing smaller bodies that can travel from the Main Asteroid Belt to the near-Earth region. Some may survive the entrance through Earth's atmosphere and become meteorites, that are studied to understand their parent asteroids. The Chelyabinsk superbolide produced a massive meteorite fall, and the pieces recovered can be analyzed to decipher the physical processes affecting the surface of its parent object. On this study we describe the physical properties of Chelyabinsk samples obtained using nanoindentation technique. We also compare ultraviolet to near-infrared spectra of the samples to connect the meteorites with asteroids, considering how impact processing has affected asteroid spectra.

1 Introduction

Impacts between large asteroids in the Solar System produce fragments of less than one km, and among them we found the Potentially Hazardous Asteroids (PHAs), bodies larger than 200 m that approach Earth's orbit at 0.05 AU or less. The probability of a collision is very small, but close approaches with terrestrial planets can release meter-sized rocks from the surface of loosely compact asteroids, which can produce bright bolide events when they penetrate into Earth's atmosphere, ablating most of their mass [13]. The resulting meteorites provide an opportunity to comprehend the properties of the Near Earth Asteroids (NEAs)[10], which are mostly S- or Q- class asteroids, typically associated with ordinary chondrites (hereafter OCs) [3]. Those meteorites usually exhibit shock metamorphism [4] and brecciation of compact regolith [5, 6]. Those features can weaken the materials of asteroids, making them easy to broke and ablate by the entrance through Earth's atmosphere [7].

The shock-wave produced after the entrance of one of those asteroids through Earths atmosphere can be a source of significant hazard to humans [11], as proven by the Chelyabinsk superbolide, occurred on Feb. 15th, 2013. The 18 m asteroid penetrated Earth's atmosphere at ∼19 km/s [8], exploding and producing ∼1000 kg of meteorites [27]. They show a relatively high S4 degree of shock [27], and were recognized to be breccias only containing lithologies related to LL OCs [5, 6]. They are mainly described as a light-colored lithology, with or without shock veins, that shows LL5 and LL6 features at different regions, a shock-darkened lithology in which interstitial spaces are filled up by opaques, and a dark, fine-grained impact melt lithology [6, 26, 27]. We compare the reflectance spectra in the ultraviolet to near-infrared of several samples of the Chelyabinsk meteorite, in order to see the spectral variations between the lithologies. Also, we performed several nanoindentacion analyses in order to know the physical properties of this meteorite. This kind of study might provide information of great interest for future missions such as the Asteroid Impact and Deflection Assessment (AIDA) mission, which will test feasibility of asteroid deflection with the binary NEA (65803) Didymos [22].

2 Experimental methods and results

Two thin sections of Chelyabinsk (PL13049, PL13050), plus a thick section, were studied. High-resolution mosaics were created from separate 50X reflected and transmitted light images taken with a Zeiss Scope petrographic microscope. They allowed us to select the features to be characterized by other techniques. We performed electron microscopy (SEM) with a FEI Quanta 650 FEG working in low-vacuum BSED mode, together with an EDS detector Inca 250 SSD XMax20 with Peltier cooling and an active area of 20 mm^2, to obtain elemental mappings and composition. The mechanical properties of the PL13049 section were studied with an UMIS nanoindenter from Fischer-Cripps Laboratories using a Berkovich pyramidal-shaped diamond tip. 500 mN indentations were carried out on three different regions of the meteorite [15]. The hardness (H) and reduced Youngs modulus (E_r) were determined from the load-displacement curves. Ultraviolet to near-infrared spectra (UV-NIR, ∼0.2 to 2.0 μm) were obtained from the lithologies of the Chelyabinsk meteorite with a Shimadzu UV3600 UV-Vis-NIR spectrometer [29]. The region between 0.8 and 0.9 μm in our spectra was deleted due to baseline noise.

The distinction between the light and dark-colored lithologies of this meteorite (Fig. 1) was found to be consistent with previous studies [9, 20]. In the Chelyabinsk spectra the main feature in the working range presented here is the characteristic 1 μm olivine absorption band, together with the forsterite bands at ∼0.5 μm, and afterwards 1.5 μm the pyroxene absorption band bends again the spectra, consistently with its composition [16]. In the dark-colored lithology those bands become much more difficult to distinguish, and the reflectance is attenuated. The spectra from Chelyabinsk are easily related to the spectra from other LL meteorites, as expected. For H and L chondrites the differences between dark and light specimens show behavior resembling that of Chelyabinsks lithologies.

Table 1: Nanoindentation results

Lithology	E_r (GPa)	H (GPa)
Light-colored	65	9.2
Dark-colored	65	11
Impact melt	77	11.8

16 nanoindentations with a maximum applied force of 500 mN were performed on each lithology of the PL 13049 section, to obtain their mechanical properties (Table 1). The highest hardness (H) and Youngs modulus (E_r) are found in the impact melt lithology, while the lowest values correspond to the light-colored. In some of the indentations performed small cracks appeared at their edges. The formation and length of these fractures can be correlated with the fracture toughness of the materials indented [15]. Thus, in Chelyabinsk the impact melt lithology seems to be more propitious for fractioning.

3 Discussion

S-class asteroids constitute the most complex and populated fraction of MB asteroids that share similar reflectance spectra. They have stony compositions revealed by their 1 and 2 μm olivine and pyroxene bands, and they are moderately bright [12, 14, 24]. Q-class asteroids are similar, showing subtle variations of depth and width in these bands, but with a lower slope of the spectrum [12, 14].

The distinction between the light- and dark-colored lithologies in Chelyabinsk can be tentatively connected to the distinction between S- and Q-type asteroids [9]. Indeed, the spectral differences could be a consequence of the progressive darkening associated with shock metamorphism and brecciation [9]. That would be consistent with the optical darkening observed in the dark-colored lithology of Chelyabinsk due to a higher degree of shock, and also with its definition as a breccia [6].

Mechanical properties play a key role in modeling the reaction of an asteroid to the impact of a solid projectile. Porosity, which is known to cause a reduction on both H and E_r [23], does not vary much between the lithologies of our Chelyabinsk samples [21]. The composition and mineralogy of the lithologies are also very similar [16, 21], and therefore there must be a different reason for the variations in mechanical properties. Shock processes increase the amount of structural defects and promote the formation of shock-melt metal and troilite veins, which introduce noticeable variations in the mechanical behavior. The formation of fractures in the impact-melt suggest that this lithology contributes to reduce

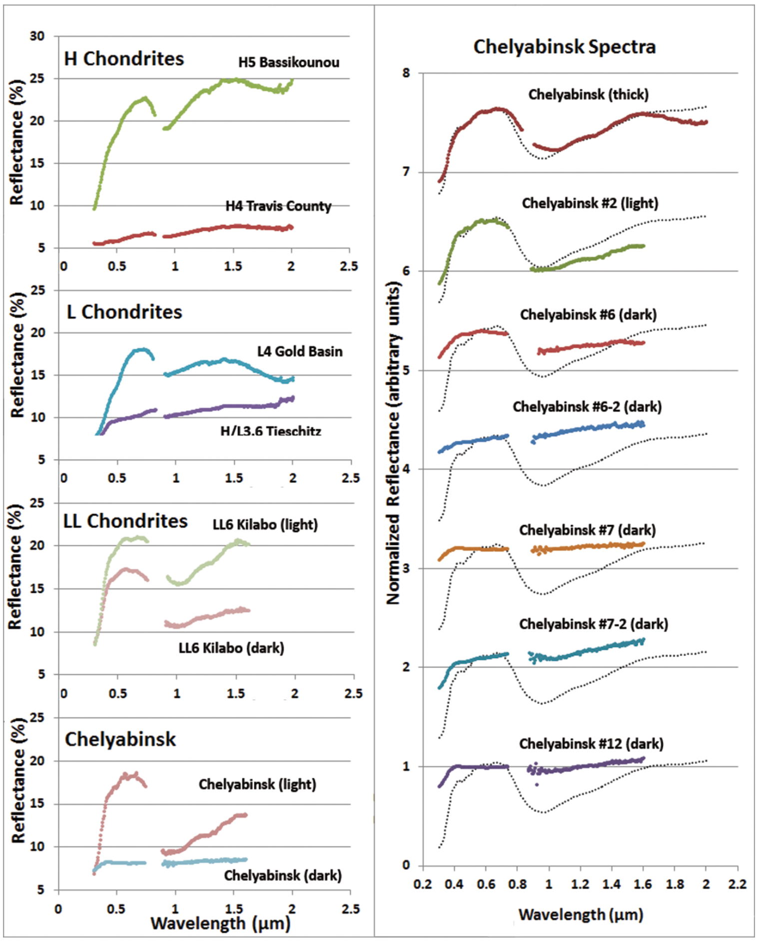

Figure 1: At left, UV-NIR spectra of H, L and LL chondrites, showing the changes in OCs spectra between darker and lighter regions. At right, Chelyabinsk spectra (shifted) compared to a spectrum obtained from the 2 to 1 mixture of olivine (Fo70) and pyroxene (En75) from the RELAB database (average composition of the Chelyabinsk meteorite [17, 21, 26]).

the hardness of objects similar to the parent body of Chelyabinsk [25]. Lower hardness promotes the formation of impact craters and therefore the release of material from the body receiving the impact, which implies an efficient multiplication of momentum [2, 19]. Furthermore, in low porosity bodies such as Chelyabinsk, less impact energy is dissipated in the process of compacting pores, also promoting the transmission of momentum [2, 18, 19]. These results show that an impact on the light-colored lithology of Chelyabinsk would be more efficient than in the dark-colored, and therefore that a proper selection of the impact site is crucial even if the composition of the asteroid seems homogeneous. In Chelyabinsk the two lithologies are strongly mixed to be selected as targets, but it is not necessary the case for all NEAs.

The mechanical properties of meteorites like Chelyabinsk can provide key information to properly model the effects of a kinetic impact in this type of asteroid. However we should expect significant macroporosity in the parent asteroid, probably a rubble pile, which would have an important effect on the reaction to a kinetic projectile. The difference in scale between a meteorite sample and an asteroid is also important for both nanoindentations and UV-Vis-NIR spectra. The difference between quasi-static experiments, like nanoindentations, and dynamic experiments, should also be considered [1, 28]. Additional experimental studies are therefore required to understand the direct application to a large rubble pile asteroid.

4 Conclusions

We conclude that the presence of shock darkened regions on this meteorite affects the overall reflectance as a function of the amount of darkened lithology, which implies that the collisional history has a deep influence in the reflectance of asteroids. The different UV-NIR spectral behavior of the lithologies in Chelyabinsk resembles those between S and Q-type asteroids, implying that Q-type asteroids could be the surviving shocked and dark-colored fragments of S-type asteroids.

The mechanical properties of Chelyabinsk are consistent with a low porosity compact object, which implies a high momentum multiplication. However, the different lithologies of Chelyabinsk show different mechanical behavior, being the light-colored the one which would more efficiently react to a kinetic impact, due to its lower hardness. Since their UV-Vis-NIR spectra can be easily distinguished, we would be able to select the best region to be impacted. Also, we have seen that the impact melt veins in Chelyabinsk are more easily fractured than the other lithologies, and thus contribute to reduce the strength and induce fracture of a Chelyabinsk type asteroid.

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