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Tensile strength as an indicator of the degree of primitiveness of undifferentiated bodies

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Abstract

The extremely porous structure and low strength of most comets and their fragments is opposed to the properties observed in relatively pristine chondritic asteroids, even although both are sharing important chemical similitude. Laboratory experiments and observational evidence suggest that the original extremely porous aggregates that were born from the protoplanetary-disk-forming materials were highly retentive of water and organic compounds present in their forming environment. After consolidation, many of them experienced a particular dynamic history. Some bodies, quickly scattered during the formation of the giant planets and later stored in the Kuiper Belt (KB) or the Oort Cloud (OC) regions, would have suffered a lower degree of impact processing than previously thought. In such category would be comet 81P/Wild 2, whose materials have not experienced aqueous alteration. Other bodies originally volatile-rich that were transiting other regions with higher impact rate were experiencing progressively significant compaction processing, together with subsequent aqueous alteration and loss of volatiles. The release of water from hydrated minerals or interior ices, participated in soaking the forming materials, and transforming their initial mineralogy and physical properties. As a consequence of the physico-chemical evolution promoted by impact processing of undifferentiated bodies, most of the bodies present in the inner solar system are not representative of the planetesimals. Thus, highly porous progenitors and their fragments are the preferential sources of water and organics to the early Earth, even in higher amounts than previously thought.

Keywords: Comets; Asteroids; Meteoroids; Meteorites; Minor bodies; Pristine bodies; Tensile strength

1. Introduction

Although the first stages of planetsimals and cometesimal formation are now well established, due to extensive laboratory work (see the review by Blum and Wurm, 2008), the step from decimeter-sized dust aggregates to km-sized bodies are still purely speculative. It is, however, clear that, due to the low-velocity-collision environment in the protoplanetary-disk phase, planetesimals and cometesimals must be highly porous (Blum and Schräpler, 2004; Blum et al., 2006). Under such restricted conditions, low-density bodies would be the result of primeval accretion in those regions. We think that this is consistent with the present evidence of layering in comets 9P/Tempel 1, 19P/Borrelly and 81P/Wild 2 (Belton et al., 2007), together with the pristine nature of materials for comet 81P/Wild 2 recovered by the Stardust mission (Brownlee et al., 2006), which is suggestive of more moderate collisional histories than previously thought. This is obviously incompatible with numerical models on the Kuiper Belt (KB) formation that suggested that virtually all 1–10 km KBOs are collisional fragments (rubble piles) resulting from the breakup of larger bodies (Farinella and Davis, 1996; Davis and Farinella, 1997) so these models should be revisited.

From laboratory experiments and observational evidence we suspect that most solar system minor bodies have not preserved their primeval physical properties, being

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evolved samples (Blum et al., 2006). For example, meteorites associated with primitive chondritic asteroids suffered collisional compaction and aqueous alteration (Brearley and Jones, 1998; Zolensky and McSween, 1998). New constraints on the link between collisional evolution and aqueous alteration in primitive meteorites like e.g. carbonaceous chondrites (CCs) have been obtained (Trigo-Rodríguez et al., 2006; Rubin et al., 2007).

In the context of deciphering primordial properties of the planet-forming bodies, remote observations of the disruption of cometary nuclei or the fragmentation of meteoroids in the Earth's atmosphere are very valuable. The reason is the importance of compiling information on the bulk density and tensile strength of fragile cometary materials. During the cometary formation phase, the compaction and disruption behavior of the cometesimal material determined its evolution (Sirono, 2004). It is believed that meteorite collections are not fully representative of the interplanetary materials because dynamic stress produced on fragile bodies during atmospheric entry induces their disintegration before reaching the Earth's surface. This is a selection effect that causes that only the toughest interplanetary materials survive atmospheric interaction. Even under particularly soft shallow-angle and low-velocity entry conditions (accomplished rarely like e.g. in the Tagish Lake meteorite fall) survival is only possible for the highest-strength rocks that probably are not representative of the full incoming meteoroid (ReVelle, 2002). This selection effect—when we look into recovered meteorites—must be taken into account if we wish to decipher the initial physico-chemical properties of primitive bodies. Highly porous progenitors will have an enormous capacity to grow and retain water ice and organics in their empty structure. The present paper tries to find out the point of departure of some basic properties like e.g. porosity and bulk density of primitive bodies on the basis of present observational evidence in several research areas. We suggest that the first bodies formed from the accretion of the protoplanetary disk materials had very different physical properties than most of the present solar system minor bodies. In fact, most of the asteroidal or cometary fragments arrived to the Earth seem to be compacted samples. Despite of this, in the outer regions of the solar system some comets preserved their primordial physico-chemical properties and are producing extremely fragile meteoroids that still now are reaching the Earth. Bulk density estimations of cometary nuclei are also suggesting that some comets preserve primordial properties (Davidsson and Gutiérrez, 2004, 2005).

2. How primitive are the properties of chondritic asteroids?

The oldest and most primitive rocks reaching the Earth's surface are the chondrites. Their name originates from the characteristic rounded-shape spherules, so-called chondrules, that are forming part of their internal structure. We can say that chondrites are cosmic samples containing the materials that were forming the protoplanetary disk at the particular heliocentric distance and time when they formed. Chondritic meteorites are undifferentiated materials (e.g. non metamorphosed in large bodies) that comprise carbonaceous, ordinary and enstatite classes that are subdivided into 12 groups (Brearley and Jones, 1998). All chondrites are considered chemically primitive by the fact that the ratios of their major, non-volatile elements (Fe, Si, Mg, Al, Ca, etc.) are close to those observed in the Sun (Anders and Grevese, 1989). Among chondrites, the CC class is thought to be especially pristine (Zolensky and McSween, 1988). Inside CCs, several groups (mainly CM, CO and CRs) exhibit volatile-rich contents and are hydrated, mainly located in the fine dust that is cementing these rocks with typical grain sizes of 1 μm or less. In fact, the different chondrite classes are basically conglomerates of fine dust (a mixture of silicates, oxides, metal, sulfides and organic constituents), chondrules, and refractory or mafic inclusions (Brearley and Jones, 1998). We also know that they are unprocessed because they also contain interstellar grains that survived processing in the solar nebula and that were incorporated to these rocks during accretion (Anders and Zinner, 1993). On the other hand, thermal metamorphism was not very severe in CM and CI chondrites as is indicated by the peak temperature of 50 °C for CMs, and <150 °C for CIs derived by Zolensky et al. (1993). Other CC groups (like e.g. COs) were thermally metamorphosed at temperatures up to 500 °C and above, followed by cooling and aqueous alteration. The different degree of metamorphism experienced by the CC groups suggests a collisional origin, affecting the amount of volatiles, aqueous alteration and compaction observed in the different groups. Even relatively pristine groups like e.g. CMs experienced compaction, as preferential lineation and shear features in their structure are suggesting (Trigo-Rodríguez et al., 2006).

It is believed that CCs can provide insights on the early processes of accretion in the inner solar nebula. However, we should be cautious because these meteorites are not in a pristine stage and probably suffered important volatile depletion processes. The parent bodies of these meteorites experienced parent-body processing in different degrees after accretion (Zolensky and McSween, 1988; Brearley and Jones, 1998). The main processes, which occurred to the chondrite parent bodies after accretion, were aqueous alteration, thermal metamorphism, and shock metamorphism (Brearley and Jones, 1998). We should seriously consider the effects of these processes on the solar-system-building materials in order to compare theoretical or laboratory-simulation results with the physical properties of these meteorites. We should not forget that every solar system minor body has undergone a particular history of 4.5 Gyr of physical processes since their formation. For example we expect impact processing being particularly intense for bodies stored in the main belt (Chapman and Davis, 1975; Asphaug, 2004). Despite of this, some CM chondrites are still thought to be very