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Effects of atmospheric entry heating on the noble gas and nitrogen content of micrometeorites

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ABSTRACT

Fragments of the carbonaceous chondrite Orgueil were subjected to pulse-heating sequences in order to simulate the heating conditions experienced by micrometeorites (MMs) upon entry into Earth's atmosphere. By increasing the experimental run times from 2 to 120 s at a fixed temperature of 1350 °C, the different textures of natural MMs (from non-vesicular fine-grained particles to melted cosmic spherules) were reproduced, and the noble gas (He, Ne, Ar) and nitrogen abundances and isotope ratios of the MM analogues were subsequently determined by CO_2 laser extraction-static mass spectrometry analysis. The starting material shows a heterogeneous He–Ne–Ar–N signature, consistent with the mineralogical heterogeneity of CI chondrites and the inhomogeneous distribution of various noble gas and nitrogen components among meteoritic minerals. Nonetheless, our experiments demonstrate that moderately to strongly heated Orgueil fragments retain only a few percent of their initial noble gas and nitrogen inventories, indicating that atmospheric entry heating results in extensive degassing of meteoritic dust particles. The evolution of the noble gas and nitrogen isotope ratios may, in part, be explained by equilibration with the atmosphere; however, the decreasing $\delta^{15}N$ values may also indicate preferential degradation of a ^{15}N-rich component by thermal processing of chondritic matter. Furthermore, the efficient loss of helium and cosmogenic neon during heating will lead to an underestimate of the ^{3}He and ^{21}Ne exposure ages of MMs, as well as to large uncertainties for cosmic dust accretion rates derived from extraterrestrial ^{3}He abundances in deep-sea sediments or polar ice cores. While the relative proportions of infalling cometary and asteroidal dust on Earth are unknown, the contribution of noble gases, nitrogen, and water from cosmic dust to the terrestrial volatile inventory appears negligible.

1. Introduction

The current flux of extraterrestrial matter entering Earth's atmosphere is dominated by cosmic dust. However, the present-day dust accretion rate is highly debated, with estimates based on satellite measurements ranging from a few thousand tons/yr to up to ~40,000 tons/yr (Cremonese et al., 2012; Love and Brownlee, 1993; Mathews et al., 2001). Cosmic dust comprises interplanetary dust particles (IDPs), which are collected in the stratosphere by NASA aircraft (Brownlee et al., 1977), and micrometeorites (MMs), recovered on the surface of the Earth from deep sea sediments (Blanchard et al., 1980; Murrell et al., 1980) as well as from the Greenland and Antarctic ice sheets (Brownlee, 1985; Duprat et al., 2007; Engrand and Maurette, 1998; Maurette et al., 1986, 1994; Nakamura et al., 1999a; Taylor et al., 1996, 1998; Wagstaff and King, 1981). Both IDPs and MMs appear to sample a mixture of debris from the asteroidal belt and Jupiter family comets (JFCs) (Brownlee, 1985; Flynn, 1989b, 1990; Briani et al., 2011; Nesvorný et al., 2010; Trappitsch and Leya, 2013), but the two particle populations differ in sizes, with MMs being larger (~20 up to 400 μm) than IDPs (<50 μm).

Most MMs share many chemical and/or textural similarities with carbonaceous chondrites (i.e., CI, CM, CR, or Tagish Lake) (Engrand and Maurette, 1998; Engrand et al., 1999; Genge et al., 1997; Kurat et al., 1994; Nozaki et al., 2006; Tayor et al., 2012; Genge, 2008). On entering Earth's atmosphere, however, micrometeorites suffer severe heating, which leads to significant changes in their original texture, mineralogy, and chemical composition. Numerical calculations have shown that the degree of heating depends on the particle size, velocity, and entry angle (Flynn, 1989a; Fraundorf, 1980; Love and Brownlee, 1991; Whipple, 1951). A 200 μm-sized MM with a velocity of 12 km/s

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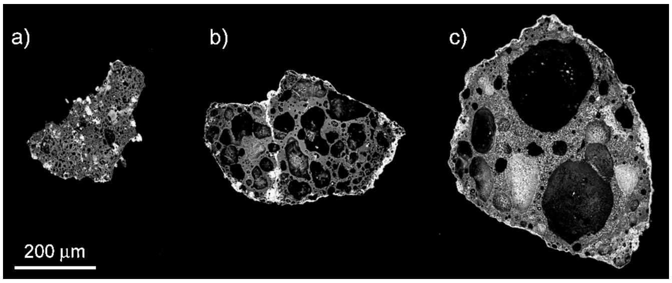

Fig. 1. Backscattered electron images of polished sections of pulse-heated Orgueil fragments heated at a fixed temperature of 1350 °C under an oxygen fugacity ($\log fO_2$) of −0.68 for run times (a) 5 s, (b) 10 s and (c) 20 s (see Toppani et al., 2001 for details). By increasing the heating duration, the different textures of natural MMs are reproduced, i.e., non-vesicular fine-grained (a), vesicular fine-grained (b), scoriaceous (c).

(typical of asteroidal particles) will experience peak temperatures of ∼1200–1500 °C for a few seconds during atmospheric entry, whereas some dust particles generated by comets with velocities ⩾15 km/s and steep entry angles may be heated up to 1700 °C (Kortenkamp et al., 2001; Love and Brownlee, 1991). In addition, a set of pulse-heating experiments using fragments of the Orgueil meteorite as analogue material revealed that most MM textures, from the vesicular fine-grained MMs to the melted cosmic spherules, can be reproduced by varying the temperature or heating duration (Fig. 1; Toppani et al., 2001). Thus, depending on the degree of heating, chondritic material may yield a variety of micrometeorite types, such as unmelted MMs (fine-grained or crystalline), partially melted 'scoriaceous' MMs, and completely melted cosmic spherules (e.g., Greshake et al., 1998; Kurat et al., 1994). Notably, some Antarctic micrometeorites (AMMs) with melted rims preserve unmelted cores, indicating that entry heating of these particles is not isothermal (Brownlee and Bates, 1983; Genge et al., 1997; Genge, 2006).

Noble gases are key indicators of the extraterrestrial origin of MMs and provide valuable constraints on the origin and history of these particles. However, several studies have shown that the noble gas concentrations and isotope ratios of AMMs are highly variable (Marty et al., 2005; Olinger et al., 1990; Osawa, 2012; Osawa and Nagao, 2002a, 2002b; Osawa et al., 2000, 2003a, 2003b, 2010; Stuart et al., 1999). While some crystalline AMMs contain up to two orders of magnitude more noble gases (^{3}He, ^{20}Ne, and ^{36}Ar) than generally observed in carbonaceous chondrites (Marty et al., 2005), the majority of AMMs are highly depleted in helium compared to the abundances observed in stratospheric IDPs (Osawa, 2012; Osawa and Nagao, 2002a; Stuart et al., 1999). Since most MMs recovered on Earth show evidence of thermal processing (e.g., Genge et al., 1997; Taylor et al., 2000), the low He contents are indicative of noble gas degassing during atmospheric entry (Farley et al., 1997; Stuart et al., 1999). As a consequence of the helium loss, estimates of the total mass of MMs reaching the Earth's surface based on extraterrestrial ^{3}He abundances in oceanic sediments and polar ice samples (Karner et al., 2003, and references therein) are generally lower than the dust accretion rate derived from direct measurements on a satellite collector (Love and Brownlee, 1993; Mathews et al., 2001). In addition, a coupled nitrogen-noble gas study revealed that nitrogen is present in low abundances in AMMs (i.e., only about one tenth of the chondritic value), suggesting that the nitrogen host phase is efficiently degraded during atmospheric entry, or, alternatively, that the precursor material had a low initial N content (Marty et al., 2005). These observations illustrate that entry heating processes may obscure the extraterrestrial origin and primary volatile characteristics of many cosmic dust particles recovered at the Earth's surface.

In this study, we investigate the effects of atmospheric entry heating on the He–Ne–Ar–N characteristics of micrometeorites using Orgueil fragments as compositional proxies of the precursor material. We evaluate the volatile retention capabilities of thermally processed meteoritic particles, and compare their residual noble gas and nitrogen abundances with micrometeorites recovered on Earth. Furthermore, since it has been suggested that cosmic dust has represented a significant source of volatiles and organics to the Earth and Moon, as well to the other terrestrial planets (Anders, 1989; Füri et al., 2012; Maurette, 1998, 2006; Maurette et al., 2000), we estimate the volatile influx associated with the accretion of cosmic dust through time.

2. Samples and analytical techniques

In order to simulate the atmospheric entry conditions experienced by micrometeorites, we performed pulse-heating experiments using 200–400 μm-sized fragments of the CI carbonaceous chondrite Orgueil as starting materials. The smaller fragments are comparable in size to the bulk of the extraterrestrial material accreted by Earth (∼200 μm diameter; Love and Brownlee, 1993). Furthermore, petrological studies have revealed that most unmelted fine-grained MMs are rich in phyllosilicates in addition to their thermal decomposition products (i.e., glass and anhydrous silicates; Genge et al., 1997; Kurat et al., 1994; Nakamura et al., 2001; Noguchi et al., 2002). Therefore, Orgueil, which consists mainly of a phyllosilicate-rich matrix (Greshake et al., 1998; Tomeoka and Buseck, 1988), represents an appropriate compositional analogue of primitive MM precursor material.

Pulse-heating sequences were carried out at atmospheric pressure in a 1700 °C GERO HTVR 70–250 closed vertical furnace under an oxygen fugacity ($\log fO_2$) of −0.68 (see Toppani et al., 2001 for details). Based on the previous work of Toppani et al. (2001), we chose a fixed temperature of 1350 °C and run times (t) ranging from 2 to 120 s in order to reproduce the different textures of natural MMs, i.e., non-vesicular fine-grained MMs ($t = 2$ s), vesicular fine-grained MMs ($t = 5$ s), scoriaceous MMs ($t = 10$ s), and cosmic spherules ($t = 120$ s). Pairs of Orgueil fragments were loaded into crucibles made of platinum wire spirals, placed into the hotspot of the furnace, and subsequently quenched in air. Two series of pulse-heating experiments were carried out, and most heating steps were duplicated.

Noble gas (He, Ne, Ar) and nitrogen abundances and isotopic compositions were determined by laser extraction-static mass spectrometry (Hashizume and Marty, 2004; Humbert et al., 2000). Both unheated and pulse-heated Orgueil samples (i.e., 1–5 grains with a total mass ranging from 0.1–0.8 mg) were loaded into different pits of the laser chamber connected to the purification line of the Micromass© VG5400 mass spectrometer at the CRPG noble gas analytical facility. The chamber was heated over night at a temperature of 100 °C, and samples were left under ultra high vacuum for several weeks prior to analysis to ensure efficient removal of terrestrial contaminants. The samples were heated using a de-focused CO_2 laser beam ($\lambda = 10.6$ μm), and the extracted gas fraction was split into two calibrated volumes for specific noble gas and nitrogen purifications. The noble gas aliquot was purified using Ti sponge getters, and noble gas abundances and isotope ratios were measured using the CRPG VG5400 mass spectrometer after separation using a charcoal finger held at liquid nitrogen temperature and a cryogenic trap. Procedural blanks averaged 2.6×10^{-14} mol ^{4}He, 5.0×10^{-16} mol ^{20}Ne, and 8.6×10^{-17} mol ^{36}Ar during the first measurement series, and 2.3×10^{-15} mol ^{4}He, 3.5×10^{-16} mol ^{20}Ne, and 4.9×10^{-17} mol ^{36}Ar during the second series.

The nitrogen aliquot was purified using a CuO furnace cycled between 723 and 993 K, and a U-shaped cold trap held at 93 K. Nitrogen isotope data were collected on the VG5400 mass