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A fiery birth of aluminosilica analogs of refractory dust in the upper stratosphere

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Abstract

Following a successful dust collection flight in the upper stratosphere our DUSTER (Dust in the Upper Stratosphere Tracking Experiment and Retrieval) made a safe remote landing at its assigned location on Baffin Island during early June 2009. When the balloon payload that included DUSTER was retrieved it was found part of the payload had experienced a lithium-sparked fire while the payload was being dragged across the landing site. In this process the housing of DUSTER had developed a pin-sized hole that allowed smoke of the fire to enter the collector. Numerous smoke particles were found covering both the DUSTER collection and blank collector surfaces an indication that our experiment to collect upper stratospheric dust had failed! Both collector surfaces were covered by numerous carbon smoke and amorphous, aluminosilica nanoparticles. The compositions of vast majority of these aluminosilica nanoparticles, $Al_2O_3 = 49$ wt% and $SiO_2 = 51$ wt%, was both surprising and unique because it was an exact match of the Deep Metastable Eutectic (DME) nanoparticles found in vapor phase condensation experiments. These vapor phase condensation experiments were conducted to explore the formation of extraterrestrial dust particles. We are not claiming an extraterrestrial origin for these particles from this DUSTER experiment. We submit that given the appropriate conditions of high temperature alumina and silica vapors and rapid quenching in a contained natural environment, DME aluminosilica nanoparticles will likely condense. This serendipitous result can be used to explore nanoparticle formation inside incandescent clouds associated with bolides and fireballs.

Keywords: Stratospheric dust; Stratospheric balloon; Refractory particles; Meteoric dust

1. Introduction

"Given that nature always behaves according to the laws of physics and chemistry, rather than according to currently popular models and theories, experimental results should always be considered correct even when the results are far from those that one might initially expect." (Nuth et al., 2016). This paper reports a case of serendipitous 'success' showing how refractory aluminosilica meteoric analog nanoparticles formed outside the laboratory. Incoming meteors decelerating in the Earth atmosphere will convert a major fraction of their kinetic energy into meteoric plasma species in the mesosphere but another fraction survives as meteorites, micrometeorites, fragments, dust and condensed-liquid nanoparticles, while another fraction is

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turned into vapors that condense into meteoric dust smokes. The extent of these processes critically dependents on the original amount of energy of a decelerating meteor. During the ninety-sixties dust collectors were deployed by high-flying aircraft and high-altitude balloons up into the lower thermosphere to capture meteoric dust for laboratory analyses. These efforts recovered solid spheres, fragments and smoke particles, between ~200 nm and ~5 μm in size, with compositions listed as (1) Al, Si, (2) Fe, Ti, Mg, Ca, (3) Al, Si, Fe, (4) Ti, Ca with minor Mg, Fe, Si (Hemenway and Soberman, 1962; Hemenway et al., 1964; Witt et al., 1964; Bigg et al., 1970, 1971). Most of these meteoric particles had refractory chemical compositions. These early collection efforts suffered from chemical and particulate contamination but the findings seemed to show a preference for the survival of refractory, so-called high-temperature, nanoparticles. Addressing the earlier problems, DUSTER (Dust in the Upper Stratosphere Tracking Experiment and Retrieval) was designed to collect intact, contamination-free, meteoric dust in the upper stratosphere (Della Corte et al., 2012, 2014). To date DUSTER has successfully collected forty-five meteoric particles in the stratosphere between altitudes 37–38.5 km (2008) and 31.6–33.7 km (2011). Among the collected meteoric particles were refractory alumina (Al_2O_3) particles, and platy and massive aggregate aluminosilica particles (Fig. 1).

The particles are of special interest because they are non-equilibrium phases that required very high cooling rates from initially high temperatures.

The DUSTER-2009 flight that sampled the upper stratosphere between 34 and 39 km altitude for a total of 25 h between July 1 and July 3, 2009 was a disaster although the telemetry data showed nominal instrument

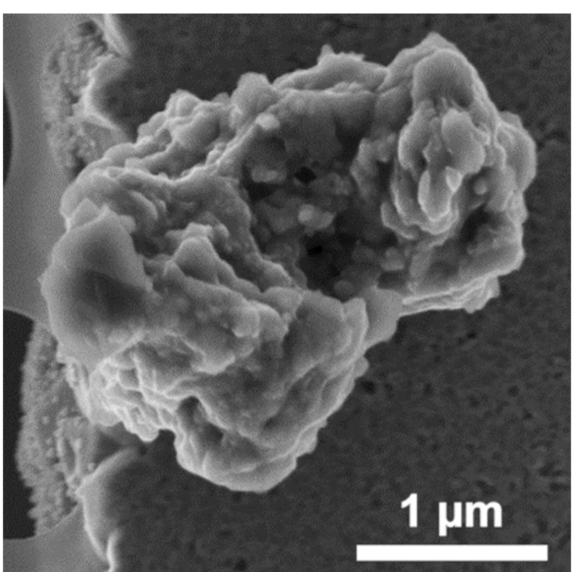

Fig. 1. FESEM/SE image of a compact low-Mg aluminosilica particle that is a dense aggregate of sub-spherical grains collected by DUSTER 2011. Magnesium is present in very small grains at its surface. (reproduced from Rietmeijer et al., 2016, Icarus, Elsevier).

performance throughout the flight. This DUSTER flight was piggybacking on a larger scientific payload that, as planned, landed safely on Baffin Island (Canada). After landing the lithium batteries on-board the gondola caught fire as it was dragged along when high winds caught its parachute. The payload suffered structural damage and unfortunately the DUSTER housing developed a pinhole that allowed hot smoke to enter and contaminate the holey-carbon thin-film substrates that serve as the collecting surfaces. Inspecting two collecting surfaces found numerous refractory aluminosilica nanoparticles. Refractory minerals typically require high-temperature thermodynamic equilibrium conditions. They will be very stable over long periods of [geological] time. Refractory minerals are found in many chondritic meteorites (Brearley and Jones, 1998), the most Al, Ca, Mg, Ti rich non-chondritic meteorites (Mittlefehldt et al., 1998) and among the dust ejected from the nucleus of Jupiter-Family comet 81P/Wild 2 (Simon et al., 2008). Refractory Mg, Ca, Al-rich dust was also present in Leonid meteors from comet 55P/Temple-Tuttle (Jenniskens, 2007).

Refractory particles that formed rapidly will be amorphous, thermodynamically metastable, solids without a stoichiometric mineral composition. Instead, these nanoparticles that form during extreme undercooling have a DME (Deep Metastable Eutectic) composition that is constrained in between the compositions of two adjacent eutectic compositions in a thermodynamic equilibrium phase diagram (Nuth et al., 2000; Rietmeijer and Nuth, 2015). These, non-equilibrium gas-to-solid vapor phase condensation experiments using Al_2O_3-SiO_2 vapors yielded nanoparticles with unique DME aluminosilica compositions (Rietmeijer and Karner, 1999) that match those of the meteoric aluminosilica nanoparticles collected by DUSTER. In fact, ultrafast vapor quenching from high temperatures is the key to produce DME nanoparticles in the laboratory (Nuth et al., 2000; Rietmeijer and Nuth, 2015).

The physiochemical conditions conducive to produce contemporary DME meteoric nanoparticles will exist in fireballs, *i.e.* a meteor brighter than −8 magnitude, and bolides, *i.e.* a meteor brighter than −17 magnitude (Ceplecha et al., 1999). The thermal-emitting debris cloud of the Chelyabinsk superbolide with the equivalent energy of 570 ± 150 kt TNT was the most extreme event ever witnessed (Popova et al., 2013). It was estimated that 76% of the initial meteoroid had evaporated because the intense radiation in the incandescent debris cloud that caused evaporation of most fragments with the remainder being further reduced to dust (Popova et al., 2013). About 5 s after formation the smoke cloud temperatures in this were 700 ± 100 K. Assuming that the initial temperature in the cloud was that of the dust evaporation, the resulting cooling rate was ≥240 K/s (Popova et al., 2013). This physiochemical environment was conducive to produce DME nanoparticles but there are no reported efforts to sample the atmosphere after this event. The radiating gas temperatures in the Šumava fireball (−20 mag.), a fragile cometary body, and