PRELIMINARY ELECTRON MICROBEAM ANALYSES OF LIGHTNING INDUCED EVAPORATION AND GAS PHASE MIXING

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Transient high-energy events such as reconnecting magnetic fields, chemical energy in amorphous solids, frictional heat (infall model) and lightning are invoked for the formation of chondrules in the solar nebula. It remains an open question whether any single one of these events, or a combination of them, is responsible for the variety of chondrule properties in meteorites. We used the Langmuir Laboratory's Triggered Lightning Research Facility on South Baldy Mountain near Socorro (New Mexico) to conduct an exploratory experiment on lightning induced alteration of refractory materials in conjunction with an ongoing experiment to study the formation of lodestone in natural deposits. Blankets of glass wool (~1 cm thick) were placed in a cylindrical container as separations between three samples of natural magnetite. The samples were placed perpendicular to its axis and were about 1 cm thick. The lightning strike passed through the container from top to bottom thereby passing through the three samples and two intervening blankets of glass wool.

LIGHTNING. The passage of the lightning strike through the container left a hole in each blanket with $\phi \simeq 1$ cm. The hole's wall in the blanket between the samples of pure magnetite sample and magnetite with some amounts of (Mg,Fe,Ca)-silicates and calcite shows an orange-brown discoloration. A spray pattern with similar discoloration occurred on this blanket surface surrounding the hole. Several millimeter-sized black spheres and (rare) black fragments were located around the hole where the lightning strike exited the blanket.

AEM ANALYSES. A JEOL 2000FX AEM equipped with a TN-5500 Tracor Northern energy dispersive spectrometer for *in situ* determination of elements with atomic number > 11 was used for mineralogical and chemical characterization of crushed samples of (1) black spheres (ϕ < 1 mm), (2) black fragments (± 1 mm), (3) discolored wall of the hole, (4) the blanket surface at ~20 mm and ~40 mm from the hole, (5) the blanket interior far away from the hole, and (6) glass wool from the stock that provided the blankets. The crushed samples were dispersed onto clean holey carbon thin films on Cu TEM grids. All samples, including a sample from the stock, contain unexpectedly high abundances of mineral impurities that are associated with the fibres. These fibres, 42 wt% SiO_2 and 58 wt% Al_2O_3, are mostly amorphous. Some degree of devitrification is shown by weakly-developed polycrystalline electron diffraction patterns with a symmetry typical of fibrous material.

Compositions of the hollow to highly vesicular black spheres and the black fragments are shown in a ternary diagram SiO_2-Al_2O_3-Fe_2O_3 (wt%) [Figure 1]. The spheres and fragments are silica-rich compared to the glass wool fibres. Pure Al_2O_3 occurs as patches in the (Al,Fe)-SiO material and as individual grains. The high Fe_2O_3 contents coincide with the skeletal growth texture at the sphere surface. This texture is reminiscent of iron-oxide dendrites in meteorite fusion crusts [*e.g.* ref. 1]. The only other Fe-bearing aluminosilica materials (< 2 wt% Fe_2O_3) were from the blanket surface at ~20 mm from the hole. Porous vapor phase condensate domains are scattered among the spheres. The compositions of this "rutile" smoke are clustered at TiO_2 = 81.6 wt%, SiO_2 = 17.1 wt% and CaO = 1.3 wt% but are up to TiO_2 = 53 wt% and SiO_2 = 47 wt%. One crystalline sphere fragment was identified as mullite, SiO_2 = 37 wt%, Al_2O_3 = 58 wt% and CaO = 5 wt% [Figure 1]. The impurities make up ~15% of each sample. They include euhedral Ti-oxide grains (< 200 nm) closely associated with the fibres, dense clusters (~200 nm in size) of sub- to euhedral Ti-oxides ($\phi \simeq 30$ nm), Au-Ag-Te fragments and spheres (< 500 nm), Ca-phosphates (< 400 nm) with measurable concentrations of Ce, Nd, La and Th in their center, and a nanometer sized Co [Fe,Ni,Cr] particle. All samples contain amorphous silica spheres (ϕ = 100-250 nm). In general, there are no obvious mineralogical and chemical differences among these different samples. It does not appear that the impurities were affected by the lightning strike with the exception of the production of a "rutile" smoke from the Ti-oxide impurities.

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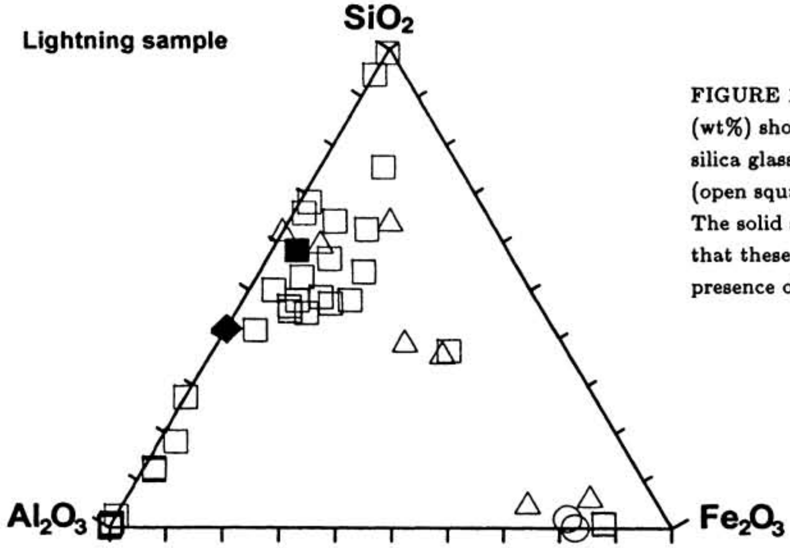

FIGURE 1: The ternary diagram SiO_2-Al_2O_3-Fe_2O_3 (wt%) showing the bulk composition of the alumino-silica glass wool (solid diamond), the black spheres (open squares) and black fragments (open triangles). The solid square is mullite. The open circles indicate that these Fe-rich phases were recalculated for the presence of TiO_2 grains.

DISCUSSION. The evidence that the lightning strike interacted with the aluminosilica glass wool blanket and magnetites consist of a penetration hole, the orange-brown discoloration, highly vesicular to hollow (Al,Fe,Si)-O spheres, "rutile" smoke particles, and crystalline mullite. The spheres and smoke particles suggest that evaporation and condensation occurred as a result of the lightning strike. The compositions of the black spheres and fragments show a distribution pattern in the SiO_2-Al_2O_3-Fe_2O_3 (wt%) diagram similar to those for individual condensate droplets in an Al,Fe-SiO smoke [2]. Condensation of this vapor at canonical solar nebula pressures produced a fluffy smoke of dense spherical grains [2]. The lightning experiment was conducted at atmospheric pressure which promotes formation of hollow spheres as, for example, during efficient firing of natural coals at high temperatures [3]. The spheres in typical coal fly-ash are condensates of mineral impurities in natural coals. The black spheres in the sample formed from an Al,Fe-SiO vapor due to lightning induced melting and evaporation of magnetite slabs and aluminosilica glass wool at atmospheric pressure. Assuming mullite in the spheres represents a quenched equilibrium melt, its presence suggests temperatures of 1700-1800°C in the SiO_2-Al_2O_3-CaO (wt%) phase diagram. Cotectic melting of aluminosilica glass wool suggests temperatures of ~1850°C based on the system SiO_2-Al_2O_3-Fe_3O_4 (wt%). Melting of Ti-oxides (assuming TiO_2) occurs between 1830-1850°C. The small size of Ti-oxide grains may allow melting at slightly lower temperatures. Quenching of this melt occurs at ~1800°C in the system SiO_2-TiO_2-CaO (wt%). These temperatures imply that the impurity elements probably made no contributions to the vapor phase (for example, the boiling points of Au, Ag and Ni are between 2100 and 3200°C, at P=1 atm).

CONCLUSIONS. This experiment was a first attempt to investigate the use of triggered lightning to form new phases via melting and evaporation of analogs of natural materials that might reflect conditions in the solar nebula. Samples were chosen for this experiment in order to investigate the possibility of forming lodestone via lightning strikes in natural ore deposits. We took the opportunity of placing glass wool blankets between the samples to investigate vapor phase effects. The lightning strike produced Al,Fe-SiO and Ti-SiO vapors from magnetite, glass wool fibres and Ti-oxides, plus a small amount of CaO vapor, at 1700-1800°C. It is encouraging that this first attempt not only shows unambiguous evidence of vaporization and condensation but also efficient vapor phase mixing. Future experiments will be conducted under much more controlled conditions.

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