THE LUNAR DEVITRIFIED GLASS SPHERULES: IMPLICATIONS FOR THE ORIGIN OF METEORITIC CHONDRULES. Derek W. G. Sears, Steve Symes, Anne Taunton, Glen Akridge, Shaoxiong Huang and Paul Benoit, Cosmochemistry Group, Department of Chemistry and Biochemistry, University of Arkansas, Fayetteville, Arkansas 72701, USA.

Devitrified glass spherules (DGS) from three thin sections of Apollo 14 regolith breccias (14318, 6; 14318, 46 and 14315, 20) have been classified (type X, equant plagioclase, and type Y, plagioclase lathes both in a devitrified mafic mesostasis), the abundance and size distributions determined and their bulk compositions and the compositions of plagioclase and mesostasis in type Y have been determined. The abundance and size distributions of the DGS resembled those of chondrules in the CM chondrite Murchison. Their coarse textures suggest fairly slow cooling (<1°C/s). The bulk compositions of the DGS do not resemble any of the regoliths of the Apollo sites, including Apollo 14, or any of the common impact glasses, but resemble those of impact spherules from the lunar meteorites. It is suggested that the DGS are ejecta from the Imbrium impact and that only impact events of this size are capable of producing melt spherules with sufficiently slow cooling rates and the long free flight times required on the moon. Smaller impacts produce glassy spherules and agglutinates. While much remains unclear, difficulties with a nebula origin and new developments in chondrule chronology, asteroid surfaces and impact ejecta behavior, mean that the formation of meteoritic chondrules by impact is a reasonable possibility to explore.

For many years, devitrified glass spherules of impact origin found in lunar regolith samples, most particularly the Apollo 14 regolith breccias 14315 and 14318, were widely regarded as chondrules and were thought to constitute strong evidence that meteoritic chondrules were impact in origin (1-5). Because of what we consider to be major difficulties with theories for the origin of chondrules in the nebula (6, 7), and because several key arguments against an impact origin no longer appear convincing, we have been re-examining the Apollo 14 devitrified glass spherules. We mapped three thin sections and located ~170 DGS using their CL and optical properties, sorted them into classes, obtained statistical data for their size and abundance and determined bulk and phase compositions using electron microprobe analysis.

We distinguished four types, but most consisted of plagioclase lathes (type Y, 22% by number) or equant plagioclase grains (type X, 66% by number) both set in a devitrified relatively mafic mesostasis. Basaltic and quartz-rich types will not be discussed here. The abundance and size distributions of the type X and Y DGS resembled those of group A (FeO-poor) and group B (FeO-rich) chondrules in the CM chondrite Murchison (Fig. 1). Single spherules consisting of both textures, objects consisting of two or more spherules engulfing or abutting each other, and spherules with "relic" grains were also found. The relatively coarse-grained textures of both types, especially type Y, suggests minimal supercooling and relatively slow cooling rates (8-10). Probably cooling rates were <1°C/s and similar to those of meteoritic chondrules (13,14). The bulk compositions of the two types of DGS are very similar to each other and closely resemble those of the so-called "ANT chondrules" of Prinz *et al.* (15) and Kurat *et al.* (5). The plagioclase lathes in type Y DGS are An_{95-85}, while the mesostases are more mafic (12-20wt%FeO and 5-21wt% MgO). Phases in type X have not yet been analyzed.

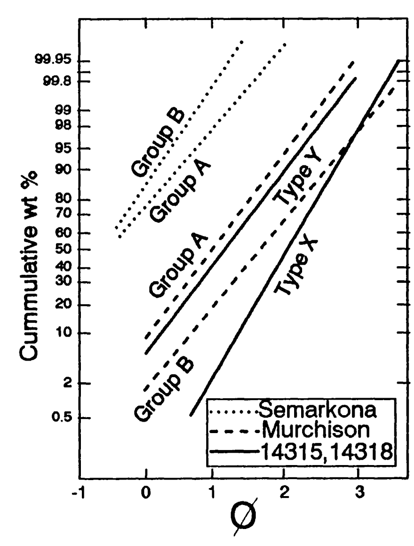

Figure 1. Cumulative frequency distributions for lunar devitrified glass spherules compared with chondrules from the Murchison CM (11) and Semarkona ordinary (12) chondrite meteorites. "Group A" and "group B" refer to FeO-poor and FeO-rich meteoritic chondrules, respectively. $\phi = -log_2$ (diameter in mm) is a commonly used parameter for describing grain-size distributions in sediments.

Delano (16) and others have argued that impact spherules have bulk compositions similar to the regolith from which they formed, and that while most lunar impact spherules were formed from the regolith in which they are currently found,

LUNAR DEVITRIFIED GLASS SPHERULES AND METEORITIC CHONDRULES: Derek W. G. Sears *et al.*

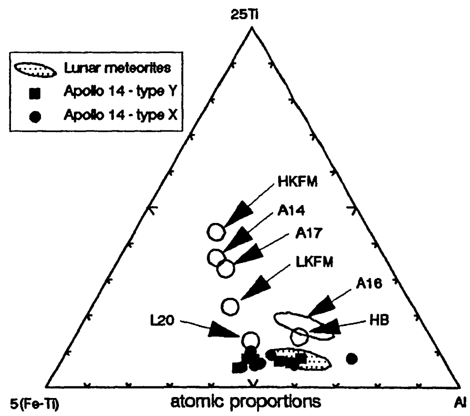

Figure 2. A ternary plot, after Delano (16), of element ratios thought to be diagnostic of impact glass spherule sources. A14, A16, A17 and L20 refer to Apollo 14, 16, 17 and Luna 20 highland regolith compositions, while HKFM, LKFM, HB refer to high-potassium, low-potassium Fra Mauro basalts and highland basalts. These are the compositional fields of the widespread impact glasses. The Apollo 14 DGS resemble the impact spherules in lunar highland meteorites but are unlike the common impact glasses or any Apollo highland regoliths, including that of Apollo 14.

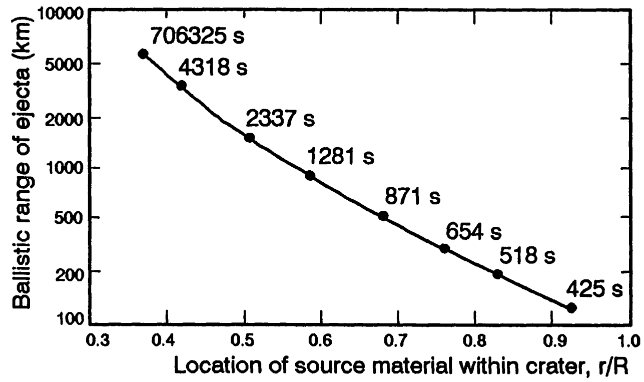

Figure 3. Plot of the ballistic range of material ejected from the crater during the formation of the Imbrium basin against the original location of the source material in the crater (in terms of fractions of the crater radius). Material originally within ~0.36 crater radii of the center achieves escape velocity. The time above each datum is the free-flight duration. (Method of Ahrens and O'Keefe, ref. 17, and 45° ejection angle were used).

ballistic transport can sometimes result in the presence of exotic material. Figure 2 is the plot proposed by Delano which uses diagnostic ratios of non-volatile elements to identify source materials for impact spherules. Most strikingly, the DGS from the Apollo 14 regolith breccias do not plot with the Apollo 14 highland regolith, or the highland regolith of any of the Apollo sites, but instead have compositions identical impact spherules in the lunar highland meteorites (Y 791179, ALH 81005, Y 82192, Y 86032, MAC 88105). Several DGS identical to those reported here and discussed by previous workers (1-5) have recently been reported in several lunar meteorites, most particularly MAC88105 (18).

The Apollo 14 landing site was chosen because it was thought to contain ejecta from the Imbrium impact (19). Unlike the agglutinates and glassy spherules that are common impact products at all Apollo sites, the production of DGS requires long flight times and an impact large enough to produce considerable dust and gas to cause slow cooling rates (*c.f.* 9,10). Using the equations of Ahrens and O'Keefe (15) and assuming an ejection angle of 45°, we calculate free-flight times for ejecta from the Imbrium impact to reach the Fra Mauro site 1200 km away of about 40 minutes, which would permit cooling rates of ~0.25°C/s before the spherules were quenched on returning to the surface. As indicated by various laboratory experiments (13), differences in the structure of chemically similar DGS probably reflects differences in nucleation details. While there may be several remaining difficulties for an impact formation of chondrules, the many difficulties of poorly constrained nebula models (6,7), changing views concerning chondrule chronology and the probability of energetic impacts during meteoritic chondrule formation (20) and the nature of asteroid surfaces and impact processes (21,22), mean that the matter should not be considered closed. The formation of meteoritic chondrules by impact onto a planetary surface remains a possibility to be explored.

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