THE ORIGIN OF Ca,Al-RICH METEORITIC INCLUSIONS: IMPLICATIONS OF ISOTOPIC FRACTIONATIONS. J. Ray and D. Heymann, Rice University, Houston, Texas 77001.

Considerable effort has been devoted to tracing the origins of the Ca,Al-rich meteoritic inclusions, the so-called high-temperature condensates which are found abundantly in the carbonaceous chondrite Allende (C3V). Petrologic and mineralogic considerations have dominated the debate over genesis of these bodies yielding the following principal hypotheses: a) direct condensation from the preplanetary nebular gas to the solid (1,2); b) crystallization from a metastable Ca,Al-rich liquid (3); c) refractory residue remaining after heating and evaporation of volatile constituents (4). We propose here to interpret the large isotopic mass fractionations observed for several elements in the two inclusions EK1-4-1 and C1 as indicators of the formative history of, at least, the coarse-grain type B Allende inclusions.

In Table 1 we have assembled measurements from the literature of maximum isotopic mass fractionations (in units of ‰ per mass unit) for six elements in EK1-4-1, C1 and on lunar grain surfaces. Positive values refer to enrichment of heavier isotopes. The lunar data has been determined by partial fluorination in the cases of O and Si (5), and by a leaching process for Ca (6). Fractionated O and Si are found only in the first percent or so of material removed, which presumably reflects a surface siting because of the extraction technique employed. Bulk S analysis of grain size separates (7) suggests a surface correlation for the isotopic fractionation of this element as well. A comprehensive model has been proposed (8) which attempts to account for lunar fractionation via a combination of differential sputter rates in grain surfaces and of gravitational separation of those liberated atoms which subsequently return to the Moon's surface. Assuming that dilution with bulk unfractionated material has not caused the measured fractionations to be much smaller than the actual magnitude of whatever process is operating, then the model of Haff *et al.* (8) can be considered reasonably consistent with observations for O, Si and S. However, the comparative absence of any fractionation in lunar Ca poses a problem for this approach and, indeed, represents a severe constraint for any such model.

The striking observation seen in Table 1 is the similarity of magnitudes for those three elements measured in both the Allende inclusions and in fines. Large fractionations exist for O and Si, with the Si anomaly consistently smaller, and there is a uniform absence of a notable effect in Ca. While such an occurrence, especially for so small a suite of elements, may well be nothing more than fortuity, it is nevertheless interesting and perhaps instructive to assume that a similar mechanism has been involved in the production of both sets of anomalies. Specifically, we propose to consider the consequences of the hypothesis

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that EK1-4-1 and C1 formed from impact melts which incorporated substantial fractions of material derived from a planetary regolith. The most obvious difficulty with this viewpoint is understanding how an effect restricted to the surfaces of soil particles can be preserved through a melt phase, which surely redistributes the fractionation, without being diluted beyond detection. Two possible reasons are offered: a) preferential assembly of surface-correlated material (i.e., small grain sizes)into melts; b) much higher overall fractionation on meteorite parent body due to differing environmental factors (e.g., sputter rate, regolith turnover rate, etc.). Fortunately, studies of agglutination may shed light on the first possibility. Signer et al. (9) have shown that agglutinates have much higher concentrations of Ar36 than do mineral fragments of the same size fraction (150-200μm), by a factor of 10 to more than 60. Also, at least as much Ar36, likely even more than that, was probably lost during the agglutination process making these enhancement factors even more impressive. If $C_m(r)$ is taken as the measured concentration of Ar36 in spherical minerals of radius r and if we assume that the gas in such phases is restricted to a thin skin of depth d, then we can estimate the concentration C_m^* of Ar36 in that skin:

$$C_m^* = C_m(r)\,\frac{V_{core}}{V_{skin}} \quad \text{where} \quad \frac{V_{core}}{V_{skin}} = \frac{4/3\pi r^3}{4\pi r^2 d} = \frac{r}{3d} \quad \text{for } d \ll r \ .$$

So, $C_m^* = (r/3d)C_m(r)$. Since $C_m(r)$ varies approximately as $1/r$, C_m^* then is independent of grain size, as we expect. For the particle size interval considered by Signer et al., $r \sim 175\mu$m and taking $d \sim 0.1\mu$m, then $C_m^* \sim 580\ C_m(r)$. But the concentration of gas in the agglutinates, C_a, is as high as $C_a \sim 60\ C_m(r)$. Had the agglutinates been able to trap all of the Ar36 which cycled through them as would happen for mineral-forming elements then C_a could be as large as 120 to about 200 times $C_m(r)$; that is, within a factor of 3 or so of the gas concentration in the outer skin of soil particles. While is is obvious that meteoritic inclusions are not regolithic agglutinates, this exercise indicates that composite particles can be formed in regolith from smaller grains in such a way as to preferentially incorporate very large amounts of surficially-sited material. We suggest that an analogous process may be responsible for the appearance of large fractionation anomalies in EK1-4-1 and C1, consistent with the petrologically-based model of Kurat et al.(4). In addition to the importance of impact-generated volatization for enriching refractories as proposed by Kurat et al., we note that planetary differentiation will certainly play a significant role in determining the chemistry of regolith target material. In particular, the relative abundance of Al and Ca in the lunar highlands, thought to be typical of the ancient Moon's crust, may indicate that an explanation of the importance of these two elements in EK1-4-1 and C1

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may partially entail planetary differentiation.

Our hypothesis for inclusion formation has several intriguing, often obvious, corollaries. Foremost is the requirement that a large positive fractionation of Mg isotopes should exist on the surfaces of lunar grains, as can be seen from Table 1. Its magnitude may be as large as 50‰ per mu (by analogy with the Mg to O fractionation seen in Cl) which is far larger than the 20‰ effect predicted by the model of Haff et al.(8). Also, our argument concerning agglutinitic incorporation of surficial material in a volume-correlated manner necessitates fairly substantial fractionations of (at least) O, Si and Mg isotopes in bulk agglutinates. Both of these conjectures are testable and the first is a necessary, but not sufficient, condition for our hypothesis to be deemed viable.

Within this scheme, a planetary surface must have existed prior to the formation of Allende inclusions. Because the O in EK1-4-1 and Cl is apparently fractionated from a reservior greatly enriched in O16 relative to terrestrial O (10), any such planetary surface must have had similar O16 enrichments. This reasoning, however, does not necessarily require that the planet had bulk O16 enrichment of the magnitude indicated by Allende data, only that the surface did. Consequently, a passage of the early solar system through a dense interstellar cloud, in the manner of Butler et al.(11) though in this case of decidely non-solar composition, may be capable of effecting the necessary surface alteration. Similarly, the same cloud passage may be the source of radioactive Al26 which has been detected as excess Mg26 in an ever-growing number of meteoritic inclusions.

TABLE 1

	Allende Inclusions				Surface of Lunar Fines	
Element	EK1-4-1		Cl			
O	10	(10)	15	(10)	25	(5)
Si	7.5	(13)	12	(12)	13	(5)
Mg	20	(14)	30	(14)	--	
S	--		--		10	(7)
Ca	-1.8	(15)	0.3	(15)	1	(6)

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