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Terrestrial Planet Chemistry Explained by Evaporation of Dust in the Early Solar Nebula

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Elemental abundances in the diffuse interstellar medium show that virtually all of the rock-forming elements reside in the dust phase, including the moderately volatile elements like K and Fe. Infrared spectroscopic data confirm that silicates and ices are important constituents of the placental cloud from which low-mass stars are formed. Apparently, rock-forming elements enter protoplanetary systems as dust and ice rather than as gas.

Correspondence between the relative abundances of rock-forming elements in chondrites and those in the photosphere of the Sun indicates that the Sun and the chondrites accreted from the same dust. Although many chondrite groups exhibit solar-like elemental abundances, CI chondrites exhibit the best correlation with solar values. The bulk composition of CI chondrites is therefore a useful analogue for the bulk composition of the progenitors of rocky bodies in the Solar System. A CI analogue has been rejected in the past because CI $^{17}O/^{16}O$ and $^{18}O/^{16}O$ are far removed from those of Earth, Moon, and other differentiated rocky bodies represented by achondrites. However, CI oxygen isotope ratios may have been much closer to those of other carbonaceous chondrites prior to water-rock interaction within parent bodies (Young et al. 1999), and carbonaceous chondrites combined with ordinary chondrites in general make suitable starting materials for differentiated bodies when the effects of aqueous alteration are considered.

The depletion in moderately volatile elements (e.g., alkalis) among differentiated, rocky bodies of the Solar System relative to solar abundances is well known. It is less commonly acknowledged that this depletion extends to the moderately refractory lithophiles like Si and Mg. Depletions in the less volatile elements has been largely ignored because of the conventional practice of normalizing elemental concentrations to Si. However, laboratory experiments show that Si is volatile at high temperatures. Residues of evaporation exhibit losses in the mass of Si (but little change in the concentration of Si). Unlike Si, refractory elements like Ca and La are conserved in the residues of evaporated liquids and crystalline solids (masses of Ca and La are unchanged while their concentrations rise with total mass loss). Normalization to Ca rather than Si shows that the precursor material from which Earth was made lost nearly 30 per cent of its Si and nearly 20 per cent of its Mg if it had a CI (solar) bulk composition and Ca was conserved. Similarly, the material from which Moon was made lost 40 to 50 per cent of its CI complement of both Si and Mg.

Evaporation of a multimineralic mixture of crystalline solids can explain the first-order observation that moderately refractory and moderately volatile elements are all depleted in the terrestrial planets relative to solar abundances. Calculations based on measured vapor pressures and evaporation rates show that when the early solar nebula was at its hottest (approximately 1000 K at 2.7 AU), 1 to 10 μm sized dust grains of feldspathic material would survive for hours to perhaps several years before completely evaporating at the heliocentric distances now occupied by the main asteroid belt. Similar sized grains of forsterite would persist for millions of years with moderate mass losses under the same conditions, an interval that exceeds best estimates for the life span of the nebula prior to its dissipation. As a result, evaporation can explain the general pattern of volatility controlled element distributions among inner Solar System rocky bodies. For example, the data are explained if alkalis entered the early solar nebula as feldspathic material while Si and Mg resided primarily in olivine and pyroxene.

Lack of isotopic heterogeneity in $^{41}K/^{39}K$ (Humayun and Clayton, 1995) and $^{25}Mg/^{24}Mg$ (Galy et al., 2000) among Solar System rocks shows that rock precursors did not experience evaporation in the molten state at low pressures in the early solar nebula (millibar and less) before accretion. Homogeneity in light element isotope ratios is consistent with evaporation of crystalline dust, supporting the hypothesis that evaporation of progenitor dust grains composed of a mixture of crystalline phases gave rise to the distribution of elements among bodies of the inner Solar System.

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