BULK COMPOSITIONS OF THE MOON AND EARTH, ESTIMATED FROM METEORITES

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Extending the work of Krähenbühl et al. (1), we have calculated the compositions of the Earth and Moon, on the assumption that these planets formed by exactly the same processes as the chondrites. The basic framework is the condensation sequence of the elements from a solar gas (2), augmented by 3 fractionation processes observed in chondrites (3): fractionation of early condensate and of metal from silicate, and partial remelting of the condensate. A schematic outline is shown in Fig. 1. Presence of moderately (= M) and highly (= H) volatile elements is indicated by light and dark shading. Partial condensation is indicated by parentheses.

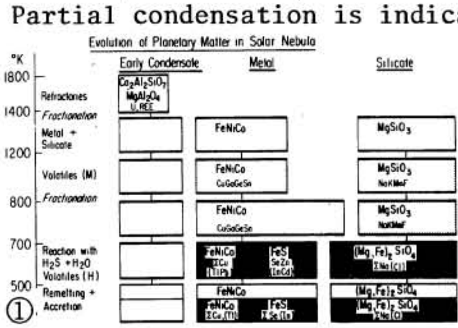

Table 1. Compositional Models for the Earth and Moon

Component	U ppb	Fe % Earth	Fe % Moon	Mn* ppm	K* ppm	Tl* ppb	Mass Fraction Earth	Mass Fraction Moon
Early condensate	252						0.0714	0.2353
Remelted silicate		5.90	3.59				0.4502	0.6336
Unremelted silicate		5.75	3.49	4650	1494		0.0999	0.0621
Volatile-rich sil.		5.56	3.39	4500	1445	346	0.0144	0.00047
Troilite		63.53					0.0455	0.0086
Metal (total)		93.4	91.6				0.3180	0.0599
FeO/(FeO+MgO) %							10.0	6.15
Fe/Si (atomic)							1.23	0.214
Remelted fraction							0.798	0.910

*Values for the Moon are higher by 1.032.

According to this picture, chondrites and planets are mixtures of the 6 components shown at the bottom of Fig. 1. The proportions of these components in a differentiated planet can be estimated from abundance ratios of elements that belong to different components but do not readily fractionate from each other in igneous processes. We used the following (mass) ratios for the Moon and Earth, in conjunction with absolute values for U (59 and 18 ppb; 4) and Fe (9 and 38%; 5,6): K/U = 1625 and 9440; Tl/U = 0.0028 and 0.277; FeO/MnO = 82 and 62 (7). Compositions of the various components were calculated from Cameron's abundance table (8). Abundances of the diagnostic elements are shown in Table 1.

Thirteen volatile elements of $T_{cond} < 600K$ (Cd,Hg,B,In,Tl,Pb,Bi,Cl,Br,I,H, C, and N) tend to be incompletely condensed in chondrites, to a degree that is hard to predict in advance. For the sake of definiteness, we have therefore assigned these elements to a special, volatile-rich component, containing the first 10 elements in cosmic proportions and the last 3, in the amounts found in C3 chondrites, relative to Tl.

The calculated amounts of the 6 components are given in the last two columns of Table 1. They differ from our earlier estimates (1), owing to changes in input parameters or the model itself. The composition and U content of the early condensate is now based on cosmic abundances and Grossman's

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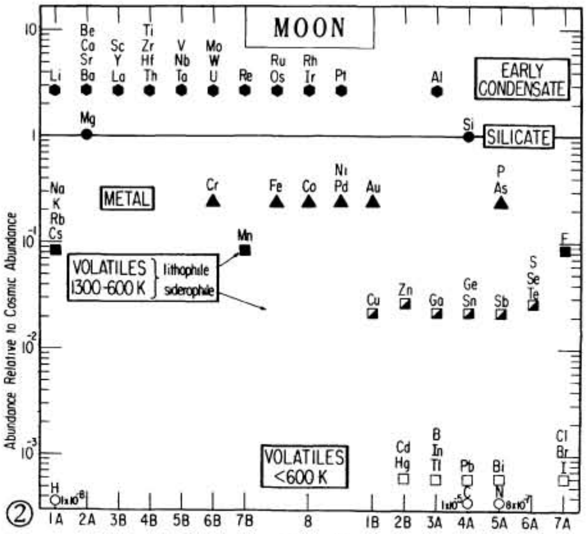
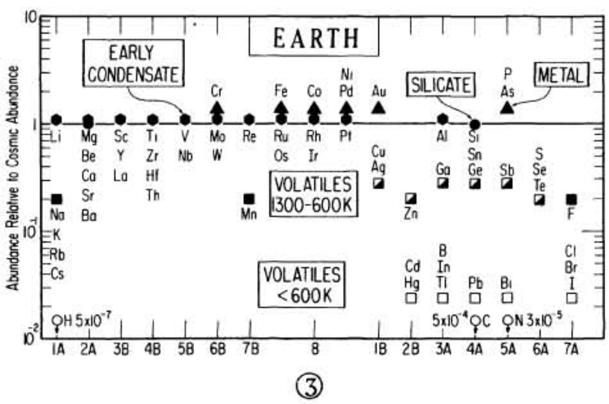
condensation sequence, rather than the measured composition of Allende inclusions; bulk Fe in the Moon is 9 rather than 13%; FeO/(FeO+MgO) content is based on FeO/MnO rather than being arbitrarily fixed at 30 mol %.

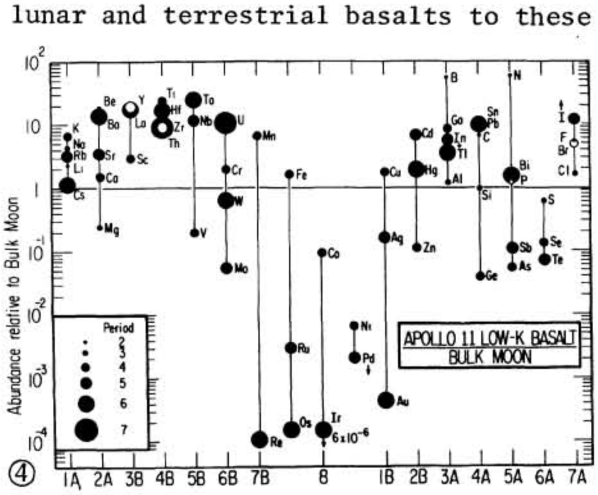
Table 2 gives whole-planet abundances of individual elements. Figs. 2 and 3 show the same data plotted against cosmic abundance. The gross trends

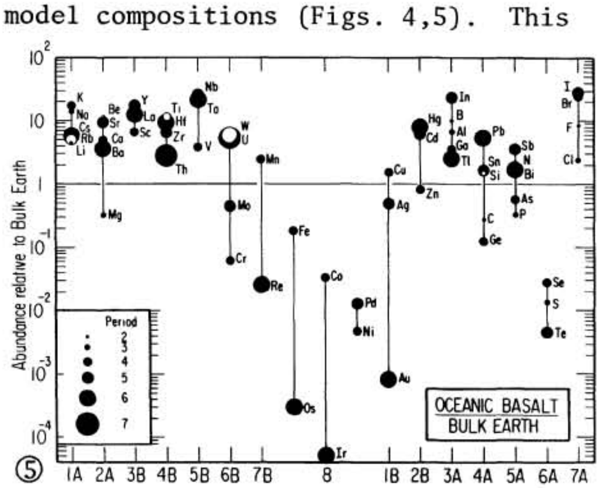




are unsurprising, having been qualitatively predicted by many authors, but the quantitative detail is new and worthy of contemplation. The abundances of 12 highly volatile elements (open symbols) are lower limits, having been arbitrarily pegged to that of Tl, one of the most volatile elements in the group. The true values may be higher, up to the plateau of the moderately volatile group (half-filled symbols) as an upper limit.

For an illustrative application of the model, we normalize abundances of lunar and terrestrial basalts to these model compositions (Figs. 4,5). This





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should give a clearer picture of igneous processes on these two planets, undistorted by the differences in bulk composition. The following trends emerge. (a) All LIL elements now show substantially the same enrichment. Alkalis on the extreme left and volatiles on the right are enriched to nearly the same degree as refractory LIL elements on the left, Groups 2A to 6B. Most volatiles are as strongly concentrated in the crust as are U, K, and REE. (b) The gross differences between lunar and terrestrial basalts are greatly diminished, although some differences (Cr,Mo,W,Re,Fe,S,Se,Te) persist. (c) On the Earth, none of the trace elements often regarded as chalcophile (Cu,Ag,Zn,Cd, Ga,Pb,Sb, etc.) are as depleted as S,Se, and Te. Apparently the geochemical behavior of these elements during the initial differentiation of the Earth was dominated by their volatile rather than chalcophile character.

Though this model has led to some interesting insights, it must be regarded as speculative until it has been checked against geophysical and petrological constraints.

(1) KRÄHENBÜHL U. et al. (1973) GCA Suppl. 4, 1325. (2) LARIMER J.W. (1967) GCA 31, 1215; GROSSMAN L. (1972) GCA 36, 597. (3) LARIMER J.W. and ANDERS E. (1967) GCA 31, 1239; (1970) GCA 34, 367. (4) LANGSETH M.G. et al. (1973) Lunar Sci. IV, 455. (5) PARKIN C.W. et al. (1973) NASA TM X-62,279. (6) REYNOLDS R.T. and SUMMERS A.L. (1969) J. Geophys. Res. 74, 2494. (7) LAUL J.C. and SCHMITT R.A. (1973) GCA Suppl. 4, 1349. (8) CAMERON A.G.W. (1973) Explosive Nucleosynthesis, eds. D.N.Schramm and W.D. Arnett, 3.

Table 2. Abundances of the Elements in the Moon and Earth (ppm)

Element	Moon	Earth	Element	Moon	Earth	Element	Moon	Earth
H	1.6	50	Zn	15.8	84	Pr	0.40	0.121
Li	6.5	2.0	Ga	0.52	4.9	Nd	2.1	0.65
Be ppb	140	42	Ge	1.29	12.2	Sm	0.65	0.20
B ppb	16	480	As	0.84	3.5	Eu	0.25	0.074
C	7.2	225	Se	1.04	5.5	Gd	0.89	0.27
N	0.19	5.8	Br ppb	4.6	140	Tb	0.166	0.050
O %	41.92	28.65	Rb	0.30	0.52	Dy	1.11	0.34
F	27	48	Sr	45	13.6	Ho	0.25	0.075
Na	810	1430	Y	8.1	2.46	Er	0.72	0.22
Mg %	18.52	13.56	Zr	49	14.7	Tm	0.108	0.033
Al %	4.35	1.32	Nb	2.47	0.75	Yb	0.71	0.22
Si %	19.98	14.76	Mo	7.3	2.21	Lu	0.120	0.036
P	504	2130	Ru	3.7	1.11	Hf	0.71	0.22
S %	0.31	1.66	Rh	0.78	0.24	Ta ppb	72	22
Cl	0.86	26	Pd	0.23	0.99	W	0.56	0.170
K	96	170	Ag ppb	7.5	71	Re ppb	190	57
Ca %	5.49	1.67	Cd ppb	0.70	21	Os	2.7	0.82
Sc	29.9	9.1	In ppb	0.092	2.8	Ir	2.6	0.79
Ti	2520	770	Sn	0.066	0.62	Pt	5.2	1.6
V	250	77	Sb ppb	6.5	56	Au	0.067	0.29
Cr	1120	4720	Te	0.160	0.85	Hg ppb	0.34	10.2
Mn	300	530	I ppb	0.59	18	Tl ppb	0.166	5.0
Fe %	8.52	35.98	Cs ppb	30	53	^{204}Pb ppb	0.067	2.0
Co	220	930	Ba	12.5	3.8	Bi ppb	0.126	3.8
Ni %	0.48	2.02	La	1.17	0.36	Th ppb	210	62
Cu	5.3	50	Ce	3.1	0.95	U ppb	59	18