Chemical Compositions of the Moon, Earth, and Eucrite Parent Body

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Chemical compositions of the Moon, Earth, and eucrite parent body

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[Plate 1]

Model compositions of the Moon and Earth were calculated on the assumption that these planets had experienced the same nebular fractionation processes as the chondrites. The proportions of 7 basic components (early condensate, metal, etc.) were estimated from geochemical constraints, such as K/U, bulk U and Fe abundances, etc., and used to construct abundance tables for 83 elements.

When lunar and terrestrial basalt data are normalized to these model compositions (to cancel differences in bulk composition), the abundance patterns become strikingly similar. This would seem to demonstrate the essential sameness of igneous processes on both planets. The model correctly predicts the abundance ratios of certain volatile/refractory element pairs (e.g. Cd/Ba, Ga/La, Sn/Th, and Pb/U), the density of the Moon, and the major rock types.

The model is also used, in the reverse direction, to reconstruct the composition of the eucrite parent body. It resembles the Moon to a remarkable degree, except for a lower content of refractory elements. Because of this similarity, it is unlikely that the Moon acquired its composition by some unique chance event, such as disintegrative capture. More likely, such compositions represent the natural outcome of nebular fractionation processes, which may have been more extreme in the inner solar system than in the asteroid belt.

All input data required by this model can be obtained by unmanned spacecraft or ground-based observations. Thus, if this model proves viable, it will permit construction of a detailed geochemical profile of a differentiated planet after a single visit by an unmanned spacecraft.

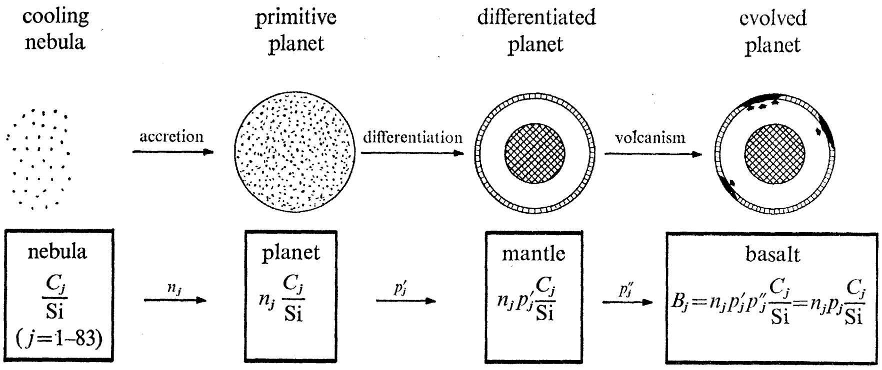
Introduction

One of the most fundamental, yet elusive properties of a planet is its bulk chemical composition. The basic abundance pattern was established during accretion of the planet from the solar nebula, but was then grossly distorted and obscured by the initial, gross differentiation and by later geologic activity (figure 1). The problem is to reconstruct the original pattern from the present composition of surface rocks. Basalts are especially suitable for this purpose, because their geochemistry is fairly straightforward and well-understood.

The abundance of a given element J in basalt, B_j, relative to some reference element such as silicon, is the product of its original (cosmic) abundance in the nebula, C_j, and two fractionation factors, n for nebula and p for planet:

$$B_j/\mathrm{Si} = n_j p_j\,(C_j/\mathrm{Si}) \quad j = 1\text{–}83. \tag{1}$$

In these 83 equations, B_j and C_j are known, but n_j and p_j are not. The problem thus reduces to finding either n or p for each of 83 elements. (As shown in figure 1, p is the product of two factors p' and p'', representing the initial differentiation into crust, mantle, and core, and the later formation of basalts by partial melting of the mantle. For the present analysis, it is permissible to combine p' and p'', because we are interested only in the initial and final states. However, in any detailed comparison of two planets, the two factors, and their variation from planet to planet, must be taken into account individually.)



C_j, abundance of J in nebula — n_j, nebular fractionation factor

B_j, abundance of J in basalt — p_j, p'_j, p''_j, planetary fractionation factors

FIGURE 1. Schematic model for the chemical steps linking basalts to the primordial nebula. Fractionation factors n_j or p'_j, p''_j indicate enrichment or depletion of element J in each step.

Lunar and terrestrial basalts

We can tell in a general way what happened in planetary differentiation and basalt formation (figures 2 and 3). The siderophile elements in the middle of the periodic table are easily reduced to metal and therefore went into the core. The elements on the left tend to form large, positive ions that cannot be accommodated in mantle minerals (mainly $\mathrm{(Fe,Mg)_2SiO_4}$ and $\mathrm{(Fe, Mg)SiO_3}$), and therefore concentrated in the basaltic liquid during partial melting. (These elements are often designated by the acronym 'l.i.l.', for 'large-ion, lithophile'.) The elements on the right also form large ions, but in addition are volatile and chalcophile (sulphide-seeking). Their low abundance must reflect the interplay of these three factors, but it is not at all clear which factor was dominant.

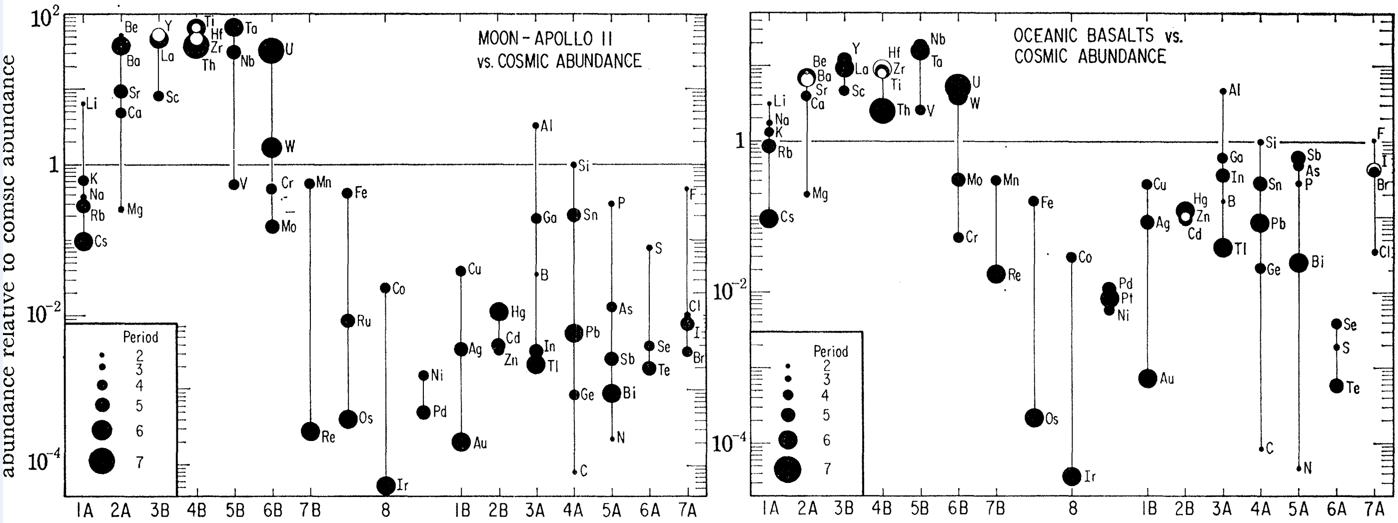
Though the lunar and terrestrial basalt patterns are grossly similar to each other, they differ in detail. The lunar basalts show rather more extreme fractionations: l.i.l. elements are more enriched and volatiles are more depleted than in terrestrial basalts. But does this reflect bulk composition or planetary differentiation trends, i.e. nebular or planetary fractionation factors?

Chondrites: key to nebular fractionations

A novel (and as it turns out, fruitful) approach to the problem is to assume that the inner planets (or their precursor planetesimals) had formed by exactly the same processes as the chondrites. It has been obvious for some time that chondrites are primitive nebular condensates that escaped planetary differentiation, and hence provide an undistorted record of nebular processes. Four such processes, leading to a total of 6 components, have been recognized (Wood 1962, 1963; Anders 1964, 1971; Larimer & Anders 1967, 1970; Grossman 1972; Grossman & Larimer 1974). We assume that the Earth and Moon were made from the same components, but in different proportions.

The problem is then greatly simplified, because in nebular fractionations each component carries its characteristic suite of elements in predictable, generally solar proportions. *All* the elements in a given cosmochemical group will generally have the same nebular fractionation factor *n*. Thus only 6 different values of *n* need to be determined, not 83. They can be found from appropriate geochemical constraints such as K/U ratios, as shown below.

We have reported three successive iterations of this model (Krähenbühl, Ganapathy, Morgan & Anders 1973; Ganapathy & Anders 1974*a*, *b*). The present paper is a condensed version of the third iteration, with new data on the eucrite parent body and substantial changes in interpretation.



Figures 2 and 3. Compositions of lunar and terrestrial basalts, normalized to 'cosmic' abundance (Cameron 1973). Elements are arranged according to position in Periodic Table. Lunar basalts show more extreme enrichment of lithophile elements on the left and depletion of volatile-chalcophile elements on the right. For references see paper 3.

A similar approach has been developed independently by Wänke *et al.* (1973, 1974). However, they use only two components: early condensate and a chondritic component of adjustable composition.

Planetary components

Condensation sequence of a solar gas

The basic framework of the model is the equilibrium condensation sequence of a solar gas (figure 4), as worked out by Larimer (1967), Grossman (1972), and Grossman & Larimer (1974). Three kinds of primordial dust condense from such a gas on cooling: (1) an early condensate, consisting of refractories; (2) metallic nickel-iron; (3) magnesium silicates. Together, these three materials comprise about 70 % of the potentially condensable 'rocky' material. They collect volatiles on cooling; metal reacts with H_2S to give FeS and with H_2O to give FeO, which finds its way into the silicates (Larimer & Anders 1967).

Fractionation processes

This is not the whole story, however. The study of chondrites has shown that 3 additional processes (italicized in figure 5) take place on cooling. They double the number of components and alter their proportions (Larimer & Anders 1970).

(1) *Fractionation of refractories.* Early condensate is gained or lost, presumably by settling to the median plane before the other two condensates have precipitated from the gas.

(2) *Fractionation of metal.* Nickel-iron is gained or lost, presumably by ferromagnetic attraction (Wood 1962; Harris & Tozer 1967).

(3) *Remelting* (= *chondrule formation*). Just before or during accretion, some portion of the micrometre-sized dust is briefly remelted and converted to millimetre-sized chondrules, probably by collisions (Whipple 1972). Volatiles are lost, FeS reverts to metal, but time is too short to permit reduction of FeO to Fe. This process is non-selective, and affects the same fraction of all three components.

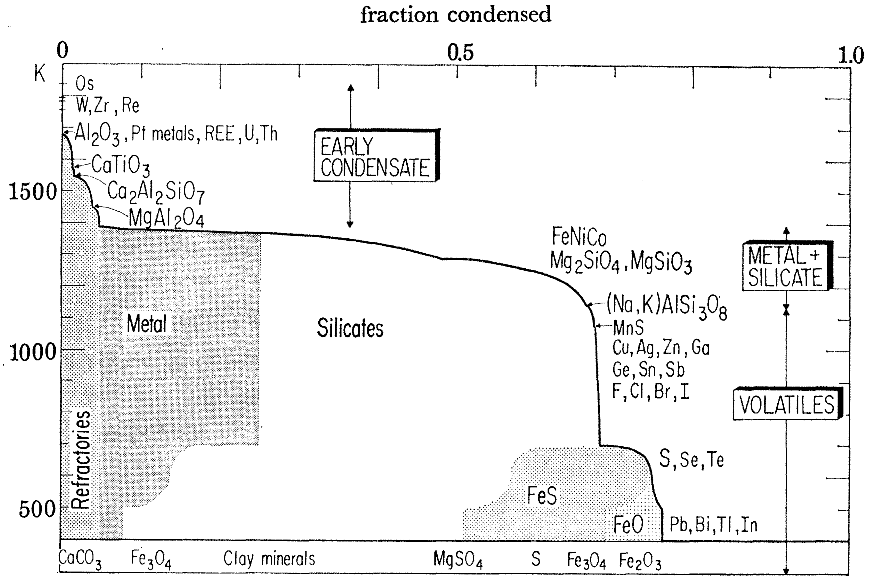


FIGURE 4. Condensation of solar gas at 10^{-4} atm (10 Pa). Three types of dust condense from a solar gas: refractories, metallic nickel-iron, and magnesium silicates. On cooling, iron reacts with H_2S and H_2O to give FeS and FeO. Further major changes take place below 400 K.

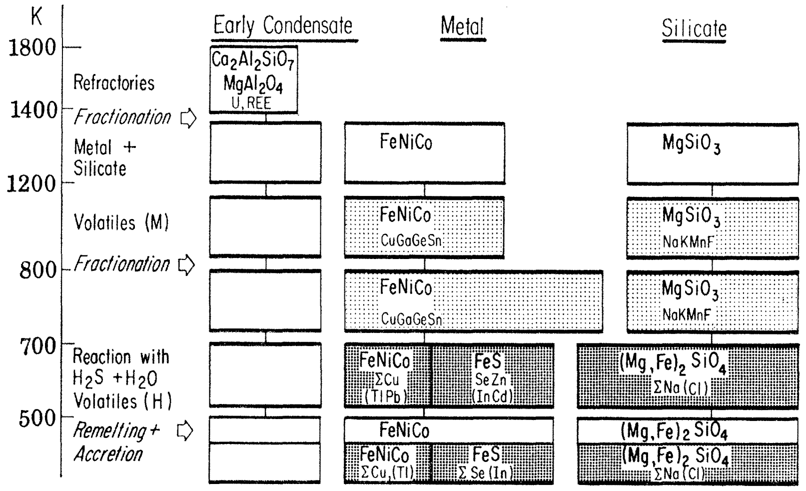


FIGURE 5. Evolution of planetary matter in solar nebula. Three additional processes, not predicted by the condensation sequence, take place on cooling (cf. arrows on left). They effectively double the number of components, from 3 to 6. Presence of moderately (M) and highly (H) volatile elements is indicated by light and dark shading. Partial condensation is indicated by parentheses.

The first two processes merely alter the proportions of the components. The last process doubles their number, to a total of 6: one early condensate, two metals (unremelted and remelted), one sulphide, two silicates (unremelted and remelted). The trace element content of these components can generally be predicted from the condensation sequence, as summarized in figure 6. Elements fully condensed at the temperature of fractionation will be present in their host component in cosmic proportions. Thus, if we know the abundance of one element from the early condensate, such as U, we can predict the abundance of 37 others.

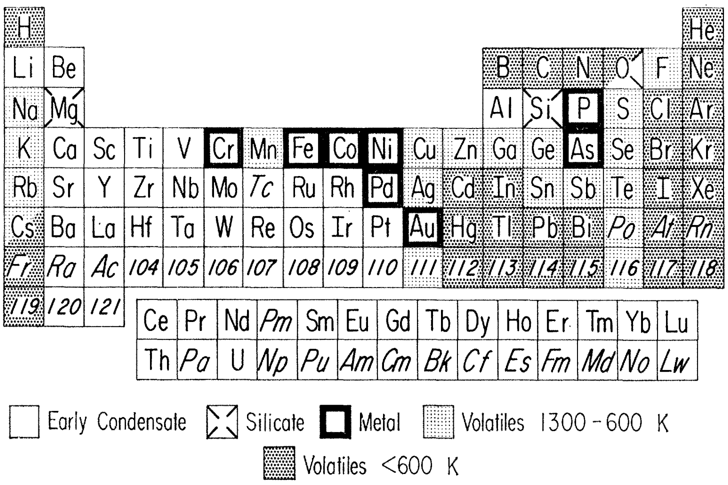


FIGURE 6. Condensation behavior of the elements from a solar gas, at 10–0.1 Pa (10^{-4}–10^{-6} atm). Elements divide into major groups that stay together in gas-solid fractionations. Both groups of volatile elements may be further subdivided according to their preference for metal, silicate, or sulphide substrates, but these distinctions are not shown here.

Problems arise for 16 elements that condense below 600 K: Cd, Hg, B, In, Tl, Pb, Bi, Cl, Br, I, H, C, N, Ar, Kr and Xe. They will be only partially condensed at the temperature of accretion, to a degree that is hard to predict in advance. For the sake of definiteness, we have therefore assigned these elements to a seventh, volatile-rich component, containing the first 10 elements in cosmic proportions (Cameron 1973), and the last 6 in the amounts found in C3 chondrites, relative to Tl.

This step may not be as arbitrary as it sounds. There are indications that the Earth and Moon may have acquired their volatiles mainly as a thin veneer of carbonaceous-chondrite-like material (Kokubu, Mayeda & Urey 1961; Anders 1968; Turekian & Clark 1969; Krähenbühl *et al.* 1973).

It is actually possible to see 6 of these 7 components in a primitive meteorite such as the C3V chondrite Leoville (figure 7, plate 1).

THE MODEL

Geochemical constraints

In terms of the model, the above 7 components are the basic ingredients of chondrites and planets. Their composition is substantially fixed; only their proportions vary from one body to the next. We must now try to estimate these proportions for the Moon and Earth.

We can use various geochemical constraints to estimate the extent of the fractionation processes and hence the proportions of the components. Whole-planet abundances of a single element are most useful, but they are known only for U, Fe, and a few other elements (Larimer 1971). We must therefore rely mainly on basaltic abundance ratios of elements that belong to different cosmochemical groups and hence have different n, but are geochemically coherent in igneous processes and thus have the same p (e.g. K/U, Tl/U, Tl/Cs, FeO/MnO). If $p_j = p_k$, then $B_j/B_k = (C_j/C_k)\ (n_j/n_k)$, and so if n_j and the two abundance ratios are known, n_k is uniquely determined.

Table 1. Constraints on composition

	constraint				component affected†					
					metal			sil.		vola-tile-rich
process		Moon	Earth	EC	R	U	FeS	R	U	
refractory fractionation	bulk U, ppb	59	18	×						
metal-silicate fractionation	bulk Fe, %	9	36		×	×	×			
oxidation of Fe	FeO/MnO	82	62		×	×	×	×	×	
formation of FeS	supply of:	Fe°	S		×	×	×			
remelting	K/U	1625	9440		×	×	×	×	×	
volatiles, < 600 K	Tl/U	0.0023	0.27							×

† EC, early condensate; R, remelted; U, unremelted.

The constraints used in this work are given in table 1. Their sources and uncertainties were discussed in detail by Ganapathy & Anders (1974*b*; hereafter paper 3). The only point that needs elaboration is the use of FeO/MnO to constrain the degree of remelting. Manganese is more volatile than iron, and is therefore lost from chondrules during remelting. But data for meteorites show that the loss is not complete; about 1/3 of the Mn is retained by carbonaceous chondrites and even more by other classes. Using the symbols f = fraction remelted and α = fraction of Mn retained by remelted material, we can write for the FeO/MnO ratio in the silicate phase of the planet:

$$\mathrm{FeO/MnO} = \mathrm{FeO/(MnO)}\ (1 - f + \alpha f)$$

The value of α controls the FeO content of the silicate; as α rises above 0, more FeO must be put into the silicate to keep FeO/MnO at the observed value. Regrettably, α itself cannot be determined *a priori*. It depends on the peak temperature and duration of remelting, and may be greater or smaller than 1/3 for the Moon. We have therefore done the calculation both for the limiting value of $\alpha = 0$ (models 2 and 3*a*), and for the more realistic values of 0.1 and 0.2 (models 3*b* and 3*c*). None of these values can be justified on objective grounds, and so the FeO content of the silicates and the metal content of the Moon remain poorly constrained.

Components

The composition of the individual components was determined from the condensation sequence of figure 4 (Grossman 1972; Grossman & Larimer 1974) and Cameron's (1973) solar-system abundances, with a few modifications. The boundary between early and main condensate was drawn at the condensation threshold of diopside, $T = 1387$ K. Detailed compositions of the components are given in paper 3.

It must be stressed that these are 'theoretical' compositions, being based on solar-system abundances and the equilibrium condensation sequence. They are similar but not necessarily identical to the compositions of meteoritic components, such as the Ca, Al-rich inclusions

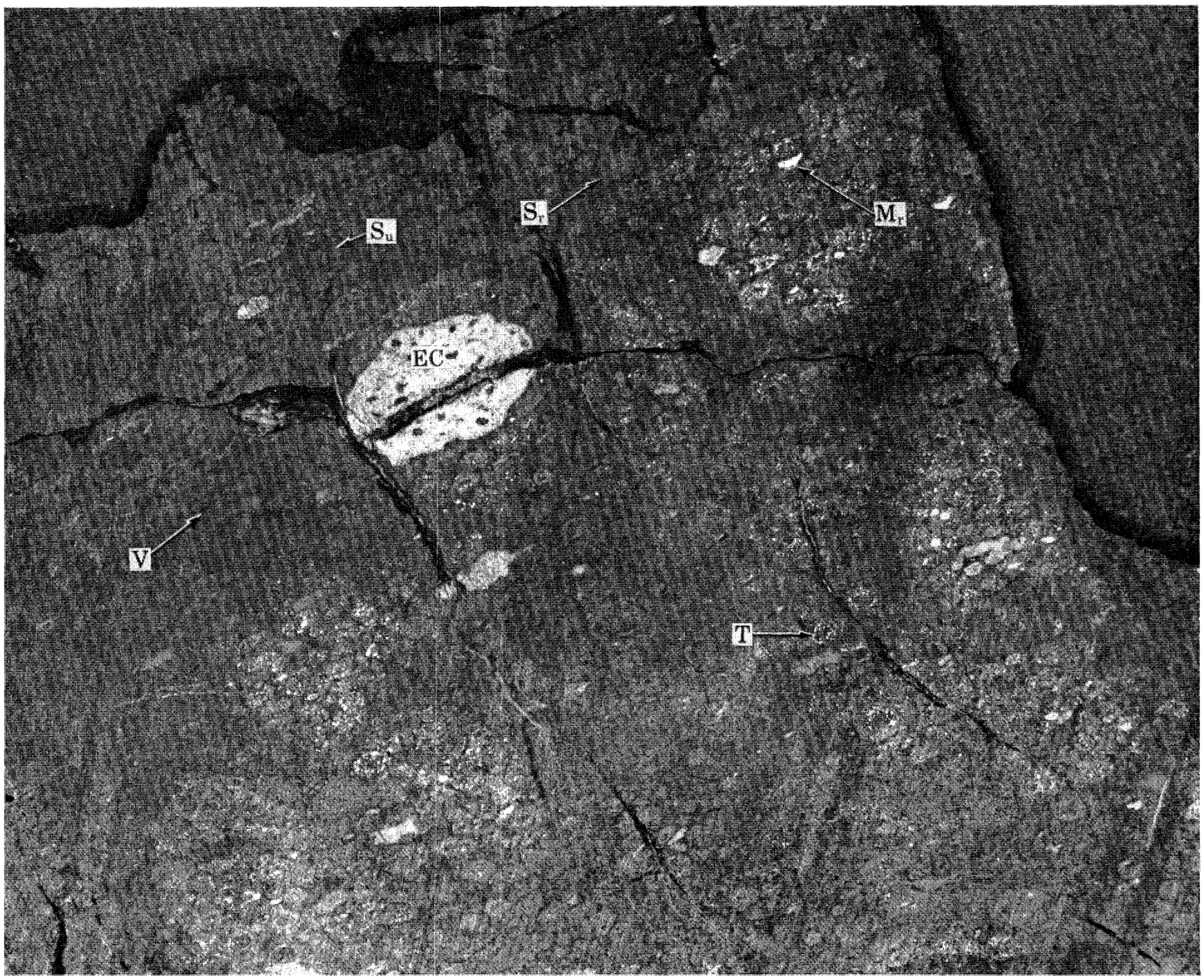


Figure 7. Six of the seven planetary components are discernible in the C3V chondrite Leoville: EC, early condensate = white inclusion; S_r, remelted silicate = chondrules; S_u, unremelted silicate = matrix; M_r, remelted metal; T, troilite; V, volatile-rich component = carbonaceous inclusion. The unremelted metal, of submicroscopic size, is not visible.

from the Allende C3 chondrite, which Wänke *et al.* (1973, 1974) and Anderson (1973) use as a principal constituent of the Moon. To be sure, this material has the right major-element composition for an early condensate, but because of certain peculiarities in the history of carbonaceous chondrites, it is afflicted with anomalies that disqualify it as an actual constituent of the Earth and Moon, e.g. low $^{18}O/^{16}O$ and $^{17}O/^{16}O$ (Grossman, Clayton & Mayeda 1974), and high Th/U ratio (paper 3).

RESULTS

The proportions of the individual components can be found from a set of simultaneous equations (paper 3), using the constraints from table 1. The results are shown in table 2.

Model 3 is the latest version from paper 3; model 2 is an earlier version from Ganapathy & Anders (1974*a*), based on a higher U content of the early condensate, and slightly different abundances of Ca and Al. Though disowned by its authors, it is included here because it gives petrologically more reasonable results than model 3.

TABLE 2. MODEL COMPOSITION OF THE MOON AND EARTH

	mass fraction†				
component	Moon model 2*a*	Moon model 3*a*	Moon model 3*b*	Moon model 3*c*	Earth model 3*a*
early condensate	0.235	0.301	0.301	0.301	0.092
metal, remelted	0.060	0.061	0.041	0.021	0.240
metal, unremelted	—	—	—	—	0.071
troilite	0.0086	0.011	0.0071	0.0031	0.050
silicate, remelted	0.634	0.557	0.577	0.598	0.418
silicate, unremelted	0.062	0.070	0.073	0.076	0.114
volatile-rich material	0.00047	0.00040	0.00042	0.00044	0.015
FeO/(FeO + MgO) mole %	6.15	7.47	12.9	17.5	11.4
Fe/Si atomic	0.214	0.243	0.245	0.247	1.26
fraction remelted	0.910	0.891	0.890	0.889	0.771

† Models 2*a* and 3*a* assume 0% retention of Mn by the remelted fraction, while models 3*b* and 3*c* assume 10 and 20% retention. Model 2 was calculated for a higher U content of the early condensate, 252 parts/10^9 rather than 197 parts/10^9. A similar composition would be obtained if the Moon's bulk U content were 46 parts/10^9 rather than 59 parts/10^9. Indeed, a change of this order is suggested by the recent downward revision of the linear heat flow value.

From these data, whole-planet abundances of all stable elements have been calculated. The results are shown in table 3 and figures 8 and 9. The underlying assumption, best illustrated in the figures, is that each trace element associates exclusively with one component. Thus a whole group of cosmochemically similar elements is depleted or enriched by the same factor, represented by the plateaus in figures 8 and 9.

Judging from chondrites, this is not a bad assumption, except for a few elements from the fringes of each volatility group (Li, Cs, Zn, Te, Na and Mn). The first 4 are probably less abundant, and the last 2, more abundant, by perhaps a factor of < 2–3. The highly volatile group (open symbols) is also uncertain, as discussed later on.

The gross trends are unsurprising, having been qualitatively stated by many authors. The Earth and especially the Moon are depleted in volatiles and enriched in refractories, as first noted by Gast (1960, 1968, 1970). The individual abundances agree fairly well with Larimer's (1971) estimates for the Earth, but are considerably higher than his values for the Moon.

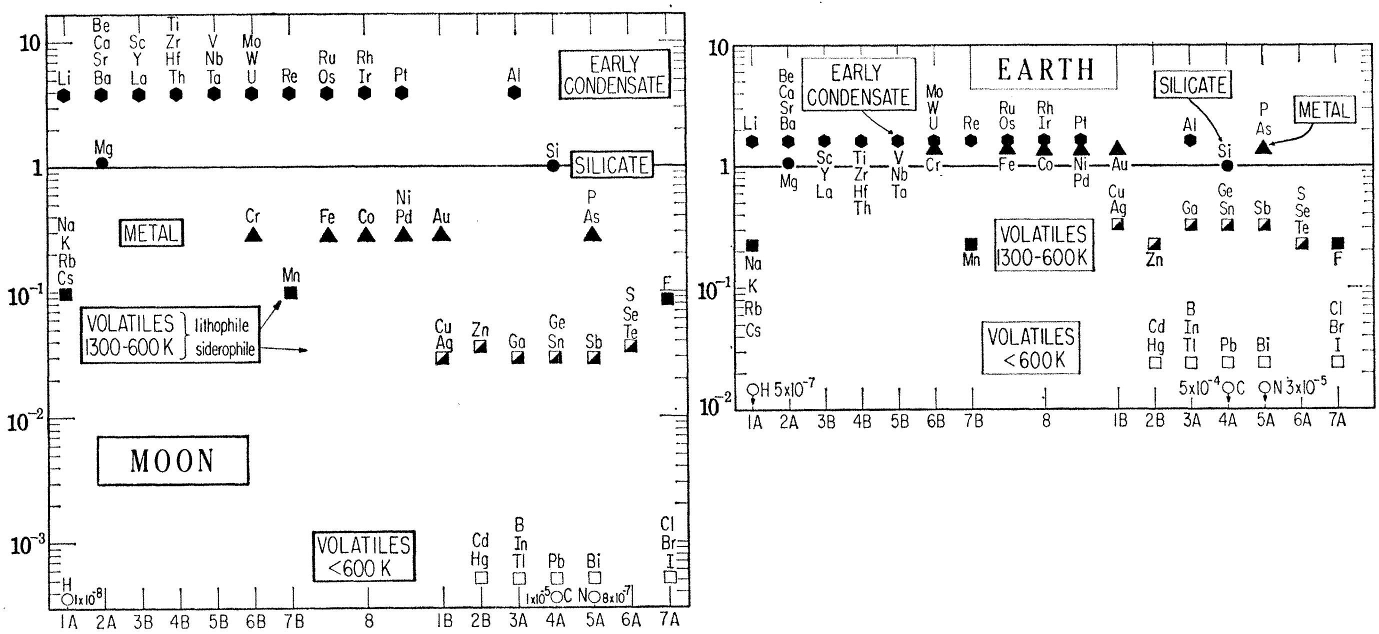
Compared to other published models, the present one gives lower Ca, Al and higher Mg, Si contents, because of the smaller amount of early condensate. The current value from table 2 is 0.30, compared to 0.42 for Krähenbühl *et al.* (1973), 0.50 for Wänke *et al.* (1974), and ~1 for Anderson (1973). Much of the difference is due to the higher U content used for the early condensate, table 1. Interestingly, composition 2 falls very close to that of Taylor & Jakeš (1974), which was derived by a rather different set of arguments.

APPLICATIONS AND TESTS

A proper test of the model is its ability to make correct predictions, explain observations, and provide new insights. Five such tests are available.

TABLE 3. ABUNDANCES OF THE ELEMENTS IN THE MOON AND EARTH, ACCORDING TO MODEL 3*a* (parts/10^6 unless otherwise marked; noble gases 10^{-10} cm^3 s.t.p./g).

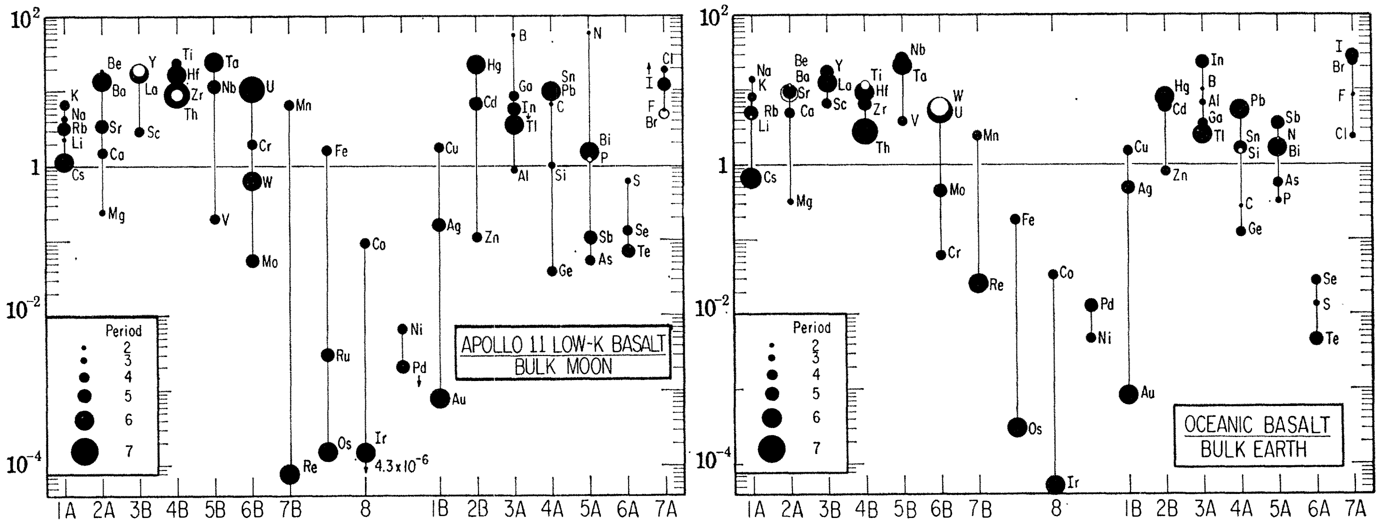
element	Moon	Earth	element	Moon	Earth
H	2.2	78	Ru	4.9	1.48
He^{4}	2100	74000	Rh	1.05	0.32
Li	8.7	2.7	Pd	0.25	1.00
Be parts/10^9	186	56	Ag parts/10^9	9.6	80
B parts/10^9	13	470	Cd parts/10^9	0.58	21
C	9.9	350	In parts/10^9	0.075	2.7
N	0.26	9.1	Sn	0.085	0.71
O %	41.42	28.50	Sb parts/10^9	7.6	64
F	30	53	Te	0.20	0.94
Ne^{20}	7	250	I parts/10^9	0.48	17
Na	900	1580	Xe^{132}	0.13	4.8
Mg %	17.37	13.21	Cs parts/10^9	33	59
Al %	5.83	1.77	Ba	16.8	5.1
Si %	18.62	14.34	La	1.57	0.48
P	538	2150	Ce	4.2	1.28
S %	0.39	1.84	Pr	0.53	0.162
Cl	0.70	25	Nd	2.9	0.87
Ar^{36}	37	1330	Sm	0.86	0.26
K	96	170	Eu	0.33	0.100
Ca %	6.37	1.93	Gd	1.18	0.37
Sc	40	12.1	Tb	0.22	0.067
Ti	3380	1030	Dy	1.49	0.45
V	340	103	Ho	0.33	0.101
Cr	1200	4780	Er	0.96	0.29
Mn	330	590	Tm	0.145	0.044
Fe %	9.00	35.87	Yb	0.95	0.29
Co	240	940	Lu	0.160	0.049
Ni %	0.51	2.04	Hf	0.95	0.29
Cu	6.9	57	Ta parts/10^9	96	29
Zn	19.9	93	W	0.75	0.250
Ga	0.66	5.5	Re parts/10^9	250	76
Ge	1.66	13.8	Os	3.6	1.10
As	0.90	3.6	Ir	3.5	1.06
Se	1.30	6.1	Pt	6.9	2.1
Br parts/10^9	3.8	134	Au	0.072	0.29
Kr^{84}	0.18	6.6	Hg parts/10^9	0.28	9.9
Rb	0.33	0.58	Tl parts/10^9	0.136	4.9
Sr	60	18.2	Pb^{204} parts/10^9	0.055	1.97
Y	10.9	3.29	Bi parts/10^9	0.104	3.7
Zr	65	19.7	Th parts/10^9	210	65
Nb	3.3	1.00	U parts/10^9	59	18
Mo	9.8	2.96			



FIGURES 8 AND 9. Model compositions of the Moon and Earth. They are based on the assumption that each component contains its cosmic complement of trace elements.

Composition of basalts

Now that we have data for the bulk composition of the two planets (table 3), we can separate nebular and planetary fractionation factors. We divide the abundance of each element in basalt (figures 2, 3) by its abundance in the bulk planet (figures 8, 9). This operation cancels out differences in bulk composition, permitting the pure igneous (= planetary) pattern to show through. The results are shown in figures 10 and 11. Several trends are apparent in a comparison of these graphs with the original data (figures 2, 3).



FIGURES 10 AND 11. Composition of lunar and terrestrial basalts, normalized to bulk composition of each planet. Elements are arranged according to position in the Periodic Table. Similarity of patterns suggests that gross differences between lunar and terrestrial basalts (figures 2, 3) reflect mainly differences in bulk composition, rather than the nature of igneous processes on the two planets.

(1) Both graphs have become symmetrical. Alkalis on the extreme left and volatiles on the right are enriched to nearly the same degree as refractory l.i.l. elements on the left, groups 2A to 6B. Apparently the volatility of those elements is important only in pre-accretional, condensation processes in the nebula, not in post-accretional, igneous processes on the planet. In the latter setting, most of these elements show 'l.i.l.' behaviour.

(2) The gross contrast between lunar and terrestrial basalts is greatly reduced. Apparently most of the difference reflected differences in bulk composition. With this factor removed, the basic sameness of partial melting processes is becoming apparent. Of the remaining differences, some may represent real differences in igneous pattern (Cr, Mo, W, Re, Fe, S, Se and Te), while others probably are due to analytical and sampling errors (the specific rocks analysed were not the same for all elements).

(3) A number of trace elements often regarded as siderophile-chalcophile (Co, Cu, Ag, Zn, Cd, Ga, Ge, Pb, As, Sb) are not as strongly depleted as the out-and-out siderophiles (Ni, Pt metals) or chalcophiles (S, Se, Te). Apparently these elements were at least slightly lithophile during initial differentiation of the planet.

Moreover, most of these elements show substantially the same depletion factors on the Moon and Earth (figures 10, 11). Perhaps these depletion factors can be interpreted as distribution coefficients.

Abundance ratios

One interesting test of the model is its ability to predict abundance ratios of trace elements belonging to different planetary components. If two elements have the same planetary fractionation factor p, then their abundance ratio in basalt should simply equal the ratio of the nebular factors, n_j/n_k, times the ratio of cosmic abundances, C_j/C_k. The condition that $p_j = p_k$ is most reliably met by incompatible elements that are largely concentrated in the liquid during partial melting. There are seven such elements available in figures 10, 11: Cd, Ga, Sn, In, Hg, Pb and Tl. Three of them must be eliminated: In (contamination), Hg (mobile on lunar surface), and Tl (used as indicator element in the model). The remaining four elements are paired off with refractory ions, generally of the same charge: Ba^{2+}, La^{3+}, Th^{4+} and U^{4+}. A survey of literature data (compiled by Dr Jeffrey L. Warner) gave mean ratios of the right order (table 4), though only two of the four pairs (Cd/Ba, Pb/U) showed reasonable linear correlations. The remaining two pairs correlated poorly, with the volatile element (Ga, Sn) showing a much smaller abundance range than the refractory element. It is interesting that the model nonetheless predicts the right ratios.

Table 4. Volatile/refractory element ratios

	Cd/Ba	Ga/La	Sn/Th	^{204}Pb/U
Moon, model 3*a*	5.6×10^{-5}	0.43	0.32	9×10^{-4}
Moon, mare basalts, mean†	5.1×10^{-5} (23)	0.41 (42)	0.26 (5)	16×10^{-4} (20)
Earth, model 3	4.0×10^{-3}	11.6	10.9	0.11
Earth, oceanic basalts	3.4×10^{-3}	3.3	5‡	0.11

† Number of samples is given in parentheses. ‡ Very poorly determined.

Petrology

Hodges & Kushiro (1974) have studied the melting relations of two earlier model compositions for the Moon (Moon 1 and 2; the latter is shown in table 2). The former was too poor in silica to yield plagioclase, and was hence disqualified. (Presumably other compositions of even lower SiO_2 content must also be ruled out for this reason.) The latter did give plagioclase, preceded by olivine, orthopyroxene, and clinopyroxene. It also produced a reasonable sequence of rock types, in thicknesses consistent with seismic data: anorthositic gabbro with an ilmenite-rich zone to about 60 km, followed by plagioclase lherzolite, lherzolite, and harzburgite to about 100 km, and dunite below. The density of this model composition (including its complement of Fe and FeS) was 3.34 g/cm^3 at 2 MPa (20 kbar) and a temperature slightly below the solidus (Hodges & Kushiro, 1974 and private communication). The agreement with the bulk density of the Moon (3.34 g/cm^3) is of some interest, because our model included no prior constraint on density.

Two flaws of model 2 were the relatively high Fe/Mg ratios of the anorthositic rocks, and the inability to produce troctolites or spinel troctolites. Both could be avoided if plagioclase crystallized before orthopyroxene and clinopyroxene. This requires higher Al, or lower Si, higher O, lower S (D. Walker, private communication).

Model 3 attempted to solve this problem by lowering the Ca/Al ratio from Cameron's value of 1.26 to Ahrens' (1970) value of 1.08 (paper 3). However, the absolute amount of both Ca and Al was then raised by correction of the U abundance, which in turn lowered SiO_2. Apparently these changes have overshot the mark; model 3 is less satisfactory than model 2 from a petrologic point of view (D. Walker, private communication). It remains to be seen whether the fit can be improved by further iteration. The differences between model 2 and 3 are less than 20 % for most elements, well within the error limits in the input data. However, because whole groups of elements are coupled in this model, it is not certain that the required adjustments will fall in the allowed range.

Highly volatile elements and noble gases

Anders (1968) compared the abundances of volatile elements in the Earth's crust with those in C1 and ordinary chondrites. These two meteorite classes typified material that had condensed its volatiles at low temperatures, in cosmic proportions, or at higher temperatures, in proportions declining with volatility. (The temperatures in question are ~ 360 K and ~ 420–500 K; see Grossman & Larimer (1974) for references.) The Earth's pattern was intermediate between the two: it was flat in the initial portion, like the C1 pattern, but then declined, like the ordinary chondrite pattern.

For this reason we used an intermediate material for our model, containing H, C, N and noble gases in C3 chondrite proportions, and all other highly volatile elements in cosmic proportions. It corresponds essentially to a 400–430 K condensate.

To test this feature of the model, we compare the predicted abundances of volatiles with their observed abundances in the crust and atmosphere. Volatile elements, like l.i.l. elements, tend to concentrate in the Earth's outer regions, and so it is instructive to calculate the fraction of each element released into the crust and atmosphere. We define a 'release factor' R:

$$R = A_c M_c / A_\oplus M_\oplus$$

where A_c, $A_\oplus$ are the abundances in the crust and (model) Earth, and M_c, $M_\oplus$ are the masses of the crust and Earth. Since $M_c = 0.004\, M_\oplus$, $R = 0.004\ (A_c/A_\oplus)$.

These release factors are shown in figure 12 for both model 3 (solid circles) and a variant using C1 rather than C3 abundances for the last 6 elements (open circles). Crustal abundances were taken from Larimer (1971) and unpublished) except Tl (de Albuquerque, Muysson & Shaw 1972) and Cl (Garrels & Mackenzie 1971).

Taken at face value, the C3-based pattern suggests that most of these elements have been released from the mantle to a rather uniform extent of 8–40 %.† Similar results are obtained for less volatile, l.i.l. elements such as Rb, K, U and La (horizontal lines on left). These release factors are not too different from earlier estimates by Gast (1968), Hurley (1968), Larimer (1971), and others. The agreement may be significant, because the present approach, in contrast to the earlier ones, involves no prior assumptions about the degree of outgassing of volatiles.

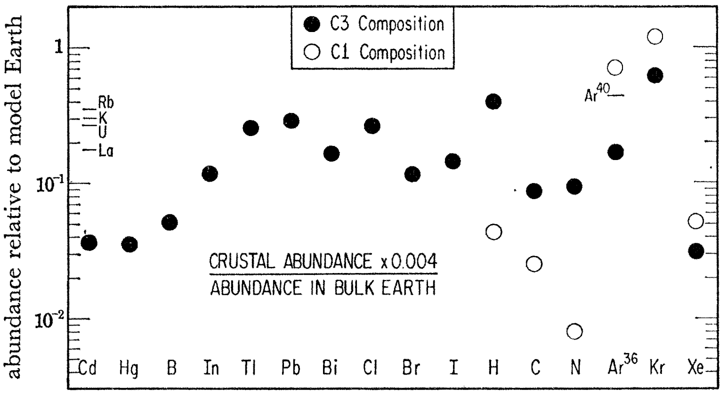


FIGURE 12

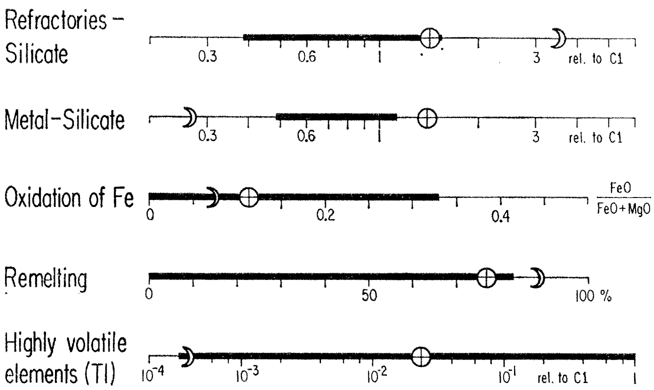


FIGURE 13

FIGURE 12. Most highly volatile elements are present in the Earth's crust in about the proportions assumed in the model: cosmic proportions for the first 10; C3 chondrite proportions for the last 6 (●). A variant using C1 proportions for the last 6 elements (○) is also shown. It terms of this model, about 8–40% of Earth's inventory of most volatiles has been released into the crust.

FIGURE 13. Fractionations for the Earth fall within chondritic range (black bars) in 4 cases out of 5. For the Moon, they fall well outside the chondritic range in 3 cases out of 5. Either the observed range in chondrites does not cover the full gamut of these processes, or the Moon formed under special conditions (Earth orbit?) where fractionation was enhanced.

The C1-based variant gives less uniform release factors for the last 6 elements. The factor for H_2O (0.04) is lower than that for most other volatiles, and since various authors, beginning with Rubey (1951), have shown that the water content of the mantle must be low, this argument alone would seem to rule out C1 composition. On the other hand, C1 composition does have one advantage over C3. The ^{40}Ar content of the atmosphere, for a terrestrial K abundance of 170 parts/10^6, corresponds to a release factor of 0.44. For comparison, the release factors of Ar ^{36} are 0.12 on the C3 model and 0.53 on the C1 model. Now, it does not make any sense for the ^{36}Ar factor to be smaller than the ^{40}Ar factor, because primordial ^{36}Ar, having been present in the Earth from the beginning, should be outgassed more completely than radiogenic ^{40}Ar which was produced gradually over geologic time. We conclude that the volatile-rich fraction of the Earth must have had a lower ^{36}Ar/K ratio than C3 chondrites, by a factor of 4 or more. Such meteorites exist (C1 or H3, L3, LL3 chondrites), but they have other shortcomings.

The model also gives reasonable results for the light noble gases, because the ^{20}Ne/^{36}Ar ratio in the atmosphere (0.52) is similar to that in C3 chondrites used here (0.19). The release

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† Values for Cd, Hg, B and Xe are lower, but at least the last two may be in error. Cameron's cosmic abundance of B may have been overestimated (Reeves 1974), and Larimer's crustal abundance of Xe is too low, being based on the atmosphere alone. Substantial amounts of Xe are locked up in shales (Canalas, Alexander & Manuel 1968).

factor for ^{20}Ne is 0.60, close to that for most other elements in figure 12. The ^{4}He value is based on the assumption that the ^{4}He/^{20}Ne ratio in the volatile-rich material was equal to the mean ratio in C3V chondrites (292; Mazor, Heymann & Anders 1970). Interestingly, Tolstikhin (1974) has obtained similar ^{20}Ne release factors and ^{4}He abundances by an entirely different line of reasoning, based on the high ^{3}He/^{4}He ratios in some volcanic gases (Tolstikhin, Mamyrin & Khabarin 1972).

Range of cosmochemical fractionations

Our model has been based on the premise that the Earth and Moon were made by the same processes as the chondrites. It is proper to ask whether any of these processes had to be stretched beyond their observed range in chondrites, in order to account for the Earth and Moon.

Figure 13 attempts to answer this question. The chondritic range is indicated by heavy black bars. Evidently the Earth falls outside the chondritic range just once, and then only barely. The Moon, on the other hand, falls outside this range in 3 cases out of 5.

An obvious excuse is that we know only 8 classes of chondrites. There may be hundreds of others not sampled by the Earth (Anders 1964), and it would be very provincial to assume that these 8 classes cover the full gamut of these processes. Indeed, the range could be expanded greatly by including mesosiderites, a class of meteorites that may possibly represent another type of primitive condensate (J. A. Wood, private communication). Still, it is rather disturbing that the lunar point falls so far outside the chondritic range for the first two fractionations. No chondrite and no known planet has so low a metal/silicate ratio. Not even the extinct basin-forming objects seem to have had Fe/Si ratios as low as the lunar value (Morgan *et al.* 1974).

Two factors may be invoked to explain the Moon's extreme composition. The Moon is the only body in figure 13 that is a satellite. Perhaps its peculiar composition reflects competition with the central planet. And the Moon presumably originated much closer to the Sun (~ 1 AU?) than the parent bodies of the chondrites (2–3 AU?). Fractionation processes may have operated more efficiently closer to the Sun. Admittedly, the Earth does not have so extreme a composition, though it evidently also formed at 1 AU. But the Earth probably accreted from many smaller planetesimals (Safronov 1972), and in this process compositional differences would average out. The Moon, being smaller, must have been built from fewer planetesimals (or may in fact be a single planetesimal; Urey 1972), and may have preserved a composition farther from the mean. Let us consider these two possibilities in the next two sections.

Competitive accretion

Within the general framework of accretion from a cooling nebula, two scenarios may be envisioned for the Moon: formation as a sunbound planet or as an earthbound satellite.

Formation in Sun orbit

At first sight, it seems that the Earth–Moon differences can be explained by heterogeneous accretion of two independent bodies from a cooling nebula. Consider two planets in heliocentric orbits at about 1 AU, sweeping up dust as fast as it condenses. The mass accretion rate is approximately proportional to the 4/3 power of the mass (Öpik 1971), and so the larger body will outgrow the smaller one at an ever-increasing pace. Ganapathy, Keays, Laul &

Anders (1970) have drawn attention to an important chemical consequence of this fact. If the composition of the accretable material changes with time, the smaller body will be relatively richer in 'early' material (= refractories), and the larger body, in 'late' material (= volatiles).

Qualitatively, this is just the trend observed for the Earth and Moon. But the model fails in at least one quantitative respect. Though it accounts reasonably well for the relative abundances of early condensate and main condensate, it does not reproduce the extreme difference in volatile content. It predicts a maximum Earth/Moon ratio of 3.6, compared to the observed ratio of 37 (tables 2 and 3).

Moreover, if all Earth/Moon differences were due to heterogeneous accretion in heliocentric orbit, then bodies smaller than the Moon should be still richer in early condensate and poorer in volatiles. One such example, the eucrite parent body, will be discussed in the next section. There exist compositional data on two other groups of bodies: the parent bodies of the chondrites and the extinct objects that produced the lunar mare basins (Morgan *et al.* 1974). The latter are particularly germane, because they presumably formed in the Moon's neighbourhood.

Abundance patterns for 6 such bodies show exactly the opposite trend. They are lower in refractories and higher in volatiles than the bulk Moon (Morgan *et al.* 1974). This is also true of all known chondrite classes. Some special factors, reversing the trend, must have been at work when the Moon was built.

Formation in Earth orbit

The depletion of volatiles can apparently be accounted for by accreting the Moon in Earth orbit. Owing to its orbital motion, an earthbound Moon would encounter dust grains in heliocentric orbits at high velocities, and hence have a small cross section for their capture. The original treatment by Ganapathy *et al.* (1970) was quantitatively incorrect, as noted by Singer & Bandermann (1970), but a recent, more thorough treatment by Whipple (1973) that takes into account the effects of gas shows that this mechanism can indeed explain the observed compositional differences. The orbital motion of the Moon produced a wind that aerodynamically prevented the capture of dust and smaller planetesimals. The same mechanism would also favour selective accretion of chondrules over dust (Whipple 1972), thus explaining the larger amount of remelted material in the Moon (table 2).†

This picture is adequate as long as it is limited to only two bodies, the Earth and Moon. However, serious difficulties arise when we consider a third body on which we have information: the eucrite parent body.

† Some authors have contended that accretion in geocentric orbit would lead to 'impact differentiation', with selective loss of volatiles from the Moon owing to the higher impact velocity. It seems unlikely that such loss will be significant. Studies of the micrometeorite component in lunar soils (Anders, Ganapathy, Krähenbühl & Morgan 1973) show that even highly volatile metals such as Bi are retained by the Moon, although they are vaporized on impact.

THE EUCRITE PARENT BODY: IMPLICATIONS FOR THE ORIGIN OF THE MOON

We have samples of another small, differentiated planet: the eucrite parent body. Many authors have suspected a relationship between eucrites and the Moon: some, beginning with Duke & Silver (1967), have suggested that eucrites are derived from the Moon, while others (Clayton & Mayeda 1975) have argued that the Moon is derived from eucrites.

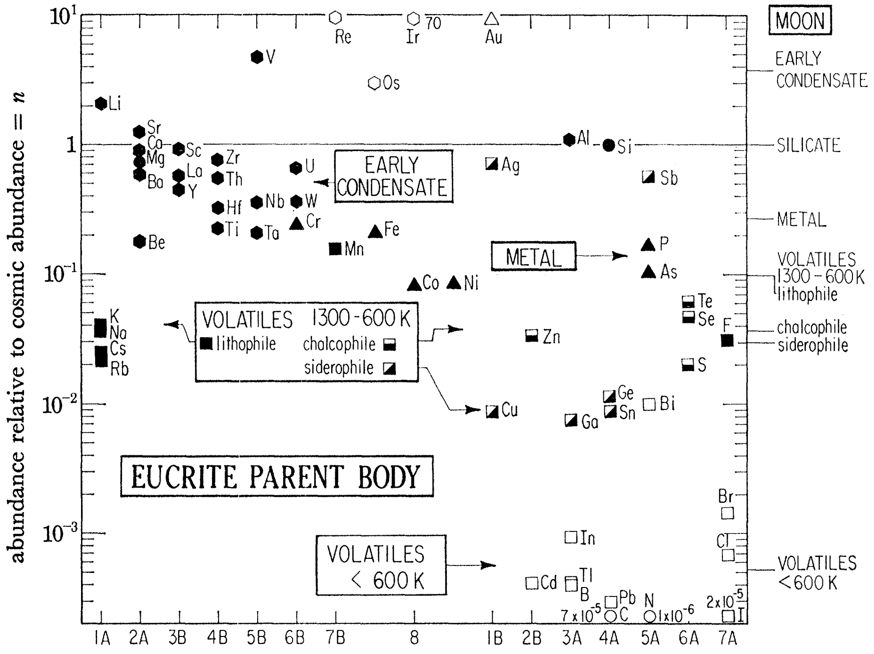

FIGURE 14. Composition of eucrite parent body, reconstructed from observed compositions by means of planetary fractionation factors from figure 10. Mean abundances of the various element groups (horizontal arrows) are remarkably similar to those in the Moon (right-hand ordinate), except for refractories. Presumably the Moon and eucrite parent body formed under similar conditions.

The present model offers a way to reconstruct the composition of the eucrite parent body. It is merely necessary to run the model in reverse, using planetary fractionation factors to find nebular fractionation factors. This exercise has been carried out by Vizgirda & Anders (1975). They used mean compositions of eucrites from Ahrens & Danchin (1970), Laul *et al.* (1972), and other sources, and divided these abundances by p_j for the Moon (figure 10) to find n_j. (Terrestrial p_j values were used for the feldspar constituents Na, Ca, Sr and Al, because on the Moon these elements are largely sequestered in the anorthositic highland crust. Their nominal lunar p_j values from figure 10 therefore are too high, being based on the bulk planet rather than the mantle. Judging from the absence of anorthositic meteorites, and the absence of a Eu anomaly in eucrites (Morgan & Higuchi 1975, in prep.), the eucrite parent body did not have an anorthositic crust, and so the terrestrial p_j values may be appropriate.)

The results for eucrites are shown in figure 14. Geometric mean n_j values for each element group are indicated by arrows. Those for the Moon are shown on the right-hand ordinate for comparison.

Data for the early condensate look worst, scattering as they do by over an order of magnitude. Strongly siderophile elements (open hexagons) may be disregarded, because they are least likely to obey a single set of p_j values, and are probably enriched in brecciated eucrites by meteoritic contamination. The mean for the remaining refractory elements is 0.5, decidedly less than the lunar value of 3.8. Part of the difference may represent a greater degree of partial melting, i.e. a breakdown of our assumption that p_j'' is the same for the two planets. But this factor alone cannot account for the entire difference; the eucrite parent body seems to be much poorer in refractories than is the Moon.

The remaining 5 element groups show less scatter. None shows a perfect plateau, but all form reasonably narrow bands, with only Bi and a few strongly siderophile elements (Au, Ag, Sb) falling out of line. The 'metal' group falls in a narrow band near the top, the 'volatiles < 600 K' cluster at the bottom, and the other 3 groups fill the middle ground.

Table 5. Geochemical profiles of planets

(Abundance relative to cosmic abundance.)

element group	high-iron chondrites	Earth	Moon	eucrite planet
refractories	0.73	1.6	3.8	0.5 ± 0.3
silicate	1	1	1	1
iron group	0.92	1.4	0.27	0.14 ± 0.03
volatiles, lithophile	0.61	0.22	0.10	0.040 ± 0.004
volatiles, siderophile	0.30	0.33	0.030	0.0090 ± 0.0008
volatiles, chalcophile	0.16	0.22	0.036	0.038 ± 0.009
highly volatile	0.011	0.024	0.0005	0.0006 ± 0.0002

What is most remarkable is that the means of all 5 groups fall close to the lunar values. The closeness of this match is brought out in table 5, where the comparison is extended to the Earth and H-chondrites. Clearly, the Moon and eucrite parent body resemble each other to a high degree.

One cannot completely rule out the possibility that this resemblance is fortuitous. However, a more plausible interpretation is that the Moon and the eucrite parent body had similar origins. Either both formed as independent planets, in which case the Moon is a captured planet, or they both formed as satellites, in which case the eucrite parent body is an escaped satellite. Neither possibility can be excluded on the basis of present evidence.

It should be clear in any case that the extreme composition of the Moon is no longer unique. Nature produced such a composition not just once but at least twice. This calls into question an entire class of models that invoke *ad hoc* processes to explain the Moon by a unique chance event, e.g. disintegrative capture (Smith 1974; Mitler 1975). Such an event now has to happen twice, with similar chemical consequences but different dynamical consequences: once leading to a satellite and next time to an independent planet.

Thus the problem of accounting for the Earth–Moon differences has been greatly complicated by the existence of a third body of similar composition. Competitive accretion based on size differences alone can explain the high refractory and low metal content of the Moon relative to the Earth, but predicts an even higher content of refractories for the smaller eucrite parent body. Another variable must be introduced, such as heliocentric or geocentric distance, but that should also lead to great differences in the abundances of volatiles. Perhaps one should not be surprised that data on three bodies do not suffice to constrain a model with 7 variables

(4 fractionation processes, size, heliocentric distance, planetocentric distance). The main use of the model at the present stage is to reconstruct planetary compositions and to describe them in terms of a small set of parameters. Perhaps the interplay of these parameters will become clear when data on more bodies are available.

Applications to other planets

Obviously, this model will have to pass a number of tests before it deserves to be taken seriously. However, if it does survive, it may become a useful planetological tool. Because of its conceptual rigidity, it can make very detailed predictions (e.g. abundances of 83 elements; table 3) from a limited set of input data (6 constraints in table 1). All of these constraints can be determined by unmanned spacecraft, or by ground-based observations.

The U content can be determined by a heat flow measurement. The bulk Fe content can be estimated from the planet's density. The K/U ratio can be measured by a γ-ray spectrometer, as was recently done for Venus (Vinogradov, Surkov & Kirnozov 1973). The FeO content can be measured remotely, as demonstrated by the Surveyor α-scattering instrument (Turkevich 1973). The MnO and Tl contents have not been measured on past missions, but it seems that appropriate methods could be developed, if a strong scientific incentive were provided.

The feasibility of this approach can be checked for the eucrite parent body, where a model composition has been determined from a much more extensive set of data (figure 14). It turns out that we could have obtained nearly the same results from a few key elements alone. The estimated abundances of early condensate, lithophile volatiles, and highly volatile elements (horizontal arrows) closely match those of the indicator elements U and Th, K and Tl. And the amount of metal could have been estimated from the crustal abundance of 3 siderophiles that are abundant enough to be easily measureable by remote methods: Fe, Cr and Co.

It thus seems that it may indeed be feasible to construct a detailed cosmochemical profile of a differentiated planet in a single visit by an unmanned spacecraft.

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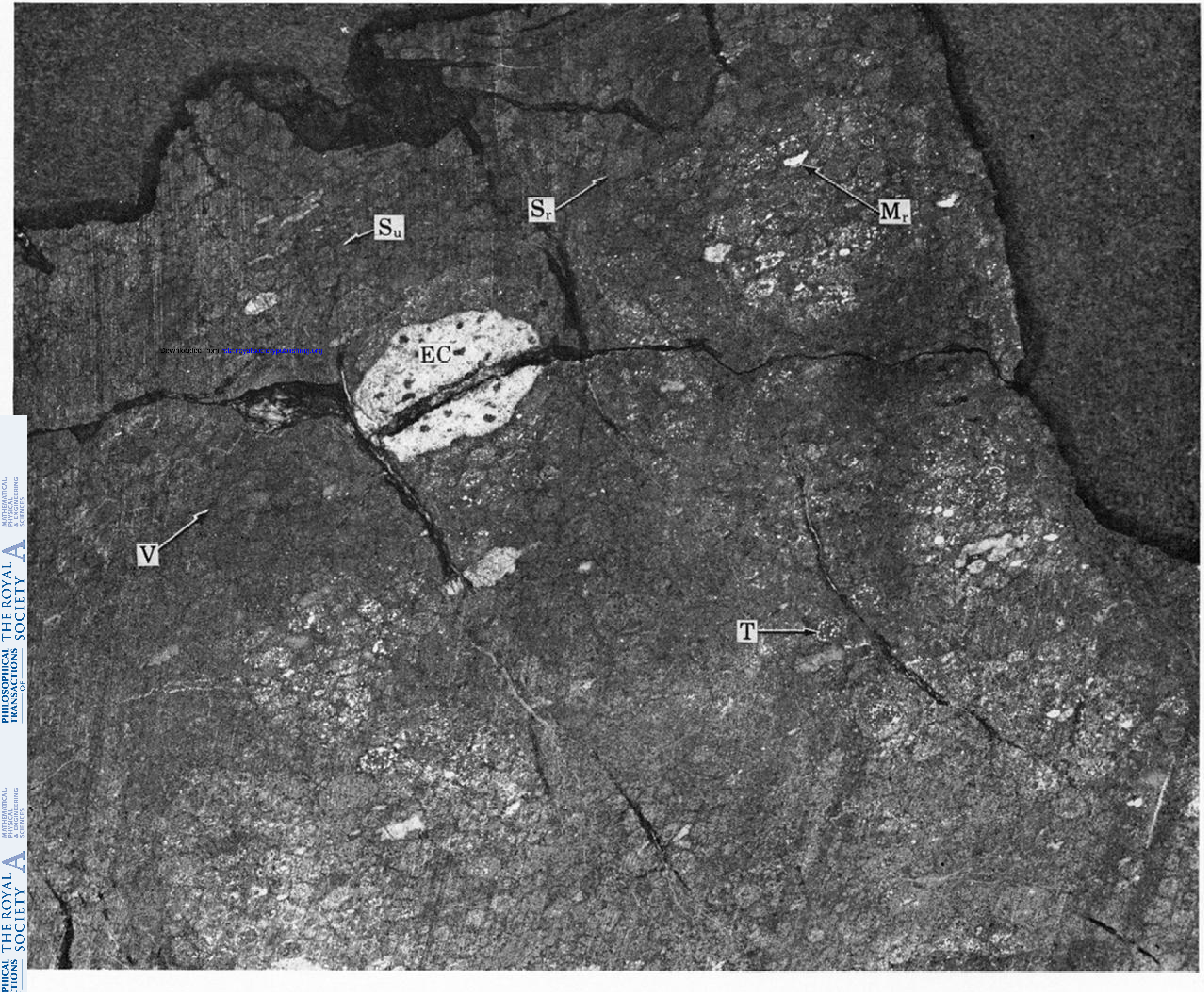

FIGURE 7. Six of the seven planetary components are discernible in the C3V chondrite Leoville: EC, early condensate = white inclusion; S_r, remelted silicate = chondrules; S_u, unremelted silicate = matrix; M_r, remelted metal; T, troilite; V, volatile-rich component = carbonaceous inclusion. The unremelted metal, of submicroscopic size, is not visible.