Radioactivity of the Moon, Planets, and Meteorites

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This paper reviews and summarizes analytical data for the content of natural radioactive elements in meteorites, eruptive terrestrial rocks, and also in lunar samples returned by Apollo missions and the Luna series of automatic stations.

The K-U systematics of samples analyzed in the laboratory are combined with data for orbital gamma-ray measurements for Mars (Mars 5) and with the results of direct gamma-ray measurements of the surface of Venus by the Venera 8 lander.

Using information about the radioactivity of solar system bodies and evaluations of the content of K, U, and Th in the terrestrial planets, we examine certain aspects of the evolution of material in the protoplanetary gas-dust cloud and then in the planets of the solar system.

As we know, radioactive elements play a special role in the history of the solar system. The study of their abundance in various celestial bodies is a key to the development of our concepts of the solar system. However, the small number of thoroughly studied extraterrestrial objects creates certain difficulties in an attempt at quantitative estimation of the abundance of radioactive elements in the solar system.

In recent years the study of this problem has been influenced by a stream of new information on the celestial bodies, particularly the Moon.

Measurements of the gamma radiation of the Moon were performed by the Luna 10 automatic spacecraft in 1966 and first established that lunar rocks are similar to terrestrial basalts in their content of natural radioactive elements (refs. 1 and 2).

Many further investigations of lunar specimens returned by automatic and manned spacecraft have shown that for natural radioactive elements and a number of other as-pects of their chemical compositions, lunar rocks from the mare regions are similar to terrestrial tholeiitic basalts (and to stony meteorites—the Ca achondrites), while the lunar continents are similar to anorthositic rocks (refs. 3 through 8).

In 1972, the Venera 8 automatic spacecraft produced the first data on the natural radioactivity of Venus, and allowed certain conclusions about the nature of Venusian rocks and their formation (refs. 9 and 10).

In 1974, the Mars 4 and Mars 5 automatic spacecraft first measured the intensity and spectral composition of the gamma radiation of Mars (ref. 11).

Combination of all this information on the radioactivity of solar system bodies expands our ability to understand certain aspects of the evolution of material both in the proto-planetary gas-dust cloud and in the planets of the solar system.

The history of the radioactive elements is closely related to the history of all chemical elements. However, as we know, radioactive

elements play a special role in the evolution of the material of the solar system. In this work we study the cosmochemical aspect of the history of the natural radioactive elements from their formation to the present.

We can imagine that during the earliest stage of formation of the solar nebula radioactive elements were homogeneously distributed in the gas cloud whose density decreased with increasing distance from its center to its periphery. The entire subsequent evolution of solar system material and, in particular, the history of the natural radioactive elements can be divided into two main periods: the preplanetary stage when the material was in a gas-dust state and the planetary stage when the material was concentrated into the large bodies of the solar system.

At the present time, the radioactivity of planetary material is due primarily to U, Th, and K. The mean content of these elements in the Earth is either estimated on the basis of the current heat flux from the interior of the planet (ref. 12) or is assumed equal to the mean content of these substances in chondritic meteorites (ref. 13). The radioactivity of the planets in the distant past was significantly higher, due not only to the higher content of these elements at that time, but also to the decay of more short-lived elements with half-lives on the order of 10^6 to 10^8 yr. These elements were made during nuclear synthesis and later became part of the young bodies of the solar system.

Finally, it is possible that during the preplanetary stage and the early stage of formation of the planets, super-heavy transuranium elements existed ($Z \sim 106$–116, $N \sim 284$), since fission tracks of these elements have been found in some meteorites and lunar rock specimens (ref. 14).

In addition to the natural radioactivity, the surface layers of all celestial bodies have a radioactivity that results from interaction with cosmic rays. Most cosmogenic isotopes are short lived (of the longer lived, Na^{22} and Al^{26} are most common) and are retained only in extremely small quantities. Cosmogenic isotopes were mostly witnesses of, while the natural isotopes were participants in, the formation of the solar system material during the various stages of its existence (ref. 15).

Natural Radioactive Elements on the Earth

We know that in the Earth's crust U, Th, and K are quite unevenly distributed. They are present in the greatest quantities in acid rocks, in lesser quantities in intermediate rocks, still less in basic rocks, and, finally, in extremely small quantities in ultrabasic rocks. Table 1 presents the mean contents of natural radioactive elements in the most common rocks of the Earth (ref. 16). Data on individual rocks have also been collected in the work of Yermolayev and Sobornov (ref. 17), as well as that of Smyslov (ref. 18). Given a general concept of the processes leading to the formation of these rocks, we can imagine the behavior of natural radioactive elements and their role in the evolution of our planet.

Figure 1 is a K-U plot showing data for the most representative terrestrial rocks. This sort of systematization using log-log plots is widely used in geochemical and cosmochemical studies. At the present time, data on the natural radioactivity of basic and ultrabasic rocks of the Earth have been significantly supplemented and refined, primarily as a result of intensive investigations of the crustal rocks of the rift zones of the oceans. In particular, there is great interest in specimens of rock collected from the central oceanic ridges where the rock complexes are formed in a single process of differentiation of the primitive material of the mantle. The central ridges are of interest for study of the composition of mantle material, the process of formation of the basalt magma, and the formation of the most primitive crust, which can serve as a prototype of the primitive crust formed in the early stage of development of the Earth, the Moon, and the other terrestrial planets. These data on deep crustal rocks have also been considered in the composition of this diagram.

Table 1.—*Content of Natural Radioactive Elements in Various Types of Terrestrial Rock*

Rock Classes	Rock Types	Contents of Radioactive Elements		
		K.10^4, g/t	U, g/t	Th, g/t
Acid	granites, granodiorities (quartz porphyries, rhyolites, dacities)	$\dfrac{3.4}{1-6}$	$\dfrac{3.5}{1-20}$	$\dfrac{18}{6-40}$
Intermediate	diorites (andesites)	$\dfrac{2.3}{1-4}$	$\dfrac{1.8}{1-3}$	$\dfrac{7}{6-30}$
Basic	gabbros (basalts), anorthosites	$\dfrac{0.8}{0.05-3.0}$	$\dfrac{0.5}{0.03-4}$	$\dfrac{3.0}{0.05-10}$
Ultrabasic	dunite, peridotite, harzburgite (picrite)	$\dfrac{0.03}{0.001-0.1}$	$\dfrac{0.003}{0.001-0.8}$	$\dfrac{0.005}{0.001-1.0}$

Petrographic and petrochemical study of specimens of oceanic rocks allowed Dmitriyev and Udintsev (ref. 19) to analyze the nature of the genetic relationship between basalts and ultrabasalts which are divided into two main groups of rocks: lherzolites and harzburgites. They classified lherzolites as upper mantle material and harzburgites as the residue following production of the primitive basalts. These opinions are apparently confirmed by the K-U systematics.

Figure 1 shows that the mean values of the K/U ratio for lherzolite nodules of the oceanic areas occupy a narrow band within limits of (2–3) $\times$ 10^3; i.e., fall significantly below the K/U ratios for the sequence of tholeiite basalts (K/U $\sim$ 7 $\times$ 10^3) and the main mass of alkaline basalts (K/U = (1–2) $\times$ 10^4). It is natural to propose that the increase of the K/U ratio in these rocks should be accompanied by a decrease in this ratio in other samples that are related to them by genetical processes. Obviously, the harzburgites are such rocks. Thus, in analyzing the data on the K/U ratios our attention is drawn by the branching of the K/U ratio for lherzolites into two series that are signifi-

cantly different from each other. The upper series begins with the oceanic tholeiite basalts and is characterized by a higher K/U ratio, while the lower series is represented by the harzburgites and has lower K/U ratios.

Among the rocks and formations of the continental crust, local reductions of the K/U ratio are not uncommon and are, as a rule, related to increased uranium concentrations that arise during the geochemical cycle for uranium. Among the oceanic formations, the group of rocks with a decreased K/U ratio is of particular interest.

In this sense, the second series, outlined by the data on harzburgites and serpentinized lherzolites and located below the continuation of the band of moderate K/U ratio values (which are strictly characteristic of the lherzolites of the mantle), is itself somewhat supplementary to the series of oceanic tholeiite basalts.

The decreased K/U ratios in the harzburgite rocks of the rift zones are due to a uranium content that is quite high for ultrabasic rocks. Based on a number of factors, we can assume that such high uranium contents result from secondary enrichment that
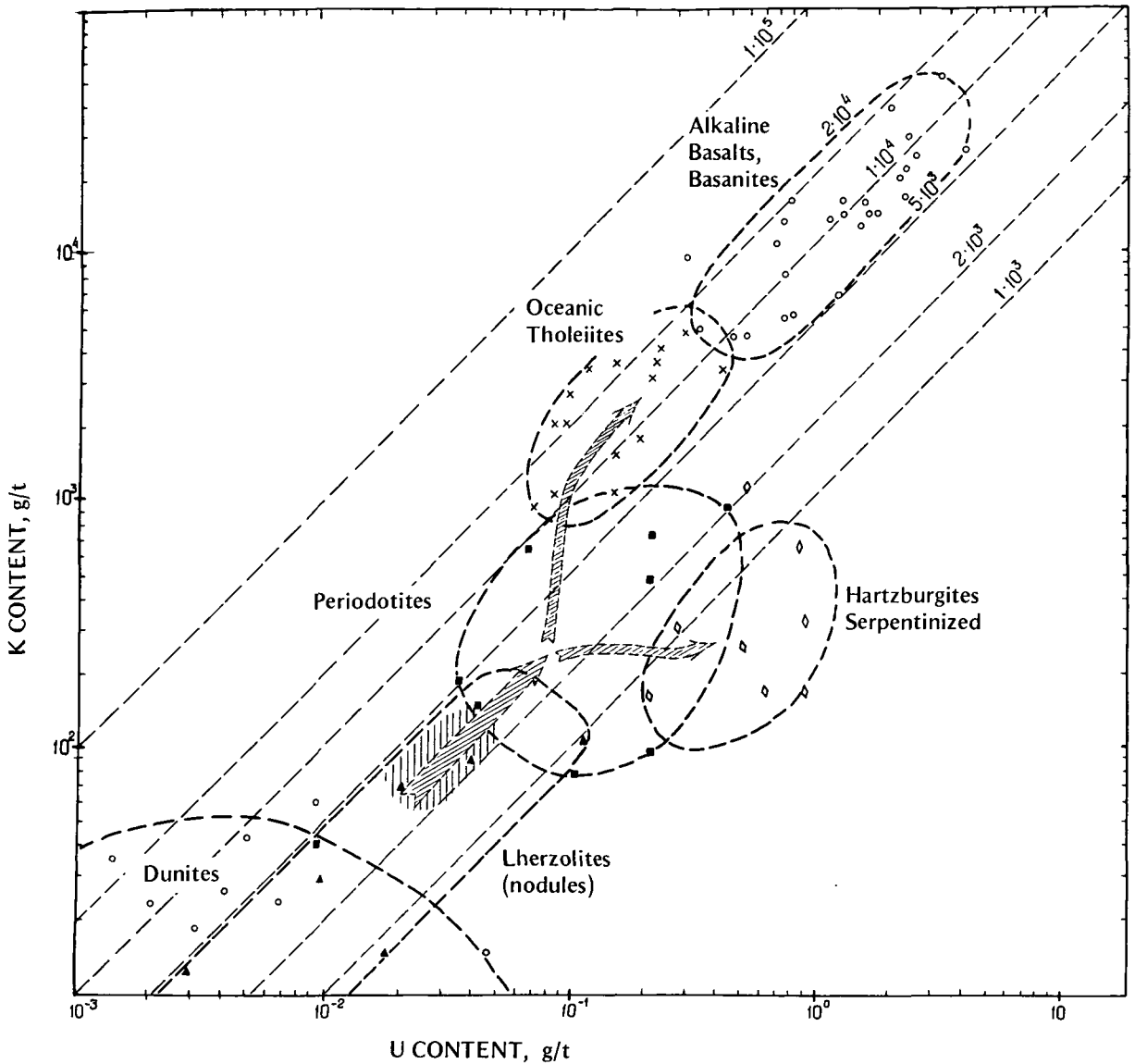
Figure 1.—*Potassium-uranium system of magmatic rocks of the earth.*

occurred when these rocks were reworked by the products of degassing of the mantle. In this case it is important that the rocks enriched by uranium were directly related to the mantle. In the rift zones there could have been no influences of the continental crust, and the variation in K/U ratios resulted only from differentiation in mantle material and its products.

Thus, using the proposal first set forth by Wakita et al. (ref. 20) that lherzolite nodules are material from the upper mantle and keeping in mind the distribution of K-U contents presented in figure 1, we can assume that in the primitive mantle material the potassium content is not over 300 g/t, and the uranium content is not over 0.1 g/t.

In estimating the mean contents of U, Th, and K for the Earth as a whole, one ordinarily starts with the following assumptions:

1. The mean heat flux at the surface of the Earth is 1.5×10^{-6} cal/cm^2 s.

2. The ratio of radioactive elements in the rocks of the upper mantle is true for the entire Earth.

3. The limits of the potassium content in the Earth are estimated on the basis of K^{40}, which is derived from the content of daughter Ar^{40} in the atmosphere of the planet (lower limit), and the established minimum possible value (50 percent) of fractional release of Ar^{40} (upper limit) (refs. 21 and 22).

Assuming that the heat flux is in equilibrium with heat formation and considering that most of the heat is generated by the decay of uranium and thorium, MacDonald (ref. 12) obtained a mean U content for the Earth of 0.031 g/t. Similar estimates using thermodynamic calculations have been made by others; particularly, Tera et al. (ref. 23) obtained a mean value (assuming that there are no radioactive elements in the core of the Earth) of U = 0.035 g/t, Th = 0.14 g/t, with Th/U = 4.

As concerns estimates of the mean content of potassium for the Earth, the value of 100 g/t, obtained from a K/U ratio of ~ 3 × 10³, seems to us preferable to the value of ~350 g/t calculated from the generally accepted ratio K/U ~ 10⁴. Furthermore, the value of 100 g/t corresponds better to the range of possible contents of potassium of 90 to 170 g/t, estimated from data on daughter Ar^{40} (ref. 22).

As we will see later, the mean contents of U and Th in the Earth occupy an intermediate position between the corresponding quantities characteristic of ordinary chondrites and of basaltic achondrites, while potassium is several times less than in the chondrites and achondrites.

Natural Radioactive Elements on the Moon

At the present time, material has already been acquired and analyzed for eight regions of the Moon: three maria (Mare Fecunditatis, Mare Tranquillitatis, and Oceanus Procellarum); three continental areas (around the crater Apollonius-C and the Cayley-Descartes and Taurus-Littrow mountain systems); and two intermediate regions (around Fra Mauro Crater and the Hadley-Apennine formations). It is of interest to systematize and summarize the data produced.

Table 2 presents data on the mean contents of K, U, and Th, as well as their ratios (K/U and Th/U) for 400 specimens of crystalline rocks, breccias, and fine fractions of regolith from all eight regions studied.

A comparison of the abundance of the radioactive elements in the specimens of igneous rock, breccia, and fine regolith fractions shows a rather wide range in K, U, and Th contents for the various collection of specimens returned by the following missions: Apollo 11, 12, 14, 15, 16, and 17 and Luna 16 and 20. The main mass of specimens studied has the following limits of radioactive element content: for potassium, 0.03 to 0.7 percent; for uranium, 0.1 to 5 g/t; for thorium, 0.4 to 18 g/t. The K/U ratio varies from 1 × 10³ to 5 × 10³. However, for individual specimens, the data produced go significantly beyond these limits. For example, one of the breccia specimens collected by Apollo 12 (12013) is rich in a high silica-feldspar differentiate and contains 10.7 g/t uranium and 34.3 g/t thorium. These values are even higher than the U and Th contents in most terrestrial granites which, characteristically, have the highest content of the radioactive elements.

Also distinguished by their high values of K/U ratio (around 7 × 10³) are specimens of anorthosite (62236) and basalt (63335) from the Apollo 16 collection, as well as specimens 15415 (Apollo 15) and 62275 (Apollo 16), which have K/U ratios of over 10⁴. On the other hand, such specimens of crystalline rock as 62295 (Apollo 16) and 10062 (Apollo 11) have K/U ratio of < 10³. Our attention is drawn by the similarity of K/U ratios (but decreased contents of potassium (200 g/t), uranium (0.07 g/t), and thorium (0.28 g/t), as compared with the main mass of lunar specimens) to the group of breccias from the collection of Apollo 15 and Apollo 16 (15418, 60135, 62237, 64435, 67455, and 69955).

Table 2.—*Content of Radioactive*

Element	Lunar Sample	Mare Tranquillitatis Apollo 11	Oceanus Procellarum Apollo 12	Mare Fecundatatis Luna 16
K, g/t	Crystalline rocks	$\dfrac{1460}{230\text{--}2515}$	$\dfrac{500}{260\text{--}670}$	1500
	Breccia	$\dfrac{1330}{940\text{--}1600}$	$\dfrac{2310}{1040\text{--}4360}$	—
	Soil	1100	$\dfrac{2200}{1700\text{--}3100}$	910
U, g/t	Crystalline rocks	$\dfrac{0.48}{0.18\text{--}0.78}$	$\dfrac{0.24}{0.21\text{--}0.31}$	0.3
	Breccia	$\dfrac{0.50}{0.29\text{--}0.63}$	$\dfrac{2.1}{0.6\text{--}3.46}$	—
	Soil	0.5	$\dfrac{1.47}{0.72\text{--}2.35}$	0.3
Th, g/t	Crystalline rocks	$\dfrac{2.4}{0.86\text{--}3.54}$	$\dfrac{0.91}{0.77\text{--}1.2}$	1.15
	Breccia	$\dfrac{2.2}{1.4\text{--}2.8}$	$\dfrac{8.1}{2.5\text{--}13.6}$	—
	Soil	2.3	$\dfrac{5.9}{3.52\text{--}8.8}$	1.1
Th/U	Crystalline rocks	$\dfrac{4.6}{3.4\text{--}5.5}$	$\dfrac{3.6}{1.9\text{--}4.0}$	3.8
	Breccia	$\dfrac{4.4}{3.8\text{--}5.0}$	$\dfrac{4.0}{3.2\text{--}4.2}$	—
	Soil	4.6	$\dfrac{3.9}{3.3\text{--}4.9}$	3.7
K/U	Crystalline rocks	$\dfrac{3000}{820\text{--}4650}$	$\dfrac{2340}{1760\text{--}4290}$	4700
	Breccia	$\dfrac{2760}{2280\text{--}3420}$	$\dfrac{1470}{1260\text{--}1740}$	—
	Soil	2200	$\dfrac{1660}{1240\text{--}2360}$	3640

Elements in Lunar Samples

| Fra Mauro Apollo 14	Hadley-Apennines Apollo 15	Apollonius-C Lune 20	Cayley-Descartes Apollo 16	Taurus-Litthrow Apollo 17
$\dfrac{3030}{880\text{–}4150}$	$\dfrac{400}{120\text{–}500}$	$\dfrac{1370}{1000\text{–}1740}$	$\dfrac{1170}{90\text{–}4000}$	$\dfrac{1610}{410\text{–}3000}$
$\dfrac{4370}{1100\text{–}4780}$	$\dfrac{1890}{86\text{–}4780}$	715	$\dfrac{1000}{50\text{–}2000}$	2800
$\dfrac{4520}{3570\text{–}5300}$	$\dfrac{1410}{750\text{–}1860}$	645	$\dfrac{940}{425\text{–}1230}$	$\dfrac{800}{600\text{–}1330}$
$\dfrac{2.14}{0.6\text{–}3.2}$	$\dfrac{0.14}{0.003\text{–}0.16}$	$\dfrac{0.7}{0.5\text{–}0.9}$	$\dfrac{0.76}{0.016\text{–}3.0}$	$\dfrac{1.02}{0.11\text{–}2.0}$
$\dfrac{3.34}{1.0\text{–}4.5}$	$\dfrac{1.18}{0.04\text{–}3.14}$	0.7	$\dfrac{0.57}{0.03\text{–}1.00}$	0.6
$\dfrac{3.69}{3.1\text{–}4.0}$	$\dfrac{1.0}{0.42\text{–}1.69}$	0.29	$\dfrac{0.56}{0.18\text{–}0.74}$	$\dfrac{0.3}{0.15\text{–}1.0}$
$\dfrac{8.44}{2.24\text{–}21.1}$	$\dfrac{0.49}{0.028\text{–}0.6}$	$\dfrac{2.55}{1.7\text{–}3.4}$	$\dfrac{2.84}{0.1\text{–}9.4}$	$\dfrac{3.96}{0.31\text{–}8.0}$
$\dfrac{12.7}{4.4\text{–}15.6}$	$\dfrac{4.53}{0.12\text{–}12.3}$	1.2	$\dfrac{2.1}{0.1\text{–}4.85}$	2.32
$\dfrac{13.6}{12.0\text{–}14.4}$	$\dfrac{3.74}{1.73\text{–}6.34}$	1.0	$\dfrac{2.08}{0.6\text{–}2.74}$	$\dfrac{1.25}{0.3\text{–}2.4}$
$\dfrac{3.8}{3.5\text{–}4.2}$	$\dfrac{3.63}{2.9\text{–}4.3}$	$\dfrac{3.6}{3.4\text{–}3.8}$	$\dfrac{3.58}{2.82\text{–}4.84}$	$\dfrac{3.46}{2.50\text{–}4.0}$
$\dfrac{3.63}{3.3\text{–}3.9}$	$\dfrac{3.78}{3.0\text{–}4.2}$	1.7	$\dfrac{3.73}{3.33\text{–}4.86}$	3.87
$\dfrac{3.7}{3.6\text{–}3.9}$	$\dfrac{3.79}{3.4\text{–}4.5}$	3.45	$\dfrac{3.75}{2.81\text{–}4.45}$	$\dfrac{3.3}{2.0\text{–}3.92}$
$\dfrac{1400}{1280\text{–}1560}$	$\dfrac{3000}{2220\text{–}4.10^4}$	$\dfrac{1970}{1930\text{–}2000}$	$\dfrac{2070}{740\text{–}7200}$	$\dfrac{2410}{1290\text{–}418}$
$\dfrac{1330}{830\text{–}1760}$	$\dfrac{1700}{1470\text{–}2150}$	1020	$\dfrac{2070}{1270\text{–}3470}$	4700
$\dfrac{1250}{1120\text{–}1390}$	$\dfrac{1520}{1230\text{–}2050}$	2220	$\dfrac{1730}{1300\text{–}2900}$	$\dfrac{2500}{1750\text{–}4200}$
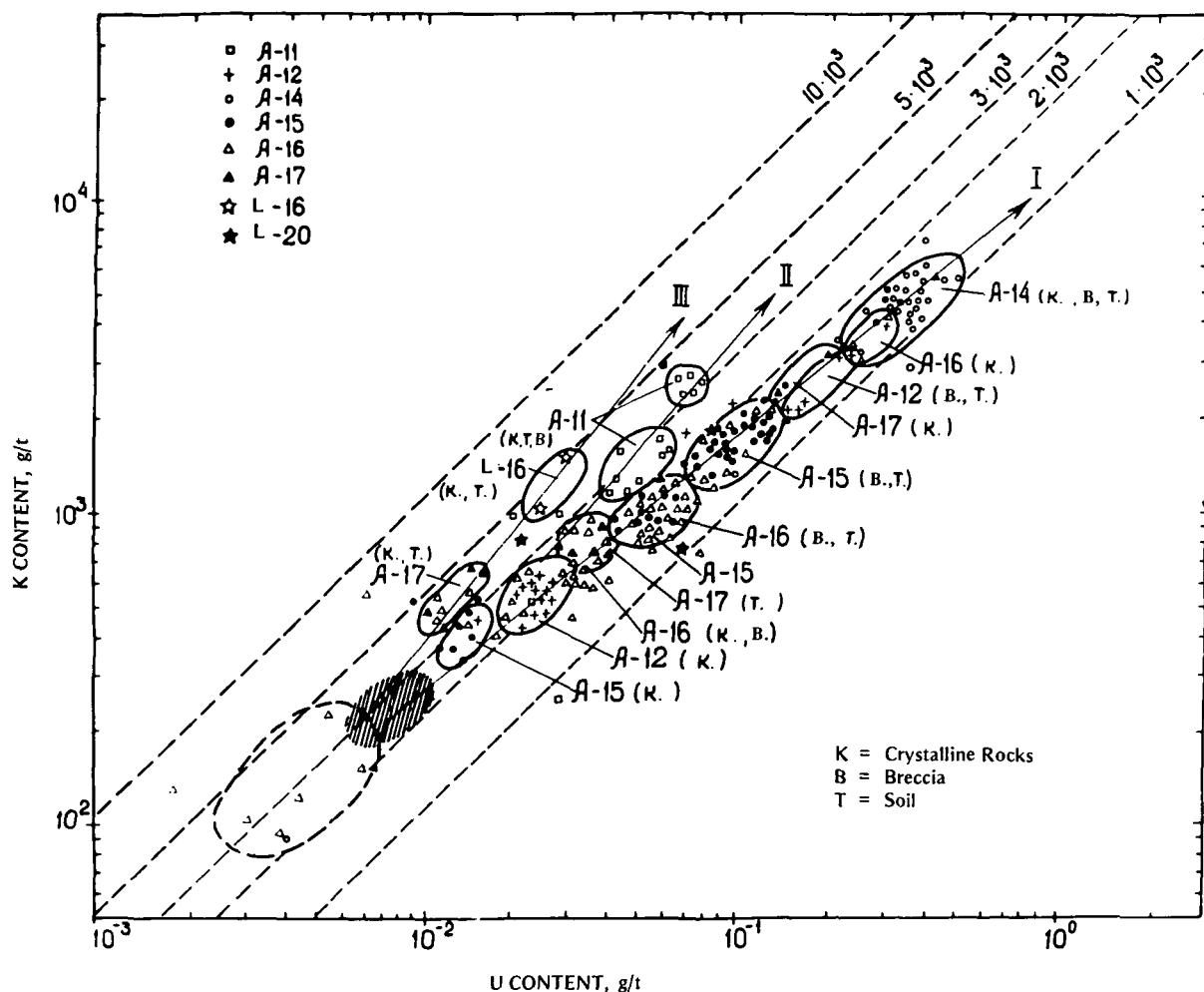
Figure 2.—*Potassium-uranium system of lunar specimens.*

Analysis shows that regions of the Moon such as Mare Tranquillitatis, Mare Fecunditatis, and the Fra Mauro region are characterized within each region by similar potassium-uranium contents and K/U ratios for specimens of various types (crystalline rocks, breccias, fine regolith fractions). This fact apparently indicates that the formation of the regolith in these regions was basically local in nature. At the same time, the increased content of radioactive elements in the regolith of the Oceanus Procellarum and the Hadley-Apennine formation in comparison with the original rocks of these regions is related to horizontal movement of the substance over the surface of the Moon.

In particular, the lunar soil and breccias in these regions are a mixture of local basalt and a foreign component with high K, U, and Th content. This material could not have been anorthosite, which has low contents of K, U, and Th and would act as a diluting agent to decrease the K–U content in comparison with those for the soil and breccia. The most probable component is the material called KREEP (UTh), which is characterized by a high content of natural radioactive elements, rare earths, and phosphorous.

Figure 2 presents the analytical results of all known lunar specimens on a K–U plot. As we can see from the figure, most lunar specimens from the regions studied can be

differentiated by their contents of potassium, uranium, and K/U ratio into a number of areas with more or less clearly defined boundaries. These areas are partially overlapping and form the links in several more or less clearly pronounced chains that connect the zone of low content of radioactive elements with several higher zones that have differing K/U ratios.

First, we see a long chain with K/U ratios of $(1-3) \times 10^3$. The lowest link in this chain is formed by the mare basalts of Apollo 15, which have the lowest content of natural radioactive elements. The highest link is formed by the KREEP (UTh) material of the Apollo 14 collection from the Fra Mauro region. In the middle portion of the chain are the links that characterize the regolith from various regions and the links that correspond to crystalline rocks from the Taurus-Littrow, Cayley-Descartes, and Apennine Mountain regions. The same values of K and U content were found by analysis of the individual fragments of crystalline rock from the Luna 20 core sample.

Obviously, formal placement of several links characterizing specimens from widely varied parts of the Moon in a single chain does not mean that they belong to a single sequence or related series of rock formed in the process of magmatic differentiation. Nevertheless, the great similarity in distribution within the very same chain of specimens from different collections such as those of Apollo 12, 15, and 16 allows us to speak of general trends manifested in the origin and evolution of the material of these regions.

The second chain, not so clearly expressed as the first and having K/U ratios in the range $(2-4) \times 10^3$, can be traced for links that include specimens from the mare regions of the Moon, particularly from the Mare Tranquillitatis. We can support that this chain also has its origin in the zone where we find the links that characterize the low-potassium basalts of the Oceanus Procellorum (Apollo 12) and the Hadley region (Apollo 15), as well as basalt 10003 from Mare Tranquillitatis (Apollo 11).

Apparently, this very same chain should include the link from the Apollo 17 series, which includes regolith specimens from Mare Serenitatis, particularly since in their content of both major and rare-earth elements these specimens are similar to the regolith specimens from the Mare Tranquillitatis.

Comparison of these two chains and their individual links leads to the conclusion that the rock specimens characteristic of mountain regions lie basically in the range of K/U ratios that are lower when compared with the range of K/U ratios characteristic of mare basalts. This enrichment of igneous rocks with uranium relative to potassium, as shown by Taylor (ref. 24), might result from fractional crystallization of melts because the physiochemical properties of these elements are different, particularly in their ionic radii and charges. According to the calculations of the author, the content of potassium in the continental crust relative to the mean content in the entire Moon is 32 percent, whereas for uranium this figure is 54 percent and for thorium 56 percent.

The third chain presented in figure 2 is less obvious and statistically weaker. It includes a number of specimens of the Apollo 17 series (coarse-grained basalts 70135 and 79155, regolith specimens 74220 and 75081, and breccia 76255, which is distinguished by comparatively high contents of potassium and uranium with K/U $\sim$ 4700); the Apollo 16 series of breccias collected at one station (67035, 67115, and 67915); the Apollo 11 series (specimens 10056 and 10058); as well as regolith and basalt fragment specimens from the Luna 16 series. In any case, the presence of a whole group of specimens distributed in the diagram along the area of elevated K/U ratios gives us reason to consider this chain as well.

These chains can be represented as approximating regression lines with different slopes relative to the straight lines for K/U = const. and probably intersecting the values of potassium-uranium content corresponding to the material of the lunar mantle. Obviously, this material should be poorer in radioactive elements than the lunar surface

rocks, since otherwise the radiogenic heat released by the Moon should have maintained it in the melted state.

As we know, zone melting of the substance of the mantle is accompanied by accumulation of a number of elements, including lithophilic K, U, and Th in the upper zone of the melt, and the corresponding impoverishment of the mantle in the zone of formation of the melt. As noted above, the presence in the collection of lunar specimens of a group of breccias of deep origin with extremely low contents of radioactive elements (area outlined by dashed line on fig. 2) allows us to affirm more reliably the existence of deep magmatic zones poor in K, U, and Th.

In order to define the initial matter of the Moon, we must establish the genetic affinity of rocks formed in a single process of mantle differentiation. This could be confirmed by the complementary nature of their chemical compositions and by data on the distribution of trace elements in them.

The difference in the approximately straight slopes that characterize various "families" of lunar specimens in a K-U plot apparently indicates the existence of complementary parts of these families that were formed as a result of magmatic differentiation in an early stage of lunar development (ref. 25).

Certainly, for the Moon, the picture of differentiation and the genetic relationship of rocks formed in a single process is not as clear as for the Earth. This is explained by the fact that the process of differentiation on the Moon was probably not as intensive as on the Earth. However, it is interesting that the primary undifferentiated material of both the Earth and Moon apparently had approximately the same ratio of natural radioactive elements $K/U \simeq 2.8 \times 10^3$ (ref. 26).

Obviously the order of magnitude difference in K/U ratios between the Moon and Earth, as used in a number of papers about similar systematics of the data, has no definite meaning because it results from comparing only secondary, differentiated rocks and not from considering the average composition of the entire planet.

We can estimate the mean content of U, Th, and K on the Moon as 0.07, 0.25, and 180 grams per ton of lunar material, respectively. This is accomplished by keeping in mind the ratios $K/U \sim 2.8 \times 10^3$ and $Th/U \sim 3.6$ and the mean heat flux values of 30–40 erg/cm²s (determined by a radio-astronomy method) (ref. 27) or 28–31 erg/cm²s (measured directly on the Moon by Apollo 15 and 17) (ref. 28).

It should be noted that these contents of natural radioactive elements for the primitive material of the internal zones of the Moon, which have been subjected to radiogenic heating and chemical differentiation, are close to the contents produced by Wanke et al. (ref. 29) in calculating the chemical composition of their two-component model of the Moon (U = 0.086, Th = 0.32, and K = 250 g/t). Finally, these data for the Moon are also close to the mean values of U, Th, and K contents in achondrites–data that will be considered below.

With these data for the mean content of the natural radioactive elements on the Moon and data on the mean content of lunar specimens (see table 2) that characterize the lunar crust, we can make a few statements concerning the thickness of the lunar crust.

For example, if we assume that at the present time practically all of the uranium has been concentrated and rather evenly distributed in the lunar crust with a mean content of ~ 0.5 g/t, then its thickness should be 60 to 70 km. If uranium has remained partially in the mantle, the crust should be thinner; if its content in the crust is uneven and decreases with depth, the crust should be thicker.

Comparing the content of radioactive elements on the Moon and the Earth, we note the following. The mean content of radioactive elements in the Moon is twofold higher than in the Earth, while the mean content of radioactive elements in the lunar crust is lower than on the Earth (e.g., for uranium ~ 0.5 g/t and ~ 2 g/t, respectively). This means that the processes of differentiation of matter on the Moon have not been as intensive as on the Earth, and as a result the en-

richment of radioactive elements in the lunar crust has been at least an order of magnitude lower than on the Earth. This might also be the reason why we do not observe Moon rocks that are highly enriched with potassium, as is the case for certain igneous terrestrial rocks that have K/U ratios of $\sim 10^4$.

Natural Radioactive Elements in Meteorites

The peculiarities of the composition of meteorites agree with their formation as a result of condensation and fractionation of the matter of the solar nebula as it cooled. This process has been thermodynamically studied in detail (refs. 30, 31, and 32). The early condensate was rich in elements (Al, Ca, Ti) that formed refactory compounds, after which the silicates and iron condensed, followed by the condensation of the more volatile elements that enter into the composition of the low-temperature phases. The fractionation of solar nebula matter led to the formation of carbonaceous, ordinary (bronzite, hypersthene, amphoterite), and enstatic chondrites and achondrites, including basaltic achondrites (eucrites and howardites). After their formation, some meteorites were subjected to secondary heating and recrystallization.

In the process of condensation of meteoritic matter, fractionation of the radioactive elements U, Th, and K obviously occurred.

The first two of these elements are relatively refractory and apparently condensed in one of the early stages of cooling. The early condensate was doubtless poor in volatile compounds, including K_2O. The contemporary distribution of the radioactive elements in various groups of meteorites is probably the result of these processes and occurred in the early existence of the solar system.

Table 3 and figure 3 show data on the distribution of K, U, and Th in stony meteorites. Naturally, the greatest quantity of published data on the content of radio-

active elements in the meteorites relates to the most representative and numerous chondrite group. For the achondrite group, statistically significant radioactivity data (for comparison of individual classes of meteorites), are available mostly for eucrites, which amount to 45 percent, and howardites, which amount to 27 percent of all known achondrites.

What are the distinguishing features of the K-U and U-Th systems of the meteorites? As regards the chondrite group, there is particular interest in data on carbonaceous chondrites whose material is generally throught to be closest to the protoplanetary matter of which the planets and asteroids were formed. More precisely, the carbonaceous chondrites are divided into three types (C1, C2, C3); what we have said relates to type C1 chondrites, whose chemical composition has atomic ratios and amounts of volatile substances that are most similar to the chemical composition of the Sun. In particular, types C2 and C3 carbonaceous chondrites are poorer in volatile elements than type C1. The content of potassium relative to silicon in C1, C2, and C3 carbonaceous chondrites is 3200, 2100, and 1700 atoms/10^6 atoms of Si, respectively; i.e., C2 and C3 are poorer in potassium than C1 by 0.63 and 0.52 times, respectively (ref. 30).

The mean values of the K/U ratio for all three types of carbonaceous chondrites differ significantly: $\simeq 4.3 \times 10^4$ for C1; $\simeq 3 \times 10^4$ for C2; and $\simeq 2.3 \times 10^4$ for C3. Unfortunately, the insufficiency of statistical material, particularly for type C1 and C3 carbonaceous chondrites, and the possibility of their contamination on Earth, forces us to approach with caution estimates of the mean values of K, U, and Th contents characteristic of any given class of meteorites.

Nevertheless, the content of potassium in ordinary chondrites is greater than in carbonaceous chondrites, although they are rather similar to type C1 carbonaceous chondrites in K/U ratio. As we can see from figure 3, the separate fields that characterize individual classes of ordinary chondrites overlap each other significantly and fall

Table 3.—*Content of Radioactive Elements in Stony Meteorites*

	Meteorites	K, g/t	U, 10^{-3} g/t	Th 10^{-3} g/t	Th/U	K/U, 10^4
Chondrites	Carbonaceous C1	510 / 380–580	11.0 / 8.7–14.0	39 / 29–59	3.5 / 2.8–4.2	4.8 / 3.9–6.7
	Carbonaceous C2	415 / 130–1100	12.6 / 10.8–15	44 / 38–61	3.5 / 3.1–4.3	3.0 / 1.5–4.1
	Carbonaceous C3	500 / 100–1400	18 / 14–24	85 / 57–120	4.4 / 4.0–5.0	2.3 / 1.6–2.8
	Amphoterite	840 / 700–1240	16.5 / 10.5–25.5	45 / 43–50	3.6 / 3.0–3.9	5.2 / 3.3–8.1
	Hypersthene	900 / 640–1660	16 / 8.6–25	42 / 38–49	3.4 / 2.5–3.9	5.3 / 3.5–11.6
	Bronzite	850 / 500–1580	13.6 / 9.0–24.5	40 / 36–42	3.4 / 2.9–3.8	6.5 / 4.4–9.1
	Enstatite	850 / 500–1740	10 / 6.0–16	34 / 29–42	3.7 / 2.6–7.0	8.4 / 4.4–11.2
Achondrites	Eucrites	360 / 150–650	93 / 15.9–200	350 / 53–590	3.8 / 2.9–6.1	0.4 / 0.37–0.76
	Howardites	250 / 170–400	52 / 23–89	167 / 63–312	3.1 / 2.6–3.45	0.4 / 0.34–0.48

within a rather limited area of potassium-uranium contents (K from 600 to 1000 g/t, U from 0.1 to 0.25 g/t). The range of uranium contents for enstatite chondrites is shifted somewhat into the area of lower U concentrations (from 0.06 to 0.16 g/t).

Achondrites of various classes have rather wide variations in potassium and uranium contents. Although due to the small number of such chondrites as aubrites, ureilites, angrites, nakhlites, and shergottites, it is difficult to draw any conclusions concerning genetic relationships; most of the calcium-rich achondrites—eucrites and howardites—show a number of common characteristics. This conclusion can be made on the basis of both structural peculiarities and mineralogical composition. As concerns radioactive ele-

ments, we can state that howardites and eucrites have practically identical mean values of K/U ratio ($\sim 4 \times 10^3$), but differ in absolute uranium and potassium contents. Whereas in figure 3 the field defined by the howardites Frankfurt and Kapoeta lies near the point with coordinates K = 200 g/t and U = 0.05 g/t, the area of eucrites extends to values of 0.2 g/t uranium and 700 g/t potassium. This point of the diagram corresponds to the eucrite Stannern, the basaltic achondrite richest in radioactive elements, and agrees with the conclusion of Ahrens (ref. 33) that Stannern is possibly an end product of the differentiation of achondritic matter.

Of the achondrites poor in calcium, our attention is drawn primarily by the group of diogenites shown in the graph. Schnetzler
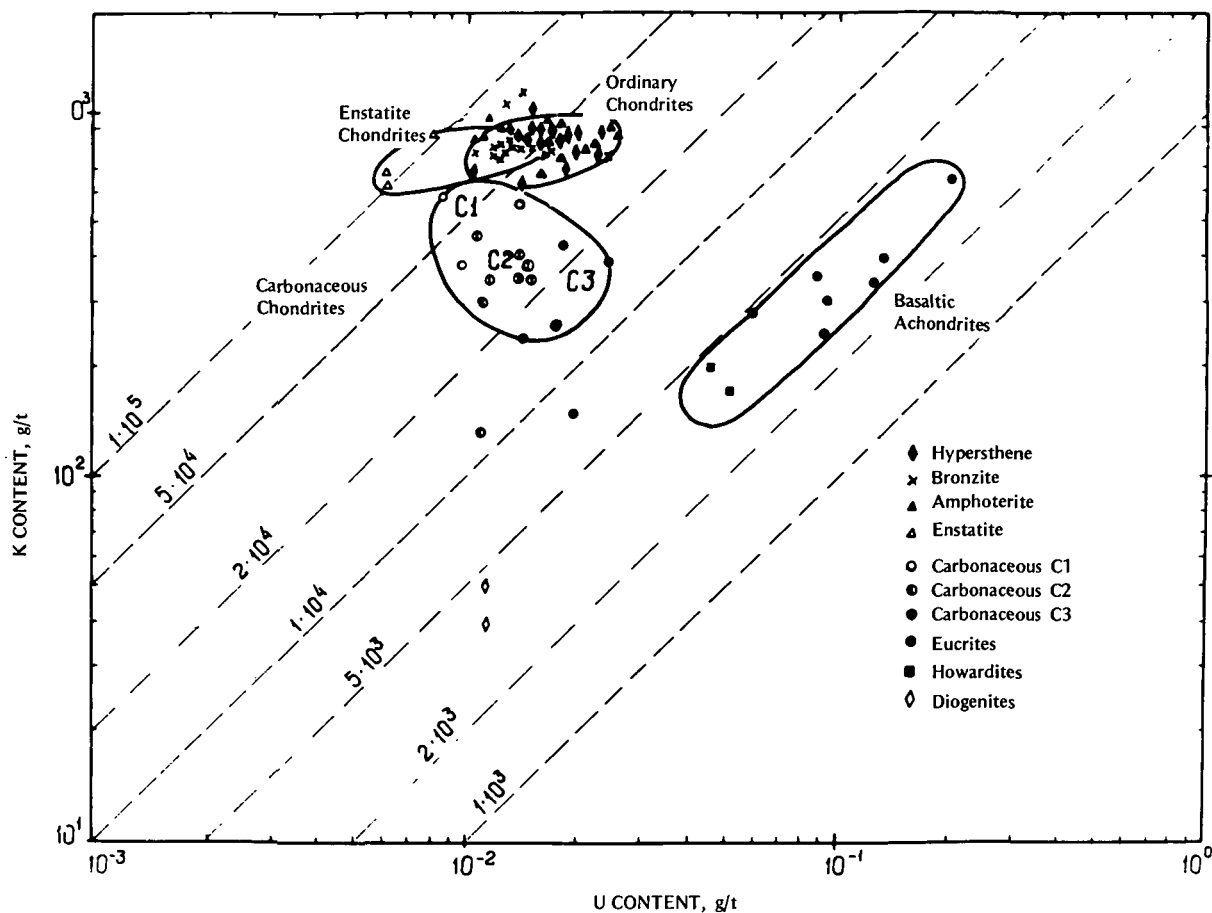
Figure 3.—*Potassium-uranium system of rocky meteorites.*

and Philpotts (ref. 34) believed that the diogenites are a residual product produced by the melting of calcium-rich achondrites out of chondrite matter. On the other hand, based on their similarity to hypersthene chondrites, the opinion has been stated (ref. 35) that diogenites were formed from iron-poor chondrites as a result of intensive metamorphism. As follows from figure 3, radioactivity data do not contradict this idea. Actually, some diogenites (Johnston and Shalka) are quite poor in potassium (by approximately one order of magnitude) in comparison with the chondrites and at the same time have K/U ratios similar to the Ca achondrites ($\sim 4 \times 10^3$), but significantly lower K and U contents.

In contrast to K/U ratios, the Th/U ratio for these classes of meteorites is less subject to fluctuations, although the actual content of Th and U in the stony meteorites is distributed over broad limits. For example, the main mass of chondrites falls within 0.03 to 0.06 g/t and 0.016 g/t for Th and U contents. Most eucrites for which thorium and uranium were determined are concentrated in the area of relatively high contents: Th = ~ 0.4 g/t and U ~ 0.1 g/t.

At the same time, howardites (Frankfurt, Kapoeta) occupy an intermediate area and even fall adjacent (Binda) to the Moore County and Serra de Mage eucrites in the lower area of Th and U contents, corresponding to the chondrite group of materials. Still poorer in U and Th are the diogenites; in particular, the Ellemeet diogenite has the
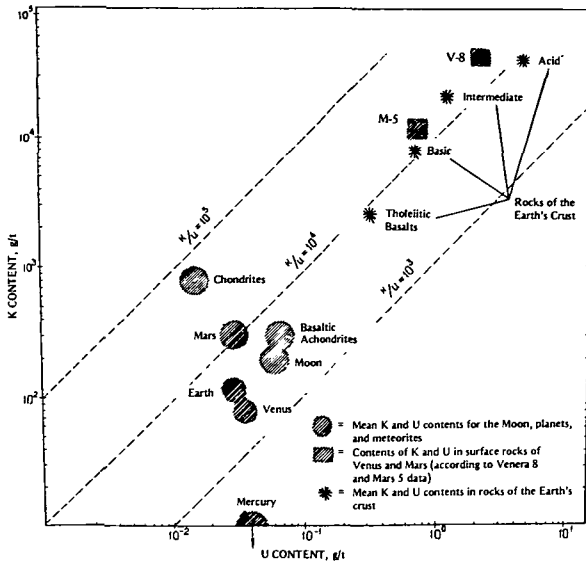
Figure 4.—*Potassium-Uranium system of bodies of the solar system.*

lowest radioactivity, with U = 0.0015 g/t and Th = 0.0038 g/t.

Nevertheless, as can be seen from table 3, the mean Th/U ratios for meteorites of various classes and types fall in a relatively narrow band of 3.6 ± 0.5, which agrees well with the value of 3.8 ± 0.3 calculated indirectly for the solar system by Fowler and Hoyle (ref. 36).

Natural Radioactive Elements in the Solar System

Whereas the fractionation of volatile elements and compounds between the terrestrial planets and the giant planets is beyond doubt and results from the variation in temperatures at various distances from the Sun, the question of fractionation dependent on heliocentric distance within the limits of the terrestrial planets remains open. However, an impression of this fractionation can be gained by analysis of both the various condensation models of planetary formation from the protoplanetary cloud and indirect data on the structure of the planets.

We will study the abundance of natural

radioactive elements in the solar system, using the previously discussed data on the Earth, Moon, and meteorites, and supplementing them with some estimates on the content of U, Th, and K in the planets. Assuming that the relationship of U and Th changes little or remains completely unchanged within at least 4 AU, we will study only the content and ratio of U and K.

Figure 4 presents the mean contents of radioactive elements on the Moon and planets and in meteorites, as well as the mean content in rocks of the crust of the Earth, Venus, and Mars.

What considerations can be used to estimate the mean contents of U, Th, and K on the planets? Obviously, the determining factors will be placement in the solar system, size and density, and current internal structure. Let us consider these characteristics.

VENUS

According to these considerations, Venus, probably more than the other planets, is similar to the Earth. It is currently known that the content of volatile components (particularly CO_2, N_2, O_2, etc.) on Venus is close to that of Earth, and only the difference in temperatures on the surface of the planets determines the quantity of these substances in the atmosphere or in the bonded state in the rocks of the planets. The presence on Venus of an atmosphere consisting of components which, as on the Earth, can be released only in the process of degassing of melted crustal material indicates that Venus should be a differentiated planet.

Finally, the contents of U, Th, and K in the Venusian rock measured by the Venera 8 spacecraft amount to 2.2, 6.5, and 4 × 10⁴ g/t, respectively (point V–8 on fig. 4), and indicate the existence of igneous rock on the surface of Venus. Even if we assume that these initial data may not be representative of the distribution of radioactive elements throughout the crust of the planet, this point, in our opinion, is quite indicative when we compare it with the K/U data for the other

planets of the solar system. It is not difficult to see that these contents correspond to those of high-potassium acidic rocks on Earth.

Vinogradov et al. (ref. 37) studied possible processes leading to the enrichment of the surface Venusian rock with natural radioactive elements. One reason for the stability of high-potassium material in particular might be related to the acid-alkaline properties of melts flowing on the surface of the planet. Korzhinskiy (ref. 38) and Yakovlev et al. (ref. 39) showed that as the acidity of a melt increases the resistance to evaporation of the alkaline components of such melts also increases. This, apparently, is the reason for the high concentration of potassium in the Venusian rocks.

Thus, everything indicates that Venus is a differentiated planet. The process of differentiation on Venus apparently occurred quite intensively, as indicated by the high contents of U, Th, and K in the Venusian rock as measured by Venera 8.

If we also keep in mind the high temperatures on the surface of the planet (ref. 40), the mountainous relief (ref. 41), and the dense atmosphere consisting of gases liberated as a result of volcanic activity (refs. 37 and 42), we can imagine that the process of differentiation is still continuing, the interior of the planet is still quite hot, and the heat flux at the present time is obviously higher than that of Earth.

Since with identical initial data (and particularly identical contents of radioactive elements) Venus should have a slightly lower heat flux, it is reasonable to assume that Venus has a slightly higher content of uranium than the Earth's 0.035 g/t. The K/U ratio for Venus might be somewhat lower than for Earth.

MARS

Quite a bit is now also known about Mars. Its mass and moment of inertia indicate a significant increase in density with depth and the possible existence of a dense core. This is also indicated by the weak dipole magnetic field of Mars (ref. 43). However, everything that we now know concerning the surface of Mars, based on the photographs of Mariner 9 (volcanism, tectonic phenomena, high mountain regions, etc.), indicates the possible existence of a Martian crust consisting of igneous rocks (ref. 44). Finally, recent measurements of the gamma radiation of Mars by Mars 5 (ref. 11) indicate a comparatively high content of natural radioactive elements in the surface rock of Mars in comparison with the possible mean content of these elements on Mars. (In fig. 4, the point corresponding to the K-U content in the Martian rock is represented by the index M–5.)

In a number of its characteristics, Mars occupies a middle position between the Earth and the Moon. At the present time it is not as active as the Earth, but not as cold as the Moon. It can be assumed that the heat flux of Mars is now intermediate between the values for the Moon and the Earth, i.e., ~ 40 erg/cm^{2}s.

Based on analysis of the internal structure of Mars, Binder and Davis (ref. 45) indicated that the composition of the Martian mantle is similar to that of the Earth; i.e., the content of olivine and fosterite should amount to 65 to 80 percent. The mass of the core of Mars should be ~ 10 percent of the mass of the entire planet, and the radius of the core is approximately 1250 km.

Mars was formed in an area of the cloud where the temperature was ~ 500 K (i.e., significantly lower than the condensation temperature of potassium and the other volatile elements and compounds). As such, we should expect that Mars has retained these volatile substances, though perhaps not to the same extent as the chondrites whose accretion occurred in the temperature range 350 to 500K (ref. 46), but obviously more than Earth.

Therefore, based on these considerations we can assume that the mean content of U on Mars is no less than on Earth and that Mars has a K/U ratio of $\sim 10^4$. The value of K/U for Mars is intermediate between the corresponding values for Earth (K/U ~ 3

$\times$ 10³) and the chondrites (K/U = (2.4–8.4) $\times$ 10⁴), which are determined by their position at 1.5 AU from the Sun.

MERCURY

There is somewhat less information available concerning Mercury. The presence of regions broken by craters and of lower, smooth regions similar to the continents and mare of the Moon (ref. 47) may indicate volcanic activity in the past and the possible existence of a crust at present. The presence of a weak magnetic field, as shown by Mariner 10 (ref. 48), probably indicates the existence of at least a partially melted core. Thus, we can assume that Mercury is also a differentiated planet. Mercury apparently is richer in refractory elements than the other planets and has little or no volatile elements, including potassium. For Mercury we can assume very approximately a K content of < 1 g/t and a U content of ~ 0.04 g/t.

All these peculiarities in the abundance of the radioactive elements on the Moon, planets, and meteorites fit into our general concept of the evolution of the matter in the solar system (refs. 49, 50, and 51).

According to these concepts, the protoplanetary matter, of which all bodies in the solar system were later formed, took on significant heterogeneity in the course of its chemical evolution, as is reflected in the composition of the Moon, planets, and meteorites. This compositional heterogeneity of the protoplanetary mass was determined primarily by the relationship between volatile and refractory elements and their compounds.

During the evolution of protoplanetary matter, the volatile elements and compounds moved to the periphery of the cloud (in the area of lower temperatures), while the refractory elements moved closer to the Sun (in the area of higher temperatures). This process of differentiation in the preplanetary period was naturally reflected in the abundance of radioactive elements (particularly their relationships) in the solar system. For example, as the distance changes from

Mercury (~ 0.4 AU) to the asteroid belt (~ 2–4 AU), the K/U ratio changes by almost five orders of magnitude.

Thus, the various bodies of the solar system that formed later inherited those quantities and relationships of radioactive elements which existed in the formation region of each body.

The formation of the planetary Earth-Moon system is somewhat more complex. In spite of the identical nature of the preplanetary matter in the zone which fed these two bodies, differences in their condensation conditions (pressure, temperature) have resulted in differences in their chemical compositions. According to condensation models, the metallic core of the Earth was able to form before the beginning of the condensation of low-temperature magnesium silicates. Due to this, the relative shortage of iron on the Moon may be related to the fact that during its accretion a significant portion consisted of high-temperature condensates enriched in refractory elements (including U and Th).

On the other hand, the mechanism of interaction of the solar wind with particles of the forming swarm must have played a significant role in the shortage of volatile elements on the Earth and the Moon. According to the model developed by Ruskol (ref. 52), the influence of the solar wind should have been particularly strong for the Moon during the final stage of accretion of its surface layers. During this period, at the periphery of the cluster around the Earth the transparency was sufficiently great that the atoms of the volatile elements, released by evaporation of matter during the processes of collision of solid particles and bodies, were partially removed from the swarm under the influence of the solar wind.

After the formation of the planets, further evolution occurred. As we know, during the course of differentiation of the matter of the planets, the crust was enriched with natural radioactive elements, particularly potassium.

Whereas in the lunar rocks the differentiation was relatively slight, Earth, Venus, and Mars underwent a long process of differ-

entiation during their thermal history, which is indicated particularly by the high K/U ratio of the surface magmatic rock in comparison to the assumed relationship of mean contents of these radioactive elements in the planets.

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