

K and U systematics and average concentrations on the moon

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Abstract—The K-U, Th-U, and Th-Al systematics for lunar samples from the Apollo 11-17 missions and the Luna 16 and 20 missions are summarized. With few exceptions (granitic portion of 12013 and the Apollo 17 mare basalts) the Th/U ratio is 3.8 ± 0.2 . The K/U ratio for lunar samples is about 2600 and is distinctly different from the K/U ratio found in terrestrial samples and in the majority of meteorites. The K-U systematics are similar to the K-La, K-Sm, K-Ba, and K-Zr systematics, suggesting that the moon accreted approximately homogeneously. Based on a model the moon contains an average abundance of about 80 ppb U, about 200 ppm K, and about 7 times chondritic abundances for all the refractory elements such as Al, Ca, Ti, Zr, Ba, Sr, and REE. The Th-Al systematics of many lunar highland rocks are dominated by the presence of the rock-type KREEP.

INTRODUCTION

THE K-U SYSTEMATICS of lunar samples, terrestrial samples and meteorites are important in understanding the processes by which the moon and the earth were formed and evolved (Gast, 1972). Also K-U systematics are useful to derive thermal models of the moon and understand the results of the heat-flow experiments. The purpose of this paper is to summarize K and U concentrations from the Apollo 11-17 missions and the Luna 16 and 20 missions and find interelemental relationships between K and U with other elements such as Th, Sm, La, Ba, Zr, and Al.

Lunar samples have a K/U ratio of about 2000 (Gast, 1972); this ratio is distinctly different from the K/U ratio found in terrestrial samples (Wasserburg *et al.*, 1964) and the majority of the meteorites (O'Kelley *et al.*, 1971; see also Fig. 1). The variation between the earth, moon, and the meteorites in the K/U ratio, along with the lack of K/U variation observed in igneous processes, suggests that the variations in K/U ratio were established by a process that dates from the formation of the moon, earth, and the meteorites (Gast, 1972). Since K is a volatile element and U is a refractory element, the variations of the K/U ratio between the moon, earth, and meteorites suggests a chemical fractionation process based on the condensation temperatures of these elements.

The chemical compositions of the lunar samples in this study are averages selected from many sources (e.g. *Proc. LSC*, 1970; *Proc. LSC*, 1971; *Proc. LSC*, 1972; *Proc. LSC*, 1973; *Lunar Science—V*, 1974; LSPET, 1973).

K-U SYSTEMATICS OF LUNAR SAMPLES

The concentrations of K, U, and Th from the Apollo 11-17 missions and Luna 16 and 20 missions were summarized and are shown (for U and K) in Figs. 1, 2,

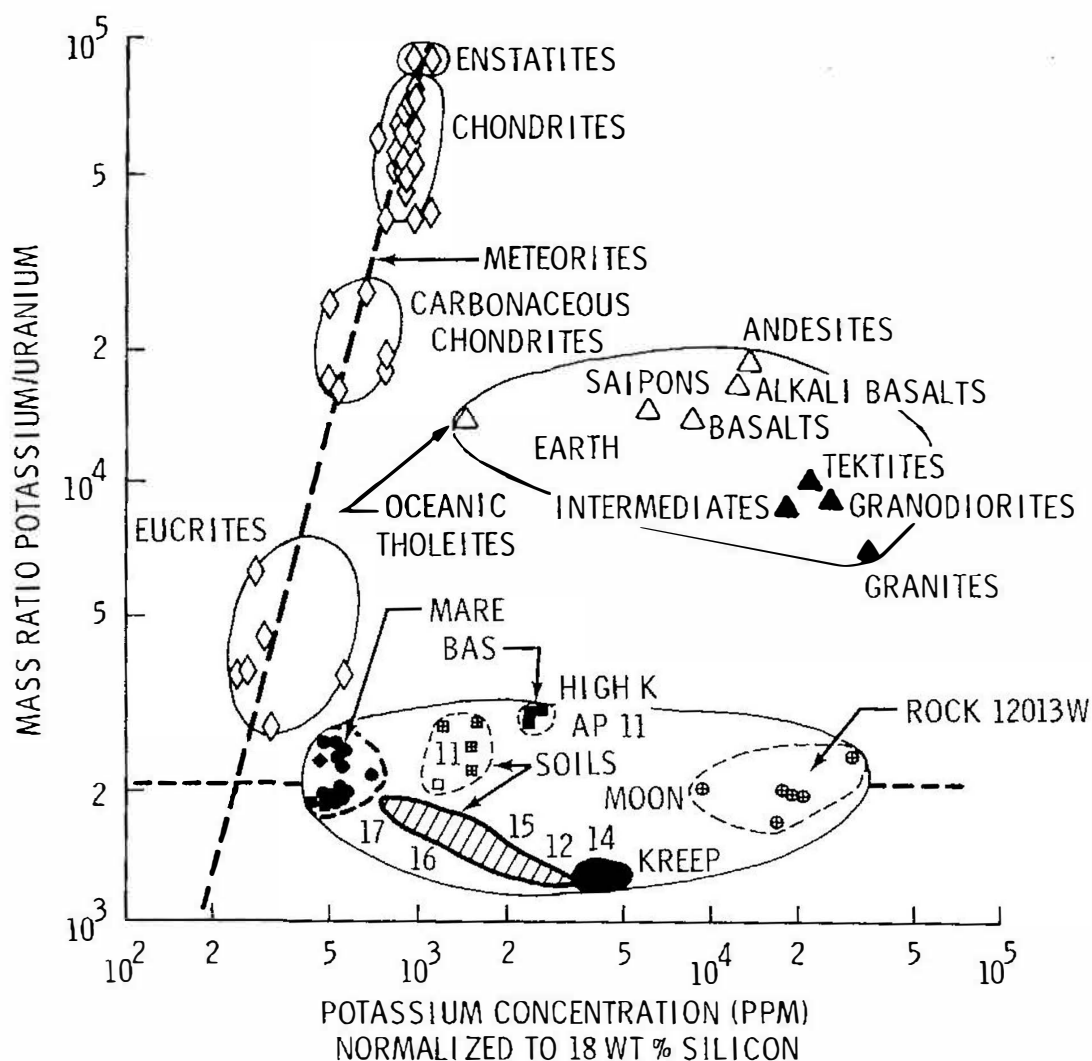


Fig. 1. K-U systematics of terrestrial samples, lunar samples, and meteorites. There are two trend lines. One is the meteoritic trend line and the other is a line representing an approximately constant K/U ratio of about 2600 for the moon. The intersection of both trend lines permits to estimate the average U and K concentrations of the source material where the lunar samples were derived. These concentrations are about 80 ppb U and 200 ppm K. A similar procedure for the earth gives concentrations of 31 ppb U and 400 ppm K (for a core free of radioactive elements).

and 3. Figure 1 represents an updated version of the K-U systematics (O'Kelley *et al.*, 1971; Gast, 1972). There are several observations one can make: (A) The K/U ratio for the lunar samples is about 2600 (O'Kelley *et al.*, 1971; Fig. 1). As shown in Fig. 3, the anorthosites are an exception with K/U ratios of 10^4 and higher. The anorthosites are not very abundant on the lunar surface and are made up of almost pure plagioclase. Since the mineral plagioclase does not concentrate U this exception to the constancy of the K/U ratio probably does not have any significance. (B) The Th/U ratio for the majority of the lunar samples is 3.8 ± 0.2

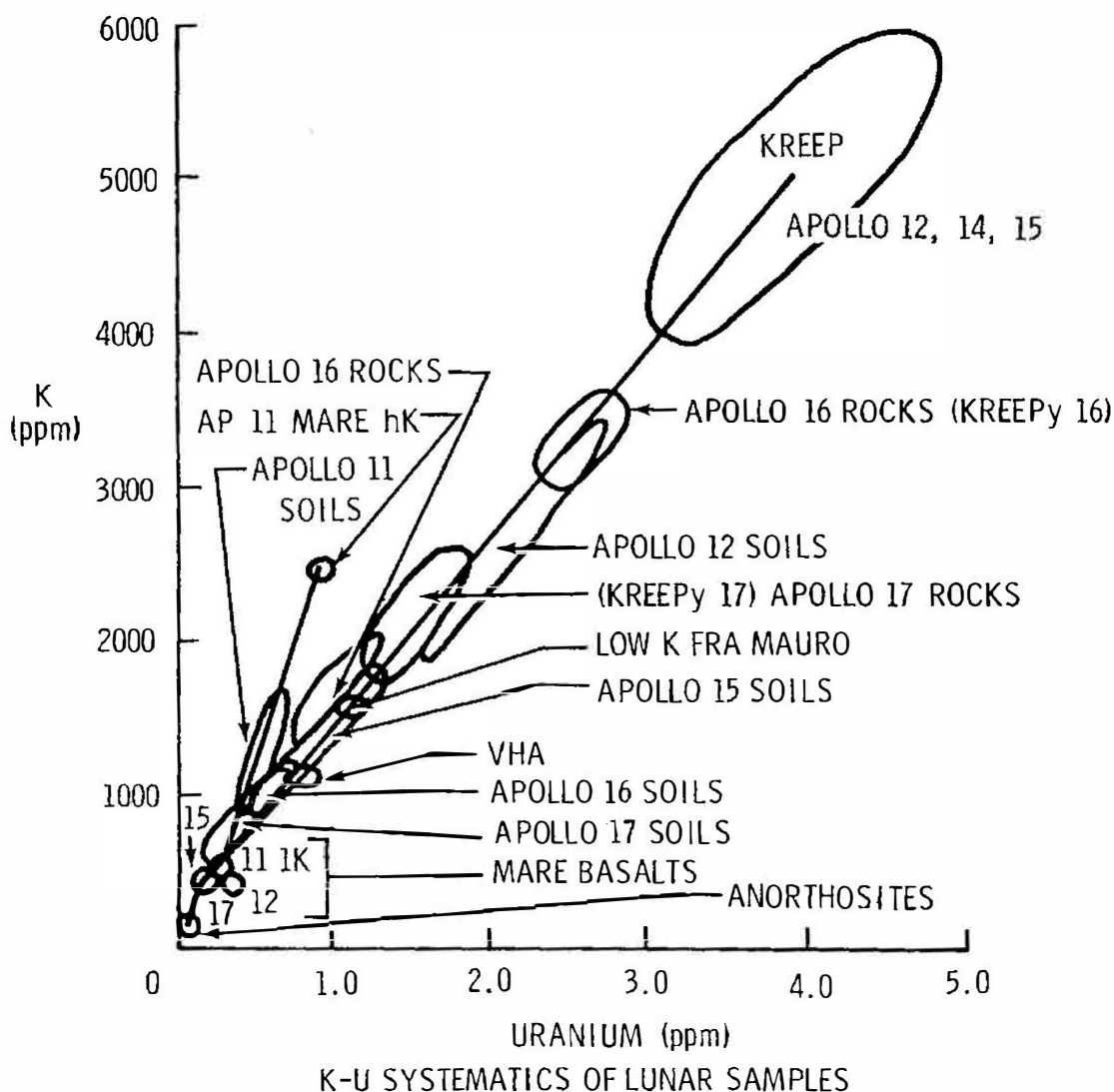
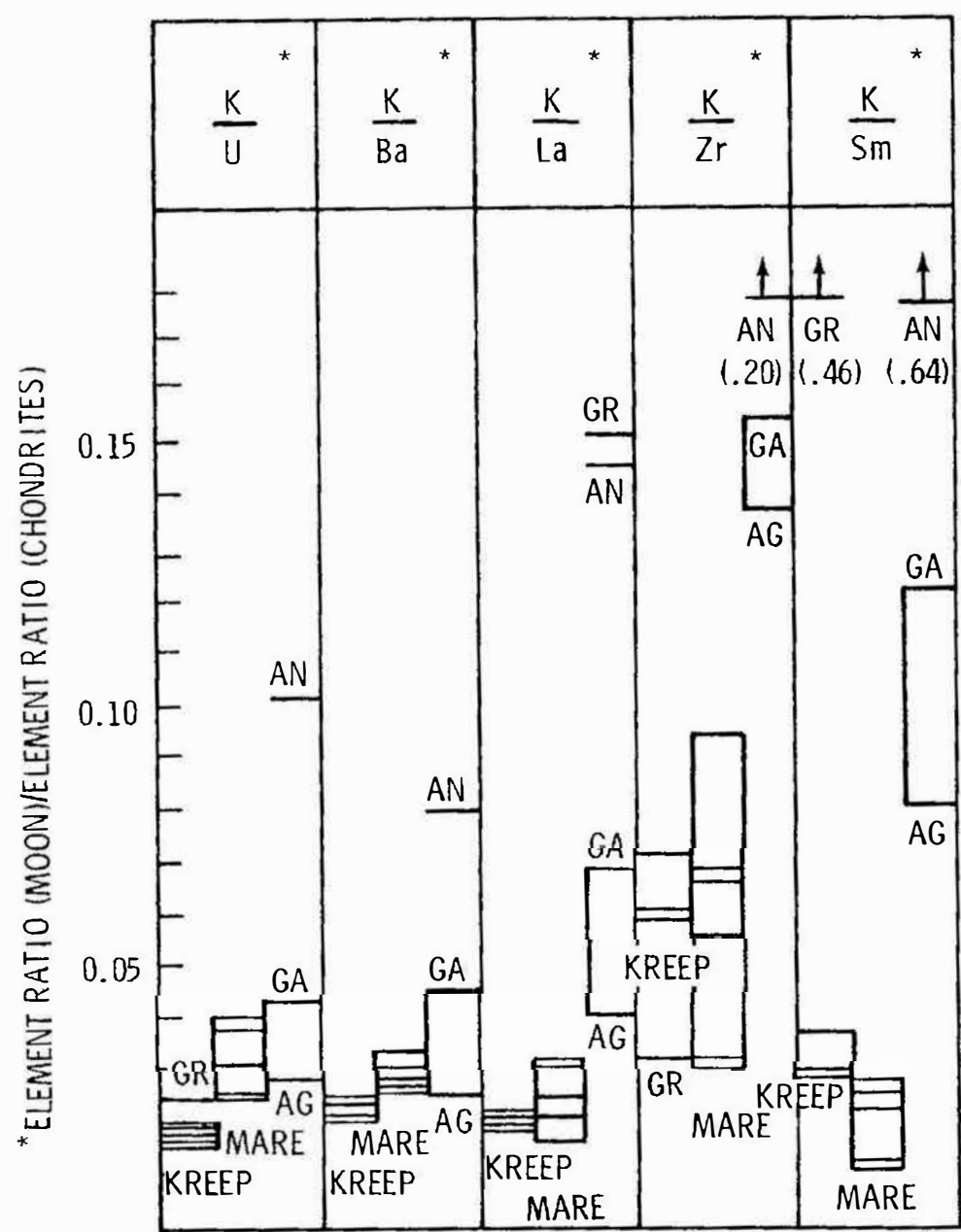


Fig. 2. K-U systematics of lunar samples. KREEPy 16 is the average of 60315, 65016, and 62235. KREEPy 17 is the average of the Apollo 17 noritic breccias (LSPET, 1973). "VHA" is the average of 61016, 61156, and 62295. Apollo 11 mare basalts hK and 1K are respectively the high-K and low-K basalts. Notice the trend line between KREEP and the mare basalts.

(O'Kelley *et al.*, 1971). The exceptions are the granitic portion of rock 12013 which has a Th/U ratio of 3.3 and the Apollo 17 mare basalts which have Th/U ratios of about 3.2 (Eldridge *et al.*, 1974). (C) The majority of the soils and breccias follow a K:U trend line (Fig. 2) between the mare basalts and KREEP suggesting simple mixtures between those two components. There are problems with this simple approach since there are other rock types such as low-K Fra Mauro basalt (Reid *et al.*, 1972), "VHA" (Hubbard *et al.*, 1973), KREEPy 16 (average of 65015, 60315, and 62235), and KREEPy 17 (noritic breccia from Apollo 17; LSPET, 1973) that have rather similar K/U ratios to KREEP and fall on the trend line shown in Fig. 2.



KREEP INCLUDES VHA, LOW K-FRA MAURO, KREEPy 16 AND 17.
 GA = GABBROIC ANORTHOSITE. AG = ANORTHOSITIC GABBRO.
 AN = ANORTHOSITE. GR = GRANITE. MARE = MARE BASALTS.

Fig. 3. K-U, K-Ba, K-La, K-Zr, and K-Sm systematics of lunar samples. The volatile (K)/refractory element ratio is normalized to chondrites. The horizontal lines in the mare basalts group represents mare basalts from different landing sites. In the case of KREEP the horizontal lines represent values for KREEP, "VHA," low-K Fra Mauro basalt, KREEPy 16, and KREEPy 17. For chondrites the values used for the K/U, K/Ba, K/La, K/Zr, and K/Sm ratio are respectively 75000, 250, 2900, 65, and 4100. The K/Ba* for granite is 0.022 (not shown).

Therefore, based only on the K-U systematics it is difficult to determine the component abundance in the soils and a multicomponent and multielement mixing model analysis is required (Schonfeld and Meyer, 1972; Schonfeld, 1974). The results of these mixing model calculations show that the relatively high K, Th, and U concentrations found in the majority of the lunar samples are associated with the presence of the lunar rock-type KREEP in these samples. (D) The Apollo 11 soils and breccias follow a different trend line (Fig. 2) between the high- and low-K mare basalts from Apollo 11. Mixing model calculations using many components and elements, show that there are other components present such as an "anorthositic" and a KREEP component in these samples (Schonfeld and Meyer, 1972). This trend line has a negative intercept in the K axis that does not have a geochemical significance since it is a mixing line.

COMPARISON OF THE K-U WITH THE K-LA, K-SM, K-BA, AND K-ZR SYSTEMATICS

The K/U ratio in lunar samples is rather constant when compared with the ratios found in terrestrial samples and meteorites (Fig. 1). Systematics of other similar pairs of volatile-refractory elements such as K/La (Wänke *et al.*, 1973), K/Ba (Schnetzler and Philpotts, 1971; Duncan *et al.*, 1973), and K/Zr (Duncan *et al.*, 1973) have also been developed showing similar relative constancy of these ratios in lunar samples. In order to compare all these ratios in a single figure, these ratios were normalized by dividing each ratio by the respective value found in ordinary chondrites. The result of this comparison is shown in Fig. 3. This figure shows that in all cases the ratios for these volatile-refractory pairs in lunar samples is much smaller than the value found in chondrites suggesting enrichment of refractory elements and/or depletion of volatile elements on the moon (e.g. Ganapathy *et al.*, 1970; Gast, 1972; Taylor, 1973). The normalized ratios for each system are rather similar but there is a "fine" structure or small degree of variability. For example, the relative position of the ratio for KREEP with respect to the ratio in mare basalts is variable. If these ratios were the same, they would suggest that the moon accreted homogeneously (Philpotts *et al.*, 1972; Brett, 1973).

THORIUM-ALUMINUM SYSTEMATICS

The Th-Al systematics of lunar samples are summarized in Fig. 4. The orbital geochemical sensors of the Apollo 15 and 16 missions (Metzger *et al.*, 1972; Adler *et al.*, 1973) measured the Th and Al concentrations for about 20% of the moon's surface. In order to understand the results of these experiments it is necessary to summarize the Th-Al systematics of the lunar samples or "ground-truth." As can be seen in Fig. 4, the Th-Al systematics of many highland rocks that have composition similar to KREEP can be distinguished from other rock types. In cases where there are mixtures, the Th-Al systematics of lunar samples can be helpful but not sufficient to precisely identify the components and determine their respective abundances (Schonfeld, 1974).

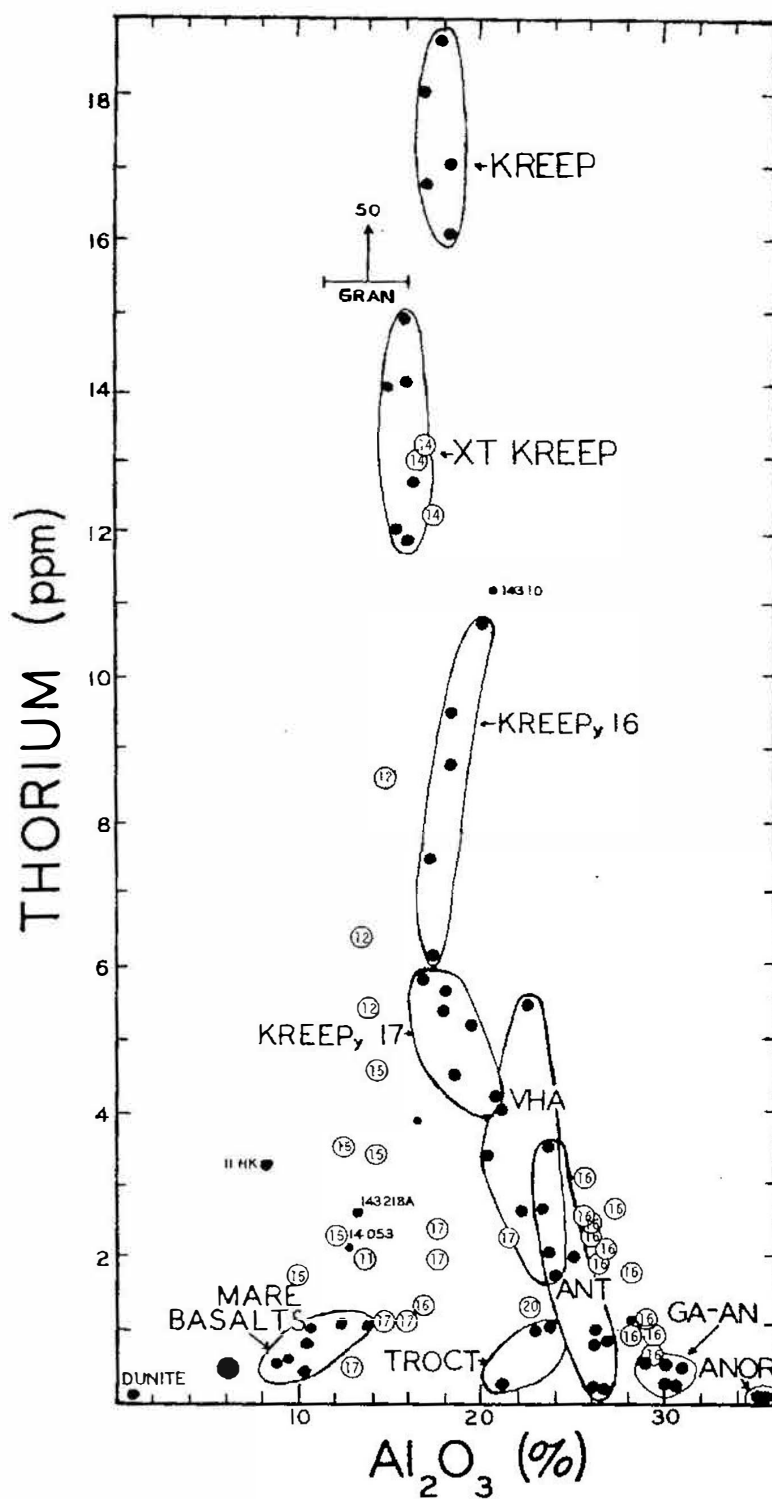


Fig. 4. Thorium- Al_2O_3 systematics of lunar samples. XT KREEP is crystalline KREEP from Apollo 15. The black circles are rocks and open circles are soils. The numbers in the open circles indicate the mission. One soil labelled 16 with an Al_2O_3 concentration of 16% is from Luna 16. The rest of the points labelled 16 are from the Apollo 16 mission. KREEP like rocks such as KREEPy 16, KREEPy 17, and "VHA" can be identified from the Th- Al_2O_3 systematics.

K AND U AVERAGE CONCENTRATION OF THE MOON

The average concentrations of K and U of the moon can be derived in the following way. In Fig. 1, two trend lines are shown. One is the meteoritic trend line (O'Kelley *et al.*, 1971) and the other is the approximately constant K/U line for the moon of about 2600. Assuming that the bulk composition of that part of the moon where most of the lunar samples were derived had K and U concentrations that follow the meteoritic trend line, then the intersection of those two trend lines would give the K and U concentrations of the upper mantle of the moon or that part of the moon where most lunar samples were derived. The intersection of those two trend lines corresponds to about 220 ppm K and 85 ppb U ($K/U = 2600$). In these calculations it was assumed that the average Si concentration for that part of the moon where most lunar samples were derived is 18% (average Si concentration in ordinary chondrites). If this last assumption is not correct, the K and U concentrations will change proportionally to the Si concentration change. For a K/U ratio of 1500 and 3500 the calculated values are 110 and 70 ppb, respectively for the U concentrations and 165 and 245 ppm, respectively for the K concentrations. Using a different model, Wänke *et al.* (1973) calculate concentrations of 86 ppb U and 250 ppm K for the whole moon. As discussed before, the ratio of volatile/refractory elements is not exactly constant and therefore it is possible to have a "fine" structure that could imply a small degree of original heterogeneity in the moon. Alternatively, the small variations of the volatile/refractory elemental ratios could be explained assuming a homogeneously accreted moon (Brett, 1973) and assuming slightly different crystal-liquid equilibria properties (Taylor, 1973) for the volatile and the refractory elements.

The calculated U and K concentrations for the moon have special significance when they are compared with the results of the heat-flow experiments of the Apollo 15 and 17 sites (Langseth *et al.*, 1973). The results of these experiments correspond to an average concentration of U of about 75 ppb (assuming a K/U ratio of about 2600 and a Th/U ratio of 3.8), suggesting that not only the upper mantle but probably the whole moon was originally enriched about 7 times in U with respect to chondritic abundances. This composition is quite similar in U concentration to the one proposed for the composition of the upper 150 km of the moon (Gast, 1972). Therefore it is possible that the moon accreted with a rather uniform composition that is enriched in all the refractory elements (e.g. Al, Ca, Ti, Zr, Ba, Sr, Th, U, and REE) about 7 times chondritic abundances.

A similar calculation as described before for the moon can be applied to the earth to estimate the average U and K concentrations. The solution of the intersection of the meteoritic trend line and the earth's K/U ratio trend line is equivalent to average concentrations of 31 ppb U and 400 ppm K (for $K/U = 13000$ and $Si = 18\%$). The average heat flow of the earth is $63.9 \text{ erg cm}^{-2} \text{ sec}^{-1}$ (Lee and MacDonald, 1963) and for a K/U ratio of 13000 and a Th/U ratio of 3.8 this average heat-flow measurement is equivalent to average concentrations of 33 ppb U and 430 ppm K (for a core free of radioactive elements). The agreement between the two methods for estimating the average K and U concentrations is good.

DISCUSSION

The model described before (intersection of two trend lines) to determine the average concentrations of U and K for the moon and the earth requires further discussion. First is the problem of deriving an average K/U ratio for the crust of the moon. At this stage we do not know the exact proportions of each rock type in the lunar crust and therefore it is difficult to determine an exact K/U ratio for the crust of the moon. An approximate method to estimate the abundance of rock types can be obtained from the results of the orbiting geochemical sensors (Metzger *et al.*, 1972; Adler *et al.*, 1973) and by the determination of rock type abundances in lunar soils using the mixing model method (Schonfeld, 1974). From these results it appears that the "anorthositic" materials (gabbroic anorthosites and anorthositic gabbros) are the most abundant materials on the surface of the moon, followed by mare basalts, and finally by KREEP. Based on these relative estimated abundances of rock types, one can derive an estimated value of 2600 for the K/U ratio of the lunar crust.

The second problem is the validity of the meteoritic trend line shown in Fig. 1. Meteorites are complicated bodies. In some cases there are chondrules and matrix present (e.g. carbonaceous chondrites type 2 and 3; Larimer and Anders, 1970), in other cases such as the howardites there are polymict breccias (Duke and Silver, 1967), that appear to be mixtures of eucrites and diogenites (McCarthy *et al.*, 1972) and in still other cases the meteorites appear to be differentiated bodies (Duke and Silver, 1967; Schnetzler and Philpotts, 1969). The majority of the eucrites are monomict breccias and when the chemical composition data (Duke and Silver, 1967; Schnetzler and Philpotts, 1969; McCarthy *et al.*, 1972) are averaged, then the relative concentration of Al, Ca, Ti, Sr, Eu, Ba, Zr, U, Th, and the rare earths with respect to ordinary chondrites are in the range of 6–8. It is difficult to obtain these concentrations by differentiating a source material similar to ordinary chondrites. Therefore, based on this argument, it is assumed that the average eucrite chemical composition represents a rather primitive body that underwent little or no differentiation. In the case of howardites, since they appear to be a rather clear case of mixtures of eucrites and diogenites they were excluded from Fig. 1. In the case of carbonaceous chondrites, the situation is not very clear at this time. Larimer and Anders (1970) postulated that the C-2 and C-3 type carbonaceous chondrites are mixtures of two components, but we do not have analysis of U and K for the chondrules. There are two other samples that were included in the derivation of this meteoritic trend line. One is the meteorite Angra dos Reis that has a K/U ratio of about 230 and fits the trend line. This meteorite is a single sample in its class and has a slight negative Eu anomaly (Schnetzler and Philpotts, 1969) and could be a differentiated body. In the case of the Ca-rich inclusions of the Pueblito de Allende meteorite, there are not enough data unless one combines data from two sources (Gast *et al.*, 1970; Wänke *et al.*, 1973). In general, combining meteoritic chemical data is not a good procedure because of possible sampling errors. The K/U ratio is about 900 and also fits approximately the trend line. It is significant that the Ca-rich inclusion of the Pueblito de Allende has a concentration of the rather volatile element K of 96.4 ppm, since according to

Larimer and Anders (1970) and Grossman (1973), it should have no K present. On the other hand, Arrhenius (1972) using a different model, where the ionization of the elements plays an important role, can account for the presence of K in the high Ca, Al, and U inclusions in Pueblito de Allende.

Even with some of the problems discussed before, the author believes that the use of a meteoritic trend line is a valid approach, and that more chemical analysis of meteorites are required to clarify this question.

CONCLUSIONS

(1) The K/U ratio for lunar samples is about 2600 and distinctly different from the K/U ratio found in terrestrial samples (about 13000) and the majority of the meteorites.

(2) The Th/U ratio in lunar samples is 3.8 ± 0.2 . Exceptions are the granitic portion of rock 12013 and the Apollo 17 mare basalts.

(3) The K-U systematics of lunar samples are similar to the K-La, K-Sm, K-Ba, and K-Zr systematics suggesting that the moon has accreted approximately homogeneously.

(4) Based on a model presented in this paper, the average concentration of the moon is about 80 ppb U, about 200 ppm K, and about 7 times chondritic abundances for all the refractory elements such as Al, Ca, Ti, Zr, Ba, Sr, REE, etc. A similar procedure for the earth gives concentrations of 31 ppb U and 400 ppm K for a core free of radioactive elements.

(5) In general, the relatively high concentrations of Th, K, and U found in lunar samples are associated with the lunar rock-type KREEP. In many highland rocks such as "low-K Fra Mauro basalt," "VHA," KREEPy 16, and KREEPy 17, the Th-Al systematics is dominated by the rock-type KREEP.

Acknowledgments—The authors thank E. Anders, D. P. Blanchard, R. Brett, J. Philpotts, S. R. Taylor, and H. Wiesmann for their critical review and C. Hardy for typing this paper.

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Title: K and U systematics and average concentrations on the moon
Authors: [Schonfeld, E.](#)
Affiliation: AA(NASA, Johnson Space Center, Houston, Tex.)
Publication: In: Lunar Science Conference, 5th, Houston, Tex., March 18-22, 1974, Proceedings. Volume 2. (A75-39540 19-91) New York, Pergamon Press, Inc., 1974, p. 1135-1145.
Publication Date: 00/1974
Category: Lunar and Planetary Exploration
Origin: [STI](#)
NASA/STI Keywords: ABUNDANCE, LUNAR COMPOSITION, POTASSIUM, URANIUM, ALUMINUM, APOLLO FLIGHTS, CHONDRITES, LUNIK LUNAR PROBES, REFRACTORY METALS, THORIUM
Comment: A&AA ID. AAA013.094.151
Bibliographic Code: 1974LPSC....5.1135S

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