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THE COSMIC ABUNDANCES OF POTASSIUM, URANIUM, AND THORIUM AND THE HEAT BALANCES OF THE EARTH, THE MOON, AND MARS

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Under the above title the writer published a paper (Urey, 1955)[1] in which an incorrect assumption was made. It is the purpose of this note to call attention to this and to make what appears at the present time to be a correct, or more nearly correct, solution of the problem.

The problem of the amounts of the radioactive elements potassium, uranium, and thorium has been a troublesome one for many years. The abundance of potassium in the meteorites has been solved satisfactorily only very recently (Ahrens, Pinson, and Kearns, 1952; Edwards, 1955; Edwards and Urey, 1955).[2] The amounts of potassium in the chondritic meteorites is remarkably constant, and the assumption that the chondritic meteorites give a reasonable sample of "cosmic" and "solar" nonvolatile matter proves to be a very reasonable hypothesis (Suess and Urey, 1956).[3] An average of Edwards' results, which are the most extensive and appear to be the most reliable, gives about 823 p.p.m. of potassium. This is slightly less than the 880 p.p.m. used previously. The achondrites contain less potassium than the chondrites, and some weight should be given to them. The uncertainty in the datum is surely greater than the difference in these two values.

A very great variability in the analytical data for uranium in chondritic meteorites exists in the literature. Davis (1950)[4] determined uranium in the Shaw and Cumberland achondrites as 4.8 and 1.0×10^{-8} gm/gm, respectively. However, the chemical composition of achondrites is very variable, and the mean uranium content of solar matter cannot be deduced from these data.

Tilton (1951)[5] found 1.1×10^{-8} gm/gm in the Modoc chondrite, but both he and his co-workers have been far from confident that the result was reliable.

Very sensitive procedures have been developed by Chackett and co-workers (1950),[6] and these have been applied to the Beddgelert chondrite. The uranium and thorium contents were reported as 0.106 and 0.335×10^{-8} gm/gm, respectively. These values were secured by averaging their results using approximately 17 per cent of metal by weight. Patterson (1955)[7] has isolated lead from the iron meteorites Canyon Diablo and Henbury and from the Modoc and Forest City chondrites and has determined their isotopic compositions and the amounts of lead in the chondrites. These data are sufficient to fix the age since the lead of the iron meteorites became separated from uranium and to determine the amounts of uranium necessary to produce the observed radiogenic leads of the chondrites. Patterson's results on uranium abundances agree with the data of Chackett *et al.*

All these recent data appear to have been obtained very carefully, and yet, if all are correct, the uranium contents of chondritic meteorites vary very greatly, and this is not true for other elements which have been determined by reliable methods. It was and is my belief that all these data are not correct, and in this case an average is not correct either. In the previous article I selected the data of Chackett *et al.*, which are essentially the same as those of Patterson. Others have used averages or have selected the data of Davis and Tilton.

Recently Turkevich, Hamaguchi, and Reed (1956)[8] have developed the neutron activation method for determining uranium. In this method the sample is exposed to neutrons before any chemical processing is used. Np^{239} is produced from U^{238}, and radiogenic lanthanum and barium are produced from U^{235}. Subsequent chemical separations are directed to the isolation of neptunium and radio barium. These do not occur in nature, and hence contamination is impossible. Tracers were used to correct for losses. Thus the great sources of error inherent in previous procedures are avoided. Their results agree with the low values of Tilton rather than with the higher values of Chackett *et al.*, and of Patterson. The data for the Forest City, Modoc, Richardton, and Holbrook chondrites vary from 0.89 to 1.51, with an average of 1.13, all $\times 10^{-8}$ gm/gm. This variation is due partly to errors of the analytical method. Thus the constancy of composition of the chondrites is indicated again. One concludes that the data of Chackett *et al.* are too high or that Beddgelert is a most unusual chondrite. Also, the amounts of uranium in Modoc and Forest City are insufficient to produce Patteron's radiogenic leads. It appears that he must have had some contamination from his reagents. It should be noted that it is very difficult to avoid contamination by lead from reagents when the concentrations of the element are so low, because lead is a commonly used metal in commercial chemical apparatus.

These new data solve the difficulties which were the primary concern of the previous article. The thorium abundance has not been determined as yet but presumably is 3 or 3.5 times that of uranium. Taking 823 p.p.m., 1.13×10^{-8} gm/gm, and 3.8×10^{-8} gm/gm for the potassium, uranium, and thorium concentrations, respectively, for the chondritic meteorites and assuming the same concentrations for the earth, moon, and Mars, no serious difficulties in heat balances occur. It is possible that the moon was formed at low temperatures and has never melted, that Mars was formed at low temperatures and has never formed a core, and that the rate of loss of heat from the earth's interior is adequate to remove all the radiogenic heat. This problem, which has been a continuing concern for the writer for some years, is solved by these new data, and the arbitrary assumption that the radioelements were concentrated in the meteorites by some process by a factor of 3.19 is unnecessary. The heats generated in 4.5×10^9 years are rather too high for a cold moon, but we still do not know heat conductivities at all well, and other constants are not too certain.

Table 2′-4′, which is a recalculation of the data given in Tables 2 and 4 of the previous paper, gives the results of calculations on meteoritic matter using the new concentrations. The rate of heat generation is now 1.57 ergs per year and gram as compared to an average of 2.2 ergs per year and gram required by the observed heat loss of the earth. Thus the rate of generation of heat by radioactive elements, assuming that the earth has the mean composition of the meteorites with respect to the radioactive elements, is less than the rate of heat loss observed. This is to be expected if the earth's rate of heat generation is decreasing with time.

TABLE 2′-4′

HEAT PRODUCTION IN CHONDRITIC METEORITES

(K = 823 p.p.m.; U = 1.13×10^{-8} gm/gm; Th = 3.8×10^{-8} gm/gm)

Nuclide	dE/dt at Present (Ergs/Yr Gr of Meteorite)	Total E in Joules per Gram of Chondritic Meteorite — In the Last 5×10^8 Years	4.5×10^9 Years	5×10^9 Years	5.5×10^9 Years	From 5.5 to 4.5×10^9 Years Ago
K^{40}	0.92	52	1,790	2,400	3,210	1,420
Th^{232}	0.31	16	159	178	199	40
U^{234}	0.01	1	118	189	313	195
U^{238}	0.33	17	217	253	290	73
Total	1.57	86	2,284	3,020	4,012	1,728

It is also evident that the radioactive heat generation during remote times, though much greater than at present, was insufficient to produce general melting of well-insulated solid objects. The melting, which produced the silicate minerals and the kamacite and taenite of the chondritic meteorites, must have occurred before $\sim 4.3 \times 10^9$ years ago as shown by the K^{10}-A^{40} age determinations. Thus it seems most improbable that radioactive heating due to these elements could have been more than a minor factor in the melting of the minerals of the chondritic meteorites.

Many details of the previous discussion must be modified as a result of these new data, but I believe no serious errors in understanding the paper will be made by the reader if the corrections presented in this note are kept in mind.

[1] H. C. Urey, these PROCEEDINGS, **41**, 127, 1955.

[2] L. H. Ahrens, W. H. Pinson, and M. M. Kearns, 1952; *Geochim. et cosmochim. acta*, **2**, 229, G. Edwards, *Geochim. et Cosmochim. Acta*, **8**, 285, 1955; G. Edwards and H. C. Urey, *Geochim. et cosmochim. acta*, **7**, 154, 1955.

[3] H. E. Suess and H. C. Urey, *Revs. Mod. Phys.*, **28**, 53, 1956.

[4] G. L. Davis, *Am. J. Sci.*, **248**, 107, 1950.

[5] G. Tilton, (1951), dissertation, University of Chicago, published in C. Patterson, H. Brown, G. Tilton, and M. Inghram, *Phys. Rev.*, **42**, 1234, 1953.

[6] K. F. Chackett, J. Golden, E. R. Mercer, F. A. Paneth, and P. Reasbeck. *Geochim. et cosmochim. acta*, **1**, 3, 1950.

[7] C. Patterson, *Geochim. et cosmochim. acta*, **7**, 151, 1955, and references given there.

[8] A. Turkervich, H. Hamaguchi, and G. Read, private communication, 1956, and Gordon Research Conference, summer, 1956.