The work is being continued and will be published in detail later.

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Where is the Earth's Radiogenic Helium ?

At the estimated 2×10^{20} gm. uranium and 5×10^{20} gm. thorium in the lithosphere, helium should be generated radiogenically at a rate of about 3×10^{9} gm./year. Moreover, the (secondary) cosmic-ray source of helium has been estimated to be of comparable magnitude. Apparently nearly all the helium from sedimentary rocks and, according to Keevil[1] and Hurley[2], about 0·8 of the radiogenic helium from igneous rocks, have been released into the atmosphere during geological times (currently taken to be about 5×10^{9} yr.). Hence more than 10^{20} gm. of helium should have passed into the atmosphere since the 'beginning'. Because the atmosphere contains only $3{\cdot}5 \times 10^{15}$ gm. helium-4, the common assumption is therefore that about 10^{20} gm. of helium-4 must also have passed out through the exosphere, and that its present rate of loss through the exosphere balances the rate of exudation from the lithosphere.

Spitzer[3] has given an exact formulation of the rate of loss of a given component from the exosphere. His result is:

$$L = 4\pi R_0^2\, C n_{0i}\, Y \exp(-Y)\, \frac{R_c}{R_0}\left(1 + \frac{R_c}{R_0 Y}\right)\bigg/(6\pi)^{1/2} \quad (1)$$

where L is rate of loss of the ith component (in atoms/sec.); R_0 is radius of the Earth at the surface (in cm.); R_c is radius at the base of the exosphere; C is root mean square velocity; v_∞ is escape velocity; $Y = 3{\cdot}2\,(v_\infty/C)^2$; n_{03} and Y_3 apply to helium-3 and n_{04} and Y_4 to helium-4.

At $C = v_\infty$ ($T = 20{,}700°$ K.), therefore, the rate of escape of helium-4 should be $1{\cdot}4 \times 10^{8} \times n_{04}$ gm. atoms per year. Now the experimental evidence from high-altitude studies indicates that hydrogen and helium do not concentrate significantly in the upper atmosphere as has previously been supposed. Since by definition $\sum_i n_{0i} = 3{\cdot}0 \times 10^{7}$ atoms/c.c. for all species present at the base of the exosphere, n_{04} may not be appreciably greater than 180 atoms/c.c., giving an escape rate of approximately

$$L \doteqdot 8 \times 10^{10}\,(20{,}700/T)^{1/2}\,(\exp(1{\cdot}5 - 31{,}400/T) \times 3\,(1 + T/31{,}400)/5 \text{ (gm. helium-4/year)} \quad (2)$$

Thus even at 20,700° K. where $C = v_\infty$, the escape-rate of helium-4 (about 8×10^{10} gm./yr.) would be only about ten to twenty times greater than that required to maintain steady state with radiogenic and 'cosmogenic' helium, and at the assumed temperature of 1,500° K. at the base of exosphere, the rate of escape of helium-4 would be only about 600 gm./yr., or only about 10^{-7} as great as the replenishment rate from the lithosphere. Spitzer computed, presumably by taking into account a theoretical increase in the concentration of helium-4 in the upper atmosphere, that the rate of escape of helium-3 would be $\{1 - \exp(-1)\} \times 3{\cdot}5 \times 10^{15}$ gm., or $2{\cdot}3 \times 10^{15}$ gm. in 4×10^{13} years at 1,000° K.; in $2{\cdot}4 \times 10^{7}$ years at 2,000°; and in about 'geological time' (5×10^{9} years) at 1,500° K. However, this does not take into account the replenishment which in 5×10^{9} years would be about 10^{5} times greater than the total loss from the atmosphere considered by Spitzer. Furthermore, results of rocket studies indicate that the temperature at the base of the exosphere may be even less than 1,500° K. To account for a supposed steady-state atmosphere as regards helium-4, a fluctuating temperature in the exosphere associated perhaps with solar disturbances has therefore been suggested[3]. Since, however, even the unreasonably high steady-state temperature of 7,000° K. would be required to remove the 6×10^{9} gm./yr., any fluctuating-temperature model seems inadequate to explain a theoretical balance between escape and replenishment as regards helium-4 in the atmosphere.

A further complication involves the ratio of helium-3 to helium-4 (^{3}He/^{4}He) shown by Alvarez and Cornog[5], Aldrich and Nier[6] and Coon[7] to be $0{\cdot}3$–$1{\cdot}4 \times 10^{-7}$ in radioactive minerals, $1{\cdot}4$–$1{\cdot}7 \times 10^{-7}$ in natural gas and $1{\cdot}2$–$1{\cdot}3 \times 10^{-6}$ in the atmosphere. Equation (1) gives for the ratio helium-3 to helium-4 in escape gases:

$$\frac{^3\text{He}}{^4\text{He}}\ (\text{escape}) = \left(\frac{4}{3}\right)^{1/2} \frac{n_{03}}{n_{04}} \exp\left(\frac{1}{4} Y_4\right) \frac{Y_3 - R_c/R_0}{Y_4 - R_c/R_0}$$

Since $n_{03}/n_{04} = 1{\cdot}3 \times 10^{-6}$, one thus finds that the ratio helium-3 to helium-4 in the escape gases should be 0·01 if the exosphere temperature is 1,500° K. and 2×10^{-4} if it is 2,500° K. If, therefore, $T = 1{,}500°$ K., one requires an unknown source of about 10^{8} gm./yr. of helium-3 and, if $T = 2{,}500°$ K., a source of about 2×10^{6} gm./yr. to maintain a constant concentration of helium-3 in the atmosphere. The tritium source of helium-3 is only about 100 gm./yr. and the lithospheric source apparently no more than about 800 gm./yr.

Where, therefore, is the 'sink' for about 6×10^{9} gm. helium-4 per year and the 'source' for helium-3 that maintains a ratio of helium-3 to helium-4 (atmosphere) nearly ten times greater than that for the lithosphere, despite a theoretical escape ratio of about 10^{-4}. Perhaps the answer may be found in a non-steady rather than a steady-state solution in which helium-4 is still increasing and in which the relatively high ratio of helium-3 to helium-4 in the atmosphere compared with that in the lithosphere may be the result of terrestrial accretion of meteoric materials which are known to have occluded helium with a very high ratio of helium-3 to helium-4 (up to[8] 0·3). This leads, however, to an 'anomalous' atmospheric chronometry which is, on the other hand, in approximate agreement with the chronometry one obtains from the annual uranium flux in river water (10^{10}–10^{11} gm./yr.) compared with the total uranium present in the oceans (about 10^{15} gm.)[9].

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