
The Age of the Earth's Atmosphere Estimated by its Helium Content

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Abstract

If the earth is billions of years old, the radioactive production of helium in the earth's crust should have added a large quantity of helium to its atmosphere. Current diffusion models all indicate that helium escapes to space from the atmosphere at a rate much less than its production rate. The low concentration of helium actually measured would suggest that the earth's atmosphere must be quite young.

Keywords

Earth's Atmosphere, Helium, Radioactive Decay, Production Rate, Primordial Helium, Losses, Thermal Escape, Flux, Polar Wind, Solar Wind, Young Earth Model

Introduction

The earth has the appearance of being quite old. In fact, many generations have lived and died on this planet. It has surface features that have been folded and buckled, worn down by erosion, and filled in with sediments. River valleys have been eroded through many layers of soil and rock, and chemicals have dissolved and precipitated into the oceans. Radioactive elements have decayed forming new elements and releasing gases into the atmosphere. But, given all of these processes, how old is the earth? Is it thousands of years old, millions of years, or billions of years? Physical processes such as those listed above have been used extensively to estimate the earth's age. But, the accuracy of these estimates is critically dependent upon the initial conditions, the particular process, and the rate at which the process works. Many different estimates have been made using many different initial conditions, processes, and process rates. The estimated age of the earth has ranged from a few thousand years to several billion years. The current "best estimate" used in the evolutionary/uniformitarian literature is 4.5 billion years. The contention of this paper is that the earth is not billions of years old but, rather, thousands of years old.

The origin and development of the earth's atmosphere involves radioactive decay processes which need to be studied in light of the age of the earth. Rubey (1951) and others have proposed that the earth's atmosphere was formed by outgassing of

volatile compounds from the solid earth after it was condensed from an original cloud of cosmic dust. Their model allows the original atmosphere to be modified by the escape of lighter gases and the action of biological processes, Walker (1977). Many problems have been encountered, however, when attempting to reconcile the composition and processes in today's atmosphere with basic tenets of this model. For example, the composition of no single planetary atmosphere in the solar system matches the assumed primordial material which supposedly made up the original nebula, even after complex heating, recombination, outgassing, and escape scenarios are considered. The controversy continues as to whether the earth originally had a reducing or oxidizing atmosphere. It is not certain how carbon dioxide maintains its equilibrium or why it has been increasing in recent years, nor is it clear why methane is so plentiful on the earth. One of the most intriguing problems with evolutionary model has been the attempt to explain why there isn't more helium in today's atmosphere, if the earth has existed for 4.5 billion years. This paper will explore this problem and suggest an alternative to the evolutionary model.

Helium in Today's Atmosphere

The earth's atmosphere is predominantly nitrogen (~78%) and oxygen (~21%). It also contains many other minor constituents. Table 1 shows the composition of the atmosphere at ground level, given by Walker (1977).

Table 1. Composition of the atmosphere (after Walker, 1977).

Constituent	Chemical Formula	Molecular Weight (¹² C = 12)	Percent by Volume in Dry Air	Total Mass (gm)
Total atmosphere				$(5.136 \pm 0.007) \times 10^{21}$
Water vapor	H ₂ O	18.01534	variable	$(0.017 \pm 0.001) \times 10^{21}$
Dry air		28.9644	100.00	$(5.119 \pm 0.008) \times 10^{21}$
Nitrogen	N ₂	28.0134	78.084 ± 0.004	$(3.866 \pm 0.006) \times 10^{21}$
Oxygen	O ₂	31.9988	20.948 ± 0.002	$(1.185 \pm 0.002) \times 10^{21}$
Argon	Ar	39.948	0.934 ± 0.001	$(6.59 \pm 0.01) \times 10^{19}$
Carbon dioxide	CO ₂	44.00995	0.0315 ± 0.0010	$(2.45 \pm 0.08) \times 10^{18}$
Neon	Ne	20.183	$(1.818 \pm 0.004) \times 10^{-3}$	$(6.48 \pm 0.02) \times 10^{16}$
Helium	He	4.0026	$(5.24 \pm 0.05) \times 10^{-4}$	$(3.71 \pm 0.04) \times 10^{15}$
Krypton	Kr	83.80	$(1.14 \pm 0.01) \times 10^{-4}$	$(1.69 \pm 0.02) \times 10^{16}$
Xenon	Xe	131.30	$(8.7 \pm 0.1) \times 10^{-6}$	$(2.02 \pm 0.02) \times 10^{15}$
Methane	CH ₄	16.04303	$\sim 1.5 \times 10^{-4}$	$\sim 4.3 \times 10^{15}$
Hydrogen	H ₂	2.01594	$\sim 5 \times 10^{-5}$	$\sim 1.8 \times 10^{14}$
Nitrous Oxide	N ₂ O	44.0128	$\sim 3 \times 10^{-5}$	$\sim 2.3 \times 10^{15}$
Carbon monoxide	CO	28.0106	$\sim 1.2 \times 10^{-5}$	$\sim 5.9 \times 10^{14}$
Ammonia	NH ₃	17.0306	$\sim 1 \times 10^{-6}$	$\sim 3 \times 10^{13}$
Nitrogen dioxide	NO ₂	46.0055	$\sim 1 \times 10^{-7}$	$\sim 8.1 \times 10^{12}$
Sulfur dioxide	SO ₂	64.063	$\sim 2 \times 10^{-8}$	$\sim 2.3 \times 10^{12}$
Hydrogen sulfide	H ₂ S	34.080	$\sim 2 \times 10^{-8}$	$\sim 1.2 \times 10^{12}$
Ozone	O ₃	47.9982	variable	$\sim 3.3 \times 10^{15}$

With the exception of water vapour, soluble gases, and particles, the atmosphere below 10km is quite well mixed. Variations in the concentration of the major components are slight. Large deviations from the near-surface composition are confined to heights near and above 100km. Between 100 and 800km, molecular oxygen is dissociated into atomic oxygen and becomes the most important neutral gas. Above about 800km, helium becomes the most abundant element. Finally, hydrogen predominates in the region where the earth's atmosphere merges with the interplanetary gas.

Of the gases listed in Table 1, argon, neon, helium krypton, and xenon are of most interest in questions regarding the age of the earth. This is due to the fact that they are noble gases which do not chemically react with other elements. Therefore, the quantity of these gases present in today's atmosphere should be related to the age of the earth, if the rate of their production and/or loss to space can be calculated. Argon is an important gas because it is present in relatively large quantities and is sufficiently heavy that it does not escape the earth's gravitational pull. It can be used as an upper limit for the production of atmospheric gases by radioactive decay. Helium occurs in two isotope forms—³He and ⁴He. Both are light enough that they can escape to space to some degree but at slightly different rates. Their diffusion rates through the lower atmosphere, however, are of

approximately the same magnitude. The total mass of ⁴He in the atmosphere is 3.8×10^{15} g or about 6×10^{38} atoms. The total mass of ³He is 5.3×10^9 g or about 1×10^{33} atoms. The ratio of ³He/⁴He in the atmosphere today is 1.4×10^{-6} .

Sources of Helium

The two isotopes of helium in the atmosphere may be traced to several sources. The first source is primordial helium. That is, the helium we observe may have been present at the time the atmosphere was formed. Since no observations of the initial conditions are available, whether the atmosphere was formed a few thousand years ago or several billion, we cannot know the original quantity of helium. The long-age model speculates that there was no helium initially because the atmosphere was yet to form. The creation model, on the other hand, would suggest that the initial conditions were very similar to those of today, although minor changes in the helium concentration may have occurred since the creation of the atmosphere. It is also possible that significant changes could have occurred during and immediately following the Flood.

The long-age model has for many years assumed no primordial helium in the earth or atmosphere. However, the recent discovery by Clarke, Beg, & Craig (1969) of ³He leaking through the crust has forced the recognition of primordial helium in the mantle.

This admission was necessary because no known radioactive decay process in the mantle is known to produce ^3He . Now it is recognized that at least a small portion of the ^4He is also primordial. The question then arises, if primordial helium can exist in the mantle, why could it not have also existed in the atmosphere when the atmosphere was formed? Of course, we can still assume that no helium existed initially and use the current process rates to calculate a maximum age. We will make these calculations in this paper for comparative purposes, but we must always remember that the amount of primordial helium could reduce the age significantly. Putting aside the question of primordial helium for awhile, let's consider other sources of helium observed today. These sources can best be described if the two isotopes are considered separately.

Sources of ^4He

The radioactive decay of uranium (^{235}U and ^{238}U) and thorium (^{232}Th) results in the formation of helium (^4He) as a by-product. Since the crust of the earth contains a large, unknown quantity of these elements, the crust is generally agreed to be the major source of ^4He for the atmosphere. It is produced in the crust, seeps to the surface, and mixes through the atmosphere. At the same time, argon (^{40}Ar) is produced in the radioactive decay of potassium (^{40}K). Wasserburg (1963) found that the atomic ratio of ^4He to radiogenic ^{40}Ar is between .2 and 5 in many samples of natural gas. It is commonly assumed that the mean value of the $^4\text{He}/^{40}\text{Ar}$ ratio in gases entering the atmosphere is on the order of unity; yet the $^4\text{He}/^{40}\text{Ar}$ ratio in the atmosphere is only 1/1800. If ^{40}Ar is too heavy to escape, and both ^4He and ^{40}Ar only enter the atmosphere by this process, then ^4He must be rapidly escaping from the atmosphere. Assuming that the number of ^4He atoms that have entered the atmosphere is the same as the number of ^{40}Ar atoms, the long-age model finds that the residence time for ^4He is approximately 2 million years. The total number of atoms of ^4He entering the atmosphere would have been about 6×10^{38} atoms at a rate of about 2×10^6 atoms/cm²/sec⁻¹ over the entire surface of the earth.

Efforts to calculate the rate of flow of ^4He from the crust to the atmosphere in other ways have met with very limited success. First, it is difficult to measure the flow of such small quantities of a gas through an average crustal interface. Secondly, the actual flow of helium seems to be concentrated in certain locations, such as near fumaroles, in volcanoes, at the mid-oceanic rise, etc. The calculation of an average rate of flow based on non-homogenous time and space releases leads to large errors. Thirdly, a direct calculation of radioactive decay rates is dependent upon an unknown distribution of uranium and thorium in

the crust and mantle. Attempts have been made to improve such compositional models of the earth using measurements of heat flow caused by radioactive decay. However, these computations are difficult, at best, and are suspect because of assumptions made in handling the initial heat of formation of the earth and the long-age time frame. Again, it is necessary to point out that the assumptions of no original helium and 4.5 billion year age of the earth are implicit in the conclusion that 6×10^{38} ^4He atoms entered the atmosphere at a rate of 2×10^6 atoms/cm²/sec⁻¹. The same rate could have been calculated, assuming only 6×10^{32} ^4He atoms entered the atmosphere over a period of 4,500 years.

Sources of ^3He

It was assumed until 1969 that the primary source of ^3He to the atmosphere was the production of tritium by cosmic bombardment in the upper atmosphere and its subsequent decay to ^3He . A second source was assumed to be direct injection of ^3He by the solar wind. These production rates were relatively small, amounting to about .5 atom/cm²/sec⁻¹, Craig & Lal (1961). In 1969 Clarke, Beg, & Craig reported the occurrence of excess ^3He in the ocean which they interpreted as evidence for terrestrial primordial helium trapped in the mantle. Craig, Clarke, & Beg (1975), Craig & Lupton (1976), Lupton & Craig (1975), and Rison & Craig (1983) subsequently traced the excess ^3He in the ocean to releases from the mantle. Since there are no radiogenic sources of ^3He in the mantle, this was direct evidence for primordial helium. Through this effort, evidence for some primordial ^4He was also discovered. Craig et al. estimated the total flux of ^3He to the atmosphere from all sources to be 4.6 atoms/cm²/sec⁻¹. The residence time for ^3He , given that the quantity of ^3He in today's atmosphere is 1×10^{33} atoms, is about 1×10^6 years.

Losses of Helium

The current best estimate for the rate of flow of ^4He from the crust to the atmosphere is 2×10^6 atoms/cm²/sec⁻¹. If this flow had occurred for 4.5 billion years, as the long-age model suggests, the total mass of helium in the atmosphere should be 7.3×10^{18} gm. This is about 2,000 times the quantity actually measured (3.8×10^{15} gm). According to the long-age model, a significant loss of ^4He has occurred. The first loss mechanism considered to explain this discrepancy was the theory of the thermal escape of gases from a planet by Jeans (1916). We will consider this theory in considerable detail since it has played such an important role in this problem.

Thermal Escape of Helium

The density of the atmosphere decreases with

height. At some level, the mean free path of the constituent particles becomes large in comparison with the scale height, and collisions above this level are infrequent. The region in which collisions are negligible is termed the exosphere. The atmosphere grades into the exosphere; however, for the purposes of escape theory, it is usual to speak of a given level as the base of the exosphere. Some fraction of the particles describing ballistic orbits have a velocity greater than the escape velocity. These particles will leave the exosphere in hyperbolic orbits. In addition, there is a component in elliptical orbits circling the planet and not passing through regions where the density is high enough for collisions to take place.

A basic problem in the theory of planetary escape is the calculation of the fraction of atoms which have a velocity greater than the escape velocity. The classical theory of escape was developed by Jeans (1925) and Lennard-Jones (1923). Their models assumed an isothermal atmosphere with a gas in equilibrium having a Maxwellian velocity distribution up to the base of the exosphere. Above this level, collisions are sufficiently infrequent as to be unimportant in slowing down outwardly traveling particles. A refinement that has influenced much of the later work is given by Spitzer (1949). This model considered the changes to the Maxwellian velocity distribution below the exosphere, as the high energy particles were removed by escape. MacDonald (1964) summarized the theory of thermal escape and applied it specifically to the escape of helium from the earth's atmosphere.

The problem of escape is complicated by the fact that for a minor constituent, the base of the exosphere must be supplied by diffusion from below. If the thermal conditions are such that the escape rate of a particular constituent is large compared with the diffusion rate, then diffusion effectively controls the scope of that constituent. If the escape rate is small compared to the diffusion rate, then the rate of escape is the controlling factor. It appears that the latter case is normally true for helium, although during unusual events such as solar storms, when the exosphere is strongly heated, the diffusion rate from below may control the flux of helium.

By using the appropriate forms of the hydrostatic equation, the ideal gas law, and Newton's law gravitation, the following relation for the concentration of gas molecules as a function of height can be found:

$$n(z) = n(z_0) \exp\left[-\frac{(z - z_0)}{H(z_0)}\right] \quad (1)$$

where n is the concentration of gas molecules, z is the height above the earth's surface, z_0 is some arbitrary height, and H is the scale height, or height of a homogenous atmosphere above z_0 . The concentration decreases exponentially with height. As a result, there

is no upper boundary to this atmosphere; it thins out gradually with elevation and the concentration goes to zero only at $z=\infty$. The height of the corresponding homogeneous atmosphere appears as a parameter. When $z-z_0=H$, the number concentration will be 1/e of its value at z_0 .

Because of their thermal energy, gas molecules are in motion and have a velocity distribution determined by their temperature. The two necessary conditions for escape to take place are that the velocity of an outgoing particle is greater than the critical escape velocity and that the particle with this velocity has a negligible chance of undergoing a collision which returns it to the lower atmosphere. The escape velocity is defined by the requirement that the particle's kinetic energy be greater than the gravitational potential energy. It is simply a function of height z . The proportion of gas molecules exceeding this velocity can be determined by judicious use of the Maxwellian velocity distribution which, in turn, is a function of temperature. The escape flux of gas molecules at the base of the exosphere is found by integrating over all velocities greater than the escape velocity resulting in the equation:

$$F_e = n_e \left[\frac{g H_e}{2\pi} \right]^{\frac{1}{2}} \left[1 + \frac{R_0 + z_e}{H_e} \right] \exp\left[-\frac{R_0 + z_e}{H_e} \right] \quad (2)$$

where F_e is the flux, n_e is the gas molecule concentration, z_e is the height, g is the acceleration due to the gravity, and H_e is the scale height; all at the base of the exosphere. R_0 is the radius of the earth. In order to evaluate the flux, we must locate the base of the exosphere. The concept of a sharp transition between the region of the atmosphere dominated by collisions and an overlying collisionless region is an idealization of a gradual transition so the location of the base of the exosphere is to some extent arbitrary. Typically the base of the exosphere is placed at a height of 100km above the surface of the earth.

The conditions for the validity of Equation 2 have been discussed in great detail by Aamondt & Case (1962), Brandt & Chamberlain (1960), Fahr & Shizgal (1983), Herring & Kyle (1961), and Opik & Singer (1959, 1960). Within the region of the atmosphere where collisions are frequent, the Maxwellian distribution on which Equation 2 is based holds quite accurately and gives a direct estimate of the outward flux. However, part of this outward flux is balanced by an inward flux due to the fact that a certain fraction of the particles in their upward paths collide and return. The net outward flux is then less than that given by Equation 2. As the base of the exosphere is approached, the total net flux is more closely approximated by Equation 2, but because of the absence of collisions, the Maxwellian distribution holds less exactly. Because of this difficulty, Fahr

& Shizgal have stated that a rigorous description of the velocity distribution function for all altitudes including the transition region near the base of the exosphere has not been achieved to date. They suggest that a kinetic theory description needs to be constructed, which takes into account both the change from collision-dominated to collision-free conditions and the effects due to the loss of particles to space. Considerable effort has gone into estimating the difference from Jean's escape caused by non-Maxwellian conditions. Fahr & Shizgal imply that the rate of actual thermal escape is probably 70–80% of Jean's escape, although some calculations have been made that indicate the actual flux to be as little as 10–20% of the rate of Jean's escape. Certainly, with these diverse estimates, more work needs to be done before any great confidence can be placed in the thermal flux estimates.

Escape occurs from an isothermal region of the atmosphere at a level sufficiently high that all of the atmospheric gases have density profiles governed by diffusive equilibrium. Under these conditions, the density of each constituent varies approximately exponentially with altitude, at a rate determined by the mass of the constituent and not by the other gases present. To evaluate Equation 2 we assume the reference density is 3.4×10^{13} atoms/cm³ at a height of about 100km. The temperature at the homopause is approximately 185K and the exospheric temperature is 1500K. The concentration is further adjusted by the helium mixing ratio shown in Table 1. With these assumptions, the value of the helium flux is calculated to be 5×10^4 atom/cm²sec. This escape rate is about 40 times less than the average source rate estimated to be coming into the atmosphere from the crust of the earth. By dividing this escape flux into the column density of helium in the atmosphere (1.1×10^{20} atoms/cm²), the characteristic escape time for atmospheric helium is found to be about 70 million years. By dividing the source flux of 2×10^6 particles/cm²sec into the column density, the residence time is found to be about 2 million years. The characteristic residence time for helium is much smaller than the characteristic escape time. In other words, it takes a much longer time for a given quantity of helium to escape from the atmosphere to space than it does to enter the atmosphere through the crust.

Since the long-age modelers are convinced that the earth is 4.5 billion years old, they then state "... there appears to be a problem with the helium budget of the atmosphere," Walker (1977). MacDonald (1964) has evaluated the escape flux averaged over an entire 11-year cycle of solar activity, using satellite data to evaluate exospheric temperature. He found an average escape flux of 6×10^4 particles/cm² sec, a factor of 30 less than the source. Spitzer (1949) and Hunten

(1973) have suggested that the bulk of the escape occurs during infrequent periods of high temperature. They suggest that if the exospheric temperature were to be raised to 2000K by solar flares or cosmic bombardment of some type, diffusion of the helium up through the lower atmosphere would become the limiting process and the escape flux would be equal to 1×10^8 particles cm²/sec. Walker suggests that if hot episodes occurred only 2% of the time an average loss rate of 2×10^6 particles/cm² sec could be attained. The helium would accumulate slowly between the hot episodes and escape rapidly during the hot episodes. He suggests that, perhaps, we have not observed such a hot episode in recent history.

Non-Thermal Escape of Helium

If one is convinced that the age of the earth is 4.5 billion years old and the present amount of helium in the atmosphere would accumulate in about 2 million years, then there must be some other loss process in addition to thermal escape. Three of the more popular suggestions are (a) the polar wind, (b) solar wind sweeping, and (c) hot ion exchange. Mechanisms other than thermal escape are considered even by the long-age scientific community to be speculative and of an undetermined significance. It should be recognized that more loss mechanisms will likely be proposed in the future in the hope that this dilemma will one day be resolved without resorting to a reexamination of the age of the earth's atmosphere.

The polar wind is the escape of light ions such as H⁺ and H_e⁺ through open field lines near the poles. The well-developed magnetosphere on earth has magnetic lines of force originating near or at the poles which are not closed onto the planet, but open out into the interplanetary medium. The field lines originating at latitudes greater than 75° are open, corresponding to about 1/40 of the earth's surface. Ions and electrons are accelerated along these open field lines and escape the earth's atmosphere at polar latitudes. The polar wind model proposed by Banks & Holzer (1969) emphasizes the importance of collisions between ions and electrons which gives a continuous nature to the escaping charged gas particles. A similar polar breeze model argues that collisions are unimportant and exhibits features similar to Jean's escape. Both are limited by thermal diffusion from the lower atmosphere and to the polar regions. Axford (1968) has applied to the polar wind model specifically to the escape of helium and calculated an escape flux of about 1×10^5 atoms cm²sec⁻¹, much lower than even Jean's escape.

Solar wind sweeping is a process by which the solar wind plasma, made up mainly of protons and electrons flowing outward from the sun at high velocities, interacts with the magnetosphere of a

planet, deforming it and sweeping particles away into space. If the planet has a strong, magnetic field like earth's, the effects will be minimized. The solar wind particles become thermalized at a bow shock which typically lies several planetary radii from the surface. The thermalized particles flow into the magnetosheath which lies between the bow shock and the magnetopause and are swept around the planet. They do not in general penetrate the magnetopause and thus have a negligible effect on the atmosphere which lies below. Michel (1971) and Cloutier, McElroy, & Michel (1969) have developed methods for estimating the loss rates due to the solar wind which, in general, are quite low for the earth.

Hot ion exchange is a process whereby an energetic ion transfers its kinetic energy to a neutral particle like helium which can then escape. Hot ion exchange is discussed by Fahr & Shizgal (1983) for hydrogen escape from earth, Venus, and Mars but little has been done on the escape of helium from earth. The escape rates by hot ion exchange seem to be low but some researchers believe this process has the best potential for explaining the loss of helium.

None of the rates for the proposed mechanisms have been accurately quantified nor have adequate observations even begun to confirm or deny them. Chamberlain (1978) states that the helium problem "... will not go away and it is unsolved."

A Young Earth Model

Cook (1957) was among the first to recognize the problem with helium in the atmosphere when he asked "Where is the earth's radiogenic helium?" He reviewed much of the same material discussed in this paper and stated that the helium problem "... leads ... to an 'anomalous' atmospheric chronometry ...". I believe we can go further today and make even stronger statements.

The helium we observe in today's atmosphere is a function of its initial concentration when the atmosphere was formed and a balance between the flux in and the flux out. The differential equation for this situation is:

$$\frac{dn}{dt} = c_1 - c_2n \quad (3)$$

where n is the helium concentration, t is time, c_1 is assumed to be a constant flux into the atmosphere, and c_2 is a constant coefficient for the flux out. The solution to this equation is:

$$n = \frac{c_1}{c_2} - \left[\frac{(c_1 - c_2n_0)}{c_2} \right] e^{-c_2t} \quad (4)$$

If n_0 is zero, then

$$n = \frac{c_1}{c_2} (1 - e^{-c_2t}) \quad (5)$$

Assuming $c_1 = 2 \times 10^6$ atoms $\text{cm}^{-2}/\text{sec}^{-1}$ and $c_2 = 4.54 \times 10^{-16} \text{sec}^{-1}$, the time required to reach the helium concentration of today's atmosphere would be 1.76 million years. This period is over 2,500 times shorter than the generally assumed age of the earth. If on the other hand, n_0 was not zero, but half of today's concentration, the time would drop to 890,000 years. If n_0 was 9/10 of today's concentration, the time would only be 180,000 years.

An alternative to the long-age model, and one which runs counter to the basic assumption of the evolutionary/uniformitarian model, is that the earth's atmosphere is relatively young (less than 10,000 years). Under this assumption, the helium content of today's atmosphere would be almost completely primordial. During the 10,000 years or so since its creation, less than 1% of today's helium would have been added by the decay of radioactive materials in the crust.

The recent discoveries of helium coming through the crust from the mantle where no radioactive decay process is known to produce helium, has led to the statement that primordial helium exists in the mantle. Why then, is it so hard to believe that primordial helium also exists in the atmosphere? The lack of an escape mechanism and the likelihood that, the helium we observe in the atmosphere is primordial provides evidence that the earth's atmosphere is quite young.

Conclusion

The study of the influx and outflux processes of gases like hydrogen, helium, argon, neon, and krypton may lead to better estimates of the age of the earth's atmosphere. Investigation of the sources of the heavier gases may be particularly illuminating, since uncertainties by thermal escape can be eliminated from consideration. Evolutionary/uniformitarian models of the earth's atmosphere have run into formidable obstacles in explaining these processes. We believe the source for these problems is the assumption that the earth's atmosphere is billions of years old.

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Discussion

The article, “The age of the earth's atmosphere estimated by its helium content,” by Dr. Larry Vardiman is excellent and shows considerable depth of study. I am, of course, pleased that, while adding valuable new information, it agrees essentially with my study of 1957 (Cook, 1957). In this regard Dr. Vardiman apparently missed the fact that I gave as my best result 12,000 years (by calculations using his [unstated] equations) as the (helium) age of the atmosphere in essential agreement with his result. (See *Prehistory and earth models*, pp. 10–14). I think this reference also would have helped Dr. Vardiman in his argument that the original helium content of the atmosphere and lithosphere was likely about what we see today. I for one am particularly pleased with the references cited by Dr. Vardiman, especially regarding “solar wind.” In studying these references myself it appears to me that we can look for our greatest opposition in the solar wind model. In this regard I think the article by Dr. Vardiman would have been improved by a more careful study of the He^3/He^4 ratio for different conditions on the earth. This may well be where we must look to show that the long-age advocates are not right in their answer to my question, “Where is the earth's radiogenic helium?” That is, according to Axford (1968) total helium loss might conceivably be *nearly* accounted for by the polar wind model but certainly not the ratio He^3/He^4 in the lithosphere vs. atmosphere vs. exosphere (and now) vs. plasma-pause. I agree with Dr. Vardiman (referring to his quotation of Chamberlain) that this problem will go away only by acceptance of the short-age model of the earth's atmosphere. Incidentally, I am curious to know the name of others implied by the first sentence in the paragraph under the heading, “A young earth model.”

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Closure

I wish to thank Mr. Cook for his kind comments on my paper. I agree with him that the He^3/He^4 ratio is probably the most fertile ground for further study. I'm sorry I wasn't able to contribute more in that regard. In response to Mr. Cook's query about other early researchers who recognized the helium budget as a problem, I provide the following additional sources to my list of references:

- Bates, D.R. & McDowell, M.R.C. (1957). Atmospheric helium. *Journal of Atmospheric and Terrestrial Physics*, 11, 200–208.
- Mayne, I.E. (1956). Terrestrial helium. *Geochimica et Cosmochimica Acta*, 9, 174–182.
- Nicolet, M. (1957). The aeronomic problem of helium. *Annals de Geophysique*, Tome 13, Fascicule 1, 1–21.
- Nicolet, M. (1961). Helium, an important constituent in the lower exosphere. *Journal of Geophysical Research*, 66(7), 2263–2264.
- Turekian, K.K. (1959). The terrestrial economy of helium and argon. *Geochimica et Cosmochimica Acta*, 17, 37–43.

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