Possible Sources of a Lunar Atmosphere

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Although the moon is usually considered to have no atmosphere, recent observations by the methods of radio astronomy are best explained by the assumption of a pressure of 10^{-13} atmosphere. Elsmore (*1*) reports the occultation by the moon of two radio sources. In each case the distribution of brightness is dependent on wavelength and has a shape which implies refraction at the day side of the moon's disk. The estimated electron density is 1000 electrons per cubic centimeter, which Elsmore attributes to an atmosphere "about 2×10^{-13} of that of the terrestrial atmosphere at N. T. P. and in no circumstances greater than 6×10^{-13}" (*2*).

As in the case of the earth, it is thought that the moon lost volatile materials during the period of formation (*3*), so that the only mechanisms of atmosphere production which can be relied upon are those which occur subsequent to the process of element formation or planet formation.

The low gravitational field of 167 centimeters per second per second gives an escape velocity of only 2.37 kilometers per second, so that gases of low molecular weight will not be retained. Kuiper (*4*) suggests that molecules of weight less than 60 will be lost during the heat of the lunar day (135°C).

This article evaluates several sources of the heavy rare gases krypton and xenon, which are thought to be too heavy to escape. These sources are (i) spontaneous fission of uranium-238, (ii) fission of uranium-235 by thermal neutrons from cosmic rays, (iii) thermal fission of uranium-235 from the reaction

$$O^{18}(\alpha,n)Ne^{21}$$

(iv) xenon production from iodine-129 produced during the formation of the elements, and (v) primeval gases trapped in rock.

Rate of Escape

To examine the rate of escape of krypton and xenon, formulae derived by Spitzer (*5*) are used. The time t_1 during which the particle density would fall by a factor of e for an isothermal atmosphere is

$$t_1 = \frac{2\sqrt{6\pi}C^3}{9gV_\infty{}^2}\, e^{3V_\infty{}^2/2C^2}$$

where g is the acceleration of gravity, C is the root-mean-square velocity of the molecule, and V_∞ is the escape velocity.

The assumption of an isothermal atmosphere is well founded, since the mean free path at 400°K and at a pressure of 10^{-13} atmosphere will be 600 kilometers, whereas the height to which a molecule with the root-mean-square velocity C can ascend against the gravitational field will be, at most, 10 kilometers. Collisions between molecules will therefore be rare events, whereas collisions at the surface will predominate. Molecular paths will not be straight but will be, rather, elliptic. Since most molecular collisions will be with the surface at a well-defined temperature, the Maxwellian gas temperature will be that of the moon's surface, 135°C at the lunar noon.

Table 1 gives the escape time for xenon and krypton at various temperatures. If the escape time is large compared with the age of the moon (4.5×10^9 years), then the gases evolved will be retained. Even though "hot spots" with temperatures as high as 700°K may develop, krypton and xenon will not be lost.

Production Mechanisms

Spontaneous fission. Uranium-238 is known to undergo spontaneous fission with a probability of 5.4×10^{-7} per alpha decay. While the decay constant is small ($\lambda = 2.7 \times 10^{-24}$ per second) on a geological scale, it cannot be neglected.

The accumulation of stable fission products or a single fission product may be represented by the expression

$$N = \frac{\lambda_i N_p}{\lambda}(e^{\lambda t} - 1)$$

where N_p is the number of parent atoms remaining at the present time, λ_i is the decay constant giving the desired product, λ is the decay constant for the disappearance of the parent, and t is the time interval during which the product has been accumulating.

The yields of xenon and krypton from the spontaneous fission of uranium-238 have been measured by Thode (*6*) and by Wetherill (*7*). The total yield of xenon is 15 percent; of krypton, 0.92 percent.

Estimates of the uranium content of the moon are restricted at the lower limit by the uranium content of stony meteorites. As an upper limit, the concentration must not be sufficiently high to cause melting of the interior. Urey (*8*) concludes that the best value is 0.012 parts per million by weight for the moon as a whole, with possible enrichment by a factor of two at the surface.

The numbers of atoms of krypton and xenon generated in surface layers of various depths are given in Table 2. The assumptions are (i) uniform uranium concentration (0.012 micrograms of uranium per gram); (ii) density of layer, 3 grams per cubic centimeter; (iii) age, 4×10^9 years; (iv) no escape of krypton or xenon; (v) complete loss of primeval rare gases during planet formation. In a surface layer 1 centimeter deep, 2.5×10^{24} xenon, and 1.5×10^{23} krypton, atoms will be generated.

If released as a free atmospheric gas, the total number of molecules will depend upon the thickness of the surface layer which has been outgassed. The atmospheric pressure at the surface, based on the assumption of an isothermal atmosphere, will be related to the total number of molecules by the following relation:

$$P = \frac{mgN}{4\pi R_0{}^2}$$

where m is the mass of the molecule, g is the acceleration of gravity, N is the total number of molecules, and R_0 is the radius of the moon. The pressure per centimeter of the surface layer outgassed will be 9.1×10^{-22} atmosphere for krypton and 1.4×10^{-20} atmosphere for xenon.

Estimates of the degree to which the moon will be outgassed depend intimately upon the detailed model chosen. The stability of the moon's surface, made evident by the existence of numerous

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Table 1. Escape times for heavy rare gases from the moon (in years).

Gas	Temperature (°K)			
	400	700	1000	1500
Xenon	10^{41}	5×10^{20}	6×10^{12}	4×10^{6}
Krypton	10^{24}	2×10^{11}	10^{6}	2×10^{2}

craters, precludes continuous outgassing of a surface layer by processes similar to geological gradation on the earth. Complete outgassing probably occurred at some stage, but this stage would be difficult to distinguish from the period of planet formation. The total stockpile of noble gases in the whole moon produced by spontaneous fission in the past 4000 million years corresponds to a pressure of 1.1×10^{-12} atmosphere (1.5×10^{32} atoms). Ten percent of the total gas accumulated in 4000 million years would have had to diffuse to the surface to produce an atmosphere of pressure 10^{-13} atmosphere.

In the event that there is some segregation of materials, uranium would undoubtedly be concentrated at the surface. Urey suggests twofold or threefold concentration at the surface. With this concentration of uranium, the thickness of crust would be perhaps 10 kilometers at a very minimum.

If one identifies certain markings on the moon's surface as cracks produced by heating and expansion of the interior, these may indicate channels of communication between the atmosphere and the outer layer. Diffusion through massive rock would then not be necessary.

Radio astronomical observations give evidence that the surface of the moon is a finely divided dust, and Urey proposes pumice as the most probable surface rock. It is therefore probable that diffusion does indeed account for the transfer of gases from a limited surface layer.

It is doubtful, however, whether all parts of a layer 10 kilometers deep are in continuous communication with the free atmosphere.

The collision of meteors has undoubtedly been responsible for the outgassing of the top few kilometers of the moon's surface. The question at issue is: When did these cataclysmic events occur? If they occurred shortly after formation of the planet, insufficient spontaneous fission would have occurred. By assuming a surface concentration sufficiently above the interior, the required amount of gas may be released. If, on the other hand (but this is not probable), meteoric activity has been uniform and continuous up to the present time, there would be no difficulty in releasing fission-product rare gases to the atmosphere in the required quantity.

Cosmic ray bombardment. Soberman (*9*) reports the total neutron flux on the earth from cosmic rays as 5.8×10^{18} neutrons per second. At the present epoch the moon, therefore, receives a total flux of 6×10^{17} neutrons per second. The effective total absorption length is 150 to 200 grams per square centimeter, so that the neutrons will be generated and absorbed within the first meter of the moon's surface. It is therefore acceptable to assume that these fission gases will continuously diffuse to the surface to form an atmosphere as a consequence of thermal cycling during the lunar day.

This proposed mechanism requires the assumption of constant cosmic ray intensity. It is only possible to say, in this regard, that studies involving carbon-14 seem to confirm this constant intensity over a few thousand years.

While cosmic ray neutrons have initial energies of many millions of electron volts, in a medium composed largely of silicon and oxygen most of them will be moderated to thermal energies of a small fraction of an electron volt before absorption.

The fraction of neutrons captured by uranium-235 to produce fission will be determined by the composition of the rock and the thermal neutron absorption cross sections. This fraction, if one assumes a composition similar to that of the earth's crust except for uranium, is 6×10^{-8}.

The generation rate at present for xenon is therefore 5×10^{9} atoms per second for the whole moon. In the past, however, the production rate was greater because of higher concentration of uranium-235. The total production of xenon is given by the expression

$$N = \frac{N_p \sigma}{\sum\limits_i N_i \sigma_i} \frac{nvy}{\lambda} (e^{\lambda t} - 1)$$

where N_p is the number of uranium-235 atoms present today, nv is the neutron flux, λ is the decay constant for uranium-235, and y is the fission yield of noble gases (assumed for thermal neutrons on uranium-235 to be 25 percent). The total number of atoms of rare gas is 4.9×10^{25} atoms for a period of a billion years and 1.5×10^{27} atoms for a period of 4×10^{9} years, a factor of 10,000 too small to account for the observed atmospheric pressure of 10^{-13} atmosphere.

Alpha-neutron source. An additional source of neutrons in geological deposits has been reported by Inghram (*10*) to be produced by nuclear interactions of alpha particles from radioactive substances. He finds unusual abundances of neon-21, neon-22, and argon-38 in uranium and thorium minerals and attributes them to the following reactions:

$$\mathrm{O}^{18}(\alpha,n)\mathrm{Ne}^{21}$$

$$\mathrm{F}^{19}(\alpha,n)\mathrm{Na}^{22}$$

$$\mathrm{Na}^{22} + e \rightarrow \mathrm{Ne}^{22}(T_{1/2} = 2.6 \text{ years})$$

$$\mathrm{Cl}^{35}(\alpha,p)\mathrm{Ar}^{38}$$

If uranium is in an environment high in oxygen, the O^{18} (α,n) reaction would predominate. The neutron yield in normal oxygen from polonium alpha rays is reported by Roberts (*11*) to be 3×10^{-5} neutron per alpha particle. Morrison (*12*) quotes yields, in typical rocks, which reflect the energy of the various alpha particles in the radioactive series, of 1×10^{-6} neutron per alpha particle for uranium and 2×10^{-6} neutron per alpha particle for thorium. With eight alpha particles per uranium atom, the rate of production of xenon from fission of uranium-235 is 10^{-6} times the rate from spontaneous fission.

Even five billion years ago, when the abundance of uranium-235 was 100 times its present abundance, thermal neutron fission did not compete with spontaneous neutron fission.

Decay of iodine-129. Iodine-129 is unstable, with a measured half-life of 1.7×10^{7} years (*13*), decaying into xenon-129. Previous speculations (*13*) concerning excess xenon-129 in the earth's atmosphere have been directed to determining the interval between the formation of the elements of which the solar system is composed and the establishment of a gravitational field capable of holding the earth's atmosphere.

On the assumption of an original iso-

Table 2. Spontaneous fission production of krypton and xenon.

Depth of surface layer (cm)	Krypton		Xenon	
	Total No. of atoms	Pressure (atm)	Total No. of atoms	Pressure (atm)
10^{2}	1.5×10^{25}	9.1×10^{-20}	2.5×10^{26}	1.4×10^{-18}
10^{4}	1.5×10^{27}	9.1×10^{-18}	2.5×10^{28}	1.4×10^{-16}
10^{6}	1.5×10^{29}	9.1×10^{-16}	2.5×10^{30}	1.4×10^{-14}

topic abundance of iodine-129 equal to that of iodine-127 of 0.014 per 10,000 atoms of silicon (*14*) and of a composition of the moon approximately that of the earth's mantle, there should be 5.6×10^{33} atoms of iodine-127 per centimeter of surface layer. The same number of atoms of iodine-129 should originally have been present.

If the observed atmosphere consists of 4×10^{31} atoms of xenon-129, this must once have been iodine-129, in a surface layer which has been outgassed after radioactive decay to xenon. Under the assumption that the astronomical body as we know it was formed immediately after the formation of the elements, the layer required to produce the present atmosphere is 0.015 centimeter. In view of the cataclysmic processes which produced the craters, this is an unrealistically small surface layer.

The other extreme assumption is the release of all xenon and the loss, through escape, of all but 4×10^{-10} of the original xenon-129. This requires communication with the interior several tens of millions of years after element formation, since this interval is required to permit the decay of the iodine. It is doubtful whether a model could be devised, which resembles the moon, which would permit of total degassing. With present values of the surface temperature and gravitational field, no mechanism seems to be available for the escape of these heavy gases.

On the basis of different thicknesses of the surface layer, which has been completely outgassed, values of the interval between element formation and the creation of the astronomical object in its present form may be derived and are shown in Table 3.

After planet formation for a period of at least 10^7 years, a mechanism must exist for outgassing the surface layer. It would be surprising if collisions with meteors, responsible for the craters, did not occur over such a period.

If we assume the *maria* to represent melted (and outgassed) rock, and if we assume the outgassing of the fragmented debris from the collision, an estimate can be made of the depth of excavation represented by present craters. A value between 10^4 and 10^6 centimeters would appear probable.

Table 3. Relation between surface layer outgassed and interval between element formation and satellite formation.

Depth of surface layer (cm)	$t \times 10^{-8}$ (years)
1	1.2
10	1.8
10^3	2.9
10^5	4.0
1.7×10^8	5.6

On this basis, the period of satellite formation would appear to be 4×10^8 years, during which time a low gravitational field and perhaps turbulent diffusion combined to rid the material of all rare gases. After establishment of a body with the present gravitational field and poor communication with the interior, the surface layer was disturbed and outgassed for a period of at least the order of a half-life. Thereafter, the body may have been completely quiescent. These conclusions would appear to agree with the analysis of Urey concerning the sequence and duration of events in the early history of the moon.

Primeval gases. If there were no mechanism for producing krypton and xenon, some primeval gas might still be present. An analysis of the concentrations in the atmosphere and rocks of the earth may give some rough magnitudes for the moon. The assumptions on which the extrapolations are based are: (i) the earth and moon have a common origin; (ii) xenon and krypton do not enter into chemical combination; (iii) on the basis of present assumptions relative to the temperature and mass of the moon, negligible amounts of the gases are currently lost. It is felt that if the physical states of temperature, mass, and material do not differ too greatly, the following figures may hold.

Brown (*15*) has inferred that the rare gases escaped during planet formation by comparing amounts found in the earth's atmosphere with estimates of the universal abundance. He has measured the concentration of neon and argon in the atmosphere, in natural gases, and in rocks, as well as the concentration of krypton and xenon in atmosphere and natural gases. He infers that 1.6×10^{-11} and 2×10^{-12} are the abundances, by weight, of krypton and xenon in rock. If these concentrations are assumed for lunar rock, the values in Table 4 result.

Table 4. Estimate of concentrations of rare gases in lunar rock, based on concentration in terrestrial rocks.

Depth of surface layer on moon (cm)	Krypton		Xenon	
	Total No. of atoms	Pressure (atm)	Total No. of atoms	Pressure (atm)
10^2	10^{31}	6×10^{-13}	7×10^{29}	6×10^{-14}
10^3	10^{32}	6×10^{-12}	7×10^{30}	6×10^{-13}
10^4	10^{33}	6×10^{-11}	7×10^{31}	6×10^{-12}

For reasonable values of the layer excavated by meteors (10^4 to 10^6 centimeters), the predictions exceed observations by a factor of more than 100. It is certainly permissible to assume increased loss of rare gases, by the necessary factor, over the loss occurring on the earth. However, samples studied on earth have, at one or more times, been affected by geological processes in the surface layer of the crust and may well have received their rare gases from the atmosphere. These occluded gases may not, therefore, be primitive in the sense that their history is independent of the earth's atmosphere.

The only other cosmic material we can subject to analysis is meteoritic material, which contains no measurable quantities of rare gases. It is therefore difficult to decide whether the analogy of the moon with the earth or of the moon with meteorites is the more valid.

Discussion

Three mechanisms appear to be adequate to account for the radio astronomy observations: (i) spontaneous fission of uranium-238, (ii) xenon-129 from iodine-129, (iii) primeval gases. A priori

Table 5. Composition of lunar atmosphere (by volume).

Gas	Spontaneous fission	Iodine-129	Primeval gas
Krypton-78			0.003
Krypton-80			0.021
Krypton-82			0.118
Krypton-83	0.002		0.108
Krypton-84	0.007		0.530
Krypton-86	0.047		0.162
Xenon-124			0.000006
Xenon-126			0.000006
Xenon-128			0.0013
Xenon-129	0.0007	1.0	0.018
Xenon-130			0.0027
Xenon-131	0.029		0.0143
Xenon-132	0.224		0.0182
Xenon-134	0.314		0.0071
Xenon-136	0.378		0.006

spontaneous fission is a certain mechanism which is quantitatively insufficient. However, by assuming sufficient segregation of uranium in the surface layer, this defect can be corrected. The mechanism involving residual primeval gases is based on analogy with the earth and is quantitatively too large. If a correction factor is applied to this mechanism, there is no good reason for not accepting data from meteors, which give values much too small.

The previous existence of iodine-129, while a matter of speculation, is well founded on present theories of element formation. If we accept this assumption, it is then possible to estimate the interval between element formation and the formation of the satellite in its present state. The interval of 4×10^8 years would not appear to be contradicted by other observations.

The three alternatives lead necessarily to explicit predictions of the composition of the lunar atmosphere. These are given in Table 5. If iodine-129 is alone responsible, there will be only xenon-129; if spontaneous fission, there will be 5 percent krypton and 95 percent xenon; if primeval gases, 93 percent krypton and 7 percent xenon.

It would appear that only a gas sample would make it possible to distinguish between the alternatives. Since the scale height is only a few kilometers, it is not probable that initial grazing rocket orbits would come sufficiently close to permit the collecting of a gas sample.

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Louis Pillemer, Immunochemist

The sudden death of Louis Pillemer, on 31 August 1957, came at a time when he had just received wide recognition for his work in the field of immunochemistry.

Dr. Pillemer was born in Johannesburg, Union of South Africa, in 1908, the son of Lithuanian parents. He was brought to the United States at the age of one and was naturalized in 1916. Although he had none of the aids which position and wealth can bestow, he managed to complete his undergraduate studies, in Kentucky, and received his B.S. degree at Duke University in 1932. While at Duke he came under the influence of the late W. A. Perlzweig, who stimulated his interest in biochemistry. On the advice of Perlzweig he came to Western Reserve University in 1935 to continue his studies, working toward a Ph.D. degree, with emphasis in immunology and biochemistry. While Pillemer was at Duke University he became interested in Perlzweig's attempts to purify and to crystallize the enzyme urease. It was then a logical step to continue this work and to study the immunological specificity of the crystallized urease. This work became the basis for his doctoral thesis, in 1938. It was entitled, "Chemical and Immunologic Studies on the Effects of Radiant Energy and of Oxidation on Crystalline Urease."

During his studies in my laboratory at the Institute of Pathology, Western Reserve University, Pillemer's great interest in immunology was readily discovered and fired. He showed great capacity for absorbing and retaining information as well as for sustained concentration at the laboratory bench. He also possessed inductive and deductive potentialities, the latter being dominant. In addition, he had the ability to spend two and even three consecutive nights in the laboratory in order to complete a given unstable preparation, and it was not uncommon for him to do so. During this time he rose from the position of demonstrator of immunology (1938–39) to that of associate professor of immunochemistry (1946–50), and to that of professor of biochemistry in 1950. Throughout these years, Pillemer's time was devoted primarily to research.

Early in his career at Western Reserve he showed great interest in our work on the elusive factor called "complement," an interest he maintained to the last days of his life. Realizing the need for more knowledge of protein separation, and being aware of the beautiful studies then under way in the laboratories of E. J. Cohn at Harvard, we decided, after consultations with Cohn, to send Pillemer to Boston to learn the basic techniques of the Harvard group. Before he left for Boston we were able to show, in collaboration with Chase Breeze Jones, that the complement complex was bound to certain globulins of the serum, but the newer methods of the Boston workers led to the separation and characterization of two of the four components of the complement complex.

In 1944 Pillemer was called to military service and was attached to the Army Medical School in Washington, D.C. Upon his discharge, he returned to Cleveland and undertook the problem of the purification of certain bacterial toxins. The support for these studies came first from John Wyeth and Sons of Philadelphia and then from Lederle Laboratories Division, in New York. By 1946, Pillemer, in collaboration with Wittler,