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INDIGENOUS ORGANIC MATTER ON THE MOON

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Studies of the early history of the solar system[1, 2] indicate that for some period after its formation the Moon possessed a reducing atmosphere of secondary origin, composed largely of CH_4, NH_3, and H_2O, with smaller amounts of H_2 and the interaction products of these molecules. The effect of solar ultraviolet light (and electric discharge) on such an atmosphere is well known; organic molecules of fair complexity—up to molecular weight $\sim$100—are produced almost independently of the relative proportions of precursors. Amino and other organic acids, pyrroles, pyridines, and simple hydrocarbons and their polymers are among the synthesized molecules.[3–5] The purpose of the present paper is to estimate the quantity of organic matter which formed in the primitive lunar atmosphere, diffused to the surface, and survived to the present day.[6]

Consider ultraviolet radiation of intensity Q photons cm^{-2} sec^{-1} in the synthetically effective wavelengths falling for t seconds on an opaque gaseous envelope surrounding the Moon, and producing molecules of mean molecular weight μ with over-all quantum yield ϕ. Neglecting lunar gravitational capture of molecules produced outside a cylinder of lunar radius extending from the Moon to the Sun, the mean surface density of synthesized material will be

$$\sigma = \frac{\phi\, Q\, \mu}{4\, N_A}\, t \quad \text{gm cm}^{-2},$$

where N_A is Avogadro's number. We have assumed that ϕ is independent of wavelength in the synthetically effective region. The values adopted for ϕ, Q, and t are now discussed in turn.

Because the molecular weight of the synthesized molecules was greater than the mean molecular weight of the lunar atmosphere, these molecules must have diffused to the surface under the influence of the lunar gravitational field. The time for such molecules to diffuse to atmospheric depths which are opaque in the photodissociating ultraviolet can be shown to be less than the time between successive absorptions of photodissociating photons.[6] The reason is essentially that, for most important organic precursors, the long wavelength limit for photoproduction exceeds the long wavelength limit for photolysis. Aldehydes are the notable exceptions. Oxygen-containing molecules must have been formed primarily near the lunar surface. Recently a series of experiments on ultraviolet synthesis of amino acids in an atmosphere similar to that of the early Moon has been performed by Groth.[7] The quantum yield is found to be approximately independent of wavelength between $\lambda 2537$ and $\lambda 1470$. Since the time between molecular collisions was much shorter than the time between successive absorptions of ultraviolet photons in the primitive lunar atmosphere, the difference in pressure, temperature, and density between early lunar and contemporary laboratory conditions should not affect the order of magnitude of the quantum yield. With these considerations in mind, we adopt from Groth's data an over-all quantum yield for the photoproduction of amino acids in the early lunar atmosphere of $\phi = 10^{-6}$, a conservative value probably uncertain by a factor of ten.

From recent models of the evolution of the Sun,[8-10] the ultraviolet black body temperatures and geometrical dilution factors can be computed, and the radiation flux shortward of a given wavelength obtained from an integration of the Planck distribution function, for any epoch in the past. At the time the Sun's evolutionary track in the Hertzsprung-Russell diagram joined the main sequence, about 5×10^9 years ago, the quiet solar ultraviolet photon flux at wavelengths shortward of $\lambda 2600$ in the vicinity of the Moon, and with no absorption in interplanetary space, is computed to be $Q = 4 \times 10^{14}$ photons cm^{-2} sec^{-1}, about half the present flux.

If not replenished from the interior, a lunar atmosphere will escape to space in roughly 10^3 years, as can be computed from the work of Spitzer.[11] Hence the lifetime of the secondary lunar atmosphere depended entirely on the supply rate of gases from the lunar interior. This is very difficult to estimate, but it is not unlikely that extensive lunar outgassing maintained an atmosphere opaque to ultraviolet radiation for at least 10^7 or 10^8 years; it is important to note that although the lunar craters are probably not volcanic in nature, other lunar surface features exist which are of undoubted igneous origin.[12]

With $\phi = 10^{-6}$, $Q = 4 \times 10^{14}$ cm^{-2} sec^{-1}, $\mu = 100$, and $t = 3 \times 10^{14}$ sec, the derived amino acid surface density is then $\sigma \simeq 5$ gm. cm^{-2}. The result is of course very rough—the principal uncertainty being the value of t—but it indicates that quite considerable quantities of organic matter may have been deposited on the primitive Moon. Miller[4] and Groth[7] find efficient production of other substances beside amino acids, some with greater quantum yields (especially formic and acetic acids) and many with lesser quantum yields. During the time of deposition, the lunar atmosphere would have inhibited thermo- and photodissociation of the deposited molecules.

As the secondary lunar atmosphere escaped to space, and replenishment from the interior gradually fell off, the rate of atmospheric organic synthesis declined, and short wavelength radiation penetrated nearer to the surface. In addition, the surface temperature slowly rose, due both to the loss of the insulating atmosphere, and to radioactive heating. The effect of heat and ultraviolet light on the molecules cited above is most remarkable. Although the second law of thermodynamics is obeyed, a large fraction of the molecules, with activation energies supplied, partake in organic syntheses of a higher order of complexity. Polypeptides arise from amino acids, hydrocarbon dimers and trimers form long-chain polymers, and in general very complex organic molecules are constructed.[3, 5, 13] Finally, because complex molecules are more resistant to heat and radiation than are simpler molecules, the syntheses are biased toward the net production of the most complex organic molecules.[14, 15]

Although continued radiation and high temperature would lead to the eventual destruction of all these molecules, we must remember that meteoritic matter was falling into the lunar atmosphere throughout the period of organic synthesis. Whipple[16] estimates that about 50 gm cm^{-2} falls on the Moon each 10^8 years at present rates of infall. In addition, it is almost certain that the rate of meteoritic infall on the Moon in primitive times was greater than today. As a consequence, the Moon's surface must have received a dust cover, probably composed primarily of silicates and ices, which can be identified, at least in part, with the present lunar surface material. The organic molecules would then be covered by a protective layer, insulating them from the extremes of lunar temperature and absorbing the incident solar radiation and subsequent meteoritic infall. At an average temperature $< 0°C$ and only mild fluctuations, the thermostability half-lives of most organic molecules are of the order of the age of the solar system.[17] Provided that no large-scale destructive events have occurred subsequently, we may anticipate the presence of complex organic matter beneath the dust layer with a mean surface density of perhaps 10 gm cm^{-2}. With a time-constant rate of meteoritic infall, and no escape of surface material to space, the layer of organic matter would be localized at a depth of some tens of meters. These remarks apply properly only to regions which have had no extensive lava flows; the southern highland appears to be such a region, as does much of the far side of the Moon.

A sample of appropriate lunar subsurface material should then have an organic fraction easily detectable by simple chemical techniques. A qualitative and quantitative analysis would give important evidence concerning prebiological organic syntheses and the early history of the solar system.

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[2] Urey, H. C., *The Planets* (New Haven: Yale University Press, 1952); Urey, H. C., in *Proc. First Intern. Symp. on the Origin of Life on the Earth*, eds. A. I. Oparin *et al.* (London: Pergamon Press, 1959), p. 16.

[3] Oparin, A. I., *The Origin of Life on the Earth* (New York: Academic Press, 1957).

[4] Miller, S. L., *J. Am. Chem. Soc.*, **77**, 2351 (1955).

[5] Noyes, W. A., and P. A. Leighton, *Photochemistry of Gases* (New York: Reinhold Press, 1941).

[6] A more complete discussion will be published as a monograph by the Panel on Extraterrestrial Life, Armed Forces—National Research Council Committee on Bio-Astronautics, National Academy of Sciences. The production of organic molecules in the atmospheres of other bodies of the solar system will be discussed elsewhere.

[7] Groth, W. (private communication, 1959). I am indebted to Prof. Groth for supplying the results of some of his recent experiments in advance of publication.

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[11] Spitzer, L., in *Atmospheres of the Earth and Planets*, ed. G. P. Kuiper (Chicago: University of Chicago Press, 1952), chap. 7.

[12] Kuiper, G. P., these PROCEEDINGS, **40**, 1096 (1954).

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[15] Sagan, C., *Evolution,* **11**, 40 (1957).

[16] Whipple, F. L., in *Vistas in Astronautics,* eds. M. Alperin and H. F. Gregory (New York: Pergamon Press, 1959), p. 267.

[17] Abelson, P. H., *Carnegie Inst. Wash. Yrbk.,* **53**, 97 (1954).

BIOLOGICAL CONTAMINATION OF THE MOON

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The extensive deposition of both hard- and soft-landing packages on the lunar surface seems to be imminent. There has been recent concern that terrestrial microorganisms and organic matter, deposited with the packages, may obscure detection of, or interact with, possible organisms or organic matter indigenous to the Moon.[1, 2] Such biological contamination of the Moon would represent an unparalleled scientific disaster, eliminating promising approaches to such problems as the early history of the solar system, the chemical composition of matter in the remote past, the origin of life on Earth, and the possibility of extraterrestrial life. Because of the Moon's unique situation as a large unweathered body at an intermediate distance from the Sun, scientific opportunities lost on the Moon may not be recoupable elsewhere.

There are four possible kinds of lunar biological contamination, which we discuss under the following headings:

1. *Biomixy.*—The Moon may contain no indigenous living organisms, and may be incapable of supporting terrestrial organisms. Nevertheless, there may be relics of primitive indigenous organisms and deposited cosmobiota on or beneath the surface. Especially on a low-gravity, high-vacuum body such as the Moon, a vehicle impacting at or near escape velocity will distribute its contents over most of the lunar surface. Subsequent investigations might then be unable to distinguish among primitive indigenous organisms, cosmobiota, and terrestrial microbiological contamination.

2. *Sapromixy.*—The Moon may contain no indigenous living organisms, and may be incapable of supporting terrestrial organisms. But subsurface prebiological organic matter may exist which would be indistinguishable from deposited terrestrial organic matter, either biological or abiological in origin.

3. *Phagomixy.*—The Moon may contain no indigenous living organisms, but may be capable of supporting some terrestrial organisms. This would require subsurface organic matter, moisture, and heat sources. The possibility then exists that a deposited terrestrial microorganism, in the absence of biological competitors or predators, will multiply at a geometric rate limited only by the availability of