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by

Carl Sagan

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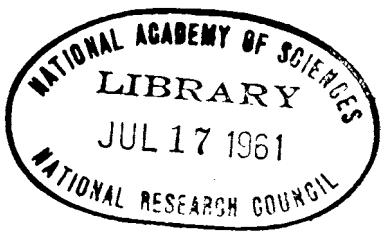

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PREFACE

The need for a critical examination of the possibilities inherent in lunar exploration for furthering our knowledge of both current and evolutionary biology has become increasingly apparent. We therefore have sought such a review and herewith present it in the hope that it will inspire the scientific community to devise new and critical experiments in preparation for this imminent exploration.

MELVIN CALVIN, Chairman
Panel 2, Extra-Terrestrial Life
Armed Forces-NRC Committee
on Bio-Astronautics

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I. INTRODUCTION

The immediate future seems to hold both the promise and the responsibility of extensive contact between man-made objects and the Moon.

Current United States plans tentatively call for the soft landing on the Moon of instrumentation designed to detect indigenous organisms or organic matter, possibly in a roving vehicle, by 1964-67 in the Surveyor and Prospector Programs. The Soviet Union apparently has the capability of performing similar experiments at an earlier date. It is clear that positive results would give significant information on 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 distribution of life beyond the Earth. By the same token, biological contamination of the Moon would represent an unparalleled scientific disaster, eliminating possible approaches to these problems. 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.

This monograph is concerned with the possibility of finding indigenous lunar organisms or organic matter, and with the possibility of their contamination by deposited terrestrial organisms or organic matter.

A summary of some of the conclusions of this monograph has been presented previously (Sagan, 1960a, 1960b).

II. PRODUCTION OF ORGANIC MATTER IN EARLY LUNAR HISTORY

A. General Theory

Investigations of the early history of the Solar System indicate that the Moon possessed a sequence of reducing gaseous envelopes during and soon after its origin (Kuiper, 1951a, 1952; Urey, 1951, 1952). The evolution of the early lunar envelopes is discussed in section II B, where reasons are discussed for believing the envelopes to have been composed largely of CH_4, NH_3, H_2O, and H_2, and to have been opaque to short-wavelength ultraviolet radiation.

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 ~ 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 (Noyes and Leighton, 1941; Miller, 1955; Oparin, 1957; Groth and von Weyssenhoff, 1960).

Because the molecular weight of these molecules and their intermediates was greater than the mean molecular weight of the primitive lunar envelopes, they tended to diffuse to the surface under the influence of the lunar gravitational field. However, the newly-synthesized molecules, having greater ultraviolet absorption cross sections than their precursors, were more readily photodissociated; a crucial datum is then the comparison between $\bar{t}_d$, the mean time for synthesized molecules to diffuse to atmospheric depths which are optically thick in the photodissociating ultraviolet, and $\bar{t}_a$, the mean time between successive absorptions of photodissociating photons. If we define a parameter β as the fraction of synthesized molecules which reach optically thick depths before being photodissociated, we have $\beta \approx 1/2$ when $\bar{t}_a \approx \bar{t}_d$, $\beta \approx 1$ when $\bar{t}_a \gg \bar{t}_d$, and $\beta \approx 0$ when $\bar{t}_a \ll \bar{t}_d$.

Consider now 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 overall quantum yield ϕ. Let r be the distance from the center of the Moon such that all molecules of molecular weight μ produced at distances less than r are

gravitationally captured, while those produced at distances greater than r will escape. The synthesized molecules will be distributed over a Moon of radius R. Assuming that ϕ is independent of wavelength in the synthetically effective region of the spectrum (v. section II D) the mean surface density of synthesized material which escapes photodissociation will be

$$\sigma = \frac{Q \phi r^2 \mu \beta}{4 N_A R^2} \quad t \quad \text{gm cm}^{-2}, \qquad (1)$$

where N_A is Avogadro's number. In the following sections we discuss the numerical values appropriate for r, R, β, ϕ, Q and t.

B. Historical Development of Lunar Gaseous Envelopes

The picture of the early evolution of the Solar System in the neighborhood of the Moon which we present here was first developed by Kuiper and Urey in the early 1950's. Urey (1956a) has since suggested that alternative views might be better able to explain certain discordant facts. but for the sake of definiteness, and because of the general success of the original picture, we adopt it here. It should be emphasized that the existence of a later secondary reducing atmosphere for the Moon seems incontrovertible, in the light of the work of Suess (1949) and Brown (1949) on the underabundance of rare gases in the terrestrial atmosphere when compared with the cosmic distribution of the elements.

The Moon, along with other bodies of the Solar System, is believed to have formed some 4 to 5 x 10^9 years ago from the solar nebula, a vast gas and dust cloud possessing a cosmic distribution of the elements. The contraction timescale for the solar nebula was the Helmholtz-Kelvin period, approximately 10^8 years. At the end of this period, the Sun approached the main sequence in the Hertzsprung-Russell diagram, thermonuclear reactions were initiated, and solar electromagnetic and especially corpuscular radiation dissipated the nebula from around the protoplanets and their atmospheres. The dissipation timescale for the solar nebula is estimated by Kuiper (1953) as between 10^8 and 10^9 years. After the clearing out of interplanetary space, hot exospheres established in the protoplanetary atmospheres led to efficient evaporation of the planetary envelopes, a process aided by the long mean free paths in interplanetary space and the low escape velocities (due to smaller mass/radius ratios for the protoplanets than for the present planets). The time for the evaporation of the prototerrestrial atmosphere appears to be roughly 10^8 years (Kuiper, 1951b).

During the events just outlined, chemical compounds and condensates were raining down on the protoplanetary surfaces, forming

the outermost layers. After the evaporation of the atmospheres of the terrestrial protoplanets, internal heating must have vaporized much of the condensates, thereby forming secondary atmospheres of chemical composition similar to the initial protoatmospheres. The present Martian, Cytherean, and terrestrial atmospheres are believed to be ultimately of such secondary origin. Similarly, the Moon must have possessed a secondary atmosphere at one time, which, however, since has been lost to space because of the low lunar escape velocity.

We now consider the penetration of solar ultraviolet radiation into the various gaseous envelopes which surrounded the Moon in its early history. The absorption cross section of ammonia, the most prominent nitrogen-containing molecule in cold cosmic gases, shortward of $\lambda 2400$ is greater than 10^{-22} cm^2. Hence, as long as the mean density of ammonia exceeded 10^9 molecules cm^{-3} between the Moon and the Sun in the solar nebula, solar ultraviolet light shortward of $\lambda 2400$ did not reach the lunar vicinity. This ammonia density corresponds to a hydrogen number density of about 10^{12} molecules cm^{-3} for cosmic abundances; i.e., about 3×10^{-11} gm cm^{-3}. Interplanetary densities of this order were reduced rapidly (Kuiper, 1953), and we conclude that during most of the 10^8 to 10^9 years in which the solar nebula was being dissipated, solar radiation shortward of $\lambda 2400$ was reaching the protoatmosphere of the Moon. Because the lunar protoatmosphere had not yet begun to escape, due to the short mean free paths within the solar nebula, the lunar protoatmosphere remained opaque to solar ultraviolet light during this period. After the dissipation of the solar nebula, the lunar protoatmosphere was opaque in the ultraviolet for most of its lifetime. In this same period, the Moon must have been situated within the protoatmosphere of the earth, and so the Moon's surface must have been protected from solar ultraviolet radiation by lunar and terrestrial protoatmospheres for almost 10^8 years. After the evaporation of these protoatmospheres, and the origin of the secondary lunar atmosphere, the secondary atmosphere was maintained for a period of time discussed in section II F, at sufficient density to absorb all incident solar radiation shortward of $\lambda 2400$.

Because of the Moon's proximity to the more massive Earth, some material produced in the early envelopes near the Moon must nevertheless have been captured by the Earth. For purposes of computation with equation (1), we adopt as a mininum value of r, $r = R$; i.e., we neglect lunar gravitational capture of molecules produced outside a oylinder of lunar radius extending from the Moon to the Sun. This approximation is, of course, very nearly exact

for the secondary lunar atmosphere; but it gives only a lower limit to σ during the times of the solar nebula and the original lunar protoatmosphere.

C. Diffusion Times of Synthesized Molecules

We have mentioned that newly synthesized molecules must rapidly diffuse to depths opaque in the photodissociating ultraviolet if they are to survive. It is very significant that the recent laboratory experiments of Groth (v. section II D) show that photons with wavelengths as long as λ2537 are synthetically as effective as photons with much shorter wavelengths, in the reducing atmospheres he chose. At the present time it is not clear to what extent the absorption at λ2537 in the absence of Hg sensitization is due to the weak predissociation continuum of ammonia and to what extent it is due to, for example, small quantities of aldehydes or aromatics possessing very large ultraviolet absorption cross-sections at these wavelengths, and maintained at some steady state concentration by the ultraviolet light itself. Whatever the primary laboratory absorber turns out to be, the same molecule is expected to exist in the primitive lunar atmosphere, and the same quantum yields should be applicable. However, these two cases have somewhat different consequences for the question of diffusion, and we distinguish them in the following discussion.

Because so many more solar photons were available at λ2600 than at shorter wavelengths in the early lunar envelopes, most of the ultraviolet synthesis of organic molecules must have occurred in the vicinity of unit optical depth for $\lambda > 2600$ Å. If the primary source of near ultraviolet absorption were ammonia, then $\tau = 1$ at $\lambda = 2600$ Å implies $\tau > 1$ at $\lambda < 2600$ Å, because the ammonia absorption coefficient increases with decreasing wavelength. As a consequence, all newly synthesized molecules with photodissociation limits $\lambda_p < 2600$ Å will already be at depths opaque in the photodissociating ultraviolet. Subsequent diffusion and convection will carry them to even deeper levels in the atmosphere, and for such molecules, the fraction which avoids photolysis, $\beta \approx 1$. Many important intermediates in the photoproduction of organic molecules are not photodissociated by $\lambda > 2600$ Å. Among these molecules are the amines, the nitriles, the saturated hydrocarbons, and some unsaturated hydrocarbons. We now discuss the fate of those molecules which are dissociated by $\lambda > 2600$ Å under the assumption of ammonia continuum absorption at these wavelengths. Such molecules include aliphatic aldehydes and ketones, aromatics, and some unsaturated hydrocarbons.

From the theory of gravitational diffusion of Chapman and Cowling (1939) the following expression can be derived for the time for a molecule of molecular mass m_i to gravitationally diffuse from a level characterized by subscript 1 to a level characterized by subscript 2:

$$t_d = \frac{n_1 k T_1 \sqrt{H_1} - n_2 k T_2 \sqrt{H_2}}{1.66 \times 10^{14} g^{3/2} (1 + m/m_i)^{1/2} (m_i - m)(\frac{1}{2} \frac{\partial H}{\partial z} - 1)} \qquad (2)$$

(Nicolet, 1954). In equation (2), n and T are the number density and temperature, respectively, of the atmosphere at the two depths, m is the mean molecular mass of the atmosphere, g is the acceleration due to gravity, $H = kT/mg$ is the scale height of the atmosphere at a given depth, $\partial H/\partial z$ is the rate of change of scale height with altitude, and k is Boltzmann's constant. The numerical factor in the denominator arises from a mean collision cross-section of $\pi (3 \times 10^8)^2$ cm^2; the precise value of this parameter will not affect the conclusions below.

Making the approximations

$$1/2 \quad (\partial H/\partial z) \quad - \quad 1 \quad \approx \quad - \quad 1$$

and

$$(1 + m/m_i)^{1/2} \quad \approx \quad 1,$$

we also set

$$n = \tau / \alpha H,$$

where τ is the optical depth and α the absorption cross-section of the atmosphere at a specified wavelength and at the given atmospheric depth. We then have for the time for the synthesized molecule to diffuse from unit optical depth in the longest effective synthesizing wavelength (here $\sim\lambda 2600$) to unit optical depth in the longest photodissociating wavelength (here $\lambda > 2600$ Å),

$$t_d = 5.5 \times 10^{-11} \frac{T^{1/2} \mu^{1/2}}{g \alpha^{(s)} \alpha^{(p)}} \frac{\alpha^{(s)} - \alpha^{(p)}}{\mu_i - \mu} ; \qquad (3)$$

μ is the mean molecular weight of the atmosphere, μ_i is the mean molecular weight of the synthesized molecule, $\alpha^{(s)}$ is the absorption cross-section of the atmosphere at the longest wavelength which effectively synthesizes molecular species i, and $\alpha^{(p)}$ is the absorption cross-section of the atmosphere at the longest wavelength which photodissociates molecular species i.

To determine β, t_d must be compared with the time between successive absorptions of photodissociating photons, t_a, which at small optical depths at the photodissociation limit is given by

$$t_a = 1/(Q' \alpha_i), \tag{4}$$

where Q' is the photon flux shortward of the photodissociation limit, and α_i is the absorption cross-section of the synthesized molecule of molecular species i at the photodissociation limit.

Because of the rapid decline of the ammonia absorption cross-section longward of λ2600, $\alpha^{(s)} >> \alpha^{(p)}$ should hold for the synthesis of aromatics, aldehydes, etc. in the case that ammonia is the principal absorber at these wavelengths. We expect $\alpha_i >> \alpha^{(p)}$ as well. Taking the most favorable case of $\alpha_i/\alpha^{(p)} \simeq 10$, and with $\mu_i = 30$, $\mu = 10$, $T = 600^{o}$ K, and $g = 160$ cm sec^{-2}, we have from (3) and (4),

$$t_a/t_d \approx 10^{11}/Q'. \tag{5}$$

Thus for the molecule to escape photolysis, the photon flux shortwards of λ_p, where $2600 < \lambda_p < 3200$ Å, must have been less than about 10^{11} photons cm^{-2} sec^{-1}. We will show in section II E that at no time in the history of the later solar nebula, the lunar proto-atmosphere, or the secondary lunar reducing atmosphere was the solar ultraviolet flux so low. Therefore under the above assumptions molecules with photodissociation limits in excess of λ2600 must have been destroyed soon after they were synthesized. This conclusion is relatively insensitive to the particular numerical values chosen in the derivation of equation (5).

In the alternate case that the principal absorbers at $\lambda > 2600$ Å were such molecules as aldehydes, ketones, and aromatic compounds, an absorbing layer must have been established in the lunar atmosphere. The layer was populated photochemically and depopulated by photolysis, by convection and by gravitational diffusion. It differed from the present terrestrial ozone layer in that layer molecules which migrated to lower depths were not instantly destroyed by chemical reaction. At the top of such an optically thick layer, depopulation occurs primarily by photolysis; at the bottom, primarily by convection and diffusion.

Layer molecules will therefore be carried to the surface of the primitive Moon. At the present time, it is not clear whether windows will exist between λ2500 and λ2800 in such an atmosphere. In the experiments of Sagan and Miller (1960) in which molecules were synthesized in simulated primitive terrestrial atmospheres, no major absorbers in this wavelength interval were found. However, only a few cm-atm of such molecules as acetaldehyde will render this wavelength interval opaque. In the case that no window exists, all molecules at the bottom of the absorbing layer will be shielded, and the effective value of $\beta \simeq 1$. In the case that such molecules as acetaldehyde are very rare, and a window between λ2500 and λ2800 exists, then molecules which absorb strongly in this wavelength interval will be rapidly destroyed, and for these molecules, $\beta \simeq 0$. Some studies of the origin of life on Earth (Sagan, 1961) suggest that many aspects of the early evolution of life can be understood if a window between λ2500 and λ2800 did exist in the primitive terrestrial atmosphere. By analogy, a similar window would have existed in the primitive lunar atmosphere. But in either situation most simple gaseous amines, nitriles, and hydrocarbons would have survived, because of very low absorption coefficients in this spectral region. Even for molecules which do absorb between λ2500 and λ2800, it is easy to show that their contribution to atmospheric absorption will generally make $\alpha^{(s)} - \alpha^{(p)}$ small or negative, so that, by equation (3), photodissociation will be avoided.

Thus, regardless of the nature of the principal absorbers in the near ultraviolet, it appears that for such molecules as amines, nitriles, saturated hydrocarbons, and some unsaturated hydrocarbons, photolysis was evaded in the early lunar envelopes. For molecules with ultraviolet absorption at longer ultraviolet wavelengths, such as aldehydes, ketones, aromatics and some unsaturated hydrocarbons, a smaller fraction of those synthesized survived. If these molecules were also responsible for the absorption near λ2600, then β might be within a few orders of magnitude of unity; but if the principal absorption near λ2600 was due to ammonia, then $\beta << 10^{-2}$. Molecules with such small β will have been destroyed efficiently; more complex molecules will be among the dissociation products, but their overall quantum yield must be much less than the values for simpler molecules.

Surviving molecules were then carried by diffusion and convection to the surface.

In the later stages of the evolution of the lunar atmosphere, open bodies of liquid water can be expected on the Moon (v. section II F). Solution of the synthesized molecules in water corresponds to the last step of contemporary laboratory experiments which produce amino acids and other organic molecules from mixtures of reducing gases. We now proceed to discuss these experiments.

D. Quantum Yields

Recently a series of experiments on ultraviolet synthesis of organic molecules which permits quantitative conclusions has been performed by W. Groth in Bonn (Groth and von Weyssenhoff, 1959; 1960). Ethane, ammonia and water vapor were irradiated by the λ1470 and λ1295 lines of xenon in one set of runs, and by the λ2537 line of mercury in another set of runs. The quantum yield for the production of amino acids alone was in both cases between 10^{-4} and 10^{-5}. With no sensitization by mercury atoms during λ2537 irradiation, the quantum yield was about 10^{-5}, only a little less than with mercury sensitization. (Groth, 1959).

The gases irradiated by the xenon lines were circulated over a water bath, while those irradiated by the mercury line were condensed out with water. In the first case the interval between irradiation and immersion for a given molecule was about 0.1 seconds; in the second case the interval between irradiation and condensation was about 1 second (Groth, 1960). The emission in the xenon lines was about 10^{16} quanta sec^{-1}, and the distance from the source to the irradiated molecules was about 2 cm. Thus the flux was about 2×10^{14} quanta cm^{-2} sec^{-1}. Even with an absorption coefficient as large as 10^{-16} cm^2, only 0.02 quanta are absorbed each second. Consequently, the interval between successive photon absorptions for a given molecule was much greater than the time between irradiation and immersion. A similar conclusion follows for the mercury line illumination with about 3×10^{18} quanta sec^{-1} and a source - molecule distance again of a few centimeters. We see that the quantum yields apply only to products which are removed from irradiation before absorbing another photon. In the primitive lunar envelopes this corresponds only to those molecules for which $\beta \gtrsim 1/2$.

In the primitive lunar envelopes, methane, not ethane, was the principal carbon molecule. The quantum yield for the photoproduction of ethane from methane is about 10^{-1} at λ1470 (v., e.g.,

Noyes and Leighton, 1941, p. 419). The number of solar photons available at λ1470 is about 10^4 times smaller than the number available at λ2600, as follows from equations developed in the next section. Thus the effective quantum yield for the photoproduction of ethane from methane in terms of the quanta available at λ2600 is about 10^{-5}. If $1/\phi_1$ quanta are required to produce one ethane molecule from methane, and if $1/\phi_2$ quanta are required to produce one amino acid molecule from ethane, ammonia and water, then the total number of quanta required to produce one amino acid molecule from methane, ammonia and water is

$$1/\phi = 1/\phi_1 + 1/\phi_2,$$

or the net quantum yield for amino acid production from methane, ammonia and water is

$$\phi = \phi_1\phi_2/(\phi_1 + \phi_2). \qquad (6)$$

With our values of ϕ_1 and ϕ_2, we obtain $\phi = 5 \times 10^{-6}$. To be conservative, we adopt for later use $\phi \approx 10^{-6}$. This computation should be checked experimentally. However, quantum yields (for the production of relatively simple molecules) $\geq 10^{-6}$ are practically inevitable in the photochemistry of such gases. Note that since ϕ_2 is independent of wavelength between λ1470 and λ2537, and ϕ_1 is already adjusted for wavelength, ϕ should be wavelength-independent in this same range, an assumption which was made in the derivation of equation (1).

From equation (4) and the photon fluxes derived in the following section, it is easy to see that for all reasonable temperatures and densities at the synthetic level of the primitive lunar envelopes, the time between collisions is much shorter than the time between successive absorptions of quanta effective in either synthesis or dissociation. Since many collisions follow each synthesis, the difference in pressures, temperatures, and densities between contemporary laboratory and primitive lunar environments should not significantly affect the overall quantum yields.

The preferential depletion of photochemically-produced aldehydes, ketones, aromatics, and some unsaturated hydrocarbons on the early Moon (Section IIC) will make the primitive lunar end-products differ from the contemporary laboratory end-products; but the overall quantum yields for organic matter should be unchanged. In the laboratory experiments in which corona discharges are used as the energy source, aldehydes have been shown to be intermediaries in the synthesis of amino acids (Miller, 1957). It is

not known whether aldehydes play a similar role in ultraviolet synthesis of amino acids. If they do, it is possible that the amino acid fraction of the primitive lunar organic matter was much less than the amino acid fraction in the laboratory. But it should be emphasized that 85% of the organic material produced in the corona discharge experiments is not amino acids and has not been identified (Miller, 1957). A similar residue should be expected in the ultraviolet experiments. It is clear that much of the residue will not have aldehydes, etc. as precursors. For example, saturated higher hydrocarbons are known to be produced photochemically from a mixture of methane, ammonia, water, and hydrogen; the quantum yields are larger than 10^{-6} (v., e.g., Noyes and Leighton, 1941). It is difficult to predict which organic compounds were produced on the primitive Moon, but it is very probable that the appropriate quantum yields were not smaller than 10^{-6}.

E. Ultraviolet Fluxes and Solar Evolution

The number of quanta emitted between frequency ν and $\nu + d\nu$ each second by each square centimeter of a black body at temperature T is given by the Planck distribution function,

$$\pi F_\nu d\nu = \frac{8\pi\nu^2}{c^2} \left[e^{h\nu/kT} - 1 \right]^{-1} d\nu \qquad (7)$$

where c is the velocity of light, and h and k are, respectively, Planck's and Boltzmann's constants. For solar photospheric temperatures and ultraviolet frequencies, $h\nu/kT \gg 1$, and eq. (7) reduces to the Wien approximation,

$$\pi F_\nu d\nu \approx \frac{8\pi\nu^2}{c^2} e^{-h\nu/kT} d\nu. \qquad (8)$$

The photon flux emitted at all frequencies larger than some reference frequency ν_o is obtained by integrating eq. (8) from ν_o to infinity:

$$\pi F = \int_{\nu_o}^{\infty} \pi F_\nu d\nu \approx 8\pi \frac{kT}{hc^2} \nu_o^2 e^{-h\nu_o/kT}. \qquad (9)$$

To find the photon flux shortward of wavelength $\lambda_o = c/\nu_o$ in the neighborhood of the Moon, πF must be multiplied by a geometrical dilution factor which allows for the inverse square attenuation of intensity with distance. If the radius of the solar photosphere is R

and the mean distance between the Sun and the Moon is a, the geometrical dilution factor is

$$W = R^2/4\,a^2 . \qquad (10)$$

In the case there is absorbing material between the Sun and the lunar atmosphere, an additional physical dilution factor less than unity must be included. Such a factor is appropriate only to the times of the early solar nebula before the clearing out of interplanetary space by solar corpuscular radiation (see section II B), and we neglect it here. Combining equations (9) and (10), we find for the photon flux shortward of λ_o at the top of the lunar atmosphere at times when the equivalent solar black body temperature in the ultraviolet is T and the radius of the solar photosphere is R,

$$Q = 2\pi \frac{kT}{h\lambda_o a}\left(\frac{R}{a}\right)^2 e^{-hc/\lambda_o kT} . \qquad (11)$$

To apply equation (11), R and T must be known for previous epochs.

During the period of the Sun's Helmholtz-Kelvin gravitational contraction, its evolutionary track in the Hertzsprung-Russell diagram was approximately along the line $L\,R^{0.78} = \text{const.}$, where L is the solar bolometric luminosity (Henyey, Levée, and LeLevier, 1955). As the interior temperatures rose to the point where thermonuclear energy sources became competitive with gravitational energy sources, the evolutionary track dipped to lower luminosities, joining the main sequence tangentially. The solar nebula is believed to have existed during this period of pre-main sequence contraction. Assuming that the effective ultraviolet temperature is proportional to the mean bolometric temperature, a typical value of T during pre-main-sequence contraction can be read off the evolutionary track of Henyey et al. Using the subscript $\odot$ to indicate present solar values, at a time when $L \approx L_\odot$, $\Delta \log T = \log T - \log T_\odot \approx -0.05$. The present solar flux in the region of $\lambda 2600$ is that of a black body of temperature about 5000° K (Tousey, 1955). Thus at a typical time during the early history of the solar nebula when the bolometric luminosity was approximately that of the present Sun, the temperature near $\lambda 2600$ was about 500° K less, $T \approx 4500^\circ$ K. Since the luminosity is proportional to $R^2 T^4$, the photospheric radius at this time is easily seen to be about $1.2\,R_\odot$. With these values for R and T, and with $\lambda_o = 2600$ Å, equation (11) yields $Q = 1.3 \times 10^{14}$ quanta $cm^{-2}\,sec^{-1}$. At a much earlier time, near the beginning of the evolutionary track of Henyey et al., $T \approx 4000^\circ$ K, $L \approx 0.6\,L_\odot$, $R \approx 1.2\,R_\odot$, and $Q \approx 2.3 \times 10^{13}$ quanta $cm^{-2}\,sec^{-1}$. We see that, except for very early times in the history of the solar nebula, the

flux of photons of wavelength shorter than λ2600 was always greater than the critical value of section II C, $Q \approx 10^{11}$ quanta cm^{-2} sec^{-1}, beyond which aldehydes, ketones, aromatics and some unsaturated hydrocarbons are photodissociated before reaching atmospheric layers thick enough to provide shielding.

We are now interested in the radiation flux after the Sun's evolutionary track has joined the main sequence, and the dissipation of the solar nebula has been completed. At the junction with the main sequence some 5×10^9 years ago, the luminosity was about half a bolometric magnitude less than at present, and the radius about 0.87 $R_\odot$ (Henyey, Levée, and LeLevier, 1955; Schwarzschild, Howard, and Härm, 1957; Hoyle, 1958). 10^9 years later, about 4×10^9 years ago, the solar radius was about $0.90 R_\odot$, while the solar luminosity had increased from about 0.69 $L_\odot$ to about 0.73 $L_\odot$ (Hoyle, 1958). The effective ultraviolet temperatures at the two times were about the same (0.975 $T_\odot$). From equation (11), the quiet solar ultraviolet fluxes at wavelength shortward of λ2600 in the vicinity of the Moon at both these times is computed to be $Q \approx 4 \times 10^{14}$ quanta cm^{-2} sec^{-1}, at $\lambda < 2400$ Å, $Q \simeq 9 \times 10^{13}$ cm^{-2} sec^{-1}; at $\lambda < 2000$ Å, $Q \simeq 2 \times 10^{13}$ cm^{-2} sec^{-1}.

F. Lifetime of Secondary Lunar Atmosphere

The time for the density of a planetary atmosphere to be reduced to 1/e its initial value by escape to space is determined by the value of T_c, the temperature at the critical level in the atmosphere above which a molecule moving outward with the velocity of escape is unlikely to encounter another molecule. If $H = kT_c/mg$ is the scale height at the critical level, and R is the planetary radius, the time of escape can be conveniently expressed as

$$t_1 \approx 2.5\, B\, (H/g)^{1/2}\, (1 + R/H)^{-1}\, e^{R/H}. \qquad (12)$$

A similar expression without the factor B was first derived by Jeans (1916). The correction factor B was introduced by Spitzer (1952) to allow for the non-isothermality of real planetary atmospheres.

For the early lunar atmospheres, the appropriate values of T_c and B depend on the detailed structure of the atmospheres, and cannot be specified precisely. However, it is obvious that the value of t_1 is small compared with geological time. If, for example, we take $T_c = 1000^\circ$ K., and the corresponding contemporary terrestrial value for B, $B \simeq 5 \times 10^5$ (Spitzer, 1952), the time for the lunar atmosphere to fall in density by a factor of 1/e is $t_1 \approx 10^3$ years. Other choices for T_c and B give similarly small results for t_1.

Hence the lifetime of the secondary lunar atmosphere depended entirely on the supply rate of gases from the lunar surface and interior.

Although it is unlikely that the lunar craters are volcanic in origin, there is evidence of extensive igneous activity in the early history of the Moon. The maria are probably frozen lava flows (v., e. g., Baldwin, 1949; Urey, 1952; Kuiper, 1954). About twenty large features have been observed on the Moon which are classified as extinct volcanoes. They are of the order of 10 km in diameter; most have central calderae (v., e. g., Kuiper, 1959a). From published photographs and from visual inspection with large telescopes, there seems little doubt as to their volcanic nature. Associated with them are lower, larger objects which Kuiper (1959a) identifies as volcanic sinks. Reports of contemporary lunar volcanic activity will be critically discussed in section III, below.

Outgassing of the lunar interior must have released material deposited there during the formation of the Moon. Since conditions at those times were highly reducing, the secondary lunar atmosphere resulting from outgassing must also have been reducing. Most of the products of contemporary terrestrial volcanic exhalations are oxidizing, but much of this material arises from recirculated ground water, and is not juvenile in origin.

A further consideration of relevance is the lifetime of open bodies of water on the early Moon. The temperatures on the primitive Moon must have been much less extreme than on the contemporary Moon, because of a greenhouse effect initiated by such molecules as NH_3, CH_4, and H_2O. If we assume that the mean temperature was no higher than 20° C, the vapor pressure over liquid water was < 20 gm cm^{-2}. The characteristic escape time of a water molecule was about 10^3 years. Hence the average escape flux was $< 10^{-9}$ gm cm^{-2} sec^{-1}. If the Moon started with the present terrestrial complement of liquid water, about 10^5 gm cm^{-2}, bodies of water would have remained for $> 3 \times 10^7$ years. For this interval, at least, there would have been an appreciable atmosphere. Thus it is not impossible that the relevant lifetime of the secondary lunar atmosphere—during which organic molecules were produced in the atmosphere and dissolved at the surface—was as long as 10^7 or 10^8 years.

G. Surface Densities of Deposited Organic Matter

We are now in a position to return to equation (1) and estimate the amount of organic matter synthesized in the primitive lunar

atmospheres, and deposited on the surface. For example, with $r \approx R$, $\beta \approx 1$, $\mu \approx 100$, $\phi = 10^{-6}$, $Q = 4 \times 10^{14}$ cm^{-2} sec^{-1}, and $t = 3 \times 10^{14}$ secs, we find $\sigma = 5$ gm cm^{-2} of amino acids. If such molecules as aldehydes or aromatic compounds were effective in near ultraviolet absorption, wavelengths longer than $\lambda 2600$ would have produced organic matter; thus Q and σ would be larger. On the other hand, if only $\lambda < 2000$ Å was effective, σ would be ~ 0.3 gm cm^{-2}. Miller and Groth find efficient production of other substances besides amino acids, some with greater quantum yields (especially formic and acetic acids) and many with lesser quantum yields. In the example the total organic matter deposition is probably near 10 gm cm^{-2}. In Table I, we have tabulated total organic matter depositions for the range of likely values of ϕ and t, and with $\lambda_o = 2600$ Å.

Table I suggests that very considerable surface densities of organic molecules were produced from the solar nebula and lunar protoatmosphere ($t = 10^7$ to 10^9 years). However, most of this material rained down while the Moon was still being formed, and therefore must either be buried at great depths below the present lunar surface, or, more likely, was thermally dissociated in the outgassing processes which evolved the secondary lunar atmosphere. Organic matter produced in the secondary lunar atmosphere appears to have a much better chance of residing near the present lunar surface and having avoided dissociative processes (cf. section II H below). The overall deposition of organic matter after the Moon's formation may well have been as great as 10 gm cm^{-2}.

TABLE I

Lunar Organic Matter Surface Densities in gm cm^{-2}

t in years	ϕ 10^{-5}	10^{-6}	10^{-7}	Envelope
10^4	10^{-1}	10^{-2}	10^{-3}	Secondary lunar atmosphere
10^5	1	10^{-1}	10^{-2}	
10^6	10	1	10^{-1}	
10^7	10^2	10	1	
10^8	10^3	10^2	10	Lunar protoatmosphere
10^9	10^4	10^3	10^2	Solar nebula

H. Protection of Deposited Molecules and Present Location of Lunar Deposits of Organic Matter

During the time of deposition, the lunar atmosphere would have inhibited thermo- and photo-dissociation of the deposited molecules. As the secondary lunar atmosphere gradually escaped to space, and outgassing declined, the rate of atmospheric organic synthesis decreased and the penetration of short wavelength radiation to the surface increased. In addition, the surface temperature gradually rose, due both to the loss of the insulating atmosphere, and to radioactive heating. The effect of heat and ultraviolet light on the molecules described 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 (v., e.g., Oparin, 1957; Fox, 1956). Finally, because complex molecules are more resistant to heat and radiation than are simpler molecules (at least in part due to the Franck-Rabinowitch cage effect), the syntheses are biased towards the net production of the most complex organic molecules (Gordy, Ard, and Shields, 1955; Sagan, 1957).

Although continued radiation and high temperatures 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 (1959) estimates that about 50 gm cm^{-2} of meteoritic matter 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 it is 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. With a temperature fluctuating mildly about 20° C., the thermostability halflives of many organic molecules are of the order of the age of the Solar System (Abelson, 1954). Temperatures of this order or lower are expected beneath a few centimeters of surface (cf. section VI A below).

Making the approximations that the rate of meteoritic infall has been constant in time at the present value, and that the mass of

surface material escaping to space because of infall is much less than the mass accreted because of infall, we find that the layer of organic matter is localized at a depth of a few tens of meters. Provided that no large-scale destructive events have occurred subsequent to deposition, we may anticipate a mean surface density of organic matter in this layer of perhaps 10 gm cm^{-2}. If meteoritic infall causes appreciable mixing of the surface material, then the organic matter should be distributed through the upper lunar surface to a depth not exceeding a few tens of meters. The organic matter should be expected only in 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.

The recent discovery of a dust belt around the Earth (A. R. Hibbs, J. Geophys. Res., 66: 371, 1961; F. L. Whipple, Nature, 189: 127, 1961) implies that not all the micrometeorites detected by impact with satellite and probe vehicles are on collision trajectories with the Earth. Consequently the rate of meteoritic deposition on the Earth is less than previously thought, and the lunar meteoritic dust layer will be reduced in depth. If all impacting meteoritic debris remains on the Moon, if there is no appreciable stirring, and if the rate of infall is constant with time, then the layer of organic matter will be localized at a depth perhaps considerably less than several tens of meters. The mean temperatures at this depth will be lower, and the temperature variation will be greater, than has been estimated above. These considerations would make the survival of lunar prebiological organic matter or life-forms somewhat more unlikely. However, it should be recalled that the rate of meteoritic infall was probably far greater in primitive times than it is today. In addition, some studies of radio scattering from the Moon indicate that in certain areas the surface dust layer may well be several tens of meters thick (K. M. Siegel, private communication, 1961). The resolution of this problem must await more definitive investigations of the lunar surface.

I. Conclusions and Suggested Experiments

We have concluded that at a depth of some tens of meters below the present lunar surface there may be localized a layer of organic material deposited during the period in which the Moon possessed a reducing atmosphere opaque in the ultraviolet. The value of the surface density is difficult to estimate, primarily due to the uncertainty in the lifetime of the secondary reducing atmosphere. But from Table I it is clear that instrumentally-detectable amounts should exist. A reasonable estimate would be one to ten gm cm^{-2}.

A qualitative analysis of such organic matter would provide important information on the types of molecules produced in prebiological organic syntheses on the Earth and elsewhere; it would furnish clues for the laboratory simulation of prebiological organic evolution, and for the reconstruction of pathways which lead to the origin of life. A quantitative analysis would supply evidence on the nature and lifetime of early lunar gaseous envelopes, on current theories of stellar evolution, and on hypotheses concerning the origin and early history of the Solar System.

Instrumentation is required to recover boring cores from a depth of perhaps several tens of meters, perform simple qualitative and quantitative analyses, and transmit the information back to Earth. The simplest analytic technique would be to determine the vapor pressure of cores from various depths as a function of temperature. This could identify many of the major categories of organic molecule, and could easily distinguish organic matter from silicates, irons, and residual ices. The temperature variation might be provided by the lunar day-night cycle itself. For more detailed analysis the relative merits and feasibilities of remote gas and paper chromatography, remote spectroscopy, and remote reagent analytic chemistry should be investigated. There is an obvious advantage for the subsurface probing device to be incorporated in a roving lunar surface vehicle; for example, mare and non-mare cores could be compared. Such instrumentation would have a wide range of non-lunar applications, the terrestrial sub-oceanic and Martian surface environments being the two most obvious.

III. REPORTS OF GAS CLOUDS ON THE LUNAR SURFACE

From time to time there have been reports—primarily by British amateur astronomers with small telescopes—of low-lying gas clouds or 'mists' on the lunar surface (v., e. g., Moore, 1952). The clouds are said to be detected either by their high albedo, or by their obscuration of surface detail. Similar observations have in general not been made by professional astronomers with large instruments; e. g., Kuiper (1960), in a continuing program of lunar visual observations with the 82-inch reflector of McDonald Observatory during the last decade has never observed cloud-like features on the surface of the Moon. Whittaker (1960) explains the mist reports as uncritical interpretations of the occasional absence of familiar fine detail because of poor seeing conditions. This explanation seems especially appropriate for the British Isles.

Alter (1957) has obtained photographs of the region of the crater Alphonsus, which show less contrast in the photographic infrared than in the visible. A gas cloud or haze would give a similar effect. However, Alter's obscuration seems—at least in the published prints—not to be restricted to the floor of the crater, but appears to cover the entire photographed area. The possibility must be raised that the difference in contrast arises in the terrestrial atmosphere rather than in a lunar gas cloud.

In 1958, N. A. Kozyrev claimed to have made spectroscopic observations of a reddish cloud in Alphonsus, which indicated the presence of carbon compounds on the Moon. Because of the peculiar circumstances surrounding this observation, and its obvious importance if verified, it will pay to examine it in some detail.

Kozyrev (1959a; v. also Alter, 1959) maintains the following: He was observing with the 48-inch reflector of the Crimean Astrophysical Observatory on November 3, 1958, with a spectrometric dispersion of 23 Å/mm, and photographing the spectrum with Kodak 103 a - F emulsion plates. While guiding the slit of the spectrograph on the central peak of Alphonsus, he noticed a reddish cloud enveloping the peak. He stopped the exposure he had been taking and inserted another plate. After a 30-minute exposure, the cloud appeared to have dissipated. Kozyrev then stopped this exposure and took a third spectrogram, this time with a ten minute exposure.

Development of the 30-minute spectrogram showed, in addition to the solar Fraunhofer absorption lines, emission features which were absent or only barely perceptible on the preceding and following plates. The wavelengths of these features agreed with the wavelengths of the molecules C_2 and C_3 familiar in cometary spectra. He concluded that the molecules were outgassed from the lunar interior in a volcanic eruption, and exhibited emission bands due to the cascade of absorbed solar ultraviolet photons to lower molecular energy levels (fluorescence).

Kozyrev delayed a week in announcing his discovery, so that when announcement was made Alphonsus was in the dark; two weeks were to pass before Alphonsus was again illuminated and corroboratory observations could be attempted. Then, a number of amateur observers (e. g., Poppendiek and Bond, 1959; Hole, 1959) claimed to have observed clouds in the vicinity of the central peak of Alphonsus; Poppendiek and Bond, with a 6-inch reflector, saw a diffuse white cloud on November 18, and Hole, with a 24-inch reflector, saw a small reddish cloud on November 26. On the other hand, Kuiper (1958) with the 82-inch McDonald reflector, and Focas with the superb seeing conditions at Pic du Midi, were unable to detect any unusual features in the vicinity of Alphonsus in the second half of November. Haas (1959) was observing Alphonsus at about the same time as Poppendiek and Bond and with a larger instrument; he observed no cloud. Hole thought he had photographic evidence of an increased emissivity in the red for Alphonsus, but then found that the photographic redness of Alphonsus was present on old photographs as well. The supplementary visual and photographic evidence for Kozyrev's observation does not seem very convincing.

The published spectra (Kozyrev, 1959a) and glossy prints available in the United States from Soviet sources show a broad diffuse structureless feature extending for at least 800 Å shortwards of the vicinity of λ4700. No other features besides the Fraunhofer lines are evident. The dominant features of C_2 in cometary spectra are the Swan bands, $B\ ^3\pi_g \longrightarrow X\ ^3\pi_u$, of which the 1 - 0 vibrational transition has a band head at λ4737. The relative transition probability of the 1 - 0 transition (λ4737) is $f = 0.36$; for 1 - 1 (λ5129), $f = 0.6$; for 1 - 2 (λ5585), $f = 0.4$ (Phillips, 1957); and from the Franck-Condon principle it can be seen that all other transitions from $v' = 1$ have smaller f-values. Since the transition probabilities are atomic quantities uninfluenced by the pressure, temperature, and density of the gas, the 1 - 1 transition must occur about half again as often, and the 1 - 2 transition about as often, as the 1 - 0 transition, regardless of the mechanism of excitation of the $B\ ^3\pi_g$ $v' = 1$ energy level. A

selective quenching of $X\ ^3\pi_u\ v' > 0$ levels is impossible; in its absence, the λ5129 and λ5585 bands should be at least as intense as the λ4737 band. λ5585 is beyond the edge of the available spectra, and is in a region of low sensitivity of the 103 a-F emulsion; but the λ5129 feature should appear strongly. Yet the region just short of the λ5184 Fraunhofer Mg triplet is remarkably devoid of detail. Kozyrev claims that the λ5129 feature appears on the original plates (Alter, 1959), but if it appears in the theoretically required strength on the plates, it must be easily visible on the prints, which it is not. This difficulty, first pointed out by Kuiper (1959b, 1959c), is a fundamental one. Unless some physically reasonable mechanism for the absence of the $B\ ^3\pi_g\ (v' = 1) \longrightarrow X\ ^3\pi_u\ (v'' = 1)$ line of C_2 can be proposed, the identification of C_2 above Alphonsus must be discounted. On the prints there is no sign of the C_3 bands in the λ4000 region, which Kozyrev says can be seen 'clearly' (Alter, 1959), and the evidence for C_3 seems nonexistent. In addition, Öpik (1960) points out that if an emitting gas were to expand adiabatically from the peak of Alphonsus for a period of thirty minutes, a spectrum taken during this interval should show emission from the area of the entire crater. Kozyrev's spectrum shows emission from the central peak only, and Öpik finds it difficult to understand how the observations can be explained as gas emission. However, if the gas were emitted from a fissure or volcanic cone at a temperature $\sim 10^4\ ^\circ K$, lunar escape velocity would be achieved, and the expanding cloud would have a conical envelope of small half-angle. But there is no evidence for such high temperatures.

Because of these difficulties, some astronomers have privately confessed doubts as to the authenticity of Kozyrev's observations themselves. However, the observations were witnessed by several astronomers at the Crimean Astrophysical Observatory, and the developed plates were examined the following day by Boyarchuk, Orletzky, and Prokoffiev (Boyarchuk, 1960). It would therefore appear that <u>something</u> was occurring on or above the central peak of Alphonsus on the evening of November 3, 1958. Very recently the spectroscopist A. A. Kalinyak has supported Kozyrev's identification of C_2 and C_3 (v. N. Calder, New Scientist, <u>8</u>: 1636, 1960), although the details have not yet been published.

The conclusion that the observations were not of a carbon-compound gas cloud is reached with great reluctance, because the most likely precursors of C_2 and C_3 would be hydrocarbons and other organic molecules, as is probably the case for comets. A verified observation of C_2 and C_3 above the Moon would have been strong evidence for lunar subsurface organic matter.

IV. LUNAR SUBSURFACE TEMPERATURES

Kozyrev attributed his gas cloud to lunar vulcanism. In an effort to provide an alternative explanation, Fremlin (1959a) made a proposal which we now discuss. It should be emphasized that Fremlin's argument in no way depends on the validity of Kozyrev's reported observations.

Portions of the Moon's surface are considered to be composed of dust particles in close physical contact. Because of the increase of hydrostatic pressure with depth, particle contact and hence the effective thermal conductivity also increase with depth, the derived relation for simple geometry being

$$k_e = 7 \times 10^{-7} \; h^{1/2}, \tag{13}$$

where k_e is the effective conductivity in cal cm^{-1} sec^{-1} C^{o-1}, and h is the depth in cm. Radioactive heat, released in the lunar interior, will tend to be localized at the depths of greatest thermal conductivity. The increase of temperature with depth from this cause is given by

$$\Delta T/\Delta h = J/k_e, \tag{14}$$

where J is the heat flux due to radioactive decay in cal cm^{-2} sec^{-1}. With a flux of 8.4×10^{-6} cal cm^{-2} sec^{-1}, Fremlin derived a temperation of about 750°C at a depth of 10 meters. He postulated that at some depth the temperature becomes so high that phase changes occur in the dust, volatiles being released as gases; with the remainder of the dust at this critical level melting and cooling. Afterwards the particulate nature of the level has been destroyed, and the heat localization effect is operative henceforth only above this level.

Jaeger (1959) has criticized the numerical values of conductivity and flux adopted by Fremlin. The high value assumed by Fremlin for the heat flux would prevent the Moon from having the tensile strength required to maintain its nonequilibrium figure, and this part of Jaeger's criticism is undeniably valid. But Fremlin (1959b) has adequately answered Jaeger's criticism of the adopted value for k_e; a surface composed of both dust layers of low

conductivity and relatively bare rock of higher conductivity is in no conflict with microwave and eclipse observations.

Taking a terrestrial value for the radioactive heat flux of $J = 1.2 \times 10^{-6}$ cal cm^{-2} sec^{-1}—a factor of seven smaller than Fremlin's value—we find from equations (13) and (14).

$$\Delta T \approx 1.7\, h^{1/2}\ C^{o},$$

so that at a depth of ten meters the excess temperature is 54 C^{o}. With $J = 2.3 \times 10^{-7}$ cal cm^{-2} sec^{-1}, a value characteristic of chondritic meteorites,

$$\Delta T \approx 0.33\, h^{1/2}\ C^{o},$$

so that at a depth of ten meters the excess temperature is 10 C^{o}. From microwave observations it is known that the temperatures less than half a meter below the surface vary between 0^{o} and - 70^{o}C during a lunar day and night (Piddington and Minnett, 1949). The temperature variation is damped with depth, and at about ten meters should be no more than a few C^{o}. We conclude that time-constant biologically-optimum temperatures exist a few tens of meters under those areas of the Moon composed of congealed dust particles.

V. POSSIBILITY OF AN INDIGENOUS LUNAR PARABIOLOGY

Because of its great potential importance, the admittedly very speculative possibility must be raised that, at some time in the remote past, life arose on the Moon. Conditions on the Moon while it still retained its secondary reducing atmosphere some 4 or 5×10^9 years ago were probably not very different from conditions on the Earth during the same epoch. Organic matter was being produced, bodies of liquid water probably abounded, and energy was available for higher order syntheses. How these conditions might lead to the origin of life has been described elsewhere (v., e. g., Oparin, 1957; Sagan, 1957). Recent thinking is increasingly inclined towards a very rapid origin of the first self-reproducing system on this planet. If a similar event also occurred on the Moon, natural selection may be expected to have kept pace with the increasingly more severe lunar environment, at least for some period of time. As the lunar atmosphere escaped to space, surface temperatures and radiation fluxes became more extreme, and meteoritic debris began covering the synthesized organic matter, it is only reasonable to anticipate that any indigenous organisms took to a subsurface existence.

It is remarkable that the depth at which surviving lunar organic matter is expected to be localized (section II) is just the depth at which temperatures appear to be optimum for familiar organisms (section IV). At such temperatures and depths, some moisture should be expected, arising from meteoritic and organic bound water. Watson, Murray and Brown (1961) have recently pointed out that ice could have been retained on permanently shaded areas of the Moon. These circumstances provide all the survival requirements of many terrestrial organisms—water and other metabolites, appropriate temperature, and negligible radiation. That autochthons evolving with the changing environment could also survive under these conditions is far from inconceivable. A somewhat analogous case is the anaerobic microflora which inhabit terrestrial petroleum deposits (v., e. g., Davis and Updegraff, 1954; ZoBell, 1950). It follows that the possibility of an extant lunar parabiology must not be dismissed in as cavalier a manner as it has been in the past. As we shall see in section VI, it is likely that relics of past lunar organisms, if any, could be preserved indefinitely if sequestered well beneath the protective cover

of the upper lunar surface material. Thus, neither should the possibility of lunar paleontology be overlooked. It is probably unnecessary to remark that the study of any extraterrestrial organism will have the deepest influence on the fundamental problems of biology. Even if the chances of success are small, attempts should be made to detect lunar subsurface autochthons, both living and dead.

VI. SURVIVAL OF CONTEMPORARY TERRESTRIAL MICROORGANISMS ON THE MOON

We now turn to the problem of the survival of contemporary terrestrial organisms in the lunar environment. This problem is directly relevant to the question of biological contamination of the Moon; it also has a bearing on the panspermia or cosmobiota hypothesis, and on the possibility of survival to the present of lunar organisms or their remains, produced in the distant past.

There seem to be three major hazards for survival of terrestrial life on the Moon—temperature, corpuscular radiation, and solar electromagnetic radiation—which we discuss below. The probable absence of oxygen, water, and other substances from the lunar surface is not, of course, evidence against survival, particularly of dormant anaerobic microorganisms; but it does preclude their reproduction on the surface of the Moon.

A. Temperature Lability

Surface temperatures range from about + 100°C to about - 180°C during the course of a lunar day and night (Wesselink, 1948). However, just beneath the surface, temperatures are much more moderate; at a depth of less than half a meter, microwave radiation data indicate a temperature variation between 0° and - 70°C (Piddington and Minnett, 1949).

It is well known that many microorganisms have extreme resistance to low temperatures, especially in the dried state and in vacuo. An especially relevant example is the experiments of Becquerel (1909, 1910) in which bacterial spores were kept at temperatures below - 180°C for periods greater than the length of the lunar night, and remained viable.

Similarly, drying and evacuation greatly increase the tolerance of microorganisms to high temperatures. Even at temperatures approaching 100°C survival of a significant fraction of the total number of vegetative bacterial cells and spores may be expected (Zamenhof, 1959, 1960). Still higher temperatures are required to inactivate desoxyribonucleic acid (Zamenhof, Alexander, and Leidy, 1953).

Thus, because of the dry vacuum conditions of the lunar surface, the temperature extremes appear not to be a serious hazard. Especially since it is likely that many of the deposited microorganisms will find themselves lodged just beneath the surface (section VI E below), the debilitating effects of the lunar surface temperatures can be neglected.

B. Deflection of Incident Charged Particles by the Lunar Magnetic Field

Cosmic rays, charged particles emitted by the Sun, and continuous and discrete solar electromagnetic radiation are all incident on the Moon. Whether they arrive at the lunar surface, however, depends on the existence of a lunar magnetic field and a lunar atmosphere.

The work of Biermann on the acceleration of comet tails indicates a flux of solar protons in the vicinity of the Moon of about 5×10^{10} protons cm^{-2} sec^{-1}, and a mean particle energy of about 1 KeV (v., e.g., Reiffel, 1959). Charged particles will be excluded from regions where the magnetic energy density exceeds the particle kinetic energy density; i.e., for magnetic deflection the magnetic field strength must satisfy the condition

$$B > (4 \pi \rho)^{1/2} v, \tag{14}$$

where ρ is the mean density of incident particles, and v the mean particle velocity. Thus for the solar proton stream, the deflection condition on the lunar surface magnetic field strength is

$$B > 10^{-2} \text{ gauss}. \tag{15}$$

The mean density of the Moon is comparable with that of terrestrial surface material. This has always been understood as indicating the absence of an extensive liquid iron core, and presumably the absence of an appreciable lunar magnetic field as well. Preliminary data from Lunik II indicate a surface field of $< 3 \times 10^{-4}$ gauss (Sedov, 1959); and in this case, solar protons would not be affected significantly by the lunar magnetic field. However, Neugebauer (1960) has called attention to the possible masking of the lunar field in the illuminated hemisphere by the solar protons themselves. At the present writing, it is not known whether inequality (15) is satisfied. If the lunar magnetic field strength is much less than the terrestrial, then low-energy cosmic rays which are deflected by the Earth's field will arrive in the vicinity of the Moon.

C. Attenuation of Incident Radiation by the Present Lunar Atmosphere

From lunar occultations of cosmic radio sources, it can be estimated that the lunar atmosphere contains less than 10^{14} molecules above each square centimeter of surface (Costain, Elsmore and Whitford, 1956; Edwards and Borst, 1958). Ultraviolet absorption cross-sections for all molecules likely to be in the lunar atmosphere are generally less than 10^{-16} cm^2 at all wavelengths, except in the centers of resonance lines. Hence the optical depth in the ultraviolet is less than 10^{-2}, and there is no attenuation of incident solar ultraviolet radiation by the lunar atmosphere. For the solar proton wind, a 1 KeV proton has a range of about 10^{-2} cm-atm, or, roughly 3×10^{17} molecules cm^{-2}. Consequently, if the lunar magnetic field strength is less than about 10^{-2} gauss, the solar proton stream strikes the Moon's surface with negligible loss of energy due to its passage through the tenuous lunar atmosphere. A similar conclusion applies to the more energetic cosmic rays.

D. Adopted Fluxes, Mean Lethal Doses, and Absorption Coefficients

We now consider the effects of these radiations on terrestrial microorganisms deposited on the lunar surface. We consider microorganisms because they are known to be much less radiosensitive than other life-forms (v., e. g., Bacq and Alexander, 1955), at least in part because there is less which can go wrong in a simple organism than in a complex one. In addition, the accidental deposition of many microorganisms on the lunar surface is a much more likely contingency than the accidental deposition of large numbers of other life-forms, particularly for the immediate future.

In the appendix, expressions are derived (eqs. A-7 and A-8) for the time in which a population of N_o organisms, having a mean lethal dose, D, for a given radiation, and characteristic dimensions, a, is reduced to N organisms by radiation of intensity I. In Table II, these lifetimes are tabulated for a number of values of N/N_o and a. The intensities are those appropriate to the lunar surface for negligible atmosphere and magnetic field strength, and so are equally appropriate to interplanetary space in the vicinity of the Earth-Moon system. Consequently the derived lifetimes are also those of an unprotected microorganism in free space, and so have a bearing on the panspermia or cosmobiota hypothesis (v., e. g., Oparin, 1957; Lederberg and Cowie, 1958). The X-ray emission in Table II is taken from a theoretical study of the solar corona

TABLE II

Lifetimes of Deposited Microorganisms on the Moon

Radiation	Intensity in ergs cm^{-2} sec^{-1}	Adopted MLD	Adopted ρ/μ in $gmcm^{-2}$	a in cm	Lethality times in seconds N/No 10^{-1}	10^{-5}	10^{-10}	10^{-15}	10^{-20}	Charring time in seconds $N/N_o = 10^{-15}$
Ultraviolet continuum λ3000 to λ2000	10^4	10^7 erg cm^{-2}	opaque		$2x10^3$	$1x10^4$	$2x10^4$	$3x10^4$	$5x10^4$	--
Ultraviolet continuum λ2000 to λ1000	10^2	10^6 erg cm^{-2}	opaque		$2x10^4$	$1x10^5$	$2x10^5$	$3x10^5$	$5x10^5$	--
Solar proton wind, quiet sun	10^2	10^7 rep	10^{-5}	10^{-3}	$2x10^4$	$1x10^5$	$2x10^5$	$3x10^5$	$5x10^5$	$2x10^8$
				10^{-4}	$2x10^3$	$1x10^4$	$2x10^4$	$3x10^4$	$5x10^4$	$2x10^7$
				10^{-5}	$3x10^2$	$2x10^3$	$3x10^3$	$5x10^3$	$8x10^3$	$2x10^6$
Soft x-rays λ ~ 50 Å, quiet sun	10^{-1}	10^7 rep	10^{-3}	10^{-3}	$2x10^8$	$9x10^8$	$2x10^9$	$3x10^9$	$3x10^9$	$3x10^{12}$
				10^{-4}	$1x10^7$	$5x10^7$	$1x10^8$	$2x10^8$	$2x10^8$	$2x10^{11}$
				10^{-5}	$1x10^7$	$5x10^7$	$1x10^8$	$2x10^8$	$2x10^8$	$2x10^{11}$
Cosmic rays, quiet sun	10^{-3}	10^7 rep	400	almost transparent	$4x10^{14}$	$2x10^{15}$	$4x10^{15}$	$6x10^{15}$	$8x10^{15}$	$6x10^{18}$

(Elwert, 1954) and is consistent with rocket observations at quiet Sun. The continuous ultraviolet intensities are computed from an integration of the Planck equation (eq. 11) for appropriate ultraviolet effective black body temperatures (Tousey, 1955). The cosmic ray flux is scaled from surface values to values expected outside the Earth's atmosphere. Discrete solar emission lines such as H Ly α, λ1215, and He II, λ304, are much less energetic than the continuous radiation, and are here neglected.

It should be mentioned that the lethality times for cosmic rays listed in Table II are lower limits, because of overkilling. An average cosmic ray primary has an energy several orders of magnitude greater than that required to kill an average microorganism. Only when the particle is absorbed by a cluster of microorganisms, and the energy distributed among them will the killing times be as short as in Table II.

For a given organism, the mean lethal dose in reps is approximately invariant, under the same environmental conditions, for all ionizing radiation, corpuscular and electromagnetic. Viruses characteristically lie in the range D = 10^5 to 10^6 rep (Luria, 1955); protozoa generally have the same range (Bacq and Alexander, 1955; Kimball, 1955). Bacteria and fungi usually have somewhat lower mean lethal doses, 10^3 to 10^4 rep for E. coli, for example, and 10^4 to 10^5 rep for the spores of B. mesentericus and A. niger (Zelle and Hollaender, 1955).

However, there has been no systematic search for radioresistant microorganisms, and it is possible that microorganisms having mean lethal doses as high as 10^7 rep exist. In addition, D in general has some functional dependence upon such factors as the temperature, the oxygen tension, the time interval in which the killing dose is applied, and the presence of an external aqueous medium. The dependence is in different directions in different organisms, and the interaction of the various effects is quite complex; but the resulting variation in D is rarely as great as a factor of ten. Considering all these points, then, it appears that a conservative estimate for an average mean lethal dose due to ionizing radiation is 10^7 rep.

For the non-ionizing ultraviolet radiation, D has a strong functional dependence on wavelength, corresponding to the wavelength variation of molecular absorption cross-sections. There is an absorption maximum at roughly λ2600 due to the biochemically ubiquitous purines and pyrimidines, and another, more pronounced, maximum shortward of λ2300, due to simple diatomic functional

groups, such as N-H. Ultraviolet mean lethal doses are given in ergs cm^{-2}, and are generally measured at λ2537. To obtain a mean value of D appropriate for a wide range of wavelengths we must know the wavelength variation of D. For common strains of E. coli, for example, D(λ3000) ≈ 10^5 ergs cm^{-2}, D(λ2537) ≈ 10^4 ergs cm^{-2}, and D(λ2300) ≈ 10^3 ergs cm^{-2} (Zelle and Hollaender, 1955). Considering the decrease of D shortward of λ2300, a conservative (i.e., upper limit) mean value of D for the wavelength region λ3000 to λ2000 appears to be the value at λ2537; this should be roughly applicable for an ultraviolet black body spectrum with a Wien peak longward of λ3000. The mean lethal dose at λ2537 for the more radioresistant bacteria, such as B. subtilis spores, Sarcina lutea, and the B/r strain of E. coli, are approximately 10^5 ergs cm^{-2} (Zelle and Hollaender, 1955). An unusual case is the protozoon Paramecium multimicronucleatum, for which D(λ2537) = 10^6 ergs cm^{-2} (Kimball, 1955). However, much lower doses serve to prevent this organism from surviving reproduction. Considering, finally, the environmental dependences of D mentioned in the preceding paragraph, and the possibility of undiscovered microorganisms of extreme radio-resistance, we adopt as a mean value of D for ultraviolet radiation in the region λ3000 to λ2000, D = 10^7 ergs cm^{-2}. For the region shortward of λ2000, D is certainly $<10^6$ ergs cm^{-2}.

From the ranges of ionizing radiation in matter, the following mass absorption coefficients were adopted: 10^5 cm^2 gm^{-1} for 1 KeV protons, 10^3 cm^2 gm^{-1} for 50 Å soft X-rays, and 2.5×10^{-3} cm^2 gm^{-1} for cosmic rays. Because of the varying energies, especially for cosmic rays, these absorption coefficients are only approximate. It should again be emphasized that the mean lethal doses are purposely high to allow for anaerobiosis and drying. The resulting lifetimes should be upper limits, except for cosmic rays, and, perhaps, where $\rho/\mu \ll \rho a$ for ionizing radiation, so the radiation does not penetrate to the interior of the organism.

E. Survival Times

Where the computed lifetimes are greater than a month, they have been divided by two—except for the cosmic ray lifetimes—to allow for the lunar night. For times shorter than a month, continuous solar illumination has been assumed, but of course, all such times may be as long as a month if the organism is deposited in a region soon after the terminator has left the region.

A 1 kg instrumented lunar package may easily contain 10^{10} microorganisms (Lederberg and Cowie, 1958); it is very unlikely

that any packages for the immediate future will contain as many as 10^{20} microorganisms. Accordingly, we see from Table II that all microorganisms deposited and exposed to the sun will be killed by ultraviolet light in a few hours. Similarly, fully illuminated microorganisms in cislunar space will also survive only a few hours. Hence the panspermia hypothesis is untenable for unprotected microorganisms of comparable radiosensitivity to terrestrial microorganisms. On the other hand, suppose some microorganisms are deposited in a lunar crevasse or other depression, always shielded from solar radiation. Then, killing will be effected only by cosmic radiation and by natural radioactivity. Because of secondary cascade, cosmic radiation reaches an intensity maximum slightly greater than the surface value at a depth of about 10 cm on the moon, according to Filosofo (1958). It is reduced to 10^{-1} the surface flux at a depth of about one meter, and to terrestrial surface values at a depth of a few meters. Hence, microorganisms shielded from the Sun, but just beneath the lunar surface will not be killed by cosmic radiation for at least several hundred million years; microorganisms at greater depths will have even longer lifetimes. Similarly, cosmobiota imbedded in, for example, a meteorite would have lifetimes comparable to the age of the Solar System, and under these circumstances the panspermia hypothesis remains tenable.

We now consider the possibility that microorganisms deposited on the Moon will actually be shielded. The nature of the lunar surface is a complex and much-debated problem (Baldwin, 1949; Urey, 1952, 1956a, 1956b; Kuiper, 1954, 1959; Gold, 1955, 1959; Whipple, 1959) which need not be reviewed here. But it is important to call attention to a few points. From eclipse temperature measurements, and polarimetric and radio observations, it is known that a dust covering exists on the Moon, possibly present in some areas, and not in others. Estimates of its depth range from millimeters to miles. However, Whipple (1959) has called attention to the experimental fact that dust, irradiated in a vacuum, will congeal, forming a low-density, semiporous matrix. If the lunar surface material has a similar sintered structure, it would appear very possible for microorganisms to be lodged in the interstices of the matrix, in such positions as to be shielded from the Sun's rays at all angles of insolation. Thus we may anticipate the survival for very great periods of time of perhaps a few percent of those dormant anaerobic microorganisms deposited at the lunar surface. A determination of the microstructure of the Moon's surface is of great importance to corroborate this conclusion.

F. Dissociation of Nonliving Organic Matter

The killing of an organism, of course, does not necessarily involve its chemical dissociation, and long after death occurs, in an anhydrous aseptic environment, many aspects of the organism's characteristic biochemical structure will be maintained. After long periods of continued irradiation, enough bonds would be broken to destroy most of the long-chain biological polymers such as proteins and nucleic acids. The problem is complicated by the existence of radiation protection devices (catalase, cytochromes, sulfhydryl compounds, photoreactivation mechanisms) in most contemporary organisms. Because of the Franck-Rabinowitch cage effect, the collection of dissociated molecules arising from the original organism would tend to remain in close physical contact. Ionizing radiation is very much more efficient than non-ionizing radiation in depolymerizing and dissociating organic molecules. Breaking of all hydrogen molecular bonds and charring occurs at about 10^{10} rep (v., e.g., Reiffel, 1959). The last column of Table II gives the times for the various radiations to effect charring of all but 10^{-15} of the exposed molecular aggregates. Charring by the solar proton wind occurs in from months to years, depending on the size of the dissociated organism. If, however, the lunar surface magnetic field exceeds 10^{-2} gauss and the proton wind does not penetrate to the surface, it may take as long as one hundred thousand years for charring to be induced by soft solar X rays. Thus the value of the lunar magnetic field strength has great relevance for the question of possible biochemical contamination of the moon.

As dissociation advances, lunar temperature effects would become more important, small molecules being readily dissociated at 100°C. For example, the most thermostable amino acid, alanine, has a thermostability half-life at 100°C of approximately 10^3 years (Abelson, 1954), with many other amino acids having half-lives not less than ten years. Molecules shielded from radiative dissociation would be relatively unaffected by lunar temperatures, and if lodged beneath a few centimeters of insulating lunar surface material, would have lifetimes determined by the cosmic ray flux and natural radioactivity.

VII. BIOLOGICAL CONTAMINATION OF THE MOON

A. Possible Kinds of Biological Contamination

There are four possible kinds of extraterrestrial biological contamination. For later discussion we categorize them, for the Moon, under the following headings:

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.

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, whether biological or abiological in origin.

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 water and metabolities. Such a biological explosion might in a short time destroy large quantities of organic matter produced in the early history of the Moon.

Ecomixy

The Moon may contain indigenous living organisms. There is then the possibility that deposited terrestrial microorganisms, by competition with or parasitism upon even one species of lunar organism, will completely disrupt the autochthonous ecology.

We are interested in evaluating these possibilities in the light of the previous discussion.

B. Distribution of Vehicle Impact Products

Existing unfueled final stage carrier rockets of vehicles capable of lunar impact have masses of the order of 10^4 kg. If the carrier rockets are solid-fueled, then burning at very high temperatures occurs through most of the carrier interior, and very few of the contained microorganisms will survive. On the other hand, if the carrier rockets are liquid-fueled, no burning occurs in the fuel tanks, and many of the contained microorganisms should survive the powered phase. The final stage of Lunik II is believed to have been liquid-fueled.

The energy of impact in a vehicle arriving at escape velocity is 2×10^{10} ergs gm^{-1}, or about 0.5 kcal gm^{-1}. Such energies applied over short time intervals are insufficient to kill most microorganisms, as the existence of shells and bombs for biological warfare proves. If the vehicle comes to a stop on the lunar surface after digging a crater one to ten meters deep, the mean acceleration will have been -10^5 to -10^6 g, applied over 1 to 0.1 secs. Extrapolation of ultracentrifugation data on whole unlysed bacteria containing no large granular inclusions suggests that accelerations of these magnitudes and durations will not be lethal for many bacteria and viruses (Marr, 1961).

Assume that a 10^4 kg liquid-fueled vehicle with a microorganism population of 10^{10} per kg impacts the Moon at escape velocity (hard landing). It is easy to show that for a Maxwell-Boltzmann distribution of velocities, the fraction of particles moving with velocities less than some critical velocity, v_c, is given by

$$F = \operatorname{erf} x - (2/\sqrt{\pi})\, e^{-x^2}\, x \qquad (16)$$

where $x = v_c/v_m$, v_m is the mean particle velocity, and

$$\operatorname{erf} x = (2/\sqrt{\pi}) \int_0^x e^{-y^2}\, dy$$

is the error function. If half the energy of impact goes into the kinetic energy of the explosion products, $v_m = v_e / \sqrt{2}$, where v_e is the velocity of escape. From equation (16), with $x = \sqrt{2}$, the fraction of particles with velocities less than the velocity of escape after impact is seen to be $F \approx 0.74$. Similarly, the fraction of particles with velocities less than the circular velocity after impact is $F \approx 0.43$. Hence the fraction of impact products with velocities between circular and escape velocity is 0.31. Half of these particles will be moving in a downwards direction. The remaining half, or about fifteen percent of the particles, will be distributed approximately uniformly over the lunar surface. Since the impact will not kill the microorganisms contained in the impacting vehicle, the example we have chosen gives a mean surface density of about 0.4 microorganisms per square meter of the Moon. Near the impact area, the surface density of microorganisms will be considerably greater. We have calculated that all but the small fraction of deposited microorganisms which is shielded from solar illumination will be killed by ultraviolet radiation in hours (section VI E). Therefore the mean surface density of viable microorganisms deposited in our example should be less than 0.01 m^{-2}.

C. Evaluation of Contamination Possibilities

This surface density of viable microorganisms is well below that detectable by existing biological techniques, such as plating. Lederberg (1959; v. also Davies and Comuntzis, 1959) believes that existing techniques can be immediately extended to detect one microorganism m^{-2}, but considerable further refinement would be required to detect 10^{-2} m^{-2} where subsurface sample-gathering is also required. Cosmobiota and remnants of indigeneous lunar organisms, if such exist, would be sequestered almost exclusively at much greater depths below the surface than would deposited terrestrial microorganisms. We conclude that the probability of biomictic contamination of the Moon is very low.

Since a typical bacterium has a mass of roughly 10^{-12} gm, the amount of organic matter deposited as microorganism in our example is 10^{-16} gm cm^{-2}, an amount completely indetectable, and entirely negligible compared with the amount of indigenous organic matter which has probably survived from the early history of the Moon (section II G). A similar conclusion follows for organic matter arising from vehicle structural components, although it is clear that the use of such substances (e.g., shellac) should be minimized. We conclude that the probability of sapromictic contamination is negligible.

We have concluded in section V that at a depth of a few tens of meters below dust-covered portions of the lunar surface there may well be large amounts of organic matter, some moisture, and constant temperatures which are near optimum for contemporary terrestrial organisms. A viable terrestrial microorganism introduced into such an environment might reproduce very rapidly. The extent of phagomictic contamination would depend on the degree to which concentrations of organic matter are in contact under the lunar surface, on possible self-limitation of the reproduction rate by accumulation of catabolites, and, of course, on the presence of the specific growth requirements for individual varieties of microorganisms. However, on the basis of the substances produced in terrestrial laboratory experiments simulating primitive conditions, and in the light of such phenomena as adaptive enzyme formation in microorganisms introduced into petroleum deposits (v., e.g., ZoBell, 1950), the presence of suitable metabolites seems possible. It is very improbable that a given organism deposited near the surface would find its way to a depth of tens of meters, but when 10^{14} microorganisms are deposited, the situation is very different. Although the presence of appropriate temperatures, moisture and organic matter for terrestrial microbiological multiplication remains to be rigorously demonstrated, at the present writing the likelihood of phagomictic contamination of the Moon is not negligible.

We have also discussed in section V the possibility that indigenous lunar organisms arose in primitive times and have survived in a subsurface existence to the present. Although, of course, no final answer can now be given to this question, we have seen that the possibility of an extant lunar parabiology is by no means so implausible as has sometimes been assumed. Since we are considering lunar organisms based on the same small molecules as are terrestrial organisms, confrontation of the two groups of organisms may well lead to ecological interaction. The chances of extraterrestrial autochthons having a dextrorotary rather than a levorotary stereochemistry are probably one in two, but it should be remembered that some terrestrial microorganisms have the enzymatic capability of transforming dextrorotary to levorotary stereoisomers. Even if indigenous lunar organisms exist, the occurrence and extent of ecomictic contamination will depend on the detailed biochemistry and ecology of both the autochthons and the contaminants; but in our present ignorance the possibility of ecomixy cannot be excluded. Of all the kinds of extraterrestrial biological contamination, this would represent the greatest loss.

It is clear that a reliable estimate of the phagomictic and ecomictic possibilities must await further information. Sterilized soft-landing instrumented probes can provide this information. Details on the microstructure of the lunar surface in areas distant from maria and large craters are needed. Subsurface borings, as described in section XXI, are of the greatest importance. In addition to the analytic chemistry recommended for boring cores, plating of samples from various depths is suggested. Automatic devices for the detection of live microorganisms by planetary probes are already under construction (Vishniac, 1959; Loderberg, 1960). Similar instrumentation should be included among the first soft-landing lunar probe to have subsurface boring capability.

An additional consideration for the question of possible biomictic or ecomictic contamination of the Moon has recently been made by A. Turkevich (v. E. Anders, "The Moon as a Collector of Biological Material," Enrico Fermi Institute for Nuclear Studies Report No. EFINS-61-8, University of Chicago, 1961; and Science, in press). He suggests that meteoritic impact on the Earth during geological time may have ejected terrestrial microorganisms to the Moon; and that samples of now extinct microorganisms may be found on the Moon. If large numbers of terrestrial microorganisms have been deposited on the Moon during geological time by this mechanism, then biological contamination may have already occurred. But recontamination by contemporary terrestrial microorganisms would destroy unique opportunities in microbial paleontology.

D. Decontamination Recommendations for Unmanned and for Manned Vehicles

It is recommended that all future lunar probes be scrupulously decontaminated. Sterilization methods have received careful attention in recent months, and working methods have now been developed (Davies and Comuntzis, 1959; Philips and Hoffman, 1960). In general there are four stages of sterilization: sterile fabrication and assembly of components which might be damaged by subsequent heat, chemical, or radiation sterilization techniques; use of germicidal substances in vehicle construction; terminal sterilization by heat, radiation, and chemicals (especially ethylene oxide); and maintenance of sterilization by encasing the probe with a shroud containing a disinfectant atmosphere, the shroud being discarded only after passing through the Earth's atmosphere.

To date, two man-made objects have impacted the Moon, the instrument package and the 7700 kg carrier rocket of Lunik II. According to reports from the Soviet Union, both were sterilized (Gause, 1959). From press reports it appears that a disinfectant atmosphere was employed, but a detailed description of the decontamination procedures has yet to appear. Sterilization of all United States lunar and planetary probes which have a substantial probability of impact has been announced as a firm objective of the National Aeronautics and Space Administration.

The microorganism population of a mammal may be as high as 10^{12}. Therefore no landing of animals or men should be attempted on the Moon until more information is available. If in the light of this information the possibilities of phagomictic or ecomictic contamination appear non-negligible, manned soft landings should be safeguarded by sophisticated decontamination techniques. Decontamination should be standard procedure during each air-lock operation, both on leaving and on re-entering the vehicle. Space suits must be designed to eliminate cracks and joints in which microorganisms might lodge inaccessible to decontamination techniques. Finally precautions against explosive decompression and accidental hard landing should be even more rigorous than is indicated by a concern for human safety.

VIII. SUMMARY

The rate of synthesis of organic molecules by solar ultraviolet radiation in the primitive lunar atmosphere is estimated. The consequent lunar surface density of organic molecules is very high, probably between 1 and 10 gm cm^{-2}. As the lunar atmosphere was dissipated, heat and radiation produced organic molecules of great complexity from the deposited material. Such organic matter would now be situated beneath overlying layers of meteoritic and other surface debris, at a depth of possibly a few tens of meters, although some distribution throughout the dust may be expected.

Reports of gas clouds on the lunar surface are discussed and shown to be probably unreliable. However, the observations of Kozyrev, if verified, would be evidence for lunar subsurface organic matter.

Fremlin's theory of heat localization by hydrostatic pressure in dust indicates that constant, biologically-optimum temperatures exist at just the level that surviving primitive organic matter is probably localized. Therefore the possibilities of multiplication of terrestrial microorganisms on the Moon and of survival of indigenous lunar organisms from the early history of the Moon are not as remote as has sometimes been thought.

The probability for survival of a terrestrial microorganism, accidentally deposited on the Moon by an impacting lunar probe, is computed. A population of the least radiosensitive dormant anaerobic microorganisms would be totally destroyed in hours if exposed to solar ultraviolet radiation. The resulting organic dissociation products would remain intact for much longer periods of time; 0.1 to 10 years if the lunar surface magnetic field strength is much less than 10^{-2} gauss (so that incident solar protons are magnetically deflected), and 10^4 to 10^5 years if the field strength exceeds 10^{-2} gauss. Organisms shielded from solar illumination, perhaps in congealed dust matrix interstices, would survive cosmic radiation and natural radioactivity for 10^9 years or more. Lunar subsurface temperatures are not too high to impede survival.

The possible kinds of lunar biological contamination are then discussed. Because of the small absolute amount of terrestrial organisms and organic matter likely to be deposited by probe, and their separation in depth from indigenous lunar organisms and

organic matter, it is improbable that the two will be confused. But the explosive reproduction of only a very small number of terrestrial microorganisms in indigenous organic matter, and the disruption of the ecologies of hypothetical lunar organisms, are remote but non-negligible possibilities.

It is recommended that all lunar probes be thoroughly decontaminated, and that the first soft-landing probes be equipped for chemical analysis and biological plating of subsurface samples.

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X. APPENDIX: SURVIVAL TIME OF AN IRRADIATED POPULATION

We consider a population of N_o organisms, each having mean density ρ gm cm^{-3}, characteristic size a cm, and mean lethal dose for a given kind of electromagnetic or corpuscular ionizing radiation of D rep. The population is irradiated with an intensity of I erg cm^{-2} sec^{-1} of the given kind of radiation, which has a mass absorption coefficient in organic matter of μ/ρ cm^2 gm^{-1}. We are interested in the time, t, in seconds, for the population to be depleted from N_o to N organisms.

Let J be the energy absorbed by unit cross-section of organism due to a dose of d rep. Then, since one rep corresponds to the absorption of 93 ergs gm^{-1},

$$J \simeq 93\ \rho\ a\ d. \tag{A-1}$$

On the other hand, if the energy incident on unit cross-section of the organism is E_o, then, by Beer's law, the energy transmitted through the organism is

$$E_t = E_o\ e^{-(\mu/\rho)\rho a}\ . \tag{A-2}$$

Consequently, the energy absorbed by the organism is

$$E_a = E_o - E_t = E_o\ \left[\ 1 - e^{-(\mu/\rho)\rho a}\ \right]\ . \tag{A-3}$$

Now if E_a ergs absorbed by 1 cm^2 corresponds to a dose of d rep, $E_a = J$, and from equations (A-1) and (A-3),

$$E_o/d = 93\ \rho\ a\ \left[\ 1 - e^{-(\mu/\rho)\rho a}\ \right]^{-1}\ \text{erg cm}^{-2}\ \text{rep}^{-1}\ . \tag{A-4}$$

Consequently, the time, τ, for one organism to accumulate D rep due to an incident flux of I erg cm^{-2} sec^{-1} is

$$\tau = (D/I)\ (E_o/d)\ . \tag{A-5}$$

Assuming an exponential survival curve for the population of organisms, the number surviving after time t will be

$$N = N_o\ e^{-t/\tau}\ . \tag{A-6}$$

Solving equation (A-6) for t, substituting from equations (A-4) and (A-5), and converting from natural to common logarithms, we obtain for the time in which the population will have been depleted to N organisms,

$$t = 214\, a\, \rho\, (D/I) \left[1 - e^{-(\mu/\rho)\rho a} \right]^{-1} \log_{10} (N_o/N). \qquad (A\text{-}7)$$

In the case that the mean lethal dose, D, is given directly in units of erg cm^{-2} instead of rep, as is the case for ultraviolet irradiation, equation (A-7) is replaced by

$$t = 2.3\, (D/I) \left[1 - e^{-(\mu/\rho)\rho a} \right]^{-1} \log_{10} (N_o/N). \qquad (A\text{-}8)$$

Table II was constructed from equations (A-7) and (A-8); ρ was taken as unity throughout.

For an organism opaque in the given radiation, $(\mu/\rho)\rho a \gg 1$, and equations (A-7) and (A-8) reduce respectively to

$$t = 214\, a\, \rho\, (D/I) \log_{10} (N_o/N), \qquad (A\text{-}9)$$

and

$$t = 2.3\, (D/I) \log_{10} (N_o/N). \qquad (A\text{-}10)$$

For an organism which is almost transparent in the given radiation, $(\mu/\rho)\rho a \ll 1$, and a Taylor series expansion of the exponential reduces equations (A-7) and (A-8) respectively to

$$t = 214\, (\rho/\mu)\, (D/I) \log_{10} (N_o/N) \qquad (A\text{-}11)$$

and

$$t = (2.3/\mu a)\, (D/I) \log_{10} (N_o/N). \qquad (A\text{-}12)$$

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