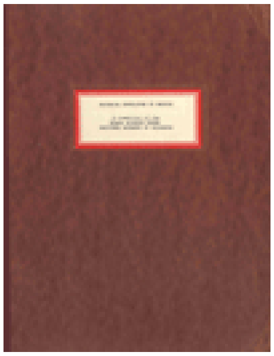
Summary Report of WESTEX



Space Science Board, National Academy of Sciences, National Research Council

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THE NATIONAL ACADEMIES
Advisers to the Nation on Science, Engineering, and Medicine

National Academy of Sciences
National Research Council
2101 Constitution Avenue, N. W.
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DRAFT

SPACE SCIENCE BOARD

Summary Report of
WESTEX
February 21, 1959 - September 26, 1959

(including selected reference material)

October 16, 1959

The following report is a brief summary of discussions and conclusions of four meetings of Westex in 1959: February 21, March 21, May 2-3, and September 26th. This committee adjourned sine die at its last meeting. It stands ready to renew its meetings whenever warranted by new business.

INTRODUCTION

Westex is a group of West Coast biologists interested in the biological exploration of the planets.[1] The aggregation of many biochemists and microbiologists on the West Coast make the San Francisco area a convenient meeting place for a regional group, saving the trouble and expense of many people's travel. This group informally complements a similar one centered at the Massachusetts Institute of Technology whose report has been circulated as SSB-93.

Westex was originally convened February 21, 1959, upon the request of Dr. Bruno Rossi to advise him and the Board on the problem of contamination of extraterrestrial targets of space exploration. This meeting was under some pressure to report[2] prior to the meeting of Cetex[3] and Cospar at The Hague on March 9-11. However, its recommendations were reviewed in great detail at subsequent meetings and were unanimously and forcefully reaffirmed.[4] The committee was also requested (and is, of course, intrinsically inclined) to review the constructive aspects of research in exobiology (viz. the biology of the exosphere, the space beyond the earth's atmosphere). "Space Biology" often connotes life-support research in connection with man-in-space and with this the influence of space craft environments on man and other forms of terrestrial life. This area is now under comprehensive review by the Armed Forces-NRC Committee on Bio-Astronautics and we have not dealt with it at all except as it bears on the ecology of the planetary targets.

The term planet used in this report also includes the moon and the satellites of other primary planets. By implication we will usually be referring to the <u>other</u> planets excluding earth.

Some aspects of this report should be elaborated further, for example in contributions to "Science in Space."

SIGNIFICANCE OF EXOBIOLOGICAL RESEARCH

The detection and analysis of planetary life is one of the major challenges of contemporary science and should be pre-eminent among the objectives of our space research programs. Our immediate concern would be to clarify the evolution of life as we now know it on earth.[5] More profoundly, biology unlike physics and chemistry has been an earth-bound science. Twenty-five centuries of scientific astronomy have expanded our conception of the universe with a profound impact on all human culture, including the physical sciences. <u>Matter</u> and <u>energy</u> aspire to be universal concepts; <u>life</u> in contemporary science still means <u>terrestrial</u> <u>life</u>.

THEORETICAL POSSIBILITIES AND PRESENT EVIDENCE FOR PLANETARY LIFE

A detailed exposition of theoretical biology could warrantably lead to far flung speculations on the essential features that characterize living systems. Theoretical and experimental work of recent years has dispelled many of the obstacles to our understanding of the transition from inorganic to living matter.[13] We consider that this will eventually be possible in the laboratory; meanwhile, a study of life in totally independent evolutionary systems may give some invaluable leads. A priori, we believe it to be highly probable that life will evolve spontaneously if concentrations of diverse organic materials are maintained for intervals $\sim 10^9$ years in temperate environments. The consequence might be life whose chemistry is not necessarily at all like our own. Such speculations should by no means be discouraged. However, it is essential to establish a pragmatic starting point for the design of experimental space flights. For the moment, and until such time as these investigations are rewarded or proven futile, we should confine our studies to living systems sharing two basic attributes with terrestrial life: the use of water as the primary solvent for biochemical interaction and the use of polymers based on carbon as structural and catalytic components. The atoms H, C, O, and N, from which water and other biochemicals are formed are so nearly universal in their distribution that the limiting parameter in a planetary environment will, as a rule, be its temperature. Living forms, which are based on the co-operation of complex molecules cannot survive at temperatures at which these polymers dissociate. Life can survive in a dormant state in the absence of water but requires this solvent for its evolution and activity. Radiation fields of sufficient intensity will be equivalent to high temperatures in the dissociation of organic molecules provided they penetrate to all relevant strata of the target planet, which will not usually be the case. The criteria just enunciated have long made Mars and Venus the only probable foci for serious interest in planetary life since some water is known to exist on Mars and our ignorance of Venus does not preclude it. The moon, whose surface must be completely devoid of water, is of interest to the biologist, as it is to the planetologist primarily as a fossil by providing a potential source of the initial composition of the solar system from which life had evolved. More information on the sub-surface composition of the moon is needed before it can be completely dismissed as a totally waterless and lifeless object. The moon might be able to furnish evidence on the possible natural dissemination of interplanetary life through space. The proximity of the moon to the earth, and the consequent density of traffic to it, may make it difficult to sustain a conservative program but strenuous efforts should be made to preserve its initial features for the benefit of the many sciences which have an interest in them.

The question of planetary life has perhaps been disreputable because of extravagant claims made by enthusiastic astronomers in the past. At the present time, as the Board already knows, the main evidence which bears directly on exobiology is Sinton's infrared study of Mars.[6] He has described bands in the reflection spectrum of Martian regions which would correspond to absorption by organic molecules, for example formaldehyde or cellulose. Few spectroscopists would be willing to insist that these bands could not be produced by any minerals although we have not been able to locate an explicit alternative. A more serious concern is whether the absorption bands, even if of organic molecules, are evidence of biochemical rather than inorganic synthesis. The surfaces of the major planets are undoubtedly too cold for the maintenance of liquid water anywhere and life of terrestrial types is thereby precluded. However, a solvent mixture of NH_3, CH_4, and H_2 which would prevail on Jupiter gives us the most provocative alternative to an aqueous system of life. In any case the impact of solar radiation on a planet so largely composed of H, C, N, and O will eventually be of great interest for our understanding of the inanimate synthesis of organic compounds.

The negligible quantity of oxygen in the Martian atmosphere has sometimes been invoked to argue that active animal life cannot exist there. While oxygen may allow for a more efficient metabolism of terrestrial nutrients, the biochemical adaptations already exhibited by terrestrial micro-organisms suggest that it would be incautious to insist on any conclusions at all on this point. For the same reason the prevalence of gases that would be toxic to man is of no consequence whatsoever in precluding forms of life that might well be adapted to them.

The chemical constitution of planetary life is far more important than its outward appearance. For fundamental studies the existence of the most "primitive" micro-organisms on Mars would be almost as consequential as the occurrence of the most highly evolved types. The most pervasive feature of terrestrial life is the nucleic acid molecule whose accurate self replication is the basis of heredity and of organic individuality. No less striking is the distribution of protein composed of a basic set of twenty particular amino acids. If we could ask just <u>one</u> question of life on a planet it would be whether it was based on the same system of nucleic acid and protein as we know on earth. But we cannot ignore such fundamental questions as whether intelligent life of any kind had evolved and whether the planetary forms have the same organization into cellular units. Finally it will be of no small interest to learn the details of the adaptations in chemistry and in outward form which planetary organisms may have evolved as a specific adaptation to their own peculiar environments.

METHODS OF INVESTIGATION

Observations from Earth

Models of planetary systems. Some of the fundamental gaps in our general scientific information which would be relevant to planetary research have been stressed by various authors in

Science in Space. Here we have already noted the lack of sufficiently broad spectroscopic data on reflections from various minerals to be sure of a final evaluation of Sinton's experiments.[7] Fortunately, Calvin and his colleagues have undertaken an intensive program of infrared analysis much of which will be an important back-up to space probe experiments. The Committee feels that these verifications are of very great importance and urges all possible support for Dr. Calvin's program. It is probable that surveys similar to Sinton's can be profitably extended and particularly with the help of balloon-mounted telescopes. Likewise, it would be very helpful to have available all possible information on the appearance of the earth from moderate altitudes at various wave-lengths. It seems certain that the Air Force must have collected considerable information along these lines and its release would be of great scientific value.

Members of the Board have also commented on the value of meteorites as samples of interplanetary matter. The existence of carbonaceous compounds in meteorites (Mueller) is almost always overlooked in summaries of their chemical composition.[8]

One of the most useful instruments for the study of planetary chemistry and biology would be the satellite telescope. We are not certain whether its technical problems are likely to be solved before or after probes are sent to the vicinity of the planets. Planetary investigation should not be overlooked in the design and mission-analysis of the satellite telescope.

VICINAL PROBES

The Committee has pondered the question whether it would be possible to collect convincing evidence of the habitation of Earth from a satellite 200 miles away. It is difficult to give a definite answer to this question without more information on color and infrared photography of the earth by high flying aircraft. On the whole, we were rather skeptical that a decisive answer to this question would be possible, except for large scale products of human culture (cities, roads, rockets). However, such a satellite should be able to improve considerably on the approach used by Sinton, namely rough chemical analysis of the surface by infrared. The vicinal probe will, however, contribute important information along these lines, and should be designed as a back-up to soft landings in the event that guidance errors limit the distance of approach. The chemistry of the planetary atmospheres is of sufficient importance that the Committee suggests a careful study be made of the relative values of early planetary probes in comparison with the lunar missions which have been given earlier priority according to present scheduling.

Planet Fall (Landing) Experiments. The Committee could make no constructive suggestions for experiments involving hard landing. Possibly experience from similar trials on the moon may justify a reconsideration of whether a useful photograph at low altitude might be made in the course of such a mission. On the other hand, the atmosphere of Mars may permit relatively soft landings by the use of atmospheric braking with the least cost in retro-rocket work. The Committee urges strenuously that all possible information be collected by instrumented landings before any effort is made to collect samples and return them to the earth and particularly before manned landings are designed. In principle it should be possible to develop instrumentation to conduct any program of biochemical investigation.

In practise, such instrumentation does not exist at the present time. An urgent requirement for all aspects of planetary science is the development of instrumentation for the automatic gathering of surface and cored samples and their subsequent chemical analysis. Lightweight mass spectrometers as are already being developed for atmospheric analysis represent an important advance; the same instruments might be profitably adapted as the terminal sensors for systems of molecular-analytical chemistry. For example, the mass spectrography of gases emitted from samples subjected to specific chemical reagents, or to controlled heating, would give substantial information on the composition of relatively complex materials. Optical, and especially infra-red spectroscopy, should be amenable to similar adaptation.

The time required to develop these instruments is long enough that they will have to be attended to promptly to be ready in time for the corresponding vehicles. Automatic chemical analysis has been the subject of a recent symposium,[9] devoted mainly to applications in the clinical laboratory: the experience in these developments might be useful for our particular requirements.

Similar, even simpler instruments, can be designed to culture possible micro-organisms, signalling information of the growth or metabolisms of inocula from dust fallout or other samples. (Dr. Wolf Vishniac, of Yale University, is engaged in the actual construction of a prototype with the aim, in part, of classifying the details of possible designs and of assessing the difficulties of a ruggedized one.) There can be little doubt that micro-organisms will occur in any habitat capable of supporting any form of life. However, we have no prior knowledge of the nutritional requirements and metabolic effects of exobial forms though some plausible inferences would follow better knowledge of their habitats. We could therefore have no way of assuring the suitability of any culture medium used in the assay. (On an arid planet like Mars, however, water may well prove to be a limiting factor, and a sufficient 'nutrient' to elicit obvious vital response from a sample of soil. Further, glycine is an attractive candidate as a nutrient: it is the simplest amino acid, and one of the simplest compounds of C, O, N and H; it is a universal constituent of terrestrial proteins, and an important metabolite in the biosynthesis of other key compounds; it is the most likely (and first identified) product of photochemical synthesis from hydrogenous atmospheres (H_2O; NH_3; CH_4).)

Perhaps the chief objection to a simple micro-culture experiment is its limited heuristic value: A quite elaborate series of controls might be needed to lend conviction to a pulse on a tracing as evidence of planetary life. In addition, we cannot gainsay more organized forms, e.g., vegetation which would be recognizable as living by their visual appearance. An early picture of the planetary surface is a compelling entrant for the first missions in any case. We have therefore concluded that the first priority in exobiological study might be to a vidicon survey.

For more precise study, the vidicon may prove to be the most useful of sensors -- if, as we are assured, communications bandwidths are likely to keep pace with the technical requirements. For example, an optical microscope input to the vidicon could give the most convincing evidence of micro-organisms, both in situ, and in the effluent from a culture vessel. Furthermore, the use of travelling films should furnish a convenient method of carrying specimens through the object plane of a fixed-focus microscope, and also of subjecting the specimens to quite informative procedures of cytochemical analysis. (Thus, the alteration of an object-particle by the enzyme deoxyribonuclease, as observed with the microscope, would be a simple, sensitive, easily controlled, and compelling test for the presence of DNA.) To be of most use, the microscope should be operable to several wavelengths, particularly in the UV around 2600 Å, as well as the visible. It would thus be usable as a microspectrophotometer, with applications for inorganic chemical analysis too.

An important factor in this priority judgment is the present commercial availability of an analogous instrument, a television microscope. We urgently recommend that the Board investigate the means for the prompt adaptation of this type of instrument for planetary science.

CONSERVATION OF SCIENTIFIC RESOURCES

Contamination of extraterrestrial objects. Previous minutes from this committee have stressed the dangers of biological contamination, especially of Mars and Venus.[2] We continue to reaffirm the necessity of maintaining strenuous precautions against such contamination. One element in such a policy is obviously the collection of the most possible information from safe (i.e. telescopic or vicinal) approaches before landings are attempted. The more information we have about the planetary habitat, the better we can assess the actual hazards entailed by a landing and the precautions that should be taken. On the basis of present information, we would urge that a tolerance level 10^{-6} be adopted as the residual, composite risk of depositing a viable micro-organism on Mars or Venus.[10] We also believe that this is a plausible objective for an energetic program of payload decontamination, which had been recommended in further detail by an ad hoc committee sponsored by the Board.

The liability of the Moon to biological contamination is more controversial. Solar UV and the proton flux would rapidly disinfect any exposed objects. However, it is difficult to make any categorical statements about deeper and protected sites (cf. Galileo)[12] and it would be rash to disregard the conservation of biological interests there before we have the benefit of closer study. There has been considerable discussion of the consequences of hard landings, which we are unable to resolve. In particular, the entire missile might be heated by impact, and the mass confined to one site; alternatively, fragments might be dissipated over a large and uncontrollable area. If this issue can be decisively resolved, it should be taken into account in efforts to meet the recommendation that lunar missions should be cleaned and decontaminated according to the best technique available at the time, with a view to reducing the residual risk per missile to a value 10^{-1}. This suggestion is, of course, also subject to revision in response to more information.

We applaud the respect for these considerations on the part of the USSR in the light of Academician Topchiev's announcement that Lunik-II had been decontaminated. We would, further, welcome an opportunity to discuss optimum techniques for decontaminating further missions conducted both by the USSR and the US.

The survival of micro-organisms in transit through space would be severely limited by their exposure to solar radiation, both the ultraviolet and the proton-corpuscular components of which would rapidly inactivate any exposed organisms.[14] However, these radiations have a very limited penetration, and they will have a negligible effect on organisms shielded within a spacecraft or imbedded in a meteorite. More penetrating radiations, e.g. cosmic rays and solar x-rays will inactivate micro-organisms only very slowly, notwithstanding their potential hazard to more sensitive, higher forms of life.

The high vacuum of free space, far from being inimical, may help in the preservation of micro-organisms. Many stocks of bacteria and fungi are routinely preserved by drying them and keeping them at reasonably low pressures. However, there has been little or no effort to test the viability of bacterial spores at very low pressures (say $\leq 10^{-9}$ atmospheres), and it has been suggested that these may result in the distillation of vital components of the cells. This experiment might be conducted in a recoverable satellite, or with some difficulty, in the laboratory. Dr. Harlyn Halvorson's proposals in this direction warrant the most sympathetic consideration, since this question is of considerable importance both for fundamental biology and its applications in space research.

IDENTIFICATION OF MISSILE COMPONENTS

Since the fate of an impacting vehicle is in some doubt, planetary expeditions may eventually discover multilated fragments of uncertain origin. These doubts might be mitigated by some system of labelling the payloads. At the least, careful records should be kept of the precise composition of all planetfalls, preferably with the retention of exact replicas of the components. (Some months ago, some unusual iron meteorites were distinguised from artefacts only after laborious study.)

CONTAMINATION OF THE EARTH

If active life exists on the planets, this raises the possibility of the introduction of new kinds of organisms to the Earth. Without more explicit information, it is difficult to assess the practical consequences of such "back-contamination." It is most unlikely that such organisms would be pathogenic for man, since the instigation of disease and the spread from person to person require many fine and long-evolved adaptations on the part of the parasite. (On the other hand, we will not have had an opportunity to evolve any specific defenses against such potential parasites.) A more likely risk is that of an ecological nuisance which would interfere with our easy occupation and exploitation of the earth's surface. Many of the antibiotics produced by soil micro-organisms are seemingly accidental byproducts of their normal metabolism; new organisms, with unique metabolic pathways might produce antibiotics which interfere in the normal cycles for carbon and nitrogen on which our agricultural (and vital) economy depends. One could, for example, visualize organisms that, having evolved electron-transfer systems other than the cytochromes, might produce carbon monoxide or nitrous oxide in large amounts. We know of many unhappy examples of biological competition from the introduction of new organisms into fresh niches -- e.g. many insect pests in the US; rabbits and prickly pear in Australia, smallpox into the New World, and syphilis into Europe. Even the relatively limited damage of these incidents should not be duplicated as a byproduct of space research.

It therefore follows that the reimportation of spacecraft that have entered the atmospheres or surfaces of the other planets* should be stringently interdicted until exhaustive biological studies have

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*This stricture probably can be relaxed for the Moon. Provided only that our general conceptions of the Moon's surface are verified by early probes, indigenous life cannot possibly have evolved independently on the surface; if any organsims are disseminated in meteorites, these will reach the earth in any case. However, the caution should be kept in mind if any chemically exceptional features are found in lunar investigation.

been made by remote methods. These studies, we may hope, can furnish the information needed to make a reasonable estimate of the hazards entailed by lifting the quarantine. Since manned spaceflight implies return trips, exobiological study must be emphasized as a prelude to this mission.

Finally, it may be remarked that the task of evaluating the potential hazard of a planetary biota will be multiplied if this has to be isolated from organisms inadvertently transferred from earth.

CO-OPERATION WITH OTHER NATIONS

Exobiological research is a common aspiration of all human culture; likewise, its successful prosecution requires the best use of available talent and instrumentation. Furthermore, the hazards of contamination of planetary targets, and even of the earth itself, can best be met by the fullest co-operation of all nations undertaking space research. These considerations are underlined by the spectacular success, in recent weeks, of the USSR in its lunar probes. We therefore urge that special stress be given to exobiology as an area for discussion of international co-operation. To this end, the members of Westex would heartily endorse an invitation to their opposite numbers in the USSR to meet together in the same spirit that has motivated our own meetings thus far. As a practical alternative, the forthcoming COSPAR meeting at Nice (January 1960) should afford an excellent opportunity for such discussions and we hope that this subject will be programmed, and that the USSR be encouraged as cordially as possible to send its representatives. We continue to urge President Bronk to use the good offices of the National Academy of Sciences to the fullest possible extent to elicit such co-operation.

Several observers have commented that it would be a striking gesture for scientific co-operation if USSR boosters, demonstrably the most technically advanced, could be made available for scientific missions that have been planned and instrumented through such international efforts. There may be some understandable reluctance in the US as well as the USSR to undertake such a co-operation. Some of us, at least, believe it cannot hurt our national prestige if we accept the obvious realities of the situation in a mature and constructive way, even while pursuing technological parity in vehicular capabilities.

References

1. The Westex Committee has consisted of the following members: (per attached sheet) Calvin, Davies, Horowitz, Marr, Mazia, Novick, Lederberg, Stent, Van Niel and Weaver.

   We have also enjoyed discussions with: Sagan, Sinton, Thomas, Bracewell, Urey.

2. Reports of Westex-1. (Copy enclosed)

3. Cetex-2 report (March 1959)

4. Westex-1D (see ref. 2)

5. Horowitz, N., 1959 Space Research and the problem of the origin of life. (Westex 1E)

6. Sinton, W. M., 1957, Spectroscopic evidence for vegetation on Mars. Astrophys. J. 126: 231-239. Also, mss, in press and paper presented at AAAS, Gainesville, Fla., Dec. 1958.

7. The development of color centers in otherwise transparent crystals as a result of heavy irradiation introduces a complication not easily controlled.

8. Lederberg, J. 1958 "Moondust" Science, 127: 1473-1475 (copy with note p. 1474 enclosed)

9. Conference on automatic analysis. New York Academy of Sciences (Nov. 12-14, 1959) (copy enclosed)

10. Davies, R. W. and Comuntzis, M. G., 1959, The sterilization of space vehicles to prevent extraterrestrial biological contamination. 10th Intl. Astronautics Cong., London, Proc., In Press. (JPL External Publ. 698.)

11. SSB-109 - Space Science Board Recommendation on Space Probe Sterilization

12. Galileo, G., 1610 - see attached quotation.

13. Oparin, A.I., 1957, The origin of life on the earth, 3rd ed. Academic Press, N.Y.; J. H. Rush, 1957, The dawn of life, Hanover House, N.Y. (I would especially recommend Rush's book for Board members and other scientists who are not biologists, as a resume of current thinking on the mechanisms of living origins. S. L. Miller, H. C. Urey, Organic Compound Synthesis on the Primitive Earth, S. L. Miller, H. C. Urey, Science, 130, p. 245-251.

14. Sagan, C., 1959, Organic matter and the moon. (Copy enclosed.) Sagan intends to give this paper (at H. J. Muller's invitation) at the NAS meeting in Bloomington in November. This is a preliminary version; some changes have been indicated, and he would invite comments. I would raise the possibility of printing this in toto, or asking for an abstract, as an appendix.

<u>Other exhibits</u> (for possible use in appendix)

15. Calvin, M. and others 1959, Bio-Astronautics Panel No. 2 Report. Dr. Calvin is quite agreeable to the republication of this report.

16. Sagan, C., 1959, Venus as a planet of possible biological interest. Report prepared under JPL auspices for use by SSB and by Bio-Astronautics Committee.
(This also is subject to final revision -- the enclosed is my only copy: it would be a service if, in any case, this could be duplicated for review by Westex and SSB.)

Ref. 1

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Ref. 2

WESTERN GROUP ON PLANETARY BIOLOGY

Discussion, February 21, 1959

Stanford University

Stanford, California

Present were:

University of California, Berkeley:

Calvin (Chemistry)
Mazia (Zoology)
Stanier (Bacteriology)
Stent (Virology)
Weaver (Astronomy)

NASA-JPL

Hibbs
Davies

Stanford University

Krauskopf (Geochemistry)
*Lederberg (Genetics)
van Niel (Microbiology)

*Recorder

University of California, Davis:

Marr (Bacteriology)

University of Oregon:

Novick (Biophysics)

California Institute of Technology

Horowitz (Biology)

Stanford Research Institute

Kamphoefner (Control Systems)

AGENDA

The appendices were distributed as working papers prior to the meeting. The MIT discussions (December 4 and December 19-20, 1958) were not available in time to be distributed to everyone in advance and will be reviewed at our next meeting, scheduled for March 21, 1959, at the JPL, Pasadena.

In view of the imminence of the CETEX meeting (March 9-10, 1959) and Pioneer IV (launched March 2, 1959), we focused attention on specific problems of celestial contamination and the decontamination of moonshots, deferring the more general aspects of a constructive program.

Hibbs outlined the dimensions of the Pioneer payload (since published in the press) and the procedure now being followed. Important features are: (1) a protective outer casing, which is shed at about 70 miles altitude; this is not airtight; (2) a scrubdown of the outer surface of the payload with absolute alcohol, followed by UV; (3) the lower part of the missile is not exposed to solar radiation at any time; (4) there was no information on the microbial status of the interior of the payload.

Hibbs also indicated a general timetable of planetary probes, which include two problematical probes at Venus in June, 1959, and several further attempts at the moon and at Mars in late 1959 and throughout 1960. While it is not highly probable that these probes will impact, this cannot be excluded.

DISCUSSION

The general principles of the CETEX report (Science, October 17, 1958) and of Appendix B were adopted with the following additions, observations, reinforcements, and revisions:

1. It would be a scientific catastrophe to make the cosmic blunder of uncontrolled contamination of another planet by terrestrial microorganisms. Our present knowledge of the planets Mars and Venus does not exclude the possibility of accomplishing this by depositing a single bacterium or spore from a probe.

2. The detection and identification of life on other planets ranks next to the recreation of terrestrial life as the outstanding challenge to contemporary biological science. We now have an increasingly plausible picture of the steps whereby life evolved on earth. This supports a strong expectation of parallel developments elsewhere, wherever the availability of carbon compounds (which are universal), water or other solvents, and a suitable temperature range are compatible with the evolution of chemical complexity. The unspoiled state of the surfaces of the other planets may be the only means ever available to human science, and certainly the only one for many years to come, whereby these speculations can be tested by explicit observation. Planetary chemistry and biology are therefore irreplaceable sources of knowledge for the origin and essential features of life on earth. Uncontrolled contamination might destroy most of the values of this experimental approach.

   (Dr. Horowitz will have prepared a more detailed exposition of this theme.)

3. Planetary biology must also rank very high in the scientific and social objectives of space research in general. The political, moral, legal, and economic consequences of premature contamination of celestial objects can hardly be estimated on the basis of present knowledge.

4. Even if these cautions constituted a serious obstacle to the achievement of other scientific aims, they would still have to

be credited, since biological missteps would do irreversible harm, while misjudgments in the physical sciences, though costly and exasperating, might still be remediable. However, we believe that it will be possible to incorporate biological precautions into the space program in a constructive way that should not impair other serious scientific aims. To do this will require, however, an earnest recognition of the importance of the problem and an intensive program of research on a wide front. This will be done in time only by awakening the interests of a number of alert biologists throughout the world.

5. The minimum condition for biological security would be the application of our full knowledge of microbial control throughout the design and assembly of the probes and terminal sterilization at launching (and atmospheric transit?). Above all, this must be accompanied by control evidence of the total efficacy of these procedures in the circumstances of their application. The development of methods of gaseous fumigation, especially with ethylene oxide, makes this aim a realistic one, so that the microbial control should not add appreciably to the total effort involved in the space research program, nor, given vigorous support, should it necessitate serious delays in the firing schedules.

Several laboratories are already involved in problems of large-scale sterilization, and their technical expertness should be exploited as far as possible.

6. We require additional information on the microbiology of missile components (e.g., are lyophilized bacteria trapped and preserved in vacuum tubes?), the launching site, and the atmospheric profile. Need, and if so can, a presterilized payload be effectively protected from atmospheric contamination? The distribution of microbes and biochemicals at high altitude would also be important knowledge for evaluating possible mechanisms of escape and infall and of photochemical synthesis of biochemically interesting compounds (e.g., what is the source of organic nitrogen in rainwater?).

7. Present methods of surface decontamination (as outlined by Hibbs) are too ineffective to be commensurate with the needs. However, they do at least contribute to the cleanliness of the payload and can, perhaps, be justified as a token effort. The contents of the payload are almost certainly more heavily contaminated and more effectively protected from sterilizing radiations. Of the methods discussed, including ionizing radiations, gaseous fumigation appears to be the most likely; however, some provision must be made for effective penetration of the fumigant, e.g., into tube sockets and screw holes, perhaps together with the use of self-sterilizing materials, lubricants, and padding and the presterilization of sealed assemblies.

8. More information is needed on the effects of missile impact. The supposition (Cetex -1) that fallout will be localized owing to the rarity of the atmosphere is unconvincing, and perhaps already contradicted by the well-known "lunar rays" which can extend for a thousand kilometers. A more likely event is the dissipation of kinetic energy as heat to very high temperatures, but more data and calculations are needed to show how much of the missile would be dispersed rather than heated (see Appendix C).

9. Although there are many telling arguments against survival of spores and their transit from one planet to another, many more or less convincing suggestions can be made for the expulsion and protection of an occasional particle. We therefore concluded that we could not decisively exclude panspermia on a priori arguments. Again more experiments are needed on the fate of spores and other particles in solar radiation fields, and more data are needed on electric or other forces in the upper atmosphere that might function in expulsion.

10. Although the moon is generally agreed to have no appreciable atmosphere, and therefore also no surface hydrosphere, Alter and Koryzev's recent observations on gaseous emissions at Alphonsus again raise the question of local sources of gases and, in turn, the possibility of interior sources of moisture. As long as there is any possibility of internal moisture, the moon may also be a sensitive target, and at least this point should be settled decisively before concluding otherwise. It is likewise difficult to preclude entirely the evolution of another form of life on the moon until we know more of its surface chemistry and particularly what may lie deep in its fissures.

11. For these reasons--namely, the remote possibilities of evidence for panspermia, of persistence of moisture, and of probiotic or biotic evolution--we suggest that the moon also be considered as a potentially sensitive target and that contaminating residues be kept to a reasonable minimum. However, it is most unlikely that terrestrial organisms could proliferate, and therefore the moon should be a legitimate testing ground for missiles on which microbial control is being developed.

12. Even if it is incapable of supporting terrestrial life, the moon is still an object of great biochemical interest, and total contamination should again be minimized. The most easily detected particle of terrestrial provenance would be a viable spore, which speaks for a contamination load of at most 10^8 per missile. This should easily be obtained. Ultimately, our biochemical techniques may be capable of detecting a similar incidence of inviable particles, and this tolerance should be a guide to the upper limits of microbial contamination before sterilization, subject to more information under heading 8. It was pointed out that "clean" supplies of distilled water may be able

to support bacteria to levels of 10^6 of 10^7 per milliliter if left standing, but special precautions should allow for cleaning to higher standards.

13. The molecular inventory of missile deposits should be of inestimable value in identifying suspicious objects found in later explorations. Some thought might be given to the consistent use of characteristic alloys as labels of terrestrial origin of metallic components and of a limited group of plastics to do the same for organic polymers.

14. We need to develop more effective channels of communication:

a. With Russion scientists, especially biologists (see Appendix C);

b. Between the space research program and U. S. Biologists with respect to missile programming and technology, and also scientific information on the solar system.

We have already recorded our urgent request to encourage Russian representation on CETEX. In addition, it would help to identify those Russian scientists most likely to be thinking about problems of planetary biology. Can we get translations or at least abstracts of papers being published in the Russian journal Astrobiology?

15. We recommend the continuation of our discussions and request prior assurance of funds from NAS or NASA to assure the continuity of our meetings.

APPENDIX A

SUGGESTED AGENDA: DISCUSSION ON PLANETARY MICROBIOLOGY, FEBRUARY 21, 1959

A. 1. What is the significance for biology of the occurrence of life on other planets? (Most laymen will appreciate this, but some physical scientists, as well as biologists in fields not closely connected with evolution, might profit from a clear statement.)

2. What is the range of our expectations? (Since this question involves a definition of the conditions under which life can be expected to evolve and persist, and therefore of the meaning of the term "life," I would suggest leaving this for continued discussion in future meetings. It might be profitable for each of us to state his own preliminary views briefly for further reflection.)

3. What would constitute "contamination": (a) for a sterile, nonhabitable planet; (b) for a sterile habitable planet; (c) for an inhabited planet? (Habitable might mean either by extant terrestrial organisms or by an indigenous biota.)

4. Is it possible to assess the relative importance of biological and other scientific exploration? A rigorous policy to avoid contamination of, say, Mars might lead to substantial delays in planetary research and therefore encounter strong opposition from other groups.

B. 5. What specific information is most urgently needed for the formulation of policy: (a) as the best assessment of existing data, or (b) that might be obtained with the help of existing instrumentation and theory? (The physicists must be told what we need to know. I have put two questions already--the distribution of moisture on the moon and on other planets [see Hess, 1958] --and the possibility that any fragment of a missile can survive a hard landing without being heated quite hot.)

6. What would be the most effective machinery for further communication along these lines?

7. What information do we need on the organization of space research in the United States and elsewhere?

8. What would be the best approach to reaching common policy on planetary biology with the USSR? Official channels? Semi-official action through CETEX and COSPAR? Coordinated or independent private communication with Russian scientists? Which Russian scientists are most likely to be our opposite numbers?

C. 9. Moonshots are being planned and executed at this time. What immediate recommendations can be forwarded? By what means (and how long would it take) should a definitive policy be formulated? (Should rockets be sterilized?

If so, how best? Should hard landings be prescribed altogether? What about soft landings? What is a tolerable level of risk that a circumlunar-orbital mission deviate into moonfall? --Programming is likely to aim at this error to help insure a more "significant" result.--)

10. What would be the most constructive program for progressive approach to the moon (if an immediate hard landing is discouraged)?

D. 11. Mars and Venus will probably be programmed within the next one to five years. What cautionary policy do you recommend? How strenuous should it be, especially if preliminary "safe approaches" give negative results?

12. What constructive proposals can we make for progressive exploration, beginning with the safe approaches outlined in the Boston resume (observation from: the earth's surface, a satellite of earth, a satellite of the planet)? Can we design a sterile planetfall? What would be the most sensitive criterion (or series of criteria on various predicates) for planetary life? To illustrate, how would a "Martian" best determine that the earth was inhabited (apart from human activity): (a) from an orbit, say, 1,000 miles up; or (b) by an instrument weighing up to 30 pounds deposited on the earth's surface?

APPENDIX B

CONTAMINATION OF A PLANETARY SURFACE BY INTERPLANETARY MISSILES

An interplanetary missile is equivalent to an artificial meteorite and is therefore unlikely to alter primitive surfaces except insofar as its composition uniquely reflects its terrestrial origin. The abundance of atomic species can be assessed so that it should be possible to obtain a consensus on tolerable levels of transport of, say, specific radioactive isotopes. We have much less basis for estimation of abundance of molecular species, especially large molecules and self-replicating particles. The problem is complicated by the ready interconversion of molecular species and especially under the catalytic mediation of either inorganic or living polymers.

As a general principle for the design of exploratory missiles, one might therefore argue that complex molecular species should be minimized in favor of elementary (*viz.* metallic) components which are already ubiquitous.

However, we cannot point to any important catalytic effect of the compounds used as industrial plastics, and in view of the possible unavoidability of carbonaceous rocket fuels, these molecules possibly cannot be excluded altogether. There may be some point to minimizing them and to maintaining a careful inventory of all substances deposited on extraterrestrial targets, at least until we have more complete information on the composition of the landing sites.

Molecular contamination can become significant when it reaches a level that we can hope to detect by analytical methods which either are now available or ever will be devised. We are not likely to be interested in infinitesimal changes over a background level. We should be interested in species of which the presence of one molecule on a planet might alter our conceptions of the uniqueness of life on the earth and the mechanism of its origin. Subjective estimates of the likelihood of finding such molecules (and by any argument this is very small for the moon) must be combined with the immensity of the consequences in evaluating the risks of exploration.

Three classes of celestial objects offer different expectations of present composition, with progressively greater risks of spoiling future research on extraterrestrial biology:

(1) Planetoids and minor satellites, owing especially to their redundancy and also to their homogeneity, negligible gravity, and total lack of atmosphere, must be the safest (if least interesting) targets. If guidance can meet the challenge, this would be an additional argument for programming, say, Deimos for the first demonstration of manned interplanetary flight. (The energetic and observational advantages are well known already.)

(2) The moon has intermediate gravity which precludes the retention of astable atmosphere, but it can still sweep out interplanetary particles. The size of the moon also allows for local singularities (e.g., deep, protected

fissures), continued seepage of internal materials to the surface, and sedimentary stratification, allowing some shielding from solar radiation.

It seems certain that there cannot be enough water anywhere on the moon to sustain the growth or spread of any terrestrial organisms. This premise is less certain now in view of Krzynev's claims and tolerances for contamination should be altered accordingly. The level of organic contamination will therefore remain at not more than the amount deposited and is certainly subject to substantial attrition by thermal, chemical, and photochemical decomposition. This factor might, however, be exaggerated by overemphasis on the unfavorable conditions prevailing at the outermost layer of the lunar surface.

To a first approximation, the tolerance should match the level we could ever hope to detect, or perhaps more realistically, to detect before precautions are relaxed under pressure of negative evidence. This is hard to predict. However, the moon's surface ~ 4 by 10^{13} m^2. The deposit of 10^{13} microorganisms would obviously be undesirable. But this would not deviate grossly from the probable level of, say, the remains in an ill-starred attempt at human landing, especially if failure involving, say, suffocation preceded a hard impact.

Present technology might hope to detect one microorganism per m^2 of surface. If we arbitrarily limit technical and scientific extensions to, say, 0.4 km^2, the corresponding tolerance would be 10^8 for certainty of confusion ($p=c^{-1}$) and 10^5 for $p=.001$ of confusion in any such sample of random surface.

It should be possible to maintain this level of sterility, viz. $\ngtr$ 105 per missile, by scrupulous cleanliness which would, in any case, be preferable to "sterile dirt" (see discussion below on chemical contamination). I would stress that this is a personal estimate of tolerance and that your group must weigh the consequences of its being too liberal against the other virtues of the experiment. I have some misgivings about the risk of a too hasty and too isolated judgment, but this seems the only tenable position in the face of national and international pressures for prompt and spectacular action. Otherwise, I would have thought it more prudent to base further plans on the findings from circumlunar satellites. If we really knew the parameters which underlie our assessments, we wouldn't need to send the device in the first place. The chemical attrition may, of course, be a decisive factor in forfending the hazard.

Soft landings may be less hazardous by concentrating a contaminating deposit in a small area, leaving others relatively cleaner. Gold has discussed large-scale movements (dust flow) that might occur even in the absence of an atmosphere. Hard impacts may well deposit particles of the missile randomly over the moon's surface, an especially disturbing possibility for a cushioned hard landing which would protect contaminants as well as instruments from evaporation.

Ref. 2

I do not feel it should be necessary to defend the plausibility of the preoccurrence of microorganisms (or more likely molecular fragments) on the moon's surface. Arrhenius's arguments are not *so* implausible that they should be totally ignored, but I would rather plead our basic ignorance than an explicit mechanism such as panspermia.

APPENDIX C

PRELIMINARY REPORT: FORMAL RECOMMENDATIONS OF AN AD HOC COMMITTEE ON PLANETARY BIOLOGY, STANFORD, FEBRUARY 21, 1959

1. Our present knowledge of the planets Mars and Venus is compatible with the possibility both of an indigenous life and of the maintenance and rapid spread of terrestrial microorganisms. The premature introduction of terrestrial organisms as contaminants on planetary probes might so distort the biology of either planet as to constitute a scientific catastrophe of the worst order. We must measure the consequences by the considered conclusion that the investigation of life on other planets is the most sensitive to irremediable harm and among the most important of the scientific objectives of space research, and is an equally cogent problem in the whole context of contemporary biological theory. It would therefore be an irresponsible act of policy to program any mission having a significant chance of introducing a single viable organism to the surface of Mars or Venus until we have all necessary information to measure the consequences. As a practical measure to effect an orderly and safe program of investigation, projects should be preferred which allow of observations from safe distances. In addition, any missiles which might have any likelihood of a landing, intentional or accidental, should be subject to careful sterilization. The sterilization should consist not only of the best currently used methods of sterilization (perhaps fumigation by ethylene oxide gas) but of empirical controls, by microbiological study, on the effectiveness of the sterilization procedure. The application of sterilization procedures, together with the indicated controls, should be a minimum condition of any code of conduct to be formulated by CETEX.

2. The status of the moon as a biologically interesting target is considerably more doubtful than that of the planets. However, if there is any possibility of persistent moisture at any accessible level of the lunar crust, it may prove to be as amenable to some form of contamination as the planets. Accepting the traditional concept of the moon as anhydrous and therefore sterile with respect to active life, we still find two important considerations: (1) the role of the moon as a gravitational trap for interplanetary material; and (2) the extent of prebiotic organic synthesis that may be indicated on its surface. The likelihood of interplanetary dissemination of spores (panspermia) is rightly considered to be remote, but we are unable to exclude it beyond further consideration. In addition, while many processes incidental to the mission and its impact may destroy a large fraction of contaminating microorganisms, information presently available does not give us assurance of the certainty of their complete destruction. We therefore recommend that vigorous sterilization procedures continue to be applies to moonshots along the lines indicated for the planets. The introduction of the microbiological factor into design and fabrication of the moonshop packages may also give useful experience relative to the deeper probes.

3. In order to minimize chemical contamination of a kind that might confuse later investigators, we recommend that a careful "molecular inventory"

should be made of each mission (perhaps together with the preservation of an actual replica of each package). Synthetic polymers are presumably unavoidable; they should always be used in place of substances of biological origin (e.g., casein glue). Finally, careful attention to overall cleanliness of the package is perhaps the most important factor in minimizing the contamination "noise" in the interest of later investigators.

4. Biologists have only recently begun to appreciate the urgency of devoting serious thought to problems of planetary biology. We recognize the validity of claims of other scientific groups and hope to generate constructive and decisive experiments at the earliest possible date, keeping in mind the novelty and subtlety of the problems facing us.

The study group considers it crucial to find channels of communication and cooperation with Soviet and other scientists for study and execution of experiments in planetary biology. It therefore requests that you forward to Dr. Bronk, as President of the National Academy of Sciences, the suggestion that urgent representations be made to the Academy of Sciences of the USSR:

a. To enlist their assistance in formulating a code of conduct in the CETEX discussions by sending a microbiologically informed delegation to this meeting.

b. To invite their cooperation in organizing an international scientific conference at the earliest possible date to discuss common objectives, exchange information, and review biological projects as the constructive counterpart for CETEX.

To avoid possible confusion with programs, such as "man-in-space" which may be identified with military objectives and the race for advantages therein, we suggest that the consideration of planetary biology be carefully dissociated in such discussions with Russian scientists.

We hope that this suggestion can be given Dr. Bronk's earliest attention if it is to have any practical effect.

APPENDIX D

COMMENTS ON CETEX-I REPORT, AS PUBLISHED IN SCIENCE, OCTOBER 17, 1958

1. The committee felt it would be difficult to place sufficient stress on the importance for theoretical biology of unimpeachable evidence on the status of life on other planets. We now have an increasingly plausible picture of the steps whereby life evolved on earth, so that we have strong expectations for parallel developments elsewhere, wherever the availability of carbon compounds (which must be universal), water or other solvents, and temperatures in a suitable range are compatible with the evolution of chemical complexity in organic (carboniferous) compounds. The unspoiled state of the surfaces of the other planets may be the only means available to the human species ever, and certainly for many years to come, whereby these speculations can be tested by explicit observation.

Laymen and other scientists may be expected to be equally strongly motivated by a fundamental curiosity as concerns the uniqueness of life in the universe to recognize planetary biology as one of the most fundamental issues in space exploration that will persist when most of the momentary pressures have been forgotten in the perspective of history.

If any errors of judgment are to be made, clearly they must be conservative ones. Would this generation of scientists ever be forgiven by its successors if it permitted the execution of a cosmic blunder that could be remotely anticipated? By their very nature, experimental missteps in biology may do irreversible harm; in the physical sciences they may lead at most to exasperation, delay, and waste.

On the whole, we believe it necessary and possible to formulate a program of space research that conserves objectives in biological science without impeding sober objectives in the physical sciences. Indeed, the two programs are not fundamentally separable.

2. The CETEX report is a clarifying document that does much to place the start of planetary biology and chemistry in reasonable perspective. We would, however, take exception to some particular points that warrant further discussion:

a. "Any contamination of the (moon) dust by space operations will be localized" owing to the low density of the atmosphere.

This premise is fundamental to a number of assurances concerning the safety of lunar probes, but can it be supported? No particle will reach the moon's surface with less than escape velocity. Any fragment which recoils, having dissipated half or less of its kinetic energy, will have sufficient velocity to orbit the moon. Residual energies of less than half will allow for parabolic trajectories to ranges approaching the whole perimeter. The absence of an atmosphere allows for the prompt dispersal of parts of the missile to any point on the moon's surface. This supposition is concordant with the widely accepted interpretation of the lunar rays, especially Tycho, precisely as the result of fallout from meteoritic infalls. These rays may extend for thousands of kilometers! (See Baldwin, The Face of the Moon, 1949.)

(A more cogent expectation is that any uncontrolled impact may result in the dissipation of most of the kinetic energy as heat. If this can be substantialted for lunar impacts, there would be no danger of biological contamination. However, it appears to be uncertain whether we could rely on impact-heat sterilization of the entire payload; indeed those fragments that were most widely dispersed might be expected to be heated the least, since they would have dissipated less of their infall energy on the impact. This question plainly has not been exhausted.)

Other means and assurances of localization of missile components must be found.

b. "Solar radiation would decompose biospores just as it decomposes cosmic dust. . . ."

This may be granted for exposed particles lying on a smooth, unprotected surface. The point of exception is obvious: The moon is not such a surface.

It is of course oa serious criticism of panspermia; how can a biospore transit the solar radiation field to reach another planet without being destroyed? To sustain the hypothesis, we might have to plead that the spore is embedded in some other protecting material, e.g., a particle of clay, or else that some hitherto unknown optical property of the spore in high vacuum might furnish some protection. The former plea makes it more difficult to accept Arrhenius' proposal of radiation pressure as the impetus to interplanetary transit. All this admitted, we do not feel that we have the intimate knowledge of conditions on the lunar surface and in interplanetary space to cast a decisive a priori judgment against the hypothesis.

In conclusion, we feel that general stress on minimizing contamination of any kind and excluding microorganisms as far as technically feasible is a plausible part of any cautious program of investigation. Rather than leave the moon for the uncontrolled deposit of uncontrolled contamination, it should be the testing ground for the same cautions as apply to the more sensitive planets.

INTERNATIONAL COUNCIL OF SCIENTIFIC UNIONS

Paleis Noordeinde,
THE HAGUE.

Second Meeting of the

ad hoc Committee

on Contamination by Extra-terrestrial Exploration

The Hague, March 9 - 10 1959

List of Participants

Convenor Professor Marcel Florkin

Representing

IAU	Dr. J. Rosch	IUGG	Professor J. Bartels
IUPAP	Dr. Donald J. Hughes	IUBS	Dr. P. Alexander
IUPS	Professor W. O. Fenn	IUB	Professor J. Roche

Observers:

Professor P. Swings
Professor H. C. van de Hulst

Summary Recommendations

CETEX was established in 1958 by ICSU to meet once to find out if the problem of contamination of extra-terrestrial objects by space vehicles represents a real problem. The report of this meeting which was held in May 1958 was that in the committee's view there is a real possibility that early experiments might spoil subsequent research. The committee therefore proposed to ICSU that a code of conduct be drawn up for space research with particular reference to the allocation of priorities and sequences of different experiments. CETEX stressed that such a report would require the active participation by experts, especially from the field of rocket technology. ICSU accepted this recommendation and at its general meeting in Washington in October 1958 asked CETEX to hold a second meeting. At the same time ICSU requested the National Academies of the U.S.A., U.S.S.R. to assist CETEX with experts in rocket technology and with prepared documents. CETEX at its second meeting held at The Hague in March 1959 was able only to start its assigned task because the complexities of the problem made it impossible for the necessary detailed technical information to be available.

In the interval between the first and second meetings COSPAR has been formed by ICSU to co-ordinate world wide space research and this new body enjoys the support of the American and Russian Academies. CETEX feels that the detailed functions proposed for its second meeting form an integral and important part of the duties of COSPAR and at this meeting CETEX confined itself to the general formulation of the problem and review of its initial report which has been slightly modified.

General principles governing space research

1. Space research offers a challenge and opportunities which should appeal to the most imaginative minds. The greatest encouragement must be given to novel and unconventional approaches and no proposal should be sanctioned which would hamper the experimenters freedom of action unless there are compelling reasons. On the other hand equally imaginative thinking is required when considering possible complications which can follow a particular type of experiment. Surprises are certain and unlikely possibilities must be borne in mind when dealing with the problem of contamination which is better defined as the problem of reducing the risk whereby one experiment may spoil the situation for other subsequent enquiries. The question of deciding whether such a conflict is likely to arise can best be dealt with by a committee or working group engaged in planning, or advising on scientific experiments.

2. Ideally scientists should be asked to inform COSPAR as early as possible of each space experiment which is envisaged and of the methods to be used in its execution. The broadly based committee of COSPAR containing scientists from all disciplines may be able to see much more clearly than the space research specialists possible conflicts introduced by such experiments and may be able to suggest ways of overcoming these difficulties.

3. There are a number of obvious and necessary experiments which are bound to be done and here the COSPAR working group dealing with experiments may be able to suggest priorities. While it may not be possible to avoid all types of contamination a proper sequence can ensure that the collection of data is not thereby hindered. For example CETEX recommends positively that no "soft" landing, which requires the release of large quantities of gases, should be made on the moon until experiments have been successfully carried out - or at least all reasonable attempts made - to determine the nature of the moon's atmosphere.

4. In view of the great uncertainties which face space research all operationswhich are not capable of conveying meaningful scientific data are to be discouraged even if they do not appear to carry with them a known source of contamination. Risks with the unexpected must be taken as otherwise no space exploration is possible but such risks must be justified by the scientific content of the experiment.

Contamination endangering physical and chemical studies

(1.) The Moon's Atmosphere The Moon's atmosphere contains only a small amount of matter (it is estimated at less than 100 tons) and is therefore extremely vulnerable to contamination. The release on the surface of any amount of volatile material (having a molecular weight of greater than 60) within this range of magnitude such as might be given off from explosions for marking purposes or to slow down the vehicle for "soft" landings is likely to remain on the moon. Another factor which a change in the lunar atmosphere might bring about is an upset in the thermal equilibrium and careful computation will be required before the magnitude of this effect can be assessed. The possibility that the impact of a rocket vehicle may itself be sufficient to alter the atmosphere by releasing trapped gases was rejected because the moon surface must occasionally be subject to bombardment by heavy meteorites.

The release of any chemical marker on the moon surface is therefore objectionable if it involves tons of material. If it has to be done, a flare releasing material quite unlike that normally present in the lunar atmosphere should be used so that in subsequent investigations it can be clearly recognised as a contaminant introduced by man. Both in this connection and because of increased ease in detection a flare produced by sodium should be considered for this purpose. The sodium D lines could be detected at low intensities if a monochromator is used to cut out scattered light of other wavelengths. Probably the quantity of material required to be visible through a telescope, though not to the naked eye, would be insufficient to cause serious contamination of the atmosphere.

The possibility that a flare of this type might disturb the lunar atmosphere due to the ionization of the sodium atoms by sunlight has been considered but such an effect is unlikely to persist for long periods.

From the foregoing it is clear that detailed exploration can very easily modify the lunar atmosphere which should, if at all possible, be studied spectroscopically from either earth or moon satellites. An accidental hit by a vehicle which has failed to orbit would probably not be serious, since the moon's surface must occasionally be subject to bombardment by heavy meteorites and the release of trapped gases by impact will not therefore cause a departure from natural conditions.

(2.) <u>Moon Dust</u>* The chemical composition of the dust on the moon's surface is of the greatest interest to a wide range of sciences. Knowledge of changes of composition at different levels would also be informative but may be difficult to interpret since bombardment by meteorites is likely to disturb the dust. For this reason mixing of some of the dust by rocket impact is unlikely to result in the loss of information.

The suggestion has been made in the recent scientific literature that there are unstable structures of a high free energy content (i.e. containing a high concentration of free radicals) on the moon, which may be caused to react explosively on coming into contact with organic substances from the earth. The suggestion has therefore been made that great care be taken to exclude organic substances from space vehicles likely to impact on the moon. The Committee could not support the view that such a hazard existed since such free radical structures would be triggered off by any impact which caused intimate mixing. Meteorites or some corpuscular radiation would act as a fuze and initiate an explosive chain reaction.

The man-made object would do no more harm in this respect.

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* The possibility that valuable information concerning cosmic dust may be lost by disturbing the moon's surface has been considered but is unlikely to be serious. Analysis of the moon's dust can only provide a very incomplete picture of cosmic dust because many of the constituents will be volatilized by solar radiation.

5. RADIOACTIVITY

A serious danger of spoiling the moon's dust will come from nuclear explosions. These will release fission products which under the conditions of extreme vacuum will enter the moon's atmosphere and be rapidly distributed. These radioactive atoms will be in a highly reactive form and on coming into contact with moon dust may form involatile compounds. In this way the whole surface of the moon may acquire additional radioactivity which may interfere with subsequent radiochemical analyses that could be of the greatest value in particular for problems relating to the history of the moon. The explosion of a fusion device is likely to be more serious than that of a fission bomb since the former will give rise mainly to volatile radioactive products, notably tritium, whereas the bulk of the volatile fission products are rare gases which will not combine with the moon dust. However, the range of the small particles by which fission bomb activity is spread is likely to be very great on the moon and a serious danger of contamination would undoubtedly arise.

Although the relative extent of the contamination of the planets from a nuclear explosion would be very much smaller than in the case of the moon it may nonetheless be sufficient to interfere with detailed radiochemical analyses under certain conditions. Also the effect of introducing radioactivity on another planet where there may be entirely different levels of background radiation from those found on earth could greatly influence any form of life found there. Although the objections against nuclear explosions on Mars and Venus may not be as compelling as in the case of the moon, they are nevertheless well justified until more information is available.

Biological Contamination

Recommendation for immediate action The sterilization of space vehicles to prevent the spreading of spores and other terrestrial microorganisms in the solar system is likely to present a number of technical problems that may not be easy to solve. CETEX suggests that COSPAR initiate a study immediately of the methods by which the inside of space vehicles can be sterilised bearing in mind the presence of delicate instruments that must not be damaged. As soon as possible methods should be published by which this can be achieved and it should be urged that all space probes be sterilised in this way. Although CETEX feels that the possibility that life can persist on the moon is sufficiently remote to justify being neglected, all moon probes should be sterilised so that the difficult techniques of sterilization may be worked out in practice.

The outside of space vehicles need not be sterilized since exposure to the unfiltered solar radiation during flight will destroy all microorganisms which have settled on the shell. The need for sterilization is only temporary. Mars and possibly Venus need to remain uncontaminated only until study by manned space ships becomes possible.

(1.) Contamination of the Moon by living cells There is no reasonable possibility by which the introduction of cells such as spores or bacteria might give rise to life on the moon of the same type (i.e. containing DNA) as on earth which might confuse later investigators. There are no cells on earth which grow or multiply in the absence of water and at the high vacuum of the moon no water can exist on its surface.

(2.) Contamination of Mars and Venus There is a possibility of biological contamination of these planets since there is a reasonable probability that the conditions on Mars are such that some terrestrial organisms might grow. Carbon compounds, light for photosynthesis and probably water and nitrogen are all available. It is therefore of the greatest importance that space vehicles should not land either accidentally or deliberately on Mars (and possibly also Venus) unless all precautions have been taken to exclude living organisms from them. Otherwise the most challenging of all planetary studies, that of extra-terrestrial life, may be put in jeopardy. The same precautions in regard to the development of complex molecules which have been dealt with in respect of lunar contamination in paragraph 4 below apply equally to both Mars and Venus.

(3.) Panspermia Hypothesis The suggestion that moon dust might help in evaluating the hypothesis that dissemination of life in the cosmos occurred by transport of forms of life in the cosmic dust must be rejected because solar radiation (in high vacuo) would decompose "biospores" just as it decomposes cosmic dust. The possibilities by which a spore might travel through space inside meteorites involve so many improbabilities that they do not justify special consideration at this stage.

(4.) The development of complex molecules The basic problem concerning the origin of life is how complex molecules (on the earth they are based on carbon) came to be built up and become replicated. It is conceivable that the interior of the moon dust may provide some valuable clues in this direction. It is not beyond the bounds of possibility that some "pre-life" processes may be occurring on the moon and these may be similar or different from those which had taken place on earth. If there are such processes then the introduction of "foreign" macromolecules from the earth may cause a serious upset in the lunar processes. The earth macromolecules may under lunar conditions act as templates and provide new foci for "pre-life" growth. If such events were started indiscriminately all over the moon the pattern might be distorted. It is important to emphasise that living cells are not envisaged for this process and that in this connection a dead bacterium from an aseptic rocket would be as harmful as a live one. The occurrence of any such growth reactions is remote and does not justify the imposition of any irksome restrictions on lunar exploration but where reasonably possible it should be borne in mind. A simple precaution against endangering future studies might be to limit the areas of landings on the moon and thereby to localise the effects - if any - of terrestrial templates.

Ref. 5

Space Research and the Problem of the Origin of Life

Part A of the following report was presented by Horowitz as background material at the Stanford conference on extra-terrestrial biology, February 21, 1959. Part B is a summary of comments on the biological importance of space exploration. Present at the conference were: Calvin, Davies, Hibbs, Horowitz, Kamphoefer, Krauskopf, Lederberg, Marr, Mazia, van Niel, Novick, Stanier, Stent, Weaver.

A. History of the Origin of Life Problem

From classic Greek times until the late 19th century, it was generally accepted that living matter in one form or another could originate spontaneously from non-living material. The frequently observed presence of insects, worms, frogs, etc. in mud or decaying organic matter was considered proof that these animals were generated spontaneously, without parents. This notion was disproved by Redi in 1668, but it was revived almost immediately following the discovery of microorganisms by Leeuwenhoek in 1675. Disproof in the case of microorganisms was difficult for technical reasons. Besides, prople clung to it because bacteria, so small and apparently simple, seemed to be in the twilight zone between living and non-living matter. (Actually, these organisms are as complex as any cell of our own bodies.) Spontaneous generation of microorganisms was finally disproved by Pasteur in 1862.

Pasteur's experiments produced a reaction. Many scientists, especially physical scientists, came to the conclusion that these experiments demonstrated the futility of inquiring into the origin of life. They proposed that life had no origin, but, like matter, was eternal. This was the view of Arrhenius, Helmholtz, and Lord Kelvin. Arrhenius, especially, elaborated this idea which he called the theory of panspermia. He proposed that life-bearing seeds are scattered through space, and that they fall on the planets and germinate wherever conditions are favorable. In addition to this, Arrhenius suggested a mechanism by which spores with diameters of the order of 0.1 micron could be carried beyond the gravitational field of the planet of their origin and be propelled (by light-pressure) through space to other planets. Arrhenius concluded from this theory that living things throughout the universe are related and should consist of cells composed of carbon, hydrogen, oxygen, and nitrogen.

The panspermia theory is much less attractive today than it was fifty years ago. Life is now regarded as a manifestation of certain molecular combinations. Since these combinations are not eternal--indeed, neither the elements nor matter itself are eternal, according to modern cosmologists--it is impossible to accept the idea that life has always existed. In addition, the escape of spores from the gravitational field of the earth and their survival in the unfiltered radiation of outer space seem much more difficult problems to us than they did to Arrhenius.

With increasing knowledge of the chemical nature of living matter has come a renaissance of the idea of spontaneous generation, this time at the molecular level. In the 'twenties, Oparin and, independently, Haldane, proposed that the origin of life was preceded by a long evolution of organic compounds of ever-increasing complexity on the earth's surface. In the pre-biotic, sterile world, these compounds could accumulate in the seas and eventually, by random combinations, produce a living molecule or molecular combination. (Differences of opinion as to the nature of the first living thing are ignored here.) Oparin pointed out that the synthesis of organic compounds requires reducing conditions, since these compounds are unstable in the presence of oxygen. He proposed an atmosphere of methane, ammonia, water, and hydrogen for the primitive earth. Urey later showed that methane, water, and ammonia are the stable forms of C, O, and N in the presence of excess hydrogen. Since hydrogen is the predominant element of the cosmos, it is reasonable to assume that it was present in large amounts on the primitive earth. Urey suggested that ultraviolet light could provide the energy for organic synthesis in the primitive atmosphere. Model experiments by Miller have shown that organic compounds including amino acids, organic acids, and urea are in fact produced when ultraviolet or an electric discharge is passed through such an atmosphere.

Finally, modern genetics and evolutionary theory show that it is possible, starting with a single living particle in an environment rich in organic compounds, to account for the evolution of all living species.

B. The Significance of Space Research for Biology

The discovery of life on another planet would be one of the momentous events of human history. Such a discovery would do more than answer a universal curiosity, however; it would also be of enormous scientific interest. Next to the synthesis of living matter in the laboratory, it would be the most important step that could be made toward an understanding of the problem of the origin of life. Among the fundamental questions which it might solve is the question of the uniqueness of systems based on nucleic acid are found on another planet, what will it be possible to say about the question of independent origin versus common origin by a mechanism of the Arrhenius type? Although it is unlikely that large numbers of spores could escape from the gravitational field of the earth by the electrostatic mechanism proposed by Arrhenius, the possibility of escape of an occasional spore cannot be excluded.

Important information which would bear on this question can be obtained now, in the neighborhood of the earth. For one thing, it would be desirable to learn more about the vertical distribution of microorganisms in the atmosphere. For another, more information about the ultraviolet flux in space is essential for estimating the chances of survival of spores.

Another basic biological problem that should be considered in advance is that of recognizing living material that is not chemically similar to our own. Such organisms may have metabolic rates and growth rates much lower than anything we are familiar with.

Although the possibility of detecting and studying life on other planets is the most exciting aspect of space exploration, the biological importance of space research is not limited to the study of extra-terrestrial life. Even if no life is found on them, the possibility of sampling the organic compounds on other worlds can yield invaluable evidence bearing on the origin of life. These sterile worlds may well provide unique clues to the organic chemical processes which preceded the development of life on the earth. The recent observations of Sinton on Mars and of Kozyrev on the moon make it appear likely that large scale chemical processes involving carbon are taking place on these bodies. Although it is virtually certain that life occurs elsewhere in the universe, the a priori likelihood of its being found on other bodies of our solar system, especially the moon, is not high; consequently, the importance for biology of geochemical research of the type mentioned should not be minimized.

In brief, there is reason to think that the results of space exploration will be of biological interest regardless of whether extra-terrestrial life is actually found. For this reason, it is all the more important to minimize contamination, either chemical or biological, of the moon and planets. It should be possible to set up tolerance limits for contaminents and rules of procedure which will safeguard the possibilities for significant biological investigations in space without impeding the development of other programs.

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Moondust

The study of this covering layer by space vehicles may offer clues to the biochemical origin of life.

Joshua Lederberg and Dean B. Cowie

Lacking an appreciable atmosphere, the moon may seem to offer little opportunity for biological research. However, astronomers suppose that the moon is covered by a layer of dust of great antiquity (*1*). This dust is cosmic material captured by the moon's gravitational field and presumably left undisturbed by atmospheric and biological alteration. It should therefore contain a continuing record of cosmic history as informative with respect to the biochemical origins of life as the fossil-bearing sediments of the earth's crust have been in the study of its later evolution.

For the biologist, this dust may furnish two striking opportunities: (i) to assess the prebiotic synthesis of organic compounds and (ii) to make an empirical test of cosmic dissemination of biospores [Arrhenius' *pan*-spermia hypothesis (*2*)]. The scope and uniqueness of these opportunities demand a cautious approach to the planning of space missions lest they be prejudicial to later scientific study.

Prebiotic Synthesis of Organic Molecules

The traditional picture of the nonliving world is colored by the composition of the earth's crust with its predominance of siliceous rocks. A comparison of the relative abundances of the elements in the earth's crust and the cosmic abundances (Table 1) reveals that the earth's crust is not a fair sample of total matter. In fact, carbon, nitrogen, and oxygen make up about three-fourths of the total matter of the universe, apart from hydrogen and helium. The formation of the earth therefore involved a fractionation which left it relatively impoverished with respect to the lighter elements which make up organic compounds (*3, 4*), and the richness of organic complexity on our own planet was formed out of the mere dregs of cosmic distillation. However, the data on cosmic abundance are based mainly on the atomic spectra of the stars, and we have only the most rudimentary information on the *molecular* chemistry of the universe (*5*).

The overabundance of H suggests that the most prevalent molecules will be more or less saturated hydrides of carbon, nitrogen, and oxygen (CH, OH, CH_4, H_2O, NH_3, . . .). Many proposals for the prebiotic appearance of complex organic molecules are based on the photoactivation of these simple precursors by ultraviolet light (*6, 7*). Furthermore, since the elements must have been formed initially at very high temperatures (*8*), they are already "activated" by their incidence as free atoms in space.

Indeed, the bulk of cosmic matter is still dispersed among the stars and galaxies as atoms and molecules and larger particles which are condensates of these, which constitute the cosmic dust. The details of these condensing processes are still most obscure. As summarized by Dufay (*9*): "Although the densities of the CH and CH^+ molecules formed by atomic and molecular reactions are very small, they are perhaps large enough to initiate the condensation. If this point is granted, it would then be necessary to examine the capture of a second atom of hydrogen or of carbon by the CH molecule. Because of the abundance of hydrogen, the first is more probable but the calculation of the probability of formation of the CH_2 molecule is very difficult. It is possible that some more hydrogen atoms attach themselves to the CH_2 molecule (CH_2 CH_3 CH_4 ?) but before long it is mainly atoms of much larger mass (C, N, O, . . .) which are captured because the large molecule formed is not sufficiently cold to prevent the evaporation of hydrogen. Thus, little by little, due to a mechanism which is difficult to evaluate in detail, minute grains which seem to serve as centers of condensation are built up." The scattering of light from distant stars indicates that the grains may grow to sizes of a few tenths of a micron. Furthermore, the observed polarization of the light from distant stars following its passage through galactic clouds speaks for the asymmetric shape of the grains and their orientation presumably by magnetic fields (*9, 10*).

The grains, being condensed from a pool of reactive free atoms among which hydrogen predominates, might be ices (crystals) of the simple hydrides— CH_4, NH_3, and H_2O—or more complex molecules containing the same elements. Which composition predominates will depend on the extent of discrimination against H which was quoted in the previous paragraph. One basis for further speculation is the occurrence of spectral lines identifiable with nonhydride molecules such as C_2, CN, and CO in the emission from comets and in the interstellar absorption (*5, 10*). The possibility of extensive macromolecular organic synthesis by this mechanism is a new point of convergence of biochemical and astro-

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Professor Lederberg is chairman of the Department of Medical Genetics, University of Wisconsin, Madison; Dean B. Cowie is a member of the staff of the Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, D.C. This paper was delivered at a symposium on "Possible Uses of Earth Satellites in Life Science Experiments," in Washington, 14–17 May, under the sponsorship of the National Academy of Sciences, the American Institute of Biological Sciences, and the National Science Foundation.

physical research. The problem is extremely complex both in theory and in the construction of laboratory models; many factors, such as local fluctuations in atomic abundance, radiation flux and polarization, magnetic orientation, temperature, and the catalytic role of nuclei of condensation, all have to be taken into account.

In favorable circumstances the chemical evolution of the growing grain will be determined in the first place by the random sequence of atomic collisions. The accretion of a colliding atom will depend in part on its kinetic energy and on its composition and that of the incipient grain. The composition of the grain between impacts will also determine its stability—that is, its temperature in the radiation field, in accord with its absorption spectrum. Thus, despite the random input of precursor atoms, the evolution of the grain will also be determined by a sort of natural selection, those agglomerates that are maladapted being vaporized, and the constituent atoms will be returned to the precusor pool. The grains rarely grow larger than 0.5 micron in diameter, perhaps due in part to evaporative collisions of such large grains with one another (*9*).

A serious difficulty in the theory of interstellar grains has been the inefficiency of diatomic reactions in free space without the participation of preformed grains to serve as nuclei of condensation (*11*). It would seem to be necessary to invoke either an independent source of nucleation in the emanation from sooty "carbon stars," as Hoyle has suggested (*12*) or a mechanism of fission of spontaneously formed nuclei so that these may increase in number as well as accrete in mass. The fission of grains might occur either by internal exergonic rearrangement, by photochemical dissociation, or by splitting from colliding atoms. The potentiality for fission is therefore another element in the chemical evolution of the grains.

Apart from the scope of its own evolutionary development, the system of organic synthesis in space is important to the origin of life in two respects: as a model of some of the reactions accompanying the formation of the planet and as a continual source of replenishment of organic precursors for life. From another viewpoint, Hoyle (*12*) has invoked the possibility of a large budget of organic material in the initial condensation of the earth. This budget would be replenished by photochemical reactions in the atmosphere and by the accretion of cosmic dust by meteoric infall. The importance of the initial budget depends on the outcome of controversial questions about the temperature of the earth during its early history (*3*, *4*).

Table 1. Relative abundance of the elements (expressed in atomic abundances). Scale: Elements other than H and He total 1.)

Element	Relative abundance: Cosmos*	Terrestrial atmosphere† and hydrosphere†	Earth's crust‡
H	1600	2	0.03
He	160		
O	0.378	0.978	0.623
N	0.269	0.003	
Ne	0.168 ±		
C	0.135	0.0001	0.0005
Si	0.017		0.211
Mg	0.015		0.018
Fe	0.012		0.019
S	0.003	0.0005	
Ca	0.002		0.019
A	0.002		
Al	0.002		0.064
Na	0.001	0.008	0.026
Ni	0.0005		
Others	0.002	0.011	0.020

* After Urey (*3*).
† After Hutchinson, in *The Earth as a Planet* (*4*).
‡ After Mason, in *The Earth as a Planet* (*4*).

Interstellar and Interplanetary Dust

Efforts to make detailed evaluations of the composition of cosmic matter are hindered by the discrepancies between interstellar and interplanetary dust, since the latter must reflect in part the fractionation of the elements in the formation of the solar system and also the local intensity of the gravitational and radiation fields of the sun. The interplanetary dust will include solar emanations, interstellar matter swept out by the proper motion of the sun, and (possibly most abundant) the debris of asteroids and comets. The former, comprising most of the meteorites, will have a stone and iron composition like that of the earth; the cometary debris, which, according to Whipple (*13*), is mainly responsible for visual meteors and for micrometeorites, is of special interest in the present context. Being formed at great distances from the sun, the comets most nearly, among all the interplanetary objects, represent the composition of interstellar matter.

The density, sources, and composition of the interplanetary material represent some of the most challenging objectives of satellite research. Published estimates of the rate of infall of this material vary widely and have dealt almost exclusively with nonvolatile constituents which can be observed in meteorites. Some of the higher estimates can be extrapolated so as to suggest that infall during geological history might have made a significant contribution to the composition of the earth's surface. For example, Petterson (*14*) has estimated an infall of 3.5 × 10^{11} g of Ni per year. If this is multiplied by the cosmic C:Ni ratio (Table 1), we obtain for C alone 10^{14} g per year, or 10^{23} g for a billion-year interval of geological history. This figure may be compared with an annual photosynthetic turnover of 10^{17}g; a biosphere of 10^{18} to 10^{19} g; 10^{20} g of C available to the biosphere in the atmosphere and oceans; and 10^{23} g of fossil C, including that trapped in the sedimentary rocks (*4*). The extrapolated estimate is ~~almost~~ certainly exaggerated. * However, a precise knowledge of infall is certainly necessary in order to evaluate its contribution to geochemical evolution, on our concept of which the analysis of biochemical evolution must be based.

Terrestrial observations of infall are of limited value with respect to the quantity and quality of interplanetary carbon, since whatever organic matter fails to be oxidized while falling through the atmosphere is likely to be degraded by or confused with the existing biosphere. Some exceptional opportunities invite more detailed analysis by modern methods; for example, the "Cold Bokeveld" meteorite is reported to contain appreciable amounts of organic acids, as well as organic compounds containing S, N, and Cl which have not been explicitly identified (*15*). Barring such exceptional finds we must look to the moon for samples of undegraded and uncontaminated dust with which to check these speculations. Owing to the loss of smaller (lighter) molecules from the weak gravitational field of the moon, our assessment of this fraction should be bolstered by whatever samples can be filtered from interplanetary space.

Panspermia

The earth and perhaps other planets might serve as sources for the cosmic dissemination of life. Because the hypothesis of panspermia does not solve the basic

* not altogether innocently

problem of the origin of life, but merely transfers it to another site, it has been discounted by most commentators. However, gene flow among the planets would alter the diversification of evolutionary patterns, and the transport of even a fragment of an organism might short-circuit an otherwise tortuous history of evolutionary progress. It should be conceded that planetary biology will have greater fundamental interest if it does reflect wholly independent origins of life so as to furnish an opportunity for comparative study of wholly different biochemical systems. On this basis, the most interesting questions will not be the expected convergent evolution of extraterrestrial organisms towards superficial resemblances in parallel habitats, but the details of their biochemical make-up. As far as we know, all terrestrial organisms have their genetic basis in nucleic acids. If, say, the Martian flora likewise proves to contain deoxyribonucleic acids, we will face a difficult problem: Have these compounds evolved recurrently as a unique solution to the requirements of genetic replication, or do we share a common ancestor? The dilemma is no less pointed if we find another genetic material: Is it an independent solution or an evolutionary divergence conditioned by a unique habitat? Thus, a definitive conclusion on Arrhenius' hypothesis will be an indispensable element of cosmic biology.

The problem of expulsion of particles no smaller than He^3 from the gravitational field of a planet like the earth by natural agencies already poses formidable difficulties for the hypothesis of panspermia. These are compounded by the radiation hazards of extra-atmospheric space (*6*), although we need more information on the potency of these hazards under the actual conditions of space. To defend Arrhenius' thesis on the basis of present information is difficult, but the thesis is too important to be rejected by prior reasoning short of an empirical test.

In fact, we can point to one mechanism which meets the requirements of ejection and safe transport from the earth: the interplanetary missile. Unless specific precautions are taken, such space craft are likely to carry terrestrial organisms to the moon or other targets. Such contaminants might make an explicit test of Arrhenius' hypothesis difficult to interpret. The surface area of the moon is 4×10^{13} m^2. Microbial populations can easily reach 10^{13} microorganisms per kilogram of contaminated material.

The same considerations apply even more strongly to other destinations. Artificial contamination might distort the microbiology of more hospitable planets and might even perform the function posited by Arrhenius of seeding a previously sterile planet.

A given level of contamination, be it biological or chemical, is significant in relation to the sensitivity of currently available methods of analysis. Advances in analytical chemistry are likely to make meaningful levels of occurrence or contamination which are beyond the scope of present techniques. Present methods are already sensitive enough that radiochemical analysis of, say, the moon's surface might be perturbed by the fallout from a single atomic missile.

Since the sending of rockets to crash on the moon's surface is within the grasp of present technique, while the retrieval of samples is not, we are in the awkward situation of being able to spoil certain possibilities for scientific investigation for a considerable interval before we can constructively realize them. However, our assessment of the validity of these risks may become more reliable with the accumulation of information on the physical parameters of extra-atmospheric space and with the astrophysical data that can be collected to great advantage from artificial satellites. There are, in addition, many model experiments in microbiology and biochemistry that can be performed in the terrestrial laboratory, and some information on the survival of spores might be collected from telemetered experiments in satellite devices.

At the present pace of missile development we urgently need to give some thought to the conservative measures needed to protect future scientific objectives on the moon and the planets. We are pleased to note that at the instance of the National Academy of Sciences of the United States, the International Council of Scientific Unions has established a special committee under the chairmanship of M. Florkin of Liège, Belgium, to review the problems of contamination of extraterrestrial objects.

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CONFERENCE

on

AUTOMATIC CHEMICAL ANALYSIS

Thursday, November 12
Friday, November 13 and
Saturday, November 14, 1959

THE NEW YORK ACADEMY OF SCIENCES
DIVISION OF INSTRUMENTATION
2 East Sixty-third Street
New York 21, N. Y.

ALL SESSIONS WILL BE HELD AT

The Barbizon-Plaza Hotel
101 West 58th Street at 6th Avenue
New York 20, N. Y.

This program will serve as a ticket of admission and is nontransferable.

Ref. 9

Conference Chairman: Ralph H. Muller
Analytical Chemistry, Santa Fe, N. Mex.

PROGRAM

THURSDAY, NOVEMBER 12, 1959

Session Chairman: Leonard T. Skeggs
Western Reserve University, Cleveland, Ohio

9:00 A.M.-

Greetings from the Academy - Duncan A. Holaday, Chairman, Division of Instrumentation, The New York Academy of Sciences, New York, N. Y.; Department of Anesthesiology, The University of Chicago Clinics, Chicago, Ill.

Introduction - Ralph H. Muller, Analytical Chemistry, Santa Fe, N. Mes.

"Automation of Enzyme Determinations" -

(1) M. K. Schwartz, Memorial Center for Cancer and Allied Diseases, New York, N. Y.
(2) Gerald Kessler, Research Laboratories, Technicon Instruments Corp., Chauncey, N. Y.
(3) O. Bodansky, Memorial Canter for Cancer and Allied Diseases, New York, N. Y.

"Cholinesterase Activity Determination in an Automated Analysis System" - George D. Winter, Research Laboratories, Technicon Instruments Corp., Chauncey, N. Y.

"Continuous Automatic Integrated Flame Photometry" - Part I, Instrumentation: Milton Pelavin and J. Isreeli, Research Laboratories, Technicon Instruments Corp., Chauncey, N. Y.; Part II, Analytical Data: Gerald Kessler, Research Laboratories, Technicon Instruments Corp., Chauncey, N.Y.

"Determination of Carbon Dioxide in Blood Serum" - Leonard T. Skeggs, Western Reserve University, Cleveland, Ohio.

"Continuous Automatic Determination of Cholesterol" - Gerald Kessler, Research Laboratories, Technicon Instruments Corp., Chauncey, N. Y.

12:30 P.M.-

Luncheon - Academy Building, 2 East 63rd Street, New York, N. Y.

Session Chairman: Leonard T. Skeggs,
Western Reserve University, Cleveland, Ohio

2:00 P.M.-

"A Random Selection System for Automatic Dynamic Biochemical Analysis by a Time-Sharing Method" - Raymond Jonnard, Prudential Insurance Company of America, Newark, N. J.

"Automatic and Continuous in Vivo Organ Perusal Experimentation" -
(1) Andres Ferrari, Research Laboratories, Technicon Instruments Corp., Chauncey, N. Y.
(2) Gerald Kessler, Research Laboratories, Technicon Instruments Corp., Chauncey, N. Y.
(3) Frank Russo-Alesi, Squibb Institute for Medical Research, New Brunswick, N. J.
(4) John Poutsiaka et al., Squibb Institute for Medical Research, New Brunswick, N. J.

"The Use of the Autoanalyzer in Studies of the Physiological Chemistry of the Parotid Gland" - Ira L. Shannon, School of Aviation Medicine, USAF Air University, Randolph Air Force Base, Tex.

"Automatic Analysis of Amino Acids" - Kenneth R. Woods and Ralph L. Engles, Jr., Cornell University Medical College, New York, N. Y.

"The Solution of Problems Involving Special Handling of Samples and Reagents in an Automatic Analysis System" - Irvin E. Taylor and Max M. Marsh, Eli Lilly and Co., Indianapolis, Inc.

5:30 P.M.-

Cocktail Hour - Academy Building

FRIDAY, NOVEMBER 13, 1959

Session Chairman: Jacques Kelly
Chas. Pfizer & Co., Inc., Brooklyn, N. Y.

9:00 A.M.-

"Automation of the Microbiological Assay of Antibiotics with an Autoanalyzer Instrumental System" -
(1) Joseph Pagano, Squibb Institute for Medical Research, New Brunswick, N. J.
(2) John Gerke, Squibb Institute for Medical Research, New Brunswick, N. J.

(3) Andres Ferrari, Research Laboratories, Technicon Instruments Corp., Chauncey, N. Y.

"Nitrogen Determination by a Continuous Digestion and Analysis System" - Andres Ferrari and Bernard Searle, Research Laboratories, Technicon Instruments Corp., Chauncey, N. Y.

"A Method for the Determination of Ammonia on the Autoanalyzer" E. E. Logsdon, Eli Lilly and Co., Indianapolis, Inc.

"Continuous, Automatic Chemical Analysis of Nitrate in the Presence of Ammonia and Urea" - Eugene Catanzaro, Research Laboratories, Technicon Instruments Corp., Chauncey, N. Y.

"Industrial Applications of the Titrilop" - Arthur E. Dean, Consolidated Electrodynamics Corp., Pasadena, Calif.

12:30 P.M. -

Luncheon - Academy Building

Session Chairman: Jacques Kelly
Chas. Pfizer & Co., Inc., Brooklyn, N. Y.

2:00 P.M.-

"Continuous Sample and Blank Analysis by Means of Differential Colorimetry" - Frank Russo-Alesi, Constance Sherman, and Jacques Kelly, Squibb Institute for Medical Research, New Brunswick, N. J.

"Partial or Complete Automation as Alternatives Available to the Analyst" - D.R. Chapman, Baird and Tatlock (London) Ltd., London, England.

"Recent Developments in Automatic Colorimetric Chemical Analysis Instruments" -

(1) Robert T. Sheen, Milton Roy Company, Philadelphia, Pa.
(2) Earl J. Serfass, Lehigh University, Bethlehem, Pa.

"An Automated Method for Determination of Terramycin" - T. C. Grenfell, D. J. McLaughlin, W. H. McMullen, and Jacques Kelly, Chas. Pfizer & Co., Inc., Brooklyn, N. Y.

"Continuous and Automatic Analysis of Process Streams by Gas Chromatography" - H. J. Maier and H. N. Claudy, Perkin-Elmer Corp., Norwalk, Conn.

Ref. 9

SATURDAY, NOVEMBER 14, 1959

Session Chairman: Dwight Gillette
Refined Syrups and Sugars Inc., Yonkers, N. Y.

9:00 A.M.-

"Automated Enzymatic Assay of Organic Phosphate Pesticide Residues" - George D. Winter, Research Laboratories, Technicon Instruments Corp., Chauncey, N. Y.

"Use of the Technicon Autoanalyzer for Determination of Protein, Phosphate, and Reducing Sugars in Yeast Molasses and Grain Work" - George Reinhart and William Hardwick, Central Research Department, Anheuser-Busch Inc., St. Louis, Mo.

"Automatic Enzymatic Analysis for L-Lysine Monohydro-Chloride via Decarboxylation" -

(1) George Schaiberger, E. Merck and Co., Elkton, Va.
(2) Andres Ferrari, Research Laboratories, Technicon Instruments Corp., Chauncey, N. Y.

"Automation of Sugar Analysis in Barometric Condensers and Boiler Waters" - Dwight Gillette and Elliot Baum, Refined Syrups and Sugars, Inc., Yonkers, N. Y.

"Methods Development for Phosphate Analysis with the Autoanalyzer" - Daniel P. Lundgren, Research and Development Division, Lever Brothers Co., Edgewater, N. J.

12:30 P.M.-

Luncheon - Academy Building

Session Chairman: T. Finnegan
Niagara Mohawk Power Corp., Buffalo, N. Y.

2:00 P.M.-

"Automatic Analytical Instrumentation in the Modern Power Plant" - W. A. Crandell, Consolidated Edison Company of New York, New York, N. Y.

"Continuous Sampling and Automatic Analysis for Silica in Modern High-Pressure Boilers" - Kenneth F. Schunk and T. Finnegan, Niagara Mohawk Power Corp., Buffalo, N. Y.

"Application of the Forward Scattering Photometer to Aerosol Measurement" - David Sinclair, Johns-Manville Research Center, Manville, N. J.

"The Design of Automatic Trace Analyzers" - Henry J. Noebels, Beckman Scientific and Process Instruments Division, Fullerton, Calif.

"Some Recent Experiences on Feed Water Analysis on Board a Naval Vessel" - A. E. Gallant, U.S.S. Tarawa, Quonset Point Naval Air Station, Quonset Point, R. I.

PANEL DISCUSSION

PROBLEMS ON AUTOMATION OF CHEMICAL ANALYSIS AND INDUSTRIAL PROCESSES

Chairman: Jacques Kelly
Chas. Pfizer & Co., Inc., Brooklyn, N. Y.

Discussants:
T. Finnegan, Niagara Mohawk Power Corp., Buffalo, N. Y.
John B. Freeman, Bethlehem Steel Co., Bethlehem, Pa.
A.E. Gallant, U.S.S. Tarawa, Quonset Point Naval Air Station, Quonset Point, R. I.
Dwight Gillette, Refined Syrups and Sugars, Inc., Yonkers, N. Y.
Ira L. Shannon, School of Aviation Medicine, Air University, United States Air Force, Randolph AFB, Tex.
Leonard T. Skeggs, Western Reserve University, Cleveland, Ohio.
Edward Wagman, Head, Chemistry Section, Research and Development Division, Bureau of Ships, United States Navy, Washington, D.C.
William Nacorsky, Consolidated Electric Co. of New York, New York, N. Y.

The Division of Instrumentation provides conferences for active workers in the special fields of biology and medicine.

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Duncan A. Holaday
Chairman

Andres Ferrari
Vice-Chairman

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THE STERILIZATION OF SPACE VEHICLES TO PREVENT EXTRATERRESTRIAL BIOLOGICAL CONTAMINATION

10TH INTERNATIONAL ASTRONAUTICS CONGRESS

Richard W. Davies
Marcus G. Comuntzis

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JET PROPULSION LABORATORY
California Institute of Technology
Pasadena 3, California
August 31, 1959

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THE STERILIZATION OF SPACE VEHICLES TO PREVENT EXTRATERRESTRIAL BIOLOGICAL CONTAMINATION*

by

Richard W. Davies
Marcus G. Comuntzis

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

presented at the

10TH INTERNATIONAL ASTRONAUTICS CONGRESS

London, England

August 31 - September 5, 1959

INTRODUCTION

Speculation on the existence of extraterrestrial life is sufficiently commonplace to suggest that the concept is subtly imbedded in our social culture. However, it is difficult to verify the origin of the extraterrestrial life concept because of a tendency to ascribe original authorship of many ideas to antiquity.[1]

The discovery of life on any of the planets would be one of the most exciting events in human history. Satisfying society's general

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*This paper presents the results of one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under Contract No. NASw-6, sponsored by the National Aeronautics and Space Administration.

[1] According to P. Duhem, Le Système du Monde (Vol. 1, pp. 17-18, 1913) the Pythagorean Philolaus (5th century B.C.) postulated the existence of an inhabited anti-earth which was always in opposition to the earth in relation to the sun.

curiosity would, however, be only one facet of the discovery. The event would also have tremendous scientific interest because, next to the synthesis of living matter in the laboratory, it would be the most important step that could be made toward understanding of the problem of the origin of life. Systems based on nucleic acid and proteins as bearers of life may or may not be unique. This is one of the fundamental questions that the discovery of extraterrestrial life might answer.

The biological importance of the planets is not limited to detecting and studying life on them. Even if no life is found to exist, the opportunity to sample organic compounds on the planets might give some valuable clues to the origin of life. Sterile worlds may provide the information necessary to the understanding of the organic chemical processes that preceded the development of life on the earth.

Present knowledge (as well as the lack of it) of the planets Mars and Venus is compatible with the possibility both of an indigenous life and of the support and rapid proliferation of terrestrial microorganisms. The introduction of terrestrial organisms and contaminants might so distort the biology of either planet as to constitute a scientific catastrophe. The processes are irreversible and they make the search for life on other planets most sensitive to irremediable harm. If the earth were sterile, it would require only months or years to universally populate it with the descendants of a single cell. A common bacterium, E. Coli, has a mass of 10^{-12} grams and a fission interval of 30 minutes. Ideally, it would take 66 hours for the progeny to attain the mass of the earth. The progeny never reach this magnitude principally because the food supply is insufficient. Nevertheless, this extrapolation illustrates that the exponential growth rate of bacteria is truly explosive and, therefore, the timescale of planetary biological distortion need not be long. Indeed, it could be considerably less than the time interval of earth-planet oppositions. Space probes which have any likelihood of a landing, intentional or accidental, should be subject to careful sterilization.

DEFINITION OF BIOLOGICAL CONTAMINATION

It is convenient to separate biological contamination into two kinds, pollution and infection. Biological pollution is meant to be a deposit of a large enough number of micro-organisms to be scientifically significant, as such, without further growth. Infection is meant to describe the growth of one or more viable organisms. Likewise, pollution can be divided into two categories; viable pollution, which does not grow by nature of its environment, and non-viable pollution.

Pollution

Pollution is a type of contamination that applies to the Moon, Mars, and Venus. Pollution would be most likely if a mammal were splattered on any one of these three bodies. For example, the Moon's area is $4x10^{13}$ square meters, and the intestines of a mammal can contain 10^{12} micro-organisms per kilogram. If the mammal died in flight, the putrified tract could contain 10^{13} micro-organisms per kilogram (1). Present techniques are capable of detecting one micro-organism per square centimeter. These techniques could be immediately extended to detect one micro-organism per square meter. Future improvements in technique may increase the detecting sensitivity by a few orders of magnitude; therefore, a single probe leaving a residue of from 10^9 to 10^{10} dead bacteria could provide a misleading background noise for future investigators.[2]

Infection

Infection appears least likely on the Moon because water is the lowest common denominator of all known terrestrial organisms, and all present evidence of solvents on the Moon's surface is highly controversial (2, 3). The hypothesis that beneath the lunar surface material one would find both water traces and relics of primitive organisms is not so unreasonable as to warrant the immediate dismissal of the matter of infection.

Mars is arid by terrestrial standards; its polar caps consist of thin hoar frost, and dense terrestrial type water clouds have never been observed. However, the polar caps retreat and the equatorial dark areas advance with the onset of the Martian spring. The pressure (85 mb, or less) and temperature (200-300°K) are so low it is frequently supposed that the presence of liquid water on the surface is very rare. This point has been refuted (4, 5). If salts are present on the Martian surface, an anti-freeze mechanism can occur.

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[2] These comments would be unnecessary but for the fact that many people (not all laymen) presuppose that no significant discoveries will be made until a man is landed on the planets.

It is reasonable to suggest that the dark areas of the planet contain salts, perhaps in the form of deposits left behind by dried-up seas.

Sinton (6, 7) has found three small absorption dips, at 3.43, 3.57, and 3.67 microns, associated with the dark areas of Mars. This suggests the presence of organic matter on Mars, but the question of its origin is an open question.

These few facts indicate Mars may be a promising subject, both for basic biological research and infection.

Theories of Venus are so varied, and the facts so few, it is imperative to be very cautious, at least in the early stages of exploration.

SPACE-FLIGHT ENVIRONMENT

On cursory examination, probe sterilization may appear to be unnecessary because the space-flight environment is so hostile to terrestrial organisms. Several self-sterilizing mechanisms which immediately suggest themselves are:

1) Ultraviolet radiation from the sun
2) Space vacuum
3) High temperatures on the Moon's surface
4) Heat of impact, or impact explosion on the Moon
5) Heat of entry into a planetary atmosphere

We shall discuss these in order.

Parts of the probe will never be exposed to sunlight. Ultraviolet radiation will destroy organisms which are nakedly exposed, but its penetrating power is so low that organisms can survive if surrounded by only a small group of dead ones.

Laboratory vacuum is employed to help preserve micro-organisms. There is, as yet, no knowledge on space vacuum being bactericidal. Perhaps this question can be answered in the near future by means of a satellite experiment.

The Moon and the Planets most likely have cracks and fissures on their surfaces which would protect organisms from exposure to high temperatures and ultraviolet radiation, (5, p. 306).

A probe hard-landed on the Moon would have an impact velocity of approximately 3 kilometers per second. This is not sufficient kinetic energy to melt or vaporize the probe on impact, but it is sufficient to scatter parts of the payload all over the Moon's surface if the initial impact were on a hard surface, such as a mountain. The orbital velocity of a satellite in the Moon's gravitational field is roughly 2 kilometers a second. It is contended that the probe would bury itself in the Moon's surface. We do not believe that any of the supporting arguments presented thus far are sufficiently convincing to be dogmatic.

A probe that unintentionally enters an atmosphere has a high probability of coming in at a shallow angle, which is the ideal approach for a successful landing (8, 9). The probe may shed a few parts during the planet fall, but the bulk of it would strike the surface. A successful descent on Mars would be comparatively simple because the tenuous atmosphere of Mars extends so far out from its surface. Furthermore, meteors have been found whose interiors show no evidence of having been heated appreciably (10). It is evident that the rigors of a space journey are not a reliable means of preventing biological contamination.

INTERNATIONAL DISCUSSION

CETEX (Committee on Contamination by Extraterrestrial Exploration,) representing the International Scientific Unions, has published two reports (11, 12) in an attempt to set a tone for developing a code of conduct in space research. These reports imply that, particularly as regards biological exploration, a purely national program does not have much chance of being fruitful.

The CETEX reports recommend the sterilization of space probes, but they do not suggest a procedure for sterilizing probes nor do they suggest what tolerances would be acceptable. In this paper, we discuss both an operational approach to sterilization and the value judgements that will have to be faced by the operational agencies responsible for launching space vehicles.

OPERATIONAL TACTICS

Sterilizing space probes is an engineering nuisance, however, the same ordeal has confronted surgical crews for quite some time. In both instances, anticipation of the task is necessary.

At this time, it is possible to anticipate and recommend four phases of payload sterilization for all deep space missions. They are, in sequence:

1. Sterile assembly of components, particularly heat sensitive ones,
2. Built-in sterilization of parts, particularly where traces of water are admissable,

3. Terminal sterilization,
4. Maintaining sterilization.

A microbiological testing procedure must also be integrated into the sterilization operations.

Terminal Sterilization

Phase three, terminal sterilization, is the most important operation and we shall discuss it first.

All known micro-organisms perish when subjected to dry steam at 160°C for twenty minutes (13). There is a time-temperature effect. Micro-organisms can survive much higher temperatures over a shorter period of time; such as, the flash temperatures in explosions. However, approximately 20% of the components that go into payloads with which we are now familiar cannot endure 160°C. A more general disinfectant for this purpose is ethylene oxide gas (14).

Ethylene oxide (C_2H_4O) is the simplest of the ethers. It is a very small molecule and therefore dissolves in many substances, such as rubber, plastic, and oil. As a result of these properties, under slight pressure ethylene oxide is quite penetrating, working its way into the small interstices of most components. It is non-corrosive, and its human toxicity is low.

Ethylene oxide is a few thousand times more effective as a sporicide than other powerful disinfectants (15). Viruses are more sensitive to ethylene oxide than many other organisms, whereas, they are much more resistant to radiation.

Ethylene oxide is inflammable in air in concentrations as low as 3%. However, a mixture of 10% ethylene oxide and 90% carbon dioxide (sometimes called carboxide) is not inflammable even when infinitely diluted with air. This mixture at 2 atmospheres pressure and 25°C would sterilize most parts of the probe in four hours. The sterilization could take place in a polyethylene tent and left there to retain its sterility for quite some time.

This part of the sterilization technique is well established. The U. S. Chemical Corps has sterilized many pieces of delicate laboratory apparatus without damage. They have also sterilized Air Force bombers and a commercial aircraft, in which a vial of live polio virus was accidentally broken.

Gaseous sterilization will not prove effective on certain impenetrable components. For these parts (paper capacitors for example) heat sterilization or radiation can usually be employed.

It is impractical to sterilize an entire payload with radiation. It is useful for certain small, sealed heat-sensitive components such as mylar capacitors.

The radiation dose required for some specified degree of sterilization is proportional to the natural logarithm of the number of bacteria. For 10^5 bacteria per gram of material, a dosage of 10^6 to 10^7 rem is required for good sterilization depending upon the organism. Actually 10^5 bacteria is a very high bacteria loading for most payload materials.

The Jet Propulsion Laboratory selected some sealed heat-sensitive components for radiation treatment by the General Electric Corporation. Two packages of identical parts were exposed to 10^6 and 10^7 rem from a Co^{60} source of gamma rays. A majority of these components withstood 10^7 rem. The most important exceptions were transistors and mercury cell batteries.

We estimate that, between gas, heat, and radiation (terminal sterilization), 95% of the payload parts can be readily sterilized without fear of degrading their performance characteristics.

Sterile Assembly

The removal of dust and foreign particles from the space probe eliminates a major source of biological pollution and it is, at the same time, an engineering virtue. (Most atmospheric pollution is borne by dust particles, except perhaps in closed rooms crowded with human beings.)

The washing and scrubbing of parts of the payload with water and detergents (or other more acceptable solvents) can reduce the number of microbes on the probe by three orders of magnitude.

Other aspects of sterile assembly include using compounds that are made sterile. Parts such as screws and bolts can be dipped in any of a number of sterilizing solutions. If screws and fitting holes are made to fit exactly, then care must be taken to sterilize before joining. Such fittings will remain sterile. If the fittings are not perfectly joined, the ethylene oxide gas will penetrate and sterilize these interstices.

Built-In Sterilization

Wherever possible, substances which are inimical to the well being of micro-organisms should be employed. Certainly, substances of biological origin, such as casein glue or shellac, should be avoided.

Recently, germicides that contain organo-metallic compounds as active ingredients have been used to disinfect hospitals. These substances might prove valuable during the fabricating of sealed components with parts that get slightly contaminated with handling. This reduction of the contamination load during the initial stages, provides an opportunity to attempt terminal sterilization by radiation at a considerably reduced dosage, something of the order of 10^4 rem.

Built-in sterilization is not so much a specific technique as it is a philosophy of preparation for terminal sterilization.

Maintaining Sterilization

Once the space probe is sterilized, it will be necessary to mount it on the rocket boosters. The technical problem is then one of keeping microbes from coming into contact with the probe.

The probe is encased in a protective metal shroud during the launch phase of the space flight. The shroud can be employed to house a disinfectant atmosphere throughout the count down and flight through the atmosphere. The disinfectant can be either carboxide, employed in the terminal phase, or a faster acting but less penetrating gas, such as beta-propiolactone or ethylene imine.

Testing Procedure

In the past, several identical payloads were made for each mission. If this policy can be continued, it will not be difficult to produce convincing statistical arguments as to whether or not the payload meets the desired sterilization standard. Difficulties may arise, however, when the payloads become larger and more expensive.

In this respect, it would be most practical to turn terminal sterilization and the sterilization certification over to an organization outside the space-flight groups. It would still be the space agency's responsibility to integrate this independent statistical estimate of sterilization with the other probabilities involved. This brings us to the problem of determining acceptable contamination tolerances.

BIOLOGICAL CONTAMINATION TOLERANCES

Now we get to the heart of the matter as it is not practical to pursue codes of conduct and to employ testing techniques unless the community places a subjective value upon what the biologists want to protect. Discussions of the ethics of contamination are made confusing by people who persist in believing that sterility is an absolute, to which only a yes or no answer applies.

The answer to the question of probe sterility can be given only in terms of probabilities. When large numbers of micro-organisms are subjected to lethal treatment, the live count drops off exponentially with time, or approximately so. The process is mathematically similar to the radioactive decay of an unstable nucleus. The death of a micro-organism has no clear-cut definition.

A group of biologists in the United States, including some of the nation's most eminent microbiologists, biochemists, and biophysicists, who are also sensitive to the engineering areas in space research, have given this problem some intensive thought.

For Mars and Venus, the consensus is that the probability of landing one viable organism should be less than one in a million. This means that if the probability of successfully impacting a probe were judged a priori to be one in a hundred it would be necessary to sterilize the payload to a tolerance of one chance in ten thousand that it have a live organism. We are investigating what degrees of sterilization can be expected as the space program evolves.

As previously indicated, the status of the Moon as a biologically interesting target is considerably more doubtful than that of the planets; therefore, it is more difficult to get an intuitive grasp of what tolerances are acceptable. We tenatively suggest that one chance in ten (perhaps one hundred) of a viable organism remaining on the probe be an acceptable infection tolerance. We also suggest that pollution be kept less than 10^8 dead organisms per probe for Moon and planetary shots.

These tolerance levels are submitted here for general evaluation, with the understanding that, as more information on the celestial bodies becomes available, the levels should be revised.

RECOMMENDATIONS AND CONCLUSIONS

Planetary biology is one of the most exciting areas of space exploration. The unnecessary destruction of potential information in this research field by contamination would be an uncultural event. It is feasible to sterilize probes in such a manner that the loss of information to future investigators is minimized. This can be accomplished utilizing ethylene oxide, heat and radiation, accompanied by the sterile assembly of special components, as sterilizing agents.

Pollution tolerances should be kept to 10^8 dead bacteria per missile. Infection tolerances should be kept to less than 10^{-6} per missile for the planets and 10^{-1} for the Moon.

A molecular inventory, preferably in the form of payload duplicates, should be kept for each space flight. More information on the chemical composition of space-probe materials should be acquired.

An agency specially qualified to handle sterilization should perform the terminal disinfection and ascertain the degree of sterilization.

ACKNOWLEDGMENTS

American scientists have been very patient while rocket technicians have picked their brains for information of value to space research. It has been precisely by this technique that we accumulated the facts contained in this paper. We hope that, by recognizing the gravity of the problem, we have partially compensated for our lack of originality.

Numerous people working with the National Academy of Sciences have assisted us in formulating our ideas and we thank them all. In particular we want to mention Joshua Lederberg for his characteristic insight, and Charles Phillips for making his work known to us.

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Washington 25, D. C.

SPACE SCIENCE BOARD

September 21, 1959

<u>MEMORANDUM - SSB-109</u>

To: Members: Space Science Board, Committee 1, Committee 6, Committee 11, WESTEX, and Ad Hoc Group on Space Probe Sterilization

From: Space Science Board Secretariat

Subject: Space Science Board Recommendation on Space Probe Sterilization

For your information, the following letter is provided on a "For Official Board Use Only" basis until the National Aeronautics and Space Administration has had an opportunity to consider the Board's recommendations. This letter conveys the recommendations of the Space Science Board formulated on the basis of the report of its ad hoc Committee on Space Probe Sterilization.

Enclosure

2101 CONSTITUTION AVENUE
WASHINGTON 25, D. C.

CABLE ADDRESS: NARECO
WASHINGTON, D. C.

NATIONAL ACADEMY OF SCIENCES
NATIONAL RESEARCH COUNCIL
OF THE UNITED STATES OF AMERICA

SPACE SCIENCE BOARD

September 14, 1959

To: Dr. T. Keith Glennan, National Aeronautics & Space Administration
Mr. Roy Johnson, Advanced Research Projects Agency

From: Hugh Odishaw, Executive Director, Space Science Board

Subject: Space Probe Sterilization

The following recommendation of the Space Science Board is herewith submitted:

> "Considering: (i) that insufficient factual information is currently available concerning the contamination levels of parts, subassemblies, or complete payloads for prospective space probes; (ii) the scientific importance associated with scientific investigations of the moon and planets in their natural environment; and, (iii) that suitable means for effective sterilization of space probes presently appears to be relatively simple, effective and practical;
>
> "The Space Science Board therefore strongly recommends: (1) that an immediate study program be undertaken to determine sterilization requirements for space probes and to develop recommendations, compatible with present design and assembly processes, regarding necessary sterilization procedures; (2) that procedures be immediately established and implemented to insure a complete inventory of all components of all space probes."

The Board recommends that NASA promptly undertake a project relating to (1) above through the U. S. Army Biological Warfare Laboratories with provisions for co-ordinating the interests of other groups having competence in this field. It is recognized that maintenance of sterile conditions may be costly: The initial study program may well include consideration of engineering and operational aspects as guidance to further steps.

Recommendation (2) involves action by NASA and ARPA.

Relevant to the Board's position in these matters are the discussions and findings of the ad hoc Group on Space Probe Sterilization convened at Stanford University on July 8, 1959, by the Space Science Board. The minutes of this meeting are enclosed.

The Board believes that this subject is of high import, and notes the Soviet press report that the USSR moon rocket of September 13 had been decontaminated before launching. It is quite clear that extra-terrestrial contamination could seriously interfere with proper studies of fundamental importance relating to biological developments in the solar system. These interests are not only domestic ones but international (cf. activities of CETEX and COSPAR). The Board accordingly hopes that close liaison may be maintained so that it can follow the activity recommended above, and the Board will make available its services, including the ad hoc group, as necessary.

Hugh Odishaw
Executive Director

Enclosure

cc: Dr. L. V. Berkner
Dr. G. B. Kistiakowsky
Dr. A. T. Waterman

Galileo Siderus Nuncius 1610

"the surface of the moon is not perfectly smooth, free from inequalities and exactly spherical, as a large school of philosophers considers with regard to the moon and the other heavenly bodies, but that, on the contrary, it is full of irregularities, uneven, full of hollows and protuberances, just like the surface of the earth itself, which is varied everywhere by lofty mountains and deep valleys."

CURRENT PROBLEMS IN RESEARCH

Organic Compound Synthesis on the Primitive Earth

Several questions about the origin of life have been answered, but much remains to be studied.

Stanley L. Miller and Harold C. Urey

Since the demonstration by Pasteur that life does not arise spontaneously at the present time, the problem of the origin of life has been one of determining how the first forms of life arose, from which all the present species have evolved. This problem has received considerable attention in recent years, but there is disagreement on many points. We shall discuss the present status of the problem, mainly with respect to the early chemical history of, and the synthesis of organic compounds on, the primitive earth.

Many of our modern ideas on the origin of life stem from Oparin (*1*), who argued that the spontaneous generation of the first living organism might reasonably have taken place if large quantities of organic compounds had been present in the oceans of the primitive earth. Oparin further proposed that the atmosphere was reducing in character and that organic compounds might be synthesized under these conditions. This hypothesis implied that the first organisms were heterotrophic—that is, that they obtained their basic constituents from the environment instead of synthesizing them from carbon dioxide and water. Horowitz (*2*) discussed this point further and outlined how a simple heterotrophic organism could develop the ability to synthesize various cell constituents and thereby evolve into autotrophic organisms.

In spite of the argument by Oparin, numerous attempts were made to synthesize organic compounds under the oxidizing conditions now present on the earth (*3*). Various sources of energy acting on carbon dioxide and water failed to give reduced carbon compounds except when contaminating reducing agents were present. The one exception to this was the synthesis of formic acid and formaldehyde in very small yield (10^{-7} H_2CO molecules per ion pair) by the use of 40-million-electron-volt helium ions from a 60-inch cyclotron (*4*). While the simplest organic compounds were indeed synthesized, the yields were so small that this experiment can best be interpreted to mean that it would not have been possible to synthesize organic compounds nonbiologically as long as oxidizing conditions were present on the earth. This experiment is important in that it induced a reexamination of Oparin's hypothesis of the reducing atmosphere (*5*).

The Primitive Atmosphere

Our discussion is based on the assumption that conditions on the primitive earth were favorable for the production of the organic compounds which make up life as we know it. There are many sets of conditions under which organic compounds could have been produced. All these conditions are more or less reducing. However, before accepting a set of conditions for the primitive earth, one must show that reactions known to take place will not rapidly change the atmosphere to another type. The proposed set of conditions must also be consistent with the known laws for the escape of hydrogen.

Cosmic dust clouds, from which the earth is believed to have been formed, contain a great excess of hydrogen. The planets Jupiter, Saturn, Uranus, and Neptune are known to have atmospheres of methane and ammonia. There has not been sufficient time for hydrogen to escape from these planets, because of their lower temperatures and higher gravitational fields. It is reasonable to expect that the earth and the other minor planets also started out with reducing atmospheres and that these atmospheres became oxidizing, due to the escape of hydrogen.

The meteorites are the closest approximation we have to the solid material from which the earth was formed. They are observed to be highly reduced—the iron mostly as metallic iron with some ferrous sulfide, the carbon as elemental carbon or iron carbide, and the phosphorus as phosphides.

The atmosphere under these reducing conditions would contain some hydrogen, methane, nitrogen, and ammonia; smaller amounts of carbon dioxide and carbon monoxide; and possibly small amounts of other substances such as higher hydrocarbons, hydrogen sulfide, and phosphine. These substances were probably not present in equilibrium concentrations, but compounds which are thermodynamically very unstable in this highly reducing atmosphere —such as oxygen, oxides of nitrogen, and oxides of sulfur—could not have been present in more than a few parts per million. This is true of compounds which are unstable in the present oxidizing atmosphere of the earth, such as hydrogen, ozone, methane, and nitrous oxide.

The over-all chemical change has been the oxidation of the reducing atmosphere to the present oxidizing atmosphere. This

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is caused by the loss of hydrogen, which results in the production of nitrogen, nitrate, sulfate, free oxygen, and ferric iron. As is discussed below, many complex organic compounds would have been formed during the course of this over-all change, thereby presenting a favorable environment for the formation of life. Whether the surface carbon of the present earth was all part of the initial atmosphere or whether it has been escaping from the earth's interior in a somewhat reduced condition is not important to the over-all picture.

Escape of Hydrogen

We have learned in recent years that the temperature of the high atmosphere is 2000°K or more, and there is no reason to suppose that the same temperature was not present in the past. One might expect that a reducing atmosphere would be cooler than an oxidizing atmosphere because methane and ammonia can emit infrared radiation while the diatomic molecules, nitrogen and oxygen, cannot. Curtis and Goody (*6*) have shown that carbon dioxide is ineffective in emitting infrared radiation in the high atmosphere. This is due to the low efficiency of energy transfer from the translational and rotational to the vibrational degrees of freedom, and it seems likely that this would apply to methane as well.

The loss of hydrogen from the earth is now believed to be limited by the diffusion of H_2 to the high atmosphere, since almost all the water is frozen out before it reaches the high atmosphere. Urey (*7*) has discussed this problem and finds that the loss is entirely due to these effects and not to the Jeans escape formula.

The present rate of escape is 10^7 atoms of hydrogen per square centimeter per second, and it is proportional to the concentration of molecular hydrogen in the atmosphere, which is now 10^{-6} atm at the earth's surface. This rate would result in escape of hydrogen equivalent to 20 g of water per square centimeter in the last 4.5×10^9 years. This rate is not sufficient to account for the oxygen in the atmosphere (230 g/cm²).

In addition, we must account for the oxidation of the carbon, ammonia, and ferrous iron to their present states of oxidation. The oxidation of the 3000 g of surface carbon per square centimeter present on the earth from the 0 to the +4 valence state (that is, from C or H_2CO to CO_2) would require the loss of 1000 g of hydrogen per square centimeter. At the present rate of escape this would require 2.5×10^{12} years. In order for this escape to be accomplished in 2.5×10^9 years (that is, between 4.5×10^9 and 2.0×10^9 years ago), a pressure of hydrogen at the surface of the earth of 0.7×10^{-3} atm would have been required. In order for the nitrogen, sulfur, and iron also to be oxidized, even larger losses and a higher pressure of hydrogen would have been needed. We use a figure of 1.5×10^{-3} atm for the hydrogen pressure in the primitive atmosphere.

These calculations are greatly oversimplified, since methane and other volatile hydrogen compounds would be decomposed in the high atmosphere and therefore a higher concentration of hydrogen might exist in the high atmosphere than is indicated by surface partial pressures. However, the results of the calculation would be qualitatively the same for hydrogen pressures different from the chosen value by an order of magnitude.

Equilibria of Carbon Compounds

The partial pressure of CO_2 in the atmosphere is kept low by two buffer systems. The first system, which is rapid, is the absorption in the sea to form HCO_3^- and H_2CO_3. The second, which is slow, is the reaction of carbon dioxide with silicates; for example

$$\begin{aligned}&CaSiO_3 + CO_2 \rightarrow \\ &\qquad CaCO_3 + SiO_2 \qquad K_{25^\circ} = 10^8\end{aligned}$$

The partial pressure of CO_2 at sea level (3.3×10^{-4} atm) is somewhat higher than the equilibrium pressure (10^{-8} atm), but very much lower than would be the case without the formation of limestones ($CaCO_3$).

The equilibrium constant at 25°C in the presence of liquid water for the reaction

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$$

is 8×10^{22}. Assuming that equilibrium was attained, and using partial pressures $P_{CO_2} = 10^{-8}$ atm and $P_{H_2} = 1.5 \times 10^{-3}$ atm, we find that the pressure of CH_4 would be 4×10^3 atm. In order to have a reasonable pressure of CH_4, the partial pressure of CO_2 would have to be less than 10^{-8} atm, and limestones would not form.

Complete thermodynamic equilibrium could not exist in a reducing atmosphere because of the dependence of the equilibrium proportions of compounds on pressure and hence on altitude. It is more likely that the steady-state concentrations of CO_2 and CH_4 would be determined not by the equilibrium at sea level but rather by the equilibrium at higher altitude, where the ultraviolet light would provide the activation energy to bring about rapid equilibrium. Under these conditions water would be a gas, and the equilibrium constant would be 10^{20}, so

$$\begin{aligned}K_{25} = 10^{20} &= P_{CH_4} P^2_{H_2O} / P_{CO_2} P^4_{H_2} \\ &= X_{CH_4} X^2_{H_2O} / X_{CO_2} X^4_{H_2} \quad P^{-2}\end{aligned}$$

where the *X*'s are the mole fractions and *P* is the total pressure. If the surface partial pressures were $P_{CH_4} = 1$, $P_{CO_2} = 3.3 \times 10^{-4}$ (the present value), and $P_{H_2} = 1.5 \times 10^{-3}$, the *X*'s would be equal to these partial pressures. We use $X_{H_2O} = 10^{-6}$, which is the present value for H_2O above the tropopause. Equilibrium will be established under these conditions where $P = 2.5 \times 10^{-9}$ atm—the present atmospheric pressure at about 180 km. It is reasonable to assume that equilibrium was established at some high altitude; therefore, carbon dioxide and hydrogen could both have been present at small partial pressures and methane could have been present at a moderate partial pressure in a reducing atmosphere where the pressure of hydrogen was 1.5×10^{-3} atm.

Carbon monoxide should not have been an important constituent of the atmosphere, as can be seen from the following reaction

$$\begin{aligned}&CO_2 + H_2 \rightarrow CO + H_2O_{(l)} \quad K_{25} = 3.2 \times 10^{-4} \\ &\qquad P_{CO}/P_{CO_2} = 3.2 \times 10^{-4} P_{H_2}\end{aligned}$$

Using $P_{H_2} = 1.5 \times 10^{-3}$, we have the ratio $P_{CO}/P_{CO_2} = 5 \times 10^{-7}$, which is independent of pressure. Furthermore, carbon monoxide is a relatively reactive compound, and should any significant quantities appear in the atmosphere, it would react rather rapidly to give organic compounds, carbon dioxide and hydrogen, and formate.

Rubey (*8*) and Abelson (*9*) have argued that the surface carbon and nitrogen have come from the outgassing of the interior of the earth instead of from the remaining gases of the cosmic dust cloud from which the earth was formed. The carbon from the outgassing of the earth is a mixture of CO_2, CO, and CH_4, and hydrogen may be present. While outgassing may have been a significant process on the primitive earth, this does not mean that the atmosphere was necessarily composed of CO_2 and CO. The thermodynamic considerations discussed above would still apply. The carbon dioxide would dissolve in the ocean to form bicarbonate, and $CaCO_3$ would be deposited, and the CO would be unstable, as is demonstrated above.

Many writers quote "authorities" in regard to these questions without understanding what is fact and what is opinion. The thermodynamic properties of C, CO, CO_2, CH_4, N_2, NH_3, O_2, H_2O, and other similar substances are all well known, and the equilibrium mixtures can be calculated for any given composition without question. The only point open to argument is whether equilibrium was approximated or whether a nonequilibrium mixture was present. A mixture of hydrogen and carbon monoxide or hydrogen and carbon dioxide is very unstable at 25°C, but does not explode or react detectably in years. But would such mixtures remain in an atmosphere for millions of years subject to energetic radiation in the high atmosphere? We believe the answer is "No." These mixtures would react even without such radiation in geologic times. Hydrogen and oxygen will remain together at low temperatures for long times without detectable reaction by ordinary methods. The use of radioactive tracers shows that a reaction is proceeding at ordinary temperatures nonetheless.

The buffer systems of the ocean and the calcium silicate–calcium carbonate equilibrium were of sufficient capacity to keep the partial pressure of the carbon dioxide in the atmosphere at a low value; hence, the principal species of carbon in the atmosphere would have been methane, even though the fraction of surface carbon in the oxidation state of carbon dioxide was continuously increasing. This would have been true until the pressure of H_2 fell below about 10^{-6} atm. It is likely that shortly after this, significant quantities of molecular oxygen would have appeared in the atmosphere.

Equilibria of Nitrogen Compounds

The equilibrium concentrations of ammonia can be discussed by considering the reaction

$$\frac{1}{2}N_2 + \frac{3}{2}H_2 \rightarrow NH_3 \qquad K_{25} = 7.6 \times 10^2$$

Using $P_{H_2} = 1.5 \times 10^{-3}$, we have $P_{NH_3}/P_{N_2}{}^{1/2} = 0.04$.

Table 1. Present sources of energy averaged over the earth.

Source	Energy (cal cm^{-2} yr^{-1})
Total radiation from sun	260,000
Ultraviolet light	
$\lambda < 2500$ A	570
$\lambda < 2000$ A	85
$\lambda < 1500$ A	3.5*
Electric discharges	4 †
Cosmic rays	0.0015
Radioactivity (to 1.0 km depth)	0.8‡
Volcanoes	0.13§

* Includes the 1.9 cal cm^{-2} yr^{-1} from the Lyman α at 1216 A (*39*). † Includes 0.9 cal cm^{-2} yr^{-1} from lightning and about 3 cal cm^{-2} yr^{-1} due to corona discharges from pointed objects (*40*). ‡ The value, 4×10^9 years ago, was 2.8 cal cm^{-2} yr^{-1} (*41*). § Calculated on the assumption of an emission of lava of 1 km^3 ($C_p = 0.25$ cal/g, $P = 3.0$ g/cm^3) per year at 1000°C.

Ammonia is very soluble in water and therefore would displace the above reaction toward the right, giving

$$\frac{1}{2}N_2 + \frac{3}{2}H_2 + H^+ \rightarrow NH_4{}^+$$

$$(NH_4{}^+)/P_{N_2}{}^{1/2}P_{H_2}{}^{3/2} = 8.0 \times 10^{18}(H^+)$$

which is valid for *p*H's less than 9. At $pH = 8$ and $P_{H_2} = 1.5 \times 10^{-3}$, we have

$$(NH_4{}^+)/P_{N_2}{}^{1/2} = 47$$

which shows that most of the ammonia would have been in the ocean instead of in the atmosphere. The ammonia in the ocean would have been largely decomposed when the pressure of hydrogen fell below 10^{-5} atm, assuming that the *p*H of the ocean was 8, its present value. A higher *p*H would have made the ammonia less stable; the converse is true for a lower *p*H.

All the oxides of nitrogen would have been unstable and therefore rare. Hydrogen sulfide would have been present in the atmosphere only as a trace constituent because it would have precipitated as ferrous and other sulfides. Sulfur would have been reduced to hydrogen sulfide by the reaction

$$H_2 + S \rightarrow H_2S \quad K = 6 \times 10^4$$

It is evident that the calculations do not have a quantitative validity because of many uncertainties with respect to temperature, the processes by which equilibrium could be approached, the atmospheric level at which such processes would be effective, and the partial pressure of hydrogen required to provide the necessary rate of escape. In view of these uncertainties, further calculations are unprofitable at the present time. However, we can conclude from this discussion that a reducing atmosphere containing low partial pressures of hydrogen and ammonia and a moderate pressure of methane and nitrogen constitutes a reasonable atmosphere for the primitive earth. That this was the case is not *proved* by our arguments, but we maintain that atmospheres containing large quantities of carbon monoxide and carbon dioxide are not stable and cannot account for the loss of hydrogen from the earth.

Synthesis of Organic Compounds

At the present time the direct or indirect source of free energy for all living organisms is the sunlight utilized by photosynthetic organisms. But before the evolution of photosynthesis other sources of free energy must have been used. It is of interest to consider the sources of such free energy as well as the origin of the appropriate chemical compounds containing excess free energy which supplied the energy for chemical evolution prior to the existence of what should be called living organisms, and before the evolution of photosynthesis.

Table 1 gives a summary of the sources of energy in the terrestrial surface regions. It is evident that sunlight is the principal source of energy, but only a small fraction of this is in the wavelengths below 2000 A which can be absorbed by CH_4, H_2O, NH_3, CO_2, and so on. If more complex molecules are formed, the absorption can move to the 2500-A region or to longer wavelengths where a substantial amount of energy is available. With the appearance of porphyrins and other pigments, absorption in the visible spectrum becomes possible.

Although it is probable, it is not certain that the large amount of energy from ultraviolet light would have made the principal contribution to the synthesis of organic compounds. Most of the photochemical reactions at these low wavelengths would have taken place in the upper atmosphere. The compounds so formed would have absorbed at longer wavelengths and therefore might have been decomposed by this ultraviolet light before reaching the oceans. The question is whether the rate of decomposition in the atmosphere was greater or less than the rate of transport to the oceans.

Next in importance as a source of energy are electric discharges, such as lightning and corona discharges from pointed objects, which occur closer to the earth's surface and hence would have effected more efficient transfer to the oceans.

Cosmic-ray energy is negligible at present, and there is no reason to assume it was greater in the past. The radioactive disintegration of uranium, thorium, and potassium was more important 4.5 × 10^9 years ago than it is now, but still the energy was largely expended on the interior of solid materials such as the rocks, and only a very small fraction of the total energy was available in the oceans and atmosphere. Volcanic energy is not only small but its availability is very limited. A continuous source of energy is needed. It contributes little to the evolutionary process to have a lava flow in one part of the earth at one time and to have another flow on the opposite side of the earth years later. For a brief time heat is available at the surface of the lava, but the surface cools and heat flows slowly from the interior for years, making the surface slightly warm. Only a very small contribution to the evolutionary process could be contributed by these energy sources.

Electric Discharges

While ultraviolet light is a greater source of energy than electric discharges, the greatest progress in the synthesis of organic compounds under primitive conditions has been made with electric discharges. The apparatus used by Miller in these experiments was a closed system of glass, except for tungsten electrodes. The water is boiled in a 500-ml flask which mixes the water vapor and gases in a 5-lit. flask where the spark is located. The products of the discharge are condensed and flow through a U-tube back into the 500-ml flask. The first report (*10*) showed that when methane, ammonia, water, and hydrogen were subjected to a high-frequency spark for a week, milligram quantities of glycine, alanine, and α-amino-*n*-butyric acid were produced.

A more complete analysis (*11, 12*) of the products gave the results shown in Table 2. The compounds in the table account for 15 percent of the carbon added as methane, with the yield of glycine alone being 2.1 percent. Indirect evidence indicated that polyhydroxyl compounds (possibly sugars) were synthesized. These compounds were probably formed from condensations of the formaldehyde that was produced by the electric discharge. The alanine was demonstrated to be racemic, as would be expected in a system which contained no asymmetric reagents. It was shown that the syntheses were not due to bacterial contamination. The addition of ferrous ammonium sulfate did not change the results, and the substitution of N_2 for the NH_3 changed only the relative yields of the compounds produced.

This experiment has been repeated and confirmed by Abelson (*13*), by Pavlovskaya and Passynsky (*14*), and by Heyns, Walter, and Meyer (*15*). Abelson worked with various mixtures of H_2,, CH_4, CO, CO_2, NH_3, N_2, H_2O, and O_2. As long as the conditions were reducing conditions—that is, as long as either H_2, CH_4, CO, or NH_3 was present in excess—amino acids were synthesized. The products were the same and the yields as large in many of these mixtures as they were with methane, ammonia, and water. If the conditions were oxidizing, no amino acids were synthesized. These experiments have confirmed the hypothesis that reducing atmospheres are required for the formation of organic compounds in appreciable quantites. However, several of these mixtures of gases are highly unstable. Hence the synthesis of amino acids in these mixtures does not imply that such atmospheres were present on the primitive earth.

Heyns, Walter, and Meyer also performed experiments with different mixtures of gases, with results similar to Abelson's. These workers also used CH_4, NH_3, H_2O, and H_2S. They obtained ammonium thiocyanate, thiourea, and thioacetamide as well as compounds formed when H_2S was absent.

The mechanism of synthesis of the amino acids is of interest if we are to extrapolate the results in these simple systems to the primitive earth. Two alternative proposals were made for the synthesis of the amino and hydroxy acids in the spark discharge system. (i) Aldehydes and hydrogen cyanide are synthesized in the gas phase by the spark. These aldehydes and the hydrogen cyanide react in the aqueous phase of the system to give amino and hydroxy nitriles, which are hydrolyzed to amino and hydroxy acids. This mechanism is essentially a Strecker synthesis. (ii) The amino and hydroxy acids are synthesized in the gas phase from the ions and radicals that are produced in the electric discharge.

It was shown that most, if not all, of the amino acids were synthesized according to the first hypothesis, since the rate of production of aldehydes and hydrogen cyanide by the spark and the rate of hydrolysis of the amino nitriles were sufficient to account for the total yield of amino acids (*12*).

This mechanism accounts for the fact that most of the amino acids were α-amino acids, the ones which occur in proteins. The β-alanine was formed not by this mechanism but probably by the addition of ammonia to acrylonitrile (or acrylamide or acrylic acid), followed by hydrolysis to β-alanine.

The experiments on the mechanism of the electric discharge synthesis of amino acids indicate that a special set of conditions or type of electric discharge is not required to obtain amino acids. Any process or combination of processes that yielded both aldehydes and hydrogen cyanide would have contributed to the amount of α-amino acids in the oceans of the primitive earth. Therefore, whether the aldehydes and hydrogen cyanide came from ultraviolet light or from electric discharges is not a fundamental question, since both processes would have contributed to the α-amino acid content. It may be that electric discharges were the principal source of hydrogen cyanide and that ultraviolet light was the principal source of aldehydes, and that the two processes complemented each other.

Ultraviolet Light

It is clear from Table 1 that the greatest source of energy would be ultraviolet light. The effective wavelengths would be $CH_4 < 1450$ A, $H_2O < 1850$ A, $NH_3 < 2250$ A, $CO < 1545$ A, $CO_2 < 1690$ A, $N_2 < 1100$ A, and $H_2 < 900$ A. It is more difficult to work with ultraviolet light than with electric discharges because of the small wavelengths involved.

The action of the 1849-A Hg line on a mixture of methane, ammonia, water, and hydrogen produced only a very small yield of amino acids (*16*). Only NH_3 and H_2O absorb at this wavelength, but apparently the radical reactions formed active carbon intermediates. The limiting factor seemed to be the synthesis of hydrogen cyanide. Groth (*17*) found that no amino acids were produced by the 1849-A line of mercury with a mixture of methane, ammonia, and water, but that amines and amino acids were formed when the 1470-A and

1295-A lines of xenon were used. The 1849-A line produced amines and amino acids with a mixture of ethane, ammonia, and water. The mechanism of this synthesis was not determined. Terenin (*18*) has also obtained amino acids by the action of the xenon lines on methane, ammonia, and water.

We can expect that a considerable amount of ultraviolet light of wavelengths greater than 2000 A would be absorbed in the oceans, even though there would be considerable absorption of this radiation by the small quantities of organic compounds in the atmosphere. Only a few experiments have been performed which simulate these conditions.

In a most promising experiment, Ellenbogen (*19*) used a suspension of ferrous sulfide in aqueous ammonium chloride through which methane was bubbled. The action of ultraviolet light from a mercury lamp gave small quantities of a substance with peptide frequencies in the infrared. Paper chromatography of a hydrolyzate of this substance gave a number of spots with Ninhydrin, of which phenylalanine, methionine, and valine were tentatively identified.

Bahadur (*20*) has reported the synthesis of serine, aspartic acid, asparagine, and several other amino acids by the action of sunlight on paraformaldehyde solutions containing ferric chloride and nitrate or ammonia. Pavlovskaya and Passynsky (*21*) have also synthesized a number of amino acids by the action of ultraviolet light on a 2.5-percent solution of formaldehyde containing ammonium chloride or nitrate. These high concentrations of formaldehyde would not have occurred on the primitive earth. It would be interesting to see if similar results could be obtained with $10^{-4}M$ or $10^{-5}M$ formaldehyde. This type of experiment deserves further investigation.

Radioactivity and Cosmic Rays

Because of the small amount of energy available, it is highly unlikely that high-energy radiation could have been very important in the synthesis of organic compounds on the primitive earth. However, a good deal of work has been done in which this type of energy has been used, and some of it has been interpreted as bearing on the problem of the origin of life.

Table 2. Yields from sparking a mixture of CH_4, NH_3, H_2O, and H_2; 710 mg of carbon was added as CH_4.

Compound	Yield [moles (× 10^6)]
Glycine	63.
Glycolic acid	56.
Sarcosine	5.
Alanine	34.
Lactic acid	31.
N-Methylalanine	1.
α-Amino-*n*-butyric acid	5.
α-Aminoisobutyric acid	0.1
α-Hydroxybutyric acid	5.
β-Alanine	15.
Succinic acid	4.
Aspartic acid	0.4
Glutamic acid	0.6
Iminodiacetic acid	5.5
Iminoacetic-propionic acid	1.5
Formic acid	233.
Acetic acid	15.
Propionic acid	13.
Urea	2.0
N-Methyl urea	1.5

Dose and Rajewsky (*22*) produced amines and amino acids through the action of x-rays on various mixtures of CH_4, CO_2, NH_3, N_2, H_2O, and H_2. A small yield of amino acids was obtained through the action of 2 Mev electrons on a mixture of CH_4, NH_3, and H_2O (*23*).

The formation of formic acid and formaldehyde from carbon dioxide and water by 40 Mev helium ions was mentioned previously. These experiments were extended by using aqueous formic acid (*24*). The yield per ion pair was only 6×10^{-4} for formaldehyde and 0.03 for oxalic acid. Higher yields of oxalic acid were obtained from $Ca(HCO_3)_2$ and NH_4HCO_3 by Hasselstrom and Henry (*25*). The helium ion irradiation of aqueous acetic acid solutions gave succinic and tricarbolic acid along with some malonic, malic, and citric acids (*26*).

The irradiation of 0.1- and 0.25-percent aqueous ammonium acetate by 2 Mev electrons gave glycine and aspartic acid (*27*). The yields were very small. Massive doses of gamma rays on solid ammonium carbonate yielded formic acid and very small quantities of glycine and possibly some alanine (*28*).

The concentrations of carbon compounds and the dose rates used in these experiments are, in all probability, very much larger than could be expected on the primitive earth, and the products and yields may depend markedly on these factors, as well as on the effect of radical scavengers such as HS^- and Fe^{2+}. It is difficult to exclude high-energy radiations entirely, but if one is to make any interpretations from laboratory work, the experiments should be performed with much lower dose rates and concentrations of carbon sources.

Thermal Energy

The older theories of the formation of the earth involved a molten earth during its formation and early stages. These theories have been largely abandoned, since the available evidence indicates that the solar system was formed from a cold cloud of cosmic dust. The mechanisms for heating the earth are the gravitational energy released during the condensation of the dust to form the earth and the energy released from the decay of the radioactive elements. It is not known whether the earth was molten at any period during its formation, but it is clear that the crust of the earth would not have remained molten for any length of time.

Studies on the concentration of some elements in the crust of the earth indicate that the temperature was less than 150°C during this lengthy fractionation, and that it was probably close to present terrestrial temperatures (*29*).

Fox (*30*) has maintained that organic compounds were synthesized on the earth by heat. When heated to 150°C, malic acid and urea were converted to aspartic acid and ureidosuccinic acid, and some of the aspartic acid was decarboxylated to α- and β-alanine. The difficulty with these experiments is the source of the malic acid and urea on the primitive earth—a question not discussed by Fox. Fox has also synthesized peptides by the well-known reaction (*31*) of heating amino acids at 150° to 180°C, and the yield of peptides has been increased by using an excess of aspartic or glutamic acid (*32*). There is a difficulty connected with heating amino acids and other organic compounds to high temperatures. Geological conditions can heat amino acids to temperatures above 100°C over long periods of time, but it is not likely that this could occur over short periods. Abelson (*33*) has shown that alanine, one of the more stable amino acids, decarboxylates to methylamine and carbon dioxide. The mean life of alanine is 10^{11} years at 25°C but only 30 years at 150°C. Therefore, any extensive heating of amino acids will result in their destruction, and the same is true for most organic compounds. In the light of this, and since the surface of the primitive earth was probably cool, it is difficult to see how the processes advocated by Fox could have been important in the synthesis of organic compounds.

Surface Reactions, Organic Phosphates, and Porphyrins

It is likely that many reactions were catalyzed by adsorption on clay and mineral surfaces. An example is the polymerization of aminoacetonitrile to glycine peptides in the presence of acid clays, by Akabori and his co-workers (*34*). Formaldehyde and acetaldehyde were shown to react with polyglycine adsorbed on kaolinite to give serine and threonine peptides. This field offers many possibilities for research.

Gulick (*35*) has pointed out that the synthesis of organic phosphates presents a difficult problem because phosphate precipitates as calcium and other phosphates under present earth conditions, and that the scarcity of phosphate often limits the growth of plants, especially in the oceans. He proposes that the presence of hypophosphites, which are more soluble, would account for higher concentrations of phosphorus compounds when the atmosphere was reducing. Thermodynamic calculations show that *all* lower oxidation states of phosphorus are unstable under the pressures of hydrogen assumed in this article. It is possible that stronger reducing agents than hydrogen reduced the phosphate or that some process other than reduction solubilized the calcium phosphate. This problem deserves careful attention.

The synthesis of porphyrins is considered by many authors to be a necessary step for the origin of life. Porphyrins are not necessary for living processes if the organism obtains its energy requirements from fermentation of sugars or other energy-yielding organic reactions. According to the heterotrophic theory of the origin of life, the first organisms would derive their energy requirements from fermentations. The metabolism of sulfate, iron, N_2, hydrogen, and oxygen appears to require porphyrins as well as photosynthesis. Therefore, porphyrins probably would have to be synthesized before free energy could be derived from these compounds. While porphyrins may have been present in the environment before life arose, this is apparently not a necessity, and porphyrins may have arisen during the evolution of primitive organisms.

Intermediate Stages in Chemical Evolution

The major problems remaining for an understanding of the origin of life are (i) the synthesis of peptides, (ii) the synthesis of purines and pyrimidines, (iii) a mechanism by which "high-energy" phosphate or other types of bonds could be synthesized continuously, (iv) the synthesis of nucleotides and polynucleotides, (v) the synthesis of polypeptides with catalytic activity (enzymes), and (vi) the development of polynucleotides and the associated enzymes which are capable of self-duplication.

This list of problems is based on the assumption that the first living organisms were similar in chemical composition and metabolism to the simplest living organisms still on the earth. That this may not be so is obvious, but the hypothesis of similarity allows us to perform experiments to test it. The surprisingly large yields of aliphatic, hydroxy, and amino acids—α-amino acids rather than the other isomers—in the electric-discharge experiments, plus the arguments that such syntheses would have been effective on the primitive earth, offer support for this hypothesis. Further support can be obtained by demonstrating mechanisms by which other types of biologically important compounds could be synthesized.

Oparin (*1*) does not view the first organism as a polynucleotide capable of self-duplication but, rather, as a coacervate colloid which accumulates proteins and other compounds from the environment, grows in size, and then splits into two or more fragments, which repeat the process. The coacervate would presumably develop the ability to split into fragments which are very similar in composition and structure, and eventually a genetic apparatus would be incorporated which would make very accurate duplicates.

These two hypotheses for the steps in the formation of the first living organism differ mainly in whether the duplication first involved the relatively accurate duplication of nucleic acids, followed by the development of cytoplasm duplication, or whether the steps occurred in the reverse order. Other sequences could be enumerated, but it is far too early to discuss profitably the exact nature of the first living organism.

It was probably necessary for the primitive organisms to concentrate organic and inorganic nutrients from their environment. This could be accomplished by means of a membrane or by absorption on rocks or clays (*36*). The development of optical activity in living organisms is another important problem. This has been discussed by many authors and is not taken up here.

Life on Other Planets

Life as we know it—and we know of no other variety of life than that existing on the earth—requires the presence of water for its chemical processes. We know enough about the chemistry of other systems, such as those of silicon, ammonia, and hydrogen fluoride, to realize that no highly complex system of chemical reactions similar to that which we call "living" would be possible in such media. Also, much living matter exists and grows actively on the earth in the absence of oxygen, so oxygen is *not* necessary for life, although the contrary is often stated. Moreover, the protecting layer of ozone in the earth's atmosphere is not necessary for life, since ultraviolet light does not penetrate deeply into natural waters and also because many carbon compounds capable of absorbing the ultraviolet light would be present in a reducing atmosphere.

It is possible for life to exist on the earth and to grow actively at temperatures ranging from 0°C, or perhaps a little lower, to about 70°C. It seems likely that if hot springs were not so temporary, many plants and possibly animals would evolve which could live in such temperatures. Plants are able to produce and accumulate substances which lower the freezing point of water, and hence they can live at temperatures below 0°C. At much lower temperatures the reactions would probably be too slow to proceed in reasonable periods of time. At temperatures much above 120°C, reaction velocities would probably be so great that the nicely balanced reactions characteristic of living things would be impossible. In addition, it is doubtful whether the organic polymers necessary for living organisms would be stable much above 120°C; this is probably true even when allowance is made for the amazing stability of the enzymes of thermophilic bacteria and algae.

Only Mars, Earth, and Venus conform to the general requirements so far as temperatures are concerned. Mars is known to be very cold and Venus may be too hot. Observations of the black-body emission of radio waves from Venus indicate surface temperatures of 290° to 350°C (*37*). The clouds of Venus have the polarization of water droplets. Clearing of the clouds occurs, and this indicates that the clouds are composed of some volatile substance, for nonvolatile dust could hardly settle out locally. However, no infrared bands of water have been observed. It is possible that this is due to a very dry, high atmosphere, such as is characteristic of the earth, and to a cloud level that rises to very near the tropopause, so that there is little water vapor above the reflecting layer.

Mars is known to be very cold, with surface temperatures of +30°C to −60°C during the day. The colors of Mars have been observed for many years by many people. The planet exhibits seasonal changes in color—green or bluish in the spring and brown and reddish in the autumn. Sinton (*38*) has observed an absorption at 3.5 μ in the reflected light of Mars. This corresponds to the C-H stretching frequency of most organic compounds, but many inorganic compounds have absorptions at this wavelength. The changing colors of Mars and the 3.5 μ absorption are the best evidence, however poor it may be, for the existence of life on the planet. One thing that can be stated with confidence is that if life exists there, then liquid water must have been present on the planet in the past, since it is difficult to believe that life could have evolved in its absence. If this was so, water must have escaped from the planet, as very little water remains there now and no liquid water has been observed. Hence, oxygen atoms must escape from the planet. This is possible if the high atmosphere has a temperature of 2000°K, and this may well be the case in view of the high temperatures in the high atmosphere of the earth.

Surely one of the most marvelous feats of 20th-century science would be the firm proof that life exists on another planet. All the projected space flights and the high costs of such developments would be fully justified if they were able to establish the existence of life on either Mars or Venus. In that case, the thesis that life develops spontaneously when the conditions are favorable would be far more firmly established, and our whole view of the problem of the origin of life would be confirmed (*42*).

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Ref. 14

ORGANIC MATTER AND THE MOON

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Abstract

The problem of survival of a terrestrial microorganism, accidentally deposited on the moon, is first considered. The least radiosensitive dormant anaerobic bacteria, if exposed to solar ultraviolet radiation, would all be killed in a few hours. The resulting organic dissociation products would remain intact for much longer periods of time, possibly years. Such organisms shielded from solar illumination, perhaps in congealed dust matrix interstices, might survive for periods comparable to the age of the solar system.

The possible existence of indigenous lunar organic matter is then discussed. 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 probably greater than 10 gm cm^{-2}. As the lunar atmosphere was dissipated, thermal and radiative effects 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. If Whipple's picture of a congealed semi-porous dust matrix is a correct description of these upper layers, the likelihood of contamination of indigenous organic matter by terrestrial organic matter would appear to be fairly small. But such contamination, if it did occur, would destroy possibly unique sources of information on a variety of fundamental problems.

Since the deposition of an instrumented package on the lunar surface is apparently imminent, there has been considerable recent concern that terrestrial organisms and organis matter, deposited with the package, may obscure detection of possible organisms or organic matter indigenous to the moon (1, 2). If such a biological contamination of the moon occurred, it would represent an unparalleled scientific disaster, eliminating several possibly very fruitful approaches to such problems as the early history of the solar system, the chemical composition of matter in the remote past, the origin of life on earth, and the possibility of extraterrestrial life. Because of the moon's unique situation as a large unweathered body in the middle of the solar system, scientific opportunities lost on the moon may not be recouped elsewhere. Accordingly, it is of interest to determine (a) the survival probability of a terrestrial life-form on the moon, and (b) the possibility that organic matter was produced during the previous history of the moon, has survived to the present epoch, and could be confused with the remains of contemporary terrestrial life-forms.

Survival of terrestrial organisms on the moon

There seem to be three major hazards to survival of terrestrial life on the moon -- the temperature variation, corpuscular radiation, and solar electromagnetic radiation -- which we consider in turn. The probable absence of oxygen, water and other substances from the moon's surface is not, of course, evidence against survival, particularly of dormant anaerobic microorganisms; but it does preclude the possibility of their reproduction.

Temperatures range from about + 100° C. to about - 150° C. during a lunar day and night, but since many microorganisms, and especially bacterial spores, can survive temperatures in this range, we neglect the debilitating effects of the temperature variation.

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. At the present writing, the strength of the lunar magnetic field is not known (except perhaps in the U.S.S.R.). However the mean density of the moon is comparable with 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. On the other hand it is at least conceivable that the field strength is comparable with the terrestrial value. By terrestrial experience, and from the Stormer theory (3), energetic charged particles arriving from great distances would be constrained to strike the surface at high magnetic latitudes; cosmic rays and the solar proton stream would then be primarily excluded from a wide band around the lunar magnetic equator. Van Allen radiation belts would presumably exist, but particle leakage to the surface would again occur only outside the equatorial band.

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., 5). Charged particles will be excluded from regions where the magnetic energy density is greater than the particle kinetic energy density. For the surface of the moon, then, the lunar magnetic field strength must exceed about 10^{-2} gauss for the solar proton wind to be deflected.

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 (4). 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. Hence the optical depth in the untraviolet 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. (6), or, roughly $3 \times 10^{18}/\mu$ molecules cm^{-2} for a lunar atmosphere of mean molecular weight u. 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. The same conclusion applies to the more energetic cosmic rays.

Now what is the effect 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 (8), 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.

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 I, 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 cosmozoa hypothesis (v., e.g., 1, 22). The X-ray emission in Table I is taken from a theoretical study of the solar corona (7) and is consistent with rocket observations at quiet sun; the continuous uv intensities are computed from an integration of the Planck equation for appropriate ultraviolet black-body temperatures; and the cosmic ray flux is adopted from the flux inferred to exist at the top of the Earth's atmosphere.

For a given organism, the mean lethal dose in roentgens 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 r (10); protozoa generally have the same range (8, 11). Bacteria usually have somewhat lower mean lethal doses, 10^3 to 10^4 r for E. coli, for example, and 10^4 to 10^5 r for the spores of B. mesentericus and A. niger (12). However, there has been no systematic search for radio-resistant microorganisms, and it is possible that microorganisms having mean lethal doses as high as 10^7 r 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 r.

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 λ 2600 due to the biochemically ubiquitous purines and pyrimidines, and another, more pronounced, maximum shortward of λ 2300, 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, $D(\lambda3000) = 10^5$ ergs cm^{-2}, $D(\lambda2537) = 10^4$ ergs cm^{-2}, and $D(\lambda2300 = 10^3$

TABLE I

Lifetimes of Deposited Microorganisms on the Moon

Radiation	Intensity in ergs cm^{-2} sec^{-1}	Adapted MLD	ρ/μ in $gmcm^{-2}$	a in cm	Lethality times in seconds N/No					Charring time in seconds, $N/N_o=10^{-15}$
					10^{-1}	10^{-5}	10^{-10}	10^{-15}	10^{-20}	
Ultraviolet continuum λ 3000 to λ 2000	10^4	10^7 erg cm^{-2}	opaque		$2x10^3$	$1x10^4$	$2x10^4$	$3x10^4$	$5x10^4$	--
Ultraviolet continuum λ 2000 to λ 1000	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 r	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 $\lambda \sim 50$ Å, quiet sun	10^{-1}	10^7 r	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 r	400	almost trans-parent	$4x10^{14}$	$2x10^{15}$	$4x10^{15}$	$6x10^{15}$	$8x10^{15}$	$6x10^{18}$

ergs cm^{-2} (12). Considering the decrease of D shortward of 2300, 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} (12). An unusual case is the protozoon Paramecium multimicronucleatum, for which D(λ2537) = 10^6 ergs cm^{-2} (11). Considering finally, the environmental dependences of D mentioned in the preceding paragraph, and the possibility of undiscovered microorganisms of extreme radioresistance, 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 less than 10^6 ergs cm^{-2}.

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 (1); it is very unlikely that any packages for the immediate future will contain as many as 10^{20} microorganisms. Accordingly, we see from Table 1 that all microorganisms deposited and exposed to the sun will be killed by uv in a few hours. Similarly, fully illuminated microorganisms in cislunar soace 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. 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 recent work of Filosofo (13). 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 several hundred million years; microorganisms at greater depths will have even longer lifetimes. Similarly, cosmozoa imbedded in, for example, a meteorite would have lifetimes comparable to the age of the solar system, and the panspermia hypothesis cannot be ruled out under these circumstances.

Now what is 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 (14), which need not be reviewed here. But it is of interest to call attention to a few points. From eclipse temperature measurements and radio observations it is known that there is a dust covering on the moon, but estimates of its depth range from millimeters to miles. However, Whipple (15) has called attention to the experimental fact that dust, in a vaccuum, and irradiated with a corpuscular and electromagnetic flux of approximately solar composition, will congeal, forming a low-density, semi-porous matrix. If the lunar surface material has a similar 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. Under these conditions, the survival for very great periods of time of dormant anaerobic microorganisms deposited near the surface would seem to be a possibility which cannot be neglected. A determination of the microstructure of the moon's surface material is therefore of great importance.

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} r (v., e.g., 5). The The last column of Table I gives the eimes 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 several 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 (16) , with most 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.

In conclusion, it appears that deposited terrestrial organic material may survive for a period of time ranging from one to 10^{11} years, depending on the strength of the lunar magnetic field and on the microstructure of the lunar surface. We now consider the possibility that there is indigenous lunar organic matter with which such terrestrial organic matter could be confused.

Production of organic matter in the early history of the moon

There is reason to believe that the moon, along with other bodies in the solar system, was formed some 5 to 6 x 10^9 years ago from the solar nebula, a vast gas and dust cloud of essentially cosmic distribution of the elements (17). 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 as between 10^8 and 10^9 years (18). 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 (19).

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 similar chemical composition to the initial protoatmospheres. The present Martian, Venusian 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. If not replenished from the interior, a lunar atmosphere will escape to space in roughly 10^3 years, as can be computed from the work of Spitzer (20). Hence the lifetime of the secondary lunar atmosphere depended entirely on the supply rate of gases from the lunar interior. This is difficult to estimate, but it is not impossible that extensive lunar vulcanism lasted for 10^7 or 10^8 years. Although it is unlikely that the lunar craters are volcanic in origin, other lunar surface features exist which are of undoubted volcanic origin (32).

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 $\lambda 2600$ is greater than 10^{-19} cm^2. Hence, as long as the mean density of ammonia exceeded 10^6 molecules cm^{-3} between the moon and the sun in the solar nebula, solar uv shortward of $\lambda 2600$ did not reach the lunar vicinity. This ammonia density corresponds to a hydrogen number density of about 10^9 molecules cm^{-3} for cosmic abundances; i.e., about 10^{-15} gm cm^{-3}. Interplanetary densities of this order were reduced rapidly (18), and we conclude that during most of the 10^8 to 10^9 years in which the solar nebula was being dissipated, solar uv shortward of λ2600 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 uv during this period. After the dissipation of the solar nebula, the lunar protoatmosphere was opaque in the uv 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 uv by lunar and terrestrial protoatmospheres for almost 10^8 years. After the evaporation of these protoatmospheres, and the origin of the secondary lunar atmosphere, it is not clear how long the secondary atmosphere was maintained at sufficient density to absorb all incident solar radiation shortward of λ2600. The true time may be anywhere between 10^3 and 10^8 years, depending on the rate of gaseous exhalation from the primitive lunar interior. But from terrestrial experience, one might expect the larger value to be nearer to the truth.

The later solar nebula in the vicinity of the moon, and the primary and the secondary lunar atmospheres, all having cosmic composition, were composed largely of CH_4, NH_3, H_2O, with smaller amounts of H_2, He, N_2, CO, CO_2, A, Ne, and the interaction products of these molecules. The effect of solar ultraviolet light (and electric discharges) on such an atmosphere is well known; organic molecules of fair complexity (up to molecular weight 100) are produced efficiently, 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 (21, 22). The syntheses are in general non-equilibrium processes; radiation both produces and destroys the organic molecules, but the net production rate is proportional to the photon flux. In addition, because the molecular weight of these molecules was greater than the mean molecular weight of the nebula or atmosphere, they diffused to the surface under the influence of the lunar gravitational field. The time for such molecules to diffuse to atmospheric depths where photo-dissociating uv does not penetrate can be shown to be of the same order as the time between absorptions of photo-dissociating photons (23). Consequently, with reaction products being removed from the system, the quantum yield in the primitive lunar envelopes must have been greater than that in contemporary laboratory experiments in which reaction products are not being removed from the system.

Recently a series of experiments on uv synthesis of organic molecules which permits quantitative conclusions has been performed by W. Groth in Bonn (24). The overall quantum yield, ϕ, for the production of amino acids alone from a gas mixture of ethane, ammonia and water is between 10^{-4} and 10^{-5}. The value appears to be approximately independent of wavelength between $\lambda 2537$ and $\lambda 1470$. Because of the rapidly decreasing NH_3 absorption cross-section longward of $\lambda 2600$, radiation of much longer wavelengths should be synthetically ineffective.

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 $\lambda 1470$ (25). Assuming the synthesis of amino acids from methane, ammonia and water is as wavelength-independent as the synthesis from ethane, ammonia and water, we conclude that the ϕ appropriate to primitive conditions is about a factor of ten less than Groth's laboratory value. This point should be checked experimentally. Since the time between collisions is much shorter than the time between absorptions of uv photons in the primitive lunar atmosphere (23), the differing pressures, temperatures, and densities should not significantly alter the overall quantum yields. It is difficult to estimate by what factor the overall quantum yield should be increased to allow for the gravitational diffusion of the synthesized molecules out of the radiation field. Simultaneous irradiation over the whole range of wavelengths shortward of $\lambda 2600$ should also increase ϕ. Provisionally, let us take an overall quantum yield for the photoproduction of amino acids in the primitive lunar atmosphere or neighboring solar nebula of $\phi = 10^{-6}$ between $\lambda 2600$ and $\lambda 1470$, remembering that there is an uncertainity of at least a factor of ten. If we knew the flux of solar radiation between these wavelengths in primitive times, we would be able to compute the arrival rate of amino acids on the ancient lunar surface.

The present solar flux at $\lambda 2600$ is that of a black body of temperature about 5000°K. (26). We are interested in the radiation flux after the sun's evolutionary track in the Hertzsprung-Russell diagram has joined the main sequence, and the dissipation of the solar nebula has begun. At the juncture 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 $0.87\ R_{\odot}$ (27, 28, 29). 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 $0.73\ L_{\odot}$ (29). We write $L_{\odot}$ and $R_{\odot}$ for the present solar luminosity and radius. Knowing the luminosities and radii at these two representative times, the ultraviolet black body temperatures and geometrical dilution factors can be computed, and the radiation flux shortward of a given wavelength at the two times obtained by integrating the Planck equation. The ultraviolet temperatures were about the same at the two times (0.975 the present temperature) as are the dilution factors (about 0.8 the present value). The quiet solar ultraviolet photon fluxes of wavelength shortward of $\lambda 2600$ in the vicinity of the moon at these times is then computed to be $Q = 7 \times 10^{14}$ photons cm^{-2} sec^{-1}, roughly the present value.

Assume now that uv radiation of intensity Q falls for t seconds on an opaque gaseous envelope surrounding the moon, and produces molecules of molecular weight u with quantum efficiency ϕ. Let r be the distance from the center of the moon such that all molecules of molecular weight u produced at distances less than r are gravitationally captured by the moon, while those produced at distances greater than r will escape. The synthesized molecules will be distributed over a moon of radius R. The mean surface density of deposited material will then be

$$\sigma = (Q \phi r^2 \mu t/4 N_A R^2) \qquad \text{gm cm}^{-2}$$

where N_A is Avogadro's number.

Because of the moon's proximity to the more massive earth, much material produced in the lunar vicinity must nevertheless have been captured by the earth. We adopt as a minimum value of r, r = R; i.e., we neglect lunar gravitational capture of molecules produced outside a cylinder 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 minimum values of r for the times of the solar nebula and the original lunar protoatmosphere.

In Table II we have listed values of σ computed from the above equation for $Q = 7 \times 10^{14}$ photons cm^{-2} sec^{-1}, and $\mu = 100$, for various values of t and ϕ.

TABLE II

Lunar amino acid surface densities in gm cm^{-2}

33

	ϕ			
in years	10^{-5}	10^{-6}	10^{-7}	Envelope
10^3	10^{-2}	10^{-3}	10^{-4}	
10^4	10^{-1}	10^{-2}	10^{-3}	
10^5	1	10^{-1}	10^{-2}	secondary lunar atmosphere
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

We see that very considerable amino acid surface densities 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 have been thermally dissociated in the volcanic 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 (see below). Miller (21) and Groth (24) find efficient production of other substances beside amino acids, some with greater quantum yields (especially formic and acetic acids) and many with lesser quantum yields. The overall deposition of organic matter after the moon's formation may well have exceeded 10 gm cm^{-2}. This figure is greatly in excess of any possible accretion of cometary or interstellar organic matter (23). During the time of deposition, the lunar atmosphere would have inhibited thermo- and photo- dissociation of the deposited molecule.

As the secondary lunar atmosphere gradually escaped to space, and replenishment from the interior eventually fell off, 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 the concentration of radioactive elements towards the surface as a consequence of the formation of the lunar mantle. The effect of heat and uv 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 (almost all of which, incidentally, are utilized by and are part of contemporary terrestrial organisms) (22, 30). Finally, because complicated 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 complicated organic molecules (v., e.g., 31).

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 (15) 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 much greater than today. For example, Kuiper (32) believes the moon, receding from the earth because of tidal friction, passed through a sediment ring of silicates and ices which encircled the earth. As one consequence of this meteoritic infall in primitive times, the moon's surface must have received a dust cover, probably composed primarily of silicates and ices, which can be identified, at least in part, with the present lunar surface material. The organic molecules would then be covered by a protective layer, insulating them from the extremes of lunar temperature and absorbing the incident solar radiation and subsequent meteoritic infall. At an average temperature of 20° C., the thermostability halflives of organic molecules are of the order of the age of the solar system (v., e.g., 16). Provided that no large scale destructive events have subsequently occurred, it is therefore not unreasonable to expect the presence of both simple and complex organic molecules on the moon, beneath the dust layer, and with an average surface density of perhaps 10 $gm\ cm^{-2}$. These remarks apply properly only to regions on the moon where it is certain there have been no extensive lava flows; the southern highland appears to be such a region (32).

A sample of appropriate lunar sub-surface material should then have an organic fraction easily detectable by simple chemical analyses. When compared with suitable laboratory results, a quantitative and qualitative analysis would give important clues on the early history of the solar system.

Because of its great potential importance, the admittedly very speculative possibility must be raised that life arose on the moon before the secondary lunar atmosphere was lost. There is considerable likelihood that conditions on the moon 5×10^9 years ago were not very different from conditions on the earth 5×10^9 years ago. Recent thinking on the origin of life on this planet is increasingly inclined towards a very rapid origin for the first self-reproducing system (22, 31). 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. Although the chances of extant life on the moon seem exceedingly remote, there is a finite possibility 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.

Conclusion

Due to the possible similarity in primitive organic syntheses on the earth and the moon, assurance cannot be given that organic matter indigenous to the moon will be distinguishable from accidentally deposited terrestrial organic matter. However, indigenous organic matter will be primarily localized beneath the congealed lunar dust layer; while deposited terrestrial organic matter should be primarily localized at the surface. Even microorganisms in dust matrix interstices shielded from solar illumination would probably be far above any indigenous lunar organic matter. Hence it would seem that if instrumented lunar packages are first made scrupulously aseptic, and if care is then taken to avoid disturbing sub-surface material, the contamination probability can be minimized. If the lunar maria are frozen lava fields, a landing on them would be greatly preferable to a landing on non-lava areas such as the southern highlands. Before any moonfall is attempted, the microstructure of the lunar surface material and the lunar magnetic field should be studied as effectively as possible.

Lunar paleontology, in either the common or the literal sense, will take many years before becoming a flourishing field of study -- if, indeed, it ever does -- but the mere possibility of such a discipline should be worth a little caution in exchange.

Acknowledgements

Appendix: Survival time of an irradiated population

We consider a population of N_0 organisms, each having mean density p gm cm^{-3}, characteristic size a cm, and mean lethal dose of a given kind of electromagnetic or corpuscular ionizing radiation, D roentgens. 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/p 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 roentgens. Then, since one r corresponds to the absorption of 93 ergs/gm,

$$J = 93 \; p \; a \; d \qquad \text{(A-1).}$$

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

$$E_t = E_o \; e^{-(\mu/p)pa} \qquad \text{(A-2).}$$

Consequently, the energy absorbed by the organism is

$$E_a = E_o - E_t = E_o \quad 1 - e^{-(\mu/p)pa} \qquad \text{(A-3).}$$

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

$$E_o/d = 93 \; p \; a \quad 1 - e^{-(\mu/p)pa} \qquad \text{erg } cm^{-2} \; r^{-1} \quad \text{(A-4).}$$

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

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

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

$$N = N_o \; e^{-t/\tau} \qquad (A-6).$$

Solving eq. (A-6) for t, substituting from eqs. (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.

$$t = 214 \; a \; p \; (D/I) \quad 1 - e^{-(u/p)pa} \quad \log_{10} \; (N_o/N) \quad (A-7).$$

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

$$t = 2.3 \; (D/I) \quad 1 - e^{-(\mu/p)pa} \quad \log_{10} \; (N_o/N) \qquad (A-8).$$

Table I was constructed from eqs. (A-7) and (A-8) with the following simplifications. p was taken as unity throughout.

For an organixm opaque in the given radiation, $(u/p)pa \quad 1$, and eqs. (A-7) and (A-8) reduce respectively to

$$t = 214 \; a \; p \; (D/I) \;\; \log_{10} \;\; (N_o/N) \qquad (A-9).$$

and

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

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

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

and

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

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NATIONAL ACADEMY OF SCIENCES - NATIONAL RESEARCH COUNCIL
Division of Medical Sciences

PANEL ON EXTRATERRESTRIAL LIFE
(Panel 2)
of the
Armed Forces-NRC Committee on Bio-Astronautics

Minutes of First Meeting
16-24 July 1959
Woods Hole, Massachusetts

ATTENDANCE:

Panel:	Dr. Melvin Calvin, Chairman. Dr. Wolf Vishniac, Vice Chairman, Mr. Richard W. Davies, Dr. Matthew Meselson, Mr. Carl E. Sagan, and Dr. Harold Weaver. (Absent) Dr. George E. Hutchinson and Mr. Malcolm D. Ross.
Ex officio, Executive Council:	Major Kay Cutler, USAF (MC).
Liaison Representatives:	
U. S. Army:	Dr. Richard S. Young, Research Projects Laboratory Army Ballistic Missile Agency, Redstone Arsenal, Alabama.
National Aeronautics and Space Administration:	Dr. Gerhard Schilling, Chief, Astronomy and Astrophysics Program. Dr. Douglas L. Worf, Program Chief, Life Biology and Life Support Systems.
Guests:	Dr. C. H. Sederholm, Department of Chemistry, University of California, at Berkeley, Dr. Fred Whipple, Smithsonian Astrophysical Observatory, Cambridge, Massachusetts.
National Academy of Sciences National Research Council:	Mr. George A. Derbyshire, Space Science Board. Dr. H. Burr Steinbach, Chairman, Division of Biology and Agriculture.

Abstract

Mission and Introduction.

Panel 2 is concerned primarily with the biology of extraterrestrial life.

I. Decontamination.

It is of utmost urgency to prevent contamination of the Moon and planets by terrestrial organisms, while initial explorations of the Solar System are under way. Contamination of any celestial body may irretrievably destroy data concerning the origin of life and in an explosive manner upset planetary ecologies.

II. Exploration of the Solar System for Organic Molecules and Living Matter.

Techniques and approaches are suggested which may be useful in collecting evidence for the existence of extraterrestrial life.

III. Terrestrial Studies in Support of Solar System Explorations.

Extensive basic work is needed to facilitate the interpretation of data collected by space probes. A partial list of necessary studies is given here, together with suggested literature compilations which would facilitate such work.

IV. Conclusions and Recommendations.

Insure the sterilization of space probes. Attempt to obtain international agreement to prevent biological contamination of celestial bodies. Establish laboratories and an observatory devoted to the study of the Solar System and to necessary supporting work. Evaluate research proposals. Sponsor meetings.

INTRODUCTION AND MISSION

No great question has occupied Man's mind longer than that of his own origin. Scientific investigations of life have heretofore been confined to one small sample of the universe: Earth. Space vehicles now open to Man the wide expanse of the Solar System, and present to the scientist a host of new samples of the universe -- the planets and their satellites and the thinly scattered material in the vast space between the planets, the debris remaining from the birth of the Solar System as well as interstellar material now in the region of the Sun. We cannot afford to neglect this newly opened field of research. The new information we shall gain will be of the greatest importance to astronomy, to physics, to chemistry, to biology. It will be of the greatest interest to all thinking men; it cannot fail to exert a profound influence on Man's philosophy.

Panel 2 considers its mission to be the stimulation and promotion of such researches, of all studies concerned with the origin and nature of life in the Solar System and beyond.

To implement these aims we consider the following activities to be within our sphere:

1. Consideration of existing pertinent knowledge.
2. Consideration of the type of investigations, both observational and experimental, which might contribute to this knowledge.
3. To be available both individually and collectively to the various agencies of the Government or to the National Academy of Sciences to help in the selection and encouragement of work.
4. To take steps to facilitate the exchange of information between various groups concerned with the problem -- sponsoring meetings, etc.
5. To take immediate steps toward international agreement designed to preserve whatever information might be available to us on other celestial bodies -- agreements on decontamination, etc.

I. The Protection of Extraterrestrial Bodies from Biological Contamination

There exists the grave possibility that without sufficient thought and preparation we may unwittingly and irretrievably destroy critical evidence concerning the origin and early history of the Solar System, and the origin and prevalence of life in it. The danger is that we may accidentally deposit terrestrial organisms on the surface of the Moon and planets.

A. Astrobiological Background.

1. Origin of Organic Matter and Life in the Solar System.

Although there is much uncertainty on the detailed evolution of the Solar System, there is good reason to believe that the Moon and planets arose from a vast cloud of gas and dust in which (aside from helium) hydrogen, carbon, nitrogen, and oxygen were the most abundant elements (Kuiper, 1952; Urey, 1952). In their later stages of formation these bodies were surrounded by envelopes primarily composed of H_2, CH_4, NH_3, and H_2O. It is known that when such a mixture of gases is supplied with energy -- for example solar ultraviolet radiation, electrical discharges, or heat, a variety of organic molecules is produced (Miller, 1955; Oparin, 1958). Organic molecules produced in primitive planetary or lunar atmospheres would have drifted down to surface levels where solution in liquid water or other media could occur. As much as 10 gm. of organic matter may have been deposited on each square centimeter of the lunar surface before the lunar atmosphere escaped into space (Sagan, 1959). Under such circumstances, self-replicating systems may have originated on several bodies of the Solar System in addition to the Earth.

Several observations of Mars suggest the presence of living material (Dollfus, 1958; de Vaucouleurs, 1956). Although there is no direct evidence of the origin and survival of life on the Moon, it may be possible that beneath the present surface material, there lie the remains of primitive lunar organisms. Even if life never arose on the Moon there may still be organic matter lying beneath the surface. Verification of either of these hypotheses would be of the greatest significance.

The Moon is important in another respect: It is the only large body near the center of the Solar System, undisturbed by wind and water. It holds information concerning material which has fallen on it through its five billion-year history. Cometary and interstellar organic matter may have accumulated in measurable quantities. In addition, it would be a trap for the hypothetical cosmobiota, microorganisms carried through space and deposited on lunar and planetary surfaces.

2. Circumstances of Biological Contamination.

There are various ways in which the Moon and planets may be contaminated, depending upon the properties of the bodies.

a. A Solar System body may contain no living indigenous organisms and may be incapable of supporting terrestrial organisms. There may nevertheless 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 (2.2 km./sec. for the Moon) should distribute its contents over an appreciable fraction of the body's surface area. In subsequent attempts to detect primitive life forms and cosmobiota, it might be impossible to distinguish among the three possibilities: primitive indigenous organisms, cosmobiota, or terrestrial microbiological contamination.

b. A body may contain no indigenous living organisms, but may be capable of supporting terrestrial organisms. In addition to observing evidence on primitive indigenous organisms and cosmobiota, the possibility exists that a deposited terrestrial microorganism, in the absence of biological competitors or predators, will reproduce at a rate limited only by the availability of water and metabolites. The common bacterium Escherichia coli has a mass of 10^{-12} grams and a minimum fission interval of 30 minutes. At this rate it would take 66 hours for the progeny of one bacterium to reach the mass of the Earth. The example illustrates that a biological explosion could completely destroy the remains of prebiological syntheses. The time scale of biological explosion need not be long;

Indeed, it may be much less than the interval between oppositions for the planets. Evidence may be destroyed because of one impacting probe before observations can be made by another probe at the following opposition.

c. A body may contain indigenous living organisms. There is then the possibility that deposited terrestrial microorganisms, by competition with or parasitism upon even one species of extraterrestrial organism, may completely upset the planetary ecology. Before another probe is launched the destruction of many or even all the indigenous organisms on the contaminated extraterrestrial body may be complete.

In this context should also be mentioned the possibility of back-contamination; i. e., that return voyages from extraterrestrial bodies may carry with them virulent extraterrestrial or modified terrestrial organisms. If such organisms are introduced into human or other terrestrial populations there exists the definite possibility of pendemics and the destruction of the existing terrestrial ecologies.

B. Tolerance Recommendations.

Present ignorance of lunar and planetary conditions and our inability to anticipate reliably the nature of possible extraterrestrial life or pre-life forms constitute strong reasons for the exercise of maximum caution. It is possible that the Moon or any one of the planets is capable of supporting some form of terrestrial life and that a single viable terrestrial organism could multiply sufficiently to cause a catastrophic derangement of pre-existing conditions. Until this possibility can be confidently excluded no landing can be risked which entails a significant probability of depositing a viable organism. These considerations provide a basis for the establishment of contamination tolerances for space probes. THIS PANEL RECOMMENDS THAT DURING THE PERIOD OF INITIAL EXPLORATION OF ANY ESTRATERRESTRIAL BODY THE PROBABILITY OF LANDING ONE VIABLE ORGANISM BE KEPT BELOW ONE IN 10^6. If the number of probes to be launched and the probability of impacting are not easily estimated, then the above tolerances of one viable organism in 10^6 must be applied to each probe. It follows that it is pointless for a single nation to sterilize its probes; therefore we urge the Executive Council to request the President of the National Academy of Sciences to initiate international negotiations on this matter.

It would seem highly unlikely that dead organisms or their fragments could initiate large-scale modifications of a planetary surface. However, this possibility cannot be fully discounted at present, and, consequently contamination by dead organisms, their fragments, and vehicular materials of biological origin should be held to a minimum. Even if such materials can not act catalytically to alter pre-existing conditions, their concentration must be kept so low as not to jeopardize the possible discovery of similar materials of extraterrestrial origin. Studies should be pursued of the possible catalytic effects of organic molecules on organic media likely to be found on or beneath planetary and lunar surfaces.

The microorganism population of a mammal may be as high as 10^{12}. THEREFORE, UNTIL MORE INFORMATION IS AVAILABLE ON THE NATURE AND DISTRIBUTION OF ORGANIC MOLECULES AND LIVING ORGANISMS, NO LANDING OF ANIMALS OR MEN SHOULD BE ATTEMPTED ON THE MOON OR PLANETS, ESPECIALLY WHERE THERE EXISTS APPRECIABLE POSSIBILITY OF HARD LANDING. A program should be initiated for biological and chemical analysis of lunar and planetary surface and subsurface materials, by instrumented, unmanned, sterilized, soft-landing probes.

On worlds where further analysis indicates considerable danger of contamination, 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. Decontamination upon leaving an extraterrestrial body must be no less thorough than on leaving Earth. Space suits must be designed to eliminate cracks and joints in which microorganisms might lodge inaccessible to decontamination techniques. In the light of present knowledge these remarks must apply in particular to the Moon, Mars, and Venus, as well as to other bodies of the Solar System.

C. Sterilization and Decontamination of Space Probes.

Adequate sterilization and decontamination can be achieved only by careful and early consideration of the design and construction of payloads. It cannot be assumed that sterilization will be affected by interplanetary radiation, re-entry heating, or explosion upon landing. Microorganisms within the interior or in the surface crevices of a probe are likely to be protected from interplanetary radiation. Adequate re-entry sterilization is unlikely to occur; meteorites are known to have reached the Earth's surface without experiencing interior temperatures sufficient to kill microorganisms. Furthermore, sufficiently small contaminated particles, such as might result from the accidental fragmentation of a probe, would be able to descend through a planetary atmosphere without appreciable heating. Finally, microorganisms are known to survive chemical explosions; hence we can recommend that the impact of a probe on a planetary surface cannot insure sterilization. In the case of soft landings, it might be possible to seal contaminated objects so securely as to prevent their escape. However, this procedure may lack the high degree of reliability recommended on page 5.

Soft landings carrying terrestrial life, for example manned landings, should not be attempted until information about the extraterrestrial target is sufficient to insure the target's insensitivity to terrestrial biological contamination. In any case extensive samples of lunar and planetary surfaces and atmospheres should be gathered and safely stored for future examination before terrestrial contamination is allowed to occur.

The above considerations lead us to conclude that the sterility of a probe must be insured by procedures initiated long before the time of launching. At present it is possible to anticipate and recommend five phases of payload sterilization for all deep space missions. They are in sequence:

1. Sterile fabrication and assembly of components, particularly those which might be damaged by subsequent heat, chemical, or radiation sterilization procedures.

2. Built-in or intrinsic sterilization of parts.

3. Terminal sterilization.

4. Maintenance of sterilization.

5. Decontamination procedures.

Finally, suitable microbiological testing and control procedures must be integrated into the sterilization operation.

1. Sterile Fabrication and Assembly. The removal of dust and foreign particles from the space probe eliminates a major source of biological pollution and it is at the same time an engineering virtue. The washing and scrubbing of parts of the payload with water and detergents or other acceptable solvents can reduce the number of microbes on the probe by several orders of magnitude.

Sterile assembly will also include the use of presterilized components. Parts such as screws and bolts can be heat sterilized. If screws and fitting **holes are made to fit exactly** then care must be taken to sterilize them before joining them. If fittings are not perfectly joined, geseous antiseptics such as ethylene oxide may be used to penetrate and sterilize these interstices.

2. Built-in Sterilization. Whenever possible, substances which are lethal to organisms should be employed. Germicidal substances might be incorporated into lubricants and sealing compounds and even more generally used in the fabrication of components. Certain substances of biological origin such as casein glue or shellac should be avoided.

3. Terminal Sterilization. Microorganisms perish when subjected to dry steam at 160° centigrades for 20 minutes (Halvorsen, Bacterial Spores, 1957). However, some of the components which go into payloads, with which we are now familiar, can not endure this temperature. A more generally applicable disinfectant is ethylene oxide gas (Phillips and Kaye, 1949).

Ethylene oxide is a small molecule and therefore dissolves in many substances such as rubber, plastic, and oil. It is quite penetrating and will work its way into the interstices of most components.

In many instances where neither heat nor gas sterilization is practical radiation is a possibility. Doses of the order of 10^7 rads are required for good sterilization (Hollaender, 1952). Some component materials, perhaps battery interiors, can be subjected to this intense radiation without injuring their performance. The 1.17 and 1.33 MEV gamma rays from Co^{60} make this a useful radiation source for sterilizing small packages.

4. Maintenance of sterilization. After having obtained a sterile space probe it will be necessary to mount it on the rocket boosters. The technical problem is then one of keeping microbes from coming into contact with the probe.

The probe is encased in a protective metal shroud during the launch phase of the space flight. The shroud can be employed to house a disinfectant atmosphere throughout the count-down and flight through the atmosphere, after which it is discarded. The disinfectant can be either carboxide or a faster-acting, less penetrating, gas such as beta-propiolactone.

5. Decontamination Procedures. It is difficult to suggest specific procedures for probe decontamination, as distinct from sterilization, without increased knowledge of the possibility of serious derangement of extraterrestrial conditions by nonliving terrestrial material. The use of materials of biological

origin should be shunned in payload design, and in any case a detailed chemical inventory should be kept of the quantities of all materials deposited upon extraterrestrial surfaces. If possible, a duplicate payload should be placed in careful storage.

II. Exploration of the Solar System for Organic Molecules and Living Matter.

In spite of the long history of observational astronomy, our knowledge of many fundamental properties of the Solar System is severely limited. During the past few decades astronomy has been reborn in physics. Astrophysics has taken great forward steps, but relatively few new facts about the Solar System have been discovered and thoroughly investigated. Except for the work of a small number of widely known individuals, Solar System astronomy has languished. New methods and new instruments have been applied to the study of the Solar System far less often than they have been to the study of the stars. All too infrequently have physicists, geophysicists, chemists, and microbiologists joined the astronomer to supply new approaches to the study of the planets. Science and Man's advance into space require that detailed knowledge of all aspects of the Solar System be available. Every effort must therefore be made to vitalize and expand astrophysical and astrobiological studies of the system.

A. Observations from the Surface of the Earth.

1. Some available Observations.

Few observational data relate directly to the question of the existence of life, or, in the broader view, of organic, life-related molecules on the planets. The information that does exist has been gained from visual telescopic observations, light polarization studies, spectroscopy, and radioastronomy.

The planet Mars has held the greatest interest for many observers because of the so-called canals (Schiaparelli, 1877), objects whose nature and existence is still hotly disputed, and the circumstantial evidence for life provided by the equatorward advance of dark areas in one hemisphere of the planet (Lowell, early part of this century) as the winter polar cap of that hemisphere retreats with the advance of the Martian season of spring. The polar caps are known to be composed of hoar frost (Kuiper, 1952; Dolfuss, 1958). Dense water clouds as we know them on Earth do not exist on Mars. It has been generally stated that liquid water would occur on the surface only under very unusual circumstances, though this statement appears to be seriously in error (Sederholm, Weaver, and Sagan, 1959) if salts are present on the surface of the planet. Dried-up seas would have deposited salts; It is difficult to imagine the surface of a planet free from such salt deposits. In the region of such deposits one could now find water, derived from the Martian atmosphere, and present in liquid form despite the low temperature and vapor pressure. It is tempting to try to relate salt deposits from the ancient seas to the present dark areas of the planet.

Studies of the polarization of reflected light from the surface of Mars (Dollfus and others, 1948-1959) show that the polarization properties of the dark areas change with the advance of the Martian season while polarization properties of the desert areas do not. The polarization curves and their variations indicate that the reflecting surface of the planet, responsible for the polarization, must be composed of minute grains; and that the average size of absorption (or both) of the grains in the dark regions increases as the Martian season advances.

Infrared spectra of the dark areas of the planet (Sinton, 1957, 1958) show reflection minima in the wavelength region 3.4 to 3.7 microns, ascribed to the C-H chemical bond.

The outer planets, excepting Pluto, possess extensive reducing atmospheres, probably containing large amounts of hydrogen and helium. Methane and ammonia have been detected spectroscopically in the atmosphere of Jupiter and Saturn, as has methane in those of Uranus and Neptune. Ammonia undoubtedly exists on Uranus and Neptune but has been frozen out because of the extremely low temperatures. Water probably exists as ice beneath the atmospheres of Jupiter, Saturn, Uranus, and Neptune. The present composition of the atmospheres of the outer planets greatly resembles the presumed primitive composition of the atmospheres of the terrestrial planets. Consequently, prebiological organic syntheses which occurred on the ancient Earth may be occurring today in the outer planets.

Radio noise from the planet Jupiter (Burke and Franklin, 1958) appears to originate primarily in the region of the Great Red Spot. This radiation, according to one theory, has been explained as arising from atmospheric electrical discharge on Jupiter. If this is indeed the case, then there can be little doubt that large organic molecules must be produced in the atmosphere of the planet. Ultraviolet radiation from the Sun may also be active in producing such molecular species. However, the abundance of ammonia rather than water on Jupiter requires that new attention be focused on biochemical systems in which ammonia rather than water is the solvent.

2. Need for New Data.

Only a small number of observational details of a few of the planets have been touched upon, but these should serve to indicate the extremely great need for the extension of planetary studies. Additionally, new approaches to these problems must be devised; new instrumentation must be designed to aid in their solution.

As one new approach to the question of large organic molecules in the Solar System we call attention to the need for adequate chemical and physical analysis of a significant sample of meteorites, particularly those of the stone variety. Preliminary results (Calvin, 1959) indicate that very large, rather complex, organic molecules exist in some meteorites of the carbonaceous chondrite variety.

3. The Earth as a Control and Test Source.

Nowhere in the literature is there adequate information on the microbiological profile of the Earth's atmosphere. There is available no information on positional or seasonal variations of such a profile. Instrumentation to permit earth sampling to determine microorganism content should proceed at once. Data from high-altitude balloons, high-flying aircraft, and rockets should be considered. The profile derived should be of high resolution in the sense that it describes the height distribution of each kind of organism, not all types taken together.

We should also consider balloons, high-flying aircraft, and rockets for preliminary flight testing of any device designed to detect life or organic molecules on other planets.

4. Extra-Solar System Objects.

As a final item under the heading of observations made from the surface of the Earth, we mention a high-risk, high-return project that should not be lost from sight: the detection of high-intelligence life on extra-Solar System planets by radio signals. The probability of such detection is obviously very minute, but if detection were achieved, the results would have the farthest-reaching consequences. Primarily, we believe that support should be given to radioastronomy to make possible construction of enough large radio telescopes to permit the use of some of the total available observing time for such a project. (There are far too few telescopes available now to devote time to such a high-risk project.) We further believe that those large radio telescopes devoted to satellite or planetary probe tracking should be equipped to make extra-Solar System planetary observations when not in use for their primary purposes. Support should be given to development of high sensitivity receivers and, if we ourselves are ever to try to communicate, to development of very high power transmitters. Such development should not be charged completely to extra-Solar System investigations. Such equipment would also be of value for further radar exploration of the Solar System to investigate, for example, the distance scale, a problem of considerable importance in launching planetary probes. (Price et al., 1959)

B. Observations from Vehicles Outside much or all of the Earth's Atmosphere.

The atmosphere of the Earth provides a stringent limit on our ability to make many kinds of critical observations of the planets. Only certain wave-length ranges of the electromagnetic spectrum will pass through the atmosphere; turbulence and other effects cause unsteady telescopic images and blurr fine image details formed by the radiation that is transmitted.

1. Observations from Balloons and Airplanes.

High-flying balloons can provide a reasonably stable platform above the portion of the atmosphere responsible for "bad seeing," at least in the visible and near-visible portions of the spectrum. Observations with telescopes of moderate size (up to perhaps 36 inches aperture), made visually or photographically, can be of considerable value in improving our knowledge of planetary features, and should be tried. Polarization studies can be adequately carried out from such a balloon platform and should be made, probably photographically. Some start in spectroscopy and photometry can also be attempted, but the great forward strides will be achieved when the observations are made from outside the atmosphere.

Balloons will permit a good test of various optical devices to detect organic molecules from satellites and probes.

2. Observations from Earth Satellites.

Satellites outside the Earth's atmosphere will provide a great deal of basic planetary information. It is likely that high resolution telescopes will not be immediately available on satellites, and therefore observations will be limited to those involving the entire surface of a planet. However, from a vantage point outside the Earth's atmosphere we can, through spectroscopy, detect small amounts of O_2, O_3, H_2O, and other important molecules in planetary atmospheres. If altitude control is very accurate, it may be appropriate to attempt spectroscopic detection of gases in certain regions of the Moon's surface where activity has been suspected. As the geometrical resolving power increases, we ca can perhaps study portions of the planetary surfaces. Clearly, the basic physical data on the properties of the Earth, cosmic-ray intensities, and so forth, are of interest as important background material to the biologists interested in extraterrestrial life. Color pictures of the Earth as seen from a satellite would be of very considerable interest to the planetary astronomer.

The satellite could provide excellent tests of apparatus designed to detect life on other planets through observations made from planetary probes.

3. Observations from Probes.

Probes to the planets and to the Moon offer the greatest possibilities to the planetary astronomer and the astrobiologist. With a close approach (but not a landing) the resolution of the planetary surface becomes great, and many different types of studies should be possible. In the case of Venus, temperature determination and atmospheric studies by spcetroscopy should have highest priority. Penetration to the surface will require that microwaves of perhaps several centimeters' length be employed.

The highest priority for biological observations of Mars made from a nonlanding probe should be given to spectrographic observations in the infrared to detect major chemical bonds of organic molecules. Important spectral lines of C-H, N-H, O-H, and C=O lie in the range 3 to 7 microns and should be looked for.

Space probes offer exceedingly interesting possibilities for investigating the physical and chemical characteristics as well as velocity distribution of interplanetary particles. Direct probe contact may be used in the process of investigations; the particle properties may be studied as a function of position in the Solar System. Such investigations could lead to important conclusions in regard to the existence of interplanetary organic material and the motion of such material throughout the system. They would also provide data on the operation of the Paynting-Robertson effect as well as the influence of solar corpuscular and ultraviolet radiation on the particles.

To both the astronomer and astrobiologist determination of the chemical composition and physical structure of a comet by probe contact offers possibilities of similar great interest, particularly since such bodies (if long-period comets are chosen for the experiments) permit examination of material representative of the outermost regions of the Solar System and even interstellar space.

Until samples of the lunar surface become available, information regarding its composition might be obtained from observations of solar X-rays scattered by the lunar surface. It is not clear whether such celestrial Debye-Scherer experiments would be feasible, but their possibility deserves investigation. It is part of the mission of this Panel to encourage the development of new methods which will facilitate the collection of evidence for the occurrence of extraterrestrial life. A partial list of principles and approaches is presented here which may aid in the construction of apparatus designed to detect organic matter or living organisms. For the purpose of this report analytical devices will be divided into (i) those which will operate in interplanetary space and planetary atmospheres, and (ii) those which will operate on and below planetary surfaces.

a. Interplanetary Space and Planetary Atmosphere. The techniques for detection of organic particles in interplanetary space and in planetary atmosphere may in part be adapted from those which had been proposed for high-altitude detection of life on Earth.

(1) Measurements of Emission Spectra. Planetary probes may carry on their exterior a device for the heating of particles passing through it, so that the presence of carbon can be judged by the emission spectrum.

(2) Measurements of Electron Scattering. The scattering of an electron beam by particles passing through it may be used as the basis of an instrument which will give information on the frequency, mass, and nature of the particles.

(3) Continuous Sampling Devices. A modification of the apparatus described in section II.B.3 can be employed in the detection of organic matter in space. The occurrence of viable organisms in interplanetary space and in planetary atmospheres might be demonstrated by a further modification of this apparatus. A sterile adhesive-coated tape is drawn past a collecting window, sprayed with nutrient media, and passed over a phototube to detect any increase in its opacity with time.

b. Planetary Surface and Subsurface Samples.

(1) Measurement of Emission Spectra. An apparatus can be built which, after landing on a planet, will collect a small sample of surface material, heat it, and determine the emission of spectral lines indicative of carbon compounds. This device can also be adapted for the examination of subsurface samples if it is combined with geochemical exploration equipment.

(2) Chromatographic Separation of Planetary Soil Components. Existing automatic devices for the chromatographic analysis of mixtures, although bulky at present, could be miniaturized and adapted to the analysis of soluble components of planetary soil. The development of such an apparatus will be of equal importance in the geochemical exploration of planetary soil.

(3) Detection of Live Microorganisms. A device is presently under construction which upon impact on a planetary surface will draw atmospheric gas and surface dust through a number of selected sterile culture media (Vishniac, 1959). Changes in acidity or turbidity are telemetered. An additional culture vessel will contain only water and be seeded with a larger sample of planetary surface material. This experiment may allow extraterrestrial microorganisms to grow in a medium resembling their natural habitat.

III. Laboratory Work

The interpretation of data collected by terrestrial observatories and those which are and will be collected by space probes, as well as the planning of experiments, requires extensive basic work which can be carried out in earth-bound laboratories. Several sample topics are listed here.

A. Simulation of Present and Primitive Conditions.

1. Formation of Organic Matter.

Experiemnts on the formation of amino acids and other organic compounds under conditions resembling primitive terrestrial conditions should be extended to systems more closely resembling probable present and past environments on moons and planets other than Earth.

2. Microbial Physiology.

Understanding of the behavior of extraterrestrial microorganisms might be furthered by the observations of terrestrial microorganisms, under simulated nonterrestrial conditions.

3. Analogous Systems of Organic Chemistry.

The possible occurrence of living organisms in nonagueous environments should be considered. A better understanding of the organic chemistry of nonaqueous systems, especially liquid ammonia, will be needed.

B. Laboratory Work Related to Spectroscopic and Polarization Data.

Spectroscopic observations of other celestial bodies are among the most promising experimental methods for the detection of extraterrestrial life. However, the value of these observations is limited by our ability to interpret them. In the near future, reflection and absorption spectra of other solar system bodies in all regions of the electromagnetic spectrum will be come available. The degree of polarization of the reflected light will be available both as a function of frequency and of the angle between the incident and reflected light. These data can provide much information concerning the chemical composition and the physical properties of the materials convering the surfaces of Solar System bodies as well as the composition of their atmosphere, provided we have (1) a thorough theoretical understanding of reflection spectroscopy in relation to absorption and (2) a library of reflection spectra of various terrestrial materials. Likewise, information must be available regarding the polarization of light reflected from various surfaces. At the present time, very little of this information is available. A large amount of investigation in these areas is definitely needed immediately.

C. Monographs to be Published Under Committee Sponsorship.

1. "Organic Matter and the Moon" - Carl Sagan (completed)
2. "The Problem of Life on Mars" - Carl Sagan (in preparation)
3. "Organic Chemistry of Liquid Ammonia Systems"-Author to be chosen
4. "A Re-examination of the Cosmobiota Hypothesis"-Author to be chosen
5. "Current Theories on the Origin of the Solar System"-Author to be chosen
6. "Organic Molecules in Cometary, Interplanetary, and Interstellar Sources" - Author to be chosen.

IV. Conclusions and Recommendations.

A. Recommendation Regarding Sterilization of Space Probes.

This Panel recommends that during the period of initial exploration of any extraterrestrial body, the probability of landing one viable organism be kept below one in 10^6. Therefore, until more information is available on the nature and distribution of organic molecules and living organisms, no landing of animals or men should be attempted on the Moon or planets, especially where there exists appreciable possibility of hard landings. A program should be initiated for biological and chemical analysis of lunar and planetary surface and subsurface materials by instrumented, unmanned, sterilized, soft-landing probes.

B. Recommendation on International Agreement.

It is pointless for a single nation to sterilize its probes; therefore we urge the Executive Council to request the President of the National Academy of Sciences to initiate international negotiations on this matter.

C. Recommendation on Establishment of Institutes.

Research programs such as those proposed in this document depend to a considerable degree upon cooperative work by scientists from a number of fields - Biology, chemistry, physics, astronomy, geophysics. The new approaches to the study of the Solar System that are vital to progress can be achieved only through the cross-fertilization of ideas that will result when imaginative scientists from such a variety of disciplines work together on common problems. The Panel on Extraterrestrial Life encourages the formation of such cross-field groups with interests in the broad problems of extraterrestrial life and the Solar System. The Panel recommends that institutes for the study of the Solar System be established at several academic institutions having staff members with interests and high competence in the requisite fields. Adequate laboratory equipment and research personnel must be provided so that work can proceed at the most rapid rate possible. Groups at different institutions might concentrate on different aspects of the problem, though some overlap of activities is inevitable and, in the long run, may prove to be useful. The various groups and individuals working in the Solar System research should remain in close communication; provision should be made for frequent intergroup visits. Contract support for Solar System Institutes should be provided on a sufficiently long time scale so that an adequate degree of stability and continuity will be established from the beginning.

Much planetary observational research needs to be done; many new observational experiments will be proposed and new data required as a result of the investigations carried on in the Solar System Institute. At present, telescope time for planetary studies is not adequate for the work proposed, especially if large telescopic equipment is required. The Panel therefore recommends that an observing station should be established with telescopic and auxiliary equipment to be used for planetary studies. The operation of this Solar System Observatory, which would be built in a place chosen especially for its favorable observing conditions, would be the prime responsibility of one group, but its facilities must be available to all Solar System investigators.

D. Recommendation on Communications and Meetings.

At a future date Panel 2 may include in its functions the sponsorship of meetings which will deal with estraterrestrial life. Such meetings may either be held in conjunction with those of existing organizations, or may take the form of independent symposia or informal discussions as the occasion demands.

E. Recommendation on Evaluation of Research Proposals.

In accordance with its stated mission the members of Panel 2 are willing to aid, collectively or individually, in the evaluation of research proposals which deal with the biology of extraterrestrial organisms. Studies of terrestrial organisms concern Panel 2 only when they bear directly on the biology of extraterrestrial life.

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VENUS AS A PLANET OF POSSIBLE BIOLOGICAL INTEREST

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A. Introduction

The existence of living organisms on the earth's surface is strong evidence for the large-scale production of organic molecules at some time in the remote past. The most likely mechanism for such syntheses is the application of energy to a mixture of methane, ammonia, water vapor and hydrogen, the probable major constituents of the early atmospheres of the terrestrial planets. Both electric discharge and ultraviolet radiation are known to be effective energy sources; the latter was probably dominant in early times because much more energy is available in solar ultraviolet radiation than in, for example, lightning. Organic molecules produced in the high atmosphere would have diffused to lower depths where ultraviolet photodissociation was less probable. In general, the diffusion time will depend critically on the planetary gravitational field. Since the Cytherean surface gravity is 0.86 the terrestrial surface gravity, and since the primitive atmospheres of Venus and earth must have been very similar, it seems likely that comparable organic syntheses occurred on Venus as on earth.

Although Venus is the nearest planet to the earth, an extensive cloud layer obscrues the surface features; as a consequence, we know nothing directly about the possible presence and evolution of organic matter on that planet. In this paper we discuss what is known and what is speculated about the Cytherean physical environment, in order to assess the possible interest of Venus for the biologist.

B. Atmosphere

The existence of a Cytherean atmosphere is shown by two phenomena, the polarization of the sunlight reflected from Venus, and the prolongation of the cusps of Venus' crescent near inferior conjunction. Merely those portions of the Cytherean atmosphere which are above the cloud layer are accessible to spectruscopic investigation. Since the cloud layer may be tens of kilometers above the surface, the only information directly available pertains to the high atmosphere of Venus. If the only portions of the terrestrial atmosphere visible from the vicinity of Venus were above, say, 40 km, it is doubtful whether CO_2, H_2O, O_3 or N_2 would be discovered on earth. This limitation must be borne in mind in attempting to describe the composition of the atmosphere at the surface of Venus.

1. Carbon Dioxide

In an attempt to discover water on Venus, Adams and Dunham (1932) found three absorption features in the photographic infrared which were subsequently identified as intercombination bands of the carbon dioxide molecule (v. Dunham, 1952). Long path-length laboratory comparison spectra (Adel and Slipher, 1934; Herzberg, 1952) indicate the amount of CO_2 above the Cytherean cloud layer is of the order of 1 km-atm, or about 2×10^5 dynes/cm^2 on Venus.

2. Carbon Monoxide and Molecular Nitrogen

Kozyrev (1954) reports observing several features in the aurora and night sky of Venus corresponding in wavelength to known emission bands of N_2, N_2^+, and CO^+. In particular he reports the λ 3914 N_2^+ band which is prominent in the terrestrial aurora and twilight airglow. From general abundance considerations and terrestrial analogy, N_2 -- which has no permitted absorption spectrum in the presently accessible wavelength region -- should be expected on Venus. Similarly, in an extensive CO_2 atmosphere, CO should be expected from the reaction

$$CO_2 + h\nu \longrightarrow CO + O, \lambda < \tag{1}$$

Nevertheless, Newkirk (1959), using superior photoelectric equipment, was unable to confirm Kozyrev's observations. Newkirk found no evidence of many of Kozyrev's strongest features, including the λ 3914 N_2^+ band; on the other hand, he found strong emission at neighboring wavelengths not reported by Kozyrev and corresponding to no known molecular emission features. Unsuccessful searches for CO absorption spectra by Kuiper (1952) place the amount of CO above the cloud layer at $<$ 100 cm-atm. At the present writing one must conclude there is no direct evidence for N_2 and CO on Venus.

3. Water Vapor and Molecular Oxygen

Cursory examination of high-dispersion spectra of Venus indicates the abundances of O_2 and H_2O do not approach that of CO_2. Because of the absorption by O_2 and H_2O in the terrestrial atmosphere, identification of small amounts of these molecules in the Cytherean atmosphere is rendered difficult. When the relative radial velocity of Venus and the earth is greatest, Doppler shifts of the order of 0.5 Å can be expected. Observations made at such times permit upper limits to be placed on the amounts of these molecules above the cloud layer. There must be L $<$ OM - atm O_2 and LI cm - atm H_2O (cf. Dunham, 1952). These limits are not very restrictive; they correspond approximately to the terrestrial atmosphere above about km altitude. It is clear that, in our present state of ignorance, biologically significant quantities of oxygen and water vapor may exist beneath the cloud layer. For comparison it may be recalled that the total amount of water vapor in the Martian atmosphere and polar cap is less than a few mm-atm. Observations of Venus from an extraterrestrial observatory are required to further refine these limits.

4. Other Molecules

Kuiper (1952) places upper limits on the abundances of the following molecules: $N_2O < 1$ meter-atm; $NH_3 < 4$ cm-atm; $CH_4 < 20$ cm-atm; $C_2H_4 < 3$ cm-atm; and $C_2H_6 < 1$ cm-atm. The hydrocarbon abundances will be of interest to us below.

5. Atmospheric Composition In the Haze Layer

The prolongation of the cusps of the Cytherean crescent near inferior conjunction and the occasional coalescence of the cusps into a ring were demonstrated by Russell (1899) to be due to scattering by particles above the cloud layer and not due to refraction. Russell showed that the height of the Cytherean atmosphere which can be seen by scattered sunlight during terrestrial twilight is about 15 km, while that responsible for cusp prolongation is between 0.79 and 1.2 km.

For layers of these thicknesses, the barometric formula

$$p = p_o e^{-h/H}$$

is approximately valid, where p is the pressure at the top of the scattering layer, p_o is the pressure at the top of the cloud layer, h is the height of the scattering layer, and $H = \frac{kT}{\overline{m}g}$ is the scale height of the atmosphere at this altitude. Setting H = 15 km, T = 285°K (v. below, section D4) and $g = 860 \text{ cm sec}^{-2}$, we find for the average molecular weight of the Cytherean atmosphere immediately above the cloud layer,

$$\overline{\mu} = 20 \qquad (2)$$

The principal uncertainty in this calculation is, of course, the assignment of the apparent height of the scattering haze layer to the scale height of the atmosphere. Since the scale height of the suspended particles is unlikely to be greater than the scale height of the supporting atmosphere, these considerations would only serve to further decrease $\overline{\mu}$. However, it may well be that Russell's value of 15 km for the height of the scattering layer corresponds to a reduction in atmospheric density by a factor larger than e, and $\overline{\mu}$ would then be greater. In any case, the computation suggests the presence of molecules of lower molecular weight than CO_2, probably N_2.

A similar calculation can be made for those particles in the haze layer immediately above the cloud layer which are responsible for cusp prolongation. Taking $0.79 \text{ km} < H < 1.2 \text{ km}$, now, with the other parameters as before, we derive

$$380 > \overline{\mu} > 250 \qquad (3)$$

This result is subject to the same uncertainties and is considered to have only heuristic value; nevertheless, its order of magnitude suggests the presence of molecules of high molecular weight in the Cytherean haze larger. It is reasonable to expect some connection between these molecules and those in the immediately underlying cloud layer.

C. Cloud Layer

1. Visual Studies

Visual observations of Venus generally show very little detail, owing to the uniformly high albedo of the cloud layer. The color of Venus is a somewhat pale lemon-yellow, as is evident during daylight telescopic observations when comparisons can be made with terrestrial clouds (Pickering, 1925). The yellowness of Venus is also observed photometrically (v., e.g., Öpik, 1956). Under the best seeing conditions, faint dark markings can be perceived on the illuminated part of the Cytherean disk. A broad band of shade adjoining the terminator sometimes appears brown (Ross, 1928). Other markings, both bright and dark, can be observed; occasionally dark bands are seen extending perpendicularly from the terminator on to the disk.

The difficulties of visual observation of Venus are illustrated by the fact that E. E. Barnard, in over a decade of regular observing of Venus, was able to see distinct markings only once. On that occasion shading was evident parallel to the terminator but not perpendicular to it (Barnard, 1897).

Some features, while varying in form and intensity, show no apparent motion over periods of weeks. Danjon (1943) and Dollfus (1955) have constructed planispheres from their visual observations; they show diffuse dark markings in relatively constant position. In some drawings there is a tendency for the dark markings to radiate from the sub-solar point. Danjon and Dollfus interpret these dark markings as surface features seen through stable gaps in the clous layer. The apparent constancy in position of the dark markings have suggested to the French astronomers that the period of rotation of Venus is equal to its period of revolution, 225 days.

a. Photographic Studies

The photographic detail visible on Venus varies inversely as the wavelength; markings are most evident in the near ultraviolet, and least evident in the photographic infrared. The classic ultraviolet photographs of Venus are those of Ross (1928) taken with the 60-inch and 100-inch Mt. Wilson reflectors. His sequence of fifty plates taken over a two-month period shows a set of extremely variable bright and dark areas, sometimes stretching band-like perpendicularly from the terminator on to the disk. Generally there is a dark shading adjacent to the terminator as in visual observations. Perhaps the most striking features of Ross' photographs are the departures of the crescent from a symmetric form. Especially where there are bright features the planetary limb protrudes markedly. On the other hand, when there are nearly dark features, the terminator takes on a serrated appearance. The bright protruding features are prominent near the apparent poles, especially the southern; they were also detected visually by early observers such as Schroter and Trouvelot who explained then as enormous mountains, sixty or more kilometers high. Ross proposed the more likely explanation that the protrusions are atmospheric haze areas surrounding the planetary poles, as exist on Mars. This, in turn, implies an appreciable temperature difference between the Cytherean equator and the Cytherean poles. It would be of great interest to determine the composition of the polar haze.

The rapid day-to-day changes in the form, intensity and position of the ultraviolet markings led Ross to question the reliability of visual observations, claiming to follow the same feature for many weeks.

Consequently, the proposed equality of the Cytherean day and the Cytherean year is subject to the same objection. The rapid variation in the markings on Venus indicates a highly convective atmosphere in which adiabatic equilibrium should obtain.

Ultraviolet photographs taken by Kuiper (1954) and by Richardson (1955) give evidence for the presence of three bright and three dark bands roughly perpendicular to the position of the terminator and extending across the entire visible hemisphere of Venus. Suggestions of these features can also be seen in Ross' photographs. The inclination of the bands to the plane of the Cytherean orbit is estimated by Kuiper at 32°, and by Richardson at 14°. The difference between these values emphasizes the observational difficulties.

Ross attributed the presence of the band structure to atmospheric circulation, as is the case for the Jovian planets. If the explanation is correct, then the speed of equatorial rotation must exceed that of random atmospheric winds (v., e.g., Öpik, 1956), giving a period of rotation of a few weeks at most. The minimum value for the period of rotation is obtained from the absence of a rotational Doppler shift at the planetary limb (Slipher, 1903). Thus, the period of rotation is probably bracketed between five and thirty days.

3. Polarization Studies

A potentially powerful method for the study of the Cytherean cloud layer is the analysis of the polarization of sunlight reflected from Venus to earth. If I and I_r are, respectively, the received intensities parallel and perpendicular to the plane defined by the sun, earth and Venus, then the degree of polarization is

$$p = \frac{I_r - I}{I_r + I}$$

If $I_r = I$, the light is unpolarized; if $I_r > I$, $p < 0$; while if $I_r < I$, $p < 0$. The degree of polarization is measured as a function of the phase angle α, i.e., the angle Sun-Venus-Earth which varies from 0 to 180°. For the integrated light from the observationally accessible part of the illuminated Cytherean hemisphere, $p(\alpha)$ has the following general form (Lyot, 1929): p is slightly negative for $0° < \alpha < 8°$, reaching a relative minimum $p(6°) \simeq -0.002$; p is positive for $8° < \alpha < 23°$, reaching a relative maximum $p(18°) \simeq + 0.015$; p is negative for $23° < \alpha < 145°$, reaching a relative minimum $p(120°)$ -0.027; and p is positive for $145° < \alpha < 180°$, reaching a relative maximum $p(155°)$ $+ 0.020$. Lyot then attempted to duplicate this run of p vs. α with various substances in the laboratory. He found that only transparent particles would give relative maxima and minima with polarization of the order of a few per cent, and that $p(\alpha)$ depended strongly on the index of refraction, n, and the radius, r, of the particles. The amplitude of the curve, but not its shape, depended on the density of particles, i.e., whether light scattering was single or multiple.

In order to approach the Venus polarization curve, Lyot was obliged to experiment with micron-size droplets in colloidal suspension. The best fit to the maxima, minima, and zeroes of the Cytherean $p(\alpha)$ was obtained for a suspension of bromonaphthalene ($n = 1.33$, $r = 2.2$ u). However, even then the fit was poor. Although bromonaphthalene had the three major maxima and minima at very roughly the Cytherean , p was positive for $0° < \alpha < 8°$. Furthermore, no amount of scaling could match amplitudes; in the final amplitude assignment, $p(8°) \simeq 0.070$ for bromonaphthalene, compared with $p(8°) \simeq 0.000$ for Venus. (It is to be emphasized that in Lyot's laboratory comparisons for the polarization curves of the Moon, Mars and Mercury near-perfect fits were obtained.) Nevertheless, because of his great difficulty in finding any other substance approaching the Cytherean $p(\alpha)$ even as well as bromonaphthalene, Lyot concluded that the particles responsible for the polarization of the light reflected from Venus were characterized by $r = 2.2\mu$, $n = 1.33$. Since the index of refraction of water droplets is 1.33, he thought water was the specific substance involved. Water itself had not been tried because it was found impossible to prepare water droplets with so small a radius; a spray of such droplets is unstable and immediately condenses or precipitates.

Dollfus (1957) has measured the variation of polarization over the disk of Venus, both in the green and in the red. The general pattern is the same at both wavelengths, but the absolute value of the degree of polarization is greater in the red. Regions of high (negative) polarization are localized in the apparent polar regions. Identification with the bright visual and photographic features in the same regions is tempting. However, there appears to be no consistent difference in p between the two poles, while the bright areas near the apparent south pole are usually more brilliant than those near the apparent north pole. Indeed, comparison of visual and polarimetric observations made on the same day shows no clear correlation and it is possible that the particles responsible for the polarization are different from those responsible for the visual and photographic cloud layer. The difference between the apparent carbon dioxide pressure (170 mb) and the apparent polarimetric pressure (90 mb) supports this possibility.

Kuiper (1957) has performed some measurements of the Cytherean polarization in the 2 micron wavelength region. Comparison with theoretical polarization curves for n = 1.33 and r between 2 μ and 4 μ, shows appreciable discrepancies. Kuiper concludes that the substance responsible for the polarization of Venus is not water.

4. Nature of the Cloud Layer

a. Water Vapor

Despite the differences between the polarization curves of Venus and of water droplets, some authors continue to quote the polariscopic observations as evidence for water on Venus. Since, as we have mentioned, the particles responsible for the polarization may be different from those responsible for the cloud layer, it is interesting that there exists other evidence against the presence of water in or above the cloud layer (Öpik, 1956; Kuiper, 1957):

(i) A fog of water particles with mean radius 2u is unstable, as Lyot observed in the laboratory.

(ii) The clouds of water droplets should be white or bluish-white. The Cytherean cloud layer is yellowish.

(iii) The albedo of Venus is higher than the expected albedo of clouds composed of very small water droplets.

(The absence of spectroscopically-detectable amounts of water vapor above the cloud layer is not evidence against water clouds. Menzel and Whipple (1955) calculate that in adiabatic equilibrium the amount of saturated water vapor above a Cytherean water cloud layer would be within the spectroscopic tolerances.)

Now, despite the foregoing evidence, it should not be forgotten that the admixture of other substances may change the properties of water clouds. For example, Menzel and Whipple (1955) have suggested that

Cytherean water is carbonated because of the high carbon dioxide partial pressure. The polarization curve, droplet stability, and albedo of carbonated water clouds are unknown.

Especially considering the high cosmic abundance of water, it seems that the presence of a dirty water cloud layer on Venus cannot be definitely excluded at present.

We must conclude only that the Venus polarization is probably produced by small, transparent droplets. The present variety of laboratory polarimetric comparisons is not great enough to degermine the refractive index, radius, or composition of the particles polarizing the light on Venus.

b. Inorganic Salts

A suggestion frequently encountered in the literature is that the clouds contain a fine powder of inorganic salts which impart the yellow coloration to the cloud layer. The powder is supposed to be produced by wind erosion at the surface of Venus and transported to the high atmosphere by convection. This concept is usually associated with the windswept desert picture of the Cytherean surface (v. Section E 7 a below).

Although there is nothing untenable in the presence of small amounts of salts in the high atmosphere of Venus, it is certainly impossible that the clouds should be composed primarily of salts. In addition, the polarization curve of such substances, in general, does not resemble the Venus polarization curve, which is, as we have mentioned, most nearly approached by transparent droplets or particles. (However, van de Hulst (1952) points out that transparent spherical quartz particles -- refractive index 1.50 and radius between 5 μ and 10 μ -- give a zero in the polarization curve near $\alpha = 23^{\circ}$, as exists in the Cytherean polarization curve.)

c. Carbon Suboxide

Groth and Harteck (v. Kuiper, 1957) have suggested carbon suboxide, C_3O_2, as the substance responsible for the cloud layer. The proposed mechanism of synthesis is photoproduction from carbon dioxide and carbon monoxide by ultraviolet light:

$$2\,CO + CO_2 + h\nu \longrightarrow C_3O_2 + O_2 \qquad (4),$$

the CO arising from reaction (1) or from volcanic exhalations. According to Kuiper (1957), carbon suboxide polymerizes when irradiated,

$$nC_3O_2 + h\nu \longrightarrow (C_3O_2)_n \qquad (5)$$

forming a slightly yellowish fine powder; although doubts as to the reality of reaction (5) have been expressed (newburn, 1959). The proposal has the merit of invoking only substances known to exist (CO_2) or expected for sound physical reasons (CO, reaction (1)). Another advantage of this hypothesis was considered to be the temperature-independence of reactions (4) and (5). At the time of the writing of Kuiper's (1957) paper, Dollfus' polarimetric observations were not readily available, and it was believed that the degree of polarization was very nearly constant over the disk of Venus. We now know (Dollfus, 1957) that p may vary by a factor of two between the apparent poles and the apparent equator, an effect most readily explained by variation of temperature with Cytherean latitude and a temperature-dependent cloud layer.

However, there are other, more direct, objections which can be raised against a C_3O_2 cloud layer:

(i) It is evident from reaction (4) that a molecule of oxygen is produced for each molecule of carbon suboxide. Yet no oxygen is observed above the cloud layer.

(ii) Carbon suboxide polymers are not transparent droplets or particles, and therefore should not be expected to give a polarization curve resembling that for Venus.

(iii) Carbon dioxide emission from Venus in the 10 u region is transmitted through the terrestrial atmosphere. There are two band systems with centers at 10.41 μ and 9.40 μ (Barker and Adel, 1933) attributed to the ν_3 ———— ($_1$, $2\nu_2$) transition. The half-widths are between ν 1040 cm^{-1} and ν 930 cm^{-1} and ν 980 cm^{-1} for the 10.40 μ features and ν 1090 cm^{-1} for the 9.40 μ feature, Lampland (1941) found the emission to be extremely variable, changing from over 60% of the Cytherean black body radiation to barely detectable amounts. Since the abundance and emissivity of CO_2 cannot be expected to vary by such amounts, the variability must be due to the occasional interposition of material which absorbs at 9.40 u and 10.41 u between the bulk of the Cytherean carbon dioxide and the earth. However, the only bands of C_3O_2 in this region with comparable strength to the CO_2 features are at 9.77 u and 11.00 μ (cf. Herzberg, 1945). The centers of the stronger feature at 11.00 u (909 cm^{-1}) is seen to be well outside the half-width of the 10.41 μ CO_2 band, while the center of the weaker feature at 9.77 μ (1024 cm^{-1}) is well outside the half-width of the 9.40 μ CO_2 band. The overlap between CO_2 and C_3O_2 seems to be too small for carbon suboxide to be the material which obscrues the 10 μ emission.

(iv) Carbon suboxide vapor has a fairly strong absorption ban system extending shortwards of λ 3350 (Thompson and Healy, 1936). No prominent Cytherean features have ever been identified in this spectral region.

These considerations make it appear unlikely that C_3O_2 is the primary constituent of the cloud layer of Venus. However, some $(C_3O_2)_n$ must be formed and it is possible that the yellow tint of the clouds arises from this source. More definite checks on carbon suboxide are to be desired. Regrettably, there are no published polarization curves for C_3O_2 at any wavelength. A specific search at $\lambda < 3350$ Å for C_3O_2 would be desirable, as would the study of other carbon-oxygen compounds possibly formed in the Cytherean atmosphere, such as C_5O_2.

d. General Considerations

We have seen that the polarization and the cloud layer may be unrelated and may have dissimilar origins. The variation of polarization and cloud markings across the disk of Venus suggests some temperature-dependence in their origins; either a temperature-dependent rate of production, or a temperature-dependent rate of presentation to view. In our discussion of the prolongation of the cusps, we found some evidence for particles of mean molecular weight equal to several hundred just above the cloud layer. Now a photochemically-induced polymerization process might be expected to give something rather similar; monomers produced in the high Cytherean atmosphere, and polymerization at lower, denser levels. Molecules of $\bar{\mu} \simeq 300$ (trimers, tetramers ?) take less than a day to diffuse to low levels in the atmosphere of Venus. In this view, the long-chain polymers would be localized in the cloud layer and below, while the short-chain polymers and monomers would have an exponential density distribution above the cloud layer.

If the precursors of the polymers all exist abundantly above the cloud layer, the photoproduction process would be temperature-independent. But if essential precursors have only low abundance above the cloud layer, and have to be supplied by convection from below, the temperature-dependence of such a process can be understood. Polymerization will be most efficient where vertical convective mass transport is also most efficient. Since the existence of a great circumpolar convective vortex is to be expected on a rotating planet and is known for the earth (Rossby, 1952), the localization of high negative polarization and extensive bright cloud systems near the apparent poles of Venus is very interesting. It suggests that the substances responsible for the polarization and for the cloud layer come -- either themselves or their precursors -- from lower altitudes.

In recent years a series of experiments have been performed on the application of energy to various gases, some of which are possible constituents of the atmosphere of Venus. The original experiments of Miller (1955) using a corona discharge in a mixture of CH_3, NH_3, H_2O and H_2 have been amplified and extended by Groth (1959) using ultraviolet light, and by Abelson (1956) and others on combinations of CH_4, NH_3, H_2O, H_2, CO, CO_2, N_2 and O_2. As long as molecules containing hydrogen, carbon, nitrogen and oxygen were available and the conditions were not oxidizing, a variety of organic molecules were produced. Upon solution in liquid water, amino acids were synthesized, but the large number of gaseous intermediaries existing before solution in water occurred remain largely unknown. Miller, who has made the most extensive analysis of products to date, has identified only 15% of the end-products (Miller, 1957); intermediaries are largely inferred only from theoretical consideration.

There appears here to be a wide variety of substances of potential relevance for the problem of the Cytherean cloud layer. A material of particular interest is a fine yellowish-brown organic polymer produced in high yield out of water solution under a number of different conditions (Miller, 1959), and which has not been further identified to date. The interest in this polymer is heightened, of course, by the visual and photometric yellow color of Venus, and the brownish tint to the dark shadings near the terminator. Experiments on the ultraviolet irradiation of CO_2, N_2 and some source of hydrogen atoms followed by spectrographic and polarimetric analysis of the products, is clearly indicated. Many products of similar experiments, already mentioned, give transparent liquid droplets at the temperatures of Venus, and have at least an _a priori_ possibility of resembling the Cytherean polarization curves; some of these, such as glycolic acid, are also yellowish.

An additional source of material for the cloud layer is hydrocarbons and other organic molecules possibly existing at the surface of Venus. This possibility is discussed in Section E2 below.

In summary, any molecule or combination of molecules proposed to explain the Venus cloud and polarization data should have the following properties:

(i) The cytherean $p(\alpha)$ curve in both the visible and the infrared.

(ii) A color index ~ 0.35 magnitudes redder than the sun (cf. Öpik, 1956), i.e., yellow coloration.

(iii) An albedo ~ 0.7 (Kuiper, 1957).

(iv) Droplet stability at the size required to explain the polarization.

(v) Strong absorption at 940 μ and 10.41 μ

(vi) No strong visible absorption features at the required concentrations, either for the molecules, their precursors, their reaction products, or subsidiary products made in their synthesis besides those features already identified in Venus spectra.

D. Temperatures

1. Bolometric Measurements

Thermocouples may be used with large telescopes to determine the total radiant energy received from Venus through the terrestrial atmosphere. To derive planetary temperatures from such data, considerable correction must be made for the transmission properties of the thermocouple cell windows and of the terrestrial atmosphere. Such measurements and corrections were performed by Petit and Nicholson (1955) who found a mean temperature of 235°K. for the daylit side of Venus from eleven observations; and of 240°K. for the night side from seventeen observations. Petit and Nicholson considered the difference between the two values to have no statistical significance, but it gives some indication of the range of error. Sinton (1953) finds bolometric temperatures within a few degrees of the Petit and Nicholson results.

Two measurements made by Petit and Nicholson on the dark side in 1927 give an average temperature of 227°K., which appears significantly lower than the mean of their measurements made during four consecutive months in 1924. Thus the possibility presents itself that secular temperature changes occur in the level of the Cytherean atmosphere responsible for the radiation detected by thermocouples. Kuiper (1957) in comparing these bolometric results with temperatures obtained by spectroscopic means (see below) concludes that the e mitting level detected by thermocouple is determined by the optical density of CO_2 and not by the altitude of the cloud layer as had been assumed by Petit and Nicholson. The bolometric temperature would then be a composite quantity, giving some weighted mean of the temperatures from various depths above and below the cloud layer. It would arise in part from the 10 u CO_2 emission. This emission is known to be variable, as has been mentioned above, and the reality of secular changes in the bolometric temperature appears more likely.

Ross (1927) took the approximate equality of night and day bolometric temperature to indicate that the period of rotation must be much less than the period of revolution; otherwise the illuminated hemisphere would grow much warmer than the dark hemisphere. This conclusion is not necessarily valid if violent inter-hemispheric convection exists. On the other hand, the most likely cause for such convection is rapid rotation itself. It would be interesting to determine whether measurable differences in bolometric temperature exist between, for example, dark equatorial and bright polar regions.

2. Rotational Fine-structure Analysis

Molecular vibration bands show rotational fine-structure, which, if a Boltzmann distribution of energy levels is assumed, can be used to derive a temperature for the molecule. If equipartition exists between rotational and translational energies, the rotational temperature so derived will be the appropriate gas kinetic temperature.

Derivation of the rotational temperature requires a relation between the intensity of the rotational fine-structure features and the population of the lower energy levels. Using an optically thick Cytherean model atmosphere which scatters radiation isotropically to obtain this relation, Chamberlain and Kuiper (1956) found a rotational temperature for the atmosphere of Venus of 285° ± 9° K. The CO_2 bands in the 8000 Å region were used.

This temperature is a mean temperature along the path traveled by the light received on earth. From considerations of pressure broadening in an adiabatic atmosphere, Kuiper (1957) derived a temperature of 320°K. for the bottom of the layer emitting the 8000 features. This temperature must arise from deeper layers in the atmosphere than the composite bolometric temperature.

Since Venus appears more and more featureless at longer and longer wavelengths, infrared light must come from higher altitudes than ultraviolet and the rotational temperature must apply to higher altitudes than the ultraviolet and visible cloud layer. If the temperature continues to increase with depth, both the surface (Kuiper, 1957) and the visible cloud layer will have temperatures higher and 320°K. (47°C). Thus many substances which are solid or liquid at the temperatures of terrestrial clouds will be liquids or gaseous at the temperatures of the Cytherean cloud layer.

If the cloud layer is at $T \simeq 320°K.$ and convective equilibrium holds down to the surface, the cloud layer need only be 4 km high for the surface temperature to be above the boiling point of water. On the other hand, there is no evidence that convective equilibrium does apply down to the surface; for all we know the clouds could be at such an altitude that below them lie temperature inversion zones or isothermal layers. At the present time the data seem insufficient for definite conclusions to be made about surface conditions from the bolometric or rotational temperatures.

3. Radio Observations

Measurement have been made of the intensity of radio emission from Venus. If one assumes *ad hoc* that the signal is due to black body radiation, a Cytherean brightness temperature can be derived from the Planck distribution. If the assumption of black body emission is correct, the brightness temperature should be independent of frequency.

Observations at 3.15 cm by Mayer, McCullough and Soanaker (1958) yield brightness temperatures for the beginning of their observing period of 620° ± 110°K.; and for the end of their observing period of 560° ± 73°K. Since the end of their observing period was near inferior conjunction, the lower temperature is consistent with the hypothesis that solar radiation is the ultimate source of energy for the emission. If the difference in temperature is statistically significant, it indicates that the 3.15 cm emission does not come from a level where violent inter-hemispheric convection exists. For a cloud temperature of 320°K. and a surface temperature of 600°K. the resulting altitude difference for a convective atmosphere is 22 km. There is no *a priori* objection to a cloud layer 22 km above the surface of Venus.

Two measurements at 9.4 cm by the same workers give brightness temperatures of 430° ± 215°K. and 740° ± 370°K., the mean of which is near the 3.15 cm temperatures. On the other hand, Gibson and McEwan (1959) at 0.86 cm derive a Venus brightness temperature of 410° ± 160°K.

If we disregard the one low measurement at 9.4 cm, the limited data available suggest an increase in apparent temperature with wavelength. This is a characteristic of non-thermal energy sources and resembles the situation recently found for Jupiter. The derived apparent temperatures then give no information baout surface temperatures.

Explanations of the radio emission from Jupiter range from volcanic shock waves to Jovian van Allen belts, but there is no acceptable theory at present. The existence of a Cytherean van Allen belt is by no means unlikely, and the proximity of Venus to the sun would increase the injection rate of charged particles over the terrestrial value. However, with this explanation, the difference in temperature at 3.15 cm between inferior conjunction and quadrature should not be significant; because from terrestrial experience, charged particles trapped in the Cytherean magnetic field should drift through 360° in longitude in a few days at most. On the other hand, if the temperature difference is significant, a lower limit on the azimithal drift time and an upper limit on the time for particles to be scattered out of the belt could be obtained. These figures would provide much information on the 'geophysical' environment of Venus.

Radio reflections from Venus would be capable of providing information on the electron density distribution in the Cytherean atmosphere. With a terrestrial value for the Cytherean magnetic field, radio emission intensities from the Venus van Allen belts could then be calculated, and compared with observation.

4. Theoretical Surface Temperatures

From the value of the solar constant and the Stefan-Boltzmann law it is easy to dereive that the mean surface temperature on the bright side of an airless planet which always keeps the same face towards the sun is

$$T_1 = \frac{392}{\sqrt{a}} \quad (1 - A)^{1/4} \; {}^{o}K. \qquad (6)$$

where a is the distance of the planet from the sun in astronomical units and A is the effective visual albedo of the planet. For a rapidly rotating planet the energy is distributed over four times as much area, so the temperature is $4^1 = \sqrt{2}$ less:

$$T_2 = \frac{277}{\sqrt{a}} (1 - A)^{1/4} \, {}^{o}K. \qquad (7)$$

For Venus, the mean value of a is 0.72 A.U.; since the eccentricity of the orbit of Venus is only 0.007 the true value of a never varies appreciably from this value. The effective visual albedo of Venus lies between 0.64 and 0.71 (Kuiper, 1957). Hence,

$$358^{o}K. > T_1 > 338^{o}K. \qquad (8)$$

and

$$254^{o}K. > T_2 > 240^{o}K. \qquad (9)$$

Since it is not definitely established that Venus is rapidly rotating, it is not possible to state with confidence whether T_1 or T_2 is more appropriate. An intermediary value nearer T_2 than T_1 is most likely.

Now, of course, Venus is not an airless planet. Black-body radiation emitted by the surface will be absorbed in the atmosphere, and reradiated to the surface. This so-called greenhouse effect should be more efficient on Venus than on the earth because of the great abundance of carbon dioxide on Venus.

A method of computing the magnitude of the Cytherean CO_2 greenhouse effect was indicated by Wildt (1940). An upper limit to the surface temperature, T_s, can be derived from the energy balance equation,

$$(1 - \varepsilon) \sigma T_s^4 < \sigma T^4 - \varepsilon \sigma T_s^4 \qquad (10)$$

in which is the emissivity of the CO_2 atmosphere, σ is the Stefan-Boltzmann constant, T_A is the effective temperature of the atmospheric layer responsible for the observed outward emission and T is the temperature on an airless planet, between T_1 and T_2. The term on the left hand side of inequality (10) is the energy escaping each second between the atmospheric CO_2 bands from each square centimeter of surface; the first term on the right hand side is the incident solar energy flux and the second term on the right hand side is the outward energy flux of the CO_2 atmosphere. Wildt extrapolated from experimental work that the value of the emissivity of CO_2 for the Cytherean atmosphere is $\varepsilon = 0.35 \pm 0.05$. From the preceding discussion it is clear that the appropriate value of T_A is Nicholson and Petit's composite bolometric temperature, 235°, to 240°K. In Table I we have computed the surface temperature resulting from the range of the discussed parameters.

Table I

Surface Temperatures on Venus

in °K.

	Slowly Rotating		Rapidly Rotating	
	$T_1 = 338^\circ$K.	$T_1 = 358^\circ$K.	$T_2 = 240^\circ$K.	$T_2 = 254^\circ$K.
= 0.30	368	392	261	277
= 0.40	383	407	271	287

It is clear that the period of rotation of Venus is the critical factor in the determination of the surface temperatures. If the period of rotation is of the same order as the period of revolution, so $T \simeq T_1$, then on the bright side the surface is at or a little above the terrestrial boiling point of water; on the dark side T_s will be much lower, determined by interhemispheric convection. If, on the other hand, the period of rotation is much shorter than the period of revolution, so $T \simeq T_2$, then the surface temperature is very similar to that on earth, the higher albedo compensating for the smaller distance to the sun and the CO_2 greenhouse effect.

In the absence of vast clouds of water vapor, there seems no appropriate substance to initiate a more efficient greenhouse effect and so raise the temperature above the values of Table I. It $T_6 \simeq 280^\circ K.$, the black-body emission is centered around 10 μ, where water vapor is transparent, but if T_s is $\simeq 400^\circ K.$, the Wien peak is at 7.3 μ, which is within the very strong water vapor absorption band centered near 6 μ. Thus, if the planet is rotating rapidly, the presence of water vapor should raise the surface temperature very little; but if the planet rotates slowly, vast water clouds could raise T_s well above the terrestrial boiling point of water in the illuminated hemisphere. Hence, it appears that if the 3.15 cm brightness temperatures refer to surface black-body emission, Venus must have vast water clouds and must be rotating slowly. On the other hand, if Venus has no vast water clouds, the radio emission must be non-thermal.

In the case of slow rotation the possible existence of life on the bright side of the Cytherean surface would be marginal; better conditions might be found on the dark side or near the terminator. But if Venus rotates rapidly, it would appear that the surface temperatures are near optimum for contemporary terrestrial organisms; and in this case it is much easier to imagine the existence of indigenous Cytherean life-forms. Therefore, detailed investigation of the temperature distribution and cloud convection of Venus is urgently needed in order to determine accurately the period of rotation. At the present writing, the existence of a banded cloud pattern (see section C2 above) and the equality of day and night bolometric temperatures suggest rapid rotation, and hence $T_s \simeq 10^oC$.

E. Nature of the Cytherean Surface and the Origin of Carbon Dioxide

1. The Urey Equilibrium

Urey (1952) proposed that on a planet having both surface silicates and surface water the carbon dioxide partial pressure is maintained by equilibrium reactions such as

$$M_gSiO_3 + CO_2 \underset{\longleftarrow}{\xrightarrow{H_2O}} M_gCO_3 + SiO_2 \quad (11)$$

and

$$CaSiO_3 + CO_2 \underset{\longleftarrow}{\xrightarrow{H_2O}} CaCO_3 + SiO_2 \quad (12)$$

If, at equilibrium, the CO_2 concentration increases, e.g., by volcanism, the rate of carbonate sedimentation also increases. On the other hand, if the CO_2 concentration decreases, the reaction reverses, and silicate deposition increases.

The partial pressures of CO_2 on the earth and Mars are within an order of magnitude of the room temperature equilibrium pressures (10^{-5} atm) resulting from reactions (11) and (12). Rubey (19) has criticized the Urey equilibrium on the grounds that it is an oversimplified abbreviation of a complex series of geochemical processes. Nevertheless, there seems little doubt that the overall effect is as if reactions (11) and (12) were operative (cf. Hutchinson, 19); the agreement of the Martian and terrestrial partial pressures with the equilibrium partial pressure is strong affirmative evidence.

Now the partial pressure of CO_2 above the Venus cloud layer, 0.02 atm, $\gg 10^{-5}$ atm (cf. Section B1 above). This apparent failure of the Urey equilibrium on Venus is a potential source of information on Cytherean surface chemistry. The following explanations are possible:

a. Absence of Water Catalysis

Urey (1952) originally proposed that the high Cytherean CO_2 abundance was due to an absence of the water required to catalyze reactions (11) and (12). In this view few open bodies of liquid water exist on the surface of Venus, and the lower atmosphere is very dry. The surface would perhaps be best described as a wind-swept desert.

b. Insufficient Exposure of Surface Silicates

A second possibility is that all exposed silicates have already reacted to carbonates and no further silicates are in contact with carbon dioxide. Two ways of accomplishing this are as follows:

(i) Universal ocean

If nearly all the Cytherean surface were water- covered there would be little opportunity for reactions (11) and (12) to take place (Menzel and Whipple, 1955). In this view the surface of Venus is primarily an ocean of carbonated water, with perhaps an occasional limestone-encrusted island. Surface temperatures would have to be much less than the boiling point of water. However, since cold traps might exist between the surface and the visible cloud layer, a high surface water vapor pressure would not necessarily imply spectroscopically-detectable amounts of H_2O above the clouds. Naturally, this view is correlated with a water cloud layer.

Oparin and Fesenkov (1957) mention observations of Barabashev indicating specular reflection of sunlight from the Cytherean surface. The reflected image would be distorted and diffused by the intervening atmosphere and cloud layer. The existence of such a phenomenon would be strong evidence for the universal ocean. Similar observations have been reported for decades, but there have always been considerable reservations about their reliability (cf. Ross, 1928). This is an area meriting further study.

(ii) Carbon dioxide excess

If the quantity of CO_2 were so vast that reaction with all surface silicates still left an appreciable excess, the high carbon dioxide concentration could also be understood 'Urey, 1959). One explanation for such an excess would be extensive recent vulcanism; it is not impossible that the Venus radio emission is of volcanic origin. In this view the surface of Venus has appreciable water and features extensive igneous geomorphology.

2. Hydrocarbon-Water Equilibrium

Another explanation of carbon dioxide excess is that so much CO_2 was produced in primitive times that the rate of subsequent silicate exposure by weathering has been too small to appreciably reduce the CO_2 abundance.

Both water and hydrocarbons must have been plentiful during the early history of the terrestrial planets. Oxidation of hydrocarbons must have resulted. Perhaps the most likely mechanism is the photodissociation of water vapor in the high atmosphere, escape of hydrogen to interplanetary space, and subsequent reaction of the resulting molecular oxygen with surface and atmospheric hydrocarbons.

From cosmic abundance considerations water should initially be far more plentiful than hydrocarbons and the planetary atmosphere eventually should make the transition from reducing to oxidizing. Such appears to be the case for the earth. However, Hoyle (1955) has suggested that on Venus the abundance of hydrocarbons exceeded that of water. Oxidation of surface hydrocarbons would have proceeded until all available water was depleted, thereby producing vast amounts of carbon dioxide in the process. In this view the surface of Venus is covered with organic molecules in various states of oxidation. The water abundance would be limited by the production rate of juvenile water, and by the diffusion rate of water into that level of the Cytherean atmosphere where ultraviolet photodissociation can take place. The amount of surface water vapor would be small, but possibly not negligible. In this case, a contribution of partially oxidized hydrocarbons to the cloud layer should be expected; but the hydrocarbon abundance above the cloud layer must be less than the limits found spectroscopically by Kuiper (See Section B4). Eventual investigation of the Cytherean surface chemistry would yield invaluable information about the early history of the solar system in all cases, but especially if molecular relics of primitive conditions could be found.

3. Other Considerations of the Surface

a. Atmospheric Pressure

Comparison of the degree of polarization of sunlight reflected from Venus in the green, with that reflected in the red, indicates a total atmospheric pressure above the cloud layer of about 90 millibars (Dollfus, 1957). If we take the temperature of the cloud layer at 238°K. (see Section D1 + D2) and assume convective equilibrium to the surface, the surface atmospheric pressure can be computed from the surface temperature by

$$P_s = P_A \, (T_s \; T_A) \, \frac{\gamma}{\gamma - I} \qquad (13)$$

where the subscripts s and A refer to the surface and atmosphere, respectively; and where γ is the ratio of specific heats. Taking $P_A + 90$ mb, $T_A =$ 238°K., $\gamma = 1.4$, and $T_s = 280$°K. (See Section D4) in eq. (13),

$$P_s = 160 \text{ mb};$$

while with the same values of P_A, T_A and γ, but with $T_s = 400^oK$. (See Section D4),

$$P_s = 560 \text{ mb.}$$

The corresponding heights of the cloud layer are 3.2 km and 12.5 km, respectively. If the cloud layer temperature had been taken at 285°K. or 320°K. (see Section D2,) similar surface pressure would have been obtained; although for an adiabatic atmosphere T_s could not then be 280°K. The presence of isothermal or temperature inversion regions between the cloud layer and the surface would serve to increase P_s and the height of the cloud layer. In any case, the surface atmospheric pressure on Venus is probably somewhat less than 1 atmosphere. Since Venus has lower gravity and probably higher exosphere temperature than Earth, the rate of escape of molecules from the Cytherean atmosphere should be slightly greater than from the terrestrial atmosphere. Therefore, it is reasonable to expect P_s to be somewhat smaller on Venus than on Earth.

b. The Radiation Environment

In the absence of atmospheric constituents with high absorption coefficients in this region of the spectrum, ultraviolet radiation longward of about λ 2000 should penetrate to the Cytherean surface. Carbon dioxide will absorb effectively shortward of λ . In the absence of molecular oxygen, ozone should not be present. But in an atmosphere with so much CO_2, SO_2 may be present, especially if there exists extensive vulcanism. Sulfur dioxide absorbs shortward of λ 3000, as O_3 does, and should be looked for spectroscopically as Kuiper has done for Mars. If appreciable organic matter exists at the surface, organic gases above the surface should absorb all incident ultraviolet light. For example, a few cm-atm.

of acetaldehyde, CH_3COH, would be as effective in this regard as the terrestrial ozone layer.

c. General Remarks

We have come a long way in our knowledge of Venus in the last half-century. Forty years ago, one could find assertions that 'everything on Venus is dripping wet....A very great part of the surface of Venus is no doubt covered with swamps....The constantly uniform climactic conditions which exist everywhere result in an entire absence of adaptation to changing exterior conditions. Only low forms of life are therefore represented, mostly no doubt belonging to the vegetable kingdom; and the organisms are nearly of the same kind all over the planet.' (Arrhenius, 1918). Since 1918 we have learned nothing which definitely disproves these assertions, but we have learned a great respect for the state of our ignorance.

The extent of present knowledge of the Cytherean surface is indicated by the two extreme hypotheses: the arid planet-wide desert, and the universal ocean. At this writing there is no convincing argument against either hypothesis. Ultraviolet spectroscopy and photography from above the earth's atmosphere is desirable, but decisive information will probably have to await the forthcoming Venus probes.

F. Biological Considerations

1. Possibility of Indigenous Cytherean Organisms

Urey (1959) has emphasized that however the present Cytherean carbon dioxide arose, its presence is strong evidence for the existence of water in the early history of Venus. General analogies with the primitive earth (cf. Section A; Oparin, 1938, Sagan, 1957) suggest that the origin of life on Venus may have paralleled the features of, and been contemporaneous with, the origin of life on earth.

Survival to present times crucially depends on two factors -- temperature and water. If the surface temperatures are not much above, say, 400°K., and if there exists some surface water or water vapor, then there would seem to be a substantial probability that the first soft-landing probes will find evidence of indigenous Cytherean life-forms. The possible absence of oxygen or presence of substances poisonous to higher terrestrial organisms cannot be considered a fundamental objection; these contingencies appear to be well within biological capabilities for adaptation.

2. Venus as an Ecological Niche for Terrestrial Organisms

From what has been said, it should be clear that the surface conditions on Venus may be suitable for many terrestrial life-forms. Many plants prefer the high carbon dioxide tensions available there. The Soret bands of chlorophyll would receive appreciable light in the blue due to the greater transparency of the Cytherean atmosphere at short visible wavelengths. The possible ecological suitability of Venus has two correlaries of interest:

a. Biological Contamination

The accidental introduction of terrestrial organisms into the Cytherean environment might have disastrous consequences (CETEX, 1958, 1959; Lederberg and Cowie, 1958).

On the one hand, if there is no indigenous Cytherean life, but appreciable organic matter, the deposited organisms would reproduce at a rate limited only by the availability of metabolites. In the absence of predators and competitors, depletion and confusion of significant amounts of surface organic matter might occur, with the consequent loss of valuable data on the early history of the solar system and on prebiological organic syntheses.

On the other hand, if there is indigenous life on Venus, the interaction of deposited and indigenous organisms might cause Cytherean pandemics and seriously upset the existing ecologies. The loss of information would also be very great in this case.

Even if dead microorganisms were introduced, the possibility exists that subsequent expeditions would confuse them with the remains of primitive indigenous organisms, or even that they would serve as templates for reproduction in a Cytherean organic milieu.

The consequences of biological contamination are clearly very grave, and great care should be taken to sterilize and decontaminate all space probes likely to impact on Venus. Fortunately, the necessary precautions have already been outlined (cf. Davies & Comuntzis, 1959); and if introduced early enough into vehicle and package programming they should not cause serious delays in probe firing schedules.

b. Biological Colonization

At some time in the future, sterilized unmanned instrumented soft-landing probes will have given us much information about the surface conditions and, conceivably, the biology of Venus. It may then be desirable to deliberately introduce terrestrial organisms into the Cytherean environment, either to modify the environment for human ends, or to extend the cosmic availability of the information contained in the terrestrial genetic material. Such a step, of course, should be taken only after the most serious weighing of all possibilities, both scientific and ethical;

but in preparation for such an eventuality provision should be made for the extended preservation in the living state of all Cytherean organisms which would be affected. The morphology, biochemistry, genetics and ethology of possible Cytherean organisms can be now only dimly surmised; but their study cannot fail to have the profoundest influence on all areas of human knowledge.