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Moondust

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

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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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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 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.

References and Notes

1. D. H. Menzel, *Natl. Geographic Mag.* 113, 277 (1958).
2. S. Arrhenius, *Worlds in the Making* (Harper, New York, 1908).
3. H. C. Urey, *The Planets: Their Origin and Development* (Yale Univ. Press, New Haven, Conn., 1952).
4. G. P. Kuiper, Ed., *The Earth as a Planet* (Univ. of Chicago Press, Chicago, 1954).
5. "Les particules solides dans les astres," *Colloq. intern. d'astrophys. No. 6*; "Les molécules dans les astres," *Colloq. intern. d'astrophys. No. 7* (Inst. d'Astrophys. Univ. de Liège, Cointe-Sclessin, Belgium, 1954; 1956).
6. A. I. Oparin, *The Origin of Life on the Earth* (Academic Press, New York, ed. 3, 1957).
7. S. Miller, in *Reports on the International Symposium: The Origin of Life on the Earth* (Akad. Nauk. S.S.S.R., Moscow, 1957), pp. 73–85.
8. E. M. Burbidge *et al.*, *Revs. Modern Phys.* 29, 547 (1957).
9. J. Dufay, *Galactic Nebulae and Interstellar Matter* (Philosophical Library, New York, 1957).
10. J. A. Hynek, Ed., *Astrophysics, a Topical Symposium* (McGraw-Hill, New York, 1951).
11. D. R. Bates and L. Spitzer, *Astrophys. J.* 113, 441 (1951).
12. F. Hoyle, *Frontiers of Astronomy* (Mentor, New York, 1957).
13. F. L. Whipple, *Astrophys. J.* 113, 464 (1951).
14. H. Petterson, *Nature* 181, 330 (1958).
15. G. Nueller, *Geochim et Cosmochim. Acta* 4, 1 (1953).