THE ORIGIN OF LIFE IN A COSMIC CONTEXT

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Abstract. The significance of examinations of the planets and their satellites, asteroids, comets and the interplanetary medium for the origin of life is assessed. It appears that the deprovincialization of biology must await the search for extraterrestrial life.

In our present profound ignorance of exobiology, life is a solipsism. So far as we know, all organisms on the Earth use nucleic acids for self-replication. All organisms use proteins for enzymatic catalysis. Small molecules such as porphyrins and nucleoside phosphates are used over and over again for functionally diverse tasks. Of the billions of possibilities, life seems to have used around 50 simple molecular building blocks for all its chemical functions. There are even remarkable commonalities in such structures as the $9+2$ cross-sectional structure which is present from the flagella of protozoa to the spermatazoa of human beings. Some of these chemical or functional units – for example the particular porphyrins used in contemporary biology – may be mere historical accidents. The substitution of vanadium or niobium for iron in the circulatory fluids of ascidians; the rejection of sunlight in the frequency range where it is most plentiful by chlorophyll; and the development of accessory photosynthetic pigments to absorb in the yellow/green while chlorophyll remains the ultimate photon acceptor all seem to speak in favor of this idea. On the other hand, nucleic acids may be a unique molecule for self-replication; at least we know of no alternatives to date. But these arguments are weak. There is no aspect of contemporary biology in which we can distinguish the evolutionary accident from the biological *sine qua non*. We cannot distinguish the contingent from the necessary. The time scale of the evolutionary process is so long that it is unlikely that such questions will ever be answered by terrestrial experimentation. For this reason biology suffers from a deadening provincialism, an inevitable parochialism – like the physics of falling bodies before Newton showed that the same laws applied to the motion of apples in England, the moon in circumterrestrial space and the planets about the Sun. The deparochialization of biology can only come in the same way: by comparisons with examples elsewhere, by the pursuit of extraterrestrial life.

Not only does the understanding of the evolution of living systems after the origin of the first self-replicating system require investigations in an astronomical context, but understanding the origin of the molecular precursors of life does so as well. The universe is mostly hydrogen, oxygen, nitrogen, carbon and noble gases. Biology is mostly hydrogen, oxygen, carbon, nitrogen, phosphorous and sulfur. Materials which are of major abundance in the crust of the Earth such as iron and silicon are relatively underabundant and unimportant for cosmic abundances and for biology.

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TABLE I

Comparison of the relative abundances of the elements in the cosmos, in biology, and in the crust of the Earth

Atom	Universe	Life (terrestrial vegetation)	Earth (crust)
Hydrogen	87	16	3
Helium	12	0	0
Carbon	0.03	21	0.1
Nitrogen	0.008	3	0.0001
Oxygen	0.06	59	49
Neon	0.02	0	0
Sodium	0.0001	0.01	0.7
Magnesium	0.0003	0.04	8
Aluminum	0.0002	0.001	2
Silicon	0.003	0.1	14
Sulfur	0.002	0.02	0.7
Phosphorus	0.00003	0.03	0.07
Potassium	0.000007	0.1	0.1
Argon	0.0004	0	0
Calcium	0.0001	0.1	2
Iron	0.0007	0.005	18

After Sagan (1970).

There is at least a qualitative sense in which the atomic constitution of life on Earth is closer to the cosmic abundances of the elements than it is to the elemental composition of the planet on which it resides (see Table I). It is the Earth which has an anomalous chemistry, the reason being that the light elements were able to escape from the Earth during its formation and hydrogen has been able to escape since. The Jovian planets – Jupiter, Saturn, Uranus and Neptune – have much larger accelerations due to gravity and much colder exosphere temperatures. They have retained their original cosmic abundances. Their atmospheres are comprised – apart from noble gases – of the fully saturated hydrides of the cosmically most abundant atoms: H_2, OH_2, CH_4, and NH_3. This is also the presumptive composition of the primitive terrestrial atmosphere at the time of the origin of life. Other constituents of the early atmosphere probably included N_2, CO_2, and H_2S. An argument for ammonia in the Earth's atmosphere up to 2×10^9 yr ago which is independent of direct appeals to cosmic abundances has recently been put forth; NH_3 appears to be required in mixing ratios $\sim 10^{-5}$ to keep the Earth's temperature above the freezing point of water through the atmospheric greenhouse effect to offset the lower luminosity of the Sun (Sagan and Mullen, 1972). As Abelson (1957) and many others have shown, organic compounds are produced if and only if the net conditions are reducing. The production of the simplest molecular precursors of life depends upon the overall cosmic abundances of the elements.

Other astronomical, paleontological and geological evidence argues pursuasively that the origin of life happened quickly. There seems little doubt that the Earth was populated by a wide variety of microorganisms in the period between 2 and 3×10^9 yr ago; and at least moderately convincing evidence for organisms like bacteria and blue-green algae as long ago as 3.4 or 3.5×10^9 yr ago (Schopf, 1970). In the context of the origin of life, such organisms are highly evolved. A long period of time is required for the evolution of such organisms from the atmosphere and waters of the primitive Earth. Also there is no reason to think that the oldest organisms have been found; there is a clear observational selection effect which makes it increasingly difficult to discover older and older organisms. At the same time, the oldest rocks on the Earth are about 4×10^9 yr old, as are the oldest rocks on the Moon returned by the Apollo lunar missions. In the lunar chronology revealed by radioactive dating (Wasserburg, 1973) there is clear evidence for a set of catastrophic events which reset radioactive clocks on the Moon no later than 3.9 or 4.0×10^9 yr ago. The most likely such event is the final sweeping up by the Moon of large objects and miscellaneous debris which had been formed in the early solar system. In fact, the regularity of the planetary and satellite orbits which is observed in the solar system today is very likely the result of such a collisional natural selection in which only objects not on intersecting orbits survive (see, for example, Dole, 1970; Lecar and Franklin, 1973). Some of these objects may have been stored for a few times 10^8 yr in lunar orbit (Reid, 1973). It seems unlikely that the Earth would have been protected from these catastrophes which were inflicted upon the Moon, and it is as least plausible that the Earth – because of endogenous volcanism as well as exogenous impact melting – was unfit for the origin of life until about 4.0×10^9 yr ago. That leaves only a few hundred million years for the origin of life, perhaps much less. But if the origin of life happened fast, the origin of life is probably easy.

This conclusion is to some extent borne out by the enormous success of laboratory experiments on the recreation of primitive environments and the production of prebiological organic molecules as is discussed elsewhere in this Symposium. Typical experiments require only a few days for the production of significant quantities of organic molecules. A wide range of amino acids, nucleotide bases, five and six carbon sugars and their polymers are produced under rather general cosmic reducing conditions. The yields are startlingly high. For example, from the long wavelength ultraviolet quantum yields and the early luminosity of the Sun, some 200 kg cm^{-2} of amino acids would have been produced in the first 10^9 yr of Earth history (Sagan and Khare, 1971a). This is more carbon than there is in the sedimentary column and suggests that the production of organic molecules – at least of certain types – may have been precursor-limited and destruction-rate-limited rather than production-rate-limited. The carbon content of the sedimentary column, now in the form of carbonates, is the equivalent of 50 to 100 atmospheres of carbon dioxide or some tens of atmospheres of methane. But the synthetic rates seem to be so high that most of this carbon, once outgassed, must have been in the form of organic compounds on the early Earth. Since there is nothing in such calculations unique to the Earth – liquid water clouds for example are expected throughout the outer solar system – such highly efficient organic synthetic processes must be common throughout the universe.

TABLE II

Comparison of interstellar and cometary compounds

Microwave identifications of interstellar molecules	Optical identifications of cometary radicals
OH, H_2O	O, OH, OH^+
CO	CO, CO^+, CO_2^+
NH_3, HN_3	NH_2, NH, N_2^+
CN, HCN, HNC	CN
HCHO, CH_3CN, HC_2CN, HC_2CH_3, many other organics	CH, CH^+, C_2, C_3

TABLE III

Simple organic compounds of H, C, N, and O in the interstellar medium and in experiments on prebiological organic chemistry

	Interstellar microwave or optical identification	Laboratory identification
CO	√	√
C_2H_2	No accessible lines	√
C_2H_4	No accessible lines	√
C_2H_6	No accessible lines	√
HCHO	√	√
CH_3CHO		√
HCN, HNC	√	√
CH_3CN	√	√
NH_3	√	
HNCO, HCNO	√	
CH_3OH	√	√
C_2H_5OH		√
HC_2CN	√	√
HC_2CH_3	√	
HC_2NH_2		
HC_2CHO		
NH_2CHO	√	√
CH_3NH_2		
HCOOH	√	√
CH_3COOH		√
⋮		
Higher nitriles and polynitriles		√
Sugars		√
Amino acids		√
Nucleotide bases		√
Porphyrins	?	√
Polycyclic aromatics		√
'Intractable polymers'		√

Where the table shows no entry, the molecule in question has not been reported.

Radio astronomical line searches have uncovered a large number of simple organic compounds in interstellar space. These compounds closely resemble those formed in experiments in prebiological chemistry and those deduced in comets, as Tables II and III indicate. Particularly because of the intense interstellar UV radiation field, the lifetime of such molecules is measured in centuries. Because of the low densities in the interstellar medium, the molecules in question cannot be produced under typical interstellar conditions. The most likely sources of these molecules are the interstellar grains, in which case the grains must have a significant organic component. Organics may be made on the grains or the grains may themselves be ejected during early stages of solar system formation around other stars – either of which indicates the ubiquity of organic compounds in the galaxy. Because of the high temperatures attendant to planetary formation, interstellar organic molecules are unlikely to contribute to the origin of planetary life; because of the low interstellar densities, interstellar indigenous biology appears to be an exceedingly remote contingency (Sagan, 1972).

The origin of simple organic compounds and their polymers, including molecules resembling polynucleotides and polypeptides, is obviously relevant for the origin of life. But it is not quite the same thing as the origin of life. If polypeptides were weakly self-replicating or polynucleotides were weakly catalytic, the production of such molecules might be the same as the origin of life. In the absence of evidence for such cross-functional properties, it is clear that the critical unresolved problem in the origin of life is the origin of the genetic code. The genetic code that we note today is what the molecular biologists unselfconsciously describe as 'universal'. By this they mean that all organisms on the Earth share a common dictionary for converting polynucleotide information into polypeptide information. The use of the word 'universal' in this inappropriate context is itself an indication of the provincialism of biology. Do we have the twenty biological amino acids involved in proteins today because they perform functions which no other amino acids will perform; or because of some frozen evolutionary accident? An early genetic code much simpler than the present one would certainly have strong selective advantage even if it were substantially less accurate and more ambiguous in its coding than the present code.

A related problem is the fact that the present code is a triplet code. A primitive code could very well have been singlet or doublet. But singlet or doublet codes cannot accommodate twenty amino acids and various punctuation marks. At the same time there seems no way to convert from an initial single or doublet code to a triplet code without losing all of the painfully acquired genetic information of the preceding evolutionary process. Why therefore is the present code a triplet code? Some new insights into these questions have recently been provided by L. Orgel (these proceedings) but they remain largely unresolved. It is only the discovery and characterization of extraterrestrial life – even if very 'simple' forms are found – which can deprovincialize biology. This is the reason for the great importance of the biologically oriented experiments on the Viking Mars landers, even though such experiments are hardly the most general and sensitive conceivable experiments for the purpose. And if after an extended biological reconnaissance of Mars the planet proves lifeless, we must face a different problem critical for studies of the origin of the life: why, on two nearby planets with rather similar conditions, did life arise on one and not the other?

Just as the primitive transcription of the genetic code may have been much cruder than the contemporary code, primitive catalysis could have been much less efficient than contemporary enzymatic catalysis and still provide significant selective advantage over competing organisms which had even less efficient catalyses. For example, the functional group or active site of many contemporary enzymes is only five amino acids long, although these amino acids need not be (in fact none of them are) in consecutive order in the primary structure of the protein. But with 20 amino acids there are only about 3×10^6 possible pentapeptides. It is therefore conceivable that very short strands of primitive polynucleotides, crudely directing the synthesis of a small number of simple polypeptides nearby, could have provided a great variety of biochemical functions. The critical requirement is that the accuracy of replication be high enough that advantageous phenotypes previously selected for are not rapidly lost to subsequent generations by low-accuracy replication (see M. Eigen, these proceedings).

While amino acids are made in very high yields and nucleosides in at least modest yields in such experiments, there are a wide range of other molecules also produced. In seeking to understand the origin of life on Earth, we naturally are biased towards the molecules with which we are familiar. But very little attention has been paid to characterizing and contemplating the alkanes, the polycyclic aromatic hydrocarbons, and the wide variety of other molecules which consititute some tens of percent by mass of the total yield in such experiments. Might these molecules provide alternative starting points for self-replication and catalysis in alternative biological systems? Might it be for example that the nucleic acid/protein way of life is best fit for temperatures roughly in the terrestrial range, where hydrogen bonds have just the right energies to provide just the right compromise between inflexible stability and extreme fragility? On very low temperature worlds might van der Waals forces play the role of hydrogen bonds on Earth? On high temperature worlds, might the lower energy ionic or covalent bonds play the role of hydrogen bonds?

The carbon content of the Earth's crust, mentioned above, corresponds roughly to some 10^{-4} to 10^{-5} of the mass of the Earth. Approximately one percent of meteorites falling on the Earth are carbonaceous chondrites. Several percent by mass of carbonaceous chondrites are organic matter, largely aromatics and straight-chain alkanes but with a significant content of amino acids, possibly nucleoside bases and other molecules of terrestrial biological interest (see for example Anders *et al.*, 1973). Thus the carbon content of meteorites which fall on the Earth is of the same order as (or perhaps an order of magnitude larger than) the carbon content of the Earth itself. But recent investigations have shown that the ordinary chondrites, among the most abundant meteorites to be found on the Earth, do not correspond in their photometric or polarimetric properties with the most abundant main belt asteroids (Egan *et al.*, 1973; Chapman and Salisbury, 1973). Instead the chondrites appear to resemble such Apollo objects as Icarus. The Apollo objects lie in orbits which cross the orbit of Mars. One tantalizing possibility, stressed by Öpik, is that the Apollo objects are not strayed asteroids but, rather, dead cometary nuclei. It may therefore be that the ordinary and carbonaceous chondrites are of cometary rather than of asteroidal origin, and that their content of organic matter is not typical of the asteroid belt, but rather of the interstellar environment in which comets mainly reside and may have been produced. Because of their Mars-crossing orbits, they would impact the Earth with a much greater frequency than their mere numbers would imply. However I stress that this is a speculation; and that other interpretations of the data are possible.

While an *in situ* search for life on Mars is the most direct method at our command for deparochializing biology, it may not shed much light on the prebiological organic syntheses which preceded the origin of life. Primordial organic molecules are unlikely to have survived for several $\times 10^9$ yr on the Martian surface or immediate subsurface. The place for such investigations is the outer solar system. The Jovian planets and at least one of their satellites – Titan, the largest moon of Saturn – have reducing atmospheres and energy sources reminiscent of those conjuctured to have played a major role in the early production of organic molecules on the primitive Earth. While the upper clouds of Jupiter are at temperatures of the order of 120° K, the atmosphere is convective and the adiabatic lapse rate implies that, less than 100 km below, typical terrestrial surface temperatures are reached. While methane, ammonia and hydrogen are known to exist on Jupiter, water has not been detected. But all the water would be condensed out at 120K and there is no way for oxygen atoms to have escaped from Jupiter. It seems very likely that near the 280K level in the Jovian atmosphere there is an extensive cloud of liquid water (or, because of the presence of ammonia, ammonium hydroxide solution). A range of energy sources for organic synthesis are available in the Jovian atmosphere, including solar ultraviolet radiation, the precipitation of weakly relativistic particles from the Jovian van Allen belts; and electrical discharges in the clouds. There thus seems little escape from the conclusion that organic molecules fall from the skies of Jupiter like manna from Heaven. Similar lines of argument apply to Saturn, Uranus, Neptune and Titan.

The belts and great red spot of Jupiter, the equatorial zone of Saturn, and Titan have a similar and very red coloration (see, for example, McCord *et al.*, 1971). In the case of the Jovian reddish colored regions, we must ask why the coloration is not uniformly distributed over the disc. The most likely explanation is preferential production. This production might be from the outside or from the inside. The only plausible reason for preferential production of red chromophores from the outside would be precipitation from the van Allen belts; but the mirror points of the Jovian trapped charged particles correspond neither to the Great Red Spot nor to the North Equatorial Belt. It seems much more likely therefore that the red chromophores are produced at depth and carried up or exposed to view in these locations. Indeed, the Red Spot appears to be a great storm system propagating high into the Jovian atmosphere and carrying deep material up by convection within it (Sagan, 1971a). It is therefore of some interest that when the Jovian atmosphere is simulated and energy sources applied, a complex mixture of organic molecules with an overall reddish coloration is produced (Sagan *et al.*, 1967; Woeller and Ponnamperuma, 1969; Sagan, 1971b; Sagan and Khare, 1971b; Khare and Sagan, 1973). Upon acid hydrolysis this polymer yields amino acids in great abundance (Sagan and Khare, 1971b). It also contains high carbon number, straight chain alkanes with amino and probably hydroxyl and carbonyl groups; there are similarities between this polymer mixture and organic compounds recovered from carbonaceous chondrites and precambrian sediments (Khare and Sagan, 1973). The visible and near UV transmission spectrum of the polymer shows its optical depth to be redder than λ^{-2}. Somewhat redder polymers would be able to explain the visible and near UV reflection spectrum of the Jovian planets and Titan as a function only of the polymer/gas ratio. The near UV absorption coefficient is of the order of 10^3 cm^{-1}.

Because of their atmospheric structures and high gravitational accelerations, the Jovian planets are not easy objectives for *in situ* organic chemistry by space vehicle. Titan is a much more accessible objective. Moreover the carbon-to-hydrogen ratio on Titan is likely to be larger than for any of the Jovian planets. We know directly from polarimetric observations (Veverka, 1973; Zellner, 1973), and indirectly from requirements for a Titanian greenhouse effect (Sagan and Mullen, 1972; Sagan, 1973a; Pollack, 1973), that in the visible and UV we are observing an almost completely cloud-covered satellite, probably of similar composition to the reddish polymers described above. The surface pressures are probably at least a few tenths of a bar and the surface temperature perhaps 150K. Temperatures as high as 200K are not excluded. However the pace of plans for examination of Titan is not breathless. Apparently the earliest time for flyby spectroscopic examination of Titan from a distance of a few tens of thousands of kilometers is 1981, and a Titan landing mission probably not until many years after that. But by the late 1980's or early 1990's direct investigations of the organic chemistry of the outer solar system – the clouds of Jupiter, the surface of Titan, the heads and comas of comets – may be expected, and the results of 5×10^9 yr of prebiological organic chemistry uncovered for the first time.

There is one further cosmic context of the origin of life. In discussions of the likelihood of extraterrestrial intelligence a critical parameter is the likelihood that life arises on planets of other stars, given several $\times 10^9$ yr of planetary evolution (see, for example, Shklovskii and Sagan, 1966; Sagan, 1973b). In the view of some thoughtful investigators (for example, Francis Crick, in Sagan, 1973b) the development of technical civilizations may occur readily on planets given the origin of life there; but, in their view, the probability of the origin of life is an unknown quantity. It seems clear that a serious search for extraterrestrial radio communication is a time-consuming and moderately expensive enterprise, but one with the greatest significance for mankind whether it succeeds or fails. It is however much more likely that such a search will be mustered if the chance of success seems high. This probability can begin to be assessed by examination of the organic chemistry and biology, if such there be, on Mars, Titan, the comets, and the Jovian planets.

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References

Abelson, P. H.: 1957, *Ann. N.Y. Acad. Sci.* **69**, 276.
Anders, E., Hayatsu, R., and Studier, M. H.: 1973, *Science*, in press.
Chapman, C. R. and Salisbury, J. W.: 1973, *Icarus* **20**, in press.
Dole, S. H.: 1970, *Icarus* **13**, 494.
Egan, W. G., Veverka, J., Noland, M., and Hilgeman, T.: 1973, *Icarus* **19**, 358.
Khare, B. N. and Sagan, C.: 1973, *Icarus* **20**, 311.
Lecar, M. and Franklin, F. A.: 1973, *Icarus* **20**, in press.
McCord, T. B., Johnson, T. V., and Elias, J. H.: 1971, *Astrophys. J.* **165**, 413.
Pollack, J. B.: 1973, *Icarus* **19**, 43.
Reid, M. J.: 1973, *Icarus* **20**, 240.
Sagan, C.: 1970, 'Life', *Encyclopaedia Britannica.*
Sagan, C.: 1971a, *Comm. Astrophys. Space Phys.* **3**, 65.
Sagan, C.: 1971b, *Space Sci. Rev.* **11**, 73.
Sagan, C.: 1972, *Nature* **238**, 77.
Sagan, C.: 1973a, *Icarus* **18**, 649.
Sagan, C. (ed.): 1973b, in *Communication with Extraterrestrial Intelligence*, MIT Press, Cambridge, Massachusetts.
Sagan, C., Dayhoff, M. O., Lippincott, E. R., and Eck, R.: 1967, *Nature* **213**, 273.
Sagan, C. and Khare, B.: 1971a, *Science* **173**, 417.
Sagan, C. and Khare, B.: 1971b, *Astrophys. J.* **168**, 563.
Sagan, C. and Mullen, G.: 1972, *Bull. Am. Astron. Soc.* **4**, 368.
Schopf, J. W.: 1970, *Biol. Rev.* **45**, 319.
Shklovskii, I. and Sagan, C.: 1966, *Intelligent Life in the Universe*, Holden-Day, San Francisco, California.
Veverka, J.: 1973, *Icarus* **18**, 657.
Wasserburg, G. J.: 1973, Paper presented to the Division for Planetary Sciences at the American Astronomical Society Meeting, Tucson, Arizona, March, 1973.
Woeller, F. and Ponnamperuma, C.: 1969, *Icarus* **10**, 386.
Zellner, B.: 1973, *Icarus* **18**, 661.