COULD LIFE HAVE EVOLVED IN COMETARY NUCLEI?

A. BAR-NUN

Department of Geophysics and Planetary Sciences, Tel-Aviv University, Tel-Aviv, 69978, Israel

A. LAZCANO-ARAUJO

Instituto de Astronomia, Universidad Nacional Autónoma de México, México 20, D.F.; México

and

J. ORÓ

Departments of Biophysical Sciences and Chemistry, University of Houston, Houston, Texas 77004, U.S.A.

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Abstract. Hoyle and Wickramasinghe have recently suggested that life may have originated in cometary nuclei rather than directly on Earth. Even though comets are known to contain substantial amounts of organic compounds which may have contributed to the formation of biochemical molecules on the primitive Earth, it is doubtful that the process of chemical evolution has proceeded in comets beyond the stage that has occurred in carbonaceous chondrites. Some of the arguments which do not favor the occurrence of biopoesis in comets are:

1. A large layer of cometary ices is ablated from the nucleus' surface each time the comet passes through perihelion, so that essentially most of the organic products on the surface would be sublimed, blown off or polymerized.
2. Because of the low temperatures of the cometary ices, polymers formed on one perihelion passage would not migrate deep enough into the nucleus to be preserved before they would be ablated away by the next perihelion passage.
3. In the absence of atmosphere, and discrete liquid and solid surfaces, it is difficult to visualize the synthesis of key life molecules, such as oligopeptides, oligonucleotides and phospholipids by condensation and dehydration reactions as is presumed to have occurred in the evaporating ponds of the primitive Earth.
4. Observations suggest that cometary nuclei have a rather weak structure. Hence, the low central pressures in comets combined with the high vapor pressures of cometary ices at the melting point of water ice, suggest that a liquid core is not a tenable structure. Yet, even if a cometary nucleus is compact enough to hold a liquid core and a transient liquid water environment was provided by the decay of ^{26}Al, the continuous irradiation in water of most of the biologically relevant polymers would have hydrolyzed and degraded them.
5. Needless to say that the effects of radiation on self-replicating systems would also have caused the demise of any life forms which may have appeared under any circumstances.
6. Concerning viruses, the high specificity of host-parasite relationships and their coevolutionary lines of descent, rule out a cometary origin for them.

In summary, the view that life originated in comets is untenable in the light of all the available evidence.

In recent years Hoyle and Wickramasinghe have brought forward two provocative suggestions, namely, that bacteria and viruses are widespread in the interstellar medium (Hoyle and Wickramasinghe, 1979a, b, c, 1980), and that the first forms of life which inhabited the primitive Earth originated in cometary nuclei (Hoyle, 1978; Hoyle and Wickramasinghe, 1978), reaching our planet at a later time on board incoming comets or on cometary debris. In fact the significant role of comets in the

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prebiotic formation of biochemical compounds on the primitive Earth was proposed a long time ago by one of us (Oró, 1961), and additional complementary evidence has been presented more recently (Oró *et al.*, 1980; Lazcano-Araujo and Oró, 1981). Also, from recent radioastronomical observations (Oró, 1972; Turner, 1980), it has been found that the chemical precursors of almost all the monomers of biological significance are among the most abundant interstellar molecules (Oró *et al.*, 1978; Lazcano-Araujo and Oró, 1981). However, we feel that it is not warranted to extrapolate from these observations to the existence of interstellar or cometary life. First, the low densities of the interstellar gas-and-dust clouds, their very low temperatures, high levels of radiation, and principally the lack of liquid water, constitute such drastic conditions and hostile environment that preclude *ipso facto* the emergence of any organism in interstellar space (Ponnamperuma, 1972; Sagan, 1973; Lazcano-Araujo, 1978; Oró *et al.*, 1980; Lazcano-Araujo and Oró, 1981), at least on the basis of what we know about terrestrial life. Beyond that, the primary purpose of this paper is to show that even though abiotic organic synthesis may take place in cometary nuclei, it is rather unlikely that other prerequisites for the appearance of life are fulfilled in comets.

The suggestion that life might have originated in cometary nuclei rather than directly on the Earth, is brought forward by Hoyle and Wickramasinghe in order to overcome two apparent obstacles which are seemingly encountered by the contemporary theory of the origin of life, namely, the composition of the primitive atmosphere of the Earth, and the concentration of molecules of biological significance in its primitive oceans. The first obstacle was surmounted by demonstrating experimentally that different amounts of molecules of biological importance are formed in gas mixtures consisting of practically any combination of carbon, nitrogen, hydrogen, and oxygen, as long as free oxygen is not present (Kenyon and Steinman, 1969; Miller and Orgel, 1974; Abelson, 1957; Hubbard, 1976; Bar-Nun and Hartman, 1978). For the absence of high partial pressures of free oxygen in the terrestrial atmosphere between 4.6 and 2.0×10^9 yr ago there is ample geological and paleontological evidence (Schidlowski, 1978; Walker, 1977), and therefore biomolecules could have been formed during this period. The second obstacle is more serious as, because of efficient scavenging mechanisms in the oceans, the concentration of these molecules in solution could not have been large (Nissenbaum, 1976). This, however, is a limitation upon further chemical evolution only if the processes had to take place in dilute solutions in the oceans. If life could have originated in tide pools, evaporating ponds, or at the bottom of shallow seas, in the layer composed of organic deposits (Nissenbaum *et al.*, 1975) and clay minerals (Paecht-Horowitz, 1976), the concentration of the solution in these microenvironments was probably much higher. Furthermore, very high concentrations of organic compounds could have been reached in the internal milieu of microvesicles or liposomes self-assembled from prebiotically synthesized phospholipids or other amphiphilic molecules (Oró *et al.*, 1978., Deamer and Oró, 1980; Oró and Lazcano-Araujo, 1981). As will be shown below, comets do not have advantage over the oceans even in this respect.

Comets may have inherited complex organic molecules from the solar nebula (Greenberg, 1978, Donn, 1972) since abundance considerations suggest that they are the most primitive minor bodies in the solar system (Delsemme, 1977). Just how far can chemical evolution proceed in a cometary nucleus is still an open question, and for which fly-by missions, landings on cometary nuclei, and eventually the recovery of a sample of cometary material will provide the answer. Nevertheless, experiments in which frozen mixtures of different combinations of H_2O, CH_4, C_2H_6, HCHO, NH_3, N_2, have been irradiated with electrons (Glasel, 1961; Oró, 1963), protons (Berger, 1961), and high energy ^{14}C ions (R. M. Lemmon, private communication) and UV photons (Greenberg *et al.*, 1972; Ausloos *et al.*, 1965), have yielded non-volatile organic material, including amino acids, nitrogen bases and low molecular weight hydrocarbons, therefore suggesting that such molecules may form on the surface or external layers of cometary nuclei during residence times in the Öpik-Oort cloud (Moore *et al.*, 1980) and during approach to perihelion (Lazcano-Araujo and Oró, 1981).

According to Hoyle and Wickramasinghe (1978), the molecules which were preformed in an interstellar cloud reach considerably higher concentrations in the cometary nucleus environment. Approaching perihelion, the ices of the nucleus are melted and the solar UV radiation promotes further chemical evolution towards more complex biomolecules, which are frozen in the ice as the comet recedes from the Sun. After many such cycles, it is suggested, primitive forms of life could have emerged in the nucleus. Inherent in this model of chemical evolution is the preservation of the products over many cycles. Such preservation seems, however, to be quite difficult, if not impossible to achieve, because of the large mass which is blown off the nucleus. Layers of approximately constant thickness will be blown off during each passage, since the mass loss is proportional to the amount of solar radiation absorbed which, in turn is proportional to the surface area. Since UV radiation cannot penetrate deeper than at most a few meters of ice, the photochemical processes are confined to this layer. The products thus formed before perihelion have to diffuse very fast inward, in order to escape the receding surface. Otherwise they would be carried away with the ice particles which, as observations and laboratory simulations suggest (Delsemme, 1976), are blown away from the nucleus. The polymers formed after perihelion, when the ablation is slowed down, would have to diffuse a length of 100 m through a layer of ice which is cooling down to 100 K or otherwise would be blown away during the next cycle. This migration seems to be quite impossible for large organic polymers such as polypeptides or polysaccharides.

These organic polymers could migrate inward at a sufficiently fast rate only if the ice were molten. In this case, the solution of organic material would have been favorable for further chemical evolution, as might have happened in the primitive oceans of the Earth (Miller and Orgel, 1974). This attractive situation, however, is not supported in the case of comets by simulation experiments such as the irradiation of deuterated frozen water (Glasel, 1962), nor by the experimental results of Kajmakov (1974), and Dobrovolsky and Kajmakov (1977). When an icy body at 133 K was irradiated by fluxes corresponding to those between 3 and 0.35 AU the equilibrium temperature everywhere in the ice ranged between 150 and 213 K, respectively. The temperature could not have risen above these values because the energy was used mainly for the evaporation of the ice into the surrounding volume, which was maintained at a pressure of 10^{-5} torr. When metallic particles, Al_2O_3, SiO_2, salts, carbamide or phenylalanine were dissolved in the ice, a matrix was formed on the surface as the ice evaporated. This matrix, however, collapsed after a while and was blown off by the emerging gases. Liquid was not formed anywhere in the ice, as the temperature and pressures were not within the range of liquid on the phase-diagram of water. In the nucleus' interior, temperatures even lower than those of the surface are expected, according to Kelvin's solution (cf. Carslaw and Jaeger, 1959) to the temperature of a periodically heated solid body.

Observations suggest that cometary nuclei have a rather weak structure. Hence, the low central pressure in comets, combined with the high vapor pressure of cometary ices at the melting point of water ice, suggest that a liquid core is not a tenable structure (Donn, 1963, 1980). If, however, the cometary nucleus is compact enough to hold a liquid core, such a transient liquid environment could have been provided by the decay of ^{26}Al. As Irvine *et al.* (1980a, b) have shown, for typical comets with radii of the order of 10 km, the decay of ^{26}Al and other short-lived isotopes could have led, for at least the first 10^7 yr of the solar system, to the existence of liquid environments in the interior of their nuclei. In the extreme cases of comets of radii of 100 km, a liquid core could have been maintained for as long as 10^9 yr. Whereas it is possible that *in situ* radiation-induced chemical synthesis may have occurred in such transient liquid environment (Irvine *et al.*, 1980a, b) exactly the same scavenging mechanisms which operate in the Earth's oceans (Nissenbaum, 1976; Nissenbaum *et al.*, 1975) would have kept the concentration of dissolved organics low in the molten cometary core. Therefore, considerations of the concentration of the organic solution do not show any advantage of comets over the Earth's oceans.

Another difficulty arises from the reduced nature of most of the organic compounds present in comets; in fact, the hydrogen abundance in comets is 10 times higher than that of C 1 carbonaceous chondrites (Delsemme, 1977). This would impose severe limitations on the further development of chemical evolution, by inhibiting the synthesis of the partially dehydrogenated compounds (Principally purines and pyrimidines) which are a prerequisite for life. Indeed, chemical evolution on the Earth was possible only because the secondary atmosphere was mildly reducing and was continully losing hydrogen (Walker, 1977; Pollack and Yung, 1980) and only under such conditions gradually evolving to a less hydrogenated state, could chemical evolution proceeed and lead to the emergence of living systems (Gabel and Ponnamperuma, 1972). Experimental evidence in support of this view is provided by the fact that when the prebiotic synthesis of adenine (Oró, 1960) is carried out by the irradiation of methane, ammonia and water, its production is inhibited in the presence of H_2 (Ponnamperuma *et al.*, 1963; Ponnamperuma, 1965). Furthermore, whereas no purines are synthesized by electric discharges from a mixture of hydrogen, methane, ammonia and water, they are formed when less reducing mixtures are used.

But perhaps the most serious limitation of continued prebiotic evolution is the absence of an atmosphere and discrete liquid and solid surfaces as they are found on the Earth. A closed liquid environment would not allow the evaporation of water and the occurrence of dehydration reactions, necessary for the formation of oligopeptides, oligonucleotides, phospholipids and other amphiphilic lipids, key molecules of life, without which the existence of semipermeable membranes and self-replicating systems cannot be visualized. The above compounds are readily formed under the moderate conditions of a primitive Earth evaporating pond model (Oró *et al.*, 1978; Deamer and Oró, 1980; Oró and Lazcano-Araujo, 1981). If one assumes that these molecules were preformed, namely that they were already present when the comet was formed by condensation of interstellar or solar nebula matter, then the fact that they were immersed in a closed liquid-water environment, which was continuously irradiated, would certainly have led, in a relatively short span of time, to their hydrolysis and degradation.

Following this line of argument another major difficulty for the emergence of life in the liquid core which, as shown above, is quite uncertain to exist at all, would be the radiation which is required to maintain the core molten. According to Irvine *et al.* (1980a, b), the ^{26}Al could have provided energy at the rate of $\sim 2 \times 10^{-3}$ erg g^{-1}s^{-1}. Since the half life of ^{26}Al is only 7.4×10^5 yr, this energy could have maintained the core molten only during the initial $10^7 - 10^9$ yr, after which the core froze again. Also, with 1 Mev γ-rays and positrons being emitted from the ^{26}Al, the flux of γ photons would have been $\sim 10^3$ gr^{-1}s^{-1}. Therefore, such a flux acting over a long period of time would have destroyed any replicating, information carrying system, had such one had a chance to develop (Nygaard *et al.*, 1974).

Hoyle and Wickramasinghe (1978) have also suggested that the so-called organized elements which have been described in several C 1 chondrites represent fossil remnants of cometary organisms. In the first place, although it has been suggested that some C 1 chondrites may have a cometary origin, the only three orbits which have been determined so far for meteorites – Pribram, Lost City and Innisfree – show that these objects came from the asteroidal belt (Nagy, 1975); secondly, about 75% of the asteroids have spectral reflectance curves similar to those of carbonaceous chondrites (Zellner, 1978; Matson *et al.*, 1978), and these dark asteroids or their parent bodies are considered the most logical source of the carbonaceous meteorites. Thirdly, with the exception of contaminants, these meteoritic microfossil-like features are currently recognized as of nonbiological origin (Anders and Fitch, 1962; Fitch and Anders, 1963), whose size distribution strongly differs from that of living and fossil prokaryotic cells (Schopf, 1976) and whose similarity to biogenic structures is only superficial (Rossignol-Strick and Barghoorn, 1971).

In summary, while the contribution of cometary and related meteoritic matter was significant in shaping the environments in which life first arose on Earth (Oró *et al.*, 1980; Lazcano-Araujo and Oró, 1981), the view that life originated in comets (Hoyle and Wickramasinghe, 1978) is untenable in the light of all the available evidence. Equally unlikely appears the proposition that this process of infection is still taking place and is responsible for past and present epidemics (Hoyle and Wickramasinghe, 1979a, c); no such phenomena have been associated with the Tunguska explosion, which was probably due to the collision of a fragment of comet Encke with the Earth's atmosphere (krésák, 1978; Park, 1978). Furthermore, a recent study (Carlin, 1980) on the evolution of viruses indicates that they may be as old as the organisms with which they interact and that their origin and evolution may go back in time to about 3.8 ± 0.2 billion years which is probably the time at which life emerged on Earth (Oró, 1968; Carlin, 1980; Awramik *et al.*, 1980; Lazcano-Araujo and Oró, 1981). Moreover, although additional studies of the origin and evolution of viruses are sorely needed, the high specificity they exhibit in their host-parasite relationships implies a process of coevolution (Agol, 1976; Joklik, 1974) that rules out a cometary origin for them.

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References

Abelson, P. H.: 1957, *Science* **124,** 935.
Agol, V. I.: 1976, *Origins of Life* **7,** 119.
Anders, E. and Fitch, F. W.: 1962, *Science* **138,** 1392.
Ausloos, P., Rebbert, R. E., and Lias, S. G.: 1965, *J. Chem. Phys.* **42,** 540.
Awramik, S. M., Schopf, J. W., Walter, M. R., and Buick, R.: 1981, *Science* (in press).
Bar-Nun, A. and Hartman, H.: 1978, *Origins of Life* **9,** 93.
Berger, R.: 1961, *Proc. Nat. Acad. Sci. U.S.A.* **47,** 174.
Carlin, R. K.: 1980, *J. Theor. Biol.* **82,** 353.
Carslaw, H. S., and Jaeger, J. A.: 1959, *Conduction of Heat in Solids*, Oxford Univ. Press, Oxford, 2nd Ed., 81.
Deamer, D. and Oró, J.: 1980, *BioSystems* **12,** 165.
Delsemme, A. H.: 1976, in G. P. Kuiper and R. S. Romer (eds.), *Comets: Scientific Data and Missions*, NASA–CP–129, 110.
Delsemme, A. H.: 1977, in A. H. Delsemme (ed.), *Comets, Asteroids, Meteorites*, The University of Toledo Press, Toledo, Ohio, 3.
Dobrovolsky, O. V. and Kajmakov, E. A.: 1977, in A. H. Delsemme (ed.), *Comets, Asteroids, Meteorites*, The University of Toledo Press, Toledo, Ohio, 37.
Donn, B.: 1963, *Icarus* **2,** 396.
Donn, B.: 1972, in C. Ponnamperuma (ed.), *Exobiology*, North-Holland, Amsterdam, 431.
Donn, B.: 1980, in Abstracts of the *Fifth College park Colloquium on Chemical Evolution: Comets and the Origin of Life*, College Park, Maryland, 1980.
Fitch, F. W. and Anders, E.: 1963, *Science* **140,** 1097.
Gabel, N. W. and Ponnamperuma, C.: 1972, in C. Ponnamperuma (ed.), *Exobiology* North-Holland, Amsterdam, 95.

Glasel, J. A.: 1961, *Proc. Nat. Acad. Sci. U.S.A.* **47,** 174.
Glasel, J. A.: 1962, *Proc. Nat. Acad. Sci. U.S.A.* **48,** 491.
Greenberg, J. M.: 1978, in J. A. M. McDonell (ed.), *Cosmic Dust*, Wiley, New York, 197.
Greenberg, J. M., Yencha, A. J., Corbet, J. W., and Frisch, H. L.: 1972, *Mem. Soc. Roy. des Sci. de Liège* **62,** Serie III, 425.
Hoyle, F.: 1978, *Mercury* **VII,** 2.
Hoyle, F., and Wickramasinghe, N. C.: 1978, *Lifecloud: The Origin of Life in the Universe*, Harper and Row, New york, 190 pp.
Hoyle, F., and Wickramasinghe, N. C.: 1979a, *Astrophys. Space Sci.* **65,** 241.
Hoyle, F., and Wickramasinghe, N. C.: 1979b, *Astrophys. Space Sci.* **66,** 77.
Hoyle, F., and Wickramasinghe, N. C.: 1979c, *Diseases from Space*, Dent, London, 196 pp.
Hoyle, F., and wickramasinghe, N.C.: 1980, *Astrophys. Space Sci.* **68,** 499.
Hubbard, J. W.: 1976, *Origins of Life* **7,** 281.
Irvine, W. M., Leschine, S. B., and Schloerb, F. P.: 1980a, *nature* **283,** 748.
Irvine, W. M., Leschine, S. B., and Schloerb, F. P.: 1980b, in Y. Wolman (ed.) *Origin of Life, Proc. 6th Int. Conference on the Origins of Life*, Jerusalem, Israel, June 22–27,1980 D. Reidel, Publ. Co., Dordrecht, Holland, 27.
Joklik, W. K.: 1974, in M. J. Carlile and J. J. Skehel (eds.), *Evolution in the Bacterial World: 24th Symp. Soc. Gen. Microbiol.*, Cambridge Univ. Press, Cambridge, 293.
Kajmakov, E. A.: 1974, in *The problems of Modern Physics*, Nauka, Leningrad, 231 (in Russian).
Kenyon, D. H., and Steinman, G.· 1969, *Biochemical Predestination*, McGraw Hill, New york, 302 pp.
Krésák, L.: 1978, *Bull. Astron. Inst. Czechosl.* **29,** 129.
Lazcano-Araujo, A.: 1978, in A. Lazcano-Araujo and A. Barrera (eds.), *El Origen de la Vida: Simp. en Homenaje a A. I. Oparin*, UNAM, México, 99.
Lazcano-Araujo, A., and Oró, J.: 1981, in C. Ponnamperuma (ed.), *Comets and the Origin of Life*, D. Reidel Publ. Co., Dordrecht, Holland, 217.
Matson, D. L., Veeder, G. J., and Lebofsky, L. A.: 1978, in D. Morrison and W. C. Wells (eds.), *Asteroids: An Exploration Assessment*, NASA CP–2053, Washington, D.C., 127.
Miller, S. L., and Orgel, L. E.: 1974, *The Origins of Life on the Earth*, Prentice-Hall, Englewood Cliffs, 230 pp.
Moore, M. H., A'Hearn, M. E., Donn, B. C., and Khanna, R. K.: 1980, in *Abstracts of the Fifth College Park Colloquium on Chemical Evolution: Comets and the Origin of Life*, College Park, Maryland, 1980, 17.
Nagy, B.: 1975, *Carbonaceous Meteorites*, Elsevier, Amsterdam, 748 pp.
Nissenbaum, A.: 1976, *Origins of Life* **7,** 413.
Nissenbaum, A., Kenyon, D. H., and Oró, J.: 1975, *Jour. Mol. Evol.* **6,** 25.
Nygaard, O. F., Adler, H. I., and Sinclair, W. K. (eds.): 1974, *Radiation Research*, Academic Press, New york, 420 pp.
Oró, J.: 1960, *Biochem. Biophys. Res. Comm.* **2,** 407.
Oró, J.: 1961, *Nature* **190,** 389.
Oró, J.: 1963, *Nature* **197,** 971.
Oró, J.: 1968, *J. Brit. Interplanet. Soc.* **21,** 12.
Oró, J.: 1972, *Space Life Sci.* **3,** 507.
Oró, J., and Lazcano-Araujo, A.: 1981, in B. Vennesland, E. E. Conn, C. J. Knowles, J. Westly and F. Wissing (eds.), *Cyanide in Biology*, Academic Press, London (in press).
Oró, J., Sherwood, E., Eichberg, J., and Epps, D.: 1978, in D. Deamer (ed.), *Light Transducing Membranes*, Academic Press, New York, 1.
Oró, J., Holzer, G., and Lazcano-Araujo, A.: 1980, in R. M. Holmquist (ed.), *COSPAR: Life Sciences and Space Research* VIII Pergamon Press, Oxford and New york, 67.
Paecht-Horowitz, M.: 1976, *Origins of Life* **7,** 369.
Park, C.: 1978, *Acta Astronáutica* **5,** 523.
Pollack, J. B., and Yung, Y. L.: 1980, *Ann. Rev. Earth Planet Sci.* **8,** 425.
Ponnamperuma, C.: 1965, in S. W. Fox (ed.), *The Origins of Prebiological Systems*, Academic Press, New york, 221.
Ponnamperuma, C.: 1972, *Ann. N. Y. Acad. Sci.* **194,** 56.
Ponnamperuma, C., Lemmon, R. M., Mariner, R., and Calvin, M.: 1963, *Proc. nat. Acad. Sci, U.S.A.* **49,** 737.

Rossignol-Strick, M. and Barghoorn, E. S.: 1971, *Space Life Sci.* **3**, 89.
Sagan, C.: 1973, in M. A. Gordon and L. E. Snyder (eds.), *Molecules in the Galactic Environment*, Wiley, New York, 451.
Schidlowski, M.: 1978, in H. Noda (ed.), *Origin of Life*, Center for Acad. Publication, Tokyo, 3.
Schopf, J. W.: 1976, *Origins of Life* **7**, 19.
Turner, B. E.: 1980, *J. Mol. Evol.* **15**, 79.
Walker, J. C. G.: 1977, *Evolution of the Atmosphere*, MacMillan, New york, 318 pp.
Zellner, B. H.: 1978, in D. Morrison and W. C. Wells (eds.), *Asteroids: An Exploration Assessment*, NASA CP–2053, Washington, D.C., 99.