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PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

General Discussion after Session V

N. C. Wickramasinghe, George Porter, M. E. Lipschutz, S. Chang, P. Pellas, G. J. Wasserburg, D. McKay, M. M. Woolfson, M. K. Wallis, Bernard Lovell and H. W. Kroto

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General discussion after session V

N. C. Wickramasinghe (*Department of Applied Mathematics and Astronomy, University College, Cardiff, U.K.*). The question of the origin of life is, of course, one of the most important scientific questions and it is also one of the most difficult. One is inevitably faced here with a situation where there are very few empirical facts of direct relevance and perhaps no facts relating to the actual transition from organic material to material that can even remotely be described as living. The time perspective of events that relate to this problem has already been presented by Dr Chang. Uncertainty still persists as to the actual first moment of the origin or the emergence of life on the Earth. At some time between 3800 and 3300 Ma BP the first microscopic living systems seem to have emerged. There is a definite moment in time corresponding to a sudden appearance of cellular-type living systems. Now, traditionally the evolution of carbonaceous compounds which led to the emergence of life on Earth could be divided into three principal steps and I shall just remind you what those steps are. The first step is the production of chemical building blocks that lead to the origin of the organic molecules necessary as a prerequisite for the evolution of life. Step two can be described in general terms as prebiotic evolution, the arrangement of these chemical units into some kind of sequence of precursor systems that come almost up to life but not quite; and then stage three is the early biological evolution which actually effects the transition from proto-cellular organic-type forms into truly cellular living systems. The transition is from organic chemistry, prebiotic chemistry to biochemistry. Those are the three principal stages that have been defined by traditional workers in the field, the people who, as Dr Chang said, have had the courage to make these queries and attempt to answer them. Ever since the classic experiments where organic materials were synthesized in the laboratory a few decades back, it was thought that the first step, the production of organic chemical units, is important for the origin of life on the Earth, and that this had to take place in some location on the Earth itself. Recent data relating to the presence of organic molecules in interstellar space, planetary atmospheres and comets, could be interpreted as evidence for the operation of at least stage one of this process not on a small planet like the Earth but on a somewhat grander scale, perhaps at least on the scale of the Solar System. In terms of firm evidence, one could ask what progress has been made since the early laboratory work. The original idea was that the initial terrestrial atmosphere had to be made of methane, water and ammonia which had to be energized so as to produce the organic building blocks, aminoacids, nucleotides, etc., that are needed for the origins of life. Now these processes could be considered to be somewhat redundant in a terrestrial context and so one could think of generating at least those units – the organic substrate that is needed for the origin of life – on a scale that is much bigger. In the Solar System the obvious class of objects one could look at are the comets. There are some 10^{11} to 10^{12} comets which have been proven beyond any question to be of a complex organic character and, if you put all this mass together, the organic material that could be appropriate for the origin of life in comets is tens of millions of times greater than has ever been produced in the biosphere. Now as far as step two and step three, prebiotic evolution and early biological evolution, are concerned, could they also be located at some great distance from the Earth? And here one comes to controversy among scientists. One has to stress that there is no logical requirement that the transitions to stages two

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and three took place on the Earth. There is certainly no hard evidence for it. So I would like to leave it at that and say that, from a personal standpoint, I prefer the alternative where steps two and three also take place in the context of a much bigger cosmic system.

Sir George Porter, P.R.S. (*Department of Pure and Applied Biology, Imperial College, London, U.K.*). I thank Professor Wickramasinghe; I can think of no better lead off to a discussion. He has, of course, put another view altogether which many here will support and many will not. On the more conventional side he says what a large mass of organic material is out there and available to come back, certainly more than we ever need, but that is also true of the potential for formation of organic material on the planet itself. The energy available for photosynthesis is equally far greater than we need. In fact, now I think the figure is that the carbon dioxide in the atmosphere is turned over every 100 years, the oxygen every couple of thousand of years, even all the water is turned over every 2 million years. The mass produced is enormous each year; it is renewed each year. The problem is to distinguish between the alternatives but just to say that it is possible, and we know that there are organic materials out there, presents a very interesting new possibility which we must certainly consider but, equally, there is no difficulty with the more conventional view. There are so many ways in which it could be done. The problem is to find out how and it seems to me, from listening to Dr Chang, and from what I have read about the subject, the whole problem is that we have so little information about the period 3.5 Ga BP and I would like to ask the geologists if they can make some contribution on this. How can we get this information? We have microfossils, but the microfossil Dr Chang showed us is enormously complicated. There is a great deal of chemistry to build up before we get anywhere near that. Where are the stages in between, well we don't know. Where would it be I would ask the geologists? Where would we look for it? And if I could put the question another way, Dr Chang was saying that this is a good reason for going to Mars because we might find these earlier stages even if life hadn't got any further; but where would we find them on Mars and, if he can tell me that, why can we not find them on Earth as well?

M. E. Lipschutz. Dr Chang notes that tidal effects on terrestrial oceans may have been essential for the origin of life on Earth. He notes that martian moons are too small to cause tidal effects in putative martian seas and this may preclude life ever having existed on Mars. However, a non-trivial part of the tidal effect on Earth is generated by the Sun; about 15% as I recall. At Mar's distance from the Sun, what would be the Sun's tidal effects on a putative martian sea and would this effect be enough to initiate the formation of life?

S. Chang. In the origin of life the role played by lunar tides and attendant fluctuations in environmental conditions (e.g. day length and tidal amplitude) is very poorly understood. Tidal effects may or may not have been essential, and at this stage of our ignorance, the correct answer will not be revealed by any kind of quantitative analysis. To suggest that any particular magnitude of a tidal effect, lunar or solar, would have been necessary or sufficient for the origin of life on either Mars or Earth would be groundless speculation at this time.

P. Pellas. I think that Dr Chang has forgotten an important parameter in the atmosphere because in Mars we have 10 g cm^{-2}, in other words very strong cosmic ray effects, which tend to destroy genetic material. Going back to Professor Wickramasinghe, we know that in the carbonaceous chondrites we have very complex organic systems. Of course they are prebiotic

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organic systems, but very very complex systems, so we have in some way the sum of your first two steps. In fact we have all the stuff to produce life; what is lacking is understanding of how to go from the prebiotic organic organization to the living organisms.

N. C. Wickramasinghe. I agree with what Dr Pellas says there but carbonaceous chondrites are surely not connected to the Earth; they are more likely to be related to comets, perhaps, and they are certainly extraterrestrial objects. Why should not the same steps have been recorded in the Earth's oldest sediments if those transitions did indeed take place on the Earth? I think that poses a very important question as to the lack of existence of similar structures, similar complex arrays of organics in the Earth which according to the usual point of view, must have been recorded as terrestrial prebiotic steps.

S. Chang. The reason of course is because there are none of those prebiotic sediments remaining. The ones that we do have remaining have been severely metamorphosed. Coming back to the question of Dr Pellas; to allow liquid water to occur on Mars to produce the evidence of fluvial activity you had to have a considerably more massive atmosphere than it has today. The models that have been calculated by Walker, Pollack and Casting suggests that to produce an environment with surface temperatures sufficiently high to allow the water to persist you need something of the order of $(5–10) \times 10^5$ Pa of CO_2. Of course we do not know whether there is that much CO_2 available on Mars; on the other hand it may have been available. Something had to have happened to permit that surface temperature to allow water to persist.

G. J. Wasserburg. It is reasonable to believe that the water for oceans formed very early in Earth history probably within about 10^8 a or possibly less. Certainly violent convection has to be responsible for the first 500 Ma of Earth activity, erasing the sediments which have been referred to previously, but that in no way means that the environments were ever removed. As long as there are oceans and a heat source and mechanisms, then there is a timescale that is not so compressed that you end up with Sir George's embarrassing circumstance that the first organism appears very highly developed. There are, however, two questions on which I would appreciate Dr Chang's comments. One is about the models of very high CO_2 content and it is imagined that CO_2 would be produced in the Earth, and the second is with regard to membranes which seems the key and fundamental factor in dividing the inside from outside of any reproductive system.

S. Chang. The CO_2 proposal was based on a number of models that have emerged over the years that are concerned with the development of impact origin atmospheres. The most recent one which was published in *Nature* by Mitsui & Abe (1986) in which they took the accretionary flux, made some assumptions about the amount of water associated with the accreting material, calculated the rate of development of the atmosphere as opposed to the rate of hydration of rock, which would have taken water out of the atmosphere, and concluded that, on balance, a very massive atmosphere would have prevailed. Naturally CO_2 would have been part of that steam atmosphere. As to the other question, biologists would argue that the real issue is not whether you separate inside from outside but whether you have a system that is able to self-replicate. On the other hand, I would agree with you that it would be very difficult to imagine having a process that could replicate with a degree of fidelity without having some kind of

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interface. Now to give you some indication as to the possibilities of primitive membrane material, very recently David Deemer (1985) took some carbonaceous meteorite which I sent him, and he disaggregated it in water by freeze–thaw and he extracted material which gave every indication that it could indeed serve as a physical membrane.

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Sir George Porter, The spontaneous formation of membranes must be about the least of our problems. If you shine light on almost any mixture, as long as it is of short enough wavelength, you will get surfactant materials, carboxylic acid with long tails. You will get other things as well; it is a matter of separating them. Fortunately there is a very easy way of separating them in that as soon as they fall on the surface of water, they come out of the gas phase, they do not even go into the liquid phase, they go onto the surface and then the wind can blow them along and you get a wonderful method of concentration. So I think that as long as we have had the Sun and some organic materials we have had membranes.

S. Chang. There has been a very ingenious suggestion made by a graduate student named Luis Lerman, in the Geophysics Department at Stanford, who suggests that a most interesting phenomenon is bubble formation at the sea–air interface. Apparently bubble formation is associated with concentration of organic material, phosphates and certain inorganic cations. To produce the nucleic acids, etc., that we ultimately need, it seems to me that that kind of mechanism is very interesting. Only waves and a sea–air interface are needed for it to be ubiquitous.

D. McKay. I would like to ask Dr Chang about the regolith environment of Mars. Would there be environments that would be favourable for the preservation of extramartian aminoacids which might be brought in by meteorites or comets or, taking it one step further, might be favourable for biological activity, for example, at interfaces between permafrost and liquid water, which must exist today in the martian regolith and probably existed in the past?

S. Chang. If you are interested in regolith then I suspect that the ancient crater terrain in the southern hemisphere of Mars might be a useful place to go. It is not clear to me, however, that the regolith would be the most interesting place if you are interested in biological activity. Deep below the oxidized surface material you might find layered deposits as a result of cratering activity where organic material from a projectile might survive. Neither would I view the layered terrain in the ice caps as particularly interesting because it is argued that those are relatively recent phenomenon, that is they reflect dynamic processes that have been going on in the more recent millions of years. I would, however, argue that if one were really serious about looking for ancient life on Mars then the place to look might be in those so-called layered sediments which have been observed to exist inside some of the canyons and give the appearance of having been deposited in more or less lake-like kinds of environments. If there

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were larger bodies of water early on and life arose on their margins or in volcanic islands within those bodies of water then, as the atmosphere changed and as the water went away into the regolith, the last refuge of any living entity might have been within the lakes; this is not to say that there is life there, but if it were, that is where it should be.

M. M. Woolfson, F.R.S. I am somewhat concerned about the energetics of the suggestion of Professor Wickramasinghe that life evolves on comets. The only comets of interest are those inhabiting the Oort cloud, with periods of about 10 Ma, which spend most of their lives in remote space and never penetrate into the inner Solar System. Their only available energy source is cosmic radiation, contributing some 5×10^{-8} J kg^{-1} s^{-1}. Even although the comets have about 10^9 times as much as the organic content of the biosphere they actually absorb less energy.

N. C. Wickramasinghe. The answer to that question would be that the energetics that are favourable to an origin of life certainly rule out such a process happening under present-day conditions at the distance of the Oort cloud; but our point of view has been that in the early days of the Solar System the whole of the present cometary cloud was at a much higher temperature for a few million years, enough for an initial replication event to go across the whole of the system. We do not really invoke an origin of life as such in the dim distant regions where the radiation field is weak; that, I would agree, is energetically not the best situation to envisage.

Sir George Porter. When one is looking around for sources of energy I think that one has to remember that the biological cell is an extremely delicate entity which is very rapidly destroyed by practically every sort of energy we know, such as high temperatures in most cases, certainly all forms of ionizing radiation and certainly ultraviolet light. And the way that Nature has got over this is to absorb its energy by sensitizers in the long-wavelength region of the spectrum which are not absorbed by the proteins of nucleic acids. It is extremely difficult to find any source of energy which is as effective for the production of life in a steady-state situation as the long-wavelength light of which the Sun has an abundance.

M. K. Wallis. I would follow up Professor Wickramasinghe's citation of comets by elaborating on the possible habitats for life that these bodies offer. The studies of Halley's Comet have led to a new picture of the comet nucleus, with surface of distinct phases of non-volatile and evaporating ice-organic composite (Wallis 1986). Most of the crust is dark and carbonaceous, processed by solar heating. It is centimetres deep with cohesive strength, resilient to maximum perhelion heating (*ca.* 90 °C) and stable over apparitions, except under meteorite impact or to undermining at the edges of eroding crator hollows. However, fresh crust, as forming in the temporarily shadowed crater basin, is fragile, so readily broken up and expelled by underlying volatiles. Because thermal conductivity and heat capacity are low, nightside temperatures drop below 200 K and those at 1–3 cm below the surface are always less than about 200 K. Some 10–15 % of the surface consists of actively outgassing craters (formed by erosion) whose temperature controlled by the sublimation of ice and other volatiles is also *ca.* 200 K.

We distinguish four potential habitats (figure D1).

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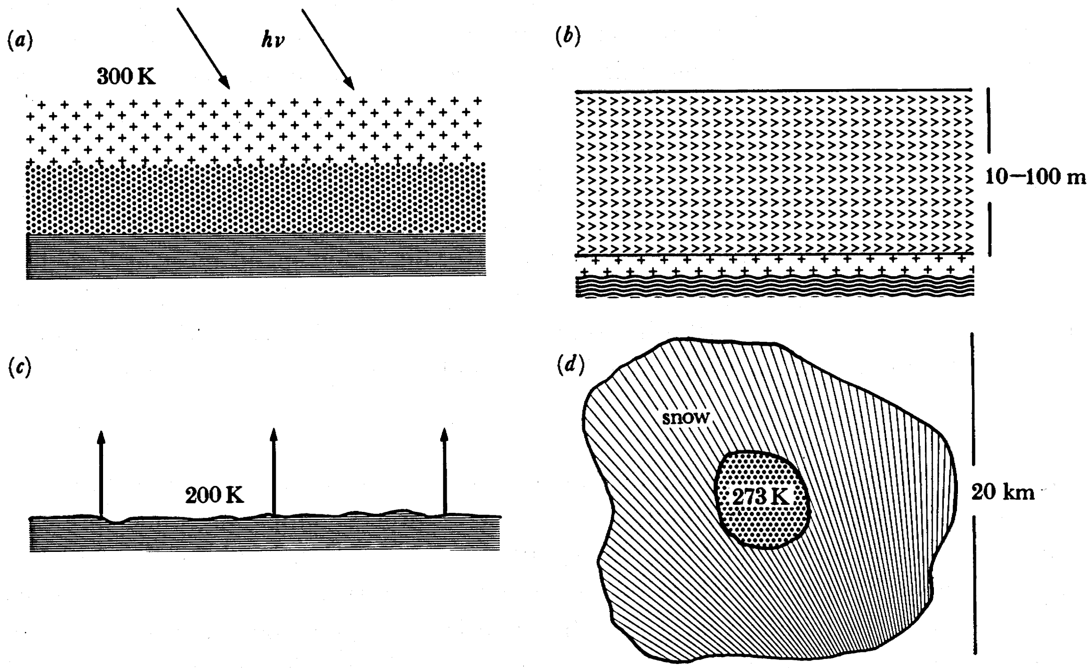

FIGURE D1. Potential comet habitats: (*a*) sub-crust; (*b*) sublimating ice-organic composite; (*c*) subsurface lake below clear ice; (*d*) early comet liquid–vapour interior.

(*a*) The warmed subcrust protected against space radiation contains small amounts of percolating gases evaporating from the interior ices, at 180 K if H_2O but this is presumably mixed with other gases.

(*b*) Contaminated ice in the craters sublimates rapidly at a few centimetres per day (giving most of the initial gas and grain emission). Photosynthesizing species can spread in crevices and cracks.

(*c*) Clear ice some tens of metres deep has 'greenhouse' properties (visible radiation penetrates, infrared cannot escape) allowing subsurface lakes to persist with rather low heat sources (solar plus chemical and metabolic).

(*d*) The interiors of large (more than about 10 km radius) comets soon after accretion may have become liquid or vapour under several kilometres of insulating 'snow', if ^{26}Al was present to provide initial heating (Wallis 1980). Chemical or metabolic energy might alternatively have supplied sufficient heat, if triggered by a large impact and/or accretion energy.

In cases (*a*) and (*d*), heterotrophic organisms living on organic material in total darkness are suited. Habitats (*b*) and (*c*) permit photosynthetic species as in the Antarctic dry valleys and the bottom of polar ice respectively. Although the subsurface lakes (*c*) may only last a few apparitions for an intermediate period comet such as Halley, the liquid or vapour interior of (*d*) could persist for 10 Ma, plenty of time for speciation.

A contrary viewpoint to Sir George's (on viability of life in space) could be argued. Svante Arrhenius early this century in propounding his theory of panspermia (Arrhenius 1908) pointed out that a fraction of bacteria survive very high doses of UV radiation, under conditions of extreme cold and high vacuum. Weber & Greenberg have recently (Weber & Greenberg 1985) published confirmatory work, although without acknowledgement. Certain bacterial

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species even develop sufficient radiation resistance to flourish within nuclear reactors. What should surprise geocentric biologists is the ability to withstand space environments and develop hardiness to space conditions, if such facility offers no evolutionary advantage.

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Sir George Porter. Once it has developed a bacterium may become very hardy but if you try to do any modelling in the laboratory, where you try to build up complex molecules from small ones, you are in real trouble because you have to use a sensitizer to do this as complex ones are destroyed faster than they are made.

Sir Bernard Lovell, F.R.S. May I ask about the timescales involved in the progression between the three evolutionary categories listed by Professor Wickramasinghe? I believe there are more than 10^{100} possible combinations of the amino acids and nucleotides and only one of these possible alternative sequences could lead to the evolution of life forms of which we are aware. As Professor Chang has shown this correct selection must have occurred within the first billion years after the formation of the Earth. The probability that this selection happened by chance in this timescale seems very small. To what extent is this an argument in favour of the view of Hoyle and Wickramasinghe and of Crick that the transition must have occurred in the far greater space–time boundaries of the extraterrestrial environment?

N. C. Wickramasinghe. That has been one of our major problems in coping with the origin of life in a limited terrestrial context. The timescale is grossly inadequate and the information content that is needed to produce life is so vast that it impossible to actually arrive at that final step on the Earth, which is the reason for looking at wider systems.

Sir George Porter. There is a question which has bothered me for a long time. If you shake tea leaves in a cup you will get a certain picture – and there it is in front of you – but the probability of that happening in 4 Ga is extremely small but it happens. The answer is that you do not know what is going to happen before you start, you do not select it. There are many, many ways that life could develop; this is the one that developed.

N. C. Wickramasinghe. My very brief response is that the large number of other possible arrangements of the tea leaves are of course indistinguishable from the one chosen by almost every character criterion, whereas the arrangements for the aminoacids in the enzymes, that are relevant for the particular system that we call life, is easily distinguished from every other arrangement.

H. W. Kroto. Professor Wickramasinghe made a very strong statement today that life could have originated on a comet in about 1 Ma but that on the Earth we haven't actually had enough time for life to develop in $4\frac{1}{2}$ Ga.

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S. Chang. We have heard a lot of commentary about how long it takes to develop a replicating system, whether there is enough time available, whether on a comet, whether on the planet Earth. I would argue that if you have a number of opportunities to do the same experiment over and over again, which is what underlies the whole notion I ended my talk with, then you have an opportunity to do the experiment correctly, to increase in complexity, to decrease the amount of garbage that gets incorporated. I would imagine that in a prebiotic era that Mother Nature was conducting this experiment all the time on the surface of this planet because we see it in biological evolution; Mother Nature does that experiment over and over again and that is why you have complex structures such as ourselves in a matter of $2\frac{1}{2}$ Ga after the origin of living systems. It is not an accident; it is an ongoing experiment.

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