LIVING COMETS

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CHAPTER 7

BIOLOGICAL ACTIVITY IN THE EARLY SOLAR SYSTEM IN ITS OUTER REGIONS

However often one learns to accept the amazing ways in which biological systems make use, not only of their gross environment but of subtle aspects of physics and chemistry, one never becomes quite inured to new surprises It was so with us on the day we learned in private communication that some species of bacteria can precipitate uranium salts from very weak solutions, 'they are practically uranium-eaters' our acquaintance told us. A possible answer to an unresolved conundrum over the Oklo reactor occurred to us thereupon to which we shall return in a moment.

Once again it was a surprise when we learned from Drs. R.B. Hoover and M.J. Hoover that some species of diatoms are able to concentrate other potentially fissile elements:

> '...it is established that many species are capable of thriving in environments containing extremely high concentrations of unusually lethal radioisotopes such as americium, plutonium, strontium, etc. Diatoms thrive in highly radioactive ponds, including the U-pond and the Z-trench at the Hanford facility, with the latter containing over 8kg of various radioisotopes of plutonium. Not only do diatoms live in this environment, but they seem to have a remarkable affinity for plutonium (c.f. R.M. Emery, D.C. Klopfer and W.C. Weimer, 1974, in Report prepared for the U.S. Atomic Energy Commission under Contract AT(45-1): 1830. BNHL-1867, p.44). The algae of these ponds, of which diatoms are by far the dominant form, concentrate ^{241}Am three millionfold, and certain isotopes of plutonium are accumulated to 400 million times the concentration in the surrounding water. The plant life in these radioactive ponds contains more than 95% of the total plutonium burden. Diatoms and *Potamogeton* alone contain more than 99% of this plutonium. In such an environment, diatoms grow in great abundance while continuously subjected to high levels of x-rays, gamma rays, alpha and beta particles'.

Deaths from leukaemia tend to show a peculiar very local clustering effect. We recall the example of a remote valley in New Zealand where over a time scale of a few years there were ~10 such deaths, a valley where there was no nuclear reactor. A cluster of six similar cases has recently come to public notice in the village of Seascale, closeby the Sellafield nuclear reactors of W. Cumbria. Somewhat naturally, the media have attributed the latter unfortunate deaths to the presence of the reactors, and as an outcome of media pressure the Ministry of the Environment of the British Government was led to set up a committee of enquiry into the matter. Members of the committee knew perfectly well from fully-attested statistics that neither the natural radioactive background nor the slight increment in the background caused by the reactors could explain the facts (except as a truly monstrous statistical fluctuation) and they also knew, which their critics apparently did not, of the existence of similar clusterings elsewhere, as in New Zealand where there had been no nuclear reactor. So the committee simply, and somewhat innocently, reported that the Sellafield reactors could not have been responsible for the six leukaemic deaths. Naturally London journalists writing for British weekly science magazines, who frequently meet together at various gatherings and perhaps over a pub lunch or two, and so tend to be of a single mind on such issues, had a field day over it. What the journalists could see with startling clarity, just like everybody else, was that while leukaemia cases might occur in small clusters it was apparently most peculiar that one such cluster should be found sitting almost on top of a considerable complex of reactors, where for one reason or another the management had not over past years been able to avoid the escape of small quantities of radionuclides into the local environment.

Diatoms do not rate highly in the educational system, and topics with low priorities receive scant attention in both books and in lecture rooms. Quite likely therefore, the facts concerning diatoms reported to us by Drs. R.B. and M.J. Hoover are unknown to the umpires of the weekly science magazines, to the media, and possibly to officialdom decked in its magisterial robes. Otherwise there would surely have been a rush to examine the water supplies at Seascale, not with a view to its dissolved contents, but with respect to microorganisms suspended within it. Especially as the nearest Lakeland valley to this part of the Cumbrian coast is Eskdale, where granite rocks containing a high level of uranium (and so of the decay products of uranium, some alpha – active) outcrop the surface. If cultures in water pipes concentrate such products in the manner described above, with local populations imbibing the microorganisms, perhaps with a further concentration occurring in the human body itself, the facts would become intelligible. One reason for the siting of the Sellafield reactors was related to the water supply from Eskdale and Ennerdale, it is ironic to notice, and this might be the connection the media have been seeking, an innocent connection that would not be much to their liking if it turned out to be true. Similar conditions obtaining elsewhere would of course produce the same effect, regardless of whether there were nuclear reactors in the districts in question.

Concerning the Oklo reactor, Dr. S.A. Durrani of the University of Birmingham wrote as follows:

> 'Nature, it would seem, had anticipated man by something like 1,800 million years in bringing about the first self-sustained nuclear chain reaction on the Earth. And, contrary to common belief, it was not in the squash court of the University of Chicago in December 1942, but in the wilds of what is today the Republic of Gabon at a place called Oklo that this fantastic phenomenon took place.
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> 'The history of the discovery of the phenomenon, as it unfolded during the symposium, is briefly as follows. In June 1972 a team working under the direction of Dr. H.V. Bouzigues at the CEA service laboratory at Pierrelatte in France noticed a marked anomaly in the abundance of the uranium-235 isotope (0.7171 ±0.0010 in atomic per cent instead of the normal 0.7202 ±0.0006) during the certification of a secondary standard of UF_6 by the gas diffusion method. Later, much larger depletions of this isotope were discovered (down to 0.621%, and eventually to 0.296% U - 235) in uranium samples from this source, which was traced back to the Oklo deposit. First positive proof of the hypothesis that a natural chain reaction was responsible for the depletion of the fissile component was furnished by Mme. M. Neuilly and co-workers of CEA through the measurement of the ratios of fission-product rare earths detected in the ore by the spark source mass spectrometry technique. Two simultaneous submissions by the above two groups on September 25, 1972, to the Proceedings of the Academy of Sciences, Paris, announced the discovery and the proposed explanation of this remarkable phenomenon. It was pointed out that at the time of the reaction the natural abundance of the relatively fast-decaying ^{235}U isotope was more than 3%. This natural "enrichment", helped by the moderation of the fission neutrons by the water content of the soil which enhanced their fission efficiency, and possibly by the relative absence of neutron-absorbing elements in the surroundings, allowed a nuclear chain reaction to develop. It is perhaps worth mentioning that such a natural chain reaction had already been predicted, on theoretical grounds, by several scientists, notably by P.K. Kuroda as early as 1956. The scientific secretary of the symposium, Dr. R. Naudet of CEN, Saclay, has since late in 1972 been leading the "Franceville Project" established by the French CEA to investigate the phenomenon, and has done a great deal to promote its study internationally.'

The first announcement from the CEA laboratory provoked scepticism among nuclear physicists, because of the point alluded to briefly in the above quotation, the need for an absence of 'neutron-absorbing elements in the surroundings'. Very little in the way of elements such as cadmium or gadolinium would have poisoned the reactor, and the difficulty was to see how under aqueous conditions all such neutron poisons could have been conveniently absent. What happened subsequently was that French physicists gathered sufficient evidence concerning the presence of fission products at the site of the reactor to convince the sceptics. But without the problem of neutron poisons being cleared up satisfactorily.

The statement that some bacteria are 'practically uranium eaters' suggested both a possible cause of the Oklo phenomenon and a resolution of the neutron poison problem. Imagine bacteria in comparatively still water precipitating around themselves a high density coating of increasing thickness of some uranium salt, uranium oxide most likely, rather as bacteria precipitate calcarious material to produce stromatolites. The increasing coating would eventually cause the bacteria to sink to the bottom of the lake or pool in which they had been suspended. In the floor of the pool, suppose there to have been a bowl where more and more uranium-coated bacteria accumulated. A stage would be reached at which the growing colony went critical in the manner of a simple boiling water reactor using enriched uranium, the 'enrichment' for ^{235}U being per cent at the epoch of the Oklo reactor. The violent motion associated with boiling could scatter the bacteria in a timescale less than the interval ~30 seconds required for the appearance of the main complement of delayed neutrons, thus maintaining stability should such a system threaten to become seriously supercritical.

All living systems produce a great measure of chemical segregation, accepting some elements and rigorously rejecting others. We have never heard of the elements gadolinium or cadmium being present in living organisms for example. In this way one could elegantly understand the absence of neutron poisons from a biological reactor, thereby overcoming the previously-mentioned difficulty which at first sight had erroneously seemed to obviate the French discovery.

If a so-called 'natural' reactor could arise 1800 million years ago, when the enrichment of ^{235}U was ~3per cent, bioreactors could arise almost trivially one might suppose in the early days of the Solar System when the enrichment was ~30per cent. This likelihood raises the possibility of an escape for life from the present-day straightjacket of temperature, the slim zone here on the Earth between being boiled alive (Venus) and being frozen silly (Mars). With a controlled heat source inside an adequately insulated body, life on the outside of the Solar System in its early history could have adjusted temperature conditions to suit itself.

The sites were planetesimals of various sizes, from a lunar scale down to a cometary scale, with liquid interiors generally at ~300K, surrounded by surface shells of frozen material having low heat conductivity. Superinsulators with porous structures have coefficients of heat conductivity $\sim 10^{-4}$ watt cm^{-1} K^{-1} (c.f. J.E. Parrott and A.D. Stukes, *Thermal Conductivity of Solids*, Pion Ltd., 1975, 143), a value that will be used in the following discussion.

The heat-release process was the one already described above, determined by the precipitation of the potentially fissile elements U, Th, by micro-organisms that subsequently sank towards the centres of the planetesimals where they contributed together to produce a critical reactor which stabilized itself by generating convective motions that mostly prevented the central concentration of fissile material from attaining a runaway supercritical condition (although a recollection of Oort's exploding planet flickers in one's mind at this point).

To estimate the potential amount of fissile material, it seems reasonable to suppose that breeding of ^{232}Th and ^{238}U to ^{233}U and ^{239}Pu could occur in a large measure – from the point of view of reactor technology this should have been 'easy' at a time when the ^{235}U enrichment was so high. Solar abundance tables by numbers of atoms give $(U + Th)/(C + N + O) \simeq 6 \times 10^{-9}$, which is a ratio by mass $\sim 10^{-7}$. This estimate rests on the amounts of U and Th actually found in meteorites, however, which raises the possibility that what has been measured for meteorites are low values subsequent to appreciable denudation by bacterial action. Calculations based on the so-called r-process for the primordial genesis of U, Th have run an order of magnitude higher than the measurements, and here we may well have the reason for this discrepancy – the meteoritic values are not primordial, thereby destroying a hallowed assumption of meteoritic chemists, which by a refusal to question it has attained the status of a religious dogma. If we take an intermediate position, with $(U + Th)/(C + N + O) = 3 \times 10^{-7}$ by mass, we shall not be far wrong.

The output of energy from the total fission of U + Th is $\sim 10^{18}$ erg g^{-1}. Hence with most of the mass of material being C, N, O, on the outside of the Solar System, the fission energy yield per gram from its content of U + Th would be $\sim 10^{18}. 3 \times 10^{-7} \simeq 3 \times 10^{11}$ erg. With $10^{29} - 10^{30}$ gm of C, N, O, the total energy available was therefore $\sim 10^{41}$ erg.

With the material having a density ~ 1 gm cm^{-3}, the mass of a body of radius R was $\sim 4\pi R^3/3$, and the total energy available for release inside the body $\sim 3 \times 10^{11} \times 4\pi R^3/3$ erg, with R in cm. Suppose such a body to have a surface shell of thickness 1 km through which the temperature fell from 300K on the inside to ~100K at the outer surface. With a heat conductivity of 10^{-4} watt cm^{-1} K^{-1} the heat loss through the shell would be $10^3 \times (4\pi R^2)(200/10^5)$ erg s^{-1}, with R again in cm. The heat availability is sufficient to make good this loss for a time T seconds given by

$$10^3\,(4\pi R^2)\,(200/10^5)\,T = 10^{11} \times 4\pi R^3. \tag{24}$$

Or with T in years and R now in kilometres,

$$T \simeq 2 \times 10^8 R \text{ years.} \tag{25}$$

There would evidently be no difficulty for a body of lunar size, $R > 1000$ km, maintaining a liquid condition in its interior, and some comets might have been able to do so over at least the first 500 million years in the history of the Solar System. Excess energy output would simply lead to a thinner surface shell, while a reduction of output would thicken the shell, in effect with the shell thickness adjusting itself to the reactor output.

This solves the problem for the existence of chemoautotrophic biological systems under anaerobic conditions. If we reckon 3×10^{10} erg gm^{-1} as the average chemical energy available for chemoautotrophy, the total for the whole outer Solar System is $\sim 10^{40}$ erg, about an order of magnitude less than the radioactive energy, but still a very large amount. It is here that the considerations of the previous chapter become relevant, that there should be no way to unlock this great store of energy except through biology.

Unlocking the store of chemical energy degrades the material in a thermodynamic sense, which consideration raises a further critical question: Could there be any means of achieving photosynthesis and so avoiding the progressive degeneration due to chemoautotrophy? Very readily, provided fibre optics existed to channel light through the cold surface shell to the reservoir of warm liquid below. A little thought shows that such a possibility is not as fantastic as it might appear at first sight. Since biology has produced eyes with their ability to function over an exceedingly large light intensity range, eyes with sophisticated chromatic and spherical aberration corrections included, and with such acuity of focus that a bird can distinguish small scraps of food from unwanted debris at distances of several hundred metres, fibre optics should not have been any great obstacle. From a physical point of view, such a requirement amounts to combining translucence with low heat conductivity, and also with a high opacity in the infrared, conditions that together would permit the surface shell of material to act as a powerful greenhouse, thus easing the load on the internal heat production considered above, and extending the estimate (25) for the length of time T over which biological activity could continue.

A greenhouse effect could reduce very greatly the thickness of the required outer shell, making the penetration of visible light much less of a problem.

Light penetrates typically about 10 metres through many translucent materials, for example, through water-ice. For a fall of 200K through a 10 metre thickness of material with heat conductivity 10^{-4} watt cm^{-1} K^{-1} the heat flux is 2×10^2 erg cm^{-2} s^{-1}, which equals the flux of sunlight at a heliocentric distance of ~80 AU. This is for sunlight at normal incidence. On a rotating body the generally oblique incidence of sunlight (and no sunlight at all on the dark side) reduces the average flux by 4, so decreasing the corresponding calculated heliocentric distance by 2, from ~80 AU to ~40 AU, i.e. to the outskirts of the present-day distribution of planets. Hence there seems no reason in principle why a vast biological ensemble should not have persisted on the outside of the Solar System over an extended period of several hundred million years, and why it should not have done so in an ongoing replicative state. There seems no reason also why life forms on the Earth, especially among invertebrates, should not have been derived directly from this former condition, assuming a feasible form of transportation being available from the outer regions of the Solar System to the Earth. Comets perturbed by stellar encounters into orbits with perihelion distances $q < 1$ AU are the obvious candidates for such a means of transportation. There appears to be no reason either why bubbles of gas should not become established as vacuoles within the objects, so permitting subaerial biological forms to arise. If the present-day complexities of life can arise by evolution in a biosphere of only $\sim 10^{18} - 10^{19}$ gm, the possibilities for a supersystem with mass $\sim 10^{29} - 10^{30}$ gm would almost surely be immense, especially as collisional interchanges which must have taken place from time-to-time among the many objects would have permitted evolutionary steps to be widely shared among them.

On this view, comets are relics of a former large-scale biological environment existing in the outer regions of the Solar System. The total mass of the relics, say 10^{11} comets of individual masses $\sim 10^{18}$ gm, again enormously exceeds the terrestrial biosphere. The total cometary storage of biomaterial could be as high as $\sim 10^{29}$ gm, and it would be surprising if this large quantity of material had not dominated conditions at the terrestrial surface throughout the history of the Earth. We tend to think the opposite simply because the total mass of the Earth, $\sim 6 \times 10^{27}$ gm, is much greater than the mass of an individual comet. But the total mass of the Earth is an irrelevancy here. It is the mass of the terrestrial biosphere that in the present discussion really counts, and the biosphere matches only a single comet out of the $\sim 10^{10}$ comets which must have passed through the inner regions of the Solar System during the history of the Earth. The weighting factor in favour of comets controlling the evolutionary situation is evidently enormous.

We end this chapter by asking what happens should the nuclear engine inside a comet finally give out? With the internal heat source gone, and yet with heat losses continuing at the surface, the comet must eventually become cold and frozen throughout its interior. If water is an appreciable constituent, a liquid interior inside a solid shell could not freeze without dramatic events occurring, simply because of the volume expansion that water undergoes on freezing. First, as the engine gave out convection currents stirring the liquid would cease, and all solid particles hitherto suspended in the liquid would fall gently towards the centre. Among the particles could be small silicate grains together with other refractories as well as micro-organisms. Hence an aggregate of particles would be deposited by sedimentation, as the carbonaceous meteorites have been formed by sedimentation, and with an admixture of micro-organisms as Hans Pflug finds to be present in these meteorites. The sedimentation would proceed higgledy-piggledy, just as the small particles happen to settle out of the now-unstirred liquid.

Freezing goes progressively from the outside inwards. Water immediately inside the outer shell cannot freeze without space being created for it to squeeze into. However, unlike water freezing downwards in a lake, which can simply lift the surface skin of ice bodily in order to create the needed space, water inside a closed frozen shell cannot lift the shell without cracking it into two halves. This requires a pressure of the order of the tensile strength of hard-frozen ice to develop throughout the liquid interior, $\sim 3 \times 10^7$ dyne cm^{-2}, a pressure which then acts compressively on the central concentration of small particle sediments, just as the carbonaceous meteorites were acted on compressively by a pressure of this order.

If freezing were a discrete one-step affair, an entire cracking of the outer shell into two halves might happen, but with the freezing process occurring continuously, a steady pressure $\sim 3 \times 10^7$ dyne cm^{-2} would be maintained against the inner surface of the shell, and within small cracks as they opened up, probably in many places throughout the shell. The lowest density components of the liquid would be squeezed up into the cracks, and likely enough would eventually emerge at the outer surface of the shell. In such a continuous multicracking process the needed extra space to provide for the expansion of the water would be found through geyser-like spurts of liquid, up through newly-opened cracks, with the liquid welling out and eventually freezing on top of the shell, the needed space being thus found on the outside of the comet. Since there are many organic liquids with densities less than water it would be these that would pour out of the freezing comet in preference to water, so explaining the observed situation discussed in Chapter 2, where we saw that comets typically have highly volatile organic materials deposited on their outer surfaces.

The final picture to emerge of a frozen comet is not of a single fused solid ball, but of an exceedingly complex multicracked affair, with the whole comet internally stressed at $\sim 3 \times 10^7$ dyne cm^{-2}. The situation is analogous to a mass of coiled springs, all ready to go off at a touch, which happens whenever evaporation due to sunlight weakens particular holding points in the structure. Or like a group of drunks leaning on each other – take one out and repercussions are felt throughout the whole party. On this picture a comet would not be exactly the most restful place one might visit. Comets which approach close to the Sun often lose fair-sized chunks of themselves, which separate apart quite gently at speeds of no more than one or two metres per second. If comets were homogeneous solids, the tensile strength of the material would have to be less than 10^5 dyne cm^{-2} to permit this phenomenon (Z. Sekanina in *Comets*, ed. L.L. Wilkening, University of Arizona Press, p.251). Since no well-frozen solid material has a tensile strength remotely as low as this, we can conclude that either a comet is a multicracked ensemble, with bits of itself only very lightly attached to other bits, or the interior material is still liquid.

With $R = 5$ km, (25) gives $T = 10^9$ years. This estimate for the time scale over which a cometary nuclear engine could maintain a liquid condition in the interior is so close to the ages of comets that we might reasonably argue both ways, with smaller comets having undergone freezing, and with larger ones still maintaining liquid interiors, and perhaps still maintaining something of their original biological activity. We are tempted to associate P/Schwassmann-Wachmann I with this condition. The sporadic outbreaks of this comet can then be understood in terms of an accumulation of biochemically-produced gas within the interior, pockets of which break from time-to-time to the surface, expelling visible clouds of gas and particles, perhaps in a similar fashion to the generation of dust storms on Mars.