A MODEL FOR A NON-CHEMICAL FORM OF LIFE: CRYSTALLINE PHYSIOLOGY

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Abstract. A definition of fundamental living units is given according to which they are constituted by the material support of some 'memory'; the latter is required

- to be stable,
- to contain rich information,
- to diffuse it into the surrounding medium.

It is then shown that the complex dislocation networks encountered in crystals can in some cases follow these criteria and lead to a crystalline physiology. The places of possible occurrence in nature of this kind of physiology, terrestrial and extraterrestrial rocks, interplanetary dust, white dwarfs and neutron stars are then discussed.

1. Introduction

The study of alternative (non-chemical) forms of life is useful to understand the qualitative nature of the phenomenon called life. Furthermore life is expected to occur in space outside the Earth. Although most of the studies devoted to extra-terrestrial life are mainly concerned with chemical life on the other planets, it is worthwhile to foresee the possibility of non-chemical forms of life. (Otherwise searches for life on other planets and attempts at interstellar communication could have less chances of success.)

It is in this spirit that the author has studied a form of life which can occur in the crystalline phase of matter.

I will successively discuss three points:

(1) What is life?
(2) A model of crystalline physiology.
(3) Possible places of occurrence in Nature.

2. What is Life?

Molecular biologists (Eigen, 1973) usually characterize life by objective properties like

- self-reproduction,
- variability and selection,
- adaptation,
- metabolism.

These characteristics do not constitute a *definition* of life but are *properties* of what we have previously recognized as living (on the Earth) on intuitive and subjective grounds. I think that there is no objective definition of life (especially of extra-terrestrial life) but only a subjective definition: we will decide that a system is 'living' when we will have relations with it (essentially based on communication) which will appear to us sufficiently rich, interesting, complex. Since any type of

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communication needs a physical support, the system considered must itself have (or be) a complex physical structure. The living systems on the Earth have a hierarchical structure of the following type: living system → organs → cells → 'central memory' (DNA). The transition from one stage to another in this scheme may be contingent and have no logical necessity. One could treat the problem at any of these levels. But molecular biologists are used to build the macroscopic from the microscopic. Since there is no other well established working method, I will thus restrict myself to the aim of finding a model of 'central memory.' It will be required to have the fundamental characteristics of DNA:

- to be stable,
- to contain rich information,
- to diffuse, thanks to a reading mechanism, this information into the surrounding medium (protein synthesis in the case of the cell).

These will be the minimal characteristics of what I shall call a physiology.

3. Model for a Crystalline Physiology

The type of 'central memory' I look for must occur in a state of matter which allows for complex structures. A promising possibility is offered by dislocations in crystals. A dislocation is an imperfection in the regular structure of the crystal. It has the following property: A 'square' circuit around the dislocation consisting of four linear sequences with the same number of atoms does not close onto itself. The vector joining the beginning of the circuit to its end is called the Burgers vector of the dislocation (see Figure 1). In the two-dimensional representation of Figure 1, the dislocation is reduced to a point. In the three-dimensional physical space, they are in the form of lines. The world of dislocations is very rich; it thus constitutes a good candidate for the physical realization of complex phenomena required for a physiology. To be more specific, the main facts at the basis of models one can envisage are then:

(1) Line dislocations in crystals are often in the form of loops or networks.

(2) When a mechanical stress σ is applied on a crystal, the force per unit length exerted on a dislocation is $F = b\sigma$ (b is the Burger's vector of the dislocation). This force makes the dislocation glide in the crystal.

(3) A dislocation can be blocked (pinned down) at some of its points, where there is an impurity atom of the crystal or an intersection with another dislocation. The dislocation does not glide at these points when a stress is applied on it. A pinned dislocation presents a barrier to the motion of another one: the intersection of two dislocations needs an applied stress $\sigma_1 = \mu b/d$ (where μ is the shear modulus of the crystal, d the length of the moving dislocation). Consider then two intertwinned loop dislocations (Figure 2); here d is roughly the diameter of the loops. From an elementary point of view, if $\sigma < \sigma_1$, this system is stable and will split only if $\sigma > \sigma_1$. This intertwinning of dislocations is the key trick with which I shall try to construct models for physiology.

(4) When a stress σ acts on a line dislocation with pinned ends, it can generate from the latter a loop dislocation leaving, at the end of the process, the initial line dislocation intact. In Figure 3, five steps of the process are shown. I shall

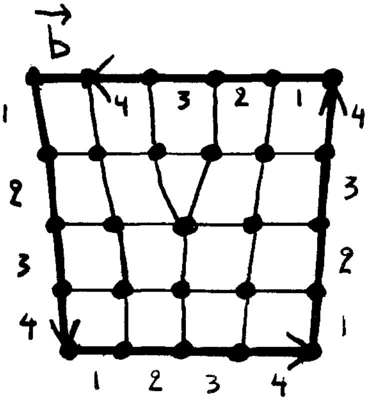

Fig. 1. Burger circuit around a dislocation. **b** is the Burger vector.

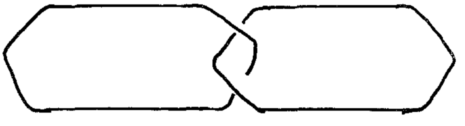

Fig. 2. A pair of interlocked dislocation loops.

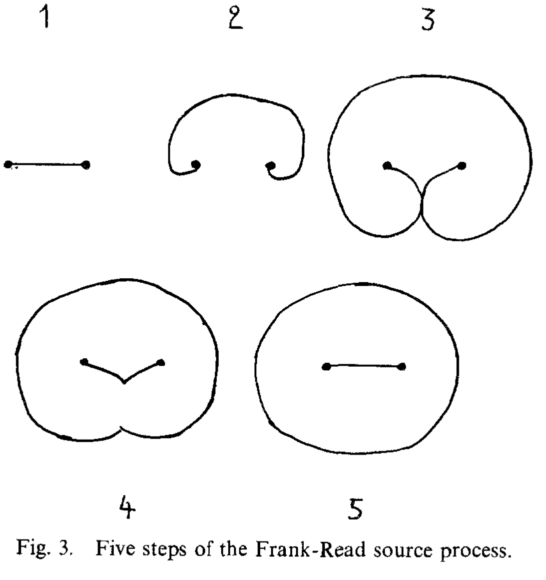

Fig. 3. Five steps of the Frank-Read source process.

symbolize this mechanism, named the Franck-Read sources, (Friedel, 1964) in the way shown in Figure 4. This mechanism is effective when $\sigma > \mu b/l$ where l is the distance between the pinning points.

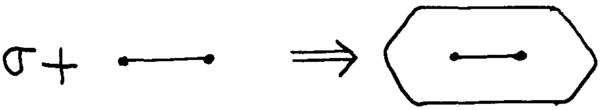

Fig. 4. Schematization of the Frank-Read source mechanism.

For the physiology I seek, I suggest in a first model the use of several kinds of complex interlocking chains of dislocation loops like that shown on Figure 5.

These chains could be the material for some kind of 'molecular biology'. Some of them could play the role of DNA, others that of 'proteins'. Then the information can be represented by the topological type of these chains; the precise shape of the loops is here of no importance.

Fig. 5. Complex chain of dislocation loops.

The 'dislocational' reactions can be made of the elementary reactions shown in Figure 6.

We thus have complex chains which

- are stable,
- can contain rich information,
- can diffuse it into the surrounding through complex sets of dislocational reactions.

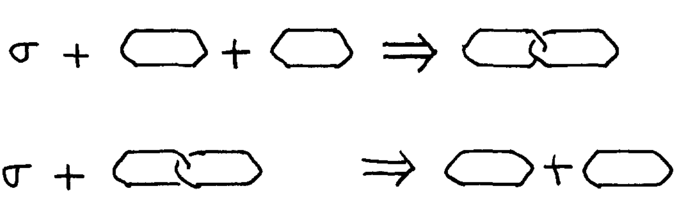

Fig. 6. Schematization of a 'dislocational' reaction.

This is a first model of physiology. Just to show the variety of models one can try, here is a second example: consider a network of dislocations for instance of the type shown in Figure 7. It can clearly contain a high degree of structural (topological) information. Here the reading mechanism I suggest is an application of Franck-Read sources. When an oblique stress acts on an element of the network, it can produce a pair of linked loop dislocations (Figure 8). Thus it is conceivable that a network like in Figure 4 can generate by the Franck-Read mechanism, a complex chain of interlocking loops. The whole process would then be similar to protein synthesis starting from DNA.

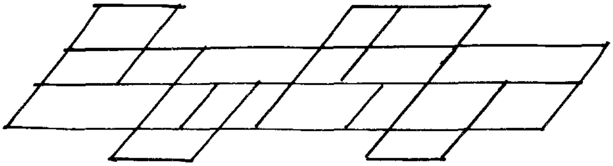

Fig. 7. A dislocation network.

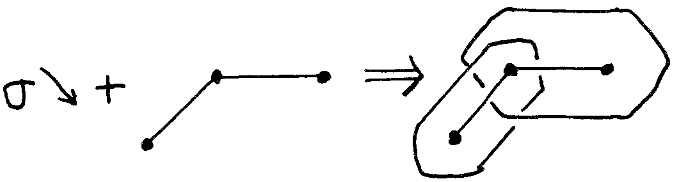

Fig. 8. Production of a pair of interlocked loops by the Frank-Read mechanism from an elementary network.

The elementary structures could then organize themselves in macroscopic 'intelligent' organisms.

In models of physiology of the above type, the energy required for the process taking place has a mechanical origin. The solid inside which the above mechanisms are supposed to take place must be submitted to some external constraints.

4. Where can Crystalline Physiology Occur in Nature?

There are four types of natural bodies which are known or supposed to be solids:

- the rocks on the Earth and other planets,
- the interplanetary or interstellar dust grains,
- the white dwarfs,
- the crust of neutron stars.

The cosmic dust is not interesting for the present purpose because there is no source of mechanical stresses which can cause the glide of dislocations. Furthermore, the grains are too microscopic to contain macroscopic dislocational structures.

In the case of planets, including Earth, the energy source for the crystalline physiology described here is of seismic origin. For the stars (white dwarfs, neutron stars), the energy required is stored in the rotation of the stars. The stresses continuously needed can have two origins. First, they can be due to the incessant rearrangement in the crust or the core due to the slowing down of the star rotation. Or, for neutron stars they can be due to frictions at the boundary of the superfluid and the crust or the core, due to the differential rotation of the star; these frictions can then induce the required stresses in the form of acoustic waves.

5. Conclusion

Of course there are still objections which can be made to this model. It is not only too elementary but, for instance, there is a more serious difficulty: networks or chain hardly move globally without being broken or one does not see what kind of 'replication' mechanism could take the place of networks. To escape the first difficulty, one could for instance introduce displacements realized by grain motion when there exists a liquid solid core interface: otherwise the crystalline life would be condemned to immobility. Nevertheless the suggestions made here show that the possibility of complex structuration is not completely excluded. One could also ask why should life not exist in this form in terrestrial rocks? The answer is probably that the chemical branch was more favourable than the dislocational one.

It has been speculated by F. Dyson (Sagan, 1973) F. Drake (1973) and myself (Schneider, 1975) that life based on nuclear rather than electromagnetic forces could perhaps develop inside neutron stars. One could hope that the model proposed here could serve to build a nuclear physiology inside the crystalline neutron core which may exist (Pines *et al.*, 1972; Anderson *et al.*, 1975) in some neutron stars. But this core is a quantum crystal whose dislocations are too instable (a few 10^{-21} s) to constitute a model of memory satisfying the criteria required in Section 2. Thus the question of finding a model of nuclear physiology is still open.

In conclusion, the author thinks that the details presented here may perhaps not be effectively realized. But the various technical objections one can make to such a model can not be definitive, because the range of validity of physical conditions required for crystalline life might be very narrow, and that is just what seems to be the case on the Earth for chemical life.

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