ON THE OCCURRENCE AND APPEARANCE OF GALACTIC LIFE FORMS : A THERMODYNAMIC APPROACH.

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ABSTRACT. Biological life is an evolving complex dissipative structure, in the sense introduced by Prigogine. The question is considered how life in an advanced stage of evolution manifests itself to an outside observer. Fundamental uncertainties are inherent to the process of self-organization as manifested by dissipative structures. Their evolution is determined by stochastic fluctuations in far from equilibrium conditions, where instabilities arise that cause bifurcations in the behavior of the process system. Since no specific physical or chemical properties of extraterrestrial life can be predicted, general characteristics based on fundamental thermodynamic principles should guide us in our SETI programs. A biological system necessarily must be macroscopic, open with regard of the rest of the universe, and far from thermodynamic equilibrium. The processes within the system must be strongly nonlinear. We should therefore look for life in environments that are in a stationary far from equilibrium state, such as planetary surfaces and cool interstellar molecular clouds, where an extreme nonequilibrium exists between radiation and kinetic temperature. In any case an advanced form of life should manifest itself by a large entropy emission, possibly carried by low-grade energy radiation, and propably not by information-rich communication channels intended for internal process regulation.

1. General characteristics of life.

Life is a remarkable natural phenomenon of self-organization of matter. It develops in an environment out of thermodynamics equilibrium, and it builds upon the irreversible processes that occur spontaneously in a state of nonequilibrium.

A necessary condition therefore is that the system in which life grows (the "biosphere") is open with regard to the rest of the universe. In this way matter and energy that feed the processes can be supplied to the system, and the degraded energy and waste products that inevitably are produced by the irreversible processes, can be removed from the system.

M. D. Papagiannis (ed.), The Search for Extraterrestrial Life: Recent Developments, 255–259.

Biological organisms organize their processes in such a way that their entropy production is high, but the entropy is removed efficiently from the system. This behaviour is characteristic of dissipative structures, as introduced by Glansdorff and Prigogine (1971), of which biological systems may be regarded to be very complex chemical examples. A necessary condition for dissipative structures to form is that the processes occurring within the system are nonlinear. In biological systems the nonlinearity arises form the many autocatalytic and crosscatalytic reaction steps in the metabolisms. For such nonlinear processes it has been shown that instabilities may arise allowing small fluctuations within the system to be amplified, and to further determine its future evolution. Beyond a critical instability point bifurcations occur in the solutions of the system of equations. New solutions arise with physical characteristics that cannot be explained by classical equilibrium thermodynamics, manifesting themselves by their highly ordered spatial or temporal structures.

New solutions that grow from small fluctuations will survive only if they acquire some degree of stability. For this to happen, the structure has to be macroscopic in the sense defined by statistical mechanics. The stability of a system depends on the magnitude of its fluctuations. The larger these fluctuations, the less the system is stable. However the magnitude of the fluctuations of a system is inversely proportional to the square root of the number of particles constituting the system. For a structure to exceed and to survive local noise, it has to be macroscopic.

Due to their internal process dynamics, dissipative structures keep however the capability of transformation. Small fluctuations may be amplified and induce innovation in the system, leading to a new, more or less stable configuration. It is here that appears a new ordering principle, called "order through fluctuations" by Prigogine (Prigogine et al. 1972). The order of a dissipative structure corresponds with the nonlinear amplification of small deviations from the reference state of the system (arising, for example, from external perturbations), and their ultimate stabilization by the flow of matter and energy through the system.

The formation of fluctuations is a stochastic process. As long as the system damps the fluctuations, its behaviour obeys the deterministic laws of classical thermodynamics, expressed in terms of macroscopic variables. But when fluctuations are amplified they are able to drive the system towards new behavioral regimes and classical descriptions break down. Therefore evolution is deterministic in stable regimes, as in a near to equilibrium state, but stochastic near the transition threshold of instabilities, such as encountered far from equilibrium. This makes biological evolution an essentially unpredictable course of events. Life as other more simple dissipative structures, is subjected to an evolution that is not determined by its initial conditions, but is created along the way. Spontaneous innovations occur, and these make evolution a process of creation and invention, uncertain and unpredictable at each moment as to the direction of its future course.

2. Essential properties.

In view of these fundamental uncertainties we have to discard all attempts to guess the characteristics or typical features and physical properties of extraterrestrial life. It is conceivable that at this very moment we observe phenomena that are manifestations or products of advanced extraterrestrial life forms, but that we are unable to recognize their true nature. It should be realized too that the order in a biological structure is functional and specific; one may say that it has only a subjective meaning. No regular mathematical patterns recognizable by whatever universal property have to be expected. If the polypeptide chain of a terrestrial protein had to be investigated by an extraterrestrial he would be unable to find any kind of meaningful order in the sequence of amino acids. The distribution of the amino acids in the chain appears to be completely random. The highly structured order of this molecule might remain hidden since it only manifests itself in its associative stereospecific functions, operative in the context of a coherently functioning organism.

Since it is not feasible to guess the features that are the result of a biological evolution, we should concentrate on essentials, not on features.

It is essential for a biological system to be open to the rest of the universe, making it in principle always observable (not necessarily intelligible). Moreover it is essential for a biological system to be far from thermodynamic equilibrium and consequently it has to be a source of entropy. In our search for extraterrestrial life we should look therefore for non-relaxing nonequilibrium environments, consuming free energy and emitting waste and heat in their surroundigs. The phenomena that are displayed and produced in such places could be related to (or could be) biological processes.

Survivability of a life form is ensured by the stability of its structure, and its evolutionary history by its instability. Hence any advanced life has to display a certain degree of both. Too much stability would stop evolution, in fact it would lead to death since a dominance of stability is characteristic of state of equilibrium. Any remaining structure has a cristal-like pattern, not a functional biological order. Too much instability would inevitably lead to a runaway situation resulting in desintegration of the structures. Instability it a consequence of complexity, since complexity increases the number of possible bifurcations of the system state. On the other hand, stability of a non-equilibrium state can only be enhanced by increasing the size of the system and allowing fast communications within the system. In large system the influence of small fluctuations is diminished, and fast communications allow a coherent and coordinated reaction on the system to perturbations.

It seems reasonable to assume that extraterrestrial life in advanced state of evolution should have expanded far beyond the boundaries of a single planet (as terrestrial life now is starting to do), and at the same time keeping contact between its many organs, populations or whatever subsystems, by means of high quality communication systems.

3. Where should we search ?

Perhaps the search for extraterrestrial life until now has concentrated too narrowly on concepts of biology that are too specifically earth-related. We are inclined to be excited when hydrocarbons or amino acids are found in an extraterrestrial environments, regarding them to be possible precursors (or products) of a biological evolution, even though the place is, such as the jovian atmosphere, a chemical reducing environment, where such compounds are quite in chemical equilibrium. Despite their resemblance with terrestrial organic molecules, these products in a nonoxidizing atmosphere are as a-biotic as silicates on earth.

Therefore we should concentrate less on substance, and more on phenomena. A chemical vessel, containing an oscillating Belousov-Zhabotinsky reaction, is more a form of "primitive life" than a mixture of polypeptide chains in an hydrogen rich environment.

According to the criteria established above, we should look for places in permanent thermodynamic nonequilibrium. Although planetary surfaces, with their relatively cool temperatures embedded in a high temperature radiation field of their nearby sun, are appropriate places in this respect, interstellar space could be more promising, especially within cool molecular clouds. Here the radiation field is dominated by hot O and B stars, and has a blackbody spectrum of about 30000 K. However the kinetic temperature of the gas in these clouds is only about 100 K, or less. We thus have an extreme thermal nonequilibrium that could be the source of many irreversible processes. Interstellar space may be better suited for advanced life than the hot and noise-rich immediate surroundings of stars where planets are found. The interstellar medium offers more possibilities for growth and diversification than planetary surfaces, restricted by limited resources and their inevitable gravitational wells.

Despite intrinsic difficulties of interpretations the chances to detect advanced life forms beyond the solar system are probably better than those of finding primitive life. Terrestrial life in its present technological stage is detectable (with terrestrial technology) over interstellar distances, due to strong narrow-band television and radar emissions (Sullican et al., 1978). Although the terrestrial case may be irrelevant in general, openness is an essential characteristic of life, and other biological forms also may manifest themselves in a conspicuous way. However the present terrestrial radio emissions are an inefficient behaviour of probable temporal character. The emission are intended for internal use and should not leak from the earth (except for some rare astronomical radar experiment or CETI attempts). It seems doubtful that a search for information-rich emissions will ever succeed in detecting an advanced form of life. Any advanced biological structure should rather manifest itself by its high rate of entropy production and consequent entropy removal. Hence intense radiation of low energy photons emerging from nonrelaxing nonequilibrium systems, could be a sign post of advanced biological activity.

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