More than planetary-scale feedback self-regulation: A Biological-centred approach to the Gaia Hypothesis

Sergio Rubin and Michel Crucifix

Georges Lemaître Centre for Earth and Climate Research, Earth and Life Institute, Université catholique de Louvain. Place Louis Pasteur 3, SC10-L4.03.08 B-1348 Louvain-la-Neuve, Belgium. e-mail: sergio.rubin@uclouvain.be , Tel: +32 10478501

(*This work is under consideration for publication by The Journal of Theoretical Biology*)

Abstract

Recent appraisals of the Gaia theory tend to focus on the claim that planetary life is a cybernetic regulator that would self-regulate Earth's chemistry composition and climate dynamics, following either a weak (biotic and physical processes create feedback loops), or a strong (biological activity control and regulates the physical processes) interpretation of the Gaia hypothesis. Here, we contrast with the regulator interpretation and return to the initial motivation of the Gaia hypothesis: extending Schrödinger's question about the nature of life at the planetary scale. To this end, we propose a relational and systemic biological approach using autopoiesis as the realization of the living and the (M,R)-system as the formal theory of biological systems. By applying a minimum of key categories to a set of interacting causal processes operating on a wide range of spatial time scales through the atmosphere, lithosphere, hydrosphere, and biosphere of the Earth system, we suggest a one-to-one realization map between the Gaia phenomenon and (M,R)-Autopoiesis. We show that metabolic molecular *self-production* by *closure to efficient causation* on a planetary scale is plausible. This suggests that the Gaia phenomenon may be the embodiment of *Life itself in the planetary domain,* a *sui-generis biological unity* and thus more fundamental than self-regulation by feedback mechanisms. Formulating the Gaia theory in biological terms provides a formal basis for the claim that planetary biology elsewhere in the universe must involve and have a formal equivalence to a self-referential physical process which cannot be implemented by a Turing machine and, therefore, has a non-computable character.

Keywords: *Schrödinger's question, (M,R)-systems, Autopoiesis, Self-production, Closure to efficient causation.*

1. Introduction

Lovelock's hypothesis that Life is a planetary-scale phenomenon (Lovelock, 1979) followed attempts to detect life on other planets by inspecting absorption spectra of their atmospheres (Lovelock, 1965). The underlying idea was that chemical disequilibrium would be the signature of life on a planetary scale (Hitchcock and Lovelock, 1967; Lovelock and Giffin, 1969, Lovelock, 1972), thereby extending Schrodinger's (1945) characterization of life as maintaining '*negative entropy*'[1] at this planetary scale. The land-based measures of Mars's atmosphere spectra then revealed that Mars's atmosphere is in chemical equilibrium, hence, lifeless (Lovelock, 1975, 1980). In contrast, Earth's atmosphere is in chemical disequilibrium because of the continuous biological production of a molecular mixture of highly reactive gases (Margulis and Lovelock, 1974). The claim that life is a planetary phenomenon was later coined the *Gaia hypothesis* (Lovelock and Margulis, 1974).

The Gaia hypothesis has motivated a 'research programme' (Margulis and Sagan, 1997) on which experimental evidence show how biological activity affects Earth's dynamics (Lovelock 2003a). Today, it is not much disputed that Earth's climate, water, and trace elements dynamics involve biological activity on a wide range of time and spatial scales. Examples include i) metabolic-enhanced rock weathering, ii) the existence of a cloud albedo feedback to algal gas emission, iii) geological evidence that the Archaean atmospheric chemistry dominated by methane, iv) the metabolic production and balanced levels of oxygen in the atmosphere, v) impact of boreal forest and biodiversity on local and global climates, and vi) ocean to land transfer of elements by biogenic gases. These empirical evidences have framed the present-day *Gaia theory* (Thompson, 1991, 1987; Bunyard and Goldsmith, 1989; Barlow, 1992; Bunyard, 1996; Schneider and Boston, 1992; Schneider et al., 2004; Crist et al., 2009).

However, as we argue in Section 2, much of the theoretical work associated with the Gaia hypothesis addressed the question of whether life on Earth 'regulates' Earth's climate, and therefore appeals to the notion of self-regulation by 'feedback mechanisms' which are a legacy of the development of cybernetic systems (Wiener 1948; Von Foerster et al., 1951; Ashby 1956). Lovelock originally, and later with Margulis, advocates the notion that Gaia is a "*a biological cybernetic system able to homeostat the planet for an optimum physical and chemical state appropriate to its current biosphere"* such that *"life moderates the global environment to make it more favorable for life"* (Lovelock, 1972, p. 579). That is, the physiological conditions of Earth were *regulated by* and *for* the biosphere (Lovelock and Margulis, 1974). However, initially this conception has been viewed as teleological and implausible to any neo-Darwinist mechanism of evolution (Doolittle 1981). Lovelock and Margulis later used slightly different heuristic explanatory notions to represent and maintain the Gaia hypothesis strictly in the scientific field, and to dissociate teleology from it. Over time, advocates and opponents have used or proposed other multiple explanatory notions, and different catalogs and dictionaries to address the Gaia hypothesis. It is therefore no wonder that the epistemological status of the Gaia hypothesis -as Life as planetary scale phenomenon- grew unclear and controversial (Schneider 1986; Kirchner, 2002; Lenton and Wilkinson, 2003; Lovelock, 2003b; Margulis, 1993; Kleidon, 2002, Volk, 2003, Margulis 2004, Lenton and Latour, 2018). We argue therefore that a clear-cut mathematical formulation of the Gaia hypothesis is necessary. It could focus, reinvigorate, and consolidate the Gaian research programme towards the recognition of central features associated to biological phenomenon such as cognition and learning across scales of organization.

The present article attempts to place some key biological formal theory and clear-cut characterizations of living systems in the hope to identify a common and unified grounding to the Gaia hypothesis. We propose a biological-centred formal framework of the Gaia hypothesis based on the language of relational and systemic biology. In Section 2, we distinguish the Gaia phenomenon, the Gaia hypothesis and the Gaia theory. Section 3 outlines the steps leading towards a theoretical biology framework of the Gaia hypothesis with reference to Autopoiesis and the (M,R)-system. Section 4 establishes the Gaian Autopoiesis through the modelling relation between Autopoiesis and Gaia. In Section 5 we establish rigorously the theoretical ground of the Gaia hypothesis in terms of the (M,R)-system. Section 6 outlines briefly some implications of biologizing Gaia theory in Daisyworld mechanisms. Finally, section 7 summarizes the paper.

2. Gaia hypothesis: Asking Schrödinger's question in the planetary scale

The Gaia phenomenon is the perception, distinction and recognition of the phenomenon of life on a planetary scale from the differential observables of planets like Earth, Mars or Venus. As Lovelock stated: "A*t present most biologists can be convinced that a creature is alive by arguments drawn from phenomenological evidence"* (Lovelock, 1972, p. 579). The observation that Earth is qualitatively distinct from Mars and Venus, therefore, provides the recognition of the Gaia phenomenon, and thus the expression of the Gaia hypothesis: Life as planetary scale phenomenon (Lovelock and Margulis, 1974; Lovelock, 1979)(Fig. 1).

The formulation of the Gaia hypothesis was fundamentally influenced by the question of Schrödinger's book 'What is life?' (Schrödinger, 1945). As Lovelock wrote: "*Erwin Schrödinger, whose small volume What is life?*[...] *was, I would say, the book that most influenced my own thinking"* (Lovelock, 1986, p. 646). That is, from a scientific standpoint, the most important challenge in the formulation of the Gaia hypothesis, from the observation of Gaia phenomenon, was and still is to extend Schrödinger's question to the planetary scale: what is planetary life? Is life a planetary phenomenon? As he wrote it: "*life has bulk properties and needs to be considered on a planetary scale"* (Lovelock, 1986, p. 646).

The first prediction of the Gaia hypothesis as Schrödinger's question in the planetary scale was confirmed: at the planetary scale, Mars is a lifeless planet. Yet, paradoxically, the present-day Gaia theory sidesteps the Gaia hypothesis. Either their supporters or opponents implicitly assume that *Life* must be, on a planetary scale, a stabilizing or a destabilizing *regulator*. The regulator thesis refers to cybernetic systems, which are systems with a specific organization to self-regulate by feedback mechanisms (Wiener 1948; Von Foerster et al., 1951; Ashby 1956). It has been stated that every good regulator of a system must be a model of that system (Conant and Ashby, 1970). Following the cybernetic paradigm and around the notion of the regulator, the Gaia hypothesis has been taxonomized, reinterpreted (weak and strong interpretation), and then refuted (Kirchner, 1989, 1990). In the weak interpretation of the Gaia hypothesis, both the biotic and physical processes create feedback loops and are coupled regulators (Kirchner, 1989). In the strong interpretation, the biological activity is the regulator, and it controls the Earth chemistry and physical processes (Kirchner, 1989). That is, the Gaia hypothesis, hence the phenomenon of life at the planetary scale, is reduced to an epiphenomenon of chemical and climatic regulation by negative or positive feedback mechanisms in the Earth system, as can be deduced from Kirchner's (1989, p. 225) own argument: "*Margulis and Lovelock (1974) propose that 'a test for Gaia is to consider what would happen if life were now deleted from the Earth.' This is of course, a test for life, not a test for Gaia*" (the underline is ours). Clearly, Gaia hypothesis is disentangled from the Schrödinger's question. Therefore, the Gaia hypothesis is obliterated to become amenable to testing and falsification (Kirchner, 1989, 1990).

In summary, the regulator thesis along with the neo-Darwinism confines the present-day Gaia theory to the weak and strong interpretations of the Gaia hypothesis. Indeed, much of the present-day Gaia theory addressed the question on what time-scale natural selection 'regulates' Earth's chemistry and climate. Whether it is at local, regional or at the planetary scale. Under the weak interpretations, the *adaptationist programme* (neo-Darwinism)(Gould and Lewontin, 1979; Nielsen, 2009) of natural selection (Darwin, 1859) provides the evolutionary background for explaining whether self-regulation can be explained by mechanisms involving and units of selection, competition, cheating and selfishness (Lenton, 1998, Lenton and Lovelock, 2000; Staley, 2002; Williams and Lenton, 2008, Doolittle, 2017). It also features explicative notions such as selection by survival alone, and progress by accumulation (Doolittle, 2017; Lenton et al., 2018). On the other hand, under the strong interpretations, homeostasis and optimization (Cannon, 1929) provide the explanative framework to address the thesis of self-regulation at the planetary scale. Homeostasis is framed mathematically in terms of the first-order cybernetics (Wiener, 1948), self-organization (Ashby, 1947; 1962a; Von Foerster, 1960) and ultrastability (Ashby, 1956a, 1952). The possibility of self-regulation at the planetary scale is explored with heuristic models such as Daisyworld (Watson and Lovelock, 1983), 'complex adaptive' systems (Lenton and van Oijen, 2002; Levin, 2005, 1998; Schwartzman, 2002) and sequential selection (ultrastability) (Lenton et al., 2018). When Gaia is seen as a system with many degrees of freedom, the possibility that it may optimize certain quantities finds some justification in the theory of irreversible far-from thermodynamic equilibrium (Nicolis and Prigogine, 1977) along with information theory (Shannon, 1948). Life would enhance and maximize entropy production (Karnani and Annila, 2009; Kleidon, 2009, 2004; Kleidon and Lorenz, 2004; Toniazzo et al., 2005) and reduce planetary scale gradients (Sagan and Whiteside, 2004).

In conclusion, the present-day Gaia theory is neo-Darwinized (it has been made compatible with the adaptationist programme) and physicalized (Gaia can be simulated by dynamical systems using thermodynamics and cybernetics) to fit the notion of *Life* as a planetary regulator (Fig. 1). They are important contributions because they outline possible mechanisms of planetary self-regulation across scales. However, we argue that they obliterate Schrödinger's question as the fundamental motivation of Gaia hypothesis. Indeed, certain abiotic systems display a form of self-regulation. For example, the thermostat is an evolving ultrastable machine able to regulate the temperature by feedback mechanisms (Ashby, 1952, 1956b). Mechanisms of regulation by feedback loops have been described on lifeless planets such as Mars (Chassefière, 1991; Ng and Zuber, 2006). Abiotic geochemical cycles, such as that of nitrogen, are plausible on a planetary scale (Laneuville et al., 2018). The concept of negative entropy also appears to fall short for characterizing life. Irreversible, far-from equilibrium states, symmetry breaking, and self-organization take place in abiotic systems such as Bénard convection cells or dissipative systems (Fodor et al., 2016; Sanchez et al., 2012). Chemical disequilibrium and far-from-thermodynamic equilibrium of exoplanets atmospheres have been identified in inhabitable planets (Krissansen-Totton et al., 2016). Thus, self-regulation, self-organization, chemical disequilibrium, geochemical cycles and even adaptive behaviour can and do appear in inanimate systems. Furthermore, from a strict thermodynamic perspective, the entropy of living systems does not appear to be particularly low (Martyushev, 2013). With these considerations at hand, we see that the Gaia hypothesis as the Schrödinger's question support the claim that the Gaia phenomenon is the manifestation of something more than self-regulation and the postulations behind the present-day Gaia theory. It involves more than organisms-environment coupled co-evolution, and more than the Earth system viewed as a planetary system far from thermodynamic states with feedbacks and geochemical cycles due to geochemistry and geophysics alone (Lovelock, 2009).

A parallel may be drawn with the cellular phenomenon. To fabricate a living cell, we need more than the concatenation of biosynthetic cycles (Calvin cycle, tricarboxylic cycle, etc), gene regulation by feedback circuits (such as operon Lac or ribosomal operon) and active matter (Fodor et al., 2016; Sanchez et al., 2012). Likewise, bringing an inert planet far from thermodynamic equilibrium states with feedbacks and a selection of geochemical cycles would arguably not yield the Gaia phenomenon. Therefore, the Schrödinger's question remains the key to how best pose the Gaia hypothesis (Lovelock, 1986; Margulis and Sagan, 1995). The answer to this question is the scope of the next section.

3. Towards the theoretical biology of the Gaia phenomenon

Biological analogies permeate the language around the Gaia hypothesis. Some renowned biologists like Lewis Thomas state that *'the Earth* [...] *if not like an organism* [...] *is most like a single cell'* (Thomas, 1974, p. 5). More recently, Harold Morowitz wrote "*the metabolic character of life is a planetary phenomenon, no less than the atmosphere, hydrosphere, or geosphere"* (Morowitz et al., 2008, p. 8). These claims appear today compatible with the Gaia hypothesis, if not defining it.

Since the beginning of physiology, the realization of the living of a biological system is characterized by the maintenance of its internal physiological bounds, despite forcing fluctuations and dissipation. Claude Bernard noted that "*All the vital processes, varied as they are, have only one object, to maintain the uniformity of the conditions of life in the internal milieu"* (Bernard, 1878, p. 84). This asymmetry between external and internal conditions is thus broadly recognized as important characterization of biological systems. Following the notion of conservation of the *internal milieu*, Lovelock (1991) and Margulis (1990, 1997) considered that the Gaia phenomenon can be characterized as a biological system: "*Different from a physicist, biochemist and neo-Darwinist's view…*[Gaia is]*… a bounded system that is open to a flux of energy and matter, and that is able to keep its internal conditions constant, despite changing external conditions"* (Lovelock, 1991, p. 29 brackets are ours). Or: *"Cells and Gaia display a general property...: as their surroundings change unpredictably, they maintain their structural integrity and internal organization"* (Margulis, 1997, p. 267). Furthermore, they recognized that instead of planetary homeostasis, "*Gaia's history* [ontogeny] *is characterized by homeorhesis with periods of constancy punctuated by shifts to new, different states of constancy"* (Lovelock, 1991, p. 141 brackets are ours), or "*Gaia…like the physiology of an embrio, is more homeorhetic, than homeostatic"* (Margulis, 1990, p. 866). Homeorhesis indicates system dynamics with potential transitions to multistability and stability of dynamics rather than stability of states. Waddington (1968, p. 12) indeed suggested that what "*is being held constant is not a single parameter but is a time-extended course of change, that is to say, a trajectory"*. In summary, a biological system responds to a perturbation (forcing fluctuations and dissipation), thus maintains its internal physiological bounds, by returning to a homeorhetic trajectory, not to a homeostatic state.

Since the development of cybernetic systems, the response to perturbances appealed to the notion of self-regulation by feedback mechanisms. There is, however, an alternative explanation why biological systems maintain their homeorhetic trajectories within physiological bounds. It relies on *self-fabrication* by *closure to efficient causation* in the (M,R)-system (M=metabolism, R=repair) (Rosen, 1991a, 1972, 1958) and *self-production* by *operational closure* in autopoiesis (auto=self, poiesis=production) (Maturana and Varela, 1980) characterization (Fig. 2). These explanations have become important, because for a process to be regulated, it must first be produced. That is to say, the material production precedes the regulation (Rosen, 1991a, Maturana and Varela, 1980). Therefore, it is logical to pay attention first to how the systems are constituted materially, to later study how this material production may or may not be regulated. This reflects 'what life *does'* as to best represent 'what life is', thus a way to answer Schrödinger's question (Cornish-Bowden and Cárdenas, 2017; Friston, 2013; Letelier et al., 2011; Maturana, 1980; Piaget, 1967; Ramstead et al., 2018; Rosen 1985, 1991a; von Foerster, 1974).

The (M,R)-system outlines the inferential aspects of a formal system, hence the theoretical characterization of biological systems in mathematical language (Fig. 2A). Based on the (M, R) formal system, Rosen states: "*a material system is an organism if, and only if, it is closed to efficient causation*" (Rosen, 1991a, p. 244). Rosen (1972, 1985a, 1994b) identified an efficient cause with the enzymatic 'active site' which is the operator that induces or constrains the material flow of unlikely chemical reactions, and thus, it is the generator of forcing (Jee et al., 2018). The active site is only found in the tertiary structure and three-dimensional form of an enzyme. It determines the catalytic activity of the enzyme, and is configured in the protein folding (phenotype at very basic molecular level). Protein folding is not predetermined in the DNA/RNA sequence, hence the 'active site' is not coded in the genomic sequence. It is non-isolable and non-fractionable from the folded enzyme which is produced, specified and determined only in the realization of the living of biological systems (Rosen, 1991a).

Self-fabrication by closure to efficient causation take place when the (M,R)-system models a biological system selecting a set of elements A (matter and energy) of its environment and effectively transforms them in B by its catalytic function F. The function F represents the efficient cause of this transformation. This reads F: A→B (Fig. 2A). However, the efficient cause F is subject to dissipation, and therefore needs to be repaired, fabricated, produced and replaced. A new efficient cause is introduced, the repair function ϕ which takes B as material cause to produce F. This reads ϕ: B→F. But the efficient cause ϕ is also subject to dissipation, and therefore needs to be fabricated and produced as well. It requires another efficient cause, and then yet another efficient cause for the production of this efficient cause, and so on infinitely. The (M,R)-system could, of course, be simply augmented with another mapping that would do it, but this would lead to an incipient *infinite regress*[2]. Instead of invoking efficient causes ad infinitum, the nontrivial key point in the (M,R)-system formal representation of biological systems is that the efficient cause (repair function) ϕ is fabricated from inside, rather than from the outside the system. This is done by proving, '*under stringent but not prohibitively strong conditions'*, the existence of a map β that replicates ϕ. The condition is related to the existence of a function that assigns a map β to an least one $b\in\beta$ such that, for those $b\in\beta$, $\beta_b(B)$ satisfies the relation $\beta_b(B)$: F → ϕ. The satisfaction of this condition generates closure to efficient causation, thus a clear-cut formal characterization of a biological system. In this case, each efficient cause in the system is materially produced within the system itself by metabolism (F), repair (ϕ) and replication (β). They are mutually dependent on each other, or, in the terms of formal logic, they are mutually '*entailed*' (Rosen, 1972). The fabrication of *every* efficient cause is caused (*internally entailed*) by another efficient cause produced within the biological system. The organization of the fabrication of all catalytic elements is embedded in a metabolically closed loop — a circularity of efficient causes — implying that biological systems do not require any catalyst from their environment (Cornish-Bowden, 2015). When the product of a self-fabricated catalyst (efficient cause) is used as a necessary component for the fabrication of another catalyst, which participates in the fabrication of the catalyst that gives rise to it. In the words of Rosen: "*the (M,R)-system itself describes a situation in which fabrication process itself has been pulled inside the very system in which what is fabricated is operating […] (M,R)-system is thus, in itself, a theory of fabrication [...] whenever we pull a fabricator inside a system by putting it together with what it fabricates, the results is essentially an (M,R)-system"* (Rosen, 1991a, p. 252)… *"(M,R)-system...involves an iteration of the very process that generates it [...] with enough entailment to close the realization process up on itself*" (Rosen, 1999, p. 265). As the (M,R)-system refers to itself in its operations: "*...an (M,R)-system in which the operator ϕ is itself entailed from within the system is an (M,R)-system"* (Rosen, 1989, p. 28), the (M,R)-system theory is also a theory of self-referential systems (also known as impredicative systems). This suggests, on formal grounds, the existence and physical realization of self-referential causal systems (Rosen, 1985a).

Autopoiesis rather outlines and characterize the physical realization of the living of biological systems, thus the *causal* aspects of natural systems. That is, autopoiesis "*describes the molecular processes…taking place in the realization of the living of living systems… not a philosophical proposition of a formalization of the phenomenon of life...the molecular autopoiesis of a cell is its living in the continuous realization of their self-production without the participation of any organizing principle*" (Maturana, 2011, p. 144). An autopoietic unity is characterized as *"a network of processes of production (transformation and destruction) of components which: (i) through their interactions* [openness to flux of matter and energy] *and transformations continuously regenerate and realize the network of processes (relations) that produced them; and (ii) constitute it (the system) as a concrete unity in space in which they (the components) exist by specifying the topological domain of its realization as such a network"* (Maturana and Varela, 1980, p. 78, brackets are ours)(Fig. 2B). There is no separation between the product and the producer: Their operational closure results in the same continuous self-referential process from which it is produced: *"a closed domain of operational relations specified only with respect to the system organization that these relations constitute, and thus it defines a space whose dimensions are the relations of production of the components that realize it as a concrete biological unity*" (Maturana and Varela, 1980, p. 97).

Because the closure of both systems is explicitly related (Nomura, 2001, 1997; Zaretzky and Letelier, 2002; Letelier et al., 2003) in the notion of *metabolic closure* (Letelier et al., 2011, 2006; Soto-Andrade et al., 2011), Autopoesis and the (M,R)-system satisfy the *modelling relation*, in the way Rosen (1985, p.15) defined it: "*a process of bringing into relation two entailment structures, a material one governed by causality, and a mathematical governed by inferential rules"*. A biological system is then characterized by the autopoiesis as the physical realization of an (M,R)-system, and the (M,R)-system as the theoretical model of autopoiesis (Fig. 2C). Following this, here, we shall distinguish a biological system as an *(M,R)-autopoietic unity*, (Fig. 2D), thereby bringing about an equivalence between closure to efficient causation and operational closure.

The operational closure to efficient causation can be contrasted with a chemical reaction, where the catalysts (the 'efficient cause') that transform the reactant into products are not a product of the reaction, nor the material of the reactants: the catalysts are external to the chemical reaction. Therefore, the chemical reaction is 'open to efficient cause' which makes its *causal entailments* unrelated, and thus fundamentally different from biological systems. Operational closure to efficient causation can also be contrasted with cybernetic systems (Maturana, 2011; Rosen, 1985b) and artificial intelligence (AI) in general (Maturana 1980; Rosen, 1985a). The latter have an organization determined (designed, fabricated, programmed and controlled) from outside by input / output control feedback mechanisms, while the (M,R)-autopoietic unity have an organization defined from within, which is not always amenable to input / output control parameters (Casti 1988). However, the latter is distinct from self-organized systems (Rosen, 1959, 1994a; Maturana, 1987, 2002; Maturana and Varela, 1980; McMullin, 2001, 2000), far-from thermodynamic equilibrium systems (Maturana 1980; Rosen 1978a) or the chemoton (Cornish-Bowden, 2015). That is, the chemoton (Gánti, 2003), dissipative structures (Nicolis and Prigogine, 1977), hypercycles (Eigen et al., 1977) and autocatalytic sets (Kauffman, 1986), either at molecular (Hordijk et al., 2019; Jain and Krishna, 2001) or ecological level (Cazzolla Gatti et al., 2018), do not attain operational closure to efficient causation (Chemero and Turvey, 2006; Letelier et al., 2011). Moreover, they can be surrogated to a dynamical system (Jain and Krishna, 2001), and implementable in computer simulations in contrast to the (M,R)-autopoiesis (Letelier et al., 2006; Louie, 2007; Luz Cárdenas et al., 2010; Maturana, 1980; 2011; Rosen, 1985a, 1988b, 1991a)(see section 6). In summary, the (M,R)-Autopoiesis explains how, despite forcing fluctuations and dissipation, biological systems maintain their homeorhetic trajectories within physiological bounds and why they are distinct from chemical, self-organized, thermodynamic and cybernetic systems. We conclude, therefore, that the (M,R)-Autopoiesis represents a *necessary* and *sufficient* rigorous and formal clear-cut criterion to answer the Schrodinger' question.

Although (M,R)-Autopoiesis' scope is for cellular and multicellular phenomena rather than for planetary systems, it is nonetheless *necessary* to formally express the Gaia hypothesis, and it would make sense, at first glance, to consider it as the most generic and less restrictive definition to characterize whether the Gaia phenomenon is (or not) a biological phenomenon. If so (M,R)-Autopoiesis may be common to large classes of systems, if not universal throughout a range between different discrete scales, from planets to cells and vice versa, as suggested before (Lovelock 1987; Margulis 1997). Mikulecky (2000) previously suggested that the categorical expression of the (M,R)-system may provide the theoretical biology for approaching formally the Gaia hypothesis. To this end, our main question here is whether operational closure to efficient causation takes place on a planetary scale, i.e. whether the Earth operation implements causal and inferential relations of processes of production and fabrication that are embedded in metabolic closure (Fig. 3A). To our knowledge, this has never been seriously examined. In the next section we materialize this proposal.

4. Mathematical biology of Geophysiology: A formal expression of the Gaia hypothesis

We begin by denoting all the Gaia's fluxes of matter and energy and its efficient causes of transformation (Fig. 3B)(cf. Volk, 1998) as a *single* mapping in which a planetary abiotic (Cornish-Bowden and Cárdenas, 2017; Goldford and Segrè, 2018; Hordijk and Steel, 2018; Luisi, 2014) or inorganic catalytic network I reacts and transforms matter and energy (M) into ongoing geochemical cycles (C) (Fig. 3B):

$$I: M \rightarrow C \quad (1),$$

that is, for any $m \in M$, we have:

$$m \rightarrow c = I(m).$$

The efficient cause I (hence, a mapping or function) is thus identified with a multi-scale pre-metabolism (non-enzymatic autocatalytic network) which, in a given environment, transforms M into C. M is the collection of all sets of energy and matter m ($m \in M$) of the atmosphere, lithosphere and hydrosphere which can be transformed. C includes everything that is being produced by I: the numerous geophysical and geochemical processes that generate the collection of all sets of geochemical cycles $c \in C$ (Fig. 3B). As I, the abiotic pre-metabolic-like chemical network, is a physical entity subject to decline, dissipation and disruption, it needs to be effectively repaired and/or replaced. Likewise in an (M,R)-system *every* efficient cause F must have an associate ϕ that maintains the concentration of F. On the Earth system, the *metabolic enzymatic* activity of the biosphere O (from organic) mainly linked to origin and activity of microbes (Cavicchioli et al., 2019; Magnabosco et al., 2018; Margulis and Sagan, 1986; McGenity, 2018; Falkowski et al., 2008; Raoult, 2010; Stolz, 2016) may correspond to ϕ. The efficient cause O acts as a selector of C, which becomes the material reserve to produce I.

$$O: C \rightarrow I, \quad (2)$$

O is therefore a second efficient cause (mapping) which, in a given environment or boundary condition, metabolizes selectively, catalyses and transforms C into I through multi-scale enzymatic metabolism (Caetano-Anollés et al., 2007; Medini et al., 2005; Sun et al., 2017) allowing continuous operation of I from existing C (Fig. 3C). As the metabolic transformation of C into I by O removes, geologically transforms and relocalizes compounds (Atekwana and Slater, 2009; Falkowski et al., 2008; McGenity, 2018; Tornos et al., 2018), it effectively constrains Earth's material dynamics, thermodynamics, electromagnetism and geomorphological structural changes such as the configuration of the continents, tectonic and volcanic activity, ocean salinity, pH, redox potential, ocean circulation, distribution of ice sheets, etc (Hinkle, 1996; Kleidon, 2002; Kump, 2004; Lowman and Lowman, 2002). This can be written as:

$$M \xrightarrow{I} C \xrightarrow{O} H(M,C) \quad (3)$$

where *H (M, C)* is a set of mappings from *M* to *C,* and *O* is the efficient cause that acts as a metabolic selector of existing *C* that converts its products into new *I* (Fig. 3C). However, *O* is subject to ageing, senescence, decline and thus potential disruption. It therefore requires another efficient cause to be produced and remain operating. Like in the (M,R)-system we can avoid efficient causes ad infinitum if, in the formal expression of the Gaia hypothesis, we can identify an efficient cause γ (a *replication* function) using the content of the set *C,* in which case γ will be entailed inside the Earth system and act on *I* to ensure the continuous operation of the efficient cause O, the metabolic enzymatic activity of the biosphere. This systemic and relational replication may generate closure to efficient causation at the planetary scale (Fig. 3C).

Rosen's approach (Rosen 1972) (see Mossio et al., 2009 for an computable attempt using Lambda calculus), to formalize it, and thus to prove the existence of effective self-referential functions in general, and the existence of an efficient cause γ within the set *C* in our formal definition of Gaia hypothesis in particular, is by having an *inverse evaluation map* as follows. Let X and Y be sets, and *H (X, Y)* is a set of mappings from *X* to *Y*. In general, we always regard the elements $x \in X$ as operators $\hat{x}$ on *H (X, Y)*, by defining

$$\hat{x}(f) = f(x)$$

$\hat{x}$ is in this case called the evaluation map associated with $x \to X$. Then,

$$\hat{x}: H(X,Y) \to Y.$$

One such evaluation map has an inverse $\hat{x}^{-1}$then we can define this inverse as

$$\hat{x}^{-1}: Y \to H(X,Y).$$

The inverse exists *if and only if*

$$\hat{x}(f_1) = \hat{x}(f_2) \text{ implies } f_1 = f_2, \text{ or}$$

$$f_1(x) = f_2(x) \text{ implies } f_1 = f_2.$$

that is, once x is known, $f(x)$ contains enough information to determine f within the set $H(X,Y)$

So, to formally identify γ we can identify:

$$X = C$$

$$Y = H(M,C),$$

where M and C are the sets A and B in the (M, R)-system respectively (see Fig. 2A). This shows that if an evaluation map in this case is invertible, it is precisely a map into the set

$$H[C, H(M, C)]$$

to which B belongs.

The map can be parameterized as a function of $c \in C$, where c is a particular product produced by the system for which the inversion condition is satisfied:

$$\gamma_c: H(M, C) \rightarrow H[C, H(M, C)] \quad (4)$$

such that $\gamma_c(I) = O$

That is, once the inversion condition is satisfied for a given c, it is possible to define γ_c which will ensure the replacement of O using information provided by the product of $O(c)$ (Fig. 3C).

Under these terms, the Gaia hypothesis is expressed as the existence of the closure to efficient causation: $I \rightarrow \gamma_c \rightarrow O \rightarrow I$. The existence of an inverse evaluation map would therefore imply that the operation of the Earth system is encoded in the entire system, but not in a specific component of it. Indeed, γ_c is an efficient cause of O, thus, an efficient cause of the efficient cause of C, which contains c, and which determines γ_c. This closed entailment loop implies that a subset of C (c, in this case) needs to contain information about C itself. C is, however, multifaceted. It involves multiple time scales, and contains the numerous geophysical and geochemical structures generate by Earth's metabolism, including orography, topography, heat and chemical gradients. Similar to enzymes in a cell, some of these structures play the role of an efficient cause necessary for producing the metabolism. The subset γ (c) represents this efficient cause. It is on this basis that one can say, formally, that the process of fabrication of the Earth system produces O based on what the Earth system recognizes of itself, like a biological unity. Finally, equation (5) formalizes a one-to-one map between the Gaia phenomenon and the (M,R)-system (Fig. 3A, D). The Earth processes of production would satisfy the (M,R)-system formal model, in which the efficient causes are uniquely determined by their products, requiring no external efficient cause (Fig. 3D). The efficient causes of Earth's operation need not be added from the outside. They exist inside the Earth system. The (M,R)-system is the formal expression of the Gaia hypothesis and essentially the theoretical model of Gaia phenomenon. The latter is the realization of the former. Having suggested this, in the following section, we will provide a plausible, empirically supported account of autopoiesis as the realization of the living of Gaia phenomenon.

5. The Metabolism and Repair of Gaian Autopoiesis implies conservation of organization under structural change

Vernadsky (1945) suggested that Life is not *a* form of energy and is not merely *a* geological force, rather it is *the* geological force. So, the natural question he asked was: '*How on Earth can it* (Life) *change material processes?'*. Given the limitations of characterizing life phenomenon as a mere regulator, autopoiesis was suggested as the realization of the living of Gaia phenomenon (von Foerster, 1975): the relations of production on Earth system may correspond to an autopoietic system. Several authors consider that the production of the atmosphere (mainly troposphere and stratosphere), in the same domain in which the planetary-scale metabolism continuously, generates the very same relations of production offers evidence for autopoiesis in the planetary scale (Capra, 1996; Capra and Luisi, 2014; Clarke, 2012; Jantsch, 1980; Kazansky, 2004; Levchenko et al., 2012; Margulis, 1990, 1997; Margulis and Sagan, 1995, 1986; Onori and Visconti, 2012; Sahtouris, 1996). Margulis wrote: '*Whereas the smallest recognizable autopoietic entity… is a tiny bacterial cell the largest is Gaia*' (Margulis, 1990, p. 861). Or that *'planetary physiology…is the autopoiesis of the cell write large'* (Margulis and Sagan, 1995, p. 54).

Is it, however, possible to identify on the Earth system an organization of processes of self-production? "*Since it is a defining feature of an autopoietic system that it should specify its own boundaries, a proper recognition on an autopoietic system as a unity requires a proper recognition […] that defines the limits of the system in the same domain in which it specifies them through […] relations of production of components that generate these relations and define it as a unity in a given space'* (Maturana and Varela, 1980, pp. 108–109). Accordingly, a proper recognition of Gaian Autopoiesis should offer evidence of the continuous processes of self-production by closure to efficient causation on the planetary scale. We consider here that to recognize the autopoesis as the realization of the living of Gaia phenomenon, both natural systems, Gaia and an autopoietic system should satisfy, through empirical evidence, the modelling relation as indicated in the figure (4A).

Today, it is generally accepted that the productions of troposphere: aerosols (Dani and Loreto, 2017; Fröhlich-Nowoisky et al., 2016; Gantt and Meskhidze, 2013; Lana et al., 2011), methane greenhouse gas (Conrad, 2009; Izon et al., 2017), some clouds (Charlson et al., 1987; Hughes et al., 2014), and even stratospheric ozone (Falkowski, 2006) are immediately related to multi scale planetary metabolic activity (Goldford and Segrè, 2018). The Earth's metabolism takes place in the subsurface and surface of the lithosphere and ocean, the atmosphere, the rhizosphere, the gut microbiomes, in the dark, rare and deep biosphere (Cavicchioli et al., 2019; Magnabosco et al., 2018). It is carried out mainly by prokaryotes (Margulis and Sagan, 1986; McGenity, 2018; Falkowski et al., 2008), the so-called 'Gaia microbiome' (Stolz, 2016) and its pan-genome (Medini et al., 2005), which comprises autotrophic, heterotrophic, anoxic and oxide activity. It has been suggested that the Earth's prokaryotes constitute along with eukaryotes an interconnected single *rhizome* of life (Raoult, 2010). Morowitz states that "*all organisms interact (are connected) through the gas-phase components that they take up from and give off to the atmosphere…life…persists over long geological periods only because of integrated processes of the atmosphere, the hydrosphere, the lithosphere, and the biosphere"* (Morowitz, 1993, pp. 5–6). That is, the atmosphere is not only the product of the planetary-scale metabolism, but allows its continuous operation through the hydrosphere and lithosphere suggesting a plausible scenario operational closure at planetary-scale. Indeed, one of the main motivations of proposing the Gaia hypothesis was that the planetary-scale metabolism does not merely affect the chemical composition of the atmosphere and vice versa; they self-produce in a single mutual continuous process (Margulis and Lovelock, 1975).

Recent additional empirical evidence somehow may support this possibility. The different values of the water deuterium-to-hydrogen ratio (D/H) observed recently on various bodies in the Solar system, suggest a non-asteroid origin of Earth's cycled water (Altwegg et al., 2014)(Deep mantle Earth's water is not found, so far, to be cycled water (Hallis et al., 2015)). In biological systems, a significant amount of water is produced metabolically (endogenously) (Li et al., 2016). In addition, the conservation of the core signatures of the early Earth metabolism in contemporary cellular biogeochemistry (Morowitz, 1993) suggests that most prokaryotes notably, methanogens ($CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$) (Bardgett et al., 2008), sulphate-reducing bacteria ($CO_2 + 2H_2S \rightarrow CH_2O + H_2O + 2S$) (Barton and Fauque, 2009) and subsurface cyanobacteria (Puente-Sánchez et al., 2018) contributed greatly to the metabolic origin and ongoing of the troposphere, stratosphere and hydrosphere (Harding and Margulis, 2009). Moreover, through the hydrological cycle, nutrients are geologically modified (Atekwana and Slater, 2009), mobilized (McGenity, 2018), localized (Tornos et al., 2018) and integrated in biogeochemical cycles (Falkowski et al., 2008) (Fig. 4B)

The evidence accumulated so far offers thus a plausible account of *continuous processes of molecular self-production* of the terrestrial environment. Furthermore, the fact that Earth's metabolism defines molecularly the boundary (hydrosphere, troposphere and stratosphere) in the same domain in which it is specified indicates molecular metabolic closure in the planetary scale, and henceforth, an "*Autopoietic Gaia"* (Margulis, 1990) (Fig. 4C). In fact, the explanatory scope of autopoiesis covers the phenomenological basis of broader domains of biological realization than the cellular and multicellular scales. Maturana refers to such larger-scale domain of biological realization as 'higher order autopoietic unity'. Crucially, he indicates that such realization must be molecular: "*There are autopoietic systems of higher order, integrated by* (populated by) *lower order autopoietic unities that may not be the components realizing them as autopoietic systems… there are higher order autopoietic systems whose components are <u>molecular</u> entities produced through the autopoiesis of lower* *autopoietic unities"* (Maturana, 1980, p. 53, parhentesis and subline are ours). This implies that Gaia phenomenon is the molecular constitution of planetary scale metabolic closure.

Some proposals such as the 'molecular biology of Gaia' (Williams, 1996), a 'wasteworld of by-products' (Volk, 2004) and the biogeochemical cycles as the unit of natural 'selection' bypassing taxonomic individual species (Doolittle, 2017, 2014) support somehow that Gaia phenomenon is molecular. However, operational closure to efficient causation at the planetary scale is more than these proposals. For example, biogeochemical cycles, like cellular biochemical cycles, are loops of *material* causes, but not loops of *efficient* causes (Louie and Poli, 2011). Loops of *material* causes take place because there are efficient causes that make the material elements be cycled. In other words, the biogeochemical cycles or by-products ($c \in C$ in the (M,R)-system) are necessary for enabling Gaian autopoeisis, but they are only partially constitutive of it.

The metabolism and repair of Gaian autopoiesis implies that the Earth is an *organized* system as a biological system, i.e. the present terrestrial environment is itself the result of its own fabrication processes. That is, at geological scales, there is no separation between product and producer, between biotic and abiotic elements. As such, Gaia represents a *sui generis* scale of (M,R)-autopoietic organization in the planetary scale, and thus a proper biological *domain* of realization of the living (Fig. 4C, 3D). With domain we refer to a biological *unity*, such as the cellular or multicellular organism, which is distinct from self-organized emergent systems, i.e., Gaia is different to a colony-like stigmergic assemblages of agents that can form a 'global' superorganism that emerges out of their interactions. This description fails to capture molecular operational closure to efficient causation. The (M,R) of Gaian Autopoiesis suggests that the continuous process of terrestrial self-production is a biological realization of its own at the planetary domain.

In the formulation of autopoiesis, biological systems are distinguished by their organization and structure (Maturana and Varela, 1980; Nomura, 2006). While the former is preserved, i.e. self-production by the closure to efficient causation must persist, the latter may change through the flows, cycling and continuous transformation of materials (Letelier et al., 2006; Maturana and Varela, 1980). This explains why life phenomenon persists despite structural changes during ontogeny and phylogeny (Maturana, 1980; Maturana and Mpodozis, 2000). For example, despite large structural changes, abrupt catastrophic shifts (e.g. loss of almost 90% of the biosphere) and tipping points (Lenton et al, 2008) from Pangea to the current continental configuration (Lenton and Watson, 2011) Gaia phenomenon has persisted. Indeed, whereas self-production by closure to efficient causation persists, multiple interdependent structural changes can take place and when one structural dimension is changed, the complete structure of the system may undergo correlative changes (Maturana, 1980; Maturana and Mpodozis, 2000). In this interpretation, bifurcations, critical transitions, tipping points and tipping cascades (Scheffer, 2009; Ashwin et al., 2012; Lenton and Williams, 2013; Steffen et al., 2018), may be associated with structural changes constrained by the conservation of Earth's self-production by closure to efficient causation. The structural changes in the Precambrian Vendian shows, for example, that the phenotypic transformation of multicellular organisms took place along with the transformation of the lithosphere, atmosphere and the complete biosphere through the conservation of the Gaia phenomenon (Levchenko et al., 2012). Even when the Earth has been impacted by planetesimals (Abramov and Mojzsis 2009), the Gaia phenomenon has persisted.

However, the explanatory scope of the theory and realization of (M,R)-autopoietic systems foresees that some structural perturbations (e.g. the loss of crucial information of the replication map β in the M,R-system) can send Gaia into an 'autopoietic oscillator dead' (Friston 2013) or more broadly into 'system degeneracy' (see Rosen (1988a, 1978b)), such that the conservation of system's organization, therefore its living, is lost (Letelier et al., 2006; Maturana, 1980; Maturana and Varela, 1980).

What we have discussed so far provides a plausible, empirically supported account of (M,R)-autopoiesis behind the Gaia phenomenon that goes beyond the somehow superficial 'aquarium poetic view' ascribed to it by Doolittle (2017). It turns out that the (M,R)-autopoiesis surrogates the Gaia phenomenon to a self-referential system (Soto-Andrade et al., 2011). Next, we discuss the implication of it on *simulable* approaches of the Gaia phenomenon.

6. Daisyworld is a mechanism, the Gaia phenomenon is not.

According to Rosen's *Life Itself*, in a mechanism *"there can be no closed path of efficient causation"* (Rosen, 1991a, p. 241). Moreover, a natural system is said to be a "*mechanism if every model of it can be simulated on a mathematical Turing machine"* (Rosen, 1991a)(the standard form of computing today). In other words, mechanisms are simple systems which obey dynamics that can be encoded in the form of algorithms, i.e. the system is open to efficient causation, hence its model is simulable. Mechanisms can have very complicated simulations, and the complicated connections between chemical and physical processes are captured with complicated codes resolving atmospheric and oceanic fluid motion such as general circulation models and modern Earth system simulations.

With this point of view, the Gaia phenomenon can be captured by mechanisms with even simpler simulation programmes such as the Daisyworld(s) (Watson and Lovelock, 1983). The chain of feedbacks described by Daisyworld constitutes a mechanism, in the sense that it can be captured by a recursive algorithm. It is standard to attempt capturing biological systems with algorithms. Von Neumann's self-reproducing automata (Von Neumann, 1966), neural networks, agent-based models, machine learning, deep learning and AI in general follow this principle. Under this rubric, the 'degree' of complexity would be related to connectivity, nonlinearity and size: "*there exists a critical size below which the process of synthesis is degenerative, but above which the phenomenon of synthesis, if properly arranged, can become explosive"* (Von Neumann, 1966, p. 80). Following this view, the Gaia phenomenon can be identified with 'self-organized criticality' (Bak, 1993), 'adaptive' systems (Lenton and van Oijen, 2002; Levin, 1998) or more complicated phenomena representing learning (ultrastability) at the planetary scale showing an 'emergent' and nonlinear and adaptive behaviour (Lenton et al. 2018). Such a system can be large, but which is still formally equivalent to a dynamical system that can be encoded as a (large) numerical algorithm.

However, the Gaia phenomenon by means of the closure to efficient causation suggests on formal grounds, that there is a fundamental gap between the Gaia as a biological phenomenon and any algorithmic representation (Letelier et al., 2006; Louie, 2007; Luz Cárdenas et al., 2010; Maturana, 1980; Rosen, 1988b). That is, the realization of the living cannot be implemented in a Turing machine and *"accordingly must have a nonsimulable model*" (Rosen, 1999, p. 292). No matter the resolution, in principle it will never be filled in with computing power or be *completely* surrogated to algorithmic procedures. The discrepancy of efficient causation between the Gaia as a biological phenomenon and algorithms is so severe that the former cannot even be mapped onto a dynamical system (Rosen, 1991b, 1973), self-reproducing automata (Rosen 1959, 1975; Maturana, 1980) or a collection of sequential recursive algorithms (Ashby's ultrastability) (Maturana, 2011; Rosen, 1985b). In the Daisyworld(s), sequential selection or even in any other Earth system simulation likewise as in chemical reactions described above, the recursive functions of the algorithms correspond to the repetition of a set of rules that are explicitly specified to the system from the *outside* and are implementable in a Turing machine.

This suggest that the distinction between mechanisms of cybernetic systems and the living of biological systems is not a matter of degree, but of character. Such as in a cellular or any other biological system, Gaia phenomenon either occurs or not. There are no increasing degrees of complexity, connectivity and gradual assembling operations in its generation. It is all or nothing phenomenon. Quoting Rosen in contrast to Von Neumann's 'critical size': "*this characterization has nothing to do with more complication, or with counting of parts or interactions; such notions, being themselves predicative, are beside the point... Just as 'infinite' is not just 'big finite,' impredicativities* (self-production by closure to efficient causation) *are not just big (complicated) predicativities. In both cases, there is no threshold to cross, in terms of how many repetitions of a rote operation such as 'add one' are required to carry one from one realm to the other, nor yet back again*" (Rosen, 1999, p. 44, parentheses are ours).

Moreover, the Gaia phenomenon by means of the closure to efficient causation entails the existence of an self-referential (impredicative) "effective" process ("effective" because it is physical) (Rosen, 1991a; Soto-Andrade et al., 2011) that rises paradoxes to Von Neumann's self-reproducing automata and AI in general (Ashby, 1962b; Rosen, 1959; Ben-David et al., 2019, Reyzin, 2019). Therefore, Gaia as a biological phenomenon may be of a non-simulable, non-algorithmic, and hence non-computable character (Letelier et al., 2006; Louie, 2007; Luz Cárdenas et al., 2010; Maturana, 1980; Rosen, 1988b, 1989). That is, the Gaia phenomenon, in principle, may have at least one model that cannot be simulated by finite-state machines (e.g., Turing machines) (Louie, 2007; Luz Cárdenas et al., 2010). Therefore, in a fundamental way, the Gaia phenomenon, although physical, is neither a mechanism nor a machine (Maturana 1980; Rosen, 1991a, 1985a).

The relation between the biological character of the Gaia phenomenon and the mechanical simulable (algorithmic) models of it (Daisyworld(s)) may be linked to the situation faced by early cartographers, who were attempting to map the surface of a sphere while armed only with pieces of (tangent) planes. As long as we only map local regions, the planar approximations (mechanisms) suffice, but as we try to map larger and larger regions, the discrepancy between the map and the surface grows. Thus, if we want to make accurate maps of large regions of the sphere, we have to keep shifting our tangent planes. The surface of the sphere is in some sense a limit of its planar approximations, but to specify it in this way requires a *new concept* (the topology of the sphere) that cannot be inferred from local planar maps alone (Rosen 1985). Similarly, the (M,R)-system model of Gaian autopoiesis implies that we need to widen our concept of what the Gaia phenomenon is, or should be.

7. Concluding Remarks

In this paper, we have examined the Gaia hypothesis from a fundamental biological standpoint offered by the (M,R)-system as a formal theory and autopoiesis as the realization of the living. We have considered that the Gaia phenomenon was identified by observing the qualitative difference among Earth, Mars and Venus, i.e. from differential observables in planetary systems. Such differences between these planets, and the unique quality on Earth, has given rise to the Gaia hypothesis, which raises Schrodinger's question, 'What is life?', a central question of biology, at the planetary scale. We have pointed out that the lack of use of a clear-cut formal criterion and characterization of biological systems has led to use the adaptationist programme and the *regulator thesis,* with so-called strong and weak interpretations of the Gaia hypothesis. This has configured the present-day Gaia theory, but obliterated the Gaia hypothesis and thus Schrodinger's question.

We have further argued that (M,R)-Autopoiesis offers a necessary and sufficient answer to Schrodinger's question and therefore it characterizes and explains what life is in terms of what life does, i.e. *self-produce* by *closure to efficient causation*. Then, based on the modelling relation, a set of interacting causal processes operating on a wide range of spatial time scales through the atmosphere, lithosphere, hydrosphere, and biosphere of the Earth system has been categorized within the relational and systemic entailments of (M,R)-Autopoiesis. Consequently, we suggested a one-to-one realization map between (M,R)-Autopoiesis and the Gaia phenomenon. In other words, the Gaia phenomenon realizes the inferential and causal entailments of (M,R)-Autopoiesis, such that it generates metabolic molecular closure to efficient causation on the planetary domain. This suggests that the Earth is an organized system, not of cells, multicellular or ecosystems, but of their molecular products that together with the atmosphere, the hydrosphere and the lithosphere self-produce by metabolic closure. The Gaia phenomenon is, therefore, a *sui generis* biological system and the embodiment *of Life itself in the planetary domain*. Moreover, if something has to be regulated, it has to be produced in the first place. Hence, self-production by closure to efficient causation is more fundamental than self-regulation by feedback mechanisms.

Biologizing Gaia theory as such provides a rigorous basis to the claim that planetary biology elsewhere in the universe must involve and have a formal equivalence to self-referential physical processes, which has at least one model that cannot be implemented by a Turing machine and, therefore, is of a non-simulable, non-algorithmic, and non-computable character.

Acknowledgements

We would like to acknowledge Dr. Anselmo García-Cantú and Dr. Takahito Mitsui for fruitful discussions.

References

Abramov, O., and Mojzsis, S. J., 2009. Microbial habitability of the Hadean Earth during the late heavy bombardment. Nature, 459(7245), 419.

Altwegg, K., Balsiger, H., Bar-Nun, A., Wurz, P., et al., 2014. 67P/Churyumov-Gerasimenko, a Jupiter family comet with a high D/H ratio. Science. 347, 1261952–1261952. https://doi.org/10.1126/science.1261952

Ashby, W. R., 1947. Principles of the Self-Organizing Dynamic System. The Journal of General Psychology. 37 (2): 125–8.

Ashby, W.R., 1956. An introduction to Cybernetics. Chapman and Hall. London

Ashby, W.R., 1962a. Principles of the self-organizing system, in: Von Foerster, H ; Zopf, G.W. (Ed.), Principles of Self-Organization: Transactions of the University of Illinois Symposium. Pergamon Press, London, pp. 255–278.

Ashby, W.R., 1962b. The self-reproducing system, in: Muses, C.A., McCulloch, W.S. (Eds.), Aspects of the Theory of Artificial Intelligence. Springer, New York, pp. 9–18.

Ashby, W.R., 1956a. The effect of experience on a determinate dynamic system. Behav. Sci. 1, 35–42.

Ashby, W.R., 1956b. Design for an intelligence-amplifier. Autom. Stud. 400, 215–233.

Ashby, W.R., 1952. Design for a Brain: the origin of Adaptive Behavior. J. Wiley.

Ashwin, P., Wieczorek, S., Vitolo, R., Cox, P., 2012. Tipping points in open systems: bifurcation, noise-induced and rate-dependent examples in the climate system. Philos. Trans. R. Soc. A Math. Phys. Eng. Sci. 370, 1166–1184.

Atekwana, E.A., Slater, L.D., 2009. Biogeophysics: A new frontier in Earth science research. Rev. Geophys. 47, 1–30. https://doi.org/10.1029/2009rg000285

Bak, P., 1993. Self-organized criticality and Gaia, in: Stein, Wilfred ; Varela, F. (Ed.), Thinking about Biology: An Invitation to Current Theoretical Biology. Santa Fe Institute, Miami, pp. 255–268.

Bardgett, R.D., Freeman, C., Ostle, N.J., 2008. Microbial contributions to climate change through carbon cycle feedbacks. ISME J. 2, 805.

Barlow, C., 1992. From Gaia to Selfish Genes: Selected Writings in the Life Sciences. MIT Press. Boston

Barton, L.L., Fauque, G.D., 2009. Biochemistry, physiology and biotechnology of sulfate-reducing bacteria. Adv. Appl. Microbiol. 68, 41–98.

Ben-David, S., Hrubeš, P., Moran, S., Shpilka, A., Yehudayoff, A., 2019. Learnability can be undecidable. Nature Machine Intelligence, 1(1), 44.

Bernard, C., 1878. Lectures on the phenomena common to animals and plants. Guillemin & Guillemin. New York

Bunyard, P., 1996. Gaia in Action: Science of the Living Earth. Floris Books. New York

Bunyard, P., Goldsmith, E., 1989. Gaia and Evolution: Proceedings of the Second Annual Camelford Conference on the Implications of the Gaia Thesis, Wadebridge Ecological Centre symposium. Wadebridge Ecological Centre, New York.

Caetano-Anollés, G., Kim, H.S., Mittenthal, J.E., 2007. The origin of modern metabolic networks inferred from phylogenomic analysis of protein architecture. Proc. Natl. Acad. Sci. 104, 9358 LP-9363. https://doi.org/10.1073/pnas.0701214104

Cannon, W.B., 1929. Organization for physiological homeostasis. Physiol. Rev. https://doi.org/10.1152/physrev.1929.9.3.399

Capra, F., 1996. The Web of Life: A New Scientific Understanding of Living Systems. Anchor Books, New York.

Capra, F., Luisi, P.L., 2014. The Systems View of Life: A Unifying Vision. Cambridge University Press, Oxford.

Casti, J. L., 1988. The theory of metabolism-repair systems. Applied Mathematics and Computation, 28(2), 113-154.

Cavicchioli, R., Ripple, W. J., Timmis, K. N., Webster, N. S., et al., 2019. Scientists' warning to humanity: microorganisms and climate change. Nature Reviews Microbiology https://doi.org/10.1038/s41579-019-0222-5

Charlson, R.J., Lovelock, J.E., Andreae, M.O., Warren, S.G., 1987. Oceanic phytoplankton, atmospheric sulphur, cloud albedo and climate. Nature 326, 655.

Chassefière, E., 1991. Photochemical regulation of CO on Mars. Geophys. Res. Lett. 18, 1055–1058.

Clarke, B., 2012. Autopoiesis and the Planet. In Impasses of the post-global. Theory in the era of climate change, 2, 58–75.

Conant, R.C., Ashby, W.R., 1970. Every good regulator of a system must be a model of that system. Int. J. Syst. Sci. 1, 89–97.

Conrad, R., 2009. The global methane cycle: Recent advances in understanding the microbial processes involved. Environ. Microbiol. Rep. 1, 285–292. https://doi.org/10.1111/j.1758-2229.2009.00038.x

Cornish-Bowden, A., 2015. Tibor Gánti and Robert Rosen: Contrasting approaches to the same problem. J. Theor. Biol. 381, 6–10. https://doi.org/10.1109/ICAECCT.2016.7942556

Cornish-Bowden, A., Cárdenas, M.L., 2017. Life before LUCA. J. Theor. Biol. 434, 68–74. https://doi.org/https://doi.org/10.1016/j.jtbi.2017.05.023

Crist, E., Rinker, H.B., McKibben, B., Lovelock, J., Volk, T., Harding, S., Margulis, L., Lenton, T., Williams, H., Aitken, D., 2009. Gaia in Turmoil, MIT Press. Boston

Dani, K.G.S., Loreto, F., 2017. Trade-Off Between Dimethyl Sulfide and Isoprene Emissions from Marine Phytoplankton. Trends Plant Sci. 22, 361–372. https://doi.org/10.1016/j.tplants.2017.01.006

Darwin, C., 1859. On the origin of species by means of natural selection, or the preservation of favored races in the struggle for Life, Murray press. London.

Doolittle, W.F., 1981. Is Nature really motherly? CoEvolution Quarterly. Spring 58–62.

Doolittle, W.F., 2017. Darwinizing Gaia. J. Theor. Biol. 434, 11–19.

Doolittle, W.F., 2014. Natural selection through survival alone, and the possibility of Gaia. Biol. Philos. 29, 415–423.

Falkowski, P.G., 2006. Tracing Oxygen's Imprint on Earth's Metabolic Evolution. Science. 5768, 1724–1726.

Falkowski, P.G., Fenchel, T., Delong, E.F., 2008. The microbial engines that drive Earth's biogeochemical cycles. Science. 320, 1034–1039.

Fodor, É., Nardini, C., Cates, M.E., Tailleur, J., Visco, P., van Wijland, F., 2016. How far from equilibrium is active matter? Phys. Rev. Lett. 117, 38103.

Friston, K., 2013. Life as we know it. J. R. Soc. Interface 10, 20130475.

Fröhlich-Nowoisky, J., Kampf, C.J., Weber, B., Huffman, J.A., Pöhlker, C., Andreae, M.O., Lang-Yona, N., Burrows, S.M., Gunthe, S.S., Elbert, W., 2016. Bioaerosols in the Earth system: Climate, health, and ecosystem interactions. Atmos. Res. 182, 346–376.

Gánti, T., 2003. Chemoton theory: theory of living systems. Springer Science & Business Media. New York

Gantt, B., Meskhidze, N., 2013. The physical and chemical characteristics of marine primary organic aerosol : a review. Atmos. Chem. Phys. 13, 3979–3996. https://doi.org/10.5194/acp-13-3979-2013

Goldford, J.E., Segrè, D., 2018. Modern views of ancient metabolic networks. Curr. Opin. Syst. Biol. 8, 117–124.

Gould, S.J., Lewontin, R.C., 1979. The spandrels of San Marco and the Panglossian paradigm: a critique of the adaptationist programme. Proc. R. Soc. London. Ser. B. Biol. Sci. 205, 581–598.

Hallis, L.J., Huss, G.R., Nagashima, K., Taylor, G.J., Halldórsson, S.A., Hilton, D.R., Mottl, M.J., Meech, K.J., 2015. Evidence for primordial water in Earth's deep mantle. Science. 350, 795–797.

Harding, S., Margulis, L., 2009. Water Gaia: 3.5 thousand million years of wetness on planet Earth. Gaia Turmoil Clim. Chang. Biodepletion, Earth Ethics an Age Cris. 41–59.

Hinkle, G.J., 1996. Marine salinity: Gaian phenomenon?, in: Bunyard, P. (Ed.), Gaia in Action: Science of the Living Earth. Floris Book, Edinburgh, pp. 99–104.

Hitchcock, D.R., Lovelock, J.E., 1967. Life detection by atmospheric analysis. Icarus 7, 149–159.

Hordijk, W., Steel, M., 2018. Autocatalytic Networks at the Basis of Life's Origin and Organization. Life 8, 62.

Hughes, R.N., Hughes, D.J., Smith, I.P., 2014. The CLAW hypothesis: a new perspective on the role of biogenic sulphur in the regulation of global climate. Oceanogr. Mar. Biol. An Annu. Rev. 52, 315–336.

Izon, G., Zerkle, A.L., Williford, K.H., Farquhar, J., Poulton, S.W., Claire, M.W., 2017. Biological regulation of atmospheric chemistry en route to planetary oxygenation. Proc. Natl. Acad. Sci. 114, E2571–E2579. https://doi.org/10.1073/pnas.1618798114

Jantsch, E., 1980. The self-organizing universe: scientific and human implications of the emerging paradigm of evolution, Systems science and world order library: Innovations in systems science. Pergamon Press.

Jee, A.-Y., Cho, Y.-K., Granick, S., Tlusty, T., 2018. Catalytic enzymes are active matter. Proc. Natl. Acad. Sci. 115, E10812 LP-E10821. https://doi.org/10.1073/pnas.1814180115

Karnani, M., Annila, A., 2009. Gaia again. Biosystems 95, 82–87. https://doi.org/https://doi.org/10.1016/j.biosystems.2008.07.003

Kazansky, A. B., 2004. Planetary bootstrap: a prelude to biosphere phenomenology. AIP Conference Proceedings Vol. 718, No. 1, pp. 445-450 https://doi.org/10.1063/1.1787347

Kirchner, J.W., 2002. The Gaia hypothesis: fact, theory, and wishful thinking. Clim. Change 52, 391–408.

Kirchner, J.W., 1990. Gaia metaphor unfalsifiable. Nature 345, 470.

Kirchner, J.W., 1989. The Gaia hypothesis: can it be tested? Rev. Geophys. 27, 223–235.

Kleidon, A., 2009. Nonequilibrium thermodynamics and maximum entropy production in the Earth system: applications and implications. Naturwissenschaften 96, 653–677. https://doi.org/10.1007/s00114-009-0509-x

Kleidon, A., 2004. Beyond Gaia: thermodynamics of life and earth system functioning. Clim. Change 66, 271–319.

Kleidon, A., 2002. Testing the effect of life on Earth's functioning: how Gaian is the Earth system? Clim. Change 52, 383–389.

Kleidon, A., Lorenz, R.D., 2004. Non-equilibrium thermodynamics and the production of entropy: life, earth, and beyond. Springer Science & Business Media.

Krissansen-Totton, J., Bergsman, D.S., Catling, D.C., 2016. On detecting biospheres from chemical thermodynamic disequilibrium in planetary atmospheres. Astrobiology 16, 39–67.

Kump, L.R., 2004. Self-Regulation of Ocean Composition by the Biosphere. Sci. Debate Gaia Next Century 93.

Lana, A., Bell, T.G., Simó, R., Vallina, S.M., Poy, J.B., Kettle, A.J., Dachs, J., Bopp, L., Saltzman, E.S., Stefels, J., Johnson, J.E., Liss, P.S., 2011. An updated climatology of surface dimethlysulfide concentrations and emission fluxes in the global ocean 25, 1–17. https://doi.org/10.1029/2010GB003850

Laneuville, M., Kameya, M., Cleaves, H.J., 2018. Earth Without Life: A Systems Model of a Global Abiotic Nitrogen Cycle. Astrobiology.

Lenton, T. M., and Latour, B., 2018. Gaia 2.0. Science, 361(6407), 1066-1068.

Lenton, T., Watson, A., 2011. Revolutions that made the Earth. Oxford University Press, Oxford.

Lenton, T.M., 1998. Gaia and natural selection. Nature 394, 439.

Lenton, T.M., Daines, S.J., Dyke, J.G., Nicholson, A.E., Wilkinson, D.M., Williams, H.T.P., 2018. Selection for Gaia across multiple scales. Trends Ecol. Evol.

Lenton, T.M., Held, H., Kriegler, E., Hall, J.W., Lucht, W., Rahmstorf, S., Schellnhuber, H.J., 2008. Tipping elements in the Earth's climate system. Proc. Natl. Acad. Sci. 105, 1786–1793.

Lenton, T.M., Lovelock, J.E., 2000. Daisyworld is Darwinian: constraints on adaptation are important for planetary self-regulation. J. Theor. Biol. 206, 109–114.

Lenton, T.M., van Oijen, M., 2002. Gaia as a complex adaptive system. Philos. Trans. R. Soc. London B Biol. Sci. 357, 683–695.

Lenton, T.M., Wilkinson, D.M., 2003. Developing the Gaia Theory. A Response to the Criticisms of Kirchner and Volk. Clim. Change 58, 1–12. https://doi.org/10.1023/A:1023498212441

Lenton, T.M., Williams, H.T.P., 2013. On the origin of planetary-scale tipping points. Trends Ecol. Evol. 28, 380–382.

Letelier, J.-C., Cárdenas, M.L., Cornish-Bowden, A., 2011. From L'Homme Machine to metabolic closure: Steps towards understanding life. J. Theor. Biol. 286, 100–113. https://doi.org/https://doi.org/10.1016/j.jtbi.2011.06.033

Letelier, J.-C., Soto-Andrade, J., Abarzua, F.G., Cornish-Bowden, A., Cárdenas, M.L., 2006. Organizational invariance and metabolic closure: analysis in terms of (M, R) systems. J. Theor. Biol. 238, 949–961.

Letelier, J.C., Marın, G., Mpodozis, J., 2003. Autopoietic and (M, R) systems. J. Theor. Biol. 222, 261–272.

Levchenko, V.F., Kazansky, A.B., Sabirov, M.A., Semenova, E.M., 2012. Early Biosphere: Origin and Evolution, in: Ishwaran, N. (Ed.), The Biosphere. InTech University Campus STeP, Rijeka, pp. 2–32.

Levin, S.A., 2005. Self-organization and the emergence of complexity in ecological systems. AIBS Bull. 55, 1075–1079.

Levin, S.A., 1998. Ecosystems and the biosphere as complex adaptive systems. Ecosystems 1, 431–436.

Li, H., Yu, C., Wang, F., Chang, S.J., Yao, J., Blake, R.E., 2016. Probing the metabolic water contribution to intracellular water using oxygen isotope ratios of PO4. Proc. Natl. Acad. Sci. 113, 5862–5867.

Louie, A.H., 2007. A Living System Must Have Noncomputable Models. Artif. Life 13, 293–297. https://doi.org/10.1162/artl.2007.13.3.293

Louie, A.H., Poli, R., 2011. The spread of hierarchical cycles. Int. J. Gen. Syst. 40, 237–261.

Lovelock, J., 2009. The vanishing face of Gaia: a final warning. Allen Lane. Penguin Books, London.

Lovelock, J., 2003a. Gaia: the living Earth. Nature 426, 769.

Lovelock, J., 2003b. Gaia and emergence: A response to Kirchner and Volk. Clim. Change 57, 1–3.

Lovelock, J., 1991. Gaia: The Practical Science of Planetary Medicine. Gaia Books. London

Lovelock, J., 1987. Gaia: A model for planetary and cellular dynamics, in: Thompson, W.I. (Ed.), Gaia: Implications of the New Biology. Lindisfarne Press, New York, pp. 83–87.

Lovelock, J., 1979. Gaia, a new look at life on earth, Oxford paperbacks. Oxford University Press, London.

Lovelock, J., 1975. Thermodynamics and the recognition of alien biospheres. Proc. R. Soc. Lond. B 189, 167–181.

Lovelock, J.E., 1991. Gaia: A planetary emergent phenomenon, in: Thompson, W. (Ed.), Gaia 2. Emergence. Lindisfarne Press, New York, pp. 30–49.

Lovelock, J.E., 1986. Living alternatives. Nature 320, 646.

Lovelock, J.E., 1980. The Recognition of Alien Biospheres. Cosm. Search 8 (4), 2.

Lovelock, J.E., 1972. Gaia as seen through the atmosphere. Atmos Env. 6, 579–580.

Lovelock, J.E., 1965. A physical basis for life detection experiments. Nature 207, 568–570.

Lovelock, J.E., Giffin, C.E., 1969. Planetary atmospheres: compositional and other changes associated with the presence of life. Adv. Astronaut. Sci. 25, 179–193.

Lovelock, J.E., Margulis, L., 1974. Atmospheric homeostasis by and for the biosphere: the Gaia hypothesis. Tellus 26, 2–10.

Lowman, P.D.J., Lowman, P.D., 2002. Exploring space, exploring Earth: New understanding of the Earth from space research. Cambridge University Press, Boston.

Luisi, P.L., 2014. A new start from ground zero? Orig. Life Evol. Biosph. 44, 303–306.

Luz Cárdenas, M., Letelier, J.-C., Gutierrez, C., Cornish-Bowden, A., Soto-Andrade, J., 2010. Closure to efficient causation, computability and artificial life. J. Theor. Biol. 263, 79–92. https://doi.org/http://dx.doi.org/10.1016/j.jtbi.2009.11.010

Magnabosco, C., Lin, L.-H., Dong, H., Bomberg, M., Ghiorse, W., Stan-Lotter, H., Pedersen, K., Kieft, T.L., van Heerden, E., Onstott, T.C., 2018. The biomass and biodiversity of the continental subsurface. Nat. Geosci. 11, 707–717. https://doi.org/10.1038/s41561-018-0221-6

Margulis, L., 2004. Gaia by any other name. Sci. debate Gaia next century. MIT Press. Cambridge 7–12.

Margulis, L., 1997. Big trouble in biology: Physiological Autopoiesis versus Mechanistic Neo-Darwinism, in: Margulis, L ; Sagan, D. (Ed.), Slanted Truths. Springer, New York, pp. 265–282.

Margulis, L., 1993. Gaia in Science. Science. 259, 745.

Margulis, L., 1990. Kingdom Animalia: the zoological malaise from a microbial perspective. Am. Zool. 30, 861–875.

Margulis, L., Lovelock, J.E., 1975. The Atmosphere as circulatory system of the biosphere—the Gaia hypothesis. CoEvolution Quarterly (Summer) 5, 31–40.

Margulis, L., Lovelock, J.E., 1974. Biological modulation of the Earth's atmosphere. Icarus 21, 471–489.

Margulis, L., Sagan, D., 1997. Slanted Truths: Essays on Gaia, symbiosis and evolution, Springer-Verlag New York.

Margulis, L., Sagan, D., 1995. What is Life? Simon & Schuster, Michigan.

Margulis, L., Sagan, D., 1986. Microcosmos: Four Billion Years of Evolution from Our Microbial Ancestors. University of California Press, Los Angeles.

Martyushev, L., 2013. Entropy and entropy production: Old misconceptions and new breakthroughs. Entropy 15, 1152–1170.

Maturana, H., 2011. Ultrastability… autopoiesis? Reflective response to Tom Froese and John Stewart. Cybern. Hum. Knowing 18, 143–152.

Maturana, H., 2002. Autopoiesis, structural coupling and cognition: a history of these and other notions in the biology of cognition. Cybern. Hum. knowing 9, 5–34.

Maturana, H., 1987. Everything is said by an observer. In Thompson, W.I. (Ed) Gaia, a Way of Knowing: Implications of the New Biology. Lindisfarne Press, New York. pp, 65-82.

Maturana, H.R., 1980. Autopoiesis: reproduction, heredity and evolution, in: Autopoiesis, Dissipative Structures and Spontaneous Social Orders, AAAS Selected Symposium 55 (AAAS National Annual Meeting, Houston TX, 3–8 January 1979). Westview Press, pp. 45–79.

Maturana, H.R., Mpodozis, J., 2000. The origin of species by means of natural drift. Rev Chil Hist Nat 73, 261–310.

Maturana, H.R., Varela, F.J., 1980. Autopoiesis and cognition: The realization of the living. D. Reidel, Boston.

McMullin, B., 2000. Remarks on autocatalysis and autopoiesis. Annals of the New York Academy of Sciences, 901(1), 163-174.

McMullin, B., 2001. An Intriguing Journey: A Review of 'Investigations' by Stuart Kauffman Oxford University Press, 2000. Complexity 6, no. 5: 22-23.

McGenity, T.J., 2018. 2038 – When microbes rule the Earth. Environ. Microbiol. 20, 4213–4220. https://doi.org/10.1111/1462-2920.14449

Medini, D., Donati, C., Tettelin, H., Masignani, V., Rappuoli, R., 2005. The microbial pan-genome. Curr. Opin. Genet. Dev. 15, 589–594.

Mikulecky, D.C., 2000. Robert Rosen: the well-posed question and its answer - why are organisms different from machines? Syst. Res. Behav. Sci. 17, 419–432. https://doi.org/10.1002/1099-1743(200009/10)17:5<419::AID-SRES367>3.0.CO;2-D

Morowitz, H.J., 1993. Beginnings of Cellular Life: Metabolism Recapitulates Biogenesis, Bio-origins series. Yale University Press.

Morowitz, H.J., Smith, E., Srinivasan, V., 2008. Selfish metabolism. Complexity 14, 7–9. https://doi.org/10.1002/cplx.20258

Mossio, M., Longo, G., Stewart, J., 2009. A computable expression of closure to efficient causation. J. Theor. Biol. 257, 489–498. https://doi.org/https://doi.org/10.1016/j.jtbi.2008.12.012

Ng, F.S.L., Zuber, M.T., 2006. Patterning instability on the Mars polar ice caps. J. Geophys. Res. E Planets 111, 1–14. https://doi.org/10.1029/2005JE002533

Nicolis, G., Prigogine, I., 1977. Self-organization in Non-equilibrium Systems.

Nielsen, R., 2009. Adaptionism—30 years after Gould and Lewontin. Evol. Int. J. Org. Evol. 63, 2487–2490.

Nomura, T., 2006. Category theoretical formalization of autopoieis from perspective of distinction between organization and structure, in: Proc. Seventh German Workshop on Artificial Life (GWAL–7). pp. 31–38.

Nomura, T., 2001. Formal description of autopoiesis based on the theory of category, in: European Conference on Artificial Life. Springer, pp. 700–703.

Nomura, T., 1997. An attempt for description of quasi-autopoietic systems using metabolism-repair systems, in: Proc. the Fourth European Conference on Artificial Life. pp. 48–56.

Onori, L., Visconti, G., 2012. The Gaia theory: from Lovelock to Margulis. From a homeostatic to a cognitive autopoietic worldview. Rend. Lincei 23, 375–386.

Piaget, J., 1967. Biologie et connaissance; essai sur les relations entre les regulations organiques et les processus cognitifs. Gallimard, Paris.

Puente-Sánchez, F., Arce-Rodríguez, A., Oggerin, M., García-Villadangos, M., Moreno-Paz, M., Blanco, Y., Rodríguez, N., Bird, L., Lincoln, S.A., Tornos, F., 2018. Viable cyanobacteria in the deep continental subsurface. Proc. Natl. Acad. Sci. 115, 10702–10707.

Ramstead, M.J.D., Badcock, P.B., Friston, K.J., 2018. Answering Schrödinger's question: A free-energy formulation. Phys. Life Rev.

https://doi.org/10.1016/j.plrev.2017.09.001

Raoult, D., 2010. The post-Darwinist rhizome of life. Lancet 375, 104–105.

Reyzin, L., 2019. Unprovability comes to machine learning. Nature. 565, 166-167

Rosen, R., 1999. Essays on Life Itself. Columbia University Press, New York.

Rosen, R., 1994a. Review of 'The Origins of Order: Self-Organization and Selection in Evolution' by Stuart A. Kauffman. Oxford University Press, New York, 1993. xviii + 709 pp. Bull. Math. Biol. 56, 999–1003.

Rosen, R., 1994b. What is biology? Comput. Chem. 18, 347–352.

Rosen, R., 1991a. Life itself: a comprehensive inquiry into the nature, origin, and fabrication of life. Columbia University Press.

Rosen, R., 1991b. Beyond Dynamical Systems. J. Soc. Biol. Struct. 14, 217–220.

Rosen, R., 1989. The roles of necessity in biology, in: Casti, J.L., Karlqvist, A. (Eds.), Newton to Aristotle: Toward a Theory of Models for Living Systems. Springer, Boston, pp. 11–37.

Rosen, R., 1988a. System closure and dynamical degeneracy. Math. Comput. Model. 10, 555–561. https://doi.org/https://doi.org/10.1016/0895-7177(88)90126-4

Rosen, R., 1988b. Complexity and information. J. Comput. Appl. Math. 22, 211–218.

Rosen, R., 1985. Anticipatory systems. Pergamon Press. New York

Rosen, R., 1985a. Organisms as causal systems which are not mechanisms: an essay into the nature of complexity, in: Theoretical Biology and Complexity. Elsevier, pp. 165–203.

Rosen, R., 1985b. Second W. Ross Ashby Memorial Lecture 1984. The physics of complexity. Syst. Res. 2, 171–175 Re–printend in (Klir Ed) Facets of Systems.

Rosen, R., 1978a. Review of: Self-organization in nonequilibrium systems, by G. Nicolis and I. Prigogine, Jhon Wiley, New York, 1977, 491 pp. Int. J. Gen. Syst. 491, 266–269. https://doi.org/10.1080/03081077808960692

Rosen, R., 1978b. Feedforwards and global system failure: A general mechanism for senescence. J. Theor. Biol. https://doi.org/10.1016/0022-5193(78)90243-6

Rosen, R., 1975. On the Dynamical Realization of Automata 109–120.

Rosen, R., 1973. On the Dynamical realization of (M, R)-Systems. Bull. Math. Biol. 35, 1–9.

Rosen, R., 1972. Some relational cell models: the metabolism-repair systems, in: Rosen, R. (Ed.), Foundations of Mathematical Biology: Cellular Systems. Elsevier, New York, pp. 217–253.

Rosen, R., 1959. On a logical paradox implicit in the notion of a self-reproducing automation. Bull. Math. Biophys. 21, 387–394.

Rosen, R., 1958. A relational theory of biological systems. Bull. Math. Biophys. 20, 245–260.

Sagan, D., Whiteside, J.H., 2004. Gradient Reduction Theory: thermodynamics and the Purpose of Life. Sci. Debate Gaia 173–186.

Sahtouris, E., 1996. The Gaia controversy: a case for the Earth as an evolving system, in: Bunyard, P. (Ed.), Gaia in Action: Science of the Living Earth. Floris Books, New York, pp. 324–337.

Sanchez, T., Chen, D.T.N., DeCamp, S.J., Heymann, M., Dogic, Z., 2012. Spontaneous motion in hierarchically assembled active matter. Nature 491, 431.

Scheffer, M., 2009. Critical transitions in nature and society. Princeton University Press. New Jersey

Schneider, S. H., 1986. A goddess of the Earth?: The debate on the Gaia Hypothesis—An editorial. Climatic change, 8(1), 1-4.

Schneider, S.H., Boston, P.J., 1992. Scientists on Gaia, MIT Press. Boston

Schneider, S.H., Miller, J.R., Crist, E., Boston, P.J., 2004. Scientists Debate Gaia: The Next Century, MIT Press. Boston

Schneider, S.H., Morton, L., 1981. The Primordial Bond. Plenum Press, New York.

Schrödinger, E., 1945. What is Life?: The Physical Aspect of the Living Cell. Cambridge University Press. London

Schwartzman, D., 2002. Life, temperature, and the Earth: the self-organizing biosphere. Columbia University Press. New York.

Shannon, C.E., 1948. A mathematical theory of communication. Bell Syst. Tech. J. 27, 379–423.

Soto-Andrade, J., Jaramillo, S., Gutiérrez, C., Letelier, J.-C., 2011. Ouroboros avatars: A mathematical exploration of Self-reference and Metabolic Closure, in: Advances in Artificial Life, ECAL 2011: Proceedings of the Eleventh European Conference on the Synthesis and Simulation of Living Systems. MIT Press, Cambridge. pp. 763–770.

Staley, M., 2002. Darwinian selection leads to Gaia. J. Theor. Biol. 218, 35–46. https://doi.org/10.1006/jtbi.2002.3059

Steffen, W., Rockström, J., Richardson, K., Lenton, T.M., Folke, C., Liverman, D., Summerhayes, C.P., Barnosky, A.D., Cornell, S.E., Crucifix, M., Donges, J.F., Fetzer, I., Lade, S.J., Scheffer, M., Winkelmann, R., Schellnhuber, H.J., 2018. Trajectories of the Earth System in the Anthropocene. Proc. Natl. Acad. Sci. https://doi.org/10.1073/pnas.1810141115

Stolz, J.F., 2016. Gaia and her microbiome. FEMS Microbiol. Ecol. 93, fiw247.

Sun, C.-T., Chiang, A.W.T., Hwang, M.-J., 2017. A proteome view of structural, functional, and taxonomic characteristics of major protein domain clusters. Sci. Rep. 7, 14210. https://doi.org/10.1038/s41598-017-13297-0

Thomas, L., 1974. The lives of a cell: Notes of a biology watcher. Penguin. London

Thompson, W.I., 1991. Gaia 2: Emergence. The New Science of Becoming. Lindisfarne Press, New York.

Thompson, W.I., 1987. Gaia, a Way of Knowing: Implications of the New Biology. Lindisfarne Press, New York.

Toniazzo, T., Lenton, T.M., Cox, P.M., Gregory, J., 2005. 17 Entropy and Gaia: Is There a Link Between MEP and Self-Regulation in the Climate System?, in: Non-Equilibrium Thermodynamics and the Production of Entropy. Springer, pp. 223–241.

Tornos, F., Oggerin, M., Ríos, A. de los, Rodriguez, N., Amils, R., Sanz, J.L., Rojas, P., Velasco, F., Escobar, J.M., Gómez, C., 2018. Do microbes control the formation of giant copper deposits? Geology 47, 143–146.

Vernadsky, V.I., 1945. The biosphere and the noosphere. Am. Sci. 33, 1–12.

Volk, T., 2004. Gaia is life in a wasteworld of by-products, in: Scientists Debate Gaia. MIT Press, Boston, pp. 27–36.

Volk, T., 2003. Seeing Deeper into Gaia Theory: A reply to Lovelocks's response. Clim. Change 57, 5–7. https://doi.org/10.1023/A:1022193813703

Volk, T., 1998. Gaia's Body: Toward a Physiology of Earth, Copernicus Series. Copernicus.

von Foerster, H., Mead, M., Teuber, H. L. (1951). Cybernetics: Circular causal and feedback mechanisms in biological and social systems. Transactions of the Macy conference. Josiah Macy, Jr. Foundation. New York

von Foerster, H., 1960. On self-organizing systems and their environments, pp. 31–50 in Self-organizing systems. M.C. Yovits and S. Cameron (eds.), Pergamon Press, London

von Foerster, H., 1975. Gaia's Cybernetics Badly Expressed. CoEvolution Quarterly. 7, 51.

von Foerster, H., 1974. Notes pour une épistémologie des objets vivants, in: Morin, E., Piattelli- Palmerini, M. (Eds.), L'Unité de L'Homme, Editions Du Seuil, Paris. Paris, pp. 401–417.

von Neumann, J., 1966. Theory of self-reproducing automata. University of Illinois Press, Chicago.

Waddington C.H., 1968. The basic ideas of biology. In C.H. Waddington (Ed.), Towards a Theoretical Biology: Prolegomena, Atheneum, New York, pp. 1-41

Watson, A.J., Lovelock, J.E., 1983. Biological homeostasis of the global environment: the parable of Daisyworld. Tellus B Chem. Phys. Meteorol. 35, 284–289.

Wiener, N., 1948. Cybernetics or Control and Communication in the Animal and the Machine. MIT Press, Boston.

Williams, G.R., 1996. The Molecular Biology of Gaia. Columbia University Press, New York.

Williams, H.T.P., Lenton, T.M., 2008. Environmental regulation in a network of simulated microbial ecosystems. Proc. Natl. Acad. Sci.

Zaretzky, A.N., Letelier, J.C., 2002. Metabolic networks from (M, R) systems and autopoiesis perspective. J. Biol. Syst. 10, 265–280.

Footnotes

[1] The Nobel-laureate physicist Erwin Schrödinger suggested that biological phenomenon, contrary to the second law of thermodynamics, decreases or maintains its entropy by feeding on *negative entropy*. Schrödinger remarks on his usage of the term negative entropy: *'Let me say first, that if I had been catering for them [physicists] alone I should have let the discussion turn on free energy instead. It is the more familiar notion in this context. But this highly technical term seemed linguistically too near to energy for making the average reader alive to the contrast between the two things'* (Schrödinger, 1945, p. 74).

[2] An infinite regress arises, in a series of propositions, if the truth of proposition P_1 requires the support of proposition P_2, the truth of proposition P_2 requires the support of proposition P_3, and so on, *ad infinitum*.

Figure legends

Figure 1. Explanatory genealogy of the Gaia theory. In grey are represented the present-day Gaia theory explaining the Gaia phenomenon as a self-regulated and optimized system through feedbacks, entropy flows and adaptation. A biological-centred theory is represented in black, and explains the Gaia phenomenon as self-production by operational closure to efficient causation.

Figure 2. The (M,R)-Autopoiesis and Modelling relation. A) The categorical representation of the (M,R)-system formal model of biological systems. Continuous arrows and broken arrows represent material and efficient causation respectively. B) Autopoiesis is self-production by operational closure (circular arrow) and hence the living realization (implementation) of a (M,R)-system. Autopoiesis take place by a form of operational closure involving the molecular network (f, Φ, β in the M,R-system) and system's boundary. The self-production process must occur in structural coupling (openness)(arrows in both directions) with the ambience (curved grey line). C) Modelling relation depicting the Autopoiesis realization as a natural causal system and the (M,R)-system as a formal inferential system such that self-production by operational closure and self-fabrication by closure to efficient causation are equivalent (D) such that an (M,R)-autopoietic unity is distinguished.

Figure 3. The (M,R)-system expression of Gaia hypothesis. A) Modelling relation depicting the Earth system and the (M,R)-system as a natural and formal system governed by causal and inferential rules of implication respectively. B) In the left panel Volk's representation of Gaia flow (thick white arrows) and the efficient causes of transformation (black broken arrow) of matter and energy. Modified from Volk (cf. 1981, pg. 91). The right panel above summarizes Volk's representation in a single map $I: M \rightarrow C$. Solid and broken arrows represent the material and the efficient cause respectively. The right panel below illustrates such single map graphically, where I is represented as the Earth (containing inorganic pre-metabolic chemical networks), the black dots are material causes (M) transformed into an interconnected multifaceted, set of geochemical cycles C (black arrows) involving multiple time scales. C) Left upper panel show O (biosphere) as efficient cause (broken arrow) that maintains and transforms C into I (continuous black arrow); $O: C \rightarrow I$. In the left panel bellow grey arrows and squares represent O. The right upper panel shows Υ as an efficient cause (broken arrow) that transforms I into O (continuous black arrow). The circular arrows that connect all grey squares in the right below panel and the inverse mapping $C(\Upsilon): I \rightarrow O$ in (D) represent the systemic closure to efficient causes at the planetary scale. The diagrams of the (M,R)-system in (A) and of Gaia in (D) are the same with the correspondences (A, M), (B, C), (f, I), (Φ, O), and (β, Υ). This provides the criterion by which the Earth system organization satisfy an (M,R)-system formal model.

Figure 4. The autopoietic organization of the Earth system. A) Modelling relation depicting the Earth system and autopoiesis as natural systems governed by causal implications. B) The Earth's cycled water self-production is the main driver of geochemical cycles and heat transport. Modified from Schneider and Morton (cf. 1981, pg. 238). C) The autopoietic organization of the Earth as a system of causal processes of self-production through operational closure to efficient causation (black circular arrow) in structural coupling (black arrows in both directions) with its ambience (curve grey line).