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Gaia and the Evolution of Coherence

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1. Introduction

The Ufaina Indians in the Colombian Amazon believe in a vital force called *fufaka* which is present in all living things. The source of this vital force is the sun. From the sun, it reaches earth and is constantly recycled among plants, animals and human beings. Each group of beings requires a minimum of the vital force in order to live, and is seen to be borrowing the energy from the total energy stock. When any being dies, the energy is released and goes back to the stock. Similarly, when a living being consumes another, for example, when a deer eats the leaves of the tree, or a tree extracts nutrients from the soil, or when people cut down trees to make a clearing, the consumer acquires the energy of the consumed. What is of importance to the Ufaina is that the vital force continues to be recycled from one species to another in such a way that not too much accumulates in any one of them, since this could deprive another of its vital force, and upset the natural balance (von Hildebrand, 1988).

It is a remarkably coherent cosmology: a natural ecological wisdom that understands nature as a dynamically balanced whole linked by energy flow, with the energy arising ultimately from the sun. This cosmology is based on a total understanding that comes not just by scientific observations, but from an intimate experience of nature from within. It took Western science hundreds of years with many sophisticated instruments and a number of false starts and turns in order to arrive at a similar picture. As Peter Bunyard (1989) says, ‘The Indian conception . . . is not in principle far removed from . . . [our own] notion of energy flows and foodweb and chains, with the sun providing the necessary energy.’ The major difference between them and us is that whereas they live by their wisdom and see themselves as part of nature, we have placed ourselves above and outside the balance of nature, to the peril of all.

What we want to do in this paper is to present a vision of ecological balance from contemporary Western biophysics which shows just how intimately we are connected with one another and with nature. How all nature is one resonating and intercommunicating whole. We shall be drawing from the work of many, including ourselves, who have derived inspiration from the union of biology and physics.

Let us begin with the western ecological version of energy flow. The energy of sunlight is absorbed in individual packets or quanta called *photons* by *chlorophyll*, the colour pigment in green plants. This energy in each quantum goes into an excited electron, which, in the course of falling back to the ground state, travels around the body, its energy meted out to support all vital activities such as growth and differentiation, sensations, and movements. When animals feed on plants or on other animals, they are taking in the energy stored in the food to serve their own growth and development and all the activities that constitute being alive. Hence, the energy absorbed from the sun is circulated a long way round all the organisms in the biosphere, with fractions of the total being lost as heat on the way till finally it becomes spent, or reaches the ground state. The energy cycle is accompanied by the parallel cycling of chemicals. Both cycles branch and anastomose in a very complicated way as ecologists who study foodwebs or nitrogen and carbon cycles are well-aware. But it leaves us in no doubt that all life is a dynamic unity, it is the consequence of sunlight streaming through an open system, to maintain it far away from thermodynamic equilibrium.

Albert Szent-Gyorgi (1960), a founding father of modern biochemistry, had a nice way of putting it: that life is an interposition between two energy levels of an electron: the ground state and the excited state, and furthermore, as it is the electron that goes round the circuit, life is really a little electric current going round and connecting up all nature with the sun and the earth. This fundamental unity of physics and biology has indeed inspired a lot of people who felt that here was the key to unlocking the mystery of the living state. But as Szent-Gyorgi remarked then, and it is still largely the case now, biochemistry and molecular biology do not address such questions. They tell us a great deal about what the molecules that make up living organisms are, but very little about how they are supposed to act. How the energy plucked originally from the sun is translated so very efficiently into various forms of work - chemical, mechanical, electrical and osmotic - and in organizing matter into the splendid diversity of organisms in the biosphere. Szent-Gyorgi suggested that we can only begin to understand these characteristics of living systems if we take into account the collective properties of the molecular aggregates in terms of solid state physics. There, we would find a clue to the mystery of life.

We know, for example, that although at ordinary temperatures, the molecules in most physical matter have a high degree of uncoordinated, or random motion. The situation can change when the temperature is lowered to beyond a critical level. At that point, all the molecules so to speak, condense into a collective state, and exhibit the unusual properties of superfluidity and superconductivity. In other words, all the molecules of the system move as one, and conduct electricity with zero resistance (by a coordinated arrangement of all the electrons). Liquid helium at a temperature close to absolute zero is the first and only superfluid substance known. And various pure metals and alloys superconduct at liquid helium temperatures. Recently, technology has progressed to materials which can superconduct at much higher temperatures above absolute zero. The solid-state physicist Herbert Fröhlich (1968) in Liverpool was among the first to point out that something like a condensation into a collective mode of activity may be occurring in living systems, such that living organisms are in effect, superconductors working at physiological temperatures. He suggested that much of the metabolic energy, instead of being lost as heat, is actually stored in the form of coherent electromechanical vibrations in the body. He called these collective modes, coherent excitations.

Coherence refers to highly correlated activities in both space and time. In physics, it is usually understood as the ability of electromagnetic waves to interfere. For instance, in a version of Young’s pioneering experiment (Fig. 1), two narrow slits and are illuminated by light from a light source. The light beams, on passing through the slits, fall on the screen and form an interference pattern of differing brightness in accordance to where the oscillations in the two light beams are in phase or out of phase. The ability to form interference patterns depends on the stability of the oscillations in the two light beams, or more specifically their phase relationships. This phase stability is referred to as coherence; the more coherent the light, the sharper the interference pattern. The coherent state is fluctuationless and has the further characteristic that it is *factorizable* (Glauber, 1969). This means that the parts paradoxically behave statistically independently of one another while maintaining a coherent pattern as a whole. In other words, coherence does not imply uniformity, or that every individual part or molecule of the system is necessarily doing the same thing all the time. An intuitive way to think about it is in terms of a grand symphony, or a grand ballet; or better yet, a jazz band in which individuals are doing different things and are yet in tune or in step with the whole. It is a state of cooperativity in which the individuals cooperate simply by doing their own thing and expressing themselves.

What are the consequences of coherence? It results in properties that are characteristic of biological systems. These include the high efficiency of energy transfer and transformation which often approaches 100%; the ability of communication at all levels within cells, between cells and between organisms capable of resonating to the same frequencies; the possibility for sensitive, multiple recognition systems utilizing coherent electromagnetic signals of different specific frequencies, such as for example, the organization of metabolic activities within the cell, the operation of the immune network and a host of other biological functions involving specific recognition between hormones or ligands and their receptors; and finally, the stable persistence of the working system arising from the inherent stability of coherent states. A more detailed description of coherence is given in Ho (1993a).

2. Biophotons and coherence in living systems

Evidence for the existence of coherent excitations in biological systems came from the study of biophotons (see Popp *et al*, 1981; Popp, 1986). Practically all organisms emit light at a steady rate from a few photons per cell per day to several photons per organism per second. An increasing number of observations within the past 15 years from different laboratories all over the world suggest that biophotons are emitted from a coherent photon field within the living systems. Organisms are thus emitters and most probably, also receivers of coherent electromagnetic signals which may be essential for their functioning (see next Section).

The nature of the light emitted from living organisms is best studied after a brief exposure to weak illumination. It has been found, without exception that the the re-emitted light from living tissues follows, not an exponential decay curve as characteristic of non-coherent light, but a hyperbolic decay function which is exhibited only by coherent light (see Fig. 1). This unusual behaviour can be intuitively understood as follows. In a system consisting of non-interacting molecules emitting at random, the energy of the emitted photons are lost completely to the outside or converted into heat, which is the ultimate non-coherent energy. If the molecules are emitting coherently, however, the energy of the emitted photons are not completely lost to the outside. Instead, part of it is coherently reabsorbed by the system. The consequence is that the decay is very much delayed, and follows characteristically a hyperbolic curve with a long tail. This result can be derived rigorously from both classical and quantum mechanical considerations (Popp, 1986). A coherent system stabilizes its frequencies during decay whereas a noncoherent system always suffers a shift in frequencies. That, and the capability to reabsorb emitted energy account for the stability of coherent states.

3. The characteristics of biophotons

Where do biophotons really come from? We know that all sorts of excited molecules can emit light when they relax back to the ground state, the frequency of the emitted light being specific for each kind of molecules. When the spectrum of biophotons is examined, however, it was found that the light is always in a broad band of frequencies from the infra-red to the ultraviolet, with approximately equal numbers of photons distributed throughout the range. This is very different from the Boltzmann distribution which characterizes a system at thermodynamic equilibrium at the physiological temperature of the biological system, thus indicating that the latter is far, far away from thermodynamic equilibrium (see Fig. 2). Not only is there an excess of photons at the high energy (short wave-length) end of the spectrum, but the distribution is very nearly flat. In other words, it does not depend on the wavelength: $f(l)$ = const. This means that the light is emitted from all kinds of molecules all over the cell. The photons are stored in a delocalized manner within the system, and all the frequencies are coupled together to give, in effect, a single degree of freedom.

Evidence for the delocalization of coupled photons come from the observation that the emitted light retains its broad spectral distribution when organisms are stimulated with monochromatic light or light of limited spectral compostion. Moreover, the hyperbolic decay kinetics has the same form over the entire spectrum of emitted light (see Popp, 1986; Musumeci *et al*, 1992).

The Boltzmann distribution characteristic of a system at thermodynamic equilibrium arises from the maximization of entropy (molecular disorder, or degrees of freedom) under the constraint of a fixed energy in a closed system. As biological systems are open instead of closed, the constraint of a fixed energy does not apply. This does not mean that energy conservation is violated, as biological system + surroundings are still subject to energy conservation. Nor does it mean that there is always an overflow of energy within the system. It only means that there is always enough energy available for the system. Living systems store energy (or photons) over the whole range of space and time scales - from 10^{-10}m to metres or more, and 10^{-9}s to days or longer time intervals - in a readily mobilizable form. They do not suffer from energy shortage on account of their high storage capacity within the intricate space-time organization (see Ho, 1993a,b for details).

The $f(l)$ = const. distribution can also be seen as the consequence of the maximization of entropy when the constraint of fixed energy is removed in an open system far from equilibrium. The $f(l)$= const. profile looks somewhat like the expression of "white noise" within the system, but this is far from the case. As this distribution represents the highest possible entropy in a system far from equilibrium, fluctuations cannot be interpreted in terms of noise - in contrast to a system at thermal equilibrium. Rather, they are "signals" generated within the system. In other words, by maximizing entropy according to $f(l)$ = const., the signal/noise ratio of the biological system is optimized over all wavelengths (Popp, 1989). On the other hand, as the frequencies are all coupled together, the absolute value of entropy representing the maximum can also become arbitrarily small, theoretically even zero.

In summary, the fact that there is always enough energy available in the biological system confers on it the following properties:

1. Optimal signal/noise ratio for communication,
2. Existence at a phase threshold between a chaotic (S - , N -) and a coherent (S - 0, N - 1) regime, where S is the entropy, and N is the number of degrees of freedom, and

3. The possibility to extend energy storage, or the $f(l)$ = const. distribution to longer and longer wavelengths in the course of evolution, and hence to expand the range of communication from distances between molecular within the cell all the way to distances between individuals in a population.

4. Long range communication

The hypothesis that the $f(l)$ = const. distribution of biophotons can extend into infinitely long wavelengths is admittedly an extrapolation from measurements within and near the visible range. However, it can explain a variety of phenomena such as cancer development or group formation in organisms.

We are postulating the existence of very weak, long-range (long wave-length) interactions between living systems. These weak long-range emissions cannot be detected directly with the instrumentation now available. However, this is not a sufficient reason for excluding them from consideration, as there are methods of obtaining indirect evidence of their existence, as we shall describe below.

a. Normal and cancer cells in culture

A first experiment of this kind was performed by Schamhart and van Wijk (1987). They exposed suspensions of cultivated rat liver and rat hepatoma cell lines H35 and HTC for some seconds to white-light from a 150W tungsten lamp and registered the re-emitted light afterwards. The decay curves are, as usual, hyperbolic rather than exponential. On altering the number of cells in the suspension, the found that normal cells exhibit decreasing light re-emission with increasing cell density, whereas tumour cells show a highly nonlinear increase with increasing cell density (see Fig. 3). If there were no long-range interactions between the cells, the intensity of re-emitted photons would increase linearly with increasing number of cells, corrected by a term for self-absorption within the population. Neither the nonlinear increase of re-emission intensity from tumour cells nor the significant *decrease* of re-emission from normal cells could be explained unless there are long-range interactions between the cells, which are furthermore, correlated with their differing social behaviour, the tendency of tumour cells to disaggregation as opposed to the tendency of normal cells to aggregate.

These phenomena can be interpreted in terms of Dicke's (1954) theory of photon-emission from an ensemble of emitters. He showed that photon emission tends to bifurcate into the two branches of *superradiance* and *subradiance* as soon as the wavelength of the emitted light is large compared to the distances between the emitters which are also absorbers. Superradiance is the increase of emission intensity concomittant with a shortening of the relaxation time. The opposite branch describes the regime of subradiance where emission intensity decreases with a more and more prolonged decay time, corresponding to photon storage within the system.

In terms of Dicke’s theory, normal cells have a greater capacity for subradiance the closer they are together, while the malignancy of tumour cells is associated with the opposite behaviour, that is, the loss of subradiance. This suggests that long-range interaction is based on the coherence of the subradiance regime, with the coherence volume extending over the entire cell population. By changing the degree of coherence the cells can control and regulate their social activities. According to this model, tumour cells, unlike normal cells, seem unable to communicate. This may account for the repulsive forces that are responsible for metastasis in the malignant cells as opposed to the attractive forces responsible for population formation in normal hepatocytes (for further details see Nagl and Popp, 1987).

b. Populations of *Daphnia*

Even more clear-cut results are obtained in organisms, such as *Daphnia*; where self-emission is measured instead of stimulated re-emission. Figure 4 depicts the results of measurements made by Galle *et al* (1991). Instead of the expected linear increase in photon intensity with increasing number of individuals, a pattern of maxima and minima is observed, where the maximum and minimum values of photon intensity can be reproducibly assigned to definite numbers of individuals in the cuvette. It turns out that they invariably correspond to integer ratios of the average distances between individual animals to their body size. The results cannot be interpreted in terms of ordinary biochemistry. Instead, by treating the daphnia as a population of antennae interacting by means of resonance wavelengths related to their geometrical dimensions, a good fit to the experimental data is obtained. Regardless of whether the details of the hypothesis are correct, the experiments clearly demonstrate the existence of long-range interactions between individuals in a population. These interactions may be the basis for swarming and the regulation of growth and other collective functions. The link to body size indicates communication wavelengths in the microwave to millimeter range.

c. Superdelayed luminescence in *Drosophila*

We have recently discovered the remarkable phenomenon of superdelayed luminescence in synchronously developing populations of early *Drosophila* embryos, in which intense, often prolonged and multiple flashes of light are re-emitted with delay times of one minute to eight hours after a single brief light exposure. Some examples are presented in Figure 5 (see Ho *et al*, 1992). The phenomenon depends on the existence of synchrony in the population, and furthermore, the timing of light exposure must fall within the first 40 minutes of development. However, the occurrence of the flashes themselves do not obviously correlate with specific embryonic events. They give information concerning the physical state of the embryos at the time of light stimulation - such as the existnece of a high degree of coherence - rather than at the time during which the flashes themselves occur. Superdelayed luminescence bears some formal resemblance to the phenomenon of superradiance described above in which cooperative interactions among embryos within the entire population lead to most, if not all the embryos emitting light simultaneously. This implies that each embryo has a certain probability of re-emitting after light stimulation, so that it can either trigger re-emission in other individuals, or alternatively, its re-emission could be suppressed by them. Only whe the population is re-emitting at the same time is the intensity sufficient to be registered as the intense flashes that is detected by the photon-counting device. On the other hand, re-emission in the entire population could also be suppressed (i.e., in the subradiant mode), such that in approximately 30 to 40% of the cases, there is no clear indication of any superdelayed re-emission.

We do not know if any functional significance could be attached to superdelayed luminescence. *Drosophila* females typically lay eggs just before sunrise, so the external light source could be used as an initial synchronizaing signal or *Zeitgeber*, which maintains the circadian and other biological rhythms. The superdelayed re-emission could then be a means of maintaining communication and synchrony among individuals in the population. On the other hand, the flashes may simply be the embryos' way to inform us of their globally coherent state at the time when light stimulation is applied, enabling the embryos to interact nonlinearly to generate light emission that is coherent over the entire population, and orders of magnitude more intense than the spontaneous emission background (see Ho *et al*, 1992; and Ho, 1993a for further details).

5. Coherence and the evolution of consciousness

What does the study of coherence contribute to our understanding of the unity of life? To return to our overview on the cycle of life, we can see that sunlight is the most fundamental source of energy, which is supplied at the high frequency end, and biological systems as a whole display the natural tendency to delay the decay of this high level energy for as long as possible. This is why the earth's natural biosphere is not a monoculture, indeed, it is the very diversity of life that is responsible for delaying the dissipation of the sun's energy for as long as possible by feeding it into ever longer chains and webs and multiple parallel cycles in the course of evolution. But that is not the entire story, for the the most effective way of hanging on to this energy for as long as possible is by the formation of a coherent platform of oscillations which expands the photon field into a coherent state of growing bandwidth. This is the $f(l)$ = const. distribution which allows the sun's energy to spill over into longer and longer wavelengths. This may be why organisms have such different life-spans; the trend in evolution is towards the emergence of organisms with longer and longer life-spans and finally in the case of social organisms and human beings, we see the emergence of social traditions that span many generations. The link with social tradition is the clue to the meaning of this energy flow through a coherent field of ever increasing bandwidth. For it is at the same time a flow and a creation of information. Electromagnetic signals of different frequencies are involved in communication within and between organisms, and between organisms and the environment. The coherent platform is a prerequisite for universal communication.

Thus, it seems that the essence of the living state is to build up and extend the coherent spatio-temporal platform for communication starting from the energy of the sun initially absorbed by green plants. Living systems are thus neither the subjects alone, nor objects isolated, but both subjects and objects in a mutually communicating universe of meaning. In contrast to the neo-Darwinist point of view, their capacity for evolution depends, not on rivalry or on might in the struggle for existence. Rather, it depends on their capacity for communication. So in a sense, it is not individuals as such which are developing but living systems interlinked into a coherent whole. Just as the cells in an organism take on different tasks for the whole, different populations enfold information not only for themselves, but for all other organisms, expanding the consciousness of the whole, while at the same time becoming more and more aware of this collective consciousness. Human consciousness may have its most significant role in the development and creative expression of the collective consciousness of nature.

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Legends

- Fig. 1. Hyperbolic decay of re-emitted photons from a synchronously developing population of *Drosophila* embryos. (From Ho, 1993a).
- Fig. 2. Spectral distribution of biophoton emission compared to the Boltzmann distribution of a system at thermal equilibrium at physiological temperatures.
- Fig. 3. Total photon counts within the first seconds after exposure of cell suspensions to white light. Malignant HTC cells, -o-o-; normal heptocytes, -o-o-; and H35 cells which are only weakly malignant, -x-x-.
- Fig. 4. Self-emitted photon count-rate in daphnia as a function of population density.
- Fig. 5. Superdelayed luminescence in *Drosophila*. Continuous recordings of light emission from synchronously developing baches of embryos. Each data point on the graphs represents the aggregated photon count for 20s. Top trace, control batch not exposed to light. The other traces are from batches which have all been exposed to white light for one minute before the recording, and show different forms of superdelayed luminescence. Traces on the right are expanded versions of those on the left. (From Ho *et al*, 1992).

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