4.3: Gaia - Bioregulation of the Environment

The Gaia Hypothesis

The physical conditions under which life as we know it can exist encompass a relatively narrow range of temperature, pH, osmotic pressure, and ultraviolet radiation intensity. It seems remarkable enough that life was able to get started at all; it is even more remarkable that it has continued to thrive in the face of all the perils that have, or could have occurred, during the past 3 billion years or so.

During the time that life has been evolving, the sun has also been going through the process of evolution characteristic of a typical star; one consequence of this is an increase in its energy output by about 30 percent during this time. If the sun's output should suddenly drop to what it was 3 billion years ago, the oceans would freeze. How is it that the earth was not in a frozen state for the first 1.5 billion years of life's existence? Alternatively, if conditions were somehow suitable 3 billion years ago, why have the oceans not long since boiled away?

A rather non-traditional answer to this kind of question is that the biosphere is far from playing a passive role in which it is continually at the mercy of environmental conditions. Instead, the earth's atmosphere, and to a lesser extent the hydrosphere, may be actively maintained and regulated by the biosphere. This view has been championed by the British geochemist J.E. Lovelock, and is known as the *Gaia hypothesis*.

> *Gaia is another name for the Greek earth-goddess Ge, from which root the sciences of geography, geometry, and geology derive their names. Lovelock's book Gaia: a new look at life on Earth (Oxford, 1979) is a short and highly readable discussion of the hypothesis.*

Evidence in support of this hypothesis is entirely circumstantial, but nevertheless points to important questions that must be answered: how have the climatic and chemical conditions on the earth remained optimal for life during all this time; how can the chemical composition of the atmosphere remain in a state that is tens of orders of magnitude from equilibrium?

Note

Although the Gaia hypothesis has received considerable publicity in the popular press, it has never been very well received by the scientific community, many of whom feel that there is no justification for proposing a special hypothesis to describe a set of connections which can be quite adequately explained by conventional geochemical processes. More recently, even Lovelock has backed away from the teleological interpretation of these relations, so that the Gaia hypothesis should now be more properly described as a set of loosely connected effects, rather than as a hypothesis. Nevertheless, these effects and the mechanisms that might act to connect them are sufficiently interesting that it seems worthwhile to provide an overview of the major observations that led to the development of the hypothesis.

Teleology is the doctrine that natural processes operate with a purpose. See *No longer willful, Gaia becomes respectable.* 1988: Science 240 393-395.

Bioregulation of the Atmosphere

The increase in the oxygen content of the atmosphere as a result of the development of the eucaryotic cell was discussed above. Why has the oxygen content leveled off at 21 percent? It is interesting to note that if the oxygen concentration in the atmosphere were only four percent higher, even damp vegetation, once ignited by lightning, would continue to burn, enveloping vast areas of the earth in a firestorm. Evidence for such a worldwide firestorm that may be related to the extinction of the dinosaurs has recently been discovered. The charcoal layers found in widely distributed sediments laid down about 65 million years ago are coincident with the iridium anomaly believed to be due to the collision of a large meteor with the earth.

- **Oxygen**: Regulation of the oxygen partial pressure is probably achieved by a balance between its production through photosynthesis and its consumption during oxidation of organic matter; the present steady state requires the burial of about 0.1% the carbon that is fixed annually, leaving one O_2 molecule in the air for each atom of carbon removed from the photosynthetic cycle. The large quantities of microbially-produced methane and N_2O also constitute important oxygen sinks; if methanogenic bacteria should suddenly cease to exist, the O_2 concentration would rise by 1% in about 12,000 years. This type of regulation implies a negative feedback mechanism, in which an increase in atmospheric oxygen would increase the activity of organisms capable of generating metabolic products that react with it.

- **Nitrous oxide**: Nitrous oxide, in addition to serving as an oxygen sink, might also be a factor in the regulation of the intensity of the ultraviolet component of sunlight. N_2O acts as a catalytic intermediate in the decomposition of stratospheric ozone, which shields the earth from excessive ultraviolet radiation.
- **Ammonia**: Ammonia, another atmospheric gas, is produced by the biosphere in approximately the same quantities as methane, 10^9 tons per year, and at the expense of a considerable amount of metabolic energy. The function of NH_3 could well be to regulate the pH of the environment; in the absence of ammonia, the large amounts of SO_2 and HCl produced by volcanic action would reduce the pH of rain to about 3. The fact that the atmospheric concentration of ammonia is only 10^{-8} times that of N_2 should not imply that this "trace" component plays a less significant role in the overall nitrogen cycle than does than N_2. In fact, the annual rates of production of the two gases are roughly the same; the much lower steady-state concentration of NH_3 is due to its faster turnover time.
- **Nitrogen**: As stable as the triply-bonded N_2 molecule is, there is a still more stable form of nitrogen: the hydrated nitrate ion. How is this stability consistent with the predominance of nitrogen in the atmosphere? The answer is that it is not: if it were not for nitrogen-fixing bacteria (powered directly or indirectly by the free energy of ATP captured from sunlight), the nitrogen content of the atmosphere would disappear to almost zero. This would raise the oxygen fraction to disastrously high levels, and the additional NO_3^- concentration would increase the ionic strength and osmotic pressure of seawater to levels inconsistent with most forms of life.

Bioregulation of the Oceans

The input of salts into the sea from streams and rivers is about 5.4 x 10^8 tons per year, into a total volume of about 1.2 x 10^9 km^3 yr^{-1} . Upwelling of juvenile water and hydrothermal action at oceanic ridges provide additional inputs of salts. With a few bizarre exceptions such as the brine shrimp and halophilic bacteria, 6 percent is about the maximum salinity level that organisms can tolerate. The internal salinities of cells must be maintained at much lower levels (around 1%) to prevent denaturation of proteins and other macromolecules whose conformations are dependent on electrostatic forces. At higher levels than this, the electrostatic interaction between the salt ions and the cell membrane destroys the integrity of the latter so that it can no longer pump out salt ions that leak in along the osmotic gradient. At the present rate of salt input, the oceans would have reached their present levels of salinity millions of years ago, and would by now have an ionic strength far to high to support life, as is presently the case in the landlocked Dead Sea.

> *The present average salinity of seawater is 3.4 percent. The salinity of blood, and of many other intra- and intercellular fluids in animals, is about 0.8 percent. If we assume that the first organisms were approximately in osmotic equilibrium with seawater, then our body fluids might represent "fossilized" seawater as it existed at the time our predecessors moved out of the sea and onto the land.*

By what processes is salt removed from the oceans in order to maintain a steady-state salinity? This remains one of the major open questions of chemical oceanography. There are a number of answers, mostly based on strictly inorganic processes, but none is adequately supported by available evidence. For example, Na^+ and Mg^{2+} ions could adsorb to particulate debris as it drops to the seafloor, and become incorporated into sediments. The requirement for charge conservation might be met by the involvement of negatively charged silicate and hydroxyaluminum ions. Another possible mechanism might be the burial of salt beds formed by evaporation in shallow, isolated arms of the sea, such as the Persian Gulf. Extensive underground salt deposits are certainly found on most continents, but it is difficult to see how this very slow mechanism could have led to an unfluctuating salinity over shorter periods of highly variable climatic conditions.

The possibility of biological control of oceanic salinity starts with the observation that about half of the earth's biomass resides in the sea, and that a significant fraction of this consists of diatoms and other organisms that build skeletons of silica. When these organism die, they sink to the bottom of the sea and add about 300 million tons of silica to sedimentary rocks annually. It is for this reason that the upper levels of the sea are undersaturated in silica, and that the ratio of silica to salt in dead salt lakes is much higher than in the ocean.

These facts could constitute a basis for a biological control of the silica content of seawater; any link between silica and salt could lead to the control of the latter substance as well. For example, the salt ions might adsorb onto the silica skeletons, and be carried down with them; if the growth of these silica-containing organisms is itself dependent on salinity, we would have our negative feedback mechanism.

The continual buildup of biogenic sedimentary deposits on the ocean floor might possibly deform the thin oceanic crust by its weight, and cause local heating by its insulating properties. This could conceivably lead to volcanic action and the formation of new land mass, thus linking the lithosphere into Gaia.

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