THE ORIGIN OF CHIRALITY IN BIOMOLECULES; ARE ELECTROMAGNETIC FORCES IMPORTANT?

M. Yamauchi

Swedish Institute of Space Physics, Box 812, SE-98128 Kiruna, Sweden
tel: +46 (0)980-79120 / fax +46 (0)980-79050 / e-mail: M.Yamauchi@irf.se

ABSTRACT

This paper is a supplement to our previous paper (Yamauchi and Wahlund, 1998, hereafter referred as Paper 1) extending the discussion to the space and other planets. Static electromagnetic (Lorentz) force in the geomagnetic field may cause a chirality in chemical reactions with the help of, e.g., catalytic/polarized boundaries or layers; laminar convection or drift; strong gradient of ionized solution; shock propagation; radiation, gravitational forces; centrifugal forces of gyrating ions, and etc. Most elements favour weakly ionized fluid ($\nu_i \gg \Omega_i$) and hence the volcanic shallow sea in the ancient Earth. However, applications are found also in other solar system bodies and interstellar media. The obvious weak point of the geomagnetic field scenario (Two hemispheres should cause opposite enantiomers with opposite directions of the magnetic field) is easily overcome if the early terrestrial life started in a local heat spot in one hemisphere within less than one reversal of the geomagnetic field.

INTRODUCTION

The homochirality of the biomolecules was first recognized as the chiral nature of the biological product 144 years ago. After the identification of the DNA structure, the homochirality problem was re-formulated: "The terrestrial DNA has only one helicity (right-handed spiral), meaning that its composing materials (nucleosides/sugars) have only D-type chirality - Why?" The problem has two aspects:
(1) Which is the primary factor of determining the existing enantiomer: the homochirality or monohelicity?
(2) Is the selection of the enantiomer purely by chance or due to some external force?
These questions also give important clues to searching for and understanding possible life in the universe.

MONOHELICITY OR HOMOCHIRALITY?

The first question comes from the following consideration. Spiral is the simplest geometrical structure which allows semi-stable (i.e., possible to evolve) self-duplications, i.e., an auto-catalysis system (e.g., Kondepudi, 1994, Goldanskii, 1996). Once the self-duplication starts, small unbalance in helicity will be amplified quickly. On the other hand, the natural chirality is unstable, i.e., molecules with enantiomeric excess easily become raceme unless the environment is very cold and dry. Since the right-handed RNA consumes D-enantiomer nucleoside only, the left-over free nucleosides become L-rich when RNA duplicates itself, and the unstable nature of the nucleoside converts molecules from L-type to D-type to keep the entire free nucleosides raceme.

Thus it is possible that the monohelicity of RNA preceded the homochirality of nucleosides. In this case the by-chance mechanism is an obvious candidate. However, as pointed out in Paper 1, the geomagnetic field might have contributed to the monohelicity in two independent ways, namely the force-free mechanism and the wave-induced duct mechanism (see Figures 6 and 7 in Paper 1).

The force-free mechanism uses the minimum energy principle for the electric current in 3-D free space. It predicts that its stable trajectory must be a right-/left-handed spiral, corresponding to a parallel/antiparallel electric current to the magnetic field. The flow direction is determined by the global configuration (electric circuit), and the original energy source is the convection (e.g., solar wind or local sea flow). The wave-induced duct mechanism uses the whistler waves which are always polarized left-handed against the magnetic field direction (proton mode) in the ocean, and the wave can easily form a helical duct which attracts nucleosides in the right-handed way. The details are explained in Paper 1.

MECHANISMS FOR HOMOCHIRALITY

Table 1 summarizes the currently proposed possibility for the second question in the introduction. There are three classes. The first class "by chance" is not the topic of this paper. The second class uses radiative "line-of-incident" source for both the energy of reactions and the source of chirality. It has two subclasses: anisotropic elementary forces such as the weak interaction force of the atom (e.g., Hegstrom, 1982; Mason and Tranter, 1984) and polarized radiation (e.g., Akaboshi, 1982; Bonner, 1996; Greenberg, 1996). The expected enantiomeric excess is universal for the former case, and it depends on the polarization for the latter case.

The energy of reactions and the cause of chirality are separated in the third class in Table 1, and the static

environment is responsible for the chirality. Using the geomagnetic field traces back to 1857 when Pasteur found the homochirality of biomolecules (he found chirality itself in 1848). Although the static magnetic field does not construct the chiral asymmetry by itself (e.g., Barron, 1994), laboratory experiments have already shown that the magnetic field causes the chirality during photochemical reactions by unpolarized UV light (e.g., Rikken and Raupach, 2000). Class 3a includes such combination of a radiative source and the asymmetric environment (see also Figure 5 of Paper 1).

Class 3b in Table 1 shows examples of combining asymmetric forces that might cause the chiral reactions under the geomagnetic field without the help of radiation or energetic particles. This class is not unrealistic but rather unexplored as is discussed in Paper 1. In fact the fundamental importance of the geomagnetic field on the crystal shape (not chirality, though) has already been demonstrated by the Space Shuttle and laboratory experiments (Scaife et al., 1990; Lee and Lee, 1997). This particular experiment is explained by the gravity drift with closed boundary (container). Extending this result to more complicated cases, it is natural to assume that the Earth can provide a chiral environment for chemical reactions (three axes of asymmetry). The contributing asymmetric forces are listed in Table 1 with possible physical conditions that make such forces contribute. These conditions are best found near underwater volcanoes.

One may immediately raise questions on the scenario using the geomagnetic field: (1) The same mechanism causes one chirality in one hemisphere and the other chirality in the other hemisphere; (2) The geomagnetic field is well known to switch its polarity every million years (at present); (3) The emergence of terrestrial life is before the reported enhancement of the geomagnetic field 2.7 billion years ago, although this measurement is not certain.

The first two problems are easily overcome if early terrestrial life started in the local heat spot (such as a volcano on either hemisphere) in a short time (less than one reversal of the magnetic field). This is quite possible because underwater volcanoes are very unevenly distributed as shown in Figure 1. As an additional requirement, the other contributing factors to the chiral environment (e.g., convection or electric field) must also be fixed in certain directions. The last problem is not essential because the geomagnetic field had existed anyway before the emergence of terrestrial life (i.e., before the continent was formed) although its strength could be one order of magnitude smaller (this is still a strong field).

THE GEOMAGNETIC FIELD SCENARIO

Examples of combining factors for chiral reactions in the geomagnetic field are found in Table 1 as (a)-(i). The static conditions are (e)-(i), and some of them are illustrated in Figure 2.

Table 1. How did the homochirality arise?

1. by chance + competition/auto-catalysis?	
2. chiral forces + competition/auto-catalysis?	
2b.	Weak Boson interaction force W-interaction force (e.g., *a*) Z-interaction force (e.g., *a*)
2b.	Radiative Electromagnetic (EM) forces Polarized gamma ray (e.g., *a*) Polarized UV-IR lights (e.g., *b*) Polarized radio wave (e.g., *c, d*)
3. achiral forces + competition/auto-catalysis?	
3a.	Radiative EM forces or Discharge in anisotropic environment in magnetic field (e.g., *a-d*) in electric/gravity field (e.g., *a-d*) in plasma (e.g., *a-d, f*)
3b.	Lorentz (static EM) force + combining factor + electrostatic force (e.g., *c, e-i*) + magnetostatic force (e.g., *e, h, i*) + non-EM forces* (e.g., *f-i*)

* gravitational force, pressure gradient force, centrifugal force of gyrating ions, etc.
(*a*) cosmic ray
(*b*) solar radiation
(*c*) lightning
(*d*) ionospheric plasma radiation
(*e*) catalytic/polarized boundary or layer**
(*f*) partially ionized fluid
(*g*) laminar convection
(*h*) strong gradient of ionized solution
(*i*) shock propagation
** decreasing temperature is favoured

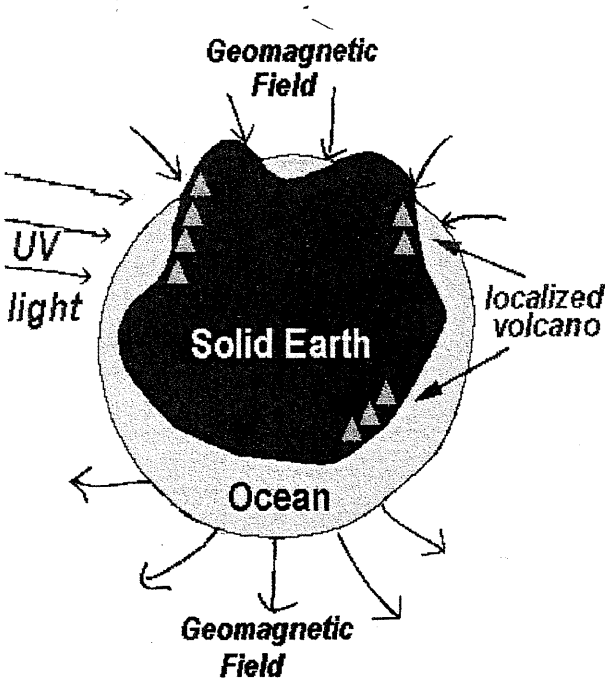


Figure 1. Distribution of volcanoes and shallow ocean of the ancient Earth should be more uneven than now.

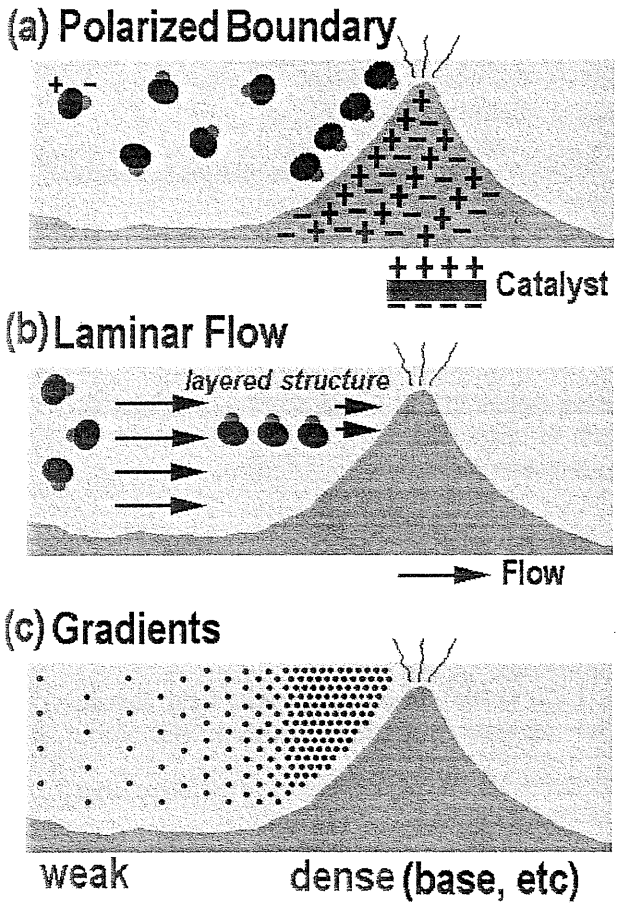


Figure 2. Examples of combining factors for chiral reaction in the geomagnetic field.

The catalytic/polarized boundary is somewhat similar to the clay system (Bernel, 1951). Catalytic materials are normally electrically polarized in a complicated way, and they may fix the direction of the reacting solution in a 2-D plane (i.e., quadralpole) with relatively strong electric force. Fixing by the magnetic dipole moment of molecules can replace the electric quadralpole to the electric dipole in this 2-D fixing scenario.

However, a 3-D fixing of solution (i.e., octagonal pole) is different from the 2-D fixing because the difference in the electric energy between D- and L-enantiomers is not large enough compared to the thermal fluctuation. Thus we need something extra which can cope with the catalyst. While radiation type incident is an obvious candidate, the geomagnetic field may also add the last anisotropy to the already 2-D fixed ionized solution because the ions approach a boundary surface from a certain direction due to the gyration.

Volcanic lava is an obvious candidate for such a catalytic boundary as illustrated in Figure 2a, whereas a laminar flow is also known to make a layered catalyst (e.g., atmospheric Lee wave in Paper 1). The laminar flow may also directly assemble the reacting solution in a fixed direction without EM forces as illustrated in Figure 2b. Similar assembly by non-EM forces is expected during shock propagation (e.g., sound wave) or in a non-uniform fluid with a strong gradient of solution as illustrated in Figure 2c.

The chiral reaction is also possible without catalysis if the reacting solutions approach to each other from limited directions with limited facing angles. Such a reaction requires two forces to fix the facing angles in addition to a force that controls the motion against the random motion of the warm molecules. To receive three different types of static forces, the solution must be ionized. This means that the geomagnetic field plays an essential role. The problem is that the Lorentz force rotates the direction of the ion motion, and hence we need frequent collisions with neutral to make the ion motion direction stay relatively fixed. Therefore, a weakly ionized state is essential in this case.

The ion drift velocity (species i) in a weakly ionized fluid under the magnetic ($\boldsymbol{B}$), electric ($\boldsymbol{E}$), and gravity ($\boldsymbol{g}$) fields is given as

$$m_i\mathbf{U}_i = [\nu_i\mathbf{F}_i + \mathbf{F}_i \times \Omega_i] / [\nu_i^2+\Omega_i^2] \qquad (1)$$

where bold faces denote vectors, q_i is the electric charge with sign, m_i is the mass, ν_i is the collision frequency with neutrals which is proportional to the neutral density, $\boldsymbol{F}_i = q_i\boldsymbol{E}+m_i\boldsymbol{g}$ is the force, and $\Omega_i = q_i\boldsymbol{B}/m_i$ is the gyro frequency. The formula states that the drift direction (average motion) is off from the external force direction (initial acceleration direction after collision), and the degree of deflection depends on the ratio of ν_i and Ω_i.

A high collision rate in weakly ionized fluid makes all ions move in a similar direction to the external force ($\boldsymbol{F}_i$) because the motion is reset by the frequent collisions. In such a case, i.e., if $\nu_i \gg \Omega_i$, we have

$$\mathbf{U}_i = \mathbf{F}_i/m_i\nu_i + \mathbf{F}_i \times \Omega_i/m_i\nu_i^2 \qquad (2)$$

and almost all particles move in the $q\boldsymbol{E}+m\boldsymbol{g}$ direction whereas the attitude is controlled by $\boldsymbol{E}$ and $\boldsymbol{B}$ directions if the molecule has both the electric and magnetic dipole moments. Thus these three forces make a chiral environment, i.e., fixing both the facing angles of positive and negative solutions and their colliding directions without boundary effects.

Another candidate for the external force in free space is the centrifugal force of gyrating ions as discussed in Paper 1, and the combination of magnetic moment, centrifugal force, and the internal electric polarization together may cause the chiral environment without catalytic boundaries.

PREFERENCE OF LOW TEMPERATURE

The class 3b scenario requires good alignment of solution against the thermal fluctuation, and hence it is most effective at low temperatures.

The degree of fixing of a "free" n-particle system by the static magnetic field against the ordinary thermal motion is obtained in Paper 1 as

$$\Delta\varepsilon \approx (\mu B/kT)\cdot n\mu B \qquad (3)$$

where $\Delta\varepsilon$ is the total energy shift due to the external magnetic field, T is the temperature, and μ is the total magnetic moment of the molecule. The formula is also valid for the electric potential if we replace B to E and read μ as the electric dipole moment. The small factor $\mu B/kT \ll 1$ represents the statistical alignment, and it amounts to about 10^{-6} /molecule for an electron in the geomagnetic field (B=10^{-4} T) at room temperature (kT = 0.02 eV). This is the worst estimation without any other fixing factors such as boundaries and laminar catalyst. Yet we have $\Delta\varepsilon \approx 10^{-14}$ eV/molecule which is larger than the weak interaction force.

SPACE APPLICATION

So far the terrestrial application (underwater volcano) has been considered for the static chiral environment. However, the same argument can also be applied to space and other planets. The Martian case is interesting because of the discovery of the permanent magnetic stripe. If the geomagnetic field played a role for the homochirality, the chances of finding the signature of ancient Martian life should be highest inside the region of the magnetic stripe.

Interstellar cloud has a very weak magnetic field with low density and low temperatures. Hence the assistance of polarized radiation has been favoured. However, we only need the $\nu_i \gg \Omega_i$ condition for the above Lorentz force scenario with possibly some boundary or layered internal structure. The low density favours the partial ionization and the low temperature favours the fixing of the polarized molecules in a certain direction. The external force (e.g., gravity) can be temporally enhanced when the cloud floats by a star.

A similar argument is possible for comets in the magnetized solar wind. Because the ionization is mainly by the solar photons, it is not difficult to find a region of $\nu_i \gg \Omega_i$ near the comet surface. Accidental planetary flybys provide extra gravitational force. Thus the comet itself can be a source of chiral molecules.

CONCLUSIONS

This paper is supplementary to our previous paper (Yamauchi and Wahlund, 1998) on the homochirality of biomolecules.

(1) One cannot ignore the possible roles of the Lorentz force in the geomagnetic field in causing chirality with the help of, e.g., catalytic/polarized boundaries or layers, laminar convection or drift, radiation, strong gradient of ionized solution, shock propagation, gravity, centrifugal forces of gyrating ions, and etc.. Weakly ionized conditions ($\nu_i \gg \Omega_i$) are favorable in this case.

(2) The geomagnetic field scenario requires that terrestrial life started in the local spot in one hemisphere within less than one reversal of the magnetic field. This is fulfilled if we assume extremely local distribution of underwater volcanoes (Figure 1).

(3) The given mechanism (Table 1) can be applied to other planets, comets, and interstellar clouds in certain conditions.

(4) Low temperature is important.

(5) It is possible that monohelicity of RNA preceded homochirality.

ACKNOWLEDGEMENT

The author thanks J.E. Wahlund, F. Thiemann, and M. Akaboshi for providing essential information and for useful discussion.

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