Possible roles of the geomagnetic field and plasma state on the right-handed nature of DNA and homochirality of biomolecules.

M. Yamauchi and J.-E. Wahlund

Swedish Institute of Space Physics
Box 812, S-98128 Kiruna, Sweden (yama@irf.se)

(Abstract)
Possible effects of the geomagnetic field in various environment are considered to explain the right-handed nature of DNA. Although the static magnetic field itself does not form a chiral field which is necessary for the chiral chemical reactions, combinations of electric field, non-electric forces (e.g., gravity and centrifugal forces for gyrating ions), laminar convection and the magnetic field may constitute more than two different directions of anisotropy, i.e., a chiral environment for ionized molecules. The asymmetric interaction in such an environment can be stronger than that given by the atomic weak-interaction force. We propose many mechanisms where the Lorentz force might have played a role on the bio-homochirality during the formation of initial DNA/RNA. These mechanisms either polarize the biomolecules to chirals or assemble the molecules to monohelical configurations. Most of those mechanisms requires that life is formed in a restricted geophysical region (such as volcano on either hemisphere), while the combination of Lorentz force and centrifugal force on gyrating ions does not require such a geophysical restriction.

1. Introduction

The reason that the terrestrial DNA's helicity is always right-handed (homochirality of biomolecules) could be either "by chance" (plus some dynamic instability such as "autocatalysis" and "competition" (e.g., Kondepudi and Nelson, 1985; Kondepudi, 1994)) or by solid physical forces. So far only few forces have been proposed (for review, e.g., Bonner, 1996), and it is worth investigating various mechanisms that may have caused the monohelicity and the homochirality of the life. This presentation is intended to promote a new viewpoint on the possible physical cause of the homochirality.

As illustrated in Figure 1, there are two main occasions to physically select the homochirality or monohelicity: (1) selection of D-type sugars (or L-type aminoes) from a non-chiral source; (2) selection of right-handed spirals from a non-chiral source. Once the process starts in one chirality, the evolution of that type of chiral molecules may win the entire process, preventing a formation of the opposite type of chirality (e.g., Kondepudi and Nelson, 1985; Bonner, 1996).

Viva Origino 20(1998)177-192

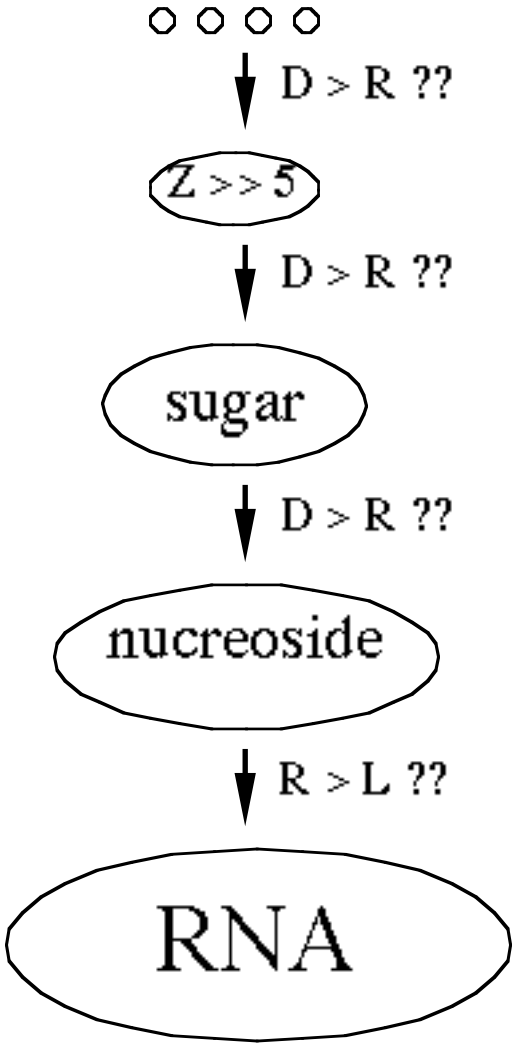

Fig. 1. Possible selection opportunities of homochirality or monohelicity.

Let us first consider the formation of the homochiral molecules, and consider the formation of the monohelicity later in section 6. A chiral reaction requires either chiral materials or fields (forces). Here, the chiral material includes catalyst such as chiral rock crystals, but in this case, the formation of the chiral catalyst becomes the problem instead of formation of the chiral biomolecules. Therefore, one may limit the discussion, without loosing generality, to combination of achiral material and chiral field (force) when considering the chiral environment.

2. Traditional considerations

It is inevitable to review the anisotropic elementary forces in order to study possible chiral fields (forces). By "anisotropy" we mean that the energy level becomes different for different pointing directions of a molecule's axes. The basic elements we consider here are (a) W- or Z-interaction force, (b) magnetic moment, (c) electric polarization, (d) combination of different static forces, and (e) polarized radiation.

(a) The only internal (basic) force that may directly cause a chirality is the weak interaction (W-interaction or Z-interaction) force. Many works have been devoted on this problem (e.g., Hegstron, 1982; Mason and Tranter, 1984; Kikuchi, 1995), concluding that this force might cause a preference of the chirality. However the difference of the production rates between D and L is very small, and the energy difference between D and L chirals is at most 10^{-15} eV / molecule (i.e., 10^{-10} J / mol). Therefore, many people believe that the weak interaction force alone did not cause the homochirality of the biomolecules.

(b) Chemical reactions under the influence of direct coupling between the electron spin and the geomagnetic field (10^{-4} T) does not lead to any preference of chirality by itself, because an uniform static magnetic field is not chiral. The coupling force itself is strong (10^{-18} N / electron), and it may lead to an energy difference of up to 10^{-8} eV / molecule between D and L chirals if the total magnetic moment of the molecule is aligned perpendicular to the external magnetic field. However, they are in average aligned to each other to minimize the total energy. and hence the substantial energy difference between D and L must become zero.

(c) The same argument applies for chemical reactions under the influence of direct coupling between the electron and ambient electric field (geo-electric field is as strong as 100 V/m in the quiet air, and is significantly enhanced during thunder storms). The coupling force working on each molecule can be up to 10^{-18} N / electron (or energy difference of up to 10^{-8} eV / molecule between D and L chirals), but substantial energy difference between D and L must be nearly zero.

(d) Even if we combine the static electric field and the static magnetic field, the resulting two axes of anisotropy is normally not sufficient to cause the chiral effects. Let us consider an ideal case, i.e., a chiral molecule with electric polarization and magnetic moment which are perpendicular each other. Under external electric and magnetic field (which are set perpendicular to each other), the energy levels of D and L chirals are yet the same if we integrate all possible directions. This is because the combination of static electric field and magnetic field does not yet construct a chiral field. In other word, we do need three different axes of anisotropy to force a chiral static field.

(e) If the electromagnetic field is no longer static, one may easily construct an chiral field such as circular polarized electromagnetic (EM) waves. The polarized radiation (i.e., dynamic electromagnetic field) and beams have been considered as the best candidate to cause the homochirality of biomolecules, and are proven to cause the chirality (e.g, Akaboshi, 1982; Bonner, 1996; Greenberg, 1996). The mechanism can be classified into several categories: (1) Electron or ion beams travelling along the background static magnetic field; (2) EM waves of long wave length such as the whistler waves propagating along the background static magnetic field; (3) EM waves propagating in a plasma; (4) Polarized light (visible, UV, X-ray) by an anonymous polarization mechanism (e.g., weak interaction force, Bremsstrahlung form beams, etc).

Under these circumstances, the static electromagnetic field (or other external forces) has been somewhat dismissed as a candidate to influence the chiral chemical reactions. However, this is simply because we have not yet found reasonable third axis of anisotropy. It is difficult to imagine such a force in a free space (i.e., neutral gas state), but knowledge from geophysics provides a new scope.

3. Geophysical and plasma physical considerations

Let us list some geophysical phenomena which seems to be relevant to the present discussion.

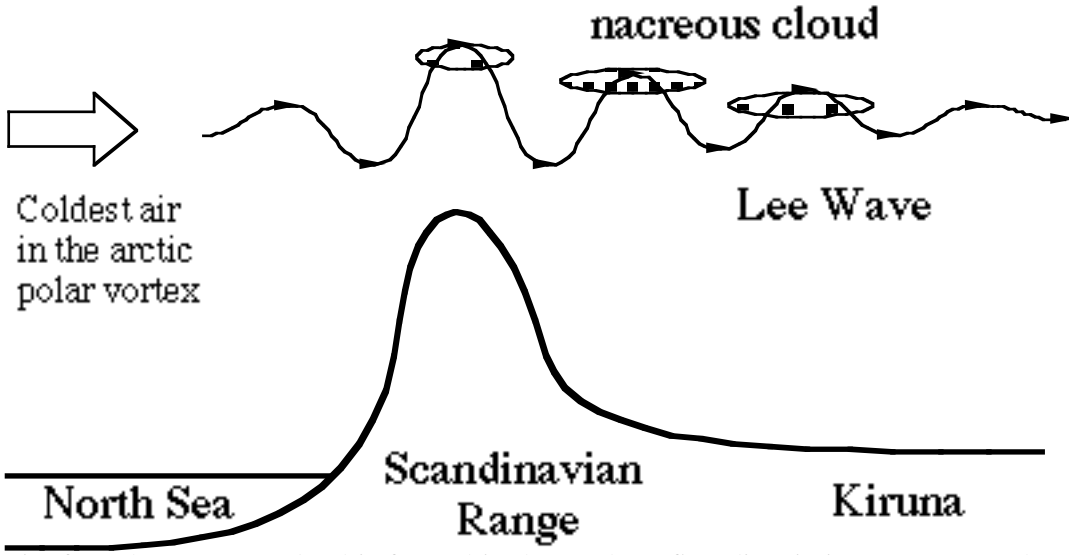

Fig. 2. The nacreous cloud is formed in the northern Scandinavia in January or February as a combined effect of polar vortex, Gulf stream, Scandinavian range, and Lee Wave.

(1) Atmospheric and stratospheric chemistry is well known to be a local process, and certain types of molecules are formed only in geographically restricted regions. For example the chain-reaction causing the ozone holes takes place inside the polar vortex (e.g., Toon and Turco, 1991; Farman et al., 1994). The nacreous cloud is another example (e.g., Farman et al., 1994): it is observed only in northern Scandinavia on the Earth because it requires extra cooling by the rarefied air, which is only possible under the combination of the cold background air over the northern Atlantic sea (i.e., locally warm air at the sea level), the eastward jet stream wind, and the mountain range right downstream which converts the laminar wind to the Lee wave as shown in Figure 2.

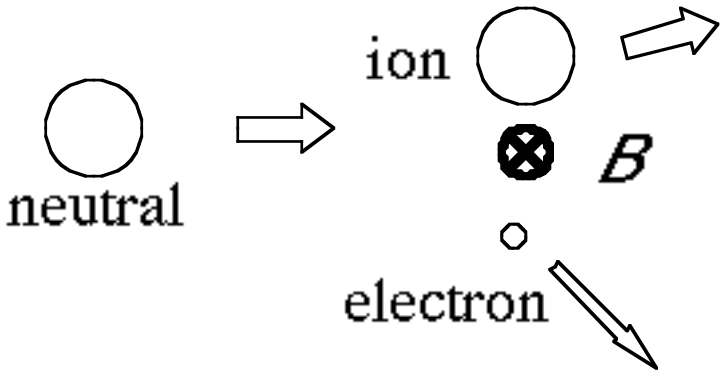

Fig. 3. Critical ionization velocity problem. If the energy of the particle motion exceeds the ionization potential the molecule becomes automatically ionized.

(2) Critical ionization velocity (CIV) phenomenon has been confirmed by space and laboratory experiments (for review, e.g., Brenning, 1992) as a phenomenon where the magnetic moments of nuclei and electrons are separated because of the magnetic field and the convection (see Figure 3). If the original convection has a component along the magnetic field, the electron motion and the ion motion become spiral (i.e., helical). Since the generated ions and electrons collide with neutrals at different frequencies, only the light-weight particles (electrons) drift away when a second force (e.g., electric field, gravity) exists. The ions does not have as long mean free path as electrons due to collisions. Thus, the distribution of left-handed gyration and right-handed gyration will become unbalanced.

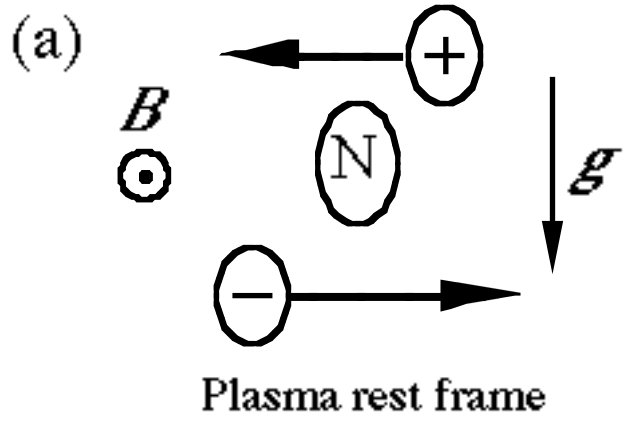

Fig. 4a. Drift directions under the presence of static magnetic field and gravity force. Collision causes a difference in speed between the positive and the negative ions.

(3) The Space Shuttle experiment (Scaife et al., 1990) and laboratory experiments (Lee and Lee, 1997) showed that crystal formation of certain types of chemical solution depends strongly on the existence of the gravity and on the strength of the external magnetic field. The experiments are carried out in a container (closed boundary), and an original solution consists ionized molecules which under the influence of the gravity field cause the anisotropy. The gravity drift of the charged particles probably explains this striking result. The drift directions are in opposite directions for positive ions and electrons (or negative ions) if the external force is a non-electric one as shown in Figure 4a. The drift directions of ions and electrons are the same for an electric force.

Lessons from the atmospheric chemistry are (I) the locality of geochemical reactions, (II) the importance of an uni-directed convection (laminar flow), (III) boundaries, and (IV) low temperature. A low temperature itself is generally not favourable for chemical reactions, but in certain conditions it causes condensation of the catalyst to enhance the chemical reaction. Importance of the laminar convection may sound against the relativity theory because one can always consider a rest frame where there is no convection. However, this is not practically true if the medium is not uniform or if boundaries exist. One may not forget the existence of the boundaries (such as solid ground or catalyst) when discussing terrestrial phenomena. Friction with the surroundings causes an axis of anisotropy, i.e., a preferable "alignment" of molecules with respect to the surroundings or gradient or medium (e.g., density). Furthermore, the laminar flow assembles the catalyst

in an organized way when interacting with the ground, a solid boundary. This allows us to use an icing model etc. against the thermal fluctuation discussed in section 5. Thus, one may not ignore the laminar convection nor the low mobility of molecules.

Similarly, the CIV phenomenon suggests the importance of (II) convection, (V) static magnetic field, and (VI) ionized state. In the ionized state, non-electric force (e.g., gravity) causes oppositely-directed "F × B" drifts for positive and negative ions. Naturally, the drift direction becomes an axis of anisotropy for chemical reactions between positive and negative ions. Lessons from the gravity drift experiment repeats the above lessons: importance of (VI) ionized state, (V) static magnetic field, (II) drift or convection, and (III) boundary.

Recently, the under-water volcanoes, which are distributed locally on the Earth, gathered attention as the possible candidates for the initial formation of the life. The under-water volcanoes are also attractive from the above viewpoint because it fulfils (I) locality, (II) laminar convection or drift (III) solid boundaries or steep gradient, (V) existence of static magnetic field, and (VI) ionized state.

4. Overlooked possibilities for chiral reactions

Based on the above discussion, we list several possible but overlooked mechanisms/elements that might contribute to the homochirality. We consider (f) gyromotion, (g) combination of electric and non-electric drift, (h) non-uniformity of the environment, (i) boundaries, (j) large-scale convection, and (k) photochemistry under magnetic field.

(f) The immediate consequence of the ionization under background magnetic field is the gyromotion. The internal electric polarization automatically forms an axis of anisotropy because the Lorentz force works in the opposite direction between the positive element and the negative element of any molecule. For example, the linear H_2CN^+ ions, which are abundant in Titian ionosphere, are easily bent because of this. It is an intrinsic anisotropy because final asymmetry is always in the same sense for all magnetic field direction and temperature. The strength of the asymmetric force is about 10^{-20} N / molecule for the linear H_2CN^+ ions at the room temperature (force is proportional to the temperature, and for volcanic ash or ionospheric plasma it could easily reach 10^{-18} N / molecule). In addition to this, there are two more internal forces: magnetostatic force due to internal magnetic moment, and centrifugal force due to the gyromotion. The magnetic moment may fix the molecules alignment with respect to the velocity vector (this is the direction of collision), and the centrifugal force might twist already bent (originally linear) molecule depending on the inertia of moment. This anisotropy appears only in a plasma but not in the neutrals because gyromotion requires a Lorentz force. Note that one may construct a three-axes system of anisotropy with a combination of the other elements discussed below. A similar centrifugal force appears when the ionized molecules travel along a bent magnetic field, but this is better included in the next case.

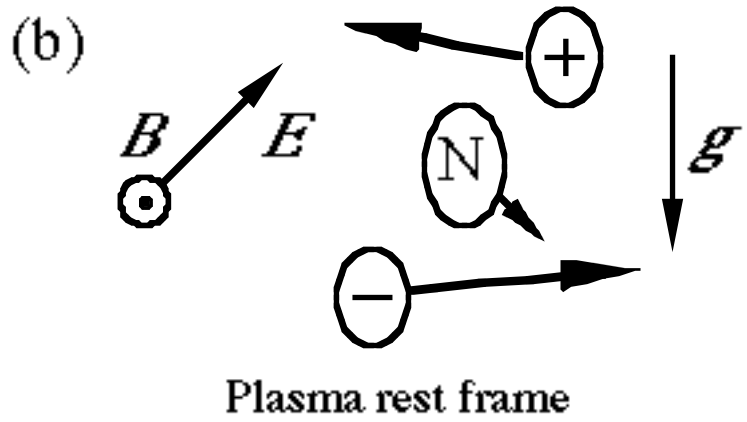

Fig. 4b. Inclusion of the static electric field in Figure 4a. The E × B drift is already removed in the figure using the Lorentz transformation.

(g) As mentioned in (3) above, external non-electric force (e.g., gravity) in a magnetized plasma (e.g., solutions) may also constitute an extra direction of anisotropy related to the drift. To see it, let us add an uniform electric field in Figure 4a. We first have to subtract a convection component related to the E × B drift by using the Lorentz transformation (**E** + **U** × **B**). Because of the friction between the drifting plasma and the surrounding neutrals, the electric field is not completely cancelled in the plasma rest frame, so that all the particles feel the remaining non-zero electric field in each particles' rest frames. The final configuration is illustrated in Figure 4b. The situation is somewhat different from those in the collisionfree space plasma where the electric field is mostly cancelled out in the plasma rest frame.

The remaining non-zero static electric field (after Lorentz transformation) causes internal polarization of ionized molecules, forming a new axis of anisotropy. In such a situation, the drifting ionized molecules has a preferred alignment direction because of the electric and magnetic fields, while the drift direction constitute the third axis of anisotropy for chemical reactions because we expect head collisions between positive and negative ions for non-electric drift. Thus, the electric force, magnetic field, and non-electric force together make a chiral environment without boundary effects. This scenario works only for weakly ionized molecules, and hence under-water volcanoes are the best candidate for such environment.

(h) Non-uniformity adds an extra complication. A gradient of the background environment (e.g., of the magnetic field) means not only a non-electric effective force (e.g., gradient |B| drift), but also a new direction of anisotropy defined by the gradient direction. For example, a sharp density gradient, which can be formed in a dynamic state (e.g., in a shear flow), causes different reaction rates in the frontside and backside of drifting particles in Figure 4. It may also help forming layer-structure of the solution and catalyst. All these effects favours chiral reactions from non-chiral materials.

(i) Although we already excluded chiral boundaries (or catalyst) in the introduction, the boundary/catalyst is still allowed to have up to two independent directions of anisotropy. This is quite likely to be at the bottom of the under-water volcanoes. So, the boundary (catalyst) may easily provide one or two extra anisotropic directions. The

boundary may also mean a sharp gradient, which is already mentioned in above. Since the effect of boundaries is quite wide in general, we cannot list all the possibilities.

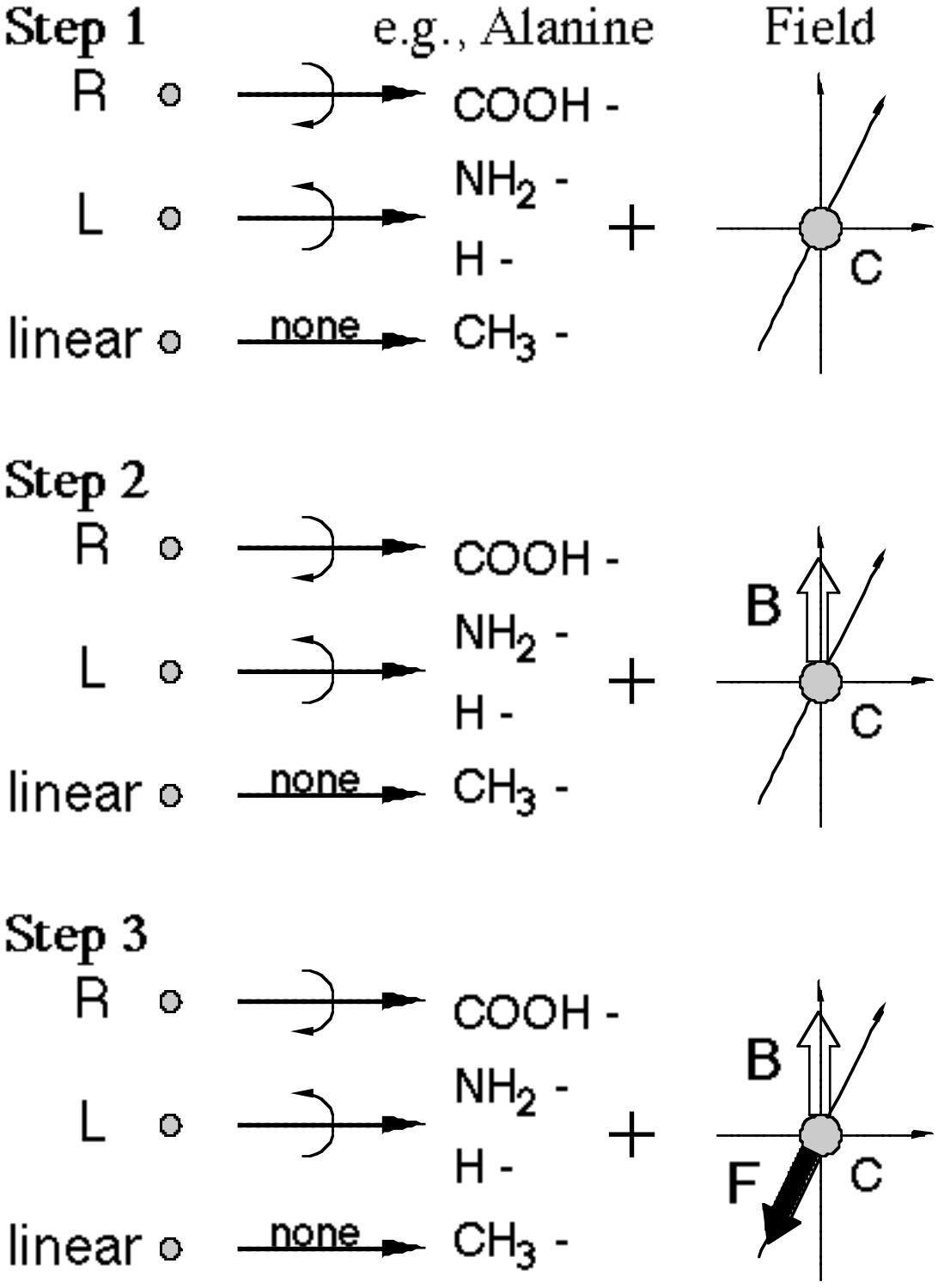

Fig. 5. Classifying all cases of photo-reactions under no background field, under magnetic field, and under magnetic and electric field. Radiation can be right-handed, left-handed, or linearly polarized.

(j) A large-scale convection might play an important roles because, as mentioned in section 3, it may arrange the molecules in certain directions with sharp gradient due to the molecule-molecule interaction (see *(h)* above) or to the existence of the boundary. The large-scale convection may also create a pair of opposite helicities, one of which will decay faster than the other due to collision (see (2) in section 3). Furthermore, we should not forget the convection component parallel to the magnetic field because any gyromotion of ionized molecule becomes systematically helical in either right hand or left handed depending only on the polarity of the charge.

(k) One strong candidate to enhance the homochirality is a combination of the polarized radiation or beam with all the above background anisotropy. Figure 5 shows photo-reactions combined with *(b)-(d)*, but the other combinations with *(f)-(j)* may result in enhanced chirality. One may also apply this to the polarized beams. The last case in the figure probably causes a chiral reaction by itself because the direction of injection means the third direction of anisotropy.

5. Thermal effect

Up to now we did not consider thermal fluctuation. However, one must always consider how much a molecule's alignment is "fixed" by the static electric and magnetic field against the thermal motion. The thermal motion includes parallel motion, rotation, and vibration. For a free n-particle system at non-zero temperature (> 1 K) , the magnetization due to the external field for a small μ (magnetic moment of the molecule) is roughly

$(n \cdot \mu^2/3kT)\ B$ (classic, i.e., $U = \mu B\cos\theta$)

or

$(n \cdot \mu^2/kT)\ B$ (quantum, i.e., $U = \mu B$)

and the energy shift is roughly

$(n \cdot \mu^2/3kT)\ B^2$ (classic, i.e., $U = \mu B\cos\theta$)

or

$(n \cdot \mu^2/kT)\ B^2$ (quantum, i.e., $U = \mu B$)

where 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 of $\mu B/kT$, which amounts to about 10^{-6} / molecule for an electron (for $\mu B = 10^{-8}$ eV / molecule and at the room temperature kT = 0.02 eV), is multiplied to the basic energy. Note that this is the worst estimation because we expect further "fixing" factors such as boundaries and laminar catalyst in the real geophysical environment (see *(h)-(j)* above and section 4). Yet we still have 10^{-14} eV/molecule change of energy which is at least comparable to the weak interaction force.

6. Mechanisms for the monohelicity

Let us move to the next opportunity of the selection as shown in Figure 1, i.e., the formation of the monohelicity. The both mechanisms proposed below apply to the formation of helical catalyst rather than the helical biomolecules.

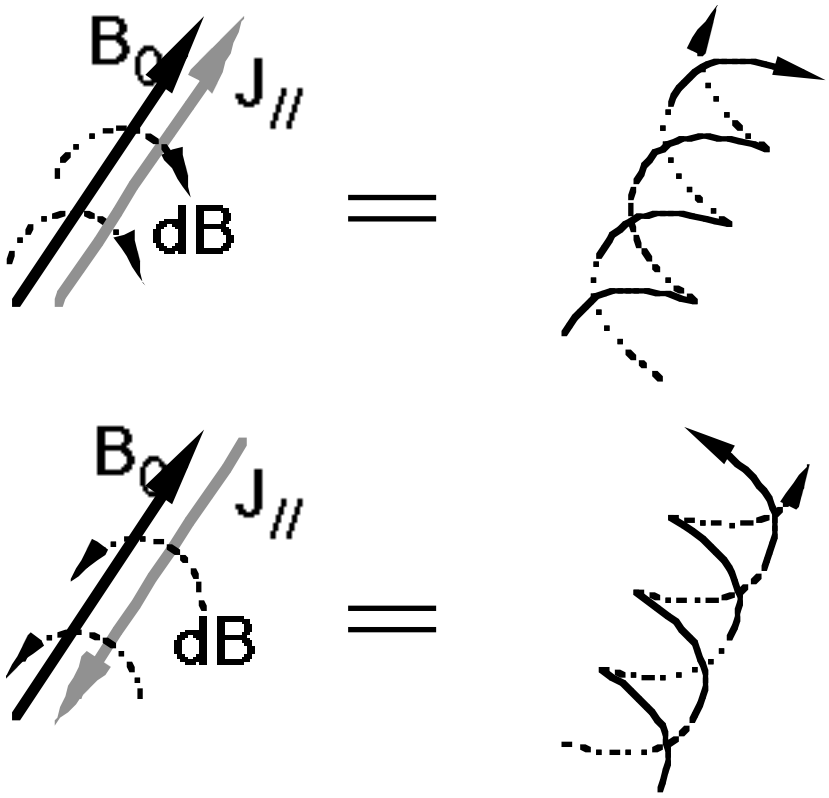

Fig. 6. Force-free magnetic field configuration (**J** // **B**). The lowest energy state of current system requires helical structure of the magnetic field.

(l) The force-free magnetic field configuration (J x B = 0) is the most frequently observed structure in the space and the Sun (e.g., Russel et al., 1990) because it is the lowest energy state of magnetofluid. This condition requires the electric current to be precisely parallel to the magnetic field, making the magnetic field (and current lines) twisted as shown in Figure 6. The helicity is right-handed if the current is parallel to the magnetic field, and left-handed for antiparallel case. Then a helical duct structures is naturally formed along the twisted magnetic field, as is always the case with the space plasma (e.g., Maeda and Kimura, 1970). The helical duct enables us to observe the twisted magnetic field from a distance. The attractive point for this mechanism is the nearly perfect auto-catalyst system (e.g., Kondepudi and Nelson, 1985); i.e., the same helicity should prevail a certain amount of area avoiding coexistence of the other helicity because of electron inertia along the magnetic field. The negative point for this mechanism is that the force-free configuration is a large-scale structure; i.e., the scale size of the spiral is much larger than an electron gyroradii. Probably we may overcome the size problem by restricting our consideration to a viscous liquid.

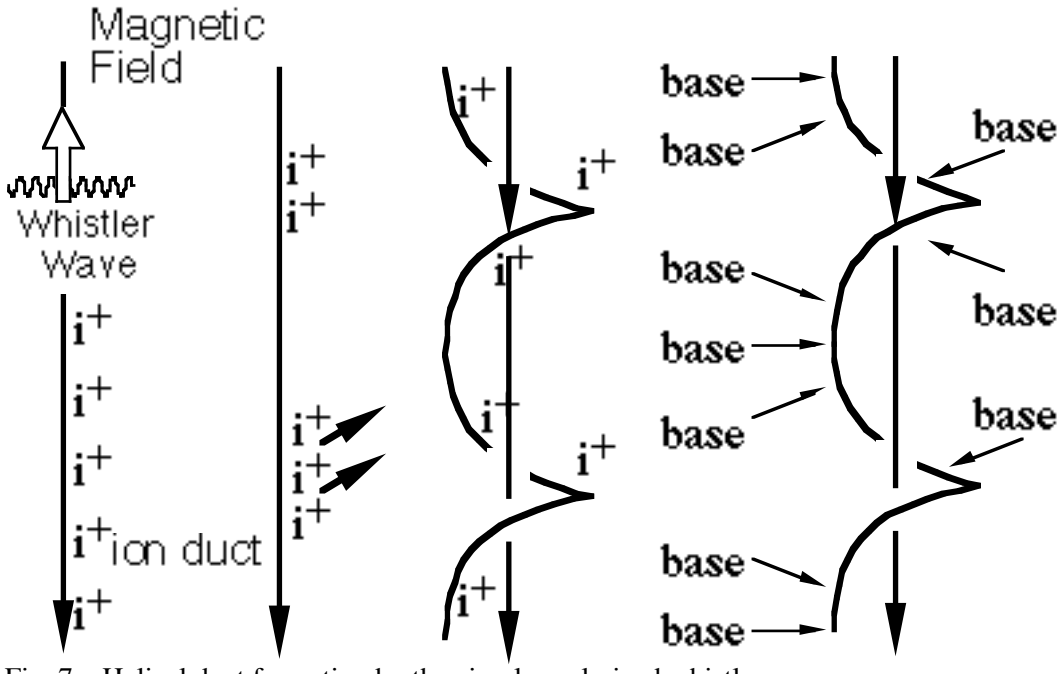

Fig. 7. Helical duct formation by the circular polarized whistler wave.

(m) The whistler waves are very frequently generated by thunder storms. The frequency of the wave is $\omega < \Omega_p \approx 1$ kHz near the Earth's surface (at 1 Gauss geomagnetic field) where Ω_p is the proton gyro-frequency. The wave is always of the proton mode in the ocean, i.e., it is polarized to left-handed against magnetic field direction because the wave resonates with proton motion (e.g., Gurnett et al., 1965; Maeda and Kimura, 1970). According to the space observation, the whistler wave forms a duct structure (e.g., Maeda and Kimura, 1970), and hence it is quite possible that this wave forms a helical duct structure also in the ancient ocean in the same manner as *(l)* above. In this case, we expect the duct structure to work as the catalyst as shown in Figure 7.

The short pitch of DNA (34Å) requires a resonance, i.e., increase of density of the resonating ions to absorb the wave. Local increase of the ionized bases is quite feasible near the under-water volcanoes. Then, the spiral motion of average proton in the geomagnetic field may resonate because of the 63° pitch of DNA. Thus this scenario again favours liquid state. One can also consider the similar situation in space such as the ionosphere, but mean-free path of the wave compared to the molecular size could be too large. The liquid requirement comes also from the uncertainty principal for resonant particles. In the gas state, uncertainty distance for such a spiral duct at non-zero temperature is much larger than the pitch of DNA.

7. Requirements

There is a problem in most of the above mechanisms *(a)-(m)* when applying the proposed effects to the actual formation of biomolecules because of the bipolar nature of the geomagnetic field; i.e., the distribution of the magnetic field direction is symmetric

between different hemispheres. Therefore, even if all the other external forces or boundaries are fixed in certain directions, the same mechanism causes one chirality in one hemisphere and the other chirality in the other hemisphere unless the interaction force is internal such as the weak interaction force or the centrifugal force. This problem arises in *(b)-(d), (g)-(j), (j)-(m)* as is summarized in Table 1 (indicated as "local"). To overcome the problem of hemispheric symmetry, one must assume that the prebiotic molecules have been formed in one hemisphere during a relatively short period (within the reversal of the geomagnetic field). Furthermore, the other forces (or direction of anisotropy) must also be fixed in certain directions, and we have to assume sufficient surrounding molecules (e.g., weakly ionized plasma). Thus we have the following necessary conditions if a static environment (e.g., electrostatic and magnetostatic forces) played some roles on the formation of homochirality or monohelicity of the biomolecules.

* The homochirality of the biomolecules must have been formed before any reversal of the geomagnetic field.

* The homochirality of the biomolecules must have been formed in a limited geographic area during that period.

* The homochirality of the biomolecules was most likely formed in a liquid state to allow the moderate mobility and density of the solutions.

All these "locality" conditions are eventually satisfied if the basic chemical reaction to form the prebiotic molecules took place near the under-water volcano within a short period (< 1 million years) after the ancient ocean was first formed (note that the initial Earth was too hot to have the ocean). The first two conditions are "by-chance" factors, but the process does not have to employ the auto-catalytic processes.

Table 1. Summary of possible anisotropic factors.

	basic element	process	anisotropy	fluctuation	main application
a	weak-interaction	global	can be chiral	independent	everywhere
b	magnetic moment	local	only 1 axis	dependent	
c	electric polarization	local	only 1 axis	dependent	
d	*b* + *c*	local	only 2 axes	dependent	
e	radiation	global	can be chiral	independent	comet, dust
f	gyromotion of ions	global	can be chiral	independent	ionosphere
g	electric + non-electric	local	can be chiral	dependent	volcanic ocean
h	non-uniformity	local	contributes	dependent	volcanic ocean
i	boundary	local	contributes	dependent	volcanic ocean
j	convection	local	contributes	dependent	volcanic ocean
k	radiation + *b, c, d*	n/a	contributes	independent	everywhere
l	force-free field	local	an be chiral	dependent	viscous liquid
m	whistler waves	local	can be chiral	dependent	volcanic ocean

8. Conclusion.

We have shown many physical possibilities (see table 1) that static fields may assist the chiral chemical reactions by reasonably forming three different alignment directions of anisotropy a molecule. In addition to static electric and magnetic fields, (1) ionized state of molecules and gyromotion, (2) drift or convection, (3) non-electric forces, (4) gradient or boundary, (5) condensation due to low temperature may contribute to the formation of chiral environment.

So far we have restricted our consideration to the Earth, but the above consideration can be applied to extraterrestrial environment such as comet, planet, and interstellar dust. The solid application to these object must be discussed in a different paper. Also, we did not make quantitative calculation or any laboratory work. This is because our purpose is just to list new possibilities of chiral reactions by the chiral/helical environment. Experimental and theoretical examination of proposed mechanisms is left for the future.

Acknowledgements. The authors thank Prof. O. Kikuchi and Prof. R. Lundin for many helpful suggestions and comments. The authors also thank Prof. M. Akaboshi who made this work well developed and presented.

References

Akaboshi M., Noda M., Kawai K., Maki H., and Kawamoto K. (1982) Asymmetrical radical formation in D- and L-alanines irradiated with tritium-β rays, *Origins of Life*, **12**, 395-399.

Bonner W.A. (1996) The quest for chirality, *AIP Conference Proceedings*, **379**, 17-49.

Brenning N. (1992) Review of the CIV phenomenon, *Space Sci Rev*., **59**, 209-314.

Farman J.C., Narris N.R.P., and Pyle J.A. (1994) EASOE special issue, *Geophys. Res. Lett*., **21**, 1189-1490 (guest eds.)

Greenberg J.M. (1996) Chirality in interstellar dust and in comets: life from dead stars, *AIP Conference Proceedings*, **379**, 185-210.

Gurnett D.A., Shawman S.D., Brice N.M., and Smith R.L. (1965) Ion cyclotron whistlers, *J. Geophys. Res.,* **70**, 1665-1688.

Hegstrom R.A. (1982) β decay and the origins of biological chirality: theoretical results, *Nature*, **297**, 643-647.

Kikuchi O. (1995) Is L-amino more stable than D-amino?, *Suurikagaku* (in Japanese), **379**, 35-39.

Kondepudi D.K. and Nelson G.W. (1985) Weak neutral currents and the origin of biomolecular chirality, *Nature*, **314**, 438-441.

Kondepudi D.K. (1994) Selection of handedness in prebiotic chemical processes, *AIP Conference Proceedings*, **300**, 491-498.

Lee M.C. and Lee C.H. (1997) Combined effect of geomagnetic field and gravity on the formation of crystals, *Geophys. Research Lett*., **24**, 607-610.

Maeda K. and Kimura I. (1970) *The theory of electromagnetic waves* (in Japanese), 289pp, chapter 6, Ohm Pub Co.

Mason S.F. and Tranter G.E. (1984) The parity-violating energy difference between enantiomeric molecules, *Molecular Phys*. **53**, 1091-1111.

Russell C.T., Priest E.R., and Lee L.C. (1990) *Physics of magnetic flux ropes*, 685pp, American Geophysical Union (eds).

Scaife C.W.J., Cavoli S.R., Blanton T.N., Morse M.D., Sever B.R., Willis W.S., and Suib S.L. (1990) Synthesis and characterization of lead (II) iodide grown in space, *Chem. Mater.*, **2**, 777

Toon O.B. and Turco R.P. (1991) Polar stratospheric clouds and ozone depletion, *Scientific American*, **264**, 40-47.