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Homochiral Selection in a Non-equilibrium Process: Origin of Life

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Abstract

Chemistry and therefore life is a manifestation of the electromagnetic interaction which cannot distinguish right from left, and all chemical reactions in the absence of an external chiral bias produce equal amounts of right and left-handed molecules. Nevertheless, the living matter is chiral biased and generally constituted of only one of the enantiomers, right handed or left handed. The origin of biochemical chirality remains an unresolved problem believed to be concurrent or an essential prerequisite to origion of life. Most hypotheses attempting to understand this issue, attribute homochiral selection to a biasing influence and presupposition that asymmentry can be begotten only from asymmetry. A system in thermodynamic equilibrium in the absence of a constant external chiral influence is indeed racemic and contain equal proportions of both enantiomers. Living systems and the origin of life itself are not equilibrium situations and could deviate from racemicity. A mathematical model is presented to show that any enantiomeric selfreplicating molecule created in the racemic prebiotic medium can proliferate exhausting all precursor molecules of both handedness. The homochirality of life is a continuation of this non-equilibrium process.

Key words : Homochirality, Origin of Life, Recenicity

Introduction

Life distinguishes right from left at macroscopic and microscopic levels. Around ninety percent of humans are right-handed. Human congnitive function depends on lateralization or the distiction in the neurological function of the right and left - hemispheres of the brain[1]. Plants and animals demonstrate conspicuous developmental right-left asymmetries [2-3]. The observation that the solution of certain organic compounds rotates the plain of polarization of transmitted light in one direction was the first clue suggesting the existence of microscopic right-left asymmetries in subtances of biological origin. Louris Pasteur showed that tartaric

acid rotating plane polarizes light towards right or left crystallize into two distinct mirror symmetric forms. Subsequently, the crystal asymmetry of the two forms of tartaric acid was attributed to two distinct types of tartaric acid molecules, one type a mirror image of the other. Biological tissues are chiral biased and constitued of only one of the right (dextro -D) or left (levo -L) forms of enantiomeric molecules proteins derived from L amino acids and DNA containing D sugars. The ordinary chemical properties of L and D isomers are hardly distinguishable. However, glaring differences appear in their interaction with living systems. Well known example is the drug thalidomide used as cure for morning sickness until it was banned in late nineteen sixties. Thalidomide molecule could arrange in both L and D enantiomeric forms. Both L and D thalidomides are potent antiemetics and cure morning sickness. However L-thalidomide is teratogenic and causes serious birth defects in the fetus if administered to pregnant women. Recently L-thalidomide found to be an effetive cure for some forms of cancer and to suppress the damages caused by the HIV virus. Another interesting biochemical distinction originating from enantiomeric difference is the aroma of lemon and orange. Everybody knows that lemon and orange smells distinctly diferent. Chemically the only difference in the essence of lemon and orange giving the aroma is that they are L and D enantiomers of the same compound.

Biosynthetic processes strictly maintain the chemical right -left asymmetry of living systems, against the natural tendency of racemization, an optically active material turning into an optically inactive material in reaching the thermodynamic equilibrium. Here, the synthesis, takes place in an asymmetric background. To begin with, there was no such asymmetric background to template stereo-specific synthesis. The origin of biochemical chirality remains an unresolved problem, believed to be concurrent or an essential prerequisite to origin of life [4-10].

Except for the minuscule effects of weak neutral currents[11-12], the electromagnetic force that dictates chemistry conserves parity and therefore the free energies of L and D enantiomers are almost identical. Consequently in an equilibrium situation, the L and D forms of all enantiomeric molecular species occur in equal proportions. In non-equilibrium molecular interactions, especially those involving non-linear kinetics, this symmetry can be broken locally [13-17]. However, the equal biases for the L and D sectors smear out any global chiral asymmetry. Undoubtedly, homochiral selection is a prelude to origin of life or both occurred concurrently and many attempts have been made to understand the mechanism involved. Most hypotheses attribute the initial cause of the observed asymmetry to a left-right distinguishing

influene in the prebiotic medium or an external source. Solid mineral sediments with chiral structure could serve as catalysts for stereoselective synthesis[18-19]. The problem here is both D and L crystal types of these minerals and distributed in equal abundance. Unless a local bias towards either right or left, rapidly propagates in the prebiotic medium, homochiral selection is not achieved.

Not only molecules, light and elementary particles also possess chiral characteristics. Plane polarized light is achiral but circularly polarized light exists as either right or left chiral forms. Circularly polarized light could induce asymmetric synthesis or degradation of organic molecules and the observed excess of L-amino acids in some meteorites seems to be a result of circularly polarized UV irradiation of extra-terrestrial material [20-23]. A remote possibility exists, that such material transport to the earth served as the seeds of chirality. Here again, on a cosmic scale, both right and left polarized photons fluxes are created with equal probabilities but deviations in regions vastly exceeding terrestrial dimensions remains a possibility. Spontaneous symmetry breaking in non-linear kinetics invoking D and L species could shift a reaction to one branch[14-17-24], owing to the neutral current influence on the rate constants, but thermal fluctuatious even in the 3 K interstellar space may erase this effect. Immediately after the discovery of non conservation of parity in beta radioactive decay, Vester and Ulbricht[25] proposed that electrons from beta decay of naturally occurring radio active minerals could have induced an asymmetry to the prebiotic chemical reactions. However, experiments with powerful beta emitting radio-isotopes did not produce an enantiomeric excess in radiolysis of racemic amino acids[23] in absence of an unequivoal explanation for any preference to right or left, the option of accidental choice of right or left handness needs to be considered seriously.

In this note an alterative scenario where the autocatalytic proliferation of a randomly created chiral (say X_1) molecular species is discussed. If this species resist racemization better than the enatiomeric molecules in the original racemic prebiotic medium, the autocatalytic reaction will proceed exhausting both L and D parent molecules and achieving complete homochirality. A mathematical model is presented to depict the mechanism analytically. The primary entity involved on autocatalysis is suggested to be a polypeptide or a primitive prion like structure resistant to UV degradation and other forms of denaturing.

Model

We denote the precursor enantiomers in the racemic prebiotic medium by L and D and the same symbols describe their concentrations. The enantiomers denoted by L and D can include more than one molecular species of each type[27]. A more complex chiral molecule X_L spontaneously produced in the reaction medium is supposed to proliferate in the reaction medium via the autocatalytic reaction,

$$L + X_l + M \longrightarrow 2X_L + M \qquad (1)$$

where, M denotes the achiral molecular species needed for the synthesis of X_l that is present in large excess so that their concentration remains practically constant. The enantiomers L and D undergo reversible transformations.

$$L \longrightarrow D,\ D \longrightarrow L \qquad (2)$$

The rate equations describing the processess (1) and (2) can be written as,

$$dL/dt = kD - kL - hLX_L \qquad (3)$$

$$dD/dt = kL - kD \qquad (4)$$

$$dX_l/dt = hLX_L \qquad (5)$$

where, k and h are first and second order rate constants.

Production of the enantiomer X_D via the parallel reaction

$$L + X_D + M \longrightarrow 2X_D + M \qquad (6)$$

is another improbable event not incorporated into reaction scheme.

The exact solution of the equations (3) and (4) cannot be expressed in analytical form.

Clearly the total sum of the concentrations (number of molecules per unit volume) of D, L and X_L remains constant, i.e.,

$$L + D + X_L = C \qquad (7)$$

The dynamical system governed by eqns. (3) - (5) have two equilibrium points, and unstable one at t = 0

$$L = D = C/2,\ X_L = O \longrightarrow \infty \qquad (8)$$

and a stable final is approached as t

$$L = D = 0,\ X_L = C \qquad (9)$$

setting $D = C/2 + \delta D$, $L = C/2 + \delta D$, $X_L = \delta X_L$ in equations. (3) and (4), where, δL, δD, δX are small deviations from the equilibrium and analysis, we obtain,

$$D \approx C/2 - Ak(hC + 4k)^{-1} \mathrm{Exp}(hCt/2) \qquad (10)$$

$$L \approx C/2 - A(hC + 2k)(hC + 4k)^{-1} \mathrm{Exp}(hCt/2) \qquad (11)$$

$$X_L = A\mathrm{Exp}(hCt/2) \qquad (12)$$

as the behavior of the solutions of equation. (3) - (5) in the vicinity of the equilibrium point. (8). To simplify the expressions we have assumed that hC> k, but even if this condition relaxed, δD and δL remain negative when δX positive (A is positive). The evolution of X/ D and L is illustrated in Fig. 1. The model demonstrates how a chiral species could grow in a racemic medium consuming both L and D precursor enantiomers and achieving complete homochiral selection. The asymptotic solution of the equations (3) - (5) can be exprressed in the form.

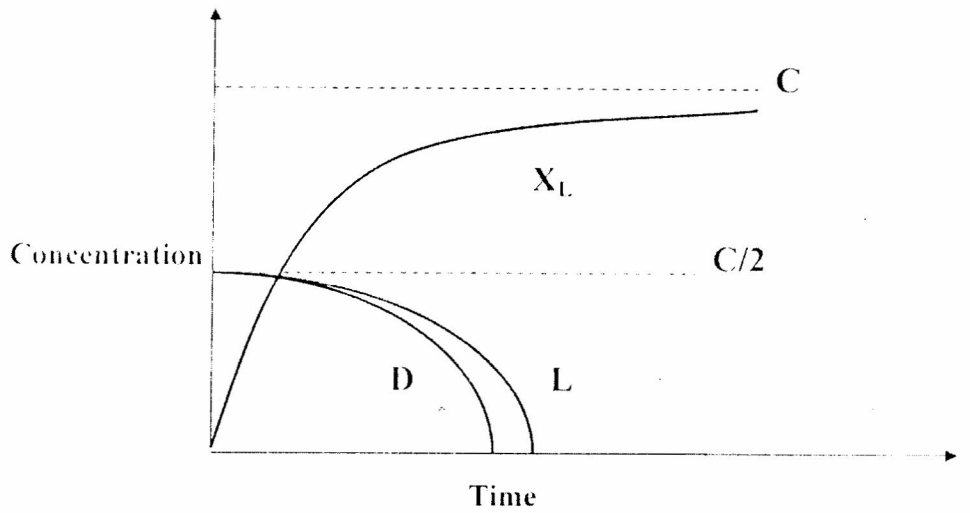

Fig. 1 Time development of the concentrations of the species L, D and X_l.

$$X_L = C - B\,Exp(-k + k^2/hc) \quad (B = \text{constant}, hC > k) \qquad (13)$$

From (4) it can be seen that the selection time is of the order of racemization time k^{-1} of the precursor enantiomers. Racemization times of organic molecules vary considerably and depend on external factors. Under ambient conditions, the racemization times of familiar amino acids are in the range 10^3- 10^7 years. Thus selection could occur in relatively short period compared to the time scales of evolution. If the racemization of X_L via.

$$X_L \longrightarrow L + D \qquad (14)$$

is taken in to account we obtain.

$L = 2\varepsilon/k$, $D \approx \varepsilon(2/h - C/k)$, (15) $X \approx C - \varepsilon(4/h - C/k)$ (16)

where ε is the rate constant of autolysis of X_L to l and D $k > \varepsilon$, giving the (left - right)/ (left + right) as,

$$[(X_l + L) - D][(X_L + L) + D]^{-1} = 1 - \varepsilon/k \qquad (17)$$

If $k >> \varepsilon$, near complete homochiral selection is a achieved. Another possibility is dissociations of X_L into the products L and M, i.e.,

$$X_L \longrightarrow M + L \qquad (18)$$

Here the rate equations are modified to read,

$$dL/dt = kD - kL - hLX_L + gX_L \quad (19)$$

$$dD/dt = kL - kD \quad (20)$$

$$dX_L/dt = hLX_L - g X_L \quad (21)$$

Eqns. (19) - (20) have an unstable solution at t = 0, i,e.,

$$L = D = C/2 \quad (22)$$

and an stable solution as $t \longrightarrow \infty$ i,e.

$$L = D = C - g/h \quad (23)$$

$$X_L = C - 2g/h \quad (24)$$

Obviously, the condition g < Ch4 needs to be satisfied, implying the importance of the stability of X_L for its proliferation.

The above scheme leading to homochrial selection may be subjected to other extraneous inhibitory reactions, notably interaction of X_L with D and to from species Y that degrade into a racemic products, i. e.,

$$X_L + D \longrightarrow Y, \quad Y \longrightarrow L + D \quad (25)$$

It turns out that selection still takes place, provided the rates of steps (25) are slower than autocatalytic reaction (6).

A question that arises is that what is the mechanism of replication of X_L ? If X_L is formed by assembly of the units of L to form a polymer chain, i, e.,

$$X_L (N-1) + L \longrightarrow X_L (N) \quad (26)$$

The chain lenght *l* will grow at constant rate K and the probability of chain breakage will be proportional to *l* , i. e.,

$$dl/dt = K - al \qquad (a = \text{constant}) \quad (27)$$

Thus there will be a critical chain lenght l_c constituted of N monomers of L. When

the chain length exceed l_c. X_L breaks into two units X_L^1 and X_L^2 which grows to a length l_c and the processes repeated, i .e,

$$X_L \longrightarrow X_L^1 + X_L^2$$

$$X_L^1 + L \longrightarrow X_L \qquad (28)$$

$$X_L^2 + L \longrightarrow X_L$$

The other question that arises is that what is X_L ? Can we relate it to any of known self-replicating molecule? The modern self-replicating bimolecules RNA and DNA are complex information storing entities susceptible to denaturing under harsh prebiotic conditions. It is more likely that the first self- replicating biomolecules are not information encoding complex structures but more stable and simpler species proliferating autocatalytically, perhaps peptides or prion like protein structures. Prions are robust self-replicating organisms resistant to extreme enviroments.

Conclusion

Prebiotic oceans must have been enriched with organic compounds as a result of photochemical reactions or transport of such materials from extraterrestrial sources. Whichever is the source, physical prosesses are unlikely to produce a significant enantiomeric excess. The reason is parity conservation in electromagnetism and the minuscule effect of the neutral current sector of the electroweak interaction. Spontaneous symmetry breaking in nonlinear complex reaction could bifurcate the system into one branch under an asymmetric bias. Several local biases which shift the system into either branch can be envisaged, but globally the cancellations will not lead to a net selection. The other alternative to abiogensis through chiral selection is accidental creation of a stable self-replication enantiomer and its growth at the expense of both L and D species in the intially racemic prebiotic medium. The precursor L and D molecules will be exhausted in time comparable to the racemization time of these molecules. The model demonstrates that in an autocatalytic non- equilibrium system homochiral selection can be achieved and the chemical handness of life is a continuation of this process.

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