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Spatial dynamics of homochiralization

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Abstract: The emergence and spread of chirality on the early Earth is considered by studying a set of reaction-diffusion equations based on a polymerization model. It is found that effective mixing of the early oceans is necessary to reach the present homochiral state. The possibility of introducing mass extinctions and modifying the emergence rate of life are discussed.

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Introduction

The question of the origin of life is closely connected with the question of how handedness (chirality) of living organisms came about (Avetisov *et al*. 1991). The sugars produced in plants via photosynthesis, for example via the rather innocent looking reaction

$$6CO_2 + 6H_2O \longrightarrow C_6H_{12}O_6 + 6O_2, \quad (1)$$

are all right-handed and rotate the polarization plane of polarized light in a right-handed sense, i.e. the sugar is said to be dextrorotatory. This preferred handedness is remarkable because the difference in binding energy between right-handed and left-handed (levorotatory) sugars is extremely tiny (relative energy difference: 10^{-17}). Once dead, the preferred handedness gradually disappears until there are equally many right- and left-handed molecules. This process, which speeds up with increasing temperature, is called racemization and can even be used as an approximate dating method (Hare & Mitterer 1967; Bada *et al*. 1970). For a simpler and closely related reaction that displays a similar behaviour, we refer the reader to the formose reaction discussed by Toxvaerd (2005).

Another example of a type of dextrorotatory sugar with five carbon atoms occurs in the backbone of RNA, therefore making RNA chiral. RNA can have autocatalytic properties, which led to the idea of an early 'RNA world' (Gilbert 1986; Joyce 1991) where naked RNA molecules could have catalysed the polymerization of other RNA molecules. However, since the RNA molecule consists of right-handed sugars, chirality selection must have occurred at an even earlier stage.

Two possibilities are commonly discussed. Either chirality was imposed by physical factors such as magnetic fields, polarized light from a nearby pulsar, or even the tiny energetic preference due to the parity-breaking electroweak interaction. In such a scenario, homochirality may well have been a *prerequisite* for the origin of life, allowing, for example, for the assembly of structurally more stable polymers. The difficulty here is that such mechanisms would hardly explain the complete homochirality observed in living matter. The other possibility is that homochirality was a *consequence* of life, and that the presently prevailing handedness was selected spontaneously during the assembly of the first polymers. As shown in the early paper by Frank (1953), such a process requires the production of left- and right-handed molecules to be mutually antagonistic. He devised pairs of ordinary differential equations demonstrating how this could possibly be described mathematically.

We also consider this latter scenario in the present paper. Significant progress has been made since Frank's early paper. In particular, the origin of the mutually antagonistic behaviour has been identified to be the so-called enantiomeric cross-inhibition, a process that spoils further polymerization once a monomer of opposite handedness has been attached to an already existing polymer. The evidence for the occurrence of this process is entirely experimental and goes back to the early work of Joyce *et al*. (1984), who found that in non-enzymatic template-directed polymerization of RNA strands, only a homochiral supply of mononucleotides that are complementary to the template can polymerize to a typical length of 20 nucleotides. Even a small amount of mononucleotides of opposite chirality prevents the formation of longer polymers, as is seen in high-performance colour chromatograms. Similar experiments have also subsequently been carried out by Schmidt *et al*. (1997) and Kozlov *et al*. (1998), for example. In the following we describe how this process can be modelled in more detail.

The polymerization model

In the polymerization model of Sandars (2003), large polymers are generated by joining successive monomers into long chains. Monomers can be both left- (L_1) and right-handed (R_1), and longer chains are formed according to the following set of reaction equations:

$$L_n + L_1 \xrightarrow{2k_s} L_{n+1}, \quad (2)$$

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Fig. 1. Polymerization process. In addition to a number of monomers, L and R, there are several isotactic dimers, LL and RR, as well as longer polymers. Semi-spoiled polymers such as $LLLLR$ and $LRRR$ can still polymerize on the unspoiled end. Polymers such as LR and $RLLR$ are dead and cannot polymerize further.

$$L_n + R_1 \xrightarrow{2k_1} L_n R_1, \tag{3}$$

$$L_1 + L_n R_1 \xrightarrow{k_s} L_{n+1} R_1, \tag{4}$$

$$R_1 + L_n R_1 \xrightarrow{k_1} R_1 L_n R_1, \tag{5}$$

where k_S and k_I are the reaction coefficients for monomers to a polymer of the same or of the opposite handedness, respectively. For all four equations we also have the complementary reactions obtained by exchanging $L \rightleftharpoons R$. Note that chains are 'spoiled' if a monomer of opposite chirality is attached to the end of a longer chain, in which case the chain can only grow at the other end. This is, in essence, what is meant by enantiomeric cross-inhibition. As a result, polymers such as $R_1L_2R_1$ and L_1R_1 can no longer grow. As discussed in the introduction, this rule is motivated by the experiments of Joyce *et al.* (1984) and others.

The monomers are initially generated from a substrate S according to

$$S \xrightarrow{k_C C_R} R_1, \quad S \xrightarrow{k_C C_L} L_1, \tag{6}$$

where k_C is proportional to the regeneration rate of monomers, and C_R and C_L determine the enzymatic enhancement of right- and left-handed monomers. The dependence of $C_{L,R}$ on the existing amount of polymer chains is essential to chirality selection as then an existing excess of either chirality can be amplified. The exact form of C is not crucial and here we follow the choice $C_A = \Sigma n A_n$, $A = L,R$ (Brandenburg *et al.* 2005; hereafter referred to as BAHN). For alternative prescriptions of C_A we refer to the papers by Sandars (2003) and Wattis & Coveney (2005). The substrate itself is being replenished by a constant source term Q.

The polymerization process is represented pictorially in Fig. 1, where one can see how monomers begin to grow into longer chains and can then be contaminated by a monomer of opposing chirality. The crossed out chains represent polymers that can no longer grow.

The feedback mechanism built into the polymerization model leads to an unstable system that, depending on the fidelity f of the enzymatic reactions, when perturbed from the initial racemic state can reach a homochiral state. The prescription for C_A discussed above assumes $f = 1$. If $f < 1$, there is some 'cross-talk' between L and R where f determines the relative mixing between the two chiralities.

The chirality of a particular state is conveniently parametrized by a parameter called the *enantiomeric excess*:

$$\eta \equiv \frac{E_R - E_L}{E_R + E_L}, \tag{7}$$

where $E_A = \Sigma n A_n$ with $A = L,R$. For f larger than a critical value (see BAHN for details), the racemic state ($\eta = 0$) is unstable with respect to small perturbations. Only for $f = 1$ is the end state fully homochiral ($\eta = \pm 1$).

Homochiralization in space

The homochiralization process considered here, and indeed in much of the theoretical literature on the subject (Frank 1953; Wei-Min 1982; Goldanskii & Kuzmin 1989; Avetisov & Goldanskii 1993; Sandars 2003; Saito & Hyuga 2004a), has been uniform in space. Relaxing this restriction can, in principle, lead to completely new chirality selection mechanisms that have no analogue in models without spatial extent. An example is the mechanism identified by Toxvaerd (2004) using molecular dynamics simulations. In the present work we simply extend the homochiralization process discussed in the previous section to allow for the interaction with neighbouring regions through diffusion and/or advection (such as ocean currents). We begin with a state that is homochiral everywhere, but with minute imbalances in space (i.e. infinitesimally small perturbations). These perturbations grow locally, leading to patches with enantiomeric excess of either handedness. It is then natural to ask how a localized homochiral state spreads to racemic surroundings and, moreover, can regions of different chirality coexist? This question is not restricted to the model considered here and needs to be addressed in all models where chirality is selected locally by a random process.

The critical ingredients necessary to answer these questions are the presence of different relevant time scales. If the appearance of a homochiral region is a rare process, say with a period of $\tau_{\rm life}$, and the global homochiralization time scale, $\tau_{\rm global}$, is comparatively short (i.e. $\tau_{\rm global} \ll \tau_{\rm life}$), then one would not expect coexisting regions of different chirality. In other words, if the emergence of life is a rare event, then life forms with different handedness probably did not coexist. This is the case modelled by Frank (1953) and many others after him. In the other extreme case, homochiral regions appear frequently compared with the speed at which they can dominate the early Earth, leading to coexisting regions of opposite chirality (see Fig. 2). Even though we are mainly concerned with chirality here, such arguments can also be applied more generally to the emergence and spread of life. For a discussion of the possibility of finding a second sample

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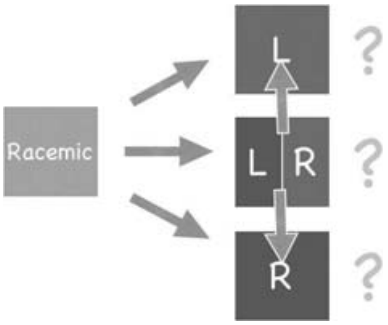


Fig. 2. Different ways of reaching a homochiral state from an initial racemic state.

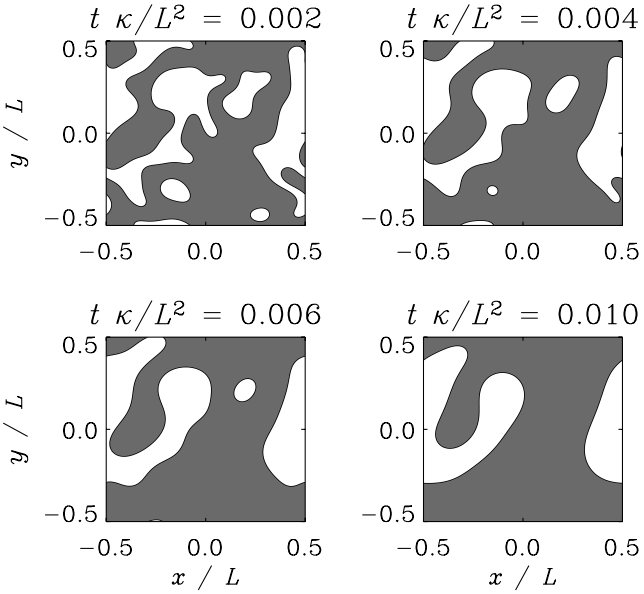


Fig. 3. The spread of homochiral regions in 2+1 dimensions. The dark (light) regions correspond to left- (right-)handed regions. Time is given in global diffusion times, $\tau_{\rm turb} = L^2/\kappa$. (Adapted from BM.)

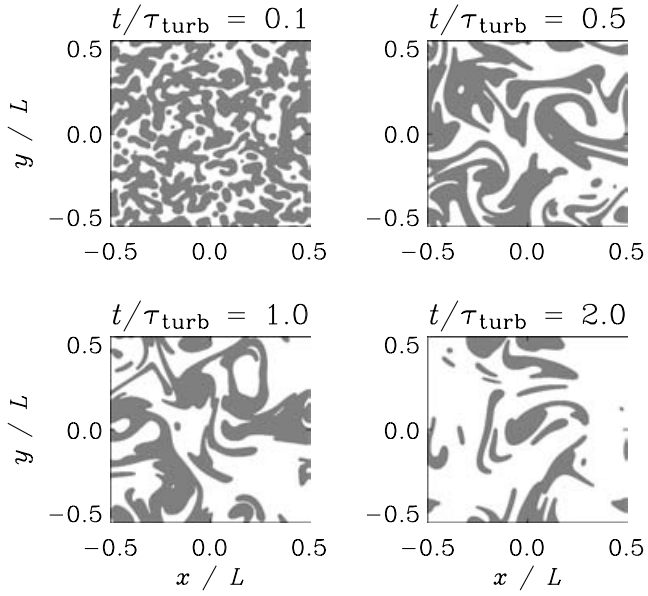


Fig. 4. The spread of homochiral regions in 2+1 dimensions. The dark (light) regions correspond to left- (right-)handed regions. Time is given in dynamical times, $\tau_{\rm turb} = \ell/u_{\rm rms}$. (Adapted from BM.)

of life on Earth, see the recent paper by Davies & Lineweaver (2005).

The spread of chirality and the coexistence of regions of different chirality were studied by Brandenburg & Multamäki (2004; hereafter referred to as BM). They considered a reduced polymerization model, with spatial extent, analytically and by numerical simulations. The importance of spatial extent has already been emphasized by Saito & Hyuga (2004b) who generalized an earlier model (Saito & Hyuga 2004a) by using a Monte Carlo method, as is used in percolation studies.

The behaviour of the reduced model can be understood qualitatively: an initial racemic mixture with small local perturbations quickly relaxes locally to regions of different chirality. Hence, in this work the emergence of life was considered to be a frequent and rapid event. The opposite-handed regions then begin to spread spatially into any possibly remaining racemic regions by front propagation until they come into contact with a region of opposite chirality. In 1+1 dimensions (one space and one time dimension) there is no further evolution and one can view the process as spontaneous symmetry breaking leading to stable, non-propagating domain walls. In more than one spatial dimension, the homochiralization process progresses further. If no advection is present, only diffusion can drive the homochiralization process. Analytical arguments can be utilized to show that a bubble surrounded by a region of opposite chirality tends to shrink. Since the equations are local, the local curvature of the front is the deciding property in determining which way a front will move. An example of this process is shown in Fig. 3, where we show a 2+1 dimensional box with regions of different chirality. The initial state in the simulation was a racemic state with small fluctuations so that one quickly arrives at a state where there are many left- and right-handed regions in the box. Here we show the evolution of these homochiral regions. From the figure it is easy to see that the curvature of the interface indeed determines the evolution of a region: e.g. small bubbles shrink and later disappear.

Again, time scales play a crucial role in the global homochiralization process. Using microphysically motivated values, we find that the local relaxation to a homochiral state is rapid compared with that of the propagation of fronts into racemic surroundings. In turn, this is a much faster process than the final stage in global homochiralization when the regions of different chirality slowly disappear as described above. Using values of molecular diffusion, one actually finds that this time scale on Earth is much too long to explain the observed homochiral final state.

In order to study the process further, we have also considered the effects of advection on homochiralization. An

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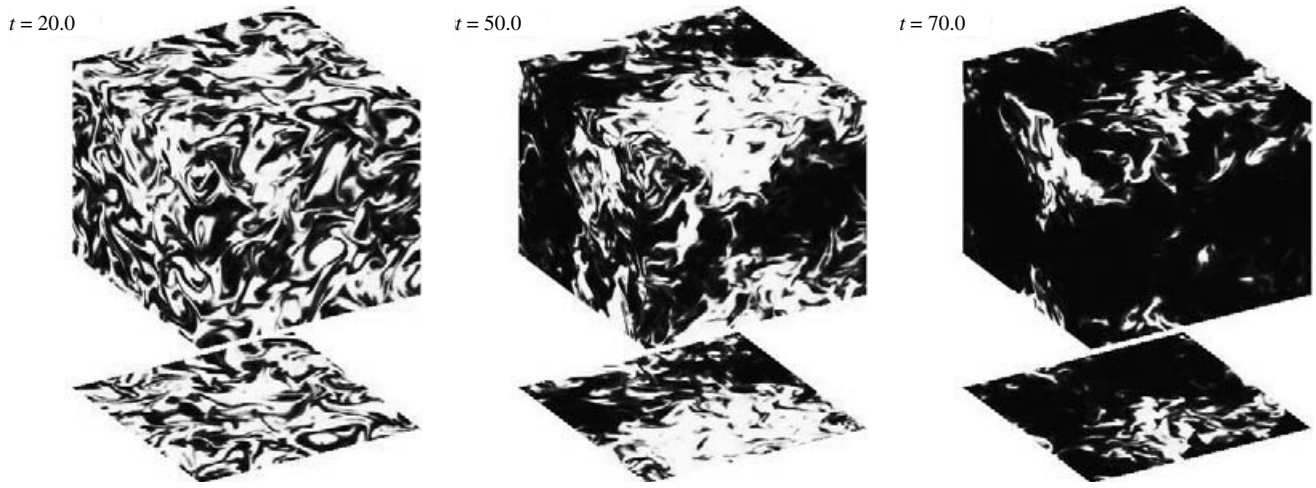


Fig. 5. The spread of homochiral regions in 3 + 1 dimensions. The dark (light) regions correspond to left- (right-)handed regions. The time $t = 50$ corresponds here to $t/\tau_{\rm turb} \approx 2$. This is also the last time shown in Fig. 4. By the time $t = 100$, corresponding here to $t/\tau_{\rm turb} \approx 4$, the right-handed life form went extinct.

example in 2 + 1 dimensions is shown in Fig. 4. The mixing process is now greatly enhanced and one finds that the global homochiral state is reached much more rapidly. The actual time scale depends strongly on the strength of the flow, e.g. for a root mean square flow of 1 cm s^{-1}, the time scale of global homochiralization is of the order of 30 years. It is then clear that if the model considered in BM captures the relevant features of chirality selection on the early Earth, the effective mixing of early oceans is vital. As the mixing is affected by many factors such as the existence of continents and the salinity of sea water, it is not difficult to speculate that in some secluded parts of the early oceans, life forms of different chirality could have coexisted.

So far we have considered spreading in two horizontal directions, which is relevant to the Earth's surface where the vertical dynamics may be eliminated by vertical averaging. However, BM also considered three-dimensional models and found that the speed of homochiralization is somewhat enhanced (by about 30 %) relative to the two-dimensional case. Furthermore, in both two and three dimensions they found that the generalized enantiomeric excess,

$$\eta = \frac{\langle E_R \rangle - \langle E_L \rangle}{\langle E_R \rangle + \langle E_L \rangle}, \tag{8}$$

where angular brackets denote averages in space, grows approximately linearly in time:

$$\frac{d\eta}{dt} = (12 \ldots 18) \times \mathcal{N} \left(\frac{2\lambda^2}{Qk_{\rm S}} \right)^{1/4} \frac{\kappa}{L^2}, \tag{9}$$

where $\mathcal{N}$ is the number of topologically disconnected domains, $\lambda/\sqrt{Qk_{\rm S}}$ is the non-dimensional growth rate in the spatially uniform case, L is the spatial extent of the domain and κ is the diffusion coefficient.

In the turbulent case, κ can simply be replaced by a turbulent coefficient $\kappa_{\rm turb}$, for which BM found from their simulation the rough estimate $\kappa_{\rm turb} \approx (0.08 \ldots 0.15) u_{\rm rms} \ell$, where $u_{\rm rms}$ is the root mean square velocity of the turbulence and ℓ is the typical length scale of the turbulent eddies. It should be emphasized, however, that such a description of turbulent mixing is rather rudimentary and ignores, for example, the fact that the shape of left- and right-handed domains is quite different with and without turbulence: it is more round in the case of molecular diffusion and more elongated in the turbulent case. The latter is a feature of the turbulence to mix fields by stretching and folding. A snapshot of a fully three-dimensional simulation[1] showing the concentration of left-handed building blocks is presented in Fig. 5.

Emergence and spread of life on the early Earth

We have made a number of underlying assumptions in studying the spread of homochiral domains on the early Earth. Firstly, we have assumed that the initial state is globally racemic. This implies that the conditions where life could have emerged are uniform and favourable everywhere and, furthermore, that a homochiral region can spread and fill the whole domain. Secondly, we have assumed that the emergence of life is a common event and that it is possible everywhere on Earth, and that there are no mass extinctions. These assumptions may not necessarily be realistic, and one should consider what new effects can possibly arise from relaxing these assumptions.

Considering the possibility of mass extinctions and that the emergence of life can be a rare event, it is clear that a new time scale, $\tau_{\rm ext}$, is inserted into the process. Assuming that mass extinctions are local events (i.e. not all life is destroyed in which case the process can start again), the relative lengths

[1] Animations of both turbulent and purely diffusive solutions can be found at http://www.nordita.dk/~brandenb/movies/chiral.

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of the different time scales determine the qualitative dynamics of the system. If $\tau_{\rm global} \ll \tau_{\rm life} \ll \tau_{\rm ext}$, life appears somewhere and takes over the whole system before life of opposite chirality can emerge. Any later mass extinction events will be insignificant as the dominant chirality will quickly win over the achiral region. If $\tau_{\rm life} \ll \tau_{\rm global} \ll \tau_{\rm ext}$, we have the situation considered earlier in this paper, where regions of different chirality compete. If mass extinctions are common, $\tau_{\rm ext} \ll (\tau_{\rm life}, \tau_{\rm global})$, and so any emergent life will quickly be wiped out – at least locally. Again, if $\tau_{\rm global} \ll \tau_{\rm life}$, it is unlikely that life will re-emerge spontaneously in the affected areas, and these areas are more likely to be re-populated by the spread of the homochiral regions surrounding the now racemic area. Thus, in this case, homochirality is preserved. On the other hand, if $\tau_{\rm life} \ll \tau_{\rm global}$, the possibility of mass extinctions allows for new life forms to emerge which, in turn, may prolong the time during which life forms of opposite chirality can have coexisted.

It is not immediately obvious how mass extinctions should be modelled within the framework of the BAHN model. It seems plausible that a mass extinction due to an impact, for example, can be modelled by removing all existing polymers. The re-emergence of life depends on the source term Q of the substrate and on the $k_{\rm C}$ parameter that controls the rate at which new monomers are created from the substrate. By locally suppressing Q or $k_{\rm C}$ as a consequence of the mass extinction, one can model the reduced habitability by slowing down the generation either of the substrate or of new monomers from the source. Alternatively, one could decrease the polymerization efficiency by decreasing $k_{\rm S}$ and $k_{\rm I}$ on the grounds that these parameters are likely to depend on external factors such as temperature, salinity and acidity.

Allowing for the additional dependencies discussed above certainly introduces a lot of additional uncertainties, but it also removes some of the sensitivity to initial conditions. If the conditions for chirality (or life) are not satisfied everywhere, the spread of chirality will stop and mass extinctions can eradicate the emergent life forms. Hence, there are various approaches to modelling the emergence of life and mass extinctions in the BAHN model. Either one can deplete the source of the substrate, or one can diminish the conversion rates for monomer formation and/or for polymerization, in which case the substrate might still be present everywhere.

Clearly, these considerations are relevant in a more realistic model and, furthermore, can bring interesting new dynamics into the system. As such they are worth considering in more detail and future work will hopefully bring us answers to these questions. Detailed numerical models of this process may elucidate further the possible outcomes. We plan to adapt the Pencil Code[2], which was also used in our earlier paper, to include the effects of a dynamical evolution of the rate at which new left- and right-handed monomers can be regenerated.

[2] See http://www.nordita.dk/software/pencil-code.

Conclusions

We have studied the spatial evolution of chirality in an initially racemic system. By utilizing analytical and numerical methods, we have shown how a globally homochiral state can be reached. The associated time scale depends strongly on the details of the system, but molecular diffusion is too slow to homochiralize the early Earth and turbulent flows are necessary. Effective mixing of the early oceans drastically reduces the required time and is hence a vital ingredient in understanding the homochiralization process.

We have also qualitatively considered how a more infrequent emergence of homochiral regions and the addition of mass extinctions would affect the evolution of the system. Adding such (possibly more realistic) processes enriches the dynamics and offers new interesting avenues of research to be explored in the future.

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References

Avetisov, V.A. & Goldanskii, V. (1993). Chirality and the equation of 'biological big bang'. *Phys. Lett.* A **172**, 407–410.

Avetisov, V.A., Goldanskii, V.I. & Kuz'min, V.V. (1991). Handedness, origin of life and evolution. *Phys. Today* **44**, 33–41.

Bada, J.L., Luyendyk, B.P. & Maynard, J.B. (1970). Marine sediments: dating by the racemization of amino acids. *Science* **170**, 730–732.

Brandenburg, A., Andersen, A.C., Höfner, S. & Nilsson, M. (2005). Homochiral growth through enantiomeric cross-inhibition. *Origins Life Evol. Biosphere* **35**, 225–242.

Brandenburg, A. & Multamäki, T. (2004). How long can left and right handed life forms coexist? *Int. J. Astrobiol.* **3**, 209–219.

Davies, P.C.W. & Lineweaver, C.H. (2005). Finding a second sample of life on Earth. *Astrobiology* **5**, 154–163.

Frank, F.C. (1953). On spontaneous asymmetric synthesis. *Biochim. Biophys. Acta* **11**, 459–464.

Gilbert, W. (1986). Origin of life – the RNA world. *Nature* **319**, 618.

Goldanskii, V.I. & Kuzmin, V.V. (1989). Spontaneous breaking of mirror symmetry in nature and origin of life. *Sov. Phys. Usp.* **32**, 1–29.

Hare, P.E. & Mitterer, R.M. (1967). Nonprotein amino acids in fossil shells. *Yearbook Carnegie Inst. Washington* **65**, 362–364.

Joyce, G.F. (1991). The rise and fall of the RNA world. *New Biol.* **3**, 399–407.

Joyce, G.F., Visser, G.M., van Boeckel, C.A.A., van Boom, J.H., Orgel, L.E. & Westrenen, J. (1984). Chiral selection in poly(C)-directed synthesis of oligo(G). *Nature* **310**, 602–603.

Kozlov, I.A., Pitsch, S. & Orgel, L.E. (1998). Oligomerization of activated D- and L-guanosine mononucleotides on templates containing D- and L-deoxycytidylate residues. *Proc. Natl. Acad. Sci.* **95**, 13 448–13 452.

Saito, Y. & Hyuga, H. (2004a). Complete homochirality induced by the nonlinear autocatalysis and recycling. *J. Phys. Soc. Japan* **73**, 33–35.

Saito, Y. & Hyuga, H. (2004b). Homochirality proliferation in space. *J. Phys. Soc. Japan* **73**, 1685–1688.

Sandars, P.G.H. (2003). A toy model for the generation of homochirality during polymerization. *Origins Life Evol. Biosphere* **33**, 575–587.

https://doi.org/10.1017/S1473550405002338 Published online by Cambridge University Press

Schmidt, J.G., Nielsen, P.E. & Orgel, L.E. (1997). Enantiomeric cross-inhibition in the synthesis of oligonucleotides on a nonchiral template. *J. Amer. Chem. Soc.* **119**, 1494–1495.

Toxvaerd, S. (2004). Domain catalyzed chemical reactions: a molecular dynamics simulation of isomerization kinetics. *J. Chem. Phys.* **120**, 6094–6099.

Toxvaerd, S. (2005). Origin of homochirality in biological systems. *Int. J. Astrobiol.* **4**, 73–78.

Wattis, J.A.D. & Coveney, P.V. (2005). Symmetry-breaking in chiral polymerisation. *Origins Life Evol. Biosphere*, in press, arXiv:physics/0402091.

Wei-Min, L. (1982). Remarks on origins of biomolecular asymmetry. *Origins Life* **12**, 205–209.

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