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On the physical origin of the homochirality of life

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It seems to be well known that life cannot arise in a racemic mixture of molecules (L = D). The various physical mechanisms that could influence the homochirality of the molecules responsible for life are reviewed together with a model where these molecules might be produced in the galaxy prior to the formation of the earth. The focus is on the influence of a powerful supernovae explosion to affect the homochirality of these molecules. Possible tests of this concept with meteorites and future space missions are described.

Chiral symmetry breaking and the origin of life

For more than a century there has been evidence for the chiral nature of life forms on Earth. Pasteur was among the first to point this out (1848–1880), and the universal nature of chiral symmetry breaking in proteins and in DNA and RNA is now very well established for all life forms.

In 1995, a symposium was held at UCLA on the 'Physical Origin of Homochirality in Life'.[1] From this meeting it became clear that 'life cannot originate in a racemic mixture' (equal Land D molecules), to quote Goldanskii. Table 1 gives a more general summary.[1,2]

The origin of life is tied to some form of chiral symmetry breaking. This can be of deterministic (physical origin) or spontaneous symmetry breaking in the molecules. In this paper we take the viewpoint that a physical origin exists for this symmetry breaking and attempt to identify the leading candidates. We consider one tentative model where this happens in the cold prebiotic reaches of the galaxy.

With the discovery of parity violation in charged current reactions in 1956 and of the weak neutral currents (WNCs) in 1973, two universal symmetry-breaking processes (WNC and β-decay) were uncovered that could have determined the

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Table 1.

1.	DNA: Self-replication would not work with heterochiral systems (50%L and 50%D).
2.	Errors in DNA Replication: Without a pure chiral structure, the error rate in replication would be unacceptable to long-lived systems (higher animal forms, trees, etc.).
3.	In a prebiotic medium: Homochirality must have been either
	(A) Established in a very short time on earth (≤ 100 Myr), or,
	(B) Existed in ISM organic materials near the solar system

handedness of DNA and RNA. The main problem is the extremely small symmetry-breaking effects for the WNC ($\Delta E/k_B T \sim 10^{-17}$). However there are plausible non-linear mechanisms that could have amplified this small, symmetry-breaking phase transition up to the full symmetry-breaking level observed in life forms. There is, nevertheless, a long-standing controversy as to whether these non-linear effects are actually large enough to have determined the selection of the handedness of life.[1,2]

Figure 1 shows examples of the homochirality of amino acids and sugars that exist or do not exist in nature.

There are several physical mechanisms that have been proposed to 'cause' this homochirality. Table 2 lists these processes.[1]

These proposed asymmetry processes follow decades of the study of weak interactions on earth and the discovery of parity violation in 1957 and the discovery of the W/7 bosons in 1983. Table 3 gives a list of these key discoveries and the time line. Many have speculated that these physical weak interaction processes somehow lead to the homochirality or chiral symmetry breaking in

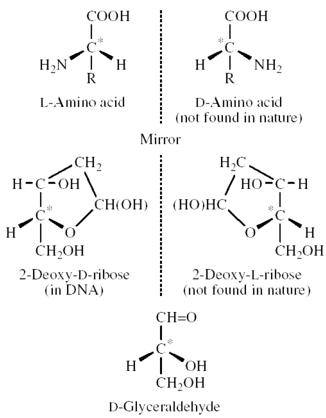

Figure 1. (a) Examples of molecules that are isomers, some of which exist in nature and some that do not.

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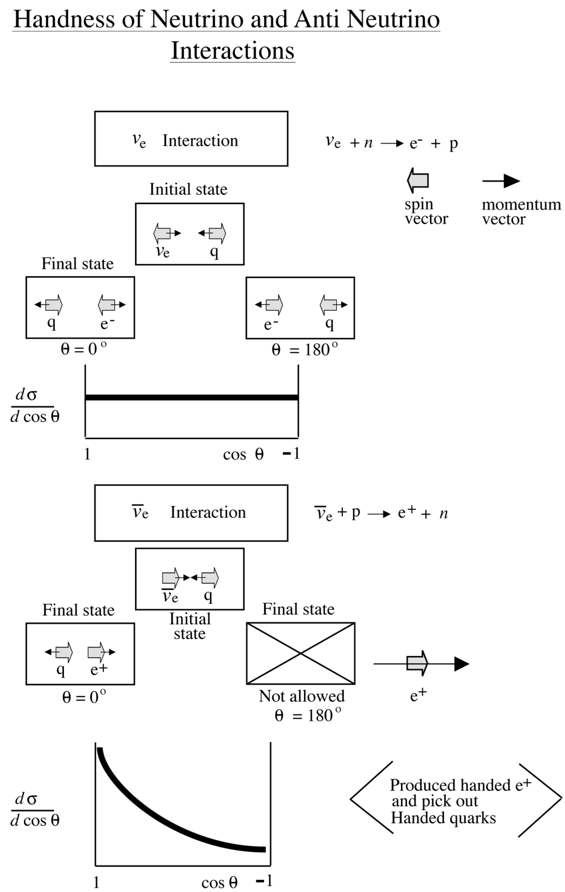

Figure 1. (b) Example of handedness in the weak interaction

Table 2.

$$d\eta/dt \sim a[1-\eta^2];\ \eta = \left[\frac{X_L - X_D}{X_L + X_d}\right]$$

Type of Symmetry Breaking	Assymetry Factor α	Comments/References
Circularly polarized light	10^{-2}–10^{-5}	Depends on position of the source (Refs. 2,3)
Polarized $e^{\pm}$ leptons	10^{-9}–10^{-10}	$N_{\mathrm{Interaction}}\tau 1/a^2$ (Refs. 4–8)
Supernova neutrino interactions	See the text	Depends on location of SN II and planet (Refs. 9, 10)
Weak neutral current/Z^0 process	10^{-17} [T/300]	$T \sim 300$ K could be enhanced by spontaneous symmetry breaking process (Refs. 11–15)

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Table 3. History of physical chiral symmetry-breaking observation (see Ref. 16)

Period	Observation	Consequences
1953–1955	τ-θ puzzle in Strange particles	Hints of parity violation
1957	Parity violation prediction/observation in C_O^{60} and $\pi^*\mu^*$ decays	V-A theory of weak interactions $\nu_e,\bar{\nu}_e,e^{\pm}$ have definite chirality
1964	CP violation ($K_L^0 \rightarrow \pi^+\pi^-$ observed)	$K_L^0 \rightarrow \pi^+ e^- \bar{\nu}_e$ and $K_L^0 \rightarrow \pi^- e^- \nu_e$ have different rates
1973	Observation of WNC	Electroweak unification
1976–1978	Parity violation in WNC	Atomic parity violation
1983	W^*/z^0 observation at CERN-UA1	Electroweak theory – left handed w ± particles
1987	$\bar{\nu}_e$ detected from SN1987A	–
1986–1994	Precision measurements of electroweak parameters	–

biological materials. Here we propose a new mechanism from a supernova type II interaction with dust clouds of hydrocarbon organic material that form the cloud, which collapses into a star and associated planets.

Cold prebiotic history of the organic molecules for life

One of the main themes of recent attempts to understand life on earth is the likelihood that most of the early organic material on Earth was brought in by comets and asteroids.[17] There are some interesting 'large numbers' to consider in this regard:

1. The estimated amount of dust matter in the galaxy is $\sim 10^{-4}$ m_G, or $\leq 10^7$ solar masses, largely in the form of dust grains. A fraction of that material is in the form of organic materials. It has not been possible to measure the amount of interstellar dust that has accumulated on the Earth (bringing organic material).
2. In a molecular cloud of density 10^4 M/cm^3 and 1 parsec radius, there could be a complex organic matter equal to 100 solar masses.
3. The Earth revolves around the galaxy with a period of ~ 250 million years, and it has likely encountered several dense layers of molecular clouds in this trajectory.

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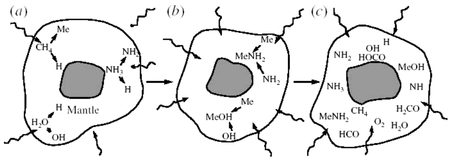

Figure 2. Structure of grains when they initially accrete is inferred from laboratory simulations in which mixtures of water, methane, ammonia and other simple molecules are subjected to ultraviolet irradiation at a temperature of 10 K. Each grain begins as a silicate core that condensed in the atmosphere of a cool giant star. Around this core a mantle of ice forms. Ultraviolet radiation breaks some of the mantle molecules into radicals, or reactive molecular fragments (a). The radicals can then recombine in new ways (b). Over a longer period the continued ultraviolet irradiation of the grain can give rise to ever more complex mixtures of molecules and radicals (c).[1]

4. It is likely that large quantities of organic material were deposited in the Earth in the first one billion years.

The above information was obtained by infrared scattering from the dust in the galaxy and by modelling various UV-driven processes here on Earth. Ultraviolet photo-processing plays an important role in the organic chemistry of the dust particles. Figure 2 shows the nature of a dust grain with prebiotic molecules inside.

There is considerable new evidence that various mechanisms in the galaxy can lead to much, if not all, of the basic building blocks of life on earth. These molecules initially reside in the cold ISM which could also be a key factor in the eventual process that caused homochirality.[18–21]

Evaluation of the different mechanisms for homochirality productions

The various methods, as summarized in Table 2, have positive and negative features.

(1) The polarized light argument will give homochirality dependent on whether the hydrocarbons are above or below the span of the star. There are some questions about whether this ever gives a net effect (see Table 1 also Table 4).
(2) The weak neutral current (Z^0) effects are very small. Normally if direct interactions are used the number would be $N_{\mathrm{wnc}} \geq 1/a^2 - 10^{34}$

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Table 4. Estimated rate of homochiral molecule production in ISM

Estimated rate of $\bar{\nu}_e$ interactions in the dense presolar cloud
$\left[\frac{N_{\bar{\nu}} \sim 10^{57}}{from\ SNII}\right]\left[\frac{Assume\ SN\ 1\ par\ \sec}{from\ cloud}\right]$
Assume: Cloud density 10^4 protons/cm^3 [fraction of organic material] 10^{-3}-range of e^+ 1 parsec;
Number of $\bar{\nu}$ interactives $\sim 10^{35}$ = Number of e^+ for interaction with organics in cloud $> 10^{30}$
We estimate that only 10^{22} interactives are necessary to produce asymmetry ($a \sim 1^{-11}$)
$<$ In this model all life in galaxy will have same homochirality $>$

a very large number. However the effect can be enhanced by autocatalytic processes or phase transitions (Table 1.)

(3) Direct $e^{\pm}$ β decay processes have the following problems:

(a) on earth the number of radiation decays $N > 1/a^2 - 10^{22}$ decays is excessive. In the galaxy a supernova could give this type of radioactive level for Al^{26} and this is one possible mechanism we have discussed before (see Table 1).

(4) A direct effect of the neutrinos from a SNII could have the required number of interactions if the SNII is in a correct position and distance from a planetary formation system, as illustrated in Figure 3 also Table 4.

In this model the chiral symmetry breaking occurs because

(1) The neutrino interaction cross-sections scale as E_ν^2.
(2) The anti-electron neutron average energy is predicted to be larger than the electron neutrino.
(3) An interaction of the electron neutrino is supposed since there are no free neutrons.

This results in an excess of handed positron production over electron production. Neutrons also decay into electrons but with much lower energy. Thus there is an excess of positrons at most energies. Table 4 lists in more detail these different processes and Figure 4 illustrates the polarized light argument.[1,3]

In this paper, we propose that weak interactions in the galaxy use a very powerful source: a supernova type II in some form or another that modifies the chirality of molecules.

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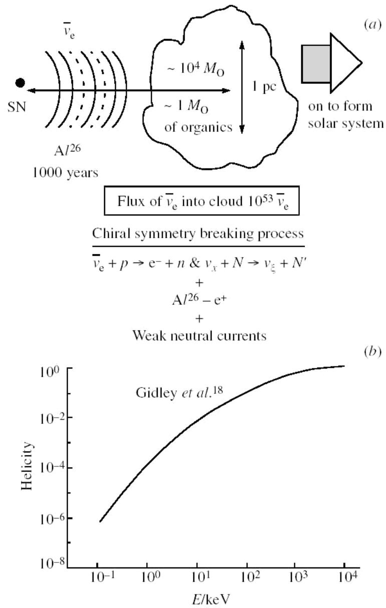

Figure 3. (A) Schematic of the effect of a supernova II on the organic molecules in a dense molecular cloud. (B) Estimated polarization of the β^* decay particles as the energy decreases by ionization in H_2O and in the dense molecular cloud. One observation of the polarization of low energy e^* by the Michigan group.[1]

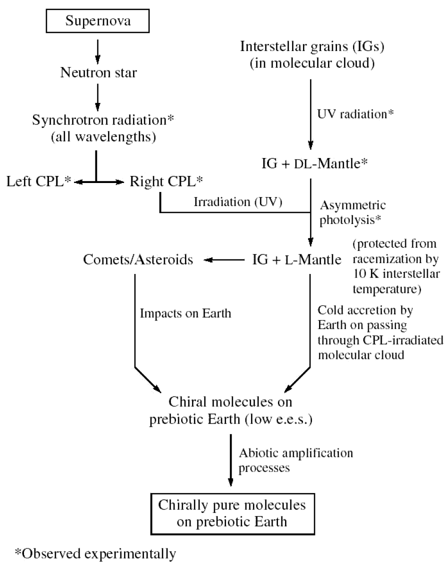

Figure 4. Possible extraterrestrial origin of terrestrial homochirality.[1,3]

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Neutrinos interact through the weak interactions in a process (Figure 3) like $\bar{\nu}_e + p \rightarrow e^+ + n$. This was the very process used to discover the neutrinos in 1957. A supernova emits 10^{57} such anti-neutrinos in the final stage. Let us consider the rate of these three effects:

(1) For $\bar{\nu}_e$ absorption and a supernova 1 parsec away (or inside a 1-parsec dense cloud), the number of interactions will be $\sim 10^{-3}$/kg of material for 100 M_O of organic material (which would be 10^{12} grams of organic matter that is *active*), therefore the positron from the $\bar{\nu}_e$ interactions would lose energy at a rate of 10^{-19} MeV/cm and thus travel over a parsec. ($\bar{\nu}_e$ is an antielectron neutrino).

(2) For the coherent $\nu_x + N \rightarrow \nu_x + N$, and for the carbon in the hydrocarbons, we would have $\sim 10^2$ more or $\sim 10^{14}$ grams of *active* material. Note ν_x stands for all types of neutrinos. This effect could be very important in light of the small energy difference that separates L and D molecules and the possibility of large coherent effects.

(3) For the Al^{26} over the half-life, there would be $\sim 10^{50}$ decays producing $\sim 10^{50}$ positrons that lose energy at the rate of 10^{-19} MeV/cm; for MeV positrons, the range would be of the order of a parsec (ignoring possible magnetic-field effects).

(4) Direct interaction of the supernova II neutrino.

Consider the example where 0.001 M_O of Al^{26} is produced and assume (M_O is the mass of the sun) for simplicity, that the energy of the e^+ is 1 MeV and is contained in the gas cloud. Assume that the could has a density of 10^4 atoms/cm^3 and that 10^{-3} of the atoms are organic, then the stopping power for e^+ will be

$$\mathrm{d}E/\mathrm{d}x \approx \mathrm{MeV/gm/cm^3}$$

and for a density of $\rho = 10^4$ atoms/cm$^3 \sim 10^{-17}$ g/cm^3, we find

$$\mathrm{d}x \approx \mathrm{d}E/\rho(\mathrm{MeV}) \approx 10^{19}\ \mathrm{cm}(\approx 3\ \mathrm{parsec})$$

and for an average energy exchange of 10eV, we have

$$10_e^5\ \mathrm{collisions/Al^{26}\ decay}$$

For 0.001 M_O of Al^{26} and 10^{-3} organic fraction, we obtain a total of $\sim 10^{50}$ collisions of polarized positrons, with organic materials in the cloud assuming all of the e^+ stop in the cloud. (We assume that only one of the collisions can result in spin exchange.) There will also be the same order of polarized photons from the $e^+e^- \rightarrow \gamma\gamma$ annihilation.

Stages of prebiotic life[1,2]

⇊	**synthesis of organic compounds**
(a) racemic organic medium (η,0)	
⇊	**strong breaking of mirror symmetry**
(b) chirally pure organic medium (η,0,99)	
⇊	**polymeric takeover of medium**
(c) homochiral polymers organic medium (η,0)	
⇊	**formation of enaniospecific (enzymatic) activity**
(d) homochiral chemical automata (η,0)	
⇊	**formation of enantiospecific (enzymatic) activity**

Figure 5. Five main stages of prebiological evolution.

The stages of prebiotic life and homochirality

In Figure 5 we show the hypothetical stages of prebiotic life as outlined by Goldanskii at the Santa Monica Symposium and in Ref. 2. In the model presented here, stage (a) occurs in the galaxy producing cold prebiotic molecules in the ISM. Stage (b) would be produced by a supernova II near the pre-solar-system. We do not know the density of this gas cloud but it could be significant. This stage may also be produced by the process in Figure 4. Stage (c) very likely occurs on the early earth. Goldanskii firmly believed that homochirality was one of the main keys to life.[1]

Possible tests of the hypothesis of a physical origin of homochirality in life

In the future (and present) there are possible tests of the concepts presented here. First, the studies of certain meteorites (Murchison and Murray) have already indicated a small excess of L amino acids over D.[22] More than 60 amino acids have been found in these meteorites.[23] This is consistent with the model presented here. Study of several additional meteorites will be of crucial importance. The viewpoint of this paper is that weak interaction could cause this symmetry breaking.[24]

Future space missions like the ESA-ROSETTA mission to a comet with the possibility to test optical activity will be of enormous importance.[24]

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