On the Possible Physical Origin of Homochirality in Living Systems*

David B. Cline
University of California Los Angeles, Department of Physics and Astronomy
405 Hilgard Avenue, Los Angeles, California 90095-1547

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Contents

1 Homochirality of Life

For more than one 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 DNA and RNA is now very well established for all life forms. Figure 1 shows how

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the Homochirality is manifest at the molecular level. With the discovery of parity violation in charged current reactions in 1956, and of the Weak Neutral Currents (WNC) in 1973, two universal symmetry breaking processes were uncovered that could have effected the handedness of DNA and RNA (WNC and β decay). Figure 2 shows these processes at the fundamental level. The main problem is the extremely small symmetry breaking effects ($\Delta E/k_B T \sim 10^{-17}$). There are plausible non linear mechanisms that could have amplified this small symmetry breaking phase transition up to the full symmetry breaking observed in life forms. However, there is a long standing controversy as to whether these non linear effects are actually large enough to have determined selection of the handedness of life[1, 2, 3, 4, 5, 6, 7, 8]. Recently there has been increasing interest in the chiral nature or handedness of biomolecules. In fact there are some who claim that the complex biomolecules structure of life must have arisen from a "Chirally Pure" medium[3]. This concept combined with the likelihood that the period on earth for life to have originated seems to be sometime between 3.8 and 3.5 billion years ago leaves a small window of 300 million years or less for life to have emerged from the prebiotic medium. Some speculate the time could be less than 10 million years. In this paper we review a recent conference sponsored by UCLA on the "Physical Origin of Homochirality in Life", held in Santa Monica, California, on 15-17 Feb 1995 and to be published by AIP Press in 1995.

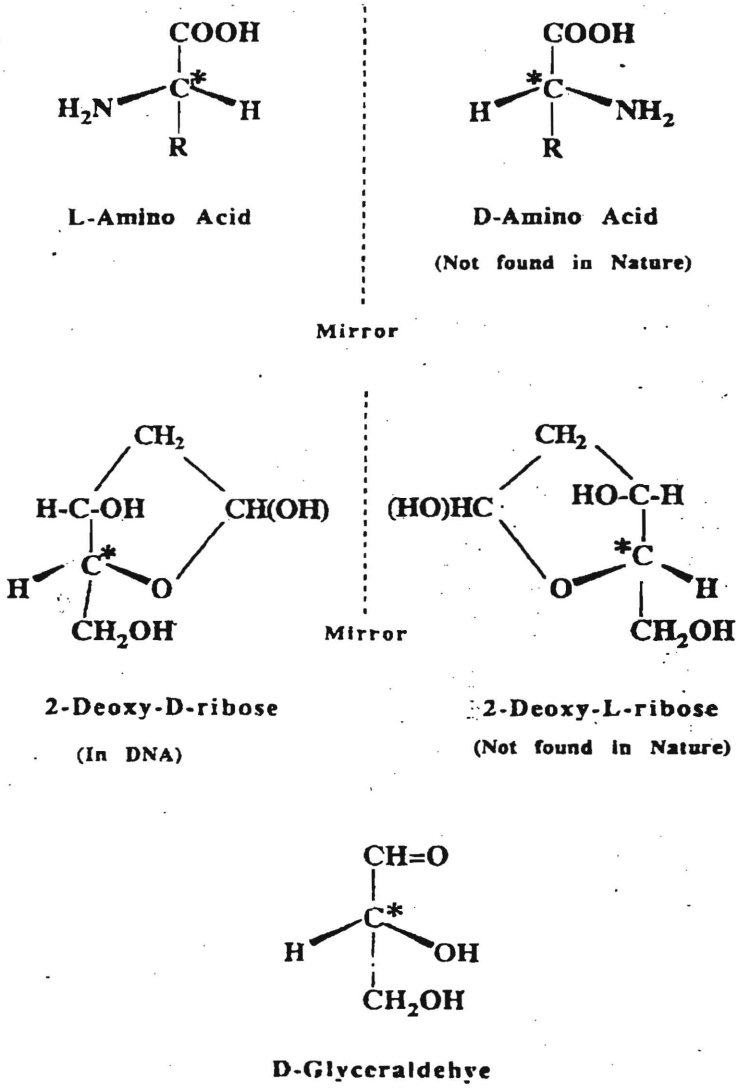

COOH
H2N
C*
H
R
L-Amino Acid
COOH
H
*C
NH2
R
D-Amino Acid
(Not found in Nature)
Mirror
CH2
H-C-OH
CH(OH)
H
C*
O
CH2OH
2-Deoxy-D-ribose
(In DNA)
Mirror
CH2
(HO)HC
HO-C-H
*C
O
H
CH2OH
2-Deoxy-L-ribose
(Not found in Nature)
CH=O
C*
H
OH
CH2OH
D-Glyceraldehye

Figure 1:

2 The Molecular Parity Selection of Charged and Neutral Currents

Charged current effects that violate parity are one candidate for the symmetry breaking[9, 10]. The WNC that interferes with the electromagnetic field and gives rise to weak distortions of virtually all electromagnetic effects, could be one of the candidates that causes symmetry breaking in the biosystem[11]. It could make the broken symmetry of the micro-world translate to the macro-world, finally leading protein and both DNA and RNA to display *left-handed* (L) and *right-handed* (R) form, respectively. For organic molecules, however, the difference between the ground state energies of the R- and L-type is about[6, 7] $\Delta E \sim 10^{-17} k_B T$ of the thermal energy at room temperature.

There have been various experimental tests of the effects of weak interactions on biological materials – all null to date (see references 12 and 13 for a review and for an excellent introduction to this subject). We will return to this issue later when we discuss possible new experiments.

There are other processes that select chiral states, for example absorption of circularly polarized light[3, 2]. For some time there has been a debate as to whether combinations of electric and magnetic fields could cause a chiral symmetry breaking[3, 13]. For a recent discussion see Barron, Science ..?..

3 The Conditions for the Small Electroweak Asymmetries in the Prebiotic Medium to be Amplified – Simulations

If the WNC interaction is possible to provide an additional energy in such order in an organic biosystem, the handedness of the organic molecules might appear. Such additional energy could be thought as a small bias in this transition process. For simulation this small bias is converted into a non-dimensional parameter $g(\Delta E/k_BT)$ to characterizes the relative difference in the time to effect the phase transition. A series of simulations with constant g has been done[1] that show an amplification process can occur.

In contrast to the gradual build up of symmetry breaking[1, 8], as proposed by Kondepudi, we propose a more general condition that allows also for an impulse of chiral symmetry breaking[14]. This will illustrate the general principle, as well. For example a natural fission reactor where large amount of U^{235} may have accumulated by accident. At first sight this might seem to be an unimportant effect and has been ignored in the past literature on this subject. But with increasing interest currently this issue should be paid more attention. Here we present some results based on our previous work[8]

$$\frac{d\alpha}{dt} = -A\alpha^3 + B(\lambda - \lambda c)\,\alpha + \epsilon^{1/2} f(t) + Cg \qquad (1)$$

becomes

$$\frac{d\alpha}{dt} = -A\alpha^3 + B(\lambda - \lambda c)\,\alpha + \epsilon^{1/2} f(t) + Cg + d\delta_{\lambda\lambda'} \qquad (2)$$

where α is the amplitude of the symmetry breaking solution, λ the control parameter, g is the interaction or bias *symmetry breaking selector*, λ_c the symmetry breaking transition point (critical point), $\epsilon^{1/2}$ is the rms value of fluctuation (noise), and $f(t)$ is the normalized fluctuation (noise), d is the amplitude of a quasi δ-pulse, and $\delta_{\lambda\lambda'}$ is the δ-function which $\delta_{\lambda\lambda'} = 1$ when $\lambda = \lambda'$ and $\delta_{\lambda\lambda'} = 0$ when $\lambda \neq \lambda'$.

$$\lambda = \lambda_0 + \gamma t \qquad (3)$$

where λ_0 is the initial value of λ, γ the evolution rate, and t the evolution time.

To solve the first order stochastic equation numerically we assigned the initial amplitude a to zero at time $t = 0$, but the $f(t)$ is a random number generated by computer within [-1,1]. To obtain the trace of the symmetry breaking amplitude a at different time for each trial we just sampled the amplitude a at different time. Finally, we assembled those data points from about 40,000 trials to produce the Figure 3. It is shown that a $P_{--} = 88\%$ chance (probability) of favored process was selected[8, 14]. This illustrates the effect of a small symmetry breaking on a slowly evolving system. In essence, the small bias is magnified by the process of signal averaging, where the noise effect essentially cancels out. This process is sometimes called the Kondepudi effect[1]. This finishes our overview of the possible physical origin of Homochirality.

PERIOD:	OBSERVATION:	CONSEQUENCES:
1953 - 55	$\tau - \theta$ puzzle in Strange Particles	Hints of Parity Violation
1957	Parity Violation prediction/observation in ^{60}Co and $\pi^{\pm}/\mu^{\pm}$ decays	V-A Theory of Weak Interactions ν_e , $\bar{\nu}_e$, $e^{\pm}$ have definite chirality
1964	CP Violation ($K^0_L \rightarrow \pi^+\pi^-$ observed)	$K^0_L \rightarrow \pi^+ e^- \bar{\nu}_e$ and $K^0_L \rightarrow \pi^- e^+ \nu_e$ have different rates
1973	Weak Neutral Currents observation	Electroweak Unification
1976-78	Parity Violation in WNC	Atomic Parity Violation
1983	$W^{\pm}/Z^0$ observation at CERN - UA1	Electroweak Theory Confirmed
1987	$\bar{\nu}_e$ detected from SN 1987A	[redacted]
1986-94	precision measurements of Electroweak parameters	

FUTURE: Test of CPT; Origin of CP Violation

Figure 2: History of physical chiral symmetry breaking observation.

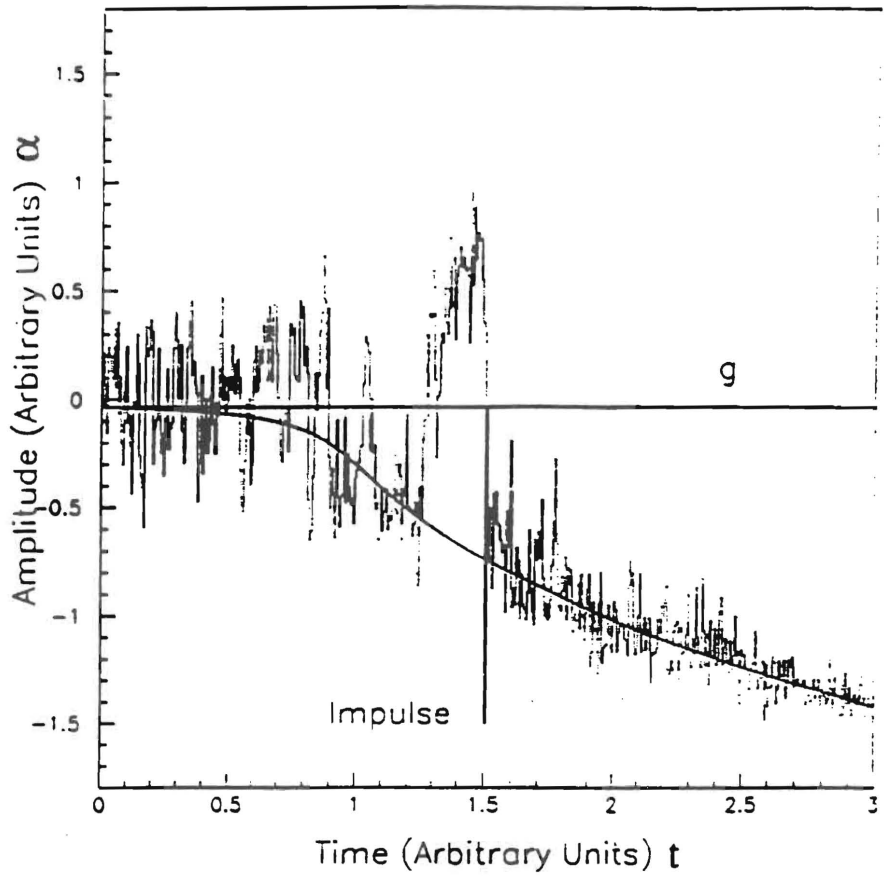


Figure 3: Single trial with impulse happened at $\lambda = 1.5$, where $\delta = d/g = 100$. The impulse strongly affects on the phase transition.

4 The Santa Monica Symposium

For many years there have been several issues associated with the homochiral structure of biomolecules, first observed by L. Pasteur in 1848:

a) Is a homochiral structure necessary for life as we know it?

b) Did homochirality precede the formation of life (homochiral prebiotic medium hypothesis)?

c) Is there any reasonable physical mechanism that could have produced the large chiral symmetry breaking in the prebiotic medium or in the observed homochiral structure?

d) Is the homochiral structure an accident that occurred in the biological systems and was later amplified?

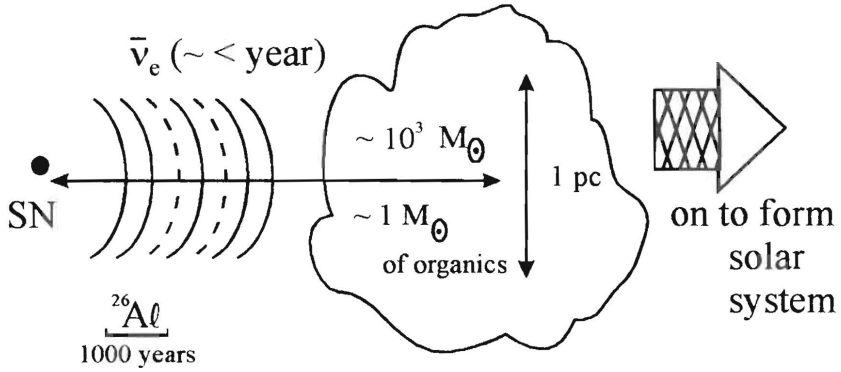
e) Can the homochirality be used as a signature for existing or previous living systems in the solar system or other parts of our galaxy?

f) Are there any experiments that can be carried out now to clarify the origin of homochirality?

These and many other questions were the basis for organizing the first symposium on this subject in Santa Monica, California. Some of the leaders of this field attended the meeting, made presentations and joined the discussions, as well.

The meeting started with an overview of the importance of homochirality in biomolecular life by Bonner (Stanford) and Goldanskii (Moscow). Their conclusions were that homochirality is almost certainly required for the formation of the complex self reproducing biomolecular structures (i.e. DNL) required for life. They both stated that the prebiotic medium should have been homochiral, although, they differed on how and even where this may have happened. Mann (U. Penn.) and Cline (UCLA) discussed the possible physical processes that could have helped produce chiral symmetry breaking. Radioactive beta particle interactions to the influence of weak neutral current all "violate parity" but are also very small effects. There was a brief discussion of the role that nearby supernova's in the ISM before the solar system formed could have played (see Figure 4). It was agreed that some powerful amplification mechanism must have intervened to achieve any large effect.

A Type II Supernova Near an Organic Rich Gas Cloud



Flux of $\bar{\nu}_e$ into cloud 10^{53} $\bar{\nu}_e$

Chiral Symmetry Breaking Process

$$\bar{\nu}_e + p \longrightarrow e^+ + \nu_x \quad \& \quad \nu + N \longrightarrow \nu_x + N'$$

$$+$$

$$^{26}A\ell \longrightarrow e^+$$

$$+$$

weak neutral currents

Figure 4:

On February 16 the first session was "Biomolecular Aspects of Homochirality." There were four very interesting presentations: Goldanskii (Moscow), Gilat (Technion), Avetisov (Moscow) and Miller (UCSD). Goldanskii discussed the Frank process, a process invented by the British chemist Frank that can be used to amplify physical or spontaneous chiral symmetry breaking in so far as no definite chemical reaction has been proposed as an example of the Frank process. Goldanskii showed that formaldehyde could be assembled in a Frank type process. Gilat indicated some other types of chiral symmetry breaking processes that should be studied in the laboratory. Avetisov discussed the very interesting question of assembling a complex structure like DNA out of homochiral monomers. He indicated that even with a homochiral prebiotic medium, a "complexity threshold" would be reached that is hard to understand passing through. Part of the final talk in this session by Miller dealt with the famous Miller-Urey experiment that showed many years ago how amino acids can be formed using an electrical discharge in a methane-water, etc. gas medium. In his talk Miller indicated that homochirality is not needed to give birth to biomolecules, however, it is a very great aid to Biology and life. Miller also pointed out that the organic materials produced in the famous Miller-Urey experiment were tested and found to be racemic!

The next part of the meeting, "Physical Origin of Homochirality - Symmetry Breaking," took the better part of February 16 and the first part of the morning of February 17, and caused the most controversy. There were three themes of this part:

a) The weak interaction which is the only universal chiral symmetry breaking system – MacDermott (Oxford U.), Hegstrom (Wake Forest U.)

b) Small effects might be amplified by auto catalytic Frank-type processes – Kondepudi (Wake Forest U.), Goldanskii and MacDermott.

c) There may be more useful mechanisms to break the symmetry either by a biochemical process or if the organic molecules are formed in the ISM and subjected to polarized light from neutron stars – Eschenmoser (Zurich), Nielsen (Copenhagen) and Bonner.

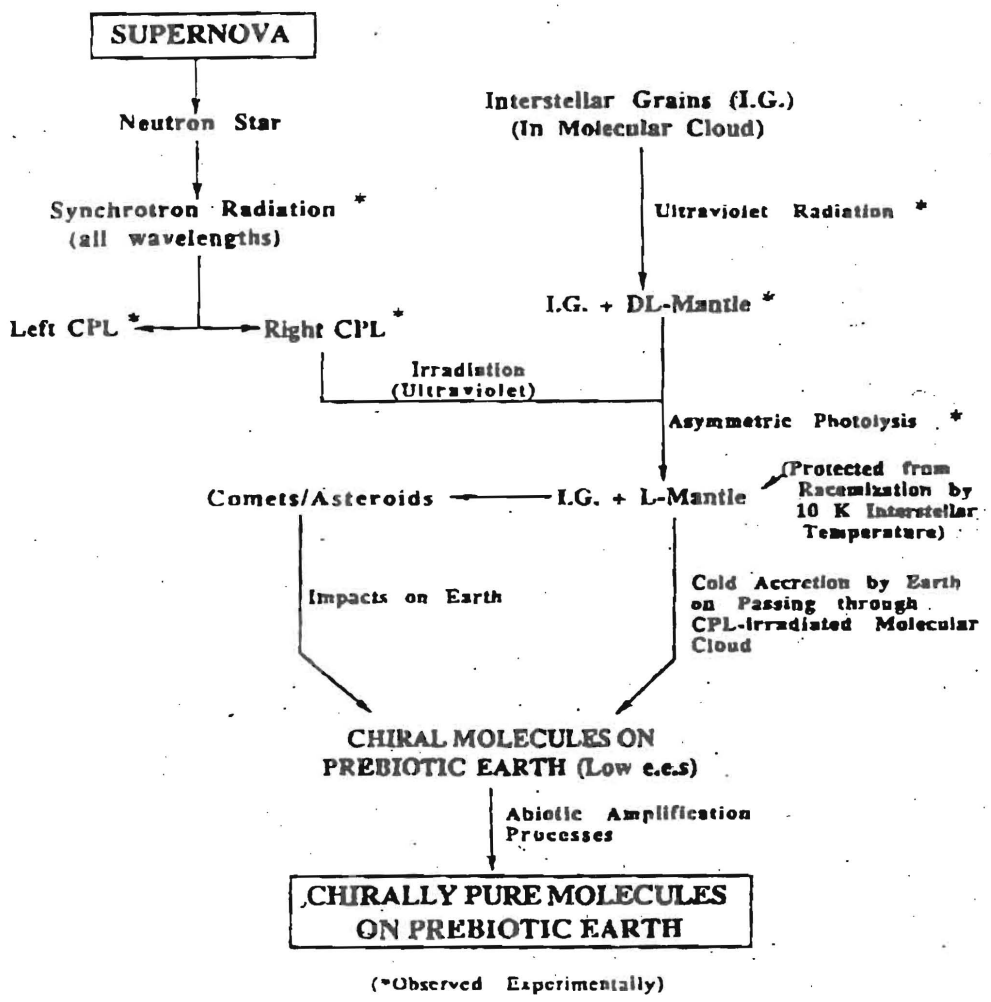
Let us elaborate a little on some of the newer results at the meeting. MacDermott has carried out some very interesting calculations of the energy difference of different chirality biomolecular configurations due to the weak neutral current and has found that some systems could have 10^{-14}/kT

energy difference, orders of magnitude larger than all previous estimates. Kondepudi once again emphasized the importance of the Frank process and the auto catalytic process and has even tested one of the ideas by studying salt crystals where the symmetry is broken by stirring the liquid! Eschenmoser showed how p-RNA could have symmetry breaking effects. Finally Bonner elaborated on the "abiotic" possibilities of the homochirality and indicated that the time available on the early earth for such a process to take place was less than 300 million years and could be even less. He indicated that a more viable possibility could be formation of homochiral molecules in the ISM and proposed a specific mechanism due to the absorption of polarized UV light from one or many neutron stars in the ISM. These ideas and others lead to a healthy debate at the meeting. One issue was associated with so called false chirality due to electric and magnetic fields discussed by Barron (U. Glasgow), who's talk was presented by MacDermott; similar ideas were discussed by Gilat.

The third session was devoted to Astrophysical and Planetary Aspects of Homochirality and Origin of Life on Earth. The presentations by Bada (Scripps/UCSD) and Greenberg (Leiden) were very interesting. Bada first showed that biomolecular systems (i.e. human teeth) progressively racemize as they age and indicated that the age of the Swiss Iceman is being determined this way. Then Bada pointed out that there is no evidence for non racemized organic molecules in micrometeorites in the polar ice or at the K-T edge in sediments. This is a serious constraint on theories where the organic molecules were brought in by comets, etc. Of course, it may not be directly relevant to what happened four billion years ago. The highlights of Greenberg's talk, titled "Photochemical Production of Non Chiral and Chiral Organics in the Interstellar Dust: Laboratory, Observation and Theory," were: organic materials make up $\sim 10^{-4}$ of the mass in the galaxy (as dust); the Halleys Comet carries 10% of the biomass on earth; organisms in dust undergo complex chemical reactions with the help of UV light (this has been studied in the laboratory where amino acids and other biochemicals are produced). Greenberg's main theme was that homochiral biomolecules could be produced from the polarized light from neutron stars over a long period of evolution of the large gas clouds in the galaxy (see Figure 5)(this concept was first discussed by W. Bonner, see Reference 12, for example). Greenberg went on to describe an experiment carried out with polarized UV light and selective destruction of D or L molecules was observed, thus confirming the Bonner hypothesis who's claim is that comets could have brought in both homochiral organisms and water to the early earth $\sim$ 4

billion years ago. (There was also a discussion that supernova in the ISM could provide a chiral impulse by the anti neutrino and ^{26}Al production.

The final section of the meeting was Future Perspectives and Experiments. It is clear that some experimental results care needed if this is to be a viable field of study. Khriplovich (Novosibirsk) discuss the possible study of high frequency radiation on homochiral substances; a careful study could yield the energy differences due to the weak neutral current. An open discussion on future experiments was held with many participants providing a suggestion for an experiment. One interesting possibility suggested is to use the new high intensity polarized electron guns for linear colliders to study the effects of polarized electrons on homochiral materials. This suggestion and other proposed experiments will be summarized in the proceedings.



POSSIBLE EXTRATERRESTRIAL ORIGIN OF TERRESTRIAL HOMOCHIRALITY

Figure 5: Possible extraterrestrial origin of terrestrial homochirality.

5 Organic Molecules in Space and the Possible Role of Nearby Supernovae and Neutron Stars

One of the main themes of the Santa Monica meeting was the likelihood that most of the early organic material on earth was brought in by comets and asteroids. Reference 15 gives a nice introduction to this concept.

There are some interesting "large numbers" to consider in this regard:

1) the estimated amount of dust matter in the galaxy is $\sim 0.001 M_G$, or $\sim 10^8$ solar masses, largely in the form of dust grains. A fraction of that material is in the form of organic materials[15];

2) the amount of interstellar dust that has accumulated on the earth (bringing organic material) is poorly known[16, 17];

3) in a molecular cloud of density $10^4 M/cm^3$ and of 1parsec radius, there could be complex organic matter equal to 100 solar masses;

4) the earth revolves around the galaxy with a period of ~ 250 million years. It likely encounters several dense molecular clouds in this trajectory;

5) it is likely that large quantities of organic material were deposited in the earth in the first one billion years.

This information is obtained by the infrared scattering from the dust in the galaxy and by modeling of various UV driven processes here on earth[15]. Ultraviolet photo processing plays an important role in the organic chemistry of the dust particles[16]. (See also Reference 19.)

There are three effects from a supernova II in the primordial cloud that may have formed the solar system:

1.) $\bar{\nu}_e$ emission – with $\bar{\nu}_e + p \rightarrow e^+ + n$ interaction in the hydrocarbon

2.) ν_e, $\bar{\nu}_e$, ν_x, $\bar{\nu}_x$ $(x = \mu, \tau)$) neutrino emission and coherent interaction with the nuclei of the organic materials

3.) intense β emittances like $^{26}A\ell$ formed by supernova – that emit polarized $e^{\pm}$ particles that interact with the organic materials.

Of course, all this time the effect of the weak neutral current can be driving the system towards a homochiral state as the equations 1 and 2.

Let us consider the rate of these effects:

1.) for ν_e absorption and a supernova 1pc away (or inside a 1pc dense cloud) the number of interactions will be $\sim 10^3$/kg of material for $100 M_\odot$ of organic material this would be 10^{12} grams of organic matter that is *active*, the positrons from the ν_e interactions would lose energy at a rate of 10^{-19}MeV/cm and thus travel nearly a parsec.

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 10^{14} grams of *active* material

3.) for the $^{26}A\ell$ – over the half life there would be $\sim 10^{50}$ decays producing $\sim 10^{50} e^+$ that lose energy 10^{19}MeV/cm for MeV e^+, the range of the positrons would be of order a parsec (ignoring possible magnetic field effects).

Consider the example where 0.001 $M_\odot$ of $^{26}A\ell$ is produced and assume for simplicity that the energy of the e^+ is 1MeV and is contained in the gas cloud. Assume the cloud has a density of 10^4 Atoms/cm^3 and that 10^{-3} of the atoms are organic the stopping power for e^+ will be

$$\frac{dE}{dx} \sim \text{MeV/gram/cm}^3 \tag{4}$$

and for a density of $\rho = 10^4 \text{Atoms/cm}^3 \sim 10^{-19}\text{gram/cm}^3$ we find

$$dx \simeq \frac{dE}{\rho}(\text{MeV}) \sim 10^{19}\text{cm} \ (\sim 3\text{par sec}) \tag{5}$$

(we neglect radiation ρ processes and magnetic fields)

and for an average energy exchange of 10eV we have

$$10_e^5 \text{ collisions} / {}^{26}A\ell \text{ decay} \tag{6}$$

For 0.001 M$\odot$ of $^{26}A\ell$ and 10^{-3} organics fraction we obtain a total of $\sim 10^{55}$ collisions of polarized positrons with organic materials in the cloud assuming all the e^+ stop in the cloud. There will also be the same order of polarized photons from the $e^+e^- \rightarrow \gamma\gamma$ annihilation. It is estimated that the asymmetry due to the weak interaction would be of order 10^{-11} to 10^{-6} depending on the positron energy (it scales like $\alpha^2 \left(\frac{v}{\nu/c}\right)^2 \lesssim 10^{-6}$ for $\nu/c \sim 0.1$). Thus it takes N $\sim 10^{22}$ interactions for the asymmetric to become statistically important. In this example there are far more interactions.

6 Future Tests in the Laboratory and Alternative Viewpoints

As a bi-product of the Santa Monica meeting there is now a renewed effort to study the effect of weak interactions on biological materials[18]. Two types of particle physics experiments are being studied:

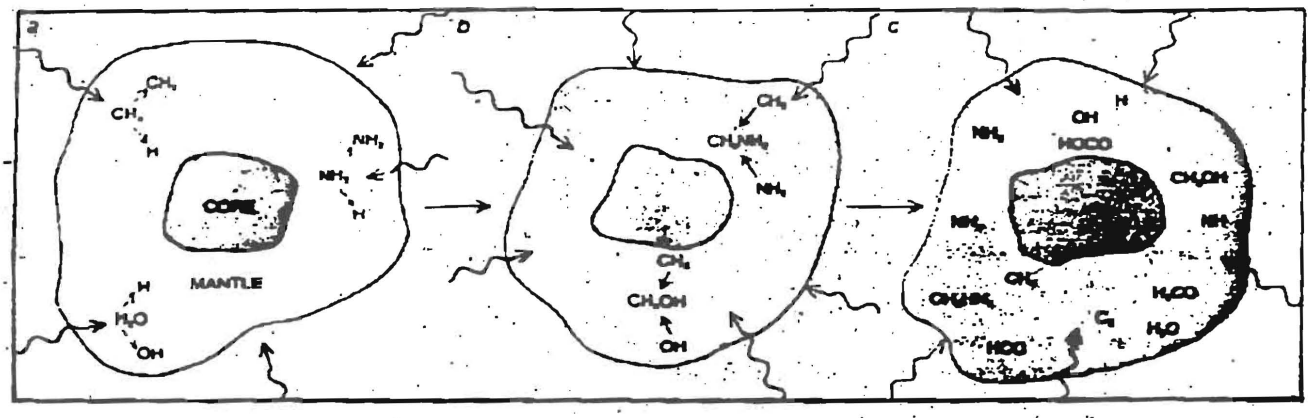
1) with the powerful RF electron guns that provide polarized electrons for the Stanford Linear Collider and other systems, one can imagine a new round of experiments to search for parity violation in biological materials. In this experiment it would be possible to decelerate the electrons to low energy where the effects should be relatively large. A Novosibirsk-UCLA team is preparing a proposal for this experiments.

2) the possible use of reactor anti-neutrinos to simulate the effects of weak interactions, including coherent scattering from the nucleus. (This could simulate the effect of supernova $\bar{\nu}^c$, for example, by taking very long time exposures to obtain an equivalent flux.)

Other terrestrial experiments include searches for homochiral materials in meteorite; experiments with crossed electrical and magnetic fields care purely chemical methods of inducing homochirality.

Another class of extra terrestrial experiment will involve the search for homochiral materials in comets, asteroids and perhaps Mars. It is obvious that, if homochiral materials are found in these systems and all displayed the homochirality as that of living systems on earth, the case for a common physical origin is made much stronger. One intriguing possible experiment would use the Rossetta Mission to a comet, a suggested detector SETH (Search for Extraterrestrial Homochirality) would be the size of a cigar and measure the optical activity of the samples in situ.

We may be entering into a new era where the very foundation of life and the physical forces of nature are seen to have a strong connection.



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 degrees 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).

J.M.Greenberg, Sci.Amer. (1984).

Figure 6:

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