Galactic Distribution of Chirality Sources

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Abstract  
Biochemical processes are known to utilize only one enantiomer, e.g. amino acids used by terrestrial life are generally the left-handed version. The concepts of chirality, optical activity and chiral enrichment are explored in the context of the origin of life in the universe before Earth. Chirality as a feature of terrestrial life suggests neither a special place for local development of homochirality nor for extra-terrestrial enrichment and delivery. Each seems to have some strengths. Chiral enrichment on asteroids or comets could have been promoted via photon polarization or preferential growth on ice mineral faces or both. Chiral enrichment in situ could have occurred via a variety of processes, including zeolite or sulfide surface templating. Stellar and planetary magnetic fields are discussed as well, and a novel mechanism for geomagnetic reversals is introduced based on analogy with stellar processes. Mineral classes and environments are also explored along with four hypothetical scenarios: asteroid/comet delivery; chemical gardens; geothermal fields; and icy worlds.

Keywords  
origin of life, chirality, geomagnetic reversal, chemical garden, circular polarization, optical activity, amino acid

Introduction  
The word habitability has as its root the Latin habitare, to possess or live in. It can imply both meanings—and in this volume, Habitability of the Universe Before Earth, we have access to background information that aims forward—to see which worlds lie beyond our ken and may be inhabited. Universe is also of Latinate origin, whereas galactic and chirality are more obviously Greek: from gala, milk, a description of the milky part of the sky denoting the galaxy wherein we reside, and from cheiros, hand. The latter term, chirality, signifies handedness. It is a geometrical property, a form of variance wherein two forms are symmetrical about a mirror plane.

Take, for example, a certain Cartesian representation of a hand with coordinates \{x, y, z\} that one may find or construct for computer animation. An inversion about the origin would give the new coordinates \{-x, -y, -z\} and even if this new form were rotated about an axis, this new form could not be translated (i.e. moved across) to overlap the original completely. These are left-hand and right-hand varieties. See Figure 1. They are not equivalent, even under rotoinversion. This property is also called chirality, or handedness.
Habitability in its planetary-science meaning is a function of the presence of liquid water. If an environment contains liquid water it can host biochemistry. As other planetary bodies are investigated, this definition for habitability will be updated, e.g. if living organisms were found on Titan, then the definition of habitability would be extended to include liquid hydrocarbons as well. Currently, astrobiology is looking for self-sustaining chemical systems that undergo Darwinian evolution (Mullen, 2013), and for now, this refers to liquid water. For some implications of this NASA definition of living organism, see Table 1.

Table 1. Elements of the NASA definition of living organisms and some implication: Self-sustaining chemical systems that undergo Darwinian evolution.

| Element            | Rationale    | Includes                      | De-emphasizes                                |
|--------------------|--------------|-------------------------------|----------------------------------------------|
| Self-sustaining    | Functional closure | Autocatalytic sets | Heredity and information transfer, Membranes |
| Chemical           | Detectable   | Chemical space                 | Other fundamental forces, Consciousness      |
| Darwinian          | Testable     | Taxonomy                       | Cooperative evolutionary processes            |

**Origin of Life: Overview**

The chemistries important to life processes in organisms involve gradients. Metabolic processes make use of differences in temperature, pH, solute concentrations, electrical charge—separated by space, or by a boundary, in order to express localized results that favor desired outcomes. Environments wherein steep chemical gradients are found in a context of gradients in pH and temperature are candidate examples for an abiogenic origin of life.

The question of life's abiogenetic origin is perhaps solved at thermal vents in *chemical gardens*. Not
only are there gradients in pH, temperature, and solute concentrations suitable to test for autocatalytic sets of chemistries that may evolve to include nucleic acids, but the rudiments of cell walls are also found, as, for example, in the experiments of Barge et al. (2015). See Figure 2. Notwithstanding which functional feature of organisms is more deeply or historically fundamental—whether membrane, metabolism, or heredity—the presence of metabolic processes is inherent in organisms. The ability to transform chemical species from one molecule to another along a pathway of catalytic or enzymatic processes that bypass the slow kinetics of the general environment is very important to life. It is from this that an interest in chirality arises.

![Figure 2. Laboratory grown mineral crust with cell-like forms. Image is approximately 0.1 mm across. Image: Modified from Barge et al. (2015).](image)

Enzymes and catalysts speed the kinetics of individual chemical reactions. By definition, an enzyme is of biological origin, and typically these incorporate metal ion catalysts into their chemical structure. The various forms of chlorophyll, for example, includes a magnesium ion at their center for the process of photosynthesis. See Figure 3. Broadly, enzymes and catalysts make use of molecular surface features and shape for their functionality.
Shape in molecules may be modeled, but these forms are constructed based on experimental data not readily available to the eyes. It is, however, possible to see the handedness of certain chemical species. The class of optically active molecular species are designated as such because of their ability to rotate incident photons that had previously been polarized, referring here to circular polarization. Propagation of photons includes electromagnetic oscillations whose components may cycle in a clockwise or anticlockwise direction around the direction of travel. A molecule that rotates an incident beam of polarized light clockwise (with respect to the source) is a right-handed molecule. Likewise, an anticlockwise rotation (with respect to the source) is designated a left-handed molecule. Measurements are taken using optical interference patterns and determine the rotation.

In biochemical systems, many reactions are homochiral, i.e. they utilize only one of two available chiral form, also called enantiomers. This is especially obvious for enzymes which themselves are proteins whose function relies on shape. Terrestrial living organisms utilize the left-handed form of amino acids, and the right handed forms of sugars and nucleic acids. The other enantiomers are not utilized. Thus, living organisms rely on homochiral populations of molecules for their proper functioning. Table 2 shows a brief outline of what is described above. It is a rationale for searching
out chirality sources within the universe. It can help set a limit to the habitability of the universe before Earth if it is later shown that certain outcomes require a homochiral starting point.

Table 2. Rationale for the importance of chiral sources in the origin of life.

| Object of Interest | Reliance | Feature                      |
|--------------------|----------|------------------------------|
| Metabolism         | relies on... | rapid chemical kinetics.    |
| Rapid chemical kinetics | rely on... | catalysts and enzymes.     |
| Catalysts and enzymes | rely on... | physical shape & chirality.|
| Physical shape & chirality | rely on... | physical processes.        |

Fundamental Forces and Delimitations

For the sake of clarity, a brief outline of the scientific perspective adopted in this chapter is presented below. Objects of study in the present chapter have the following distinction: An object of study falling outside the realm of observation will either be (1) mathematical, i.e. mental objects with reproducible properties; or (2) personal, i.e. mental objects lacking inherently reproducible properties. One reason to emphasize this distinction is to promote a respect for various perspectives. Another is to allow for some speculation within rigorous parameters. See Table 3. For physical objects, reproducibility is a function of scale, time and other parameters. In a strict sense reproducible properties at very fine scale offer challenges in measurement.

Table 3. Realms of Knowledge.

|                       | Physical Objects | Mental Objects |
|-----------------------|------------------|----------------|
| Reproducible          | Science          | Mathematics    |
| Not Reproducible      | (not specified)  | Personal       |

This chapter treats galactic sources of chirality—i.e. where chiral molecules may have arisen in this galaxy. It would be of interest to explore the early formation of the universe directly and identify processes that may have shaped what is here into chiral and achiral forms. Only a brief treatment will be given here: Jagers (2016) presents closure as a critical feature of scale-invariant organization, and specifically discusses the capture of leptons (i.e. the electron) by hadrons (i.e. the proton and neutron) as an example of a structural closure. In this case, it is the atom that is created by this physical enclosure—but only after cooling has allowed for electrons to precipitate from a plasma state. As to which leptons and hadrons were involved in this process is the result of chirality related to the fundamental physical forces they were subject to. See Figure 4. These fundamental forces are the known source of chirality in the early universe. The author wonders, for example, whether different kinds of leptons might have been captured by hadrons in local regions if energy were higher there, and whether these regions would appear different now from our local perspective. Notwithstanding, this is beyond the chapter's scope, as are ideas about what generates the chirality of the hand rules in physics. The text turns towards more immediate considerations.
Comets, Asteroids and Other Interstellar Matter

One mode of abiogenesis involves the delivery of organic materials from interplanetary or interstellar sources. Populations of amino acids exist on asteroids and comets (Elsila et al., 2009; Engel & Macko, 1997). Chirally enriched populations could exist on bodies in this and other star systems in the galaxy, arising from polarized UV photons interacting with optically active materials that are chiral, including amino acids. Meierhenrich et al. (2005) demonstrated that right-polarized synchrotron radiation induced an enantiomer excess of $d$-leucine in solid state; the levo- version was more readily broken down. Thus amino acids on meteorites and comets or in space generally could exhibit an enantiomer excess from high-energy, circularly polarized light extant in space.

During transmission, dust can polarize photons, as for example they pass through nebulae (Bailey et al., 1998). Thus, the distribution of dust may perhaps be a proxy for the likelihood of chiral enrichment of molecules that would interact with high-energy photons. This photonic method of chiral selection is summarized in Table 4. Why homochirality is important to the origin of life is depicted in Table 5. The prevalence of left-handed amino acids in living organisms may indicate a delivery of a homochiral or chirally-enriched left-handed population.

Table 4. Photonic polarization

| Thing                        | Action          | Thing                          | Result                                      |
|------------------------------|-----------------|--------------------------------|---------------------------------------------|
| Photon                       | passes through... | dust cloud.                    | Photon becomes polarized.                   |
| Polarized photon of sufficient energy | interacts with... | optically active chiral molecules. | The population becomes enriched in one enantiomer. |
Again, note that reports that show the distribution of dust within the galaxy, such as that of Drimmel and Spergel (2001) and others may be helpful in determining a likelihood of photonic polarization in different regions of the galaxy. Finally note the following two points: (1) circular polarization due to cosmic microwave background (CMB) radiation is minute or beyond detection (Lubin et al., 1983; Page et al. 2007); and (2) pulsar (and other high energy cascade) magnetospheres are not a source of photons with circular polarization where the contributions of positrons and electrons exactly cancel (Linden, 2015). Thus, galactic distributions of chiral excess due to circularly polarized photons is likely limited to nebular interactions—creating distinct polarity in different galactic regions; and also to dust effects depending on local magnetic fields as planetary and other dusty systems develop.

### Magnetic Fields and Field Reversals

Magnetic fields can trap and influence the motion of dust particles via surface charging of those particles. This influence indicates that magnetic fields may play a critical environmental role in the development of chirally abundant populations of optically active molecules, and hence of chiral organismal building blocks—if delivery of these materials is of interest. This mechanism is described in Table 6.

### Table 6. Photonic polarization in magnetic fields.

| Thing                  | Action            | Thing                  | Result                                      |
|------------------------|-------------------|------------------------|---------------------------------------------|
| Plasma convection      | induces...        | a magnetic field.      | Dust cloud in the field becomes anisotropic.|
| Photon                 | passes through... | dust cloud.            | Photon becomes polarized.                   |

Stellar magnetic fields are caused by convective processes in plasma. A magnetic field reversal process occurs in stars as remanent magnetic flux in active regions (ARs) migrates poleward. It is a surface-flux process that is episodic, but subject to local inhomogeneities in the flux (Sun et al., 2015).

The above may also describe the reversals of planetary magnetic fields. A list of key points in favor of generalizing this type of plasma process to planetary inner cores are given in Table 7. Regardless of a proposed mechanism, magnetic fields of stars, planets and satellites are known to reverse (oscillate) polarity over time. These oscillations should influence the circular polarization of photons traveling through clouds of dust affected by magnetic fields.
Table 7. Two competing inner-core models for planetary bodies that exhibit magnetic fields.

| Observed Feature                  | Solid Inner Core Hypothesis | Plasma Inner Core Hypothesis |
|-----------------------------------|-----------------------------|-----------------------------|
| Transmission of transverse seismic waves. | Yes.                       | Not known. A high-density plasma likely acts as a non-Newtonian fluid. |
| Geomagnetic Field.                | Not known. Geodynamo models all have weaknesses, including modeling reversals and end-of-life. | Yes. Reversals are modeled as stellar reversals; irregular reversal interval is attributable to turbulence processes; end-of-life processes are a result of cooling to below the plasma phase of matter. |
| Chemical phase relations.         | Not known. It is unclear why a solid phase should exist at much higher temperature and pressure than the liquid phase. | Yes. Plasma is the more energetic phase of matter. |

In short, the chirality in amino acids found in asteroids and comets (perhaps deliverable to habitable planets) may be the result of long range or local effects, though local effects seem to dominate. Large-scale polarization of photons affecting an entire galaxy via cosmic background radiation are mostly ruled out. Local effects may be linked to turbulence within plasmas exerting an influence on magnetic fields thereby affecting local photon polarization, or on local effects in situ.

**Crystal Faces and Chirality**

For the creation of homochirality in situ, it is important to look for causes that are extant and plausible. Crystalline materials that rotate photons as they are transmitted are optically active, and many minerals fall into this class. Structurally, there are left- and right-handed varieties of many minerals and many of these can serve as templates for chiral enrichment via adhesion to the face. Hazen (2004) includes most common rock-forming minerals in this category: e.g. quartz, alkali feldspar, clinopyroxene, and calcite. These fall into two classes: (1) minerals whose lattice is chiral (or whose lattice exhibit anisotropic electrical phenomena such as ferro- or paraelectricity), and (2) minerals whose surface expression lacks a mirror inversion plane. Into the first group fall many common minerals and mineral families: alunite, apatite, beryl, cancrinite, epsomite, galena, ice, nepheline, prehnite, pyrochlore, quartz, rutile, serpentine, sodalite, sphalerite, topaz, tourmaline and zeolite (Helman, 2016). Of these, a few are of particular interest in a geologic setting that might be significant to the origin of life:

- Zeolites are porous minerals and are significant because they occur in mid-ocean ridge environments, where the chemical gardens hypothesis of Barge et al. (2015) and others is favored.
- Galena is a sulfide mineral and can be abundant in that environment as well as other geothermal fields.
- Alunite and serpentine are secondary (alteration) minerals and are significant if the origin of life occurs in weathered environments.
- Apatite is of interest as a phosphate mineral, especially considering the importance of phosphorus for cellular metabolism and membranes.
Ice is a prevalent mineral in many planetary bodies and may act as a protonic pump in some occasions, as the most mobile charge carrier in ice is the proton rather than the electron.

Of those whose crystal lattice is not chiral but whose terminations may support chiral enrichment of enantiomers via template processes, calcite is perhaps the most important for its prevalence in aqueous settings (Hazen et al. 2001).

Supposing that this template process is inherently important in the chiral selection processes that occur in situ at life’s origin, one is left with a further difficulty to address: In many environments, chiral forms of minerals are evenly distributed. Exceptions include: (1) local excesses, as shown statistically in some environments, due to seeding effects (e.g. Tamara & Preston, 2009); (2) environments with structural anisotropy; (3) environments with magnetic anisotropy; and (4) highly strained environments.

Deposition of minerals within layers is a description of rock fabric, and many igneous and sedimentary rocks exhibit foliation of minerals, for example, due to primary and secondary depositional processes. Equant mineral grains may dissolve and reprecipitate along structural interfaces over many successions. Likewise, minerals that exhibit magnetic field interactions will orient along geomagnetic flux lines. Orientation of magnetic minerals at the seafloor, for example, is a plausible source of chirality enrichment there. See Figure 5.
Deformation mechanisms can also induce changes to crystal lattices in many forms, including brittle fracture, dissolution / precipitation, crystal plastic deformation, twinning and kinking, dynamic recrystallization, diffusion creep, granular flow, and others (Passchier & Trouw, 1996). Notably, crystal plastic deformation can produce lattice preferred orientation (LPO) in the entire population of a mineral in response to state parameters, e.g. pressure: strain directions. Anisotropic fabric is found in mylonite zones, and in fact many of these oriented rock fabrics are features of deformation zones, such as one would find wherever tectonic activity occurs, e.g. in geothermal fields. Such shock or strain orientation likewise is employed in industry to make anisotropic materials, e.g. permanent magnetics, by aligning magnetic domains via induced strain.
Discussion

A summary of findings from this chapter is given in Table 8. Some scenarios related to an origin of life on Earth are complementary, and a selection of these are listed in Table 9. It is hoped that this brief chapter has served to introduce the reader to some relevant concepts in the habilability of the universe before Earth, and especially of the distribution of sources of chiral bias, and why that might be of interest. It is also hoped that this may help elucidate the specific homochiralities of biochemistry and in the quest to determine whether these were a necessary condition for life on Earth.

Table 8. A list of various processes and sub-processes discussed in the chapter related to chirality and the origin of life.

| Process | Sub-Process | Sub-Process | Sub-Process |
|---------|-------------|-------------|-------------|
| Chiral building blocks are delivered from elsewhere. | Chiral enrichment of building blocks due to photon polarization. | Photon polarizaton due to interaction with dust and dust plus magnetic fields. | Magnetic fields are due to dynamic plasma processes. |
| (As above) | Chiral enrichment of building blocks due to some other local process on the surface of an interstellar body. | | Magnetic fields are due to other processes. |
| Chiral enrichment is local. | Due to crystal-face template processes. | Due to crystal face orientation. | Due to igneous or sedimentary structures. |
| (As above) | Due to some other local processes. | | Due to the influence of a local magnetic field. |

Table 9. Selected hypothetical scenarios presented in this chapter.

| Hypothetical Scenario | Details | Mediating Processes |
|-----------------------|---------|---------------------|
| Chirally-enriched amino acids are delivered via asteroid or comet. | • The near-planet environment is dusty. • High-energy, circularly polarized photons are abundant. | Stellar, planetary and satellite magnetic field strength. |
| Chirally-enriched amino acids are developed in chemical gardens at submarine divergent tectonic boundaries. | • Chiral mineral surfaces are abundant from depositional foliation and magnetic anisotropy. | Abundance of minerals such as sulfides, zeolites, alteration minerals, and others. |
| Chirally-enriched amino acids are developed in | • Chiral mineral surfaces are abundant from depositional and | Abundance of minerals such as quartz, alteration minerals, sulfides, |


### Hypothetical Scenario Details Mediating Processes

| geothermal fields. | deformational anisotropy. | and others. |
|-------------------|--------------------------|-------------|
| Chirally-enriched amino acids are developed on icy worlds. | • Anisotropic mineral surfaces are abundant in ice, as is modest electricity. | • Abundance of minerals such as water ice and salts. |

### Summary

Chirality as a feature of terrestrial life suggests neither a special place for local development of homochirality nor for extra-terrestrial enrichment and delivery. Each seems to have some strengths. Chiral enrichment on asteroids or comets could have been promoted via photon polarization or preferential growth on ice mineral faces or both. Chiral enrichment in situ could have occurred via a variety of processes, including zeolite or sulfide surface templating. The possibilities were outlined in the article to clarify these and other scenarios.

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