Origin of Chirality in the Universe

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Louis Pasteur was a French scientist of the 19th century with a passion to make a lasting contribution to science. In 1848, he postulated that a compound called racemic acid formed two distinct types of salt crystals due to some structural difference between the molecules the acid was composed of. He made solutions of the two different salt crystals and shone polarized light--light whose waves only move in one directional plane--through both, and found that each solution caused the light's direction to rotate an equal amount, but in opposite directions.

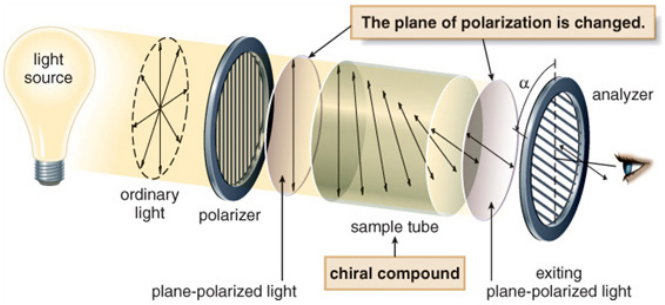


Figure 1. : Chiral compound rotating plane-polarized light.

His original postulation was later confirmed with the discovery of enantiomers, or molecules composed of the same atoms but with structures that are not the same, yet are mirror images of each other. (Newton, 2012) Such molecules are said to exhibit chirality. Sometimes, each enantiomer of a chiral pair is called "left-handed" or "right-handed," since human hands are also non-identical mirror images of each other.

Chirality and optical activity--the ability of chiral molecules to rotate plane-polarized light--may seem like minor details that only chemists and maybe physicists would be concerned with. However, one simple difference in molecular geometry, even just switching the position of two atoms relative to the other ones in a molecule, can drastically change its properties. Some can be harmless, like in carvone: the right-handed enantiomer smells like caraway seeds, but the left-handed one smells like peppermint. Other times, the switch can have less benign effects: for the molecule thalidomide, the left-handed enantiomer relieves morning sickness, but the right-handed one induces birth defects (Schirber, 2009).

Taking these differences as examples, it may not seem surprising that chiral molecules in organisms exist almost exclusively as single enantiomers. In a lab, most syntheses will yield the left- and right-handed enantiomers in equal amounts, but in fact, most enantiomers in nature exist in the left-handed form (Blackmond, 2010). Finding the origin of the increased left-handed and decreased right-handed concentrations is vital to understanding life. Finding out which chemical reactions sparked the creation of life on Earth can tell us what we might want to expect from life on other planets. Will they be left-handed molecules, like on Earth, or will their structures — and thus their characteristics — be completely different? Most scientists believe that homochirality is a precondition for life, with the argument that one hundred left- or right-handed gloves arranged in a sequence would have a well-defined structure, whereas a random mixture of both would be a mess if you tried to arrange them in a similar sequence (Schirber, 2009).

To attempt to account for the homochirality of biological molecules, scientists have created models that amplify an initial imbalance between the amount of two enantiomers in a system, which results in very large amounts of one enantiomer. These models are meant to model an amplification that, over time, may have resulted in the enantiomeric excess that we observe today. Proposed model systems include small initial imbalances in meteorites or other extraterrestrial sources, as well as random fluctuations in the physical and chemical environment that might account for a preference towards left- or right-handed molecules. Regardless of whether the excess was started off by chance or by design, an amplification mechanism is useful in understanding how the excess of left-handed enantiomers in our world got to this point (Blackmond, 2010). This article explores a few notable mechanisms that may explain the asymmetry in chirality in our world.

In 1966, David Cline, a professor at UCLA at the time, proposed a model by which organic materials, or carbon-containing compounds, were delivered to Earth from an interstellar source, such as meteorites (Cline, 1996). The homochirality observed in organic molecules may be a result of interactions with radioactive decay or supernova explosions in a dense molecular cloud. Chiral subatomic particles resulting from beta decay or effects of weak currents promotes asymmetric dominance, but this is on a very small scale. The amplification of this small asymmetry happens though a bifurcation process over a long period of time, or when a large number of these interactions happen over a short amount of time. Often, both may occur. The latter arises when radioactive decay or supernova explosions occur

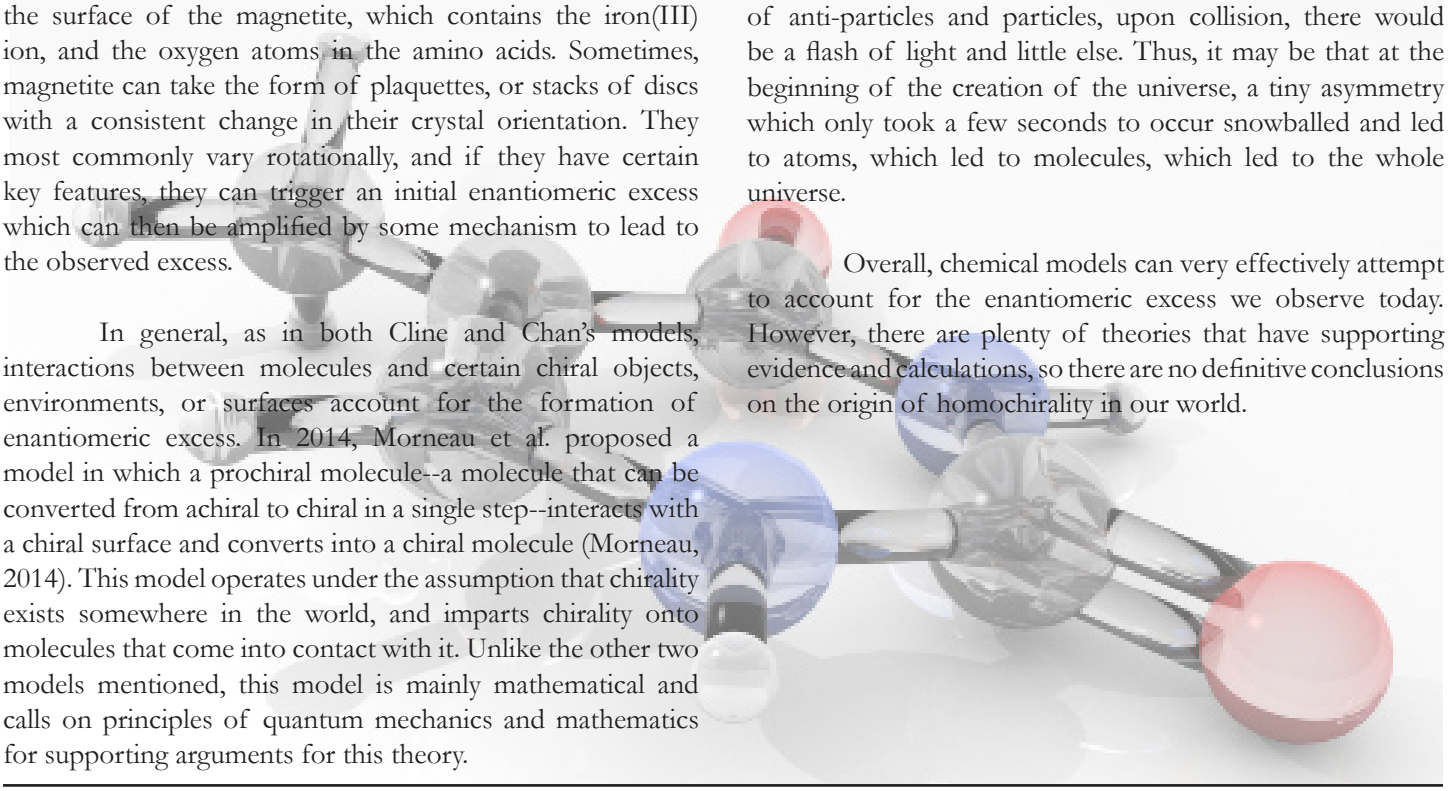
very close to a dense molecular cloud, causing intense chiral impulses, in which a large amount of molecules in the cloud actually become chiral.

Another model developed this year at Harvard and presented at the 78th Annual Meeting of the Meteoritical Society in Berkeley this summer also cites space as the source of chiral molecules on Earth (Chan et al., 2015). Magnetite is an iron oxide mineral that is the most magnetic of all naturally-occurring minerals on Earth. Its magnetic properties allow it to catalyze the formation of amino acids found in certain meteorites. Electrostatic forces, or the attractions and repulsions between charged particles, occur between the surface of the magnetite, which contains the iron(III) ion, and the oxygen atoms in the amino acids. Sometimes, magnetite can take the form of plaquettes, or stacks of discs with a consistent change in their crystal orientation. They most commonly vary rotationally, and if they have certain key features, they can trigger an initial enantiomeric excess which can then be amplified by some mechanism to lead to the observed excess.

In general, as in both Cline and Chan's models, interactions between molecules and certain chiral objects, environments, or surfaces account for the formation of enantiomeric excess. In 2014, Morneau et al. proposed a model in which a prochiral molecule--a molecule that can be converted from achiral to chiral in a single step--interacts with a chiral surface and converts into a chiral molecule (Morneau, 2014). This model operates under the assumption that chirality exists somewhere in the world, and imparts chirality onto molecules that come into contact with it. Unlike the other two models mentioned, this model is mainly mathematical and calls on principles of quantum mechanics and mathematics for supporting arguments for this theory.

A new theory developed by Alexander Kusenko diverges from previous ones; according to Kusenko, an asymmetry that was present at the formation of the universe propagated the large amounts of asymmetry in chiral molecules that we observe today (Kusenko, 2015). For every 10 billion anti-particles, this theory proposes, there are 10 billion and one particles. Particles are slightly more energetically efficient than anti-particles, so anti-particles are converted into particles in order to be as energetically favorable and efficient as possible. This leads to an asymmetry in the ratio of anti-particles to particles, and the particle creation over time led to everything else in the universe. According to Kusenko, such asymmetry is necessary for creation, because if there were an even number of anti-particles and particles, upon collision, there would be a flash of light and little else. Thus, it may be that at the beginning of the creation of the universe, a tiny asymmetry which only took a few seconds to occur snowballed and led to atoms, which led to molecules, which led to the whole universe.

Overall, chemical models can very effectively attempt to account for the enantiomeric excess we observe today. However, there are plenty of theories that have supporting evidence and calculations, so there are no definitive conclusions on the origin of homochirality in our world.



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