Polarized starlight and the handedness of life

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Abstract:
An international team of scientists has come up with the plausible theory that polarized starlight present during the formation of the earth may have something to do with the asymmetry of amino acid molecules in all living things. The group arrived at this startling conclusion after analyzing the birthplaces of stars by determining the oscillating electric field related to the faint light gathered by giant telescopes. The scientists postulate that dust grains can generate circularly polarized starlight at the ultraviolet, visible and infrared wavelengths, resulting in an enantiomeric excess.

Full Text:
The asymmetry of the amino acid molecules found in all living things may have originated in space billions of years ago We are all made of star dust. This assertion is so well known that in some circles it has become a cliche. It refers to the fact that just after the Big Bang (between 10 and 15 billion years ago-cosmologists are still not quite sure) the universe contained mostly hydrogen and helium, with just traces of lithium and beryllium. All other chemical elements have since been forged either in the nuclear furnaces at the center of stars or in titanic supernova explosions. Hence, scientists have long appreciated that our bodies, which are built mainly of oxygen and carbon, are mostly recycled star dust.

Now, an international group of investigators, of which I am privileged to be a member, may have uncovered another link between biology and astronomy. We determined that the nature of the starlight present when the earth first formed may be responsible for the curious asymmetry, or "handedness," of the amino acids now found in living things. And appropriately enough - although completely unexpectedly - the key observations came from our efforts to study star dust.

Our team was probing the birthplaces of stars by measuring the orientation of the oscillating electric field associated with the faint light gathered by giant telescopes. Hot objects such as stars emit many different light waves, with no correlation in the direction of oscillation of their electric fields; that is, the orientations of the individual electric-field vectors are essentially random. Such light is said to be unpolarized. But certain processes, such as the scattering of the light from dust grains, give rise to uniformity among the electric vectors of the component waves. If all waves oscillate back and forth in the same direction, the ray of light is said to be linearly polarized. If the orientation of the electric field rotates as it oscillates so that it spirals around the direction of propagation, the light is termed circularly polarized.

In the 1920s and 1930s, scientists determined that circularly polarized light has a peculiar effect on amino acids, which are (for the most part) chiral molecules in that they come in two mirror-image versions, or enantiomers. Although both enantiomers occur in equal proportions when amino acids are synthesized in simple laboratory reactions, living things typically use L (laevorotatory, or "left-handed") amino acids instead of their counterparts, the D (dextrorotatory, or "right-handed") variety. The names for the two types of amino acids, although now based on chemical structure, came originally from the way they rotate linearly polarized light passing through a solution containing them. Louis Pasteur discovered this optical property of chiral organic molecules more than a century and a half ago.

There are hundreds of different amino acids, but only 20 of them are found in living things. These small molecules link to form peptide chains, which themselves fold up into proteins, the large molecules that catalyze reactions and serve as structural components in cells. Certain D amino acids are found in bacteria, but nearly all proteins are built exclusively of L amino acids. Sugars - an essential part of nucleotides, the building blocks of DNA and other important nucleic acids - also have chirality, with living things using only the D variety. According to current conceptions about the origin of life, the adoption of one enantiomeric configuration or the other appears to be an absolute prerequisite for molecular self-reproduction. Yet how the uniform handedness of life first came about has been one of the great mysteries of science.

Light and Life Like chiral organic molecules, circularly polarized light comes in either left- or right-handed versions, depending on whether the electric-field vector corkscrews clockwise or counterclockwise as the light propagates. Because illumination with circularly polarized light of one type can preferentially destroy molecules of one handedness, some scientists have wondered whether this process could account for the asymmetry now seen in living things. Yet no one has been able to figure out how just right- or just left-circular polarization could have arisen on the early earth (or in the atmosphere) when life first evolved. The lack of terrestrial sources for circularly polarized light of only one kind led Stanford University chemist Edward Rubenstein and three of his colleagues to propose in 1983 that the enantiomeric excess seen in living things may have originated elsewhere in the cosmos. As remarkable as this notion seemed, there was some evidence to back up their arguments in the form of a meteorite that fell in 1969 near Murchison in Victoria, Australia.

This particular rock from outer space turned out to be extraordinarily rich in organic molecules. And a year's worth of study of the Murchison meteorite, as it was dubbed, revealed a remarkable fact: Some of the organic compounds it contained were amino acids, and like the amino acids found on earth, they showed an enantiomeric excess of the laevorotatory variety. Confusion followed because some experiments appeared to deny this conclusion and because some scientists believed that the measured excess was merely an artifact of terrestrial contamination.

The 27-year-old debate was finally settled in 1997, when Michael Engel of the University of Oklahoma and Stephen Macko of the University of Virginia studied samples of the amino acids alanine and glutamic acid extracted from the Murchison meteorite. By measuring the ratio of nitrogen-15 to nitrogen-14 in these materials, Engel and Macko firmly established that little or no terrestrial contamination had taken place. Terrestrial sources would have given a characteristic ratio, but their samples were enriched in the heavier isotope. Their analysis of the Murchison meteorite also showed L-alanine was twice as abundant as its mirror image and that L-glutamic acid was three times as abundant.

So it is now almost certain that the solar system formed with an excess of L amino acids. The recently launched space probe Stardust, which will return comet samples during the first decade of the next millennium, may put all doubts to rest if that material shows an excess of left-handed amino acids. But scientists would still want to know where these molecules originally formed and how the enantiomeric excess was created in the first place. Engel and Macko's nitrogen-isotope ratios offer an important clue, because they are similar to the values for interstellar material that astronomers have determined from spectroscopic observations. So it would seem that the amino acids in the Murchison meteorite were made from atoms that were once part of an interstellar cloud of dust and gas.

Understanding how such interstellar flotsam can wind up on earth requires some appreciation for what astronomers see elsewhere in the cosmos. About half of the interstellar matter in our galaxy is spread diffusely through space; the other half is clustered together, forming giant molecular clouds. Several thousand such concentrations pepper the Milky Way, and each one can measure up to 250 light-years across. These accumulations principally contain molecular hydrogen (about 75 percent) and helium (about 23 percent). The remaining 2 percent contains all of nature's other chemical elements.

Even at the frigid temperatures of outer space, hydrogen and helium are not capable of freezing solid. So the dust particles found in space are mostly made of other elements. Carbon and oxygen are relatively common along with nitrogen, neon, sulfur, magnesium, argon, silicon and iron. These grains can act as catalysts for chemical reactions: Atoms and molecules can bond to the surface of a dust particle and be held in storage until other atoms or molecules collide with that grain, creating new and ever more complicated compounds. Energy released by a collision will sometimes kick the resultant molecule off the grain so that it then becomes part of the interstellar gas. Astronomers have used radio telescopes to detect the telltale emissions from many kinds of compounds in giant molecular clouds including carbon monoxide, ethanol and cyano-tetracetylene (although as yet they have not detected amino acids).

A complex molecule floating freely in space would normally be destroyed by the ultraviolet radiation emanating from massive stars nearby. But the dust in giant molecular clouds serves as a protective shroud, scattering and absorbing ultraviolet rays before they travel too far. The effectiveness of this screening depends on the density of the dust and the wavelength of the light involved. The variation in penetration as a function of wavelength helps astronomers to probe molecular clouds, which are largely opaque to ultraviolet radiation but nearly transparent to infrared light and radio waves.

Astronomers are curious to study dusty regions of space because almost all the stars in the galaxy began their lives in just such places. As gas in one of these clouds coalesces into a star, the surrounding particles are naturally dragged along with it, wrapping the nascent star in a dusty cocoon. The contracting sphere of dust and gas invariably has some component of rotation. So as it collapses, it conserves its angular momentum by spinning faster. This rotation stretches the dusty orb into a large pancake. At the center of this disk, the young star finally takes shape.

A typical dusty disk formed in this way is 1,000 Astronomical Units (AU) in diameter and perhaps a few hundred AUs thick. (One AU equals about 150 million kilometers, the distance between the earth and the sun.) The Hubble Space Telescope has also revealed some spectacular examples of such star-forming regions, showing them as silhouettes against a brightly glowing background of gas.

According to theory, an embryonic star will have accumulated most of its mass by the time it has developed a thick envelope of dust and gas. Some of the material in this large sheath will ultimately end up in the star or in surrounding planets. But much of this diffuse matter will be ejected from the system entirely, propelled outward along the spin axis of the giant disk by forces that are only partially understood.

The jets of gas that shoot in opposite directions away from the disk sweep away much of the obscuring dust, allowing light from the young star to stream into distant reaches of space for the first time. But the large envelope still absorbs all rays of light in the plane of the disk, restricting the illumination to two searchlight beams, which shine in opposite directions. Some of the photons in these beams scatter off the dust grains entrained in the outflow. So when astronomers peer into the regions where stars are being formed, they see illuminated clouds, called reflection nebulae, that signal the presence of young stars nearby, even if clouds of dust have rendered those stars invisible.

Polarized Debates

Astronomers interested in reflection nebulae often use a technique that relies on polarized light to locate the position of the young stars responsible for the diffuse glow. Although originally unpolarized, the light from these stars scatters off dust grains, which impart a linear polarization that one can measure with a device called a polarimeter. When the orientations of the electric fields determined with a polarimeter are superimposed on an image of a reflection nebula, the electric vectors will tend to outline the central source of illumination with concentric rings.

Deviations from this simple pattern sometimes occur, indicating that other forces are at work. There may, for example, be multiple light sources distributed within one nebula, or there might be elongated dust grains in the path, which can alter the polarization of the scattered light. Untangling these complications is the job of theoreticians, who build computer models of reflection nebulae and scatter virtual photons through them.

Along with several colleagues at the University of Hertfordshire, I spent much of the last decade devising various computer simulations of light scattering in reflection nebulae. We were forever on the lookout for new ways to test our theoretical models, and the possibility of using circular polarization presented itself in the middle 1990s. It was clear from our computations that, regardless of what happens in the outer, relatively transparent parts of a reflection nebula, some of the light must scatter several times in the thick blanket of dust close to the young star So the light entering the nebula as bipolar beams could already be linearly polarized. In this case, a second or subsequent scatter could make some of the light become circularly polarized. All we needed to detect it was a slightly modified polarimeter, which my colleague James Hough designed and built at the University of Hertfordshire. At this point, we were blissfully unaware of the enantiomeric excesses of the Murchison meteorite and the notion that circularly polarized light might have had an important influence of the origin of life. We would stumble upon those issues only by accident.

Our circular polarimeter was commissioned at the Anglo-Australian Telescope in New South Wales, Australia in May 1995 using the infrared camera there. Its first trials were marred by bad weather. Under gloomy, cloud-filled skies we were growing increasingly despondent but managed a few hours of observation, enough to catch a glimpse of GSS30, a young, dust-enshrouded star in the constellation of Ophiucus. About two percent of the light scattering from this reflection nebula was circularly polarized - about what we would have predicted from our computer models for interstellar dust grains. Both directions of circular polarization were present, but they were segregated from one another, and the light for each appeared to be coming from different parts of the nebula. During subsequent runs we pointed the telescope toward Monoceros, Corona Australis, Cassiopeia and Taurus, and we found that some nebulae did not produce circularly polarized light, whereas others showed circular polarization at the 1-to-2 percent level. But the real surprise awaited us in Orion.

The Orion nebula is one of the most famous objects in the night sky, a fuzzy patch of gas that represents the nearest place to earth where massive stars are forming. In a sense, it is a keyhole into a much larger giant molecular cloud, and using infrared light astronomers can see through that closed door. One young star there (named IRc2) illuminates a reflection nebula. Using the polarimeter designed at Hertfordshire, my colleague Antonio Chrysostomou discovered that them are distinct patches around IRc2 in which the amount of circular polarization reaches almost 20 percent. Finding this amount of polarization stunned all of us. Subsequent observations by another of our collaborators, Francois Menard of Grenoble University, found similarly large percentages in another star-forming region called NGC6334V.

Too Much of a Good Thing?

These surprising results begged for a theoretical explanation. Yet the more my coworkers and I examined our computer models for light scattered off spherical grains, the more it became obvious that such particles are incapable of generating the amount of circular polarization we had observed - unless something extreme taking place close to the central stars is sending very high percentages of linearly polarized light into the surrounding nebula. This possibility could almost certainly be ruled out, because linear polarimetry would have shown the signature of such high source polarizations.

Everyone on the team was puzzled until my colleague Alan McCall hit upon an idea buried in some older astronomical literature: What if light were scattered from elongated dust grains aligned by a magnetic field close to the star? Working closely with Tim Gledhill, also of the University of Hertfordshire, McCall showed that this configuration can indeed produce large circular polarizations, even if the light being scattered is completely unpolarized to start with.

The biggest epiphany in this work, however, came when our longtime collaborator Jeremy Bailey of the Anglo-Australian Observatory realized just how profoundly this discovery might affect ideas about the origin of life and the possibility that the enantiomeric excess of amino acids on earth could have originated in interstellar space. He reasoned that our observations of infrared wavelengths implied that polarized ultraviolet light might also exist in these places. If so, it would preferentially destroy amino acid enantiomers of one type in the nearby interstellar medium, leading to an excess of the other variety. What is more, the circularly polarized light would be located in exactly the spot where the excess would have the most direct influence on young planets: inside molecular clouds where new solar systems are actively forming.

Our subsequent theoretical work suggests that dust grains can indeed generate circularly polarized radiation at both visible and ultraviolet wavelengths, as well as in the infrared. We hope eventually to test this result directly, by studying those reflection nebulae that can be seen at optical wavelengths, but for the moment we remain confident in our conclusion.

Still, other scientists have questioned whether the circularly polarized light created in this way would really produce an enantiomeric excess. Their concern arises because the interaction of polarized ultraviolet light with chiral molecules is rather complex. Right-circular polarization does not always destroy right-handed molecules; nor does left-circular polarization always destroy left-handed molecules, as one might assume. In reality, the sense of the effect switches back and forth in adjacent wavelength bands. Hence, illumination with a sufficiently broad range of wavelengths would provide no selectivity, because both varieties would be affected equally.

We surmise that the relevant illumination does not span much of the spectrum. Most light in space has wavelengths greater than 200 nanometers, because stars radiate comparatively little at shorter wavelengths. (For example, the flux of light at a 150-nanometer wavelength typically drops by two orders of magnitude from that at 220 nanometers.) And any light with wavelengths greater than about 230 nanometers would have too little energy in its photons to break up organic molecules. So only a narrow range of ultraviolet wavelengths matters, and in this thin slice of the ultraviolet spectrum circularly polarized light of one handedness should, in theory, destroy just one type of enantiomer.

Chemists have conducted laboratory experiments to demonstrate that light of this kind does indeed have a selectively destructive effect; thus we believe that the same mechanism must operate in space. And because different sections of molecular clouds are illuminated by opposite types of circular polarization, both L and D enantiomers could become enhanced in different and widely separated parts of these star-forming regions. If so, a lopsided mix of enantiomers would undoubtedly be delivered to any planets forming there.

The greatest influx of organic molecules would occur early on, but they would probably be destroyed by the heat and shock of the impacts that brought the material together. Only after the planetary bodies formed atmospheres would organic material have an opportunity to settle comparatively gently, as the remaining comets and asteroids circling these stars were being mopped up through ongoing collisions. Geochemists believe that a large fraction of the volatile material on earth was brought to our planet during this so-called late bombardment phase. Some scientists argue that fragile organic molecules would be destroyed by such collisions, but, clearly, the presence of organics within the Murchison meteorite suggests that many would survive.

One thus expects that planets forming around stars in regions bathed in ultraviolet light with high circular polarization will naturally incorporate amino acids with enantiomeric excesses of one sort or the other. The same probably held true for our own world some five billion years ago. So if robot probes ever discover carbon-based organisms on other planets or moons in the solar system - even if these life forms evolved completely independently of earth - chemical analyses will probably find that they were influenced by the same primordial bias and now contain L amino acids and D sugars, just as we do. But on some of the more distant worlds orbiting faraway stars, if carbon-based life exists at all, mirror-image biochemistry could well be the rule.

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Links to Internet resources for further exploration of "Polarized Starlight and the Handedness of Life" are available on the American Scientist Web site:

http://www.amsci.org/amsci/articles/99articles/clark.html

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