Did exploding stars shatter life's mirror?

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MR SPOCK is dying. Fortunately for the crew of the USS Enterprise, the Spock in question is not the real one, but an evil mirror-image version created in a freak transporter malfunction. This Spock's back-to-front body can digest only right-handed amino acids; meanwhile, like all organic matter, the food around him is made of left-handed amino acids. He is starving in the midst of plenty.

This plot line from the 1970 novel *Spock Must Die!* - the first literary spin-off from the *Star Trek* TV series - highlights one of life's fundamental mysteries. Why does biology use only one of two mirror-image forms in which most complex molecules can occur? The latest pop at an answer weaves astrophysics, particle physics and biochemistry into a startling proposal: that the stellar explosions known as supernovae are to blame.

"It is an intriguing idea," says Daniel Glavin, an astrobiologist at the NASA Goddard Flight Center in Greenbelt, Maryland. It is certainly a novel turn in this twistiest of tales: the story of how life came to be left-handed.

The property of handedness, known to chemists as chirality, is a feature of many molecules whose arrangement of atoms is not completely symmetrical. A chiral molecule comes in two forms that are rather like a pair of gloves. Right and left-handed gloves are essentially identical, with the same basic components, four fingers and a thumb, and the same function of keeping our hands snug and protected. They are not exactly the same, however: you cannot rotate or flip a glove of one type so that it will superimpose perfectly on the other. But look in a mirror, and a left-handed glove becomes right-handed.

Similar molecular mirror-image forms are called enantiomers. They are made from the same atoms and have the same chemical and physical properties. Most chemical reactions produce equal quantities of both.

That makes nature's predilection for one form - its "homochirality" - all the more strange. Only left-handed or "l" amino acids make up the proteins that provide our cells with structure and regulate their functions, and only right-handed or "d" sugars play an active part in biochemistry. It is like keeping a drawer full of only one sort of glove, while stubbornly refusing to wear the other.

Star turn

Perhaps homochirality is the result of a chance asymmetry in life's early history on Earth, amplified by time and evolution. In that case, you might expect it to be non-existent or even reversed elsewhere. Yet the builder's rubble left over from the construction of the solar system tells a different story. "For every type of amino acid found in meteorites there is an excess of the left-handed form over the right-handed of between 2 and 18 per cent," says Uwe Meierhenrich of the Nice Sophia Antipolis University in France. "An excess of the right-handed form has never been found."

Life's asymmetry might have started on Earth - but rubble left over from the solar system's construction tells another story

That alone does not prove anything: meteorites might have become contaminated when they came into contact with the Earth's surface and before they were picked up. But the strong implication is that the left-handed bias pre-dates the existence of life, our planet and indeed our solar system, even if life on Earth amplified it to an extreme.

So is the asymmetry simply a question of basic physics? That is certainly a possibility (see "Disturbance in the force"), but there are other attractive suggestions too. One was identified in 1998, when a team led by Jeremy Bailey of the University of New South Wales in Sydney, Australia, discovered regions in the Orion nebula, a star-forming zone 1300 light years away from Earth, that are suffused with circularly polarised infrared light (*Science*, vol 281, p 672).

Light becomes circularly polarised when its associated electric field vibrates in a plane that rotates clockwise or anticlockwise about its direction of travel. In a nebula, such polarisation could happen when light is scattered off the atoms and molecules, including amino acids, floating around in the gas clouds.

Circularly polarised light interferes with the arrangement of electrons that bind atoms together in such a way that it can selectively break up molecules of one or other chiral form, depending on which way it is rotating. The regions of the Orion nebula identified by Bailey and his colleagues could therefore have an excess of one form of amino acid. A similar situation in the cloud from which our solar system formed could have been the chiral seed from which asymmetric life on Earth grew.

It is a seductive possibility, but it has its problems. The selective destruction of amino acids only kicks in if the light has enough energy to trigger the necessary chemical reactions - in practice requiring the presence of ultraviolet light, rather than the less energetic infrared light seen in the Orion nebula. "No one has detected any of this light yet," says Meierhenrich - although this might be because the gas clouds scatter ultraviolet light so effectively that little of it makes it to our telescopes.

The new scenario sketched by Richard Boyd of the National Ignition Facility in Livermore, California, along with Toshitaka Kajino and Takashi Onaka of the University of Tokyo, Japan, sidesteps this problem. It too starts with a cloud in which molecules, including amino acids, have already formed. But light is not the catalyst for change; instead, it is the combined effect of the immense magnetic fields and the vast fluxes of high-energy particles that are produced in a supernova explosion.

A core-collapse, or type II, supernova occurs when a massive star, its fuel spent, collapses within seconds under its own weight to form a superdense neutron star just tens of kilometres across. This remnant generates an incredibly intense magnetic field, with field lines emerging from its north pole and returning to its south pole, as is the case with Earth's magnetic field.

Atomic nuclei have a quantum-mechanical property known as spin which, all things being equal, aligns itself with a magnetic field. The crux of Boyd's idea is the effect such magnetic fields have on nitrogen-14 nuclei in an amino acid, where a nitrogen atom attaches the defining amine (NH_2) group to a carboxyl group. Within a molecule, nitrogen spins do not have the latitude of movement they would if they were free, and calculations performed by the chemist A. D. Buckingham of the University of Cambridge in 2004 show how switching on a magnetic field in fact produces a rotational effect in different directions for molecules of opposite chiralities (*Chemical Physics Letters*, vol 398, p 1).

As a result, Boyd suggests, when the magnetic field of a supernova remnant starts up, amino acids of one chirality end up with their nitrogen spins pointing along the magnetic field lines, away from the star at the north pole and towards it at the south, while those of the opposite chirality will be forced to align with their nitrogen spins in the opposing direction.

This sets the stage for fireworks as the dying star collapses in on itself, sending an intense blast of neutrinos and antineutrinos spewing out radially in all directions, including along the magnetic field lines. Antineutrinos in particular react readily with nitrogen-14 nuclei, producing a carbon-14 nucleus and a positron. In a similar, energetically less-favoured reaction, neutrinos turn nitrogen-14 into oxygen-14 and an electron. In both cases, once the nitrogen nucleus in an amino acid is hit, the amine group is blown apart and the amino acid disintegrates.

Black hole sun

There is a caveat. Reactions in nature like to conserve spin: they occur more readily if the total magnitude and direction of the spin is equal before and after the reaction. Nitrogen-14 nuclei have a spin of magnitude 1, whereas carbon-14 and oxygen-14 nuclei have no spin. Electrons, neutrinos, positrons and antineutrinos have a spin of magnitude ½. To add to that, the spin of an antineutrino always points in its direction of travel, whereas that of a neutrino points against.

A few more quantum niggles complicate the calculations, but in essence spin conservation means that a neutrino or antineutrino is more likely to blast apart an amino acid whose nitrogen spin points in the opposite direction to its own. The end result is that around one pole, amino acids of one chirality are preferentially shot apart by antineutrinos while neutrinos do something similar to amino acids of the opposite chirality gathered around the other pole, but to a lesser extent as this reaction is energetically less likely. That creates an overall chiral imbalance in the environment of the supernova remnant (arxiv.org/abs/1001.3849).

This, think Boyd and colleagues, is the origin of the chiral preference shown not just in life, but also in the meteorites that have landed on Earth. "The stuff from which our solar system formed was processed by neutrinos from many supernovae," says Boyd. "But they all selected more left-handed amino acids than right-handed ones."

The mechanism is not without its catches. One is that a hail of high-energy gamma-ray photons produced by the supernova explosion could blast apart all the amino acids far and wide, leaving nothing from which to create a chiral imbalance. There is a way round this problem, though, if the remnant created in the supernova is not a neutron star but an even more extreme entity - a black hole.

"This happens in plenty of cases," Boyd says. A black hole simply sucks in light as it forms, eliminating the gamma-ray problem. "If we are right, we owe the left-handedness of amino acids on Earth to the action of black holes."

It is a daring suggestion, but one that so far has raised surprisingly few objections. One is that the size of the asymmetry produced is small. But that might be all that is needed, says Meierhenrich. He points out that experiments have shown that an initial chiral asymmetry of between 1 and 5 per cent can be amplified by "autocatalytic" chemical processes, in which a small excess of one chiral form encourages the production of more of that form.

This is unlikely to happen around a supernova. "The amplification requires a liquid environment like that found in watery asteroids or on the early Earth," says Glavin. So a process that started in a supernova would still have to be finished closer to home.

But are all the chiral twists and turns of this story strictly necessary? A mechanism that involves creating a chirally balanced sample of amino acids, and then selectively destroying them, does seem excessively complex. Why can't we just make a chirally imbalanced amino-acid sample in the first place?

Perhaps we can. One promising alternative explanation for life's handedness is based on the fact that, for every 99 atoms of the isotope carbon-12 that go into making organic molecules, there is one atom of the heavier carbon-13. In April 2009, Tsuneomi Kawasaki and colleagues from Tokyo University of Science in Japan showed that this small natural asymmetry could trigger an autocatalytic process that resulted in an organic product with noticeable chiral asymmetry - although it remains to be seen if this is also true for amino acids (*Science*, vol 324, p 492).

Meierhenrich is following another possible lead. Asked by the European Space Agency in 1997 to design an instrument that could distinguish the two chiral forms of amino acids for its Rosetta probe, which blasted off for a nearby comet in 2004, he and his team tested it by making a "microcomet" from carbon monoxide, carbon dioxide, methanol, ammonia and water. When they mimicked the conditions of outer space by irradiating it with ultraviolet light in a vacuum chamber held at a temperature of 12 kelvin, they found they created 16 different amino acids, in a mixture of right-handed and left-handed forms (*Nature*, vol 416, p 403).

Core question

The team is now planning to blast the samples with circularly polarised ultraviolet light from the newly constructed Soleil synchrotron light source near Paris, France. They hope this will make a chirally imbalanced sample, adding evidence to the idea suggested by Bailey and his colleagues 12 years ago.

With several mechanisms still in the running, it is too early to call an end to the homochirality debate. The next round should begin in 2014, when the Rosetta probe is due to rendezvous with the comet 67P/Churyumov-Gerasimenko. It will dispatch a lander that will drill and analyse a 20-centimetre-deep ice core from the comet, providing a sample of material from the solar system's beginnings guaranteed to be free of contamination, unlike a meteorite that has landed on Earth.

If the amino acids it finds all show a left-handed bias, that would be grist to the mill of Boyd and others who suggest supernovae are behind the asymmetry. If some amino acids are predominantly left-handed and some right-handed, then it might be possible to find a single energy of circularly polarised ultraviolet light that is to blame, putting Bailey's model squarely back in the frame.

Secretly, however, Meierhenrich hopes for another outcome. "Wouldn't it be great if all the amino acids we found were right-handed?" he says. "None of the proposed mechanisms would work then."

Someone else would be pleased with that, too. If homochirality really is a twist specific to life on Earth, somewhere out there a mirrored Mr Spock might find a world in which he could live long and prosper. n

Disturbance in the force

Is homochirality just an illusion? That could be the message from calculations of molecular energies that take into account all the details of basic physics.

When calculating the energy of molecules, chemists usually consider only one of four fundamental forces: the electromagnetic force. That produces no difference between chiral forms, or enantiomers. Some theoretical calculations, however, incorporate the effects of the weak nuclear force, which operates on the level of atomic nuclei. These produce an extremely small difference between left-handed and right-handed molecular forms.

Such calculations are fiendishly complex, and 40 years after they were first performed arguments still rage over their details. Different energies would mean different physical and chemical characteristics, so enantiomers presumed to behave identically would not do so. "If they don't have identical properties, strictly speaking enantiomers do not exist," says Ulrich Meierhenrich of the Nice Sophia Antipolis University in France. In that case, the homochirality problem might melt away on an issue of definition.

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