Final Draft StarDate story on iron-60

If you can recognize the bright reddish star Antares in the constellation Scorpius, you know how to find the “Scorpius-Centaurus OB association”—a loose group of massive young stars of type O or B. This relatively nearby stellar nursery, currently some 400 light-years away in our own Milky Way galaxy, spans the night sky from Antares (the brightest and most massive B star in the association) south and east toward the stars of the Southern Cross. Star formation in this association started about 15 million years ago and continues today. In fact, since massive O and B stars live only a few million years, many massive stars in this association have gone through their complete life spans, from newborn to supernova. It is here that astronomers think a particular supernova explosion may have occurred some 2 to 3 million years ago: a supernova explosion that, remarkably, seems to have left its imprint in biological organisms on Earth, as well as in geologic materials on Earth and on the Moon.

It’s not news, of course, that we are made of star stuff, although it is always a wonderful thing to contemplate. We have known for some time that virtually all the “heavier” elements in our solar system, such as carbon, oxygen and nitrogen, had to be built up from the lighter elements of hydrogen and helium through the process of nucleosynthesis in stars. The heavier elements were already in place 4.6 billion years ago in the cloud that condensed to form our Sun, so they must have been made in earlier generations of stars. The calcium in our bones now was formed billions of years ago in massive stars that reached the ends of their lives before our Sun was born.

What *is* news is that researchers have been able to pick up the minute evidence of much more recently-made star stuff on Earth and on the Moon. The evidence consists of an element made by a dying star—perhaps in the Scorpius-Centaurus OB association—blown into space, transported to Earth’s vicinity, and captured by our atmosphere only a few million years ago, at a time when early species of our genus *Homo* inhabited parts of Africa. The element in question is a radioactive form or isotope of iron called iron-60, and it has become mixed with more common and stable forms of iron in such tiny quantities that only an exceptionally sensitive technique, called accelerator mass spectroscopy, can detect it.

Isotope specialist Donald Clayton called Iron-60 “one of the most complex and interesting isotopes to occur in nature.” [see Resources] It forms quite abundantly in the blown-off atmospheres of supernovae: one supernova produces enough iron-60 to outweigh the Earth by a factor of 3 or 4 (although the iron-60 atoms are widely scattered in space as a result of the explosion). But this isotope of iron, with its nucleus of 26 protons and 34 neutrons, is unstable, decaying radioactively with a half-life of 2.6 million years. Scientists estimate that at the time of the formation of the Earth, one or two iron atoms in a million were of the iron-60 variety [see Clayton p. 243], with the rest being mostly iron-56. Since then the amount of iron-60 has fallen by half about 1,800 times, so it is now "extinct" rather than "live," and we can only infer its earlier existence by looking for the element it formed in undergoing radioactive decay: nickel-60, with 28 protons and 32 neutrons.

In 1999 a team of researchers from several German institutions published a study of samples taken under the South Pacific Ocean, from a deposit of minerals called a ferromanganese crust. The samples came from layers dated from recent times back to 13 million years ago. The researchers compared the amounts of iron-60 to the amounts of stable iron isotopes in this crust. If the only iron-60 dated back to the formation of the Earth, there should have been essentially none left to detect. Instead, says Thomas Faestermann, a member of the group from the Technical University of Munich, they found a "first hint" of live iron-60 on the Earth. In 2004 the researchers (with a slightly different roster) found the signal again, "weak but significant," this time in ferromanganese crust under the equatorial Pacific.

The next step for an extended group of the researchers was to try to corroborate this result with other kinds of samples. They searched unsuccessfully for the iron-60 signal in sediments from the Atlantic sea floor. "The main reason for not succeeding is most probably that the sediment contains roughly one thousand times more stable iron than the crust, for the same time span," says Faestermann. "Therefore the iron-60 is diluted much more and a delicate leaching technique is required to make the measurement."

However, in 2013 the researchers made news by detecting iron-60 in the fossilized remains of a certain kind of marine bacterium that takes up iron from its surroundings and forms it into microscopic magnetic crystals. (See sidebar on magnetotactic bacteria.) The iron-60, which presumably hit Earth's atmosphere as supernova dust grains that vaporized on impact, found its way down to the surface of the Earth and into the oceans. But instead of entering into ferromanganese crust, like that which the researchers had sampled from under the Pacific, or combining with other geological materials, some of the iron-60 was incorporated by magnetotactic bacteria living about 2 million years ago. Of course, the bacteria also incorporated more common, stable isotopes of iron. When the bacteria died, their cells decomposed, but the sediments where they lay retained the bacteria’s distinctive iron-rich crystals. The detection of iron-60 in the fossil bacteria was the first such detection in a biological organism. Work is ongoing in this area.

The researchers—who had in the meantime undertaken a delicate multi-year effort to re-measure the radioactive half-life of iron-60, in collaboration with a Swiss group—also dramatically expanded the scope of their search for live iron-60 by including the Moon. Astronauts on all six of the Apollo missions that landed on the Moon between 1969 and 1972 collected thousands of lunar “soil” and rock samples. The samples, amounting to 382 kg (more than 800 pounds) of material, are stored in a special building at the Johnson Space Center (JSC) in Houston, TX, and can be made available to scientists. Gregory Herzog of Rutgers University, an American member of the iron-60 research team, says they decided to ask for lunar soil samples. “The iron-60 might have adhered to the surfaces of larger lunar rocks as well, but sampling would probably have been much more difficult,” he notes. Their proposal was successful, and in due course a small cardboard box containing the precious sample arrived in the mail. Herzog recalls that the JSC employs “a champion packer who wraps the carboard boxes with brown paper and reinforced tape so tightly and so perfectly that no wrinkle or other purchase can be found for ripping the paper off. You need a knife to get the packages open.”

Faestermann notes that the lunar samples the researchers were fortunate enough to obtain from the Apollo collection were small, but sufficient; “We need a few milligrams of iron to do a measurement,” he said, “and the mass of the moon samples we obtained was between 60 mg and 190 mg, with an iron content between 3% and 13%.” In other words, in a moon sample weighing less than a Monarch butterfly, the researchers were looking at a total iron content weighing about as much as a half-dozen butterfly eggs. And within those butterfly-egg masses of iron, they would be able to detect iron-60 even if there were only one iron-60 atom (or, to be precise, even less than one iron-60 atom) per *quadrillion* of the “regular” iron atoms. [Illustration note: This page has pictures of Apollo astronauts collecting the samples: http://www.lpi.usra.edu/lunar/samples/apollo/tools/]

The team published the first detection of iron-60 in lunar samples in 2009, and expects more results to follow. Although iron-60 could be formed directly on the Moon from interactions between other isotopes of iron and solar or galactic cosmic rays impinging on the lunar surface, the team can estimate the amount of cosmic ray-produced iron-60 from studies of meteorites. “In the Moon samples we measure a distinctly higher concentration" of iron-60 than should be produced by cosmic rays, says Faestermann. This higher concentration should be due to the effects of a supernova.

Most encouragingly, the results the researchers obtain from the lunar samples are in alignment with the results from the deep ocean crust samples. "We can estimate the total amount of iron-60 per square centimeter that has been deposited since the last few million years on the lunar surface, probably originating from a supernova," says Faestermann. "The amount of iron-60 estimated for the moon seems to coincide with the value we estimate today for the deposition in the deep ocean crust."

The story emerging piece by piece through the iron-60 research within the past decade is an epic one. Somewhere near our solar system a supernova exploded—not so close as to extinguish life on Earth, but no doubt lighting up the sky so brilliantly as to be visible in the daytime [see Clayton p. 245]. Some iron-60 atoms from this and other supernova explosions are still floating in space, and have been detected by the European Space Agency's Integral spacecraft, by virtue of the gamma rays they emit during radioactive decay. A small number of iron-60 atoms settled onto the Earth and Moon surfaces. And now, millions of years later, thanks to detection systems of exquisite sensitivity, we can pick up the signature of that supernova explosion before it has completely died out.

Sidebar on accelerator mass spectrometry:

The accelerator mass spectrometry (AMS) system used by the German team is one of just a few worldwide that can detect iron-60. The system is part of the Maier-Leibnitz Laboratory, operated by the Ludwig Maximilians University of Munich and the Technical University of Munich.

The sample to be studied is given a negative electrical charge, and the sample ions are accelerated with electric fields to very high speeds. They shoot through a thin layer of matter which breaks up any molecules that have come along and strips away electrons, leaving the sample ions positively charged. Electric and magnetic fields then act on the high-speed ions, separating the different isotopic components according to their velocity and according to their charge-to-mass ratio. In the presence of a magnetic field, the trajectory of a charged mass depends on the charge-to-mass ratio, with particles of higher charge-to-mass having a more tightly bent trajectory. With special detectors at the end of the experimental line, individual ions can be counted.

The AMS technique is a better way to search for low levels of iron-60 in the Earth and Moon than the older method of radioactive counting. With radioactive counting and practical sample sizes, researchers would expect to see only about one radioactive decay every 38 years!

Sidebar on magnetotactic bacteria:

A number of bacteria, protozoa and animals, including migratory birds, incorporate biologically-formed magnetic crystals. Among the bacteria, several dozen species, living in freshwater and marine environments worldwide, are known to enclose magnetosomes.

Magnetosomes are iron-containing magnetic crystals enveloped in a lipid membrane. The magnetic crystals in the magnetosomes are not like those found in geological samples; they are chemically more pure and exhibit very regular shapes and sizes. The bacteria make these crystals from iron dust in the Earth's atmosphere that settles in the water. The crystals are about 50 to 100 nanometers long and often arranged in chains, like beads in a necklace.

"Both the size and the arrangement of the crystals result in an elongated nanoscale permanent magnet that acts like a magnetic compass needle, and causes the cell to migrate along the geomagnetic field as it swims," explains Dr. Richard B. Frankel, emeritus professor of physics at California Polytechnic State University in San Luis Obispo. Because the earth's magnetic field has a vertical component as well as a north-south component, the bacteria are able to use this sensitivity to the magnetic field as a way of traveling down into their preferred low-oxygen environments.

These "magnetotactic" or magnetic field-sensing bacteria have been around for a long time—at least some 600 million years, as there have been signs of them in sediments that date back to the precambrian era—and maybe as far back as 2 billion years. When they die, they settle in sediments and their membranes dissolve, leaving just the distinctive magnetic crystals known as "magnetofossils."

This paragraph may be cut if there is a lack of space: The bacteria are not choosy about what type of iron they take up to form the magnetosome crystals. They incorporate the usual stable isotopes of iron (so-called iron-54, -56, -57 and -58), and if radioactive iron-60 happens to be present, they take that up too. Scientists looking for evidence of a relatively nearby and recent supernova explosion that would have dusted the Earth with iron-60 need to separate the iron-60 from the other forms of iron found in the magnetofossils.

Resources

Internet:

www.tum.de/en/about-tum/news/press-releases/short/article/30832/

www.esa.int/Our_Activities/Space_Science/Integral/Radioactive_iron_a_window_to_the_stars

http://www.gams.ph.tum.de/index.php?id=36&L=1

In the absence of less-technical resources, will link to these abstracts of the technical papers:

journals.aps.org/prl/abstract/10.1103/PhysRevLett.93.171103

journals.aps.org/prl/abstract/10.1103/PhysRevLett.101.121101

http://journals.aps.org/prl/abstract/10.1103/PhysRevLett.88.081101

Books:

Handbook of Isotopes in the Cosmos: Hydrogen to Gallium by Donald Clayton. 2003.