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SEEDS *of* LIFE

Scientists investigate whether meteorite impacts delivered life to Earth or elsewhere

By Leila Belkora

Queenie Chan, a post-doctoral researcher at the Open University in the United Kingdom, writes about some far-out-sounding things. A recent research paper by Chan and others discusses a meteorite named Zag, studded with tiny blue crystals; a phenomenon called the YORP effect; and state-of-the-art laboratory techniques like "quadrupole time-of-flight hybrid mass spectrometry." By the time you get to the end, you might not be surprised to see a reference to Santraginus V, a fictional planet in Douglas Adams' 1979 novel *The Hitchhiker's Guide to the Galaxy*.

Yet Chan's research, published in January, is a serious investigation on a topic that excites both science fiction writers *and* scientists: What clues do meteorites hold about distant worlds that may harbor life, or even conditions favorable to the emergence of life?

Even though Zag — named after the mountain it hit in Morocco in 1998 — carried no life, scientists know that meteorites that bombarded early Earth contributed significantly to its complex chemistry. Those meteor-delivered substances, in turn, may have boosted the emergence of life.

The idea that life on our planet could be tied to extraterrestrial matter goes back a long way. In an 1871 lecture to the British Association for the Advancement of Science, William Thomson (later given the title Lord Kelvin, namesake of the Kelvin temperature scale), astonished his audience by arguing for such a connection. He took it for granted that plant and animal life was widespread in the cosmos, and had existed "from time immemorial."

Thomson said it was probable that there were "countless seed-bearing meteoric stones moving about through space," and that a meteorite landing on a newly formed Earth could lead to the planet being covered with vegetation. Indeed, Thomson noted, if Earth were to collide with another planetary body, fragments of our planet — containing its plant and animal seeds — would be similarly dispersed through space.

Many of Thomson's peers took his remarks to be, in the words of one biographer, "a huge scientific joke." The public learned of his startling idea through spirited reactions in newspapers and magazines. The popular satirical weekly *Punch* ran humorous poems about the meteoric hypothesis for a few weeks after. Some scientists pointed out that Thomson's hypothesis did nothing to clarify the question of the origin of life on Earth, but simply moved it to distant worlds, making it impossible to investigate scientifically. Others doubted that living organisms could survive a long journey through space.

Yet an interesting and valid question remained about meteorites' importance. While most are small, Earth is constantly pelted by them. Over eons, meteorites have contributed significantly to the planet's mass and composition (currently, they add 20,000 tons per year).

In the 1830s, Swedish chemist Jacob Berzelius showed that some meteorites carry carbon-rich compounds to Earth. Are they carrying anything significant to the development of life?

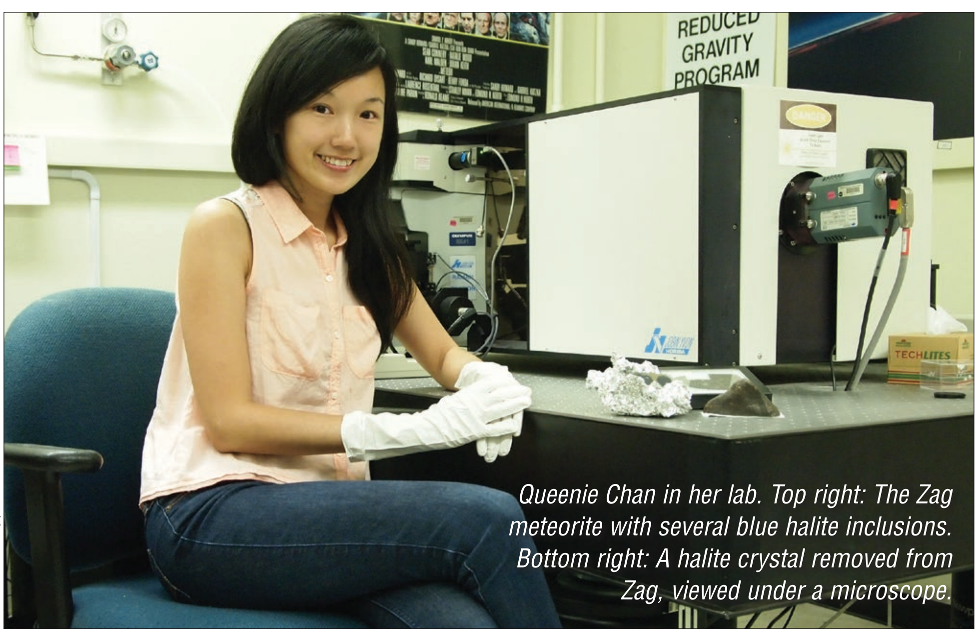
In the early 20th century, Nobel Prize-winning chemist Svante Arrhenius answered some of Kelvin's critics. He suggested a way that "germs of organic life" could survive a trip between Earth and other solar system bodies, calculating that something the size of a single bacterial spore could be carried along by small dust particles propelled by the solar wind. In this way, the tiny organic messengers would move much more quickly than larger meteoroids.

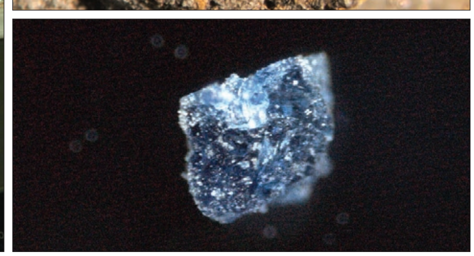
With this reduced travel time, Arrhenius thought the spores might survive. In popular books and in a 1907 article he contributed to *Scientific American*, the idea of seeds of life spreading through the cosmos became known as the theory of panspermy, or panspermia.

As the decades passed, researchers interested in the question of how life began on Earth — and potentially elsewhere — took their investigations in different directions. Biochemists explored the question of how to rec-

What is Life?

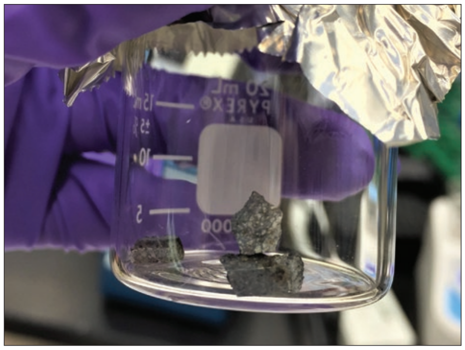
The gap between complex but totally lifeless molecules on one hand, and the simplest living things (probably single-celled organisms), is a huge and mysterious one. Much astrobiology research is devoted to exploring the naturally occurring chemical reactions that might help explain how we got from one to the other. Some scientists believe there may be gradations of living-ness rather than a clear dichotomy between life and non-life. Astrobiologists Carol Cleland and Christopher Chyba point out that the difficulties we face today in trying to define "life" may be similar to those faced by 18th-century scientists trying to define water before anyone knew about molecules. "The controversy over life's definition is inescapable as long as we lack a general theory of the nature of living systems and their emergence from the physical world," they wrote. In the meantime, many scientists rely on a working definition of life as "a self-sustained chemical system capable of undergoing Darwinian evolution." **LB**



QUEENIE CHAN (3)

Queenie Chan in her lab. Top right: The Zag meteorite with several blue halite inclusions. Bottom right: A halite crystal removed from Zag, viewed under a microscope.



QUEENIE CHAN (3)

Above: Chan studies meteorites in a class-10 cleanroom to avoid contamination; Top left: an instrument used to analyze the amino acid content of meteorites. Bottom left: small chips from the Zag meteorite.

ognize primitive life at tiny scales. Some crystals, for example, might be mistaken for living organisms, because under the right conditions they move on their own in a fluid, merge, and break apart again. Other researchers experimented with different recipes for "primordial soup," a watery mix of compounds thought to have existed on the young Earth, to see if molecules associated with living organisms might arise there naturally. Other biologists tested the ability of viruses, bacteria, and fungal spores to survive conditions in space, including temperature extremes, cosmic radiation, and low gravity. Astrobiology developed as a new field, with conferences organized around topics like "What is Life?" and discussions of how to detect life on other planets.

In the 1950s, biochemists Stanley Miller and Harold Urey made a breakthrough. They tried to re-create primitive Earth conditions in a laboratory, zapping lightning-like electric pulses through a mixture of water, methane, ammonia, and hydrogen.

The result was astonishing: Amino acids (the building blocks of proteins) formed, along with other building blocks of cells, like carbohydrates and cell membranes. The result seemed "magical" at the time, astrobiologist Robert Hazen said. The experiment suggested that laboratory scientists might be able to investigate the chemical development of life itself.

As it turned out, though, Miller and Urey's recipe for "primordial soup" — their version of primitive Earth — did not match conditions we now know existed four billion years ago, just prior to the emergence of simple cells. That means their experiment has little bearing on understanding that time period.

However, they were the first to discover that making complex organic compounds, and even molecules forming the basis of DNA, isn't as hard as was thought. Since then, experiments have shown that a wide range of complex molecules containing carbon, hydrogen, oxygen, nitrogen, and phosphorus — key ingredients in biochemistry — naturally come together in space and on planetary bodies. Indeed, complex organic molecules must have formed in interstellar space billions of years before Earth existed.

The Monahans meteorite fell to Earth in 1998, not far from a group of children playing basketball in the small West Texas town of Monahans (about 130 miles northeast of McDonald Observatory). This meteorite and Zag were analyzed at the same time. Perhaps not surprisingly, given how widespread organic compounds are in space, both meteorites were found to contain a large number of different types of organic molecules.

What is amazing is how much scientists can learn from these meteorites. Even 19th-century advocates of panspermia theory like Lord Kelvin might be consoled to know that while modern researchers are not finding seeds or eggs in meteorites, they are finding molecules that are the building blocks of living systems, as well as indications of conditions on distant worlds favorable to life.

Queenie Chan and her team analyzed the Zag and Monahans meteorites and their blue crystals extensively, using advanced tools and techniques from NASA's Johnson Space Center, the Carnegie Institution of Washington, the Lawrence Berkeley National Laboratory, and, in Japan, the High Energy Accelerator Research Organization and the Japan Agency for Marine-Earth Science and Technology. They learned that Zag is a fragment of a body that was itself an amalgam of two different asteroids or planetesimals.

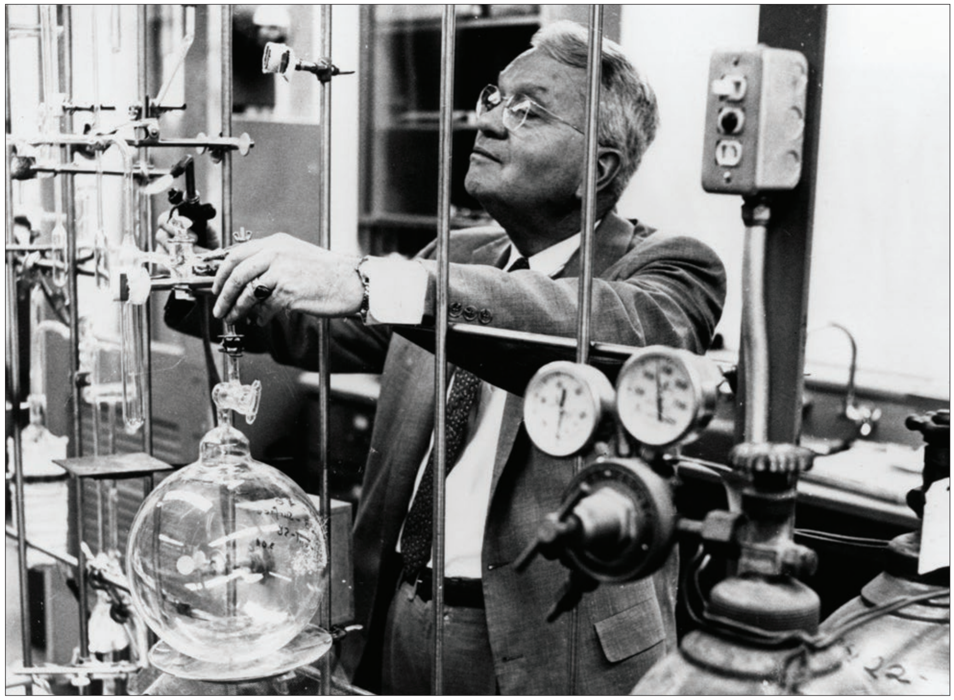
Cool Contents

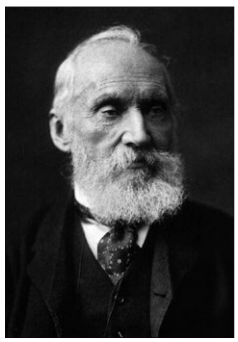
Modern techniques can uncover chemical compounds even if they occur in minute amounts — for instance, a couple of molecules of one particular type amid a billion others. When scientists inventory the contents of meteorites using such sensitive means, they find an astonishing variety of compounds. A 2010 study of the famous Murchison meteorite that landed in Australia in 1969 found that it contains, according to its authors, "tens of thousands of different molecular compositions and likely millions of diverse structures."

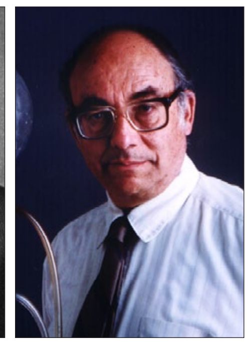
The list of organic (carbon-containing) compounds that have been found in meteorites includes not only the building blocks of proteins and DNA, but also hydrocarbons (like oil), alcohols, aldehydes, ketones (like nail-polish remover), carboxylic acids (like vinegar), amines (used in medicines like decongestants), and many more. No sure indications of living organisms have been found yet, but interstellar and interplanetary space has proven to be an impressive chemical laboratory. **LB**

WIKIPEDIA

A piece of the Murchison meteorite, seen in the National Museum of Natural History in Washington, D.C.







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Several scientists made strides that led to today's breakthroughs in the study of how life might spread through space. Some of these were (bottom, from left): in the Victorian era, British chemist William Thomson (Lord Kelvin) and Swedish chemist Jacob Berzelius; in the early 20th century, Swedish chemist Svante Arrhenius; and in the 1950s, American biochemists Harold Urey and Stanley Miller (top).

The bulk of Zag, which is classified as an "ordinary chondrite" meteorite, is similar to the asteroid Hebe. Hebe is thought to be the parent body of many stony meteorites found on Earth. It is a relatively large and dense asteroid orbiting the Sun within the main asteroid belt, between Mars and Jupiter.

The Hebe-like component of Zag — the "matrix" in which the crystals are embedded — contains minerals and compounds typical of its class of ordinary chondrites. It also contains a range of amino acids. It shows signs of having experienced physical shock and temperatures above the melting point of metals like magnesium and aluminum.

The second component of Zag — the component with the blue crystals — is quite different in composition. The crystals, which are just a millimeter or two in diameter, are mostly rock salt: potassium chloride or sodium chloride. Amino acids also are present in the crystals, as is argon gas. A previously published study of the argon in the Monahans meteorite's similar blue crystals indicated that they formed by the evaporation of water about 4.5 billion years ago, early in the formation of the solar system.

The crystals themselves hold microscopic surprises. They contain even smaller inclusions of brine — liquid water containing minerals. The brine droplets are on the scale of 1 to 10 microns, about the size of a red blood cell.

The crystals are delicate in the sense that they easily dissolve in humid conditions. Indeed, they are preserved only in samples of Zag and Monahans that were stored under dry nitrogen gas soon after they were collected. The crystals had to have been formed and continuously maintained at temperatures between about 75 and 120 degrees Farrenheit (25-50 C). This is far less than the at least 1,100 degrees Fahrenheit (600 C) experienced at one time by the Hebe-like component of Zag. From this, the researchers deduce that the microscopic blue crystals landed on the Hebe-like material and became incorporated with it *after* the Hebe-like material had changed.

Where did these crystals come from? Chan and her colleagues were thrilled to find, from a detailed study of the minerals and organic solids in the brine droplets, that the brine inclusions are "almost identical" to those of the surface of Ceres, the largest object in the asteroid belt. Scientists know a lot about Ceres thanks to the Dawn mission, which entered orbit around Ceres in 2015 and is still there. Dawn has found suggestive evidence of past oceans and recent geological activity. "These halite crystals are the only available direct samples" from Ceres or a similar asteroid, Chan wrote.

Chan and her team's paper describes a possible sequence of events leading to the formation of Zag and its intriguing blue crystals: A parent body, probably Ceres, experienced hydrovolcanism — volcanic eruptions resulting from molten rock interacting violently with water. Various kinds of organic matter formed on the parent body from formaldehyde and ammonia acted upon by water. At the end of the major episodes of volcanic activity, about 4.5 billion years ago, surface water evaporated, leaving behind the rock salt crystals and their incorporated brines.

Later, further hydrovolcanism spewed inorganic stones and their surface layers of salts into space. Radiation from the young Sun acted on the salt crystals, leading to further chemical changes and the development of the bluish color.

Next, these salt-covered stones landed on a different asteroid, possibly Hebe, which had already been modified by high temperatures. The salt-covered stones became incorporated into their new asteroid home.

Sometime later a fragment broke off from the new home, possibly through a relatively gentle process called the YORP effect (named for the astrophysicists who studied how asteroids can start to fly apart as their spin changes).

Finally, one August day in 1998, someone in the vicinity of Zag, Morocco, saw a meteorite fall to Earth.

Panspermia is still just a dream, but studying the contents of meteorites is nevertheless amply satisfying to Chan and her fellow astrobiologists. "Panspermia discusses the delivery of life itself to Earth, while we discuss the delivery of organic components, but not life, in our paper," she says. "However, via studying the chemistry of the meteoritic organics, we can postulate that the asteroidal body where the salt crystals come from was — or still is — a water-rich world with abundant organic precursors for complex chemistry to occur."

Leila Belkora is an astronomer and science writer in California and a frequent contributor to StarDate.

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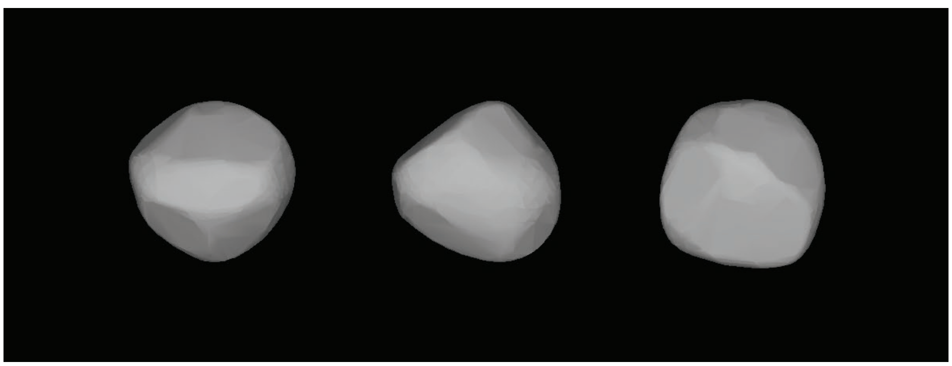

NASA/JPL-CALTECH/UCLA/MPS/DLR/IDA

The Zag meteorite is likely a combination of pieces from two asteroids in the main belt. The meteorite first chipped off of asteroid Hebe (above, seen from three angles in a computer model), and then landed on Ceres, the asteroid belt's largest body (seen at right by the Dawn spacecraft), where it incorporated some of that body's material before breaking loose and landing on Earth.

Resources

Books

Biological Cosmology, Astrobiology, Extraterrestrial Life, by Rudolf Schild and Richard Hoover, 2013

Biological Big Bang: Panspermia and the Origins of Life, edited by Chandra Wickramasinghe, 2010

Genesis: The Scientific Quest for Life's Origin, by Robert Hazen, 2005

Internet

Astrobiology at NASA
astrobiology.nasa.gov

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