Looking for Clues to the Mystery of Life on Earth

From the vast central hall in Chambord Castle, the largest of the great châteaux on France's River Loire, an ornate double-helical staircase rises to a roof terrace. It was an appropriate setting for a banquet of the International Society for the Study of the Origin of Life (ISSOL), which held its triennial meeting last month in nearby Orléans.* Without double-helical DNA and RNA molecules, life would not exist. At the meeting, nearly 300 scientists, including three Nobel laureates, grappled with the riddle of how these molecules first appeared and how they evolved into self-reproducing cells—questions that have gained new urgency with the hint that life in some form also may have evolved on Mars (see pages 864 and 924).

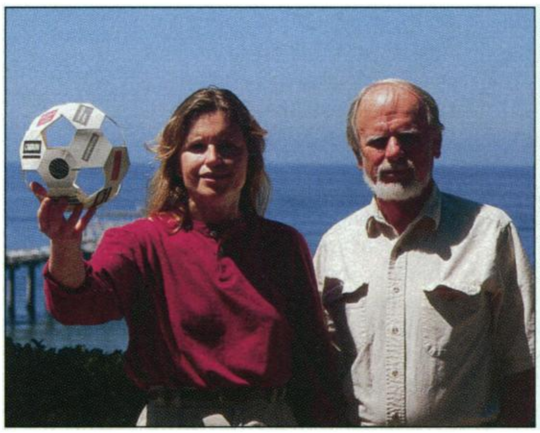
Pushing Back the Years

One of the most discussed presentations at the ISSOL conference would give life a 400-million-year head start. A team led by Stephen Mojzsis, a doctoral student in Gustaf Arrhenius's laboratory at the Scripps Institution of Oceanography in La Jolla, California, claimed that it has found evidence that life existed on Earth at least 3.87 billion years ago. This would beat the earliest established date of 3.46 billion, based on bacterial microfossils discovered by paleobiologist William Schopf of the Center for the Study of Evolution and the Origin of Life at the University of California, Los Angeles.

Arrhenius says that the importance of an earlier date for life on Earth is "not so much to establish a new Guinness book of records entry." Rather, he says, "as we push back in time, it bears on speculations about how life arose." Among other things, it suggests that the earliest life might have had to contend with the hail of impacts that pelted the early Earth.

Mojzsis and his colleagues analyzed minute specimens taken from Akilia Island off the southwest coast of Greenland, site of some of Earth's earliest known rocks. Unlike Schopf's microfossils, which resemble modern-day cyanobacteria (*Science*, 30 April 1993, p. 640), Mojzsis's specimens are composed of grains of apatite, a calcium phosphate mineral, in which "inclusions" of graphite are embedded. The team claims that these grains represent the remains of ancient organisms, offering two arguments. First, in modern-day marine sediments apatite is a byproduct of metabolism, and thus is an indicator of the presence of life, and second, the graphite inclusions appear to contain a measurably higher ratio of carbon-12 to carbon-13 than is found in inorganic carbon sources, nearer the ratio typical of living organisms.

Some researchers, however, are urging extreme caution before the new date is accepted. Schopf, the current world record holder, says that "this is very interesting work, but I think we ought to reserve judgment until we have additional experience approaching problems of this sort." Schopf is particularly concerned about the accuracy of the carbon isotope ratios, which were determined using a relatively new instrument called an ion microprobe.


SCRIPPS INST. OF OCEANOGRAPHY/UCSD

Searching for life's building blocks. Luann Becker and Jeffrey Bada, both of Scripps.

And geologist Stephen Moorbath of Oxford University, an expert on ancient rocks, says he is worried about the dating of the Akilia Island specimens, because they come from rock that has been profoundly metamorphosed by heat and pressure. Nevertheless, Moorbath says, even if the dating is wrong, the youngest Akilia rocks still appear to be at least 3.6 billion years old. Moreover, Moorbath says, his own research group has found graphite deposits—which he thinks might represent mixtures of organic and inorganic material—in the so-called Isua rocks of Western Greenland, which have been reliably dated to about 3.77 billion years.

If life did exist on our planet as early as 3.8 billion years ago, a number of researchers told *Science*, it must then have arisen either during or perilously close to a period when Earth is thought to have been regularly blasted by the comets, asteroids, and meteorites—many 100 kilometers or more in diameter—that were swarming around the early solar system. This period of heavy bombardment began soon after Earth formed, about 4.5 billion years ago, and finally tailed off about 3.9 billion years ago. If the new date is correct, it would take away the comfortable 400-million-year window between the end of the bombardment and the first appearance of life. "Something's got to give," says David Des Marais, a geochemist at NASA's Ames Research Center in California. "Either life arose in a very short time, or somehow it survived the bombardment."

James Kasting, an atmospheric scientist at Pennsylvania State University, thinks that both might be true. Kasting suggests that organisms might have developed in between large impacts, which occurred about every 10 or 20 million years and probably vaporized the uppermost 100 or so meters of the ocean. They could then have gone on to survive subsequent cataclysms, just as today's heat-loving organisms known as hyperthermophiles withstand the extreme conditions around deep hydrothermal ocean vents. Karl Stetter at the University of Regensburg in Germany and Carl Woese at the University of Illinois have analyzed the evolutionary history of modern organisms and concluded that the earliest known common ancestor of all life on earth today lived at extremely high temperatures.

Other researchers, however, doubt that the first life forms would have been that hardy. Biochemist Stanley Miller of the University of California at San Diego and evolutionary biologist Antonio Lazcano of the National University of Mexico in Mexico City argue that the hyperthermophiles were preceded by life that arose from a much cooler "prebiotic soup" of organic molecules and evolved into Schopf's cyanobacteria-like organisms in as little as 10 million years. At that rate, life would have had plenty of time to get going after the bombardment had stopped. Whichever way it goes, as Luann Becker, a geochemist at Scripps, comments: "This will be a topic of conversation in the field for a long time to come."

11th International Conference on the Origin of Life, Orléans, France, 5–12 July.

Molecules From Space?

The rain of asteroids and comets that pelted early Earth may have threatened primeval life, but it could also have nurtured it by delivering key ingredients. Space is a plausible source of building blocks for living things, say increasing numbers of researchers, pointing to the difficulty of explaining how some organic compounds could have arisen on early Earth and concrete evidence that such molecules are present in many meteorites. At the Orléans meeting, researchers discussed a possible cosmic origin for a new set of molecules along with a hint that the "handedness" of many biological molecules—the presence of just one of two possible mirror image forms—might have originated in space.

The new items on the cosmic delivery list are the phosphorus containing compounds that are key components of DNA and RNA as well as energy-carrying molecules such as adenosine triphosphate (ATP). "As far back as we can go in the geological record, phosphorus has played a role," says Stephen Mojzsis of the Scripps Institution of Oceanography. But phosphorus does not appear to have been available on early Earth in a form able to take part in the prebiotic organic reactions thought to have preceded the rise of living organisms. The most ubiquitous phosphorus compound, calcium phosphate, is insoluble in water, and the more soluble polyphosphates have been found only at exceedingly low concentrations in volcanoes. Alan Schwartz of the Evolutionary Biology Research Group at the University of Nijmegen in the Netherlands thinks, however, that at least some of the phosphorus compounds necessary for life may have been delivered by comets and meteorites during the heavy bombardment period.

Schwartz bases his proposal on a 1992 report by George Cooper of NASA's Ames Research Center and his colleagues, who detected the presence of phosphonic acids—water-soluble compounds that contain both phosphorus and carbon—in the so-called Murchison meteorite, which fell near Murchison, Australia, in 1969 and has yielded a chemist's shelf full of organic compounds. In a paper published last year in *Nature*, Schwartz and his coworkers Rob de Graaf and Johnny Visscher demonstrated that the same phosphonic acids can be easily synthesized by irradiating mixtures of phosphorous acid (which contains phosphorus but not carbon) and formaldehyde (carbon but no phosphorus) with ultraviolet light. The process offers a plausible mechanism for how these compounds might have been created in the "parent body" from which the meteorite originated.

And in new work presented at Orléans, de Graaf and Visscher demonstrated that ultraviolet light and formaldehyde can convert some of these phosphonic acids into many other reactive phosphonic acid derivatives, which might have been available for prebiotic reactions on earth. "The earliest [biochemical] pathways might have involved phosphonic acids rather than phosphates," Schwartz told the meeting. Schwartz went on to speculate further that the first genetic molecules, precursors to RNA and DNA, might have had a phosphonic acid backbone.

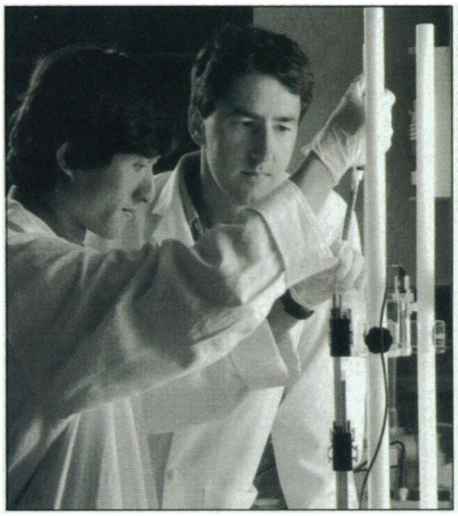
The Murchison meteorite may also contain clues to another persistent problem in understanding how life arose: The origin of the handedness, or homochirality, in many biological molecules. These molecules, including the subunits of DNA, RNA, and proteins, have two chiral forms, or enantiomers. In nature, however, one form always dominates: All of the sugar molecules in the backbone of DNA and RNA are right-handed, or *D* enantiomers, while the amino acids in proteins are left-handed, or *L* enantiomers. Exactly what twist of fate caused life to choose one form over the other is a source of often bitter debate (*Science*, 3 March 1995, p. 1265).

At the meeting, John Cronin of Arizona State University reported a hint that the choice may have been made in space. Cronin, who has spent many years analyzing the organic compounds extracted from the Murchison meteorite, recently found that for certain amino acids in the meteorite, the concentration of the *L* forms exceeded the *D* forms by as much as 10%. Sherwood Chang, chief of Ames' exobiology branch, says that this finding may show "that somewhere, sometime there was a process that gave rise to [chiral] activity." For example, organic chemist William Bonner of Stanford University in California has suggested that circularly polarized ultraviolet light from neutron stars might have introduced a chiral bias into organic molecules in space before the formation of the solar system.

Nevertheless, Chang and other researchers caution, the excesses of *L* forms found by Cronin were not in the so-called alpha amino acids, which make up proteins, but in other, nonbiological, amino acids. "It may be good news for the theorists, but it's the wrong amino acids for biochemistry," says chemist Jeffrey Bada of Scripps. But Bada adds that Cronin is "a very careful researcher," and says that he plans to go back into his own lab and take another look at the Murchison meteorite himself.

Recreating the RNA World

Wherever the molecular building blocks of life came from, they had to be organized into self-sustaining, self-reproducing units before they could qualify as life. The primordial living molecule would probably have had to both store genetic information and catalyze its own reproduction—functions now divided between RNA and DNA on the one hand and proteins on the other. Identifying this molecule is one of the greatest challenges in origins of life research and, for many, a turning point in the search came in the early 1980s with the discovery of ribozymes—RNA molecules capable of catalyzing biochemical reactions. A new result reported at the meeting has strengthened the case for a primordial "RNA world" in which RNA performed this double duty.



SCRIPPS RESEARCH INSTITUTE

Test-tube life? Gerald Joyce (*right*) favors RNA as the first living molecule.

One of the biggest boosts for the concept of an RNA world came when a number of laboratories—notably those of Jack Szostak at Massachusetts General Hospital in Boston and Gerald Joyce at Scripps—showed that ribozymes can be made to undergo "molecular evolution" in the test tube. In these experiments, a large population of different RNA molecules is set to the task of catalyzing a particular biochemical reaction, usually the creation of a phosphodiester bond like the one that binds RNA or DNA subunits together. The few RNA molecules that succeed at the task are retained and replicated in a way that allows some of them to undergo small mutations. Then they are allowed to have another go at the reaction. Within a number of generations, RNA molecules emerge that are very effective at catalyzing the reaction.

Until now, researchers had to carry out each cycle of reaction, selection, and replication of the RNA by hand. But at the Orléans meeting, Joyce reported new work carried out by Martin Wright, a postdoc in his lab, who has made the process self-sustaining. In this first demonstration of continuous evolution of ribozymes in a test tube, Wright was able to create molecules that had the ability to catalyze the creation of a specific phosphodiester bond and then retained and perfected this ability generation after generation, without further interference or manipulation.

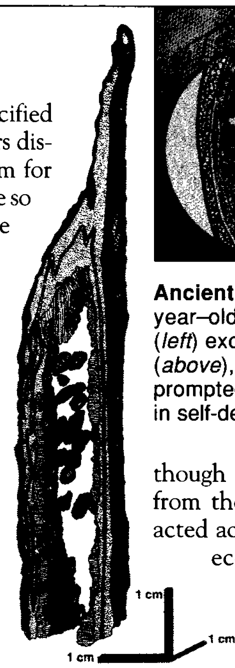
"We see no end in sight," Joyce told the meeting, but cautioned that his team's RNA molecules cannot be considered alive because they do not catalyze their own replication—Wright "cheats" by adding modern protein RNA polymerase enzymes to the system to allow the RNA to reproduce. Nevertheless, says biochemist David Deamer of the University of California at Santa Cruz, "The results Joyce described represent a major step toward the goal of finding an RNA that carries both genetic information and a catalytic site for RNA replication." And, comments James Kasting of Pennsylvania State University, "it's extremely significant just to show it can be done. Maybe he can eventually wean this molecule away from its dependence on proteins."

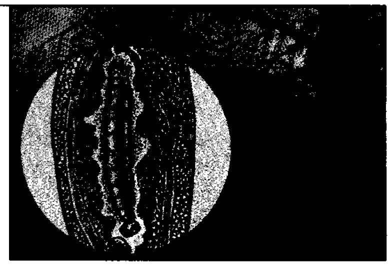
A paper in the 25 July issue of *Nature* by former Szostak associates Eric Ekland and David Bartel—who are now at the Whitehead Institute for Biomedical Research in Cambridge, Massachusetts—shows that such optimism might indeed be warranted. Ekland and Bartel report the creation of a ribozyme that can add up to six mononucleotides—the subunits that make up RNA—to the end of a growing RNA chain in a template-directed fashion, thus mimicking the activity of protein RNA polymerases in making exact copies of nucleotide sequences. If Joyce and his colleagues can harness this ability in their own experiments, they may not be too far from demonstrating a plausible RNA world. As one scientist told *Science*, "Gerald is out to create life in a test tube, and he probably will do it one day."

–Michael Balter

PALEOBOTANY

Early Start for Plant-Insect Dance





MARY PARRISH, NMNH

Ancient enemies. This 300-million-year–old fern may hold fossil pellets (*left*) excreted by insect larvae (*above*), whose appetites may have prompted plants to form a fleshy gall in self-defense.

Insects and plants have been exploiting each other for millennia, often to spectacular effect. Hungry insects, for instance, spurred plants to invent attractive flowers, which bribe insects into carrying pollen by offering them meals of nectar. Most scientists have assumed such mutual manipulations date back about 125 million years, when flowering plants first appeared. But new evidence indicates that insects and plants took some of the first steps in their intimate dance nearly 200 million years earlier—and that they paired up not for mutual benefit but in a drama of attack and self-defense.

Paleontologists Conrad Labandeira of the National Museum of Natural History and Tom Phillips of the University of Illinois, Urbana-Champaign report in the 6 August issue of the *Proceedings of the National Academy of Sciences* that they have found fleshy protuberances called galls in the fossilized remains of now-extinct tree ferns that lived 302 million years ago. In the galls of today, parasitic insects feed on this extra tissue, which the plant may form in response to the insectan attack. If the same process is responsible for the fossil galls, Labandeira says, complex interactions between plants and plant-eaters must have been underway 175 million years earlier than had been thought. Peter Price, an ecologist and an expert on modern plant galls at Northern Arizona University, says the finding opens a new view of this evolutionary pas de deux. "This is the first time we can really know what these ancient insects were doing," he says. "The detail the [scientists] have been able to see is phenomenal."

The fossils that Labandeira and Phillips describe were collected over the last 30 years from an Illinois coal mine—the remains of a swampy seaside forest that grew during the Late Carboniferous period. Having turned to coal, most of the forest is unrecognizable, but interspersed in the coal are pieces of calcified peat called coal balls. While coal miners discard the balls, paleobotanists prize them for their high-quality plant fossils, which are so well-preserved that cellular structures are often visible.

The plant experts who first examined these fossils weren't attuned to signs of insect activity, but Labandeira, an entomologist, was. As he examined cross-sections of the fossilized fern fronds, he found nearly 30 with chambers in their base about the right size and shape to host the worm-like larva of an insect. The chambers and the cells around them closely resembled modern galls, which are made from layers of rapidly dividing, swollen cells that—scientists believe—form in response to chemical signals from the invader. According to one hypothesis, the plant protects more vital tissue on the leaves or fronds by producing extra tissue for the larva to eat.

Labandeira and Phillips did not find any fossilized larvae, which would have clinched the case. But they did come up with the next best thing: The fossil chambers contained pellets that look remarkably like the pellets some insect larvae excrete today, and several galls had openings that resemble the exit holes modern insects leave behind.

This cycle of foreign invasion and host attempts at appeasement among such ancient organisms comes as a surprise. "People tend to overestimate our time and think that we are much more sophisticated," says Jarmila Kukalová-Peck, who studies Paleozoic insects at Carleton University in Ottawa, Canada. But early geologic eras can contain interactions rivaling contemporary complexity, she says.

Labandeira says the ancient galls are evidence that the flora and fauna of the time, though completely different species from those we observe today, interacted according to some of the same ecological rules. "The same niches were there," he says, "and organisms took advantage of them in remarkably similar ways."

Not everyone is convinced that the chambers are true galls, however. William Chaloner, a paleobotanist at the University of London, says the extra cells could be a plant's standard reaction to a wound rather than a specialized response induced by the insect. And David Grimaldi, an entomologist at the American Museum of Natural History in New York, notes that one crucial piece of evidence is missing. "They have a good case," he says, "but I'd still like to see a fossilized larva."

Grimaldi yet may get his wish, says Hiram Larew, a biologist and gall specialist at the U.S. Agency for International Development in Washington, D.C. He notes that the fossils Labandeira and Phillips analyzed lay in a collection for many years before anyone noticed evidence for plant galls. "People have looked at these before, but they haven't been looking with the right kind of lens," he says. "There's a lot more out there to discover."

–Gretchen Vogel