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the SEARCH for ALIEN life

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Are we alone in the universe? It's a question that every school kid has probably asked at some time—and scientists in particular want an answer. In their quest after alien beings, astronomers have scanned the heavens for radio signals from another technologically advanced civilization; they've sent probes to all but one of the planets around our Sun; they've studied extreme life forms on Earth to better understand the conditions under which life can take root; and they've scrutinized the neighborhoods around distant stars.

We may never discover whether or not extraterrestrials exist—at least not until they contact us. But researchers continue to refine their search. Discoveries that water likely flowed on Mars at one time and that Jupiter's moon Europa may house a subterranean sea have intensified the hunt for alien organisms in our own solar system. And the identification of approximately 100 extrasolar planets in recent years has raised hopes of finding inhabited worlds similar to Earth elsewhere in our galaxy.

In this special online issue, *Scientific American* authors review the evidence for and against the existence of ETs. In *Where Are They?*, Ian Crawford ponders what it means that all of our surveys so far have come up empty handed. In *Is There Life Elsewhere in the Universe?*, Jill C. Tarter, director of research for the Search for Extraterrestrial Intelligence (SETI) Institute, and her colleague Christopher F. Chyba assert that the search has only just begun. Other articles examine the cases to be made for relic life on Mars and other bodies in our solar system, as well as the plans to launch a new space telescope for spying on distant worlds. Buy the issue, read the articles and, the next time you gaze up at the night sky, make up your own mind.—*the Editors*

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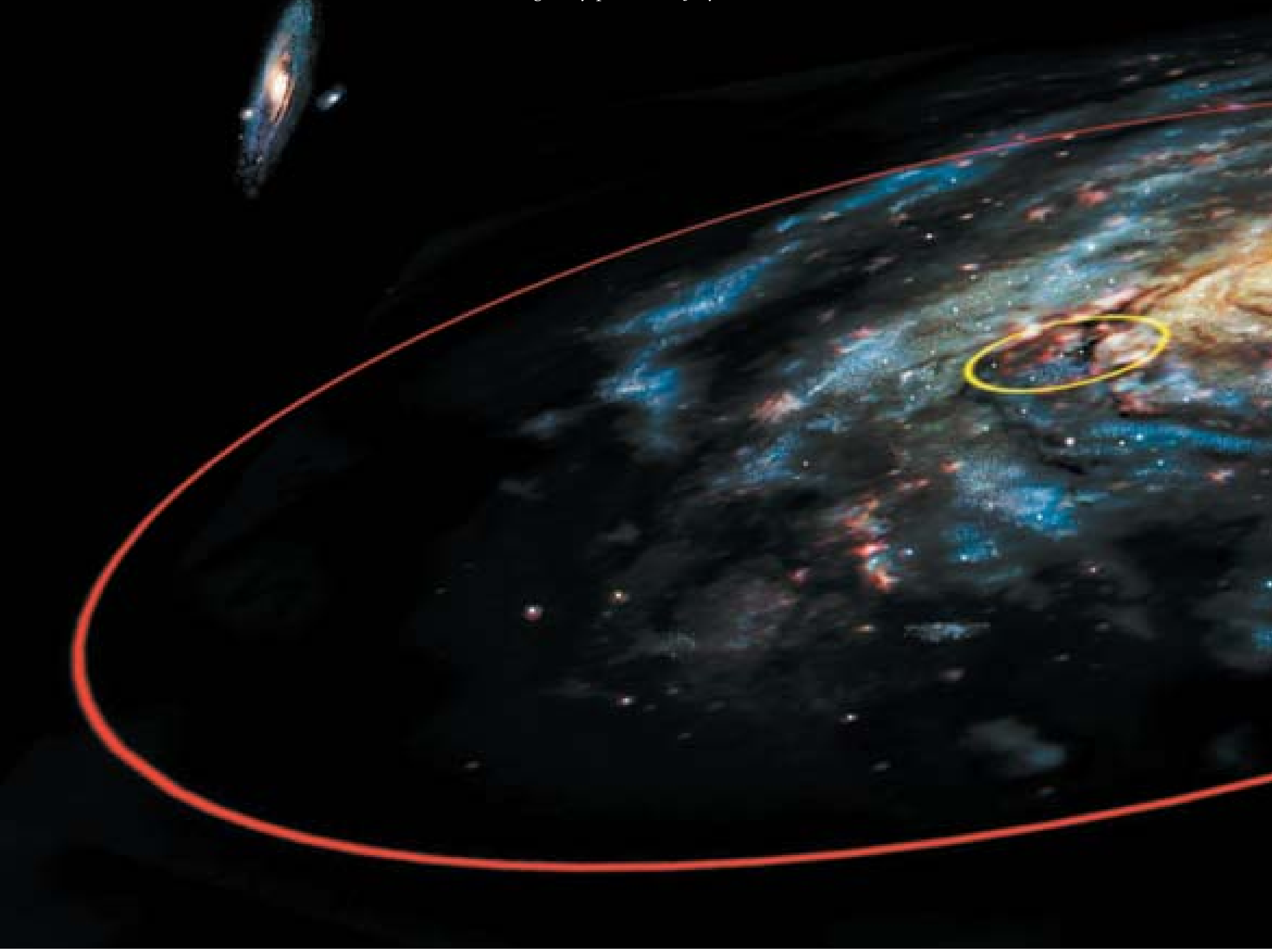


How common are other civilizations in the universe? This question has fascinated humanity for centuries, and although we still have no definitive answer, a number of recent developments have brought it once again to the fore. Chief among these is the confirmation, after a long wait and several false starts, that planets exist outside our solar system.

Over the past five years more than three dozen stars like the sun have been found to have Jupiter-mass planets. And even though astronomers have found no Earth-like planets so far, we can now be fairly confident that they also will be plentiful. To the extent that planets are necessary for the origin and evolution of life, these exciting discoveries certainly augur well for the widely held view that life pervades the universe. This view is supported by advances in our understanding of the history of life on Earth, which have highlighted the speed with which life became established on this planet. The oldest direct evidence we have for life on Earth consists of fossilized bacteria in 3.5- billion-year-old rocks from Western Australia, announced in 1993 by J. William Schopf of the University of California at Los Angeles. These organisms were already quite advanced and must themselves have had a long evolutionary history. Thus, the actual origin of life, assuming it to be indigenous to Earth, must have occurred closer to four billion years ago.

Earth itself is only 4.6 billion years old, and the fact that life appeared so quickly in geologic time—probably as soon as conditions had stabilized sufficiently to make it possible—suggests that this step was relatively easy for nature to achieve. Nobel prize–winning biochemist Christian de Duve has gone so far as to conclude, “Life is almost bound to arise … wherever physical conditions are similar to those that prevailed on our planet some four billion years ago.” So there is every reason to believe that the galaxy is teeming with living things.

Does it follow that technological civilizations are abundant as well? Many people have argued that once primitive life has evolved, natural selection will inevitably cause it to advance toward intelligence and technology. But is this necessarily so? That there might be something wrong with this argument was famously articulated by nuclear physicist Enrico Fermi in

Where Are They?

Maybe we are alone in the galaxy after all

by Ian Crawford

1950. If extraterrestrials are commonplace, he asked, where are they? Should their presence not be obvious? This question has become known as the Fermi Paradox.

This problem really has two aspects: the failure of search for extraterrestrial intelligence (SETI) programs to detect radio transmissions from other civilizations, and the lack of evidence that extraterrestrials have ever visited Earth. The possibility of searching for ETs by radio astronomy was first seriously discussed by physicists Giuseppe Cocconi and Philip Morrison in a famous paper published in the journal *Nature* in 1959. This was followed the next year by the first actual search, Project Ozma, in which Frank D. Drake and his colleagues at the National Radio Astronomy Observatory in Green Bank, W.Va., listened for signals from two nearby stars. Since then, many other SETI experiments have been performed, and a number of sophisticated searches, both all-sky surveys and targeted searches of hundreds of individual stars, are currently in progress [see "The Search for Extraterrestrial Intelligence," by Carl Sagan and Frank Drake; SCIENTIFIC AMERICAN, May 1975; "Is There Intelligent Life Out There?" by Guillermo A. Lemarchand; SCIENTIFIC AMERICAN PRESENTS: *Exploring Intelligence,* Winter 1998]. In spite of all this activity, however, researchers have made no positive detections of extraterrestrial signals.

ZIP, ZILCH, NADA has come out of any aliens with whom we share the galaxy. Searches for extraterrestrial intelligence have at least partially scanned for Earth-level radio transmitters out to 4,000 light-years away from our planet (*yellow circle*) and for so-called type I advanced civilizations out to 40,000 light-years (*red circle*). The lack of signals is starting to worry many scientists.

Of course, we are still in the early days of SETI, and the lack of success to date cannot be used to infer that ET civilizations do not exist. The searches have so far covered only a small fraction of the total "parameter space"—that is, the combination of target stars, radio frequencies, power levels and temporal coverage that observers must scan before drawing a definitive conclusion. Nevertheless, initial results are already beginning to place some interesting limits on the prevalence of radio-transmitting civilizations in the galaxy [*see box on next page*].

DON DIXON; CALCULATIONS BY ANDREW J. LEPAGE

The Fermi Paradox becomes evident when one examines some of the assumptions underlying SETI, especially the total number of galactic civilizations, both extant and extinct, that it implicitly assumes. One of the current leaders of the field, Paul Horowitz of Harvard University, has stated that he expects at least one radio-transmitting civilization to reside within 1,000 light-years of the sun, a volume of space that contains roughly a million solar-type stars. If so, something like 1,000 civilizations should inhabit the galaxy as a whole.

This is rather a large number, and unless these civilizations are very long-lived, it implies that a truly enormous number must have risen and fallen over the course of galactic history. (If they are indeed long-lived—if they manage to avoid natural or self-induced catastrophes and to remain detectable with our instruments—that raises other problems, as discussed below.) Statistically, the number of civilizations present at any one time is equal to their rate of formation multiplied by their mean lifetime. One can approximate the formation rate as the total number that have ever appeared divided by the age of the galaxy, roughly 12 billion years. If civilizations form at a constant rate and

Where They Could Hide

The galaxy appears to be devoid of supercivilizations, but lesser cultures could have eluded the ongoing searches

by Andrew J. LePage

No SETI program has ever found a verifiable alien radio signal. What does that null result mean? Any answer must be highly qualified, because the searches have been so incomplete. Nevertheless, researchers can draw some preliminary conclusions about the number and technological sophistication of other civilizations.

The most thoroughly examined frequency channel to date, around 1.42 gigahertz, corresponds to the emission line of the most common element in the universe, hydrogen—on the premise that if extraterrestrials had to pick some frequency to attract our attention, this would be a natural choice. The diagram on the opposite page, the first of its kind, shows exactly how thoroughly the universe has been searched for signals at or near this frequency. No signal has ever been detected, which means that any civilizations either are out of range or do not transmit with enough power to register on our instruments. The null results therefore rule out certain types of civilizations, including primitive ones close to Earth and advanced ones farther away.

The chart quantifies this conclusion. The horizontal axis shows the distance from Earth. The vertical axis gives the effective isotropic radiated power (EIRP) of the transmitters. The EIRP is essentially the transmitter power divided by the fraction of the sky the antenna covers. In the case of an omnidirectional transmitter, the EIRP is equal to the transmitter power itself. The most powerful on this planet is currently the Arecibo radio telescope in Puerto Rico, which could be used as a narrowly beamed radar system with an EIRP of nearly 10^{14} watts.

The EIRP can serve as a crude proxy for the technological level of an advanced civilization, according to a scheme devised by Russian SETI pioneer Nikolai S. Kardashev in the early 1960s and later extended by Carl Sagan. Type I civilizations could transmit signals with a power equivalent to all the sunlight striking an Earth-like planet, about 10^{16} watts. Type II civilizations could harness the entire power output of a sunlike star, about 10^{27} watts. Still mightier type III civilizations command an entire galaxy, about 10^{38} watts. If the capability of a civilization falls in between these values, its type is interpolated logarithmically. For example, based on the Arecibo output, humanity rates as a type 0.7 civilization.

For any combination of distance and transmitter power, the diagram indicates what fraction of stars has been scanned so far without success. The white and colored areas represent the civilizations whose existence we therefore can rule out with varying degrees of confidence. The black area represents civilizations that could have evaded the searches. The size of the black area increases toward the right—that is, going farther away from Earth.

SETI programs completely exclude Arecibo-level radio transmissions out to 50 or so light-years. Farther away, they can rule out the most powerful transmitters. Far beyond the Milky Way, SETI fails altogether, because the relative motions of galaxies would shift any signals out of the detection band.

These are not trivial results. Before scientists began to look, they thought that type II or III civilizations might actually be quite common. That does not appear to be the case. This conclusion agrees with other astronomical data. Unless supercivilizations have miraculously repealed the second law of thermodynamics, they would need to dump their waste heat, which would show up at infrared wavelengths. Yet searches performed by Jun Jugaku of the Research Institute of Civilization in Japan and his colleagues have seen no such offal out to a distance of about 80 light-years. Assuming that civilizations are scattered randomly, these findings also put limits on the average spacing of civilizations and thus on their inferred prevalence in unprobed areas of the galaxy.

On the other hand, millions of undetected civilizations only slightly more advanced than our own could fill the Milky Way. A hundred or more type I civilizations could also share the galaxy with us. To complicate matters further, extraterrestrials might be using another frequency or transmitting sporadically. Indeed, SETI programs have logged numerous "extrastatistical events," signals too strong to be noise but never reobserved. Such transmissions might have been wayward radio waves from nearby cell phones—or they might have been intermittent extraterrestrial broadcasts.

No one yet knows. Although the cutting edge of technology has made SETI ever more powerful, we have explored only a mere fraction of the possibilities.

live an average of 1,000 years each, a total of 12 billion or so technological civilizations must have existed over the history of the galaxy for 1,000 to be extant today. Different assumptions for the formation rate and average lifetime yield different estimates of the number of civilizations, but all are very large numbers. This is what makes the Fermi Paradox so poignant. Would none of these billions of civilizations, not even a single one, have left any evidence of their existence?

Extraterrestrial Migration

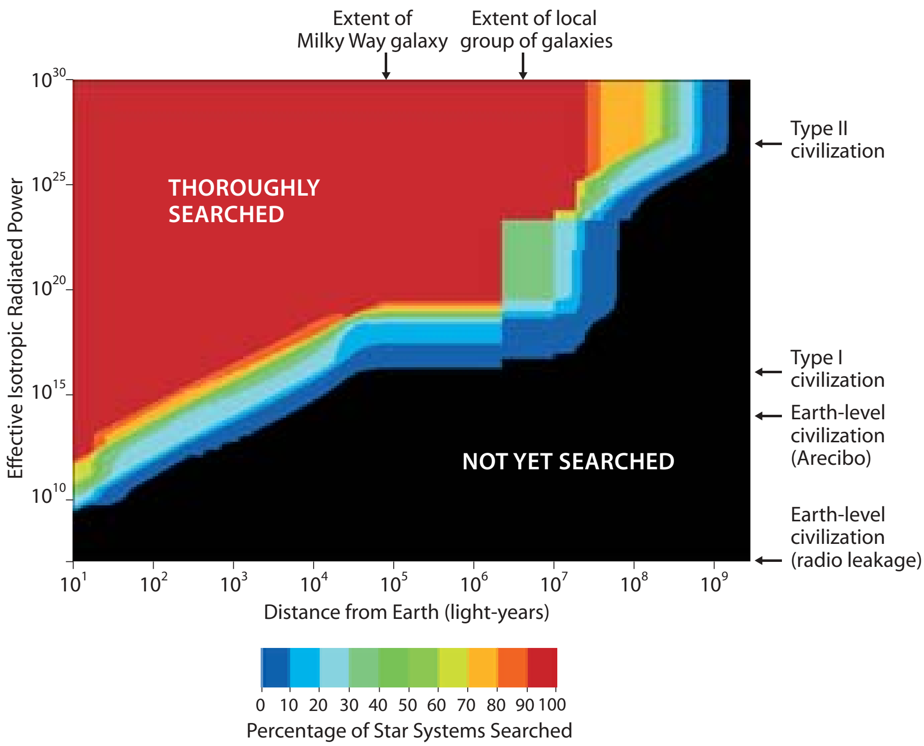
This problem was first discussed in detail by astronomer Michael H. Hart and engineer David Viewing in independent papers, both published in 1975. It was later extended by various researchers, most notably physicist Frank J. Tipler and radio astronomer Ronald N. Bracewell. All have taken as their starting point the lack of clear evidence for extraterrestrial visits to Earth. Whatever one thinks about UFOs, we can be sure that Earth has not been taken over by an extraterrestrial civilization, as this would have put an end to our own evolution and we would not be here today.

There are only four conceivable ways of reconciling the absence of ETs with the widely held view that advanced civilizations are common. Perhaps interstellar spaceflight is infeasible, in which case ETs could never have come here even if they had wanted to. Perhaps ET civilizations are indeed actively exploring the galaxy but have not reached us yet. Perhaps interstellar travel is feasible, but ETs choose not to undertake it. Or perhaps ETs have been, or still are, active in Earth's vicinity but have decided not to interfere with us. If we can eliminate each of these explanations of the Fermi Paradox, we will have to face the possibility that we are the most advanced life-forms in the galaxy.

The first explanation clearly fails. No known principle of physics or engineering rules out interstellar spaceflight. Even in these early days of the space age, engineers have envisaged propulsion strategies that might reach 10 to 20 percent of the speed of light, thereby permitting travel to nearby stars in a matter of decades [see "Reaching for the Stars," by Stephanie D. Leifer; Scientific American, February 1999].

For the same reason, the second explanation is problematic as well. Any civilization with advanced rocket technology would be able to colonize the entire galaxy on a cosmically short timescale. For example, consider a civilization that sends colonists to a few of the planetary systems closest to it. After those colonies have established themselves, they send out secondary colonies of their own, and so on. The number of colonies grows exponentially. A colonization wave front will move outward with a speed determined by the speed of the starships and by the time required by each colony to establish itself. New settlements will quickly fill in the volume of space behind this wave front [*see illustration on next page*].

Assuming a typical colony spacing of 10 light-years, a ship speed of 10 percent that of light, and a period of 400 years between the foundation of a colony and its sending out colonies of its own, the colonization wave front will expand at



ANDREW J. LEPAGE

RESULTS OF SETI PROGRAMS are summarized in this diagram. The black area shows which civilizations could have eluded our radio searches, either because they are too far away or because their transmitters are too weak. To make sense of this diagram, choose a transmitter strength (*vertical axis*), read across to the edge of the black area and go down to find the distance from Earth (*horizontal axis*). For example, an Arecibo-class transmitter of 10^{14} watts must be farther away than about 4,000 light-years to have eluded the searches altogether. The color code provides more detailed information—namely, the estimated percentage of all star systems that have been examined for transmitters of a given power or greater.

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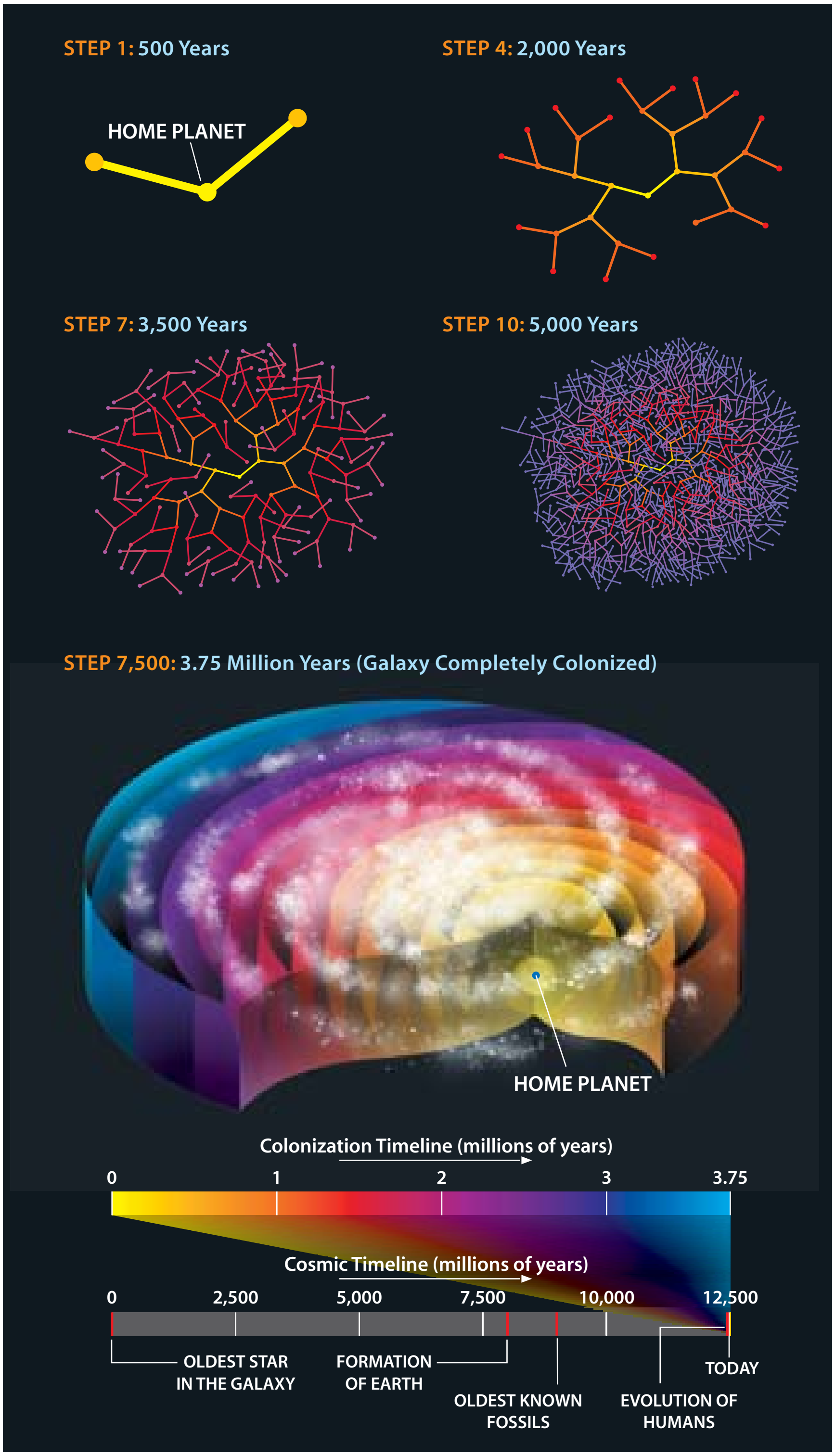

COLONIZATION OF THE GALAXY is not as time-consuming as one might think. Humans could begin the process by sending colonists to two nearby stars, a trip that might take 100 years with foreseeable technology. After 400 years to dig in, each colony sends out two of its own, and so on. Within 10,000 years our descendants could inhabit every star system within 200 light-years. Settling the entire galaxy would take 3.75 million years—a split second in cosmic terms. If even one alien civilization has ever undertaken such a program, its colonies should be everywhere we look.

an average speed of 0.02 light-year a year. As the galaxy is 100,000 light-years across, it takes no more than about five million years to colonize it completely. Though a long time in human terms, this is only 0.05 percent of the age of the galaxy. Compared with the other relevant astronomical and biological timescales, it is essentially instantaneous. The greatest uncertainty is the time required for a colony to establish itself and spawn new settlements. A reasonable upper limit might be 5,000 years, the time it has taken human civilization to develop from the earliest cities to spaceflight. In that case, full galactic colonization would take about 50 million years.

The implication is clear: the first technological civilization with the ability and the inclination to colonize the galaxy could have done so before any competitors even had a chance to evolve. In principle, this could have happened billions of years ago, when Earth was inhabited solely by microorganisms and was wide open to interference from outside. Yet no physical artifact, no chemical traces, no obvious biological influence indicates that it has ever been intruded upon. Even if Earth was deliberately seeded with life, as some scientists have speculated, it has been left alone since then.

It follows that any attempt to resolve the Fermi Paradox must rely on assumptions about the behavior of other civilizations. For example, they might destroy themselves first, they might have no interest in colonizing the galaxy, or they might have strong ethical codes against interfering with primitive life-forms. Many SETI researchers, as well as others who are convinced that ET civilizations must be common, tend to dismiss the implications of the Fermi Paradox by an uncritical appeal to one or more of these sociological considerations.

But they face a fundamental problem. These attempted explanations are plausible only if the number of extraterrestrial civilizations is small. If the galaxy has contained millions or billions of technological civilizations, it seems very unlikely that they would all destroy themselves, be content with a sedentary existence, or agree on the same set of ethical rules for the treatment of less developed forms of life. It would take only one technological civilization to embark, for whatever reason, on a program of galactic colonization. Indeed, the only technological civilization we actually know anything about—namely, our own—has yet to self-destruct, shows every sign of being expansionist, and is not especially reticent about interfering with other living things.

Despite the vastness of the endeavor, I think we can identify a number of reasons why a program of interstellar colonization is actually quite likely. For one,

BRYAN CHRISTIE; CALCULATIONS BY GEORGE MUSSER a species with a propensity to colonize would enjoy evolutionary advantages on its home planet, and it is not difficult to imagine this biological inheritance being carried over into a space-age culture. Moreover, colonization might be undertaken for political, religious or scientific reasons. The last seems especially probable if we consider that the first civilization to evolve would, by definition, be alone in the galaxy. All its SETI searches would prove negative, and it might initiate a program of systematic interstellar exploration to find out why.

Resolving the Paradox?

Furthermore, no matter how peaceable, sedentary or uninquisitive most ET civilizations may be, ultimately they will all have a motive for interstellar migration, because no star lasts forever. Over the history of the galaxy, hundreds of millions of solar-type stars have run out of hydrogen fuel and ended their days as red giants and white dwarfs. If civilizations were common around such stars, where have they gone? Did they all just allow themselves to become extinct?

The apparent rarity of technological civilizations begs for an explanation. One possibility arises from considering the chemical enrichment of the galaxy. All life on Earth, and indeed any conceivable extraterrestrial biochemistry, depends on elements heavier than hydrogen and helium—principally, carbon, nitrogen and oxygen. These elements, produced by nuclear reactions in stars, have gradually accumulated in the interstellar medium from which new stars and planets form. In the past the concentrations of these elements were lower—possibly too low to permit life to arise. Among stars in our part of the galaxy, the sun has a relatively high abundance of these elements for its age. Perhaps our solar system had a fortuitous head start in the origins and evolution of life.

But this argument is not as compelling as it may at first appear. For one, researchers do not know the critical threshold of heavy-element abundances that life requires. If abundances as low as a tenth of the solar value suffice, as seems plausible, then life could have arisen around much older stars. And although the sun does have a relatively high abundance of heavy elements for its age, it is certainly not unique [see "Here Come the Suns," by George Musser; Scientific American, May 1999]. Consider the nearby sunlike star 47 Ursae Majoris, one of the stars around which a Jupiter-mass planet has recently been discovered. This star has the same element abundances as the sun, but its estimated age is seven billion years. Any life that may have arisen in its planetary system should have had a 2.5-billion-year head start on us. Many millions of similarly old and chemically rich stars populate the galaxy, especially toward the center. Thus, the chemical evolution of the galaxy is almost certainly not able to fully account for the Fermi Paradox.

To my mind, the history of life on Earth suggests a more convincing explanation. Living things have existed here almost from the beginning, but multicellular animal life did not appear until about 700 million years ago. For more than three billion years, Earth was inhabited solely by single-celled microorganisms. This time lag seems to imply that the evolution of anything more complicated than a single cell is unlikely. Thus, the transition to multicelled animals might occur on only a tiny fraction of the millions of planets that are inhabited by single-celled organisms.

It could be argued that the long solitude of the bacteria was simply a necessary precursor to the eventual appearance of animal life on Earth. Perhaps it took this long—and will take a comparable length of time on other inhabited planets—for bacterial photosynthesis to produce the quantities of atmospheric oxygen required by more complex forms of life. But even if multicelled life-forms do eventually arise on all life-bearing planets, it still does not follow that these will inevitably lead to intelligent creatures, still less to technological civilizations. As pointed out by Stephen Jay Gould in his book *Wonderful Life*, the evolution of intelligent life depends on a host of essentially random environmental influences.

This contingency is illustrated most clearly by the fate of the dinosaurs. They dominated this planet for 140 million years yet never developed a technological civilization. Without their extinction, the result of a chance event, evolutionary history would have been very different. The evolution of intelligent life on Earth has rested on a large number of chance events, at least some of which had a very low probability. In 1983 physicist Brandon Carter concluded that "civilizations comparable with our own are likely to be exceedingly rare, even if locations as favorable as our own are of common occurrence in the galaxy." Of course, all these arguments, though in my view persuasive, may turn out to be wide of the mark. In 1853 William Whewell, a prominent protagonist in the extraterrestrial-life debate, observed, "The discussions in which we are engaged belong to the very boundary regions of science, to the frontier where knowledge ... ends and ignorance begins." In spite of all the advances since Whewell's day, we are in basically the same position today. And the only way to lessen our ignorance is to explore our cosmic surroundings in greater detail.

That means we should continue the SETI programs until either we detect signals or, more likely in my view, we can place tight limits on the number of radio-transmitting civilizations that may have escaped our attention. We should pursue a rigorous program of Mars exploration with the aim of determining whether or not life ever evolved on that planet and, if not, why not. We should press ahead with the development of large space-based instruments capable of detecting Earth-size planets around nearby stars and making spectroscopic searches for signs of life in their atmospheres. And eventually we should develop technologies for interstellar space probes to study the planets around nearby stars.

Only by undertaking such an energetic program of exploration will we reach a fuller understanding of our place in the cosmic scheme of things. If we find no evidence for other technological civilizations, it may become *our* destiny to embark on the exploration and colonization of the galaxy. SA

The Author

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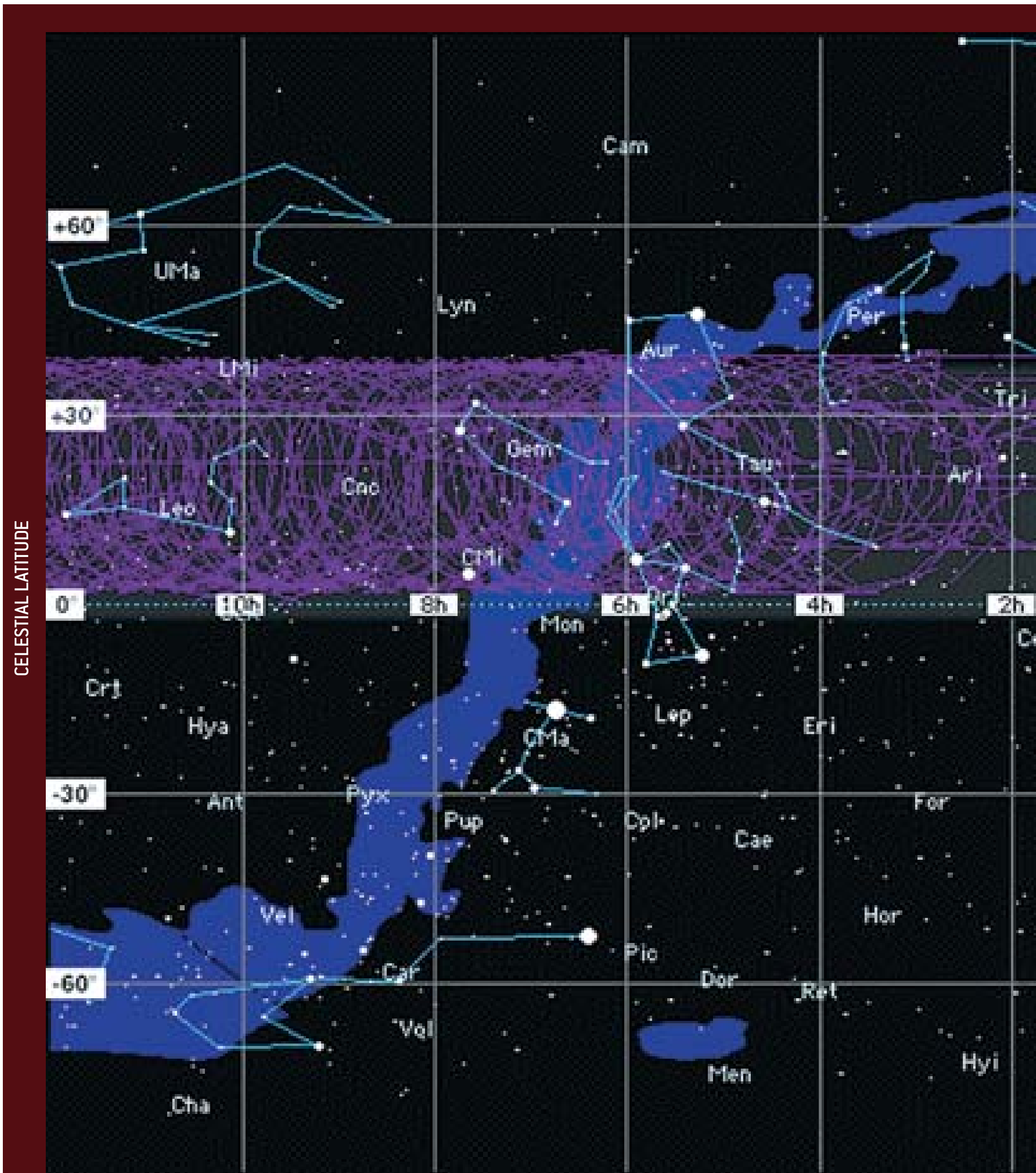
originally published December 1999

Is There Life Elsewhere in the Universe?

The answer is: nobody knows.
Scientists' search for life beyond Earth has been less thorough than commonly thought.
But that is about to change

by Jill C. Tarter and Christopher F. Chyba

One of the ongoing searches for alien radio signals, SETI@home, scans a stripe across the sky. Because the Arecibo Observatory in Puerto Rico has only a limited ability to steer, the stripe extends from the celestial equator up to a declination (celestial latitude) of 35 degrees—which fortuitously includes many of the recently discovered planetary systems. To observe year-round and avoid interfering with other astronomical observations, SETI@home simply tags along wherever the telescope happens to be pointing. Over time, it sweeps across the band.



For 40 years, scientists have conducted searches for radio signals from an extraterrestrial technology, sent spacecraft to all but one of the planets in our solar system, and greatly expanded our knowledge of the conditions in which living things can survive. The public perception is that we have looked extensively for signs of life elsewhere. But in reality, we have hardly begun our search.

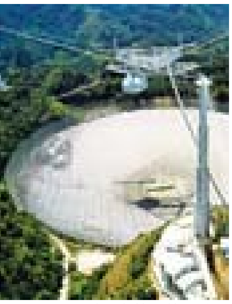
Assuming our current, comparatively robust space program continues, by 2050 we may finally know whether there is, or ever was, life elsewhere in our solar system. At a minimum we will have thoroughly explored the most likely candidates, something we cannot claim today. We will have discovered whether life dwells on Jupiter's moon Europa or on Mars. And we will have undertaken the systematic exobiological exploration of planetary systems around other stars, looking for traces of life in the spectra of planetary atmospheres. These surveys will be complimented by expanded searches for intelligent signals.

We may find that life is common but technical intelligence is extremely rare or that both are common or rare.

SETI@HOME, UNIVERSITY OF CALIFORNIA, BERKELEY

CELESTIAL LONGITUDE

For now, we just don't know. The Milky Way galaxy is vast, and we have barely stirred its depths. Indeed, we have so poorly explored our own solar system that we cannot even rule out exotic possibilities such as the existence of a small robotic craft sent here long ago to await our emergence as a technological species. Over the next 50 years, our searches for extraterrestrial intelligence will perhaps meet with success. Or the situation may remain the same as it was in 1959, when astrophysicists Giuseppe Cocconi and Philip Morrison concluded, "The probability of success is difficult to estimate, but if we never search, the chance of success is zero."



SETH SHOSTAK *SETI Institute* (*Arecibo Observatory*)

Radio-frequency interference might force us to take our search to the far side of the moon, maybe to the Saha crater.

A search for life elsewhere must by guided by a practical definition of life. Many researchers studying the origins of life have adopted a "Darwinian" definition, which holds that life is a self-sustained chemical system capable of undergoing Darwinian evolution by natural selection. By this definition, we will have made living systems of molecules in the laboratory well before 2050. The extent to which these systems will inform us about the early history of life here or elsewhere is unclear, but at least they will give us some examples of the diversity of plausible biological styles.

Unfortunately, the Darwinian definition is not terribly useful from the point of view of spacecraft exploration. How long should one wait to see whether a chemical system is capable of undergoing evolution? As a practical matter, the Darwinian approach must give way to less precise but operationally more useful definitions. Consider the biology experiments that the twin Viking spacecraft carried to Mars in 1976. Researchers implicitly adopted a metabolic definition: they hoped to recognize Martian life through its consumption of chemicals. One of the tests they conducted, the labeled-release experiment (which checked whether a soil sample fed with nutrients gave off gaseous carbon), did in fact suggest the presence of organisms. In the words of Viking biology team leader Chuck Klein, its findings "would almost certainly have been interpreted as presumptive evidence for biology" were it not for contradictory data from other experiments.

Lessons from Viking

Foremost among these other experiments was the Viking gas chromatograph and mass spectrometer, which searched for organic molecules. None were found; consequently, scientists explained the labeled-release results as unanticipated chemistry rather than biology [see "The Search for Life on Mars," by Norman H. Horowitz; Scientific American, November 1977]. In effect, they adopted a biochemical definition for life: Martian life, like that on Earth, would be based on organic carbon.

The Viking experience holds important lessons. First, although we should search for life from the perspective of multiple definitions, the biochemical definition seems likely to trump others whenever the sensing is done remotely; in the absence of organic molecules, biologically suggestive results will probably be distrusted. Second, researchers must establish the chemical and geological context in

SETH SHOSTAK *SETI Institute*

Large arrays of small dishes will conduct the next generation of searches for extraterrestrial intelligence. The plans call for hundreds or even thousands of satellite-television antennas, which collectively offer higher sensitivity, broader frequency coverage and better resilience to interference. The first such instrument, the 1hT (which will have a total collecting area of one hectare, or 2.5 acres), is projected to cost $25 million.

order to interpret putative biological findings. Finally, life detection experiments should be designed to provide valuable information even in the case of a negative result. All these conclusions are being incorporated into thinking about future missions, such as the experiments to be flown on the first Europa lander.

In addition to a biochemical instrument, a valuable life detection experiment might involve a microscope. The advantage of a microscope is that it makes so few assumptions about what might be found. But the recent controversy over Allan Hills 84001, the Martian meteorite in which some researchers have claimed to see microfossils, reminds us that the shape of microscopic features is unlikely to provide unambiguous evidence for life. There are just too many nonbiological ways of producing structures that appear biological in origin.

Europa may be the most promising site for life elsewhere in the solar system. Growing evidence indicates that it harbors the solar system's second extant ocean—a body of water that has probably lasted for four billion years underneath a surface layer of ice. The exploration of Europa will begin with a mission, scheduled for launch in 2003, designed to prove whether or not the ocean is really there [see "The Hidden Ocean of Europa," by Robert T. Pappalardo, James W. Head and Ronald Greeley; Scientific American, October]. A positive answer will inspire a program of detailed exploration—including landers and perhaps, ultimately, ice-penetrating submarines—that will check whether the ocean is home to life. Whatever the outcome, we will certainly learn a great deal more about the limits of life's adaptability and the conditions under which it can arise. On Earth, wherever there is liquid water, there is life, even in unexpected places, such as deep within the crust.

Another Jovian satellite, Callisto, also shows signs of a sea. In fact, subsurface oceans might be standard features of large icy satellites in the outer solar system. Saturn's moon Titan could be another example. Because Titan is covered with a kind of atmospheric organic smog layer, we have not yet seen its surface in any detail [see "Titan," by Tobias Owen; Scientific American, February 1982]. In 2004 the Huygens probe will drop into its atmosphere, floating down for two hours and sending back images. Some models suggest that there may be liquid hydrocarbons flowing on Titan's surface. If these organics mix with subsurface liquid water, what might be possible?

Inter(pla)net

By 2050 we will have scoured the surface and some of the subsurface of Mars. Already the National Aeronautics and Space Administration is launching two spacecraft to Mars each time it and Earth are suitably aligned, every 26 months. In addition, researchers now plan a series of Mars micromissions: infrastructure and technology demonstrations that take advantage of surplus payload available on launches of the European Space Agency's Ariane 5 rocket. By 2010 we expect to have established a Mars global positioning system and computer network. Computer users on Earth will be able to enjoy continuous live video returned from robot rovers exploring Mars on the ground and in the air. In a virtual sense, hundreds of millions of people will visit Mars regularly, and it will come to seem a familiar place. As the Internet becomes interplanetary, we will inevitably come to think of ourselves as a civilization that spans the solar system.

Within a decade, we will begin returning samples from Mars to Earth. But the best places to look for extant life—Martian hot springs (if they exist) and deep niches containing liquid water—may well be the most demanding for robot explorers. In the end, we will probably need to send human explorers. Despite the difficulties, we foresee the first permanent human outposts on Mars, with regularly rotating crews, by 2050. Humans will work closely with robots to explore in detail those sites identified as the most likely venues for life or its fossil remains.

If researchers discover life on Mars, one of the first questions they will ask is: Is it related to us? An important realization of the past 10 years is that the planets of the inner solar system may not have been biologically isolated. Viable organisms could have moved among Mars, Earth and Venus

SETI INSTITUTE

An extraterrestrial signal shows up as a slightly tilted streak on a plot such as this one. Each dot denotes the detection of radio energy at a given frequency (**horizontal axis**) and time (**vertical axis**). Scattered dots are noise; a line represents a regular signal. For an extraterrestrial signal, the line is slanted, because Earth's rotation shifts the frequency. In this case, the transmission (**arrow**) comes from a spaceship—one of ours, Pioneer 10, which is now 73 times as far from the sun as Earth is.

Lurking in the depths of Europa could be our fellow inhabitants of the solar system. The surface of Europa, mishmashed by icebergs, hints at a subterranean ocean. Life survives deep in Earth's crust and oceans. Could it survive on this world, too?

enclosed in rocks ejected by large impacts. Thus, whichever world first developed life may have then inoculated the others. If life exists on Mars, we may share a common ancestor with it. If so, DNA comparison could help us determine the world of origin. Of course, should Martian life be of independent origin from life on Earth, it may lack DNA altogether. The discovery of a second genesis within our solar system would suggest that life develops wherever it can; such a finding would buttress arguments for the ubiquity of life throughout the universe [see "The Search for Extraterrestrial Life," by Carl Sagan; SCIENTIFIC AMERICAN, October 1994].

An essential part of our exploration of Mars and other worlds will be planetary protection. NASA now has guidelines to protect the worlds that it visits against contamination with microorganisms carried from Earth. We have much to learn about reducing the bioload of spacecraft we launch elsewhere. Progress is demanded—scientifically by the requirement of not introducing false positives, legally by international treaty and, we believe, ethically by the imperative to protect any alien biospheres.

ILLUSTRATION BY RON MILLER

And what about other planetary systems? Already we know of more planets outside our solar system than within it. Well before 2050 the first truly interstellar missions will be flying out of our solar system, perhaps sent on the wings of giant solar sails. They will directly sample the prolific organic chemistry (already revealed by radio telescopes) present between the stars. They will not reach the nearest systems by 2050—with present technology, the trip would take tens of thousands of years—so we will have to study those systems remotely.

By 2050 we will have catalogues of extrasolar planetary systems analogous to our current catalogues of stars. We will know whether our particular planetary system is typical or unusual (we suspect it will prove to be neither). Currently the only worlds our technology routinely detects are giant planets more massive than Jupiter. But advanced space-based telescopes will regularly detect Earth-size worlds around other stars, if they exist, and analyze their atmospheres for hints of biological processes. Such worlds would then become compelling targets for additional observations, including searches for intelligent signals.

Window on the Worlds

Although we talk of searching for extraterrestrial intelligence (SETI), what we are seeking is evidence of extraterrestrial technologies. It might be better to use the acronym SET-T (pronounced the same) to acknowledge this. To date, we have concentrated on a very specific technology—radio transmissions at wavelengths with weak natural backgrounds and little absorption [see "The Search for Extraterrestrial Intelligence," by Carl Sagan and Frank Drake; SCIENTIFIC AMERICAN, May 1975]. No one has yet found any verified signs of a distant technology. But the null result may have more to do with limitations in range and sensitivity than with actual lack of civilizations. The most distant star probed directly is still less than 1 percent of the distance across our galaxy.

SETI, like all of radio astronomy, now faces a crisis. Humanity's voracious appetite for technologies that utilize the radio spectrum is rapidly obscuring the natural window with curtains of radio-frequency interference. This trend might eventually force us to take our search to the far side of the moon, the one place in the solar system that never has Earth in its sky. International agreements have already established a "shielded zone" on the moon, and some astronomers have discussed reserving the Saha crater for radio telescopes. If the path for human exploration of Mars proceeds via the moon, then by 2050 the necessary infrastructure may be in place.

Plans for the next few decades of SETI also envision the construction of a variety of ground-based instruments that offer greater sensitivity, frequency coverage and observing time. Currently all these plans rely on private philanthropic funding. For searches at radio frequencies, work has commenced on the One Hectare Telescope (1hT), which will permit simultaneous access to the entire microwave window. A large field of view—and a large amount of computational power—will enable dozens of objects to be observed at the same time, a mix of SETI targets and natural astronomical bodies. Radio astronomy and SETI will thus be able to share telescope resources, rather than compete for them, as is frequently the case now. The 1hT will also demonstrate one affordable way to build a still larger Square Kilometer Array (SKA) that could improve sensitivity by a factor of 100 over anything available today. For SETI, this factor of 100 translates into a factor of 10 in distance and 1,000 in the number of stars explored.

These arrays will be affordable because their hardware will derive from recent consumer products. To the extent possible, complexity will be transferred from concrete and steel to silicon and software. We will be betting on Moore's Law—the exponential increase in computing power over time. The SETI@home screensaver, which more than a million people around the globe have downloaded (from www.setiathome.ssl.berkeley. edu), illustrates the kind of parallel computation available even today. By 2050 we may have built many SKAs and used them to excise actively the growing amount of interference. If successful, such instruments will certainly be more affordable than an observatory on the lunar far side.

Recently other wavelength bands besides the radio have been receiving attention. Generations of stargazers have scanned the heavens with naked eyes and telescopes without ever seeing an artifact of astroengineering. But what if it flashed for only a billionth of a second? Limited searches for optical pulses have just begun. In the coming decades, optical SETI searches may move on to larger telescopes. If these initial searches do not succeed in finding other civilizations, they will at least probe astrophysical backgrounds at high time resolution.

The increased pace of solar system exploration will provide additional opportunities for SETI. We should keep our robotic eyes open for probes or other artifacts of an extraterrestrial technology. Despite tabloid reports of aliens and artifacts everywhere, scientific exploration so far has revealed no good evidence for any such things.

Sharing the Universe

Although we cannot state with confidence what we will know about other intelligent occupants of the universe in 2050, we can predict that whatever we know, everyone will know. Everyone will have access to the process of discovery. Anyone who is curious will be able to keep score of what searches have been done and which groups are looking at what, from where, at any given moment. The data generated by the searches will flow too quickly for humans to absorb, but the interesting signals, selected by silicon sieves, will be available for our perusal. In this way, we hope to supplant the purveyors of pseudoscience who attract the curious and invite them into a fantastic (and lucrative) realm of nonsense. Today the real data are too often inaccessible, whereas the manufactured data are widely available. The real thing is better, and it will be much easier to access in the future.

If by 2050 we have found no evidence of an extraterrestrial technology, it may be because technical intelligence almost never evolves, or because technical civilizations rapidly bring about their own destruction, or because we have not yet conducted an adequate search using the right strategy. If humankind is still here in 2050 and still capable of doing SETI searches, it will mean that our technology has not yet been our own undoing—a hopeful sign for life generally. By then we may begin considering the active transmission of a signal for someone else to find, at which point we will have to tackle the difficult questions of who will speak for Earth and what they will say.

The Authors

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JILL C. TARTER participated in her first search for extraterrestrial intelligence in 1976 while an astrophysics graduate student at the University of California, Berkeley. Her current effort is over 1,000 times as sensitive. Tarter's career bears a striking resemblance to that of Ellie Arroway, the heroine of Carl Sagan's novel *Contact.* Today she is the director of research for the SETI Institute in Mountain View, Calif. When not observing, lecturing or fundraising, she enjoys flying a private plane and dancing the samba.

SETI INSTITUTE

CHRISTOPHER F. CHYBA is a planetary scientist whose research focuses on the origins of life and exobiology. He recently led the Science Definition Team for NASA's 2003 Orbiter mission to Europa. He now chairs the space agency's Solar System Exploration Subcommittee, which recommends priorities for solar system exploration. Chyba is a former director for international environmental affairs on the National Security Council staff at the White House. At the SETI Institute, he holds the endowed chair named for his graduate school adviser, Carl Sagan.

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An Ear to the Stars

Despite long odds, astronomer Jill C. Tarter forges ahead to improve the chances of picking up signs of extraterrestrial intelligence By NAOMI LUBICK

In a photograph hanging outside her office, Jill C. Tarter stands a head taller than Jodie Foster, the actress who played an idealistic young radio astronomer named Ellie Arroway in the film *Contact*. Tarter was not the model for the driven researcher at the center of Carl Sagan's book of the same name, although she understands why people often make that assumption. In fact, she herself did so after reading the page proofs that Sagan had sent her in 1985. After all, both she and Arroway were only children whose fathers encouraged their interest in science and who died when they were still young girls. And both staked their lives and careers on the search for extraterrestrial intelligence (SETI), no matter how long the odds of detecting an otherworldly sign. But no, Tarter says, the character is actually Sagan himself—they all just share the same passion.

In her position as director of the Center for SETI Research at the SETI Institute in Mountain View, Calif., Tarter has recently focused on developing new technology for observing radio signals from the universe. The concept, first presented in the 1950s, is that a technologically advanced civilization will leak radio signals. Some may even be transmitting purposefully.

So far there haven't been any confirmed detections. Amid the radio chatter from natural and human sources, there have been some hiccups and a few heart-stoppingly close calls. On her first observing run at Green Bank Observatory in West Virginia, Tarter detected a signal that was clearly not natural. But it turned out to come from a telescope operator's CB radio.

Tarter's current project is the Allen Telescope Array, consisting of a set of about 350 small satellite dishes in Hat Creek, Calif. The system, which will span about 10,000 square meters and will be the first radio-telescope array built specifically for SETI projects, is funded by private investors. Its observing speed will be 100 times as fast as that of today's equipment, and it will expand observable frequency ranges.

Tarter has often been a lone and nontraditional entity in her environment. Her interest in science, which began with engineering physics, was nurtured by her father, who died when she was 12. As with most other female scientists of her generation, Tarter says, a father's encouragement was "just enough to make the difference about whether you blew off the negative counseling" that girls interested in science often got. Her mother worried about her when she departed in the 1960s from their suburban New York home for Cornell University, when women there were still locked in their dorms overnight. She was the only female student in the engineering school that year. (Tarter is a descendant of Ezra Cornell, the university's founder, although at the time her gender meant that she would not receive the family scholarship.)

"There's an enormous amount of problem solving, of homework sets to be done as an engineering student," Tarter recalls. Whereas male students formed teams, sharing the workload, "I sat in my dorm and did them all by myself." Puzzling out the problems alone gave her a better education in some ways, she says, but "it was socially very isolating, and I lost the ability to build teaming skills."

Her independence and eventual distaste for engineering led her to do her graduate work in physics at Cornell, but Tarter soon left for the University of California at Berkeley to pursue a doctorate in astronomy. While working on her Ph.D., which she completed in 1975, Tarter was also busy raising a daughter from her

JILL C. TARTER: SETI SEARCHER

- **Grew up in Scarsdale, N.Y., and is a descendant of Cornell University's founder.**
- **Most influential cartoon: *Flash Gordon.***
- **In the July *Astronomical Journal,* she and two colleagues conclude that there are no more than 10,000 civilizations in the Milky Way at about our level of technological advancement.**
- **"I just can't ever remember a time when I didn't assume that the stars were somebody else's suns."**

first marriage, to C. Bruce Tarter, who has directed Lawrence Livermore National Laboratory for the past eight years. The two had married in Tarter's junior year of college and moved to California together. Tarter's postdoctoral work there was on brown dwarfs, a term she coined in the 1970s for what was then a hypothetical planetlike body (only recently have they been observed directly).

By chance, an ancient computer led Tarter to SETI. She had programmed a signal-processing machine as a first-year graduate student. When astronomer Stuart Bowyer acquired the computer from a colleague several years later for a SETI project—lack of funds forced Bowyer into looking for handouts—he approached Tarter, because someone remembered that she had used it.

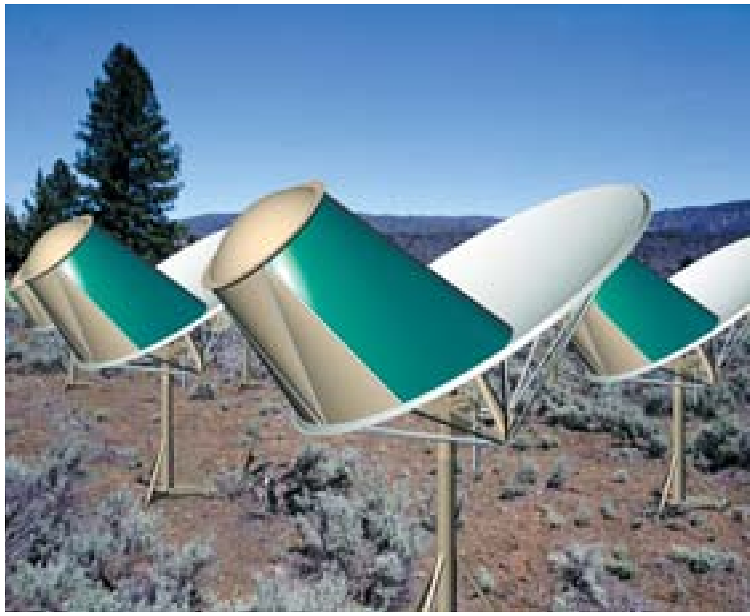
To persuade her to join the project, Bowyer placed a copy of a report on her desk called Project Cyclops, a NASA study conducted by Bernard M. Oliver of Hewlett Packard Corp. on possible system designs for detecting extraterrestrial life. Tarter read the hefty volume cover to cover in one night. Hooked on the idea of SETI, she would work with Frank Drake, who in 1960 conducted Ozma, the first American SETI project, and with William "Jack" Welch, who taught her radio astronomy and would become her second husband in 1980. Astronomer John Billingham hired her to join the small group of SETI researchers at NASA, a group that Tarter helped to turn into the SETI Institute in 1984. She became director of SETI's Project Phoenix in 1993, so named because it was resurrected after Congress removed its funding.

The SETI project has always seemed to be NASA's astronomical stepchild, Tarter explains, partly because of the "little green men" associations. But the congressional rejection of the search for intelligent life paradoxically gave new life to its pursuit.

Operating outside the confines of NASA's bureaucracy, Tarter says, the SETI Institute runs like a nonprofit business. The current funding for projects has come from venture capitalists—wealthy scientific philanthropists such as Paul G. Allen and Nathan P. Myhrvold, both formerly at Microsoft. Some contributors also serve with scientists on a board that supervises SETI's business plan, procedures and results.

Tarter's efforts to push SETI forward with private financing impress even skeptics of the enterprise. Benjamin M. Zuckerman, a radio astronomer who began his career with SETI, is blunt in his disbelief in both the search for and the existence of extraterrestrial intelligence. Still, he finds Tarter's work exceptional and notes that by keeping the public interested in SETI, Tarter has enabled astronomers to continue esoteric work.

Tarter, too, has been able to overcome her solo work tendencies. Her SETI collaborators say she has been an indomitable and tireless team leader. Yet a bout with breast cancer in 1995 may have been a defining moment of her ability to delegate authority. Radiation and chemotherapy treatment required that she step down temporarily as Phoenix project manager and cut back on her travel, thereby forcing her to assign tasks to others. She picked up her grueling pace of going to observatories and attending meetings—not to mention consulting for the movie version of *Contact*—as soon as her therapy ended.



ALLEN TELESCOPE ARRAY (based on artist's conception) will begin working in 2005. Each antenna has a shroud to block ground reflections.

LY LY *SETI Institute*

The SETI Institute's Allen Telescope Array, to start up in 2005, will be Tarter's largest contribution to instrumentation yet. Thanks to advances in computers and telecommunications, the cost of the array is much lower than that of past setups. For instance, each 27-meter-wide dish of the Very Large Array in Socorro, N.M., cost several million dollars in the late 1970s, whereas the SETI Institute paid only $50,000 per dish for the Allen array. Each dish measures 6.1 meters wide and will be set up in a carefully selected, random pattern. The U.C. Berkeley Radio Astronomy Lab and the SETI Institute will co-manage it.

The small dishes will be more mobile than the 305-meter-wide stationary dish at Arecibo, Puerto Rico, where Tarter currently does most of her observing. The Allen array will hear frequencies from 0.5 to 11.2 gigahertz, a span 20 times as wide as what radio telescopes can detect, and results will be high-resolution images of the sky, with a dozen target stars observed at once. Plus, the institute will be able to give time to other observers—instead of competing for it elsewhere.

Tarter strongly believes in the search for extraterrestrial intelligence, although unlike Ellie Arroway, she seems to accept that a momentous signal may not come in her lifetime. Meanwhile she is happy to push the technological boundaries of the earth's listening posts and is already planning even larger telescopes for future Arroways to use.

Naomi Lubick is based in Palo Alto, Calif.

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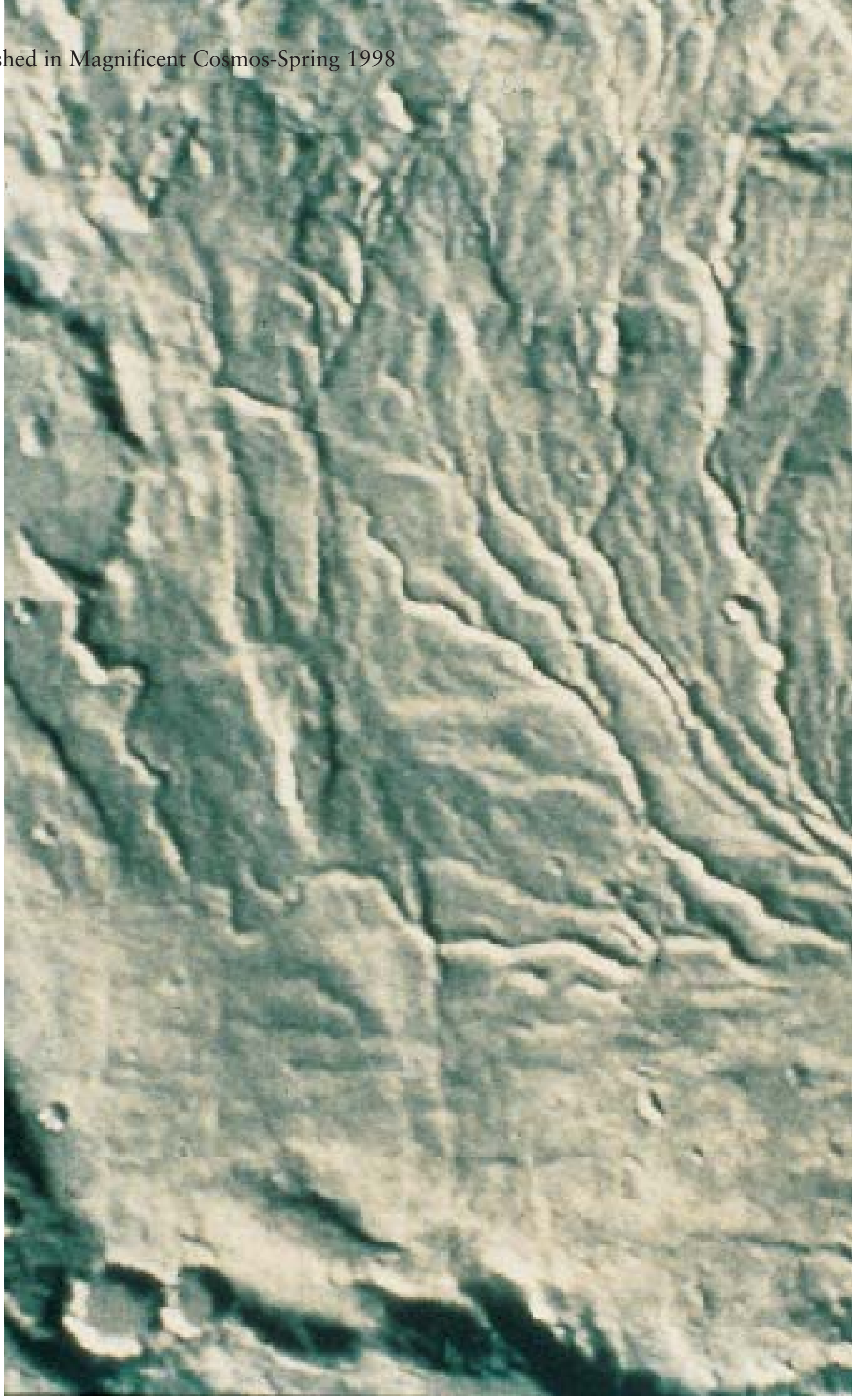


Searching for Life in Our Solar System

If life evolved independently on our neighboring planets or moons, then where are the most likely places to look for evidence of extraterrestrial organisms?

by Bruce M. Jakosky

Since antiquity, human beings have imagined life spread far and wide in the universe. Only recently has science caught up, as we have come to understand the nature of life on Earth and the possibility that life exists elsewhere. Recent discoveries of planets orbiting other stars and of possible fossil evidence in Martian meteorites have gained considerable public acclaim. And the scientific case for life elsewhere has grown stronger during the past decade. There is now a sense that we are verging on the discovery of life on other planets.

To search for life in our solar system, we need to start at home. Because Earth is our only example of a planet endowed with life, we can use it to understand the conditions needed to spawn life elsewhere. As we define these conditions, though, we need to consider whether they are specific to life on Earth or general enough to apply anywhere.

Our geologic record tells us that life on Earth started shortly after life's existence became possible—only after protoplanets (small, planetlike objects) stopped bombarding our planet near the end of its formation. The last "Earth-sterilizing" giant impact probably occurred between 4.4 and 4.0 billion years ago. Fossil microscopic cells and carbon isotopic evidence suggest that life had grown widespread some 3.5 billion years ago and may have existed before 3.85 billion years ago.

DENDRITIC VALLEYS ON MARS resemble river drainage systems on Earth, spanning roughly one kilometer across and several hundred meters deep. Occurring primarily on ancient, cratered terrain, the valleys may have formed from atmospheric precipitation or from underground water that flowed onto the surface. Compared with Earth's drainage systems, the Martian valleys show a lower channel density (number of channels per square kilometer), suggesting that on early Mars water was less abundant than it is on Earth.

COURTESY OF BRUCE M. JAKOSKY

Once it became safe for life to exist, no more than half a billion years—and perhaps as little as 100 million to 200 million years—passed before life rooted itself firmly on Earth. This short time span indicates that life's origin followed a relatively straightforward process, the natural consequence of chemical reactions in a geologically active environment. Equally important, this observation tells us that life may originate along similar lines in any place with chemical and environmental conditions akin to those of Earth.

The standard wisdom of the past 40 years holds that prebiological organic molecules formed in a so-called reducing atmosphere, with energy sources such as lightning triggering chemical reactions to combine gaseous molecules. A more recent theory offers a tantalizing alternative. As water circulates through ocean-floor volcanic systems, it heats to temperatures above 400 degrees Celsius (720 degrees Fahrenheit). When that superhot water returns to the ocean, it can chemically reduce agents, facilitating the formation of organic molecules. This reducing environment also provides an energy source to help organic molecules combine into larger structures and to foster primitive metabolic reactions.

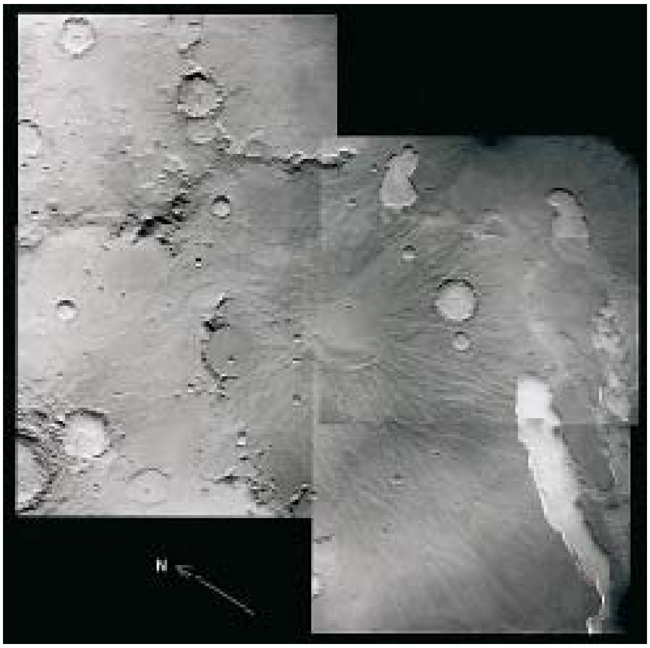
Where Did Life Originate?

The significance of hydrothermal systems in life's history appears in the "tree of life," constructed recently from genetic sequences in RNA molecules, which carry forward genetic information. This tree arises from differences in RNA sequences common to all of Earth's living organisms. Organisms evolving little since their separation from their last common ancestor have similar RNA base sequences. Those organisms closest to the "root"—or last common ancestor of all living organisms—are hyperthermophiles, which live in hot water, possibly as high as 115 degrees C. This relationship indicates either that terrestrial life "passed through" hydrothermal systems at some early time or that life's origin took place within such systems. Either way, the earliest history of life reveals an intimate connection to hydrothermal systems.

As we consider possible occurrences of life elsewhere in the solar system, we can generalize environmental conditions required for life to emerge and flourish. We assume that liquid water is necessary—a medium through which primitive organisms can gain nutrients and disperse waste. Although other liquids, such as methane or ammonia, could serve the same function, water is likely to have been much more abundant, as well as chemically better for precipitating reactions necessary to spark biological activity.

To create the building blocks from which life can assemble itself, one needs access to biogenic elements. On Earth, these elements include carbon, hydrogen, oxygen, nitrogen, sulfur and phosphorus, among the two dozen or so others playing a pivotal role in life. Although life elsewhere might not use exactly the same elements, we would expect it to use many of them. Life on Earth utilizes carbon (over silicon, for example) because of its versatility in forming chemical bonds, rather than strictly its abundance. Carbon also exists readily as carbon dioxide, available as a gas or dissolved in water. Silicon dioxide, on the other hand, exists plentifully in neither form and would be much less accessible. Given the ubiquity of carbon-containing organic molecules throughout the universe, we would expect carbon to play a role in life anywhere.

Of course, an energy source must drive chemical disequi-



COURTESY OF BRUCE M. JAKOSKY

CATASTROPHIC OUTFLOW CHANNEL on Mars—Dao Vallis—is on the flanks of the volcano Hadriaca Patera. Scientists believe the volcano's heat may have caused groundwater to well up, or erupt, onto Mars's surface at this location. The possible combination of volcanic energy and water makes this an intriguing place to search for life.

librium, which fosters the reactions necessary to spawn living systems. On Earth today, nearly all of life's energy comes from the sun, through photosynthesis. Yet chemical energy sources suffice—and would be more readily available for early life. These sources would include geochemical energy from hydrothermal systems near volcanoes or chemical energy from the weathering of minerals at or near a planet's surface.

Possibilities for Life on Mars

Looking beyond Earth, two planets show strong evidence for having had environmental conditions suitable to originate life at some time in their history—Mars and Europa. (For this purpose, we will consider Europa, a moon of Jupiter, to be a planetary body.)

Mars today is not very hospitable. Daily average temperatures rarely rise much above 220 kelvins, some 53 kelvins below water's freezing point. Despite this drawback, abundant evidence suggests that liquid water has existed on Mars's surface in the past and probably is present within its crust today.

Networks of dendritic valleys on the oldest Martian surfaces look like those on Earth formed by running water. The water may have come from atmospheric precipitation or "sapping," released from a crustal aquifer. Regardless of where it came from, liquid water undoubtedly played a role. The valleys' dendritic structure indicates that they formed gradually, meaning that water once may have flowed on Mars's surface, although we do not observe such signs today.

In addition, ancient impact craters larger than about 15 kilometers (nine miles) in diameter have degraded heavily, showing no signs of ejecta blankets, the raised rims or central peaks typically present on fresh craters. Some partly eroded craters display gullies on their walls, which look water-carved. Craters smaller than about 15 kilometers have eroded away entirely. The simplest explanation holds that surface water eroded the craters.

Although the history of Mars's atmosphere is obscure, the atmosphere may have been denser during the earliest epochs, 3.5 to 4.0 billion years ago. Correspondingly, a denser atmosphere could have yielded a strong greenhouse effect, which would have warmed the planet enough to permit liquid water to remain stable. Subsequent to 3.5 billion years ago, evidence tells us that the planet's crust did contain much water. Evidently, catastrophic floods, bursting from below the planet's surface, carved out great flood channels. These floods occurred periodically over geologic time. Based on this evidence, liquid water should exist several kilometers underground, where geothermal heating would raise temperatures to the melting point of ice.

Mars also has had rich energy sources throughout time. Volcanism has supplied heat from the earliest epochs to the recent past, as have impact events. Additional energy to sustain life can come from the weathering of volcanic rocks. Oxidation of iron within basalt, for example, releases energy that organisms can use.

The plentiful availability of biogenic elements on Mars's surface completes life's requirements. Given the presence of water and energy, Mars may well have independently originated life. Moreover, even if life did not originate on Mars, life still could be present there. Just as high-velocity impacts have jettisoned Martian surface rocks into space—only to fall on Earth as Martian meteorites—rocks from Earth could similarly have landed on the red planet. Should they contain organisms that survive the journey and should they land in suitable Martian habitats, the bacteria could survive. Or, for all we know, life could have originated on Mars and been transplanted subsequently to Earth.

An inventory of energy available on Mars suggests that enough is present to support life. Whether photosynthesis evolved, and thereby allowed life to move into other ecological niches, remains uncertain. Certainly, data returned from the Viking spacecraft during the 1970s presented no evidence that life is widespread on Mars. Yet it is possible that some Martian life currently exists, cloistered in isolated, energy-rich and water-laden niches—perhaps in volcanically heated, subsurface hydrothermal systems or merely underground, drawing energy from chemical interactions of liquid water and rock.

Recent analysis of Martian meteorites found on Earth has led many scientists to conclude that life may have once thrived on Mars—based on fossil remnants seen within the rock [*see box below*]. Yet this evidence does not definitively indicate biological activity; indeed, it may result from natural geochemical processes. Even if scientists determine that these rocks contain no evidence of Martian life, life on the red planet might still be possible—but in locations not yet searched. To draw a definitive conclusion, we must study those places where life (or evidence of past life) will most likely appear.

Europa

Europa, on the other hand, presents a different possible scenario for life's origin. At first glance, Europa seems an unlikely place for life. The largest of Jupiter's satellites, Europa is a little bit smaller than our moon, and its surface is covered with nearly pure ice. Yet Europa's interior may be less frigid, warmed by a combination of radioactive decay and tidal heating, which could raise the temperature above the melting point of ice at relatively shallow depths. Because the layer of surface ice stands 150 to 300 kilometers thick, a global, ice-covered ocean of liquid water may exist underneath.

Recent images of Europa's surface from the Galileo spacecraft reveal the possible presence of at least transient pockets of liquid water. Globally, the surface appears covered with long grooves or cracks. On a smaller scale, these quasilinear features show detailed structures indicating local ice-related tectonic activity and infilling from below. On the smallest scale, blocks of ice are present. By tracing the crisscrossing grooves, the blocks clearly have moved with respect to the larger mass. They appear similar to sea ice on Earth—as if large ice blocks had broken off the main mass, floated a small distance away and then frozen in place. Unfortunately, we cannot yet determine if the ice blocks floated through liquid water or slid on relatively warm, soft ice. The dearth of impact craters on the ice indicates that fresh ice continually resurfaces Europa. It is also likely that liquid water is present at least on an intermittent basis.

If Europa has liquid water at all, then that water probably exists at the interface between the ice and underlying rocky interior. Europa's rocky center probably has had volcanic activity—perhaps at a level similar to that of Earth's moon, which rumbled with volcanism until about 3.0 billion years ago. The volcanism within its core would create an energy source for possible life, as would the weathering of minerals reacting with water. Thus, Europa has all the ingredients from which to spark life. Of course, less chemical energy is likely to exist on Europa than Mars, so we should not expect to see an abundance of life, if any. Although the Galileo space probe has detected organic molecules and frozen water on Callisto and Ganymede, two of Jupiter's four Galilean satellites, these moons lack the energy sources that life would require to take hold. Only Io, also a Galilean satellite, has volcanic heat—yet it has no liquid water, necessary to sustain life as we know it.

Mars and Europa stand today as the only places in our solar system that we can identify as having (or having had) all ingredients necessary to spawn life. Yet they are not the only planetary bodies in our solar system relevant to exobiology. In particular, we can look at Venus and at Titan, Saturn's largest moon. Venus currently remains too hot to sustain life, with scorching surface temperatures around 750 kelvins, sustained by greenhouse warming from carbon dioxide and sulfur dioxide gases. Any liquid water has long since disappeared into space.

Venus and Titan

Why are Venus and Earth so different? If Earth orbited the sun at the same distance that Venus does, en Earth, too, would blister with heat—causing more water vapor to fill the atmosphere and augmenting the greenhouse effect. Positive feedback would

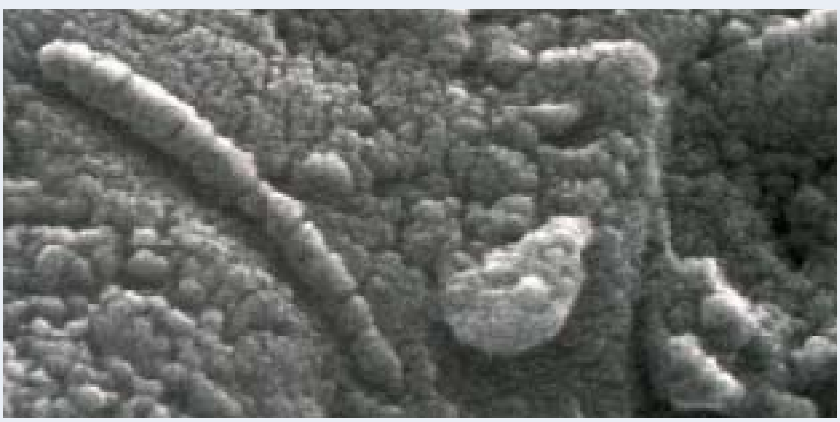
Microbial Remnants from Mars?

In 1984, surveying the Far Western Icefield of the Allan Hills Region of Antarctica, geologist Roberta Score plucked from a plain of wind-blasted, bluish, 10,000-year-old ice an unusual greenish-gray rock. Back at the National Aeronautics and Space Administration Johnson Space Center and at Stanford University, researchers confirmed that the 1.9-kilogram (four-pound), potato-size rock—designated ALH84001—was a meteorite from Mars, one with a remarkable history.

Crystallizing 4.5 billion years ago, shortly after Mars's formation, the rock was ejected from the red planet by a powerful impact, which sent it hurtling through space for 16 million years until it landed in Antarctica 13,000 years ago. Geochemists concluded that the rock's distribution of oxygen isotopes, minerals and structural features was consistent with those of five other meteorites identified as coming from Mars. Lining the walls of fractures within the meteorite are carbonate globules, each a flattened sphere measuring 20 to 250 microns (millionths of meters). The globules appear to have formed in a carbon-dioxide-saturated fluid, possibly water, between 1.3 and 3.6 billion years ago. Within those globules, provocative features vaguely resemble fossilized remnants of ancient Martian microbes.

Tiny iron oxide and iron sulfide grains, resembling ones produced by bacteria on Earth, appear in the globules, as do particular polycyclic aromatic hydrocarbons, often found alongside decaying microbes. Other ovoid and tubular structures resemble fossilized terrestrial bacteria themselves. Although the structures range from 30 to 700 nanometers (billionths of meters) in length, some of the most intriguing tubes measure roughly 380 nanometers long—a size nearing the low end of that for terrestrial bacteria, which are typically one to 10 microns long. The tubes' size and shape indicate they may be fossilized pieces of bacteria, or tinier "nanobacteria," which on Earth measure 20 to 400 nanometers long.

These findings collectively led NASA scientists Everett K. Gibson, David S. McKay and their colleagues to announce in August 1996 that microbes might once have flourished on the red planet. Recent chemical analyses reveal, however, that ALH84001 is heavily contaminated with amino acids from Antarctic ice, a result that weakens the case for microfossils from Mars. *—Richard Lipkin*



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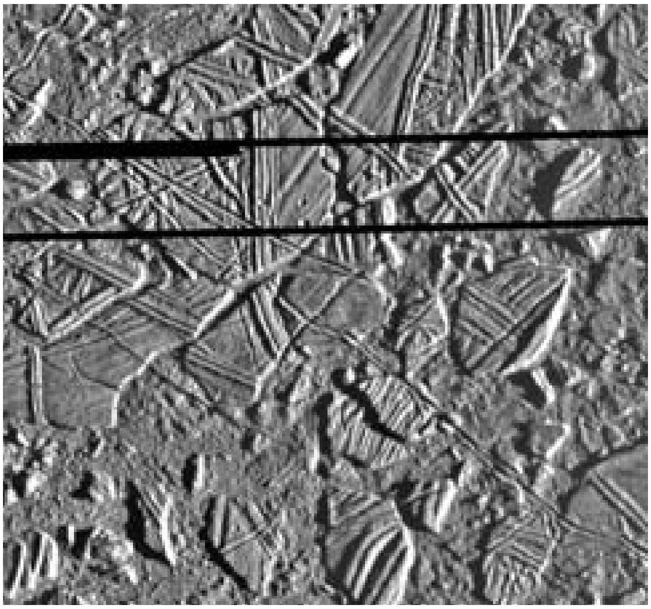
SEEMINGLY FORMED in the Martian meteorite ALH84001, a segmented object (above), some 380 nanometers long, vaguely resembles fossilized bacteria from Earth.



EUROPA'S SURFACE is lined with features that suggest "ice tectonics." Blocks of ice appear to have broken up and shifted, perhaps sliding on slush or possibly even floating on liquid water. Either way, spectral analysis of reflected light indicates nearly pure water ice on Europa's surface. The horizontal black bars through the image designate data lost during interplanetary transmission.

spur this cycle, with more water, greater greenhouse warming and so on saturating the atmosphere and sending temperatures soaring. Because temperature plays such a strong role in determining the atmosphere's water content, both Earth and Venus have a temperature threshold, above which the positive feedback of an increasing greenhouse effect takes off. This feedback loop would load Venus's atmosphere with water, which in turn would catapult its temperatures to very high values. Below this threshold, its climate would have been more like that of Earth.

Venus, though, may not always have been so inhospitable. Four billion years ago the sun emitted about 30 percent less energy than it does today. With less sunlight, the boundary between clement and runaway climates may have been inside Venus's orbit, and Venus may have had surface temperatures only 100 degrees C above Earth's current temperature. Life could survive quite readily at those temperatures—as we observe with certain bacteria and bioorganisms living near hot springs and undersea vents. As the sun became hotter, Venus would have warmed gradually until it would have undergone a catastrophic transition to a thick, hot atmosphere. It is possible that Venus originated life several billion years ago but that high temperatures and geologic activity have since obliterated all evidence of a biosphere. As the sun continues to heat up, Earth may undergo a similar catastrophic transition only a couple of billion years from now.

Titan intrigues us because of abundant evidence of organic chemical activity in its atmosphere, similar to what might have occurred on the early Earth if its atmosphere had potent abilities to reduce chemical agents. Titan is about as big as Mercury, with an atmosphere thicker than Earth's, consisting predominantly of nitrogen, methane and ethane. Methane must be continually resupplied from the surface or subsurface, because photochemical reactions in the atmosphere drive off hydrogen (which is lost to space) and convert the methane to longer chains of organic molecules. These longer-chain hydrocarbons are thought to provide the dense haze that obscures Titan's surface at visible wavelengths.

Surface temperatures on Titan stand around 94 kelvins, too cold to sustain either liquid water or nonphotochemical reactions that could produce biological activity—although Titan apparently had some liquid water during its early history. Impacts during its formation would have deposited enough heat (from the kinetic energy of the object) to melt frozen water locally. Deposits of liquid water might have persisted for thousands of years before freezing. Every part of Titan's surface probably has melted at least once. The degree to which biochemical reactions may have proceeded during such a short time interval is uncertain, however.

Exploratory Missions

Clearly, the key ingredients needed for life have been present in our solar system for a long time and may be present today outside of Earth. At one time or another, four planetary bodies may have contained the necessary conditions to generate life.

We can determine life's actual existence elsewhere only empirically, and the search for life has taken center stage in the National Aeronautics and Space Administration's ongoing science missions. The Mars Surveyor series of missions, scheduled to take place during the coming decade, aims to determine if Mars ever had life. This series will culminate in a mission currently scheduled for launch in 2005, to collect Martian rocks from regions of possible biological relevance and return them to Earth for detailed analysis. The Cassini spacecraft currently is en route to Saturn. There the Huygens probe will enter Titan's atmosphere, its goal to decipher Titan's composition and chemistry. A radar instrument, too, will map Titan's surface, looking both for geologic clues to its history and evidence of exposed lakes or oceans of methane and ethane.

Moreover, the Galileo orbiter of Jupiter is focusing its extended mission on studying the surface and interior of Europa. Plans are under way to launch a spacecraft mission dedicated to Europa, to discern its geologic and geochemical history and to determine if a global ocean lies underneath its icy shell.

Of course, it is possible that, as we plumb the depths of our own solar system, no evidence of life will turn up. If life assembles itself from basic building blocks as easily as we believe it does, then life should turn up elsewhere. Indeed, life's absence would lead us to question our understanding of life's origin here on Earth. Whether or not we find life, we will gain a tremendous insight into our own history and whether life is rare or widespread in our galaxy.

The Author

BRUCE M. JAKOSKY is professor of geology and a member of the Laboratory for Atmospheric and Space Physics at the University of Colorado at Boulder. He is also an investigator on the Mars Global Surveyor mission currently in orbit around Mars. His book *The Search for Life on Other Planets* will be published in the summer of 1998 by Cambridge University Press.

originally published April 1996

Searching for Life on Other Planets

Life remains a phenomenon we know only on Earth. But an innovative telescope in space could change that by detecting signs of life on distant planets

by J. Roger P. Angel and Neville J. Woolf

The possibility that we are not alone in the universe has fascinated people for centuries. In the 1600s Galileo Galilei peered into the night sky with his newly invented telescope, recognized mountains on the moon, and noted that other planets were spheres like Earth. About 60 years later other stargazers observed polar ice caps on Mars, as well as color variations on the planet's surface, which they believed to be vegetation changing with the seasons (the colors are now known to be the result of dust storms). During the latter part of this century, cameras on board unmanned spacecraft captured images from Mars of channels carved by long gone rivers, offering hope that life once may have existed there. But samples of Martian soil obtained in the 1970s by the *Viking* lander spacecraft lacked material evidence of any life. Indeed, the present conditions in the rest of our solar system seem to be generally incompatible with life like that found on Earth.

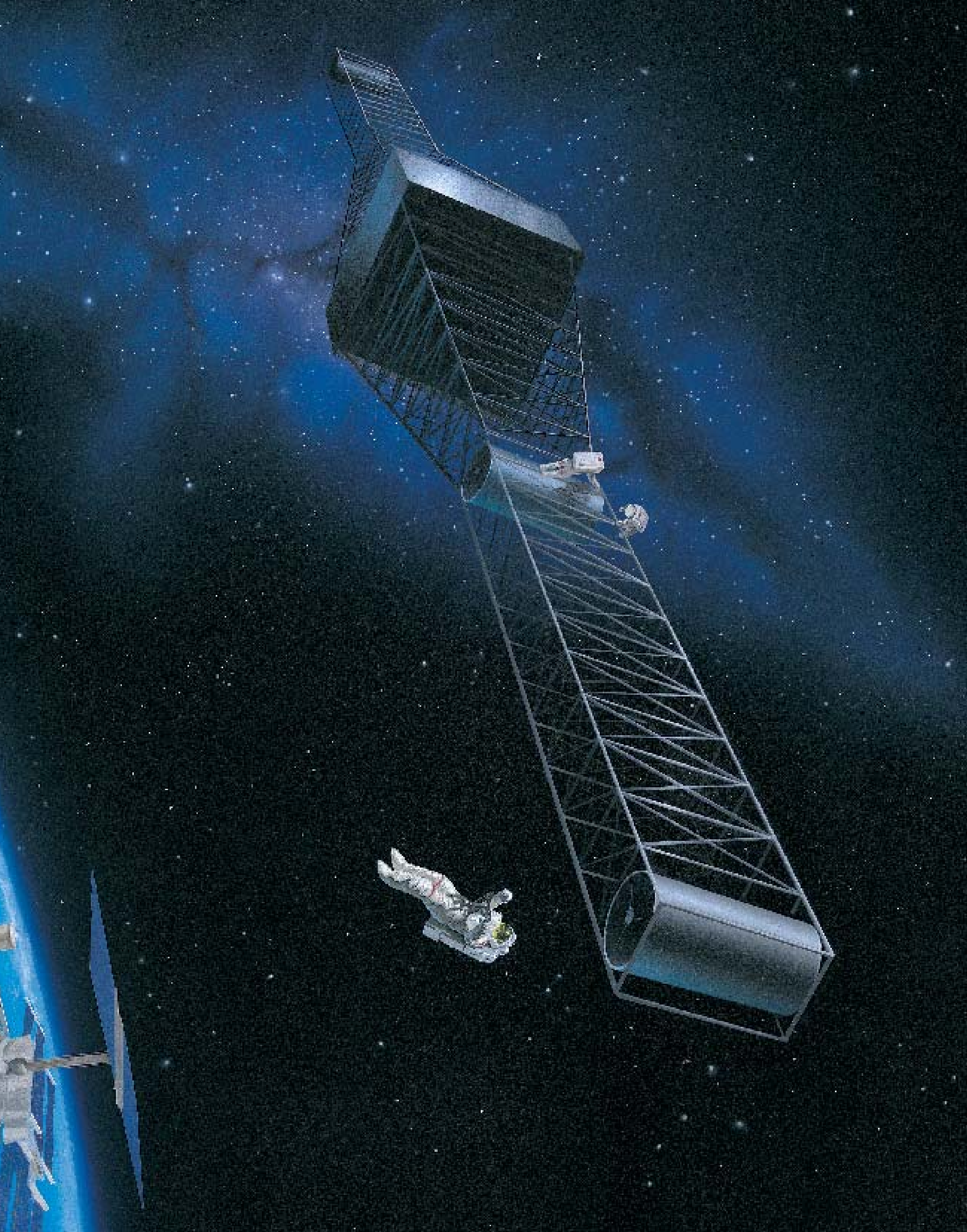
But our search for extraterrestrial life has recently been extended—we can now turn our attention to planets outside our own solar system. After years of looking, astronomers have turned up evidence of planets orbiting three distant stars similar to our sun [*see box on pages 23 and 24*]. Planets around these and other stars may have evolved living organisms. Finding extraterrestrial life may seem a Herculean task, but within the next decade, we could build the equipment needed to locate planets with life-forms like the primitive ones on Earth.

The largest and most powerful telescope now in space, the *Hubble Space Telescope,* can just make out mountains on Mars. Pictures sharp enough to display geologic features of planets around other stars would require an array of space telescopes the size of the U.S. Furthermore, as Carl Sagan of Cornell University has pointed out, pictures of Earth do not reveal the presence of life unless they are taken at very high resolution. Detailed images could be obtained with unmanned spacecraft sent to other solar systems, but the huge distance between Earth and any other planet is a distinct drawback to this approach—it would take millennia to travel to another solar system and send back useful images.

Taking photographs, however, is not the best way to start studying distant planets. Astronomers instead rely on the technique of spectroscopy to obtain most of their information. In spectroscopy, light originating from an object in space can be analyzed for unique markers that help researchers piece together characteristics such as the celestial body's tem-

ALFRED T. KAMAJIAN

SPACE-BASED TELESCOPE SYSTEM that can search for life-bearing planets has been proposed by the authors. The instrument, a type of interferometer, could be assembled at the proposed international space station (*lower left*). Subsequently, electric propulsion would send the 50- to 75-meter-long device into an orbit around the sun roughly the same as Jupiter's. Such a mission is at the focus of the National Aeronautics and Space Administration's plans to study neighboring planetary systems.



New Planets around Sunlike Stars

Until recently, astronomers had no direct evidence that planets of any kind orbited other stars resembling the sun. Then, last October, Michel Mayor and Didier Queloz of the Geneva Observatory announced the detection of a massive planet circling the sunlike star 51 Pegasi [see "Strange Places," by Corey S. Powell, "Science and the Citizen," SCIENTIFIC AMERICAN, January 1996]. Geoffrey W. Marcy and R. Paul Butler of San Francisco State University and the University of California at Berkeley swiftly confirmed the finding and, just three months later, turned up two more bodies orbiting other, similar stars, proving the first discovery was no fluke.

Nobody has actually seen these alien worlds; all three were identified indirectly, by measuring the way they influenced the movement of their parent stars. As an object orbits a star, its gravitational pull causes the star to wobble back and forth. That motion creates a periodic displacement, known as a Doppler shift, in the spectrum of the star as seen from Earth. The pattern of the shift reveals the size and shape of the companion's orbit; the shift's magnitude indicates the companion's minimum possible mass. No other details (temperature or composition, for instance) can be discerned through the Doppler technique.

Even from that limited information, it is clear that the new planets are unlike anything seen before. The one around 51 Pegasi is the oddest of the bunch. Its mass is at least half that of Jupiter, and yet it orbits just seven million kilometers from the parent star—less than one eighth Mercury's distance from the sun. At such proximity, the planet's surface would be baked to a theoretical temperature of 1,300 degrees Celsius. The planet's orbital period, or year, is just 4.2 days.

One of the planets found by Marcy and Butler orbits the star 47 Ursae Majoris; this body has somewhat less extreme attributes. Its three-year orbit takes it on a circular course about 300 million kilometers from its star (corresponding to an orbit between Mars and Jupiter), and its mass is at minimum 2.3 times that of Jupiter; it would not seem terribly out of place in our own solar system.

The third new body, also identified by Marcy and Butler, circles the star 70 Virginis. This "planet" is rather different from the other two. It is the heftiest of the group, having at least 6.5 times the mass of Jupiter, and its 117-day orbit has a highly elliptical shape. Marcy has asserted that it lies in the "Goldilocks zone," the range of distances where a planet's temperature could be "just right" for water to exist in liquid form.

Despite such optimistic talk, this giant planet probably has a deep, suffocating atmosphere that offers poor prospects for life. In fact, based on its great mass and elliptical orbit, many scientists argue that the 70 Virginis companion should be classified not as a planet at all but as a brown dwarf, a gaseous object that forms somewhat like a star but lacks enough mass to shine.

There is a reason why astronomers are finding only massive bodies in fairly short-period orbits: these are the kind that are easiest to discern using the Doppler technique. Uncovering a planet in a slow orbit akin to Jupiter's would require at least a decade of high-precision Doppler observations. One possible way to broaden the search is to look at gravitational lensing, a process whereby the gravity of an intervening star temporarily magnifies the light from a more distant one. If the lensing star has planets, they could produce additional, short-lived brightenings. Many stars can be monitored at once, so this approach could yield statistics on the abundance of planets. Unfortunately, it cannot be used to detect planets around nearby stars.

Another possibility involves searching directly for the radiation reflected by large planets around other stars. Normally, Earth's atmosphere would hopelessly blur together star and planet. Adaptive optics—a means for can-

perature, atmospheric pressure and chemical composition.

The vital signs easiest to spot with spectroscopy are radio signals designed by extraterrestrials for interstellar communication. Such transmissions would be totally unlike natural phenomena; such unexpected features are examples of the kind of beacons that we must look for to locate intelligent life elsewhere. Yet sensitive scans of faraway star systems have not come across any signals, indicating only that extraterrestrials bent on interstellar radio communication are uncommon.

But planets may be home to noncommunicating life-forms, so we need to be able to find evidence of even the simplest organisms. To expand our capacity to locate distant planets and determine whether these worlds are inhabited, we have proposed a powerful and novel successor to Galileo's telescope that will, we believe, enable us to detect life on other planets.

The simplest forms of life on our planet altered the conditions on Earth in ways that a distant observer could perceive. The fossil records indicate that within a billion years of Earth's formation, as soon as the heavy bombardment by asteroids ceased, primitive organisms such as bacteria and algae had spread around most of the globe. These organisms represented the totality of life here for the next two billion years; consequently, if life exists on other planets, it might well be in this highly uncommunicative form.

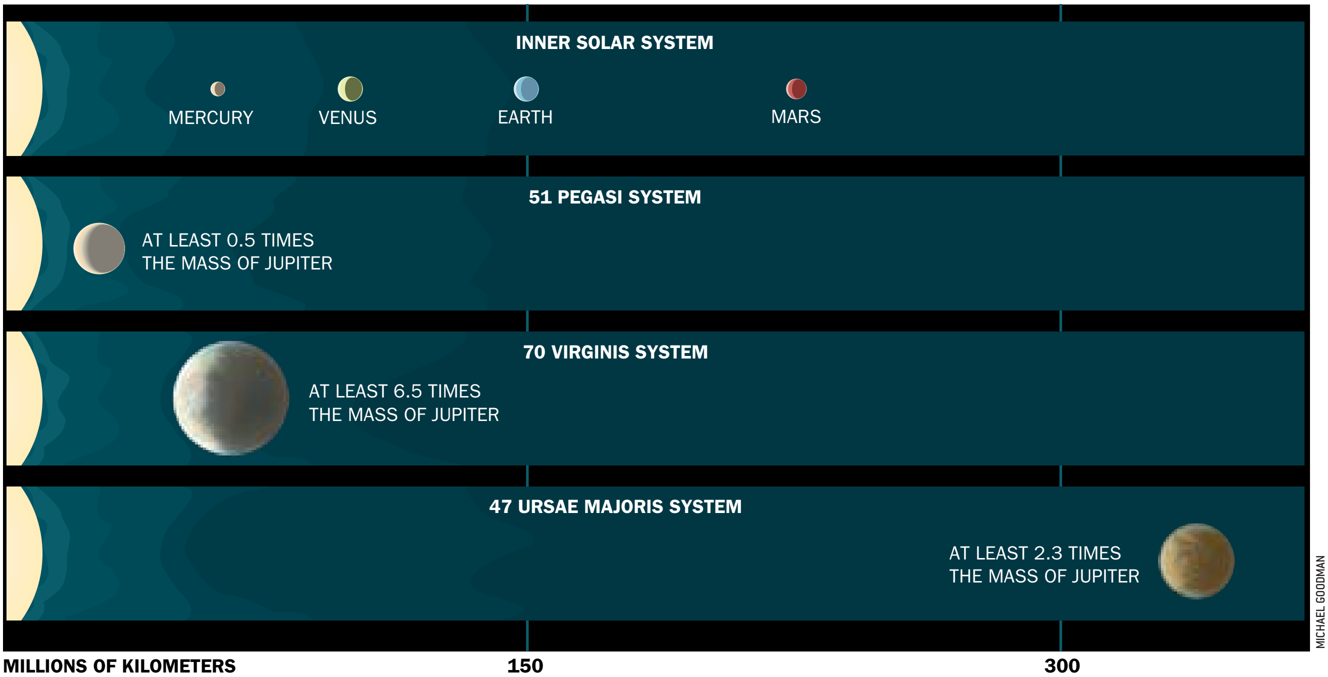
Algae and the Atmosphere

Earth's humble blue-green algae do not operate radio transmitters, but they are chemical engineers par excellence. As algae became more widespread, they began adding large quantities of oxygen to the atmosphere. The production of oxygen is fundamental to carbon-based life: the simplest organisms take in water, nitrogen and carbon dioxide as nutrients and then release oxygen into the atmosphere as waste. Oxygen is a chemically reactive gas; without continued replenishment by algae and, later in Earth's evolution, by plants, its concentration would fall. Thus, the presence of large amounts of oxygen in a planet's atmosphere is the first indicator that some form of carbon-based life may exist there.

Oxygen leaves an unmistakable mark on the radiation emitted by a planet. For example, some of the sunlight that reaches Earth's surface is reflected through the atmosphere back toward space. Oxygen in the atmosphere absorbs some of this radiation, and thus an observer of Earth using spectroscopy to study the reflected sunlight could pick out the distinctive signature associated with oxygen.

In 1980 Toby C. Owen, then at the State University of New York at Stony Brook, suggested looking for oxygen's signal in the visible red light reflected by planets, as a sign of life there. Closer to home, Sagan reported in 1993 that the *Galileo* space probe recorded the distinctive spectrum of oxygen in the red region of visible light coming from Earth. Indeed, this indication of life's existence has been radiating a recognizable signal into space for at least the past 500 million years.

Of course, there could be some nonbiological source of oxygen on a planet



celing out atmospheric distortion—may offer a way to overcome this problem. In theory, an adaptive optics system conceived by J. Roger P. Angel and refined by David Sandler and Steve Stahl of Thermotrex Corporation in San Diego could capture an image of a large planet at Jupiter's orbital distance in a single night of observation.

The newfound planets represent only the tip of the iceberg. Continued observations, careful data analysis—and innovative technologies, such as a space-based interferometer—will soon yield many more such discoveries, giving us a better sense of the true variety of worlds out there.

—Corey S. Powell, staff writer

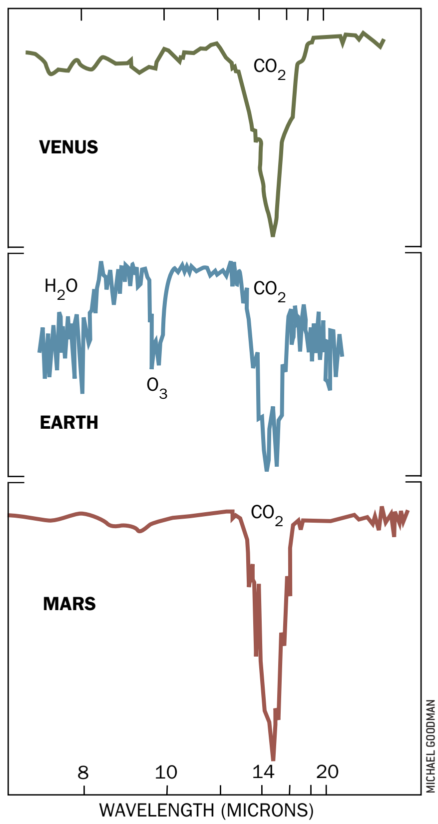
without life, so this possibility must always be explored. In addition, life could be based on some other brand of chemistry that does not produce oxygen as carbon-based life does. But compelling reasons lead us to expect that life on other planets would have a chemistry similar to our own. Carbon is particularly suitable as a building block of life: it is abundant in the universe, and no other known element can form the myriad of complex but stable molecules necessary for life as we know it.

Searching for Another Earth

Our water-rich planet is obviously favorable to life. Water provides a solvent for the biochemical reactions of life to take place and serves as a source of needed hydrogen for living matter. Planets similar to Earth in size and distance from their sun represent the most plausible homes for carbon-based life in other solar systems, primarily because liquid water could exist on these worlds. A planet's distance from its star determines its temperature—whether it will be too hot or too cold for liquid water.

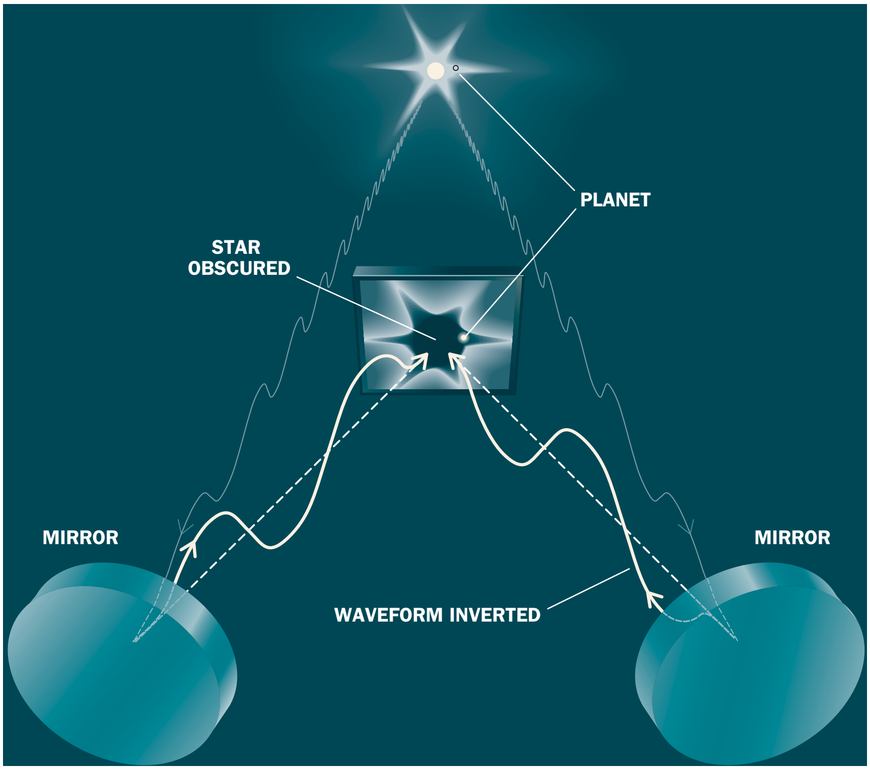
We can easily estimate the "Goldilocks orbit"—the distance at which conditions are "just right" to generate and sustain life as it exists on Earth. For a large, hot star, 25 times as bright as our sun, a hypothetical Earth-like planet would lie at about the distance that Jupiter circles the sun. For a small, cool star, one tenth as bright as the sun, the planet's orbit would resemble Mercury's course.

But proper location means little if a planet's pull of gravity cannot hold on to oceans and an atmosphere. If distance from a star were the only factor to consider, Earth's moon would have liquid



INFRARED SIGNATURE OF LIFE can be seen only on Earth: although Venus, Earth and Mars all have atmospheres rich in carbon dioxide (CO_2), only Earth carries abundant water (H_2O) and ozone (O_3), a form of oxygen usually found high in the atmosphere. Water is a vital ingredient needed to sustain carbon-based life; oxygen is a sign of its presence. Infrared radiation emitted from planets in distant solar systems might reveal other worlds similar to our own.

SOURCE: R. Hanel, Goddard Space Flight Center



CANCELING STARLIGHT enables astronomers to see dim planets typically obscured by stellar radiance. Two telescopes focused on the same star (*top*) can cancel out much of its light: one telescope inverts the light—making peaks into troughs and vice versa (*right*). When the inverted light is combined with the noninverted starlight from the second telescope (*left*), the light waves interfere with one another, and the image of the star vanishes (*center*).

water. But gravity depends on the size and density of the body: because the moon is smaller and less dense than Earth, its pull of gravity is much weaker. Any water or layers of atmosphere that might develop on or around such a body would quickly be lost to space.

Conversely, a very large planet, which has a strong pull of gravity, will attract gases from space. Scientists believe that Jupiter developed this way, gradually accumulating a huge outer shell of hydrogen and helium. Life as we know it seems unlikely to exist on massive gaseous planets like Jupiter.

Although we have a fairly specific description of the kind of planet that might be hospitable to life, finding *any* object orbiting distant stars has proved daunting. Currently the best methods for detecting such bodies actually involve looking not at the planets themselves but at their stars. Astronomers watch for slight variations in a star's orbit or light emission that can be explained only by the presence of planets. Unfortunately, indirect observation of planets tells us little about their characteristics. Indeed, all indirect techniques reveal only a body's mass and position; ascertaining whether it carries inhabitants remains impossible.

Seeing Infrared

Clearly, we need a different technique to reveal characteristics as specific as what chemicals can be found on a planet. Previously we mentioned that the visible radiation coming from a planet can confirm the presence of certain molecules, in particular oxygen, that we know support life. But distinguishing faint oxygen signals in light reflected by a small planet around even a star in our own sun's neighborhood would be extraordinarily difficult.

For example, the glow from a distant planet's sun would outshine the planet by a factor of 10 billion. So hunting for planets can be as challenging as trying to pick out a glowworm sitting next to a searchlight, both of which are thousands of kilometers away. Even if we could pick out the light reflected by a planet, any oxygen features in its visible spectrum would be weak and remarkably hard to spot.

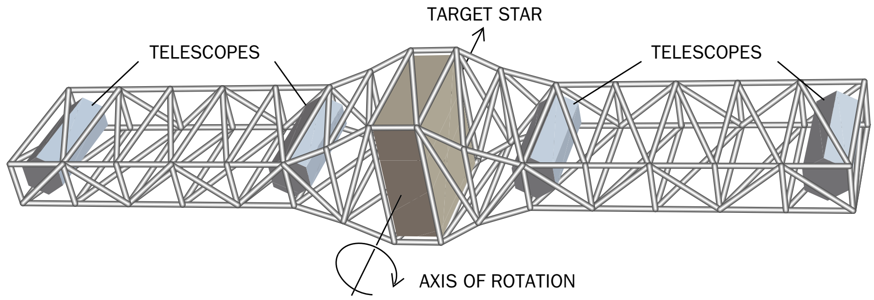
Faced with this quandary, in 1986 we proposed, along with Andrew Y. S. Cheng, now at the University of Hong Kong, that monitoring the mid-infrared wavelengths (longer than visible red wavelengths) emitted by a planet would be a better method for finding planets and looking for extraterrestrial life. This type of radiation—really the planet's radiated heat—has a wavelength 10 to 20 times longer than that of visible light. At these wavelengths, a planet emits about 40 times as many photons—particles of light—as it does at shorter wavelengths, and the nearby star would outshine the planet "only" 10 million times, a ratio 1,000 times more favorable than that which red light offers.

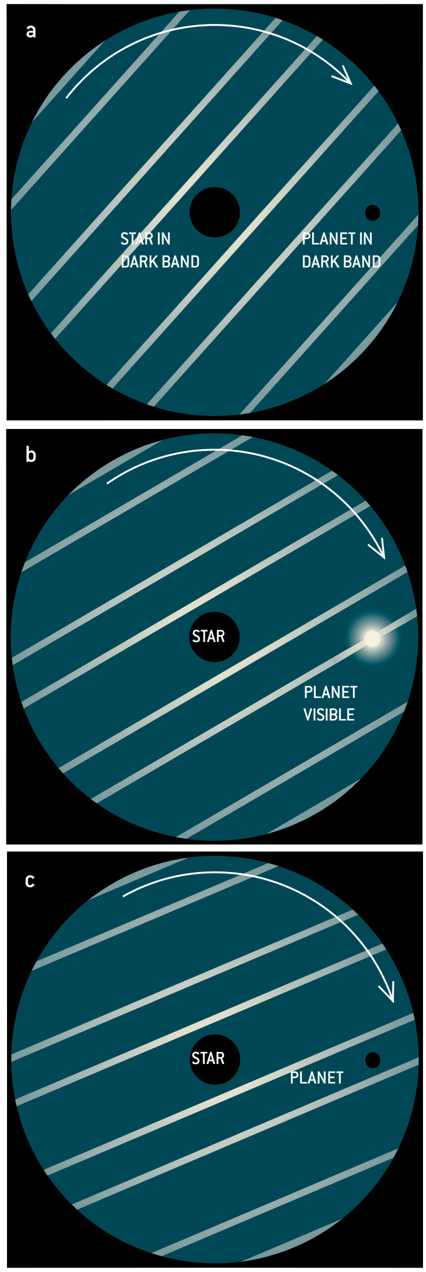
Moreover, three compounds that should appear together on inhabited planets—ozone (a form of oxygen usually located high in the atmosphere), carbon dioxide and water—are easily recognizable by examining the infrared spectrum. Once again, our solar system provides promising support for this technique: a survey of the infrared emissions of local planets reveals that only Earth displays the infrared signature of life [*see lower illustration on preceding page*]. Although Earth, Mars and Venus all have atmospheres with carbon dioxide, only Earth shows the signature of plentiful water and ozone.

What kind of telescope do we need to locate Earth-like planets and pick up their infrared emissions? Some of today's ground-based telescopes can detect the strong infrared radiation emanating from stars. But the heat emitted by our atmosphere and by the telescope itself would completely swamp any sign of a planet. Even Antarctica is not nearly cold enough to enable us to pick out such a faint image: the telescope must be cooled to at least minus 225 degrees Celsius (about 50 kelvins). More troublesome, radiation passing through Earth's atmosphere is imprinted with exactly the features of ozone, carbon dioxide and water we hope to find on another planet. Obviously, we reasoned, we must move the telescope into space.

Even then, to distinguish a planet's radiation from that of its star, a traditional telescope would have to be much larger than any ground-based or orbiting telescope built to date. Because light cannot be focused to a spot smaller than its wavelength, light from a distant point in the sky can at best be focused to a fuzzy core surrounded by a faint halo; even a perfect telescope mirror cannot form perfect images. If the halo surrounding the star extends beyond the planet's orbit, then we cannot discern the much dimmer body of the planet inside it. By making a telescope mirror and the resulting image very large, we can, in principle, make the image of a star as sharp as desired, but the size of the equipment needed to achieve such resolution renders the project infeasible.

We can predict the performance of telescopes and thus know in advance what kind of image quality we can expect. For example, to monitor the infrared spectrum of an Earth-like planet circling, say, a star 30 light-years away, we would need an enormous space telescope, close to 60 meters in diameter. With current technology, the cost of such an instrument would rival the national debt. And even telescope enthusiasts such as ourselves regard the size of this device as daunting.





ROTATING INTERFEROMETER could reveal the existence of a planet around a distant star. The four telescopes arranged as shown above in the authors' proposed instrument would produce a composite view of the sky partially darkened by numerous bands; the star to be obscured would be hidden by one strip. As the instrument rotates about the line connecting the center of the device with the star, the dark bands will also rotate. A nearby planet would pass in and out of the bands (*panels a–c*). Scientists could then analyze the pattern of blinking to determine how far the planet is from its star.

Rethinking the Telescope

To develop a more reasonably sized telescope that would allow us to locate small, perhaps habitable, planets, we knew we would have to play some tricks with our instruments. One useful stratagem had been suggested 23 years ago by Ronald N. Bracewell of Stanford University. He showed how two small telescopes could be adapted to search for large, cool planets similar to Jupiter. The instrument he proposed consisted of two one-meter telescopes separated by 20 meters. Each telescope alone would have yielded blurred pictures that would never have enabled Bracewell to resolve the faint images of planets. But together the two devices could be arranged to observe distant worlds.

If he focused both telescopes on the same star, Bracewell envisaged that he would be able to invert the light waves from one telescope, flipping peaks into troughs and vice versa. Then he would combine the inverted light with light from the second telescope. Because the first image would be the reverse of the second, when Bracewell combined the two so that they overlapped precisely, the light from the star—both the core and the surrounding halo—would be canceled out. (The light would not disappear, of course; energy must be conserved. Instead the light from the star would be diverted to a separate part of the telescope.) Scientists refer to this type of device as an interferometer because it reveals details about the source of light by employing the interference of light waves.

The interferometer designed by Bracewell can obscure a star only if the star is perpendicular to the line joining the centers of each telescope. With such an arrangement, both telescopes receive exactly the same pattern of light waves from the star. If we sweep the instrument through the sky, stars will appear to blink as they move in and out of alignment.

A planet separated from its star by even a fairly small distance, however, will not be aligned with the device when its star is brought into alignment. The two telescopes will register the planet's signal at slightly different times, so the light waves from the planet will not cancel one another out. If light shines through the interferometer after we have canceled out the star's image, we know that some additional source of infrared radiation—perhaps a planet—exists near the star. We can analyze this signal by rotating the interferometer about the line joining the instrument and the star. The image will change intensity as the device rotates; planets should display a recognizable pattern of variation [*see illustration on this page*].

After working out the design for this interferometer, Bracewell realized that the main obstacle to locating a Jupiter-like planet would not be the overpowering light from a nearby star; it would instead be the heat radiated by dust particles in our solar system, referred to as zodiacal glow. The faint signal from a distant planet would be almost imperceptible against the background glare. Any hope of discovering a planet would require averaging data for at least one month to see through this glowing background.

In addition, we found that when we tried to adapt Bracewell's design to hunt for planets smaller than Jupiter that orbit closer to a sun, a problem arose. No interferometer can perfectly cancel out starlight—the area darkened is rather small, light from the star always leaks around the edges, and any excess light presents a significant obstacle when we try to see extremely dim, small planets such as Earth.

To tackle these restrictions, a number of researchers, including the two of us, have been working on alternative strategies. In 1990 one of us (Angel) suggested that arranging four mirrors in a diamond pattern allows better cancellation of starlight. But to suppress the background glare of zodiacal light, each telescope would have to be eight meters in diameter. Alain Léger and his collaborators at the University of Paris then suggested the first practical solution to this complication. They proposed placing the device in orbit around the sun, at about the distance of Jupiter's orbit, which would naturally cool the telescopes to an appropriate temperature and would minimize background glare from zodiacal light. Because of the decrease in background glare, the orbiting interferometer could be relatively small: a sensitive instrument could be built with four individual telescopes as small as one meter in diameter. The instrument has one significant drawback, however. Because it is so effective at canceling out a star's light, the device can sometimes conceal a nearby planet as well.

Here the matter rested until 1995, when the National Aeronautics and Space Administration solicited from researchers a road map for the exploration of other solar systems. NASA selected three teams to investigate various methods for discovering planets around other stars. We assembled a team that included Bracewell, Léger and his colleague Jean-Marie Mariotti of the Paris Observatory, as well as some 20 other scientists and engineers. In particular, the two of us at the University of Arizona have been studying the potential of a new approach. We have designed an interferometer with two pairs of mirrors all arranged in a straight line. Each pair of mirrors will darken the star's main image, but significantly, each pair will also cancel the starlight leak of the other pair.

UNIVERSITY OF ARIZONA OASES PROJECT

IMAGE OF DISTANT PLANETS, created from simulated interferometer signals, indicates what astronomers might reasonably expect to see with a space-based telescope. This study displays a system about 30 light-years away, with four planets roughly equivalent in luminosity to Earth. (Each planet appears twice, mirrored across the star.) With this sensitivity, the authors speculate that the instrument could easily examine the planet recently found orbiting 47 Ursae Majoris.

It turns out that because this interferometer cancels starlight very effectively, it can be made rather long, roughly 50 to 75 meters in length. The size of the instrument offers an important advantage: with this arrangement, the signals from planets are complex and unique. With the proper analysis, we can use the data from the interferometer to reconstruct an image of a distant solar system [*see illustration on this page*]. As we envision the orbiting interferometer, it would point to a different star each day but could return to interesting systems for more extensive observations.

If pointed at our own solar system from a nearby star, the interferometer could pick out Venus, Earth, Mars, Jupiter and Saturn. And the data could be analyzed to determine the chemical composition of each planet's atmosphere. From our solar system, the device could easily study the newly discovered planet around 47 Ursae Majoris. More important, this interferometer could identify Earth-like planets elsewhere that would otherwise elude us, and the device can check all these planets for the presence of carbon dioxide, water and ozone.

Building such an instrument would be a substantial undertaking, perhaps an international project, and many of the details have yet to be completely worked out. We estimate that the proposed interferometer will cost less than $2 billion—about 10 percent of NASA's budget for space science research over the next decade. The discovery of life on another planet may arguably be the crowning achievement in the exploration of space. Finding life elsewhere, NASA administrator Daniel S. Goldin has said, "would change everything—no human endeavor or thought would be unchanged by that discovery."

Remarkably, the technology to assist in this discovery is at our fingertips. Soon we should be able to answer the centuries-old question, "Is life on Earth alone in the universe?"

The Authors

J. ROGER P. ANGEL and NEVILLE J. WOOLF have collaborated for the past 15 years on methods for making better telescopes. They are based at Steward Observatory at the University of Arizona. Angel is a fellow of the Royal Society and directs the Steward Observatory Mirror Laboratory. Woolf has pioneered techniques to minimize the distortion of images caused by the atmosphere. Angel and Woolf consider the quest for distant planets to be the ultimate test for telescope builders; they are meeting this challenge by pushing the limits of outer-space observation technology, such as adaptive optics and space telescopes.

Further Reading

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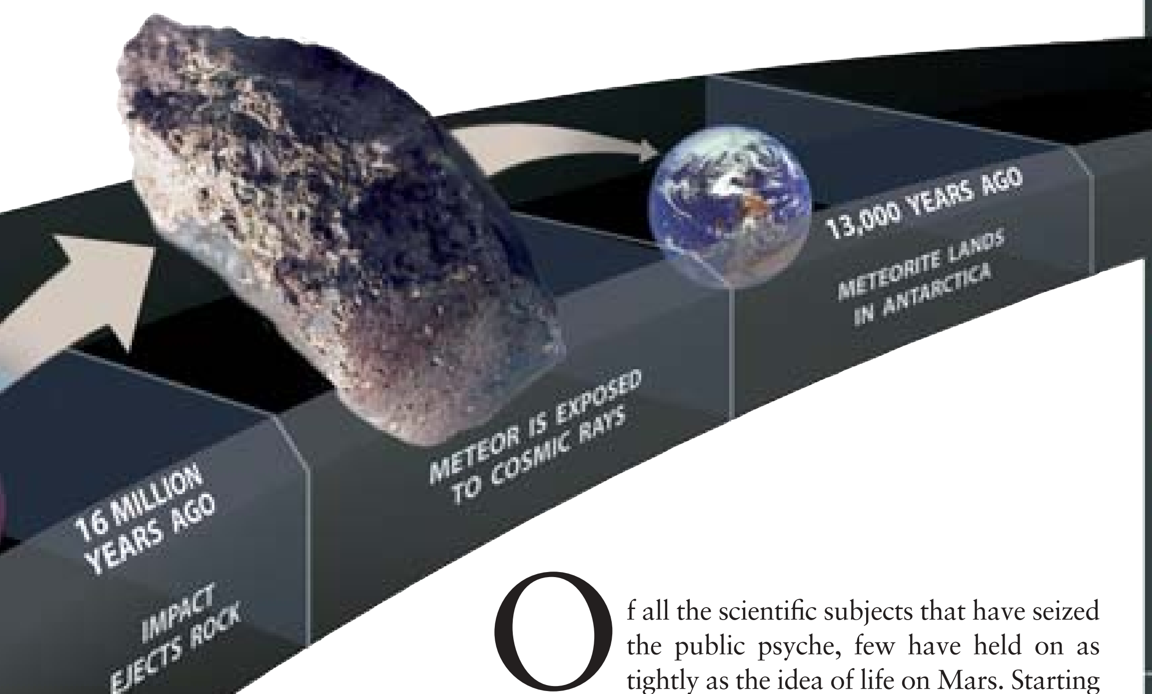
originally published December 1997

The Case for Relic Life on Mars

A meteorite found in Antarctica offers strong evidence that Mars has had—and may still have—microbial life

by Everett K. Gibson, Jr., David S. McKay, Kathie Thomas-Keprta and Christopher S. Romanek

METEORITE TIMELINE begins with the crystallization of the rock on the surface of Mars, during the first 1 percent of the planet's history. Less than a billion years later the rock was shocked and fractured by meteoritic collisions. Some time after these impacts, a water-rich fluid flowed through the fractures, and tiny globules of carbonate minerals formed in them. At the same time, molecular by-products, such as hydrocarbons, of the decay of living organisms were deposited in or near the globules by that fluid. Impacts on the surface of Mars continued to shock the rock, fracturing the globules, before a powerful collision ejected the rock into space. After falling to Earth, the meteorite lay in the Antarctic for millennia before it was found and its momentous history revealed.



1984

METEORITE COLLECTED IN ANTARCTICA

1993

SAMPLE ALH84001 IDENTIFIED AS METEORITE FROM MARS

1996

Of all the scientific subjects that have seized the public psyche, few have held on as tightly as the idea of life on Mars. Starting not long after the invention of the telescope and continuing for a good part of the past three centuries, the subject has inspired innumerable studies, ranging from the scientific to the speculative. But common to them all was recognition of the fact that in our solar system, if a planet other than Earth harbors life, it is almost certainly Mars.

Interest in Martian life has tended to coincide with new discoveries about the mysterious red world. Historically, these discoveries have often occurred after one of the periodic close approaches between the two planets. Every 15 years, Mars comes within about 56 million kilometers of Earth (the next approach will occur in the summer of 2003). Typically, life on Mars was assumed to be as intelligent and sophisticated as that of *Homo sapiens,* if not more so. (Even less explicably, Martian beings have been popularly portrayed as green and diminutive.)

It was after one of the close approaches in the late 19th century that Italian astronomer Giovanni V. Schiaparelli announced that he had seen great lines stretching across the planet's surface, which he called *canali.* At the turn of the century, U.S. astronomer Percival Lowell insisted that the features were canals constructed by an advanced civilization. In the 1960s and 1970s, however, any lingering theories about the lines and elaborate civilizations were put to rest after the U.S. and the Soviet Union sent the first space probes to the planet. The orbiters showed that there were in fact no canals, although there were long, huge canyons. Within a decade, landers found no evidence of life, let alone intelligent life and civilization.

Although the debate about intelligent life was essentially over, the discussions about microbial life on the planet—particularly life that may have existed on the warmer, wetter Mars of billions of years ago—were just beginning. In August 1996 this subject was thrust into the spotlight when we and a number of our colleagues at the National Aeronautics and Space Administration Johnson Space Center and at Stanford University announced that unusual characteristics in a meteorite known to have come from Mars could most reasonably be interpreted as the vestiges of ancient Martian bacterial life. The 1.9-kilogram, potato-sized meteorite, designated ALH84001, had been found in Antarctica in 1984.

Our theory was by no means universally embraced. Some researchers insisted that there were nonbiological explanations for the meteorite's peculiarities and that these rationales were more plausible than our biological explanation. We remain convinced that the facts and analyses that we will outline in this article point to the existence of a

PHOTOGRAPHS BY NASA JOHNSON SPACE CENTER; DIGITAL COMPOSITION BY JENNIFER C. CHRISTIANSEN primitive form of life. Moreover, such life-forms may still exist on Mars if, as some researchers have theorized, pore spaces and cracks in rocks below the surface of the planet contain liquid water. Why should researchers even care about the possible existence of such a simple form of life billions of years ago on the red planet? Certainly, the prevalence of life in the universe is among the most profound scientific questions. Yet almost no hard data exist that can be used to theorize on that issue.

Confirmation that primitive life once flourished on Mars would be extremely useful to those studying the range of conditions under which a planet can generate the complex chemistry from which life evolves. Then, too, the information could help us understand the origin of life on Earth. Ultimately, these kinds of insights could elucidate various hypotheses—which are currently little more than guesses—about how common life is in the universe.

Inhospitable Planet

Conditions on Mars today are not hospitable to life as we know it. The planet's atmosphere consists of 95 percent carbon dioxide, 2.7 percent nitrogen, 1.6 percent argon and only trace amounts of oxygen and water vapor. Surface pressure is less than 1 percent of Earth's, and daily temperatures rarely exceed zero degrees Celsius, even in the planet's warmest regions in the summer. Most important, one of life's most fundamental necessities, liquid water, seems not to exist on the planet's surface.

Given these realities, it is perhaps not surprising that the two Viking space probes that settled on the planet's surface, in July and September of 1976, failed to find any evidence of life. The results cast doubt on—but did not completely rule out—the possibility that there is life on Mars. The landers, which were equipped to detect organic compounds at a sensitivity level of one part per billion, found none, either at the surface or in the soil several centimeters down. Similarly, three other experiments found no evidence of microbial organisms. Ultimately, researchers concluded that the possibility of life on Mars was quite low and that a more definite statement on the issue would have to await the analysis of more samples by future landers—and, it was hoped, the return of some samples from the red planet for detailed study on Earth.

Although the landers found no evidence of life on present-day Mars, photographs of the planet taken from orbit by the Viking craft, as well as earlier images made by the Mariner 9 probe, strongly suggest that great volumes of water had sculpted the planet's surface a few billion years ago and perhaps as recently as several hundred million years ago [see "Global Climatic Change on Mars," by Jeffrey S. Kargel and Robert G. Strom; Scientific American, November 1996].

In addition, various meteorites found on Earth and known to be of Martian origin—including ALH84001 itself—offer tangible proof of Mars's watery past because they show unambiguous signs of having been altered by water. Specifically, some of these meteorites have been found to contain carbonates, sulfates, hydrates and clays, which can be formed, so far as planetary scientists know, only when water comes into contact with other minerals in the rock.

Of course, the entire argument hinges on ALH84001's having come from the red planet. Of this, at least, we can be certain. It is one of several meteorites found since the mid-1970s in meteorite-rich regions in Antarctica [*see box on next two pages*]. In the early 1980s Donald D. Bogard and Pratt Johnson of the NASA Johnson Space Center began studying a group of meteorites found to contain minute bubbles of gas trapped within glass inside the rock.

The glass is believed to have formed during impacts with meteoroids or comets while the rock was on the surface of Mars. Some of these glass-producing impacts apparently imparted enough energy to eject fragments out into space; from there, some of these rocks were captured by Earth's gravitational field. This impact scenario is the only one that planetary scientists believe can account for the existence on our world of bits of Mars.

Bogard and Johnson found that the tiny samples of gas trapped in the glass of some of the meteorites had the exact chemical and isotopic compositions as gases in the atmosphere of Mars, which had been measured by the Viking landers in 1976. The one-to-one correlation between the two gas samples—over a range of nine orders of magnitude—strongly suggests that these meteorites are from Mars. In all, five meteorites have been shown to contain samples of trapped Martian atmosphere. ALH-84001 was not among the five so analyzed; however, its distribution of oxygen isotopes, minerology and other characteristics place it in the same group with the other five Martian rocks.

The distribution of oxygen isotopes within a group of meteorites has been the most convincing piece of evidence establishing that the rocks—including ALH84001—come from Mars. In the early 1970s Robert N. Clayton and his co-workers at the University of Chicago showed that the isotopes oxygen 16, oxygen 17 and oxygen 18 in the silicate materials within various types of meteorites have unique relative abundances. The finding was significant because it demonstrates that the bodies of our solar system formed from distinct regions of the solar nebula and thus have unique oxygen isotopic compositions. Using this isotopic "fingerprint," Clayton helped to show that a group of 12 meteorites, including ALH84001, are indeed closely related. The combination of trapped Martian atmospheric gases and the specific distribution of oxygen isotopes has led researchers to conclude that the meteorites must have come from Mars.

Invader from Mars

Other analyses, mainly of radioisotopes, have enabled researchers to outline ALH84001's history from its origins on the red planet to the present day. The three key time periods of interest are the age of the rock (the length of time since it crystallized on Mars), how long the meteorite traveled in space and how long it has been on Earth. Analysis of three different sets of radioactive isotopes in the meteorite have established each of these time periods.

The length of time since the rock solidified from molten materials—the so-called crystallization age of the material—has been determined through the use of three different dating techniques. One uses isotopes of rubidium and strontium, another, neodymium and samarium, and the third, argon. All three methods indicated that the rock is 4.5 billion years old. By geologic standards the rock is extremely old; the 4.5-billion-year figure means that it crystallized within the first 1 percent of Mars's history. In comparison, the other 11 Martian meteorites that have been analyzed are all between 1.3 billion years old and 165 million years old.

It is remarkable that a rock so old, and so little altered on Mars or during its residence in the Antarctic ice, became available for scientists to study.

The duration of the meteorite's space odyssey was determined through the analysis of still other isotopes, namely helium 3, neon 21 and argon 38. While a meteorite is in space, it is bombarded by cosmic rays and other high-energy particles. The particles interact with the nuclei of certain atoms in the meteorite, producing the three isotopes listed above. By studying the abundances and production rates of these cosmogenically produced isotopes, scientists can determine how long the meteorite was exposed to the high-energy flux and, therefore, how long the specimen was in space. Using this approach, researchers concluded that after being torn free from the planet, ALH84001 spent 16 million years in space before falling in the Antarctic.

To determine how long the meteorite lay in the Antarctic ice, A. J. Timothy Jull of the University of Arizona used carbon 14 dating. When silicates are exposed to cosmic rays in space, carbon 14 is produced. In time, the rates of production and decay of carbon 14 balance, and the meteorite becomes saturated with the isotope. The balance is upset when the meteorite falls from space and production of carbon 14 ceases. The decay goes on, however, reducing the amount in the rock by one half every 5,700 years. By determining the difference between the saturation level and the amount measured in the silicates, researchers can determine how long the meteorite has been on Earth. Jull's finding was that ALH84001 fell from space 13,000 years ago.

From the very moment it was discovered, the meteorite now known as ALH-84001 proved unusual and intriguing. In 1984 U.S. geologist Roberta Score found the meteorite in the Far Western Icefield of the Allan Hills Region. Score recognized that the rock was unique because of its pale greenish-gray color. The sample turned out to consist of 98 percent coarse-grained orthopyroxene [$(Mg,Fe)SiO_3$], a silicate mineral. There are also relatively minor amounts of feldspathic glass, which is also known as maskelynite ($NaAlSi_3O_8$), olivine [$(Mg,Fe)_2SiO_4$], chromite ($FeCr_2O_4$) and pyrite (FeS_2) as well as carbonate phases and phyllosilicates.

Carbonates Are Key

The most interesting aspect of ALH-84001 are the carbonates, which exist as tiny discoids, like flattened spheres, 20 to 250 microns in diameter. They cover the walls of cracks in the meteorite and are oriented in such a way that they are flattened against the inside walls of the fractures [*see illustration on page 60*]. The globules were apparently deposited from a fluid saturated with carbon dioxide that percolated through the fracture after the silicates were formed. None of the other 11 meteorites known to have come from Mars have such globules.

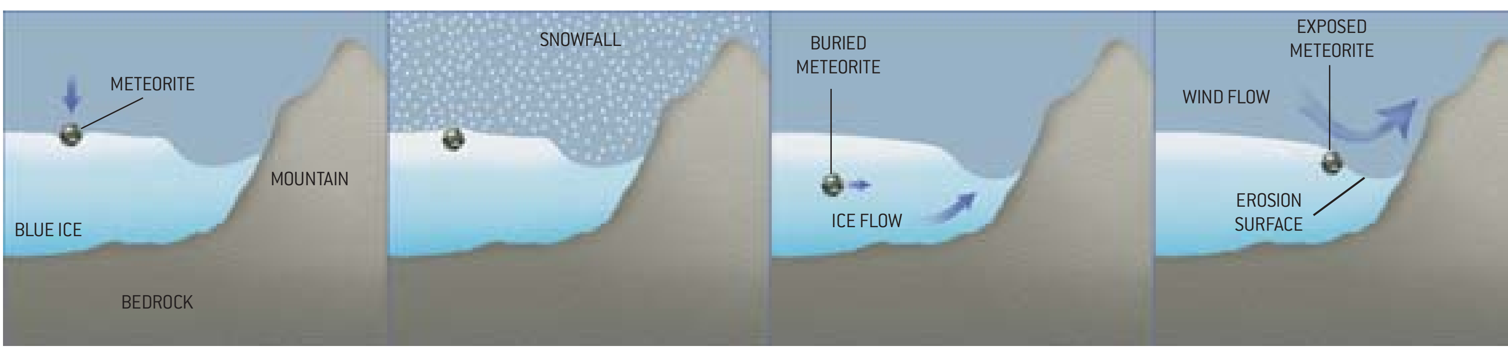
It was within the carbonate globules that our research team found the assortment of unique features that led us to hypothesize that microbial organisms came into contact with the rock in the distant past. Basically, the case for ancient microbial life on Mars is built almost entirely around the globules.

Individually, none of the features we found are strongly indicative of life. Collectively, however—and especially within the confines of the tiny discoids—the globules can be plausibly explained as the ancient vestiges of microbial life. The features fall into several categories of evidence. One category centers on the presence of tiny iron oxides and iron sulfide grains, which resemble those formed by terrestrial bacteria. The second group revolves around the presence of organic carbon molecules in and on the globules. Finally, unusual structures found within the globules bear a striking resemblance to bacteria fossils found on Earth. Another relevant piece of evidence suggests the globules formed from a water-rich fluid below 100 degrees C.

NASA Johnson Space Center researchers, along with Monica Grady of the British Museum of Natural History and workers at the Open University in the U.K., performed the first isotopic analysis of carbon and oxygen in the carbonate globules. The carbon analysis indicates that the globules have more carbon 13 than any carbonates found on Earth but just the right amount to have come from Mars.

Most carbon on Earth is made up of 98.9 percent carbon 12 and 1.1 percent carbon 13. Various reactions, however,

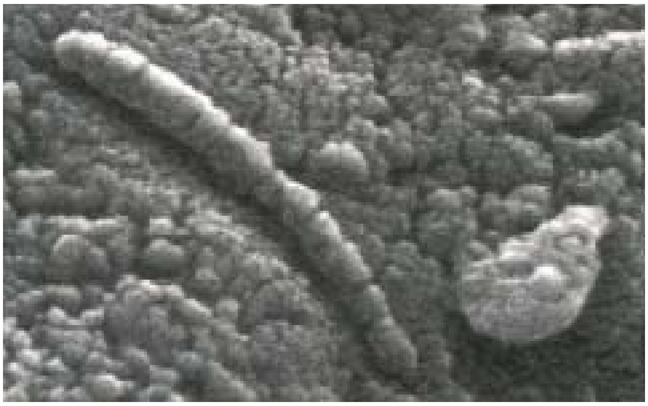
The Budget Space Probe

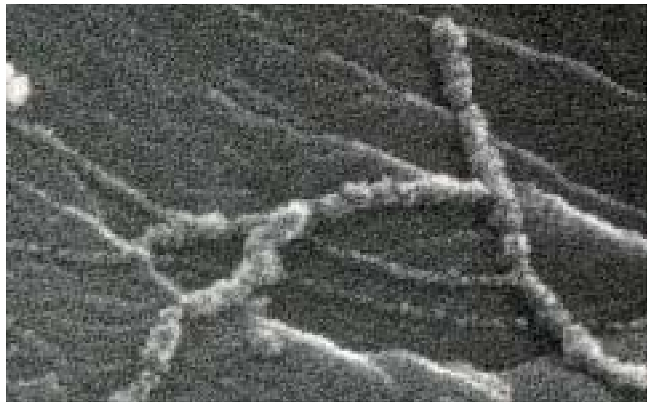


LAURIE GRACE

A combination of geologic and meteorological phenomena gather meteorites at the bases of Antarctica's mountains. After landing, the meteorites become buried in compressed snow, which eventually becomes ice. Sheets of ice move toward the edges of the continent, carrying the meteorites with them. If a mountain blocks horizontal movement of the meteorites, they will in time become exposed near the mountain. The reason is that the winds slowly but continuously "ablate" the ice above the meteorites, turning it into a gas. Ablation exposes areas of ice that had been buried deep under the surface, so meteorites are found on ice that is generally more than 10,000 years old and is bluish in color.

NASA JOHNSON SPACE CENTER





SEGMENTED OBJECT (*above, left*) is 380 nanometers in length and was found in a carbonate globule in meteorite ALH84001. The minute structure resembles fossilized bacteria, or microfossils, found on Earth. For example, the vertically oriented object to the right in the right-hand photograph is believed to be a microfossil. The object, which is also 380 nanometers long, was found 400 meters below Earth's surface (in Washington State) in a type of geologic formation known as Columbia River Basalt.

can alter this ratio. For example, in general a sample of carbon that has been a part of an organic chemical system—say, in plant matter—is somewhat more enriched in carbon 12, whereas carbon in limestone is relatively enriched in carbon 13. The carbon in the globules of ALH84001 is more enriched in carbon 13 than any natural materials on Earth. Moreover, the enrichment is different from that of the other 11 Martian meteorites. This fact suggests that the carbon in the globules—unlike the trace amounts of carbon seen in the other Martian meteorites—may have been derived from Mars's atmosphere.

Analysis of the distribution of oxygen isotopes in the carbonates can provide information about the temperature at which those minerals formed. The subject bears directly on the question of whether the carbonates were formed at temperatures that could support microbial life, because terrestrial organisms do not survive at temperatures above about 115 degrees C. The NASA-U.K. team analyzed the oxygen isotopes in the carbonate globules. Those findings strongly suggest that the globules formed at temperatures no higher than 100 degrees C. Earlier this year John W. Valley of the University of Wisconsin–Madison used an ion microprobe technique to confirm our finding.

It should be noted that another research group, led by Ralph P. Harvey of Case Western Reserve University, has analyzed the chemical composition of the minerals in the carbonates with an electron microprobe and concluded that the carbonates formed at 700 degrees C. In our view, Harvey's findings are at odds with a growing body of evidence that the globules formed at relatively low temperatures.

We are extremely interested in the age of the carbonates, because it would allow us to estimate when microbial life left its mark on the rock that became ALH84001. Yet all we can say for sure is that the carbonates crystallized in the fractures in the meteorite some time after the rock itself crystallized. Various research groups have come up with ages ranging from 1.3 to 3.6 billion years; the data gathered so far, however, are insufficient to date the carbonate globules conclusively.

Biomineral Clues

The first category of evidence involves certain minerals found in-

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In 1969 a team of Japanese glaciologists working near the Yamato Mountains in Antarctica discovered eight meteorites in an ice field known to be more than 10,000 years old. The discovery was remarkable because the meteorites were of four different types, indicating that they could not have all fallen at the same time, as fragments of the same meteorite. It did not take glaciologists long to figure out how ice flows consolidate the rocks. Meteorites landing on the Antarctic ice become buried in compressed snow, called firn, which in time becomes ice. This ice eventually becomes "old" ice, which is bluish in color.

Propelled by gravity, masses of ice move at a rate of about two to three meters a year from the relatively lofty interior of the Antarctic continent to the edges (*left*). If an obstacle such as a mountain range impedes the flow of ice, the ice mass pushes upward against the barrier. The ice—and the meteorites it contains—can make no more horizontal progress. In the meantime, as the winds blow over it, the surface layer of ice is slowly removed by a process known as ablation. Ablation, in which the solid ice converts directly to a gas, removes typically two to three centimeters of ice per year. As ice is removed, the meteorites within are exposed on the surface of the ice sheet. The end result is that meteorites are continuously accumulating and being exhumed at the base of Antarctica's mountains. Because ablation exposes areas of ice that had been buried deep under the firn, the meteorites are always found on regions of old, bluish ice. Nowhere else in the world does this marvelous concentration mechanism occur. Only the Antarctic has the necessary combination of moving glaciers and mountainous barriers.

Over the past 28 years, scientific teams have recovered more than 17,000 meteorites. The vast majority of samples came from the asteroid belt, but the Antarctic harvest has also yielded 14 samples from the moon and six from Mars.

Delivered as they are free of charge, meteorites have been called the poor man's space probe. Before the discovery of the Antarctic meteorite cache, the world's meteorite collections had only between 2,000 and 2,500 different specimens.

—E.K.G., D.S.M., K.T.-K. and C.S.R.

side the carbonate globules; the type and arrangement of the minerals are similar, if not identical, to certain biominerals found on Earth. Inside, the globules are rich in magnesite ($MgCO_3$) and siderite ($FeCO_3$) and have small amounts of calcium and manganese carbonates. Fine-grained particles of magnetite (Fe_3O_4) and sulfides ranging in size from 10 to 100 nanometers on a side are present within the carbonate host. The magnetite crystals are cuboid, teardrop or irregular in shape. Individual crystals have well-preserved structures with little evidence of defects or trace impurities.

An analysis of the samples conducted with high-resolution transmission electron microscopy coupled with energy-dispersive spectroscopy indicates that the size, purity, morphology and crystal structures of all these magnetites are typical of magnetites produced by bacteria on Earth.

Terrestrial magnetite particles associated with fossilized bacteria are known as magnetofossils. These particles are found in a variety of sediments and soils and are classified, according to size, as superparamagnetic (less than 20 nanometers on an edge) or single-domain (20 to 100 nanometers). The magnetites within ALH84001 are typically 40 to 60 nanometers on an edge.

Single-domain magnetite has been reported in ancient terrestrial limestones and is generally regarded as having been produced by bacteria. Most intriguing, some of the magnetites in ALH84001 are arranged in chains, not unlike pearls in a necklace. Terrestrial bacteria often produce magnetite in precisely this pattern, because as they biologically process iron and oxygen from the water, they produce crystals that naturally align themselves with the Earth's magnetic field.

Organic Carbon Molecules

The presence of organic carbon molecules in ALH84001 constitutes the second group of clues. In recent years, researchers have found organic molecules not only in Martian meteorites but also in ones known to have come from the asteroid belt in interplanetary space, which could hardly support life. Nevertheless, the type and relative abundance of the specific organic molecules identified in ALH84001 are suggestive of life processes. The presence of indigenous organic molecules within ALH-84001 is the first proof that such molecules have existed on Mars.

On Earth, when living organisms die and decay, they create hydrocarbons associated with coal, peat and petroleum. Many of these hydrocarbons belong to a class of organic molecules known as polycyclic aromatic hydrocarbons (PAHs). There are thousands of different PAHs. Their presence in a sample does not in itself demonstrate that biological processes occurred. It is the location and association of the PAHs in the carbonate globules that make their discovery so interesting.

In ALH84001 the PAHs are always found in carbonate-rich regions, including the globules. In our view, the relatively simple PAHs are the decay products of living organisms that were carried by a fluid and trapped when the globules were formed. In 1996 a team at the Open University showed that the carbon in the globules in ALH84001 has an isotopic composition suggestive of microbes that used methane as a food source. If confirmed, this finding will be one of the strongest pieces of evidence to date that the rock bears the imprint of biological activity.

In our 1996 announcement, Richard N. Zare and Simon J. Clemett of Stanford used an extremely sensitive analytical technique to show that ALH84001 contains a relatively small number of different PAHs, all of which have been identified in the decay products of microbes. Most important, the PAHs were found to be located inside the meteorite, where contamination is very unlikely to have occurred. This crucial finding supports the idea that the carbonates are Martian and contain the vestiges of ancient living organisms.

PAHs are a component of automobile exhaust, and they have also been found in meteorites, planetary dust particles and even in interstellar space. Significantly, ultrasensitive analysis of the distribution of the PAHs in ALH84001 indicated that the PAHs could not have come from Earth or from an extraterrestrial source—other than Mars.

Perhaps the most visually compelling piece of evidence that at least vestiges of microbes came into contact with the rock are objects that appear to be the fossilized remains of microbes themselves. Detailed examination of the ALH-84001 carbonates using high-resolution scanning electron microscopy (SEM) revealed unusual features that are similar to those seen in terrestrial samples associated with biogenic activity. Close-up SEM views show that the carbonate globules contain ovoid and tube-shaped bodies [*see photomicrographs on preceding page*]. The objects are around 380 nanometers long, which means they could very well be the fossilized remains of bacteria. To pack in all the components that are normally required for a typical terrestrial bacterium to function, sizes larger than 250 nanometers seem to be required. Additional tubelike curved structures found in the globules are 500 to 700 nanometers in length.

Nanobacteria or Appendages?

Other objects found within ALH-84001 are close to the lower size limit for bacteria. These ovoids are only 40 to 80 nanometers long; other, tube-shaped bodies range from 30 to 170 nanometers in length and 20 to 40 nanometers in diameter. These sizes are about a factor of 10 smaller than the terrestrial microbes that are commonly recognized as bacteria. Still, typical cells often have appendages that are generally quite small—in fact about the same size as these features observed within ALH84001. It may be possible that some of the features are fragments or parts of larger units within the sample.

ALH84001's numerous ovoid and elongated features are essentially identical in size and morphology to those of so-called nanobacteria on Earth. So far little study has been devoted to nanobacteria or bacteria in the 20- to 400-nanometer range. But fossilized bacteria found within subsurface basalt samples from the Columbia River basin in Washington State [see "Microbes Deep inside the Earth," by James K. Fredrickson and Tullis C. Onstott; Scientific American, October 1996] have features that are essentially identical to some of those observed in the ovoids in ALH84001.

ALH84001 was present on Mars 4.5 billion years ago, when the planet was wetter, warmer and had a denser atmosphere. Therefore, we might expect to see evidence that the rock had been altered by contact with water. Yet the rock bears few traces of so-called aqueous alteration evidence. One such piece of evidence would be clay minerals, which are often produced by aqueous reactions. The meteorite does indeed contain phyllosilicate clay mineral, but only in trace amounts. It is not clear, moreover, whether the clay mineral formed on Mars or in the Antarctic.

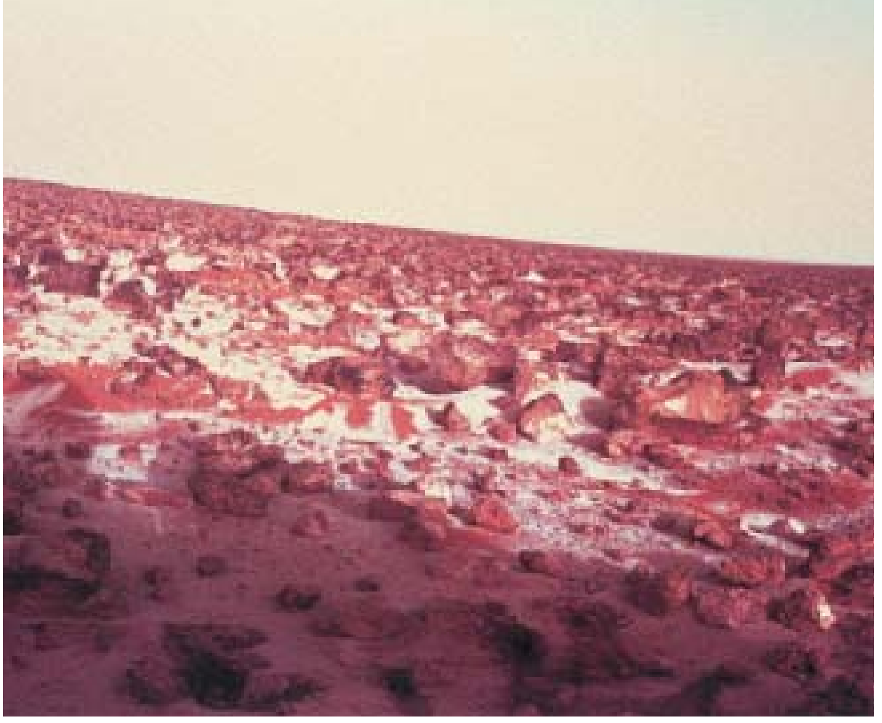
Mars had liquid water on its surface early in its history and may still have an active groundwater system below the permafrost or cryosphere. If surface microorganisms evolved during a period when liquid water covered parts of Mars, the microbes might have spread to subsurface environments when conditions turned harsh on the surface. The surface of Mars contains abundant basalts that were undoubtedly fractured during the period of early bombardment in the first 600 million years of the planet's history. These fractures could serve as pathways for liquid water and could have harbored any biota that were adapting to the changing conditions on the planet. The situation has an analogue on Earth, where thin gaps between successive lava flows appear to serve as aquifers for the movement and containment of groundwater containing living bacteria.

Organisms may also have developed at hot springs or in underground hydrothermal systems on Mars where chemical disequilibriums can be maintained in environments somewhat analogous to those of the mineral-rich "hot smokers" on the seafloor of Earth.

Thus, it is entirely possible that if organisms existed on Mars in the distant past, they may still be there. Availability of water within the pore spaces of a subsurface reservoir would facilitate their survival. If the carbonates within ALH-84001 were formed as early as 3.6 billion years ago and have biological origins, they may be the remnants of the earliest Martian life.

The analyses so far of ALH84001 are consistent with the meteorite's carbonate globules containing the vestiges of ancient microbial life. Studies of the meteorite are far from over, however. Whether or not these investigations confirm or modify our hypothesis, they will be invaluable learning experiences for researchers, who may get the opportunity to put the experience to use in coming years. We hope that in 2005 a "sample-return" mission will be launched to collect Martian rocks and soil robotically and return them to Earth two and a half years later. To take off from the Martian surface for the return to Earth, this revolutionary mission may use oxygen produced on the Martian surface by breaking down carbon dioxide in the planet's atmosphere.

Through projects such as the sample return, we will finally begin to collect the kind of data that will enable us to determine conclusively whether life came into being on Mars. This kind of insight, in turn, may ultimately provide perspective on one of the greatest scientific mysteries: the prevalence of life in our universe.



NASA JET PROPULSION LABORATORY

WATER FROST, probably only microns thick, covers parts of red, rocky Martian soil in a photograph taken by the Viking 2 lander in May 1979. The image was seen as further evidence that water exists on the surface of the planet, albeit in solid form.

The Authors

EVERETT K. GIBSON, JR., DAVID S. McKAY, KATHIE THOMAS-KEPRTA and CHRISTOPHER S. ROMANEK were members of the team that first reported evidence of past biological activity within the ALH84001 meteorite. Gibson, McKay and Thomas-Keprta work at the National Aeronautics and Space Administration Johnson Space Center in Houston, Tex.; Romanek, a former National Research Council postdoctoral fellow at the Johnson center, is with the department of geology and the Savannah River Ecology Laboratory at the University of Georgia. Gibson, a geochemist and meteorite specialist, and McKay, a geologist and expert on planetary regoliths, are senior scientists in the Johnson center's Earth Sciences and Solar System Exploration Division. Thomas-Keprta, a senior scientist at Lockheed Martin, is a biologist who applies electron microscopy to the study of meteorites, interplanetary dust particles and lunar samples. Romanek's specialty is low-temperature geochemistry and stable-isotope mass spectrometry. Gibson can be reached via egibson@ems.jsc.nasa.gov

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