

The Search for Extraterrestrial Life

*The earth remains the only inhabited world
known so far, but scientists are finding that the universe
abounds with the chemistry of life*

by Carl Sagan

In the past few decades the human species has begun, seriously and systematically, to look for evidence of life elsewhere. While no one has yet found living organisms beyond the earth, there are some reasons to be encouraged. Robotic space probes have identified worlds where life may once have gained a toehold, even if it does not flourish there today. The *Galileo* spacecraft found clear signs of life during its recent flight past the earth—a reassurance that we really do know how to sniff out at least certain kinds of life. And rapidly accumulating evidence strongly suggests that the universe abounds with planetary systems something like our own.

In practice, the community of scientists concerned with finding life elsewhere in the solar system has contented itself with a chemical approach. Human beings, as well as every other organism on the earth, are based on liquid water and organic molecules. (Organic molecules are carbon-containing compounds other than carbon dioxide and carbon monoxide.) A modest search strategy—looking for necessary if not sufficient criteria—might then begin by looking for liquid water and organic molecules. Of course, such a protocol might miss forms of life about which we are wholly ignorant, but that does not mean we could not detect them by other methods. If a silicon-based giraffe had walked by the *Viking* Mars landers, its portrait would have been taken.

Actually, focusing on organic matter and liquid water is not nearly so parochial and chauvinistic as it might seem. No other chemical element comes close to carbon in the variety and intricacy of

the compounds it can form; liquid water provides a superb, stable medium in which organic molecules can dissolve and interact. What is more, organic molecules are surprisingly common in the universe. Astronomers find evidence for them everywhere, from interstellar gas and dust grains to meteorites to many worlds in the outer solar system.

Some other molecules—hydrogen fluoride, for example—might approach water in their ability to dissolve other molecules, but the cosmic abundance of fluorine is extremely low. Certain atoms, such as silicon, might be able to take on some of the roles of carbon in an alternative life chemistry, but the variety of information-bearing molecules they provide seems comparatively sparse. Furthermore, the silicon equivalent of carbon dioxide (silicon dioxide, the major component of ordinary glass) is, on all planetary surfaces, a solid, not a gas. That distinction would certainly complicate the development of a silicon-based metabolism.

On extremely cold worlds, where water is frozen solid, some other solvent—liquid ammonia, for instance—might be a key to a different form of biochemistry. At low temperatures, certain classes of molecules require very little activation energy to undergo chemical reactions, but because our laboratories are at room temperature and not, say, at the temperature of Neptune's satellite Triton, our knowledge of those molecules may well be inadequate. For the moment, though, carbon- and water-based life-forms are the only kinds we know or can even imagine.

On the earth the signature molecules of life are the nucleic acids (DNA and

RNA), which constitute the hereditary instructions, and the proteins, which, as enzymes, catalytically control the chemistry of cell and organism. The codebook for translating nucleic acid information into protein structure is essentially identical for all life on the earth. This profound uniformity in the hereditary chemistry suggests that every organism on our planet has evolved from a common instance of the origin of life. If so, we have no way of knowing which aspects of terrestrial life are necessary (required of all living things anywhere) and which are merely contingent (the results of a particular sequence of happenstances that, had they gone otherwise, might have led to organisms having very different properties). We may speculate, but only by examining life elsewhere can biologists truly determine what else is possible.

The obvious place to start the search for life is in our own solar system. Robot spacecraft have explored more than 70 planets, satellites, comets and aster-

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SATURN'S MOON TITAN (at the upper right in this *Voyager 2* composite image) is an intriguing natural laboratory for prebiotic chemistry. Titan has a thick atmosphere in which complex organic solids form and rain down onto the surface.

oids at distances varying from about 100 to about 100,000 kilometers. These ships have been equipped with magnetometers, charged-particle detectors, imaging systems, and photometric and spectrometric instruments that sense radiation ranging from ultraviolet to kilometer-wavelength radio. For the moon, Venus and Mars, observations from orbiters and landers have confirmed and expanded on findings transmitted back from flyby spacecraft.

None of these encounters has yielded compelling, or even strongly suggestive, indications of extraterrestrial life. Still, such life, if it exists, might be quite unlike the forms with which we are familiar, or it might be present only marginally. Or the remote-sensing techniques used for examining other worlds might be insensitive to the conceivably subtle signs of life on another world. The most elementary test of these techniques—the detection of life on the earth by an instrumented flyby spacecraft—had, until recently, never been attempted. The National Aeronautics and Space Administration's *Galileo* has rectified that omission.

Galileo is a dual-purpose spacecraft that incorporates a Jupiter orbiter and entry probe; it is currently in interplanetary space and is scheduled to reach the Jupiter system in December 1995. For technical reasons, NASA was unable to send *Galileo* on a direct course to Jupiter; instead the mission incorporated three gravitational assists—two from the earth and one from Venus—to send it on its journey. This looping course greatly lengthened the transit time, but

it also permitted the spacecraft to make close-up observations of our planet. *Galileo*'s instruments were not designed for an earth-encounter mission, so circumstance fortuitously arranged a control experiment: a search for life on the earth using a typical modern planetary probe. The results of *Galileo*'s December 1990 encounter with the earth proved quite enlightening.

An observer looking at the data from *Galileo* would immediately notice some unusual facts about the earth. When my co-workers and I examined spectra taken by *Galileo* at near-infrared wavelengths (just slightly longer than red light), we noted a strong dip in brightness at 0.76 micron, a wavelength at which molecular oxygen absorbs radiation. The prominence of the absorption feature implies an enormous abundance of molecular oxygen in the earth's atmosphere, many orders of magnitude greater than is found on any other planet in the solar system.

Oxygen slowly combines with the rocks on the earth's surface, so the oxygen-rich atmosphere requires a replenishing mechanism. Some oxygen is freed when ultraviolet light from the sun splits apart molecules of water (H_2O), and the low-mass hydrogen atoms preferentially escape into space. But the great concentration of oxygen (20 percent) in the earth's dense atmosphere is very hard to explain by this process.

If visible light, rather than ultraviolet, could split water molecules, the abundance of oxygen could be understood, because the sun emits many more pho-

tons of visible light than of ultraviolet. But photons of visible light are too feeble to sever the H-OH bond in water. If there were a way to combine two visible light photons to break apart the water molecule, then everything would have a ready solution. Yet so far as we know, there is no way to accomplish this feat—except through life, specifically through photosynthesis in plants. The prevalence of molecular oxygen in the earth's atmosphere is our first clue that the planet bears life.

When *Galileo* photographed the earth, it found unmistakable evidence of a sharp absorption band painting the continents: some substance was soaking up radiation at wavelengths around 0.7 micron (the far red end of the visible spectrum). No known minerals show such a feature, and it is found nowhere else in the solar system. The mystery substance is in fact just the kind of light-absorbing pigment we would expect if visible photons were being added together to break down water and generate molecular oxygen. *Galileo* detected this pigment—which we know as chlorophyll—covering most of the land area of the earth. (Plants appear green precisely because chlorophyll reflects green light but traps the red and blue.) The prevalence of the chlorophyll red band offers a second reason to think that the earth is an inhabited planet.

Galileo's infrared spectrometer also detected a trace amount, about one part per million, of methane. Although that might seem insignificant, it is in startling disequilibrium with all that oxygen. In the earth's atmosphere, methane



What Is Life?

The search for extraterrestrial life must begin with the question of what we mean by life. "I'll know it when I see it" is an insufficient answer. Some functional definitions are inadequate: one might identify life as anything that ingests, metabolizes and excretes, but this description applies to my car or to a candle flame. Some more sophisticated definitions—for example, life as recognizable by its departure from thermodynamic equilibrium—fall afoul of the circumstance that much of nature (such as lightning and the ozone layer) is out of equilibrium.

Biochemical definitions—for example, defining life in terms of nucleic acids, proteins and other molecules—are clearly chauvinistic. Would we declare an organism that can do everything a bacterium can dead if it was made of very different molecules? The definition that I like best—life is any system capable of reproduction, mutation and reproduction of its mutations—is impractical to apply when we set down a spacecraft on another world: reproduction may not be done in public, and mutations might be comparatively infrequent.

rapidly oxidizes into water and carbon dioxide. At thermodynamic equilibrium, calculations indicate that not a single molecule of methane should remain. Some unusual processes (which we know to include bacterial metabolism in bogs, rumina and termites) must steadily refresh the methane supply. The profound methane disequilibrium is a third sign of life on the earth.

Finally, *Galileo's* plasma-wave instrument picked up narrow-band, pulsed, amplitude-modulated radio emissions coming from the earth. These signals begin at the frequency at which radio transmissions on the earth's surface are first able to leak through the ionosphere; they look nothing like natural sources of radio waves, such as lightning and the earth's magnetosphere. Such unusual, orderly radio signals strongly suggest the presence of a technological civilization. This is a fourth sign of life and the only one that would not have been apparent to a similar spacecraft flying by the earth anytime within the past two billion years.

The *Galileo* mission served as a significant control experiment of the ability of remote-sensing spacecraft to detect life at various stages of evolutionary development on other worlds in the solar system. These positive results encourage us that we would be able to spot the telltale signature of life on other worlds. Given that we have found no such evidence, we tentatively conclude that widespread biological activity now exists, among all the bodies of the solar system, only on the earth.

Mars is the nearest planet whose surface we can see. It has an atmosphere, polar ice caps, seasonal changes and a 24-hour day. To generations of scientists, writers and the public at large, Mars seemed the world most likely to sustain extraterrestrial life. But flybys past and orbiters around Mars have found no excess of molecular oxygen, no substances—whatever their nature—enigmatically and profoundly departing from thermodynamic equilibrium, no unexpected surface pigments and no modulated radio emissions. In 1976 NASA set down two *Viking* landers on Mars. I was an experimenter on that mission. The landers were equipped with instruments sensitive enough to detect life even in unpromising deserts and wastelands on the earth.

One experiment measured the gases exchanged between Martian surface samples and the local atmosphere in the presence of organic nutrients carried from the earth. A second experiment brought a wide variety of organic foodstuffs marked by a radioactive trac-



LIFE ON THE EARTH betrays its presence in images and measurements made by the *Galileo* spacecraft. This false-color infrared image reveals a mysterious red-absorbing pigment (chlorophyll, which appears orange-brown here) painting the continents. No such pigment is seen anywhere else in the solar system. Spectra indicate that the earth's atmosphere is unusually rich in molecular oxygen and methane. *Galileo* has boosted scientists' confidence that they may be able to spot the telltale signs of life even if it is different from life on the earth.

er, to see if there were life-forms in the Martian soil that ate the food and oxidized it, giving off radioactive carbon dioxide. A third experiment exposed the Martian soil to radioactive carbon dioxide and carbon monoxide to determine if any of it was taken up by microbes.

To the initial astonishment of, I think, all the scientists involved, each of the three *Viking* experiments gave what at first seemed to be positive results. Gases were exchanged; organic matter was oxidized; carbon dioxide was incorporated into the soil.

But there are reasons that these provocative results are not generally thought to provide a convincing argument for life on Mars. The putative metabolic processes of Martian microbes occurred under a wide range of conditions: wet and dry, light and dark, cold (only a little above freezing) and hot (almost the normal boiling point of water). Many microbiologists deem it unlikely that Martian microbes would be so capable under such varied conditions. Another strong reason for skep-

ticism is that an additional experiment to look for organic molecules in the Martian soil gave uniformly negative results, even though the instruments could detect such molecules at a sensitivity of around one part per billion. We expected that any life on Mars—as with life on the earth—would be an expression of the chemistry of carbon-based molecules. To find no such molecules at all was daunting for the optimists among the exobiologists.

The apparent positive results of the life-detection experiments on the two *Viking* landers is now generally attributed to chemicals that oxidize the soil. These chemicals form when solar ultraviolet light irradiates the Martian atmosphere. A handful of *Viking* scientists still wonder whether extremely tough and resilient organisms might exist, so thinly spread over the Martian soil that their organic chemistry could not be detected but their metabolic processes could. Those scientists do not deny the presence of ultraviolet-generated oxidants, but they emphasize that nobody



VIKING 2 LANDER scooped up bits of Martian soil and tested them for the presence of life and organic molecules. Despite tantalizing initial results, the *Viking* experiments suggest that Mars is, at present, a dead world. Future missions may search for fossils of organisms that might have lived billions of years ago, when Mars was warmer and wetter.

has yet been able to explain fully the *Viking* life-detection results on the basis of oxidants alone. A few researchers have made tentative claims of finding organic matter in a class of meteorites (the SNC meteorites) that are thought to be bits of the Martian surface blasted into space during ancient impacts. More likely, the organic material consists of contaminants that entered the meteorite after its arrival on our world. So far there are no claims of discovering Martian microbes in these rocks from the sky.

For the moment, it is safe to say that *Viking* found no compelling case for life on Mars. No unambiguous signatures of life emerged from four very different, extremely sensitive experiments conducted at two sites 5,000 kilometers apart on a planet where fast winds transport fine particles around the globe. The *Viking* findings suggest that Mars is, today at least, a lifeless planet.

Could Mars have supported life in the distant past? The answer depends very much on how quickly life can arise, a topic about which we remain sadly ignorant. Astronomers are quite certain that, initially, the earth was inhospitable to life because of the collisions of planetesimals, the planetary building blocks that accreted together to form the earth. Early on, the earth was covered by a deep layer of molten rock. After that magma froze, the occasional arrival of large planetesimals would have boiled the oceans and steril-

ized the earth, if life had already arisen.

Things did not calm down until about 4.0 billion years ago. And yet fossils reveal that by 3.6 billion years ago the earth abounded with microbial life (including large, basketball-size stromatolites, colonies of microorganisms). These early forms of life seem to have been biochemically very adept. Many were photosynthetic, slowly contributing to the earth's bizarre oxygen-rich atmosphere. Manfred Schidlowski of the Max Planck Institute for Chemistry in Mainz has studied carbon isotope ratios preserved in ancient rocks; that work provided (disputed) evidence that life was already flourishing 3.8 billion years ago.

The inferred time available for the origin of life on the earth is thus being squeezed from two directions. According to current knowledge, that amount of time may be as brief as 100 million years. When I first drew attention to this "squeeze"—in 1973, after lunar samples returned by *Apollo* clarified the chronology of impacts on the moon—I argued that the rapidity with which life arose on the earth may imply that it is a likely process. It is dangerous to extrapolate from a single example, but it would be a truly remarkable circumstance if life arose quickly here while on many other, similar worlds, given comparable time, it did not.

Between 4.0 and 3.8 billion years ago, conditions on Mars, too, may have favored the emergence of life. The surface of Mars is covered with evidence of ancient rivers, lakes and perhaps even oceans more than 100 meters deep. The Mars of 4.0 billion years ago was much warmer and wetter than it is today. Taken together, these pieces of information suggest, although they hardly prove, that life may have arisen on ancient Mars as it did on the ancient earth. If so, as Mars evolved from congenial to desolate, life would have held on in the last remaining refugia—perhaps saline lakes or places where the interior heat

had melted the permafrost. Most planetary scientists agree that searching for chemical or morphological fossils of ancient life should have high priority in future Martian exploration. Although it is a long shot, searching for life in contemporary Martian oases might also be a productive endeavor.

It is now clear that organic chemistry has run rampant through the solar system and beyond. Mars has two small satellites, Phobos and Deimos, which, because of their dark color, seem to be made of (or at least covered by) organic matter. They are widely thought to be captured asteroids from farther out in the solar system. Indeed, there seems to be a vast population of small worlds covered with organic matter: the so-called C- and D-type asteroids in the main asteroid belt between Jupiter and Mars; the nuclei of comets such as Halley's Comet; and the newly discovered class of asteroids near the outermost planets. In 1986 the European Space Agency's *Giotto* spacecraft flew directly into the cloud of dust surrounding Halley's Comet, revealing that its nucleus may be made of as much as 25 percent organic matter.

A fairly abundant type of meteorite on the earth, known as carbonaceous chondrite, is thought to consist of fragments from C-type asteroids in the main belt. Carbonaceous meteorites contain an organic residue rich in aromatic and other hydrocarbons. Scientists have also identified a number of amino acids (the building blocks of the proteins) and nucleotide bases (the "rungs" of the DNA double helix, which spell out the genetic code).

Asteroidal and cometary fragments plunging into the atmosphere of the early earth carried with them vast stores of organic molecules. Some of these survived the intense heating on entry and therefore may have made a significant material contribution to the origin of life. Impacts would have delivered sim-

ilar supplies of organic matter, along with water, to other worlds. Those worlds need not be as richly endowed with liquid water as is the earth for critical steps in prebiological chemistry to occur. The water could be found in ponds, in subsurface reservoirs, as thin films on mineral grains or as ice melts formed by impacts.

One of the most fascinating and instructive worlds illustrating prebiological organic chemistry is Saturn's giant moon, Titan (which is as large as the planet Mercury). Here we can see the synthesis of complex organic molecules happening before our eyes. Titan has an atmosphere 10 times as massive as the earth's, composed mainly of molecular nitrogen, along with a few percent to 10 percent methane. When *Voyager 2* approached Titan in 1981, it could not see the surface, because this world is entirely socked in by an opaque, reddish orange haze. The surface temperature is very low, about 94 kelvins, or -179 degrees Celsius. If

we can judge from its density (much lower than that of solid rock) and from the composition of nearby worlds, Titan should have a great deal of water ice on and near its surface. A few simple organic molecules—hydrocarbons and nitriles—are found to be minor constituents of Titan's atmosphere.

Ultraviolet light from the sun, charged particles trapped in Saturn's magnetosphere and cosmic rays all bombard Titan's atmosphere and initiate chemical reactions there. When W. Reid Thompson of Cornell University and I considered the effects of ultraviolet irradiation and simulated those of auroral electron bombardment, we found the results agree well with the observed abundances of gaseous organic constituents.

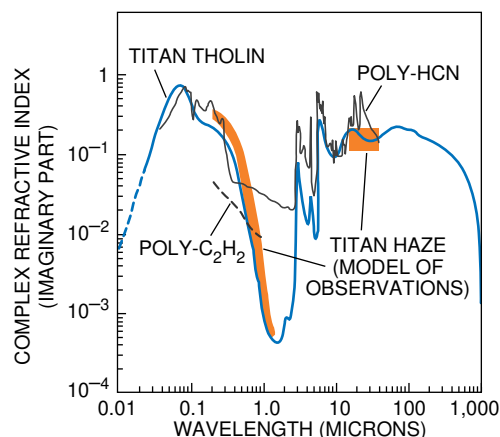
My colleague Bishun N. Khare and I at Cornell simulated the pressure and composition of the appropriate levels in Titan's atmosphere and irradiated the gases with charged particles. The experiment produced a dark, organic solid that we call Titan tholin, from the Greek word for "muddy." When we measure

the optical constants of Titan tholin, we find that it beautifully matches the optical constants derived from observations of the Titan haze. No other proposed material comes close.

Organic molecules continually form in the upper atmosphere of Titan and slowly fall out as new tholins are generated in the upper air. If this process has continued over the past four billion years, Titan's surface must be covered by tens, maybe even hundreds, of meters of tholin and other organic products. Moreover, Thompson and I have calculated that over the history of the solar system, a typical location on Titan has something like a 50-50 chance of having experienced centuries of liquid water from the heat released by impacts. When we mix Titan tholin with water in the laboratory, we make amino acids. There are also traces of nucleotide bases, polycyclic aromatic hydrocarbons and a wonderful brew of other compounds. If 100 million years is enough for the origin of life on the earth, could 1,000 years be enough for



LABORATORY SIMULATION of Titan's nitrogen-methane atmosphere (*left*) yields a tarlike accumulation of complex organic molecules, which the author calls Titan tholin. Analogous chemical reactions may give rise to the haze that obscures Titan's surface (*top right*). The optical characteristics



of Titan tholin closely match those of Titan's haze (*bottom right*). When combined with liquid water, Titan tholin produces amino acids, nucleotide bases and other molecules important to terrestrial life. Such molecules might have formed in temporary lakes created by cometary impacts on Titan.

Does Intelligent Life Exist on Other Worlds?

The search for extraterrestrial intelligence is an attempt to use large radio telescopes, sophisticated receivers and modern data analysis to detect hypothetical signals sent our way by advanced civilizations on planets around other stars. Necessarily, there are great uncertainties in selecting the appropriate wavelength, band pass, polarization, time constant and decoding algorithm with which to search for those signals. Nevertheless, radio technology is inexpensive, likely to be discovered early in the evolution of a technological civilization, readily detectable (not just over interplanetary distances, as *Galileo* has done, but over vast interstellar distances) and capable of transmitting enormous amounts of information. The first large-scale, systematic search program, covering a significant fraction of the wavelengths thought optimal for interstellar communication, was initiated by the National Aeronautics and Space Administration on October 12, 1992. Congress canceled the program a year later, but it will soon be resuscitated using private money. Meanwhile some smaller efforts have made provocative findings.

One promising project is the Megachannel Extraterrestrial Array (META), which is led by Paul Horowitz, a physics professor at Harvard University, and funded mainly by the Planetary Society, the largest space interest group in the world. The antenna used for META appears below. After five years of continuous sky survey and two years of follow-up, Horowitz and I found a handful of candidate radio signals that have extremely narrow bandwidths, that do not seem to share the earth's rotation and that cannot be attributed to specific sources of noise or interference. The only trouble is that none of these sources repeats, and in science nonrepeating data are usually not worth much. The tantalizing aspect of the META findings is that the five strongest signals all lie in the plane of the Milky Way. The likelihood that this alignment happens by chance is something like 0.5 percent. We think more comprehensive searches are worth doing.

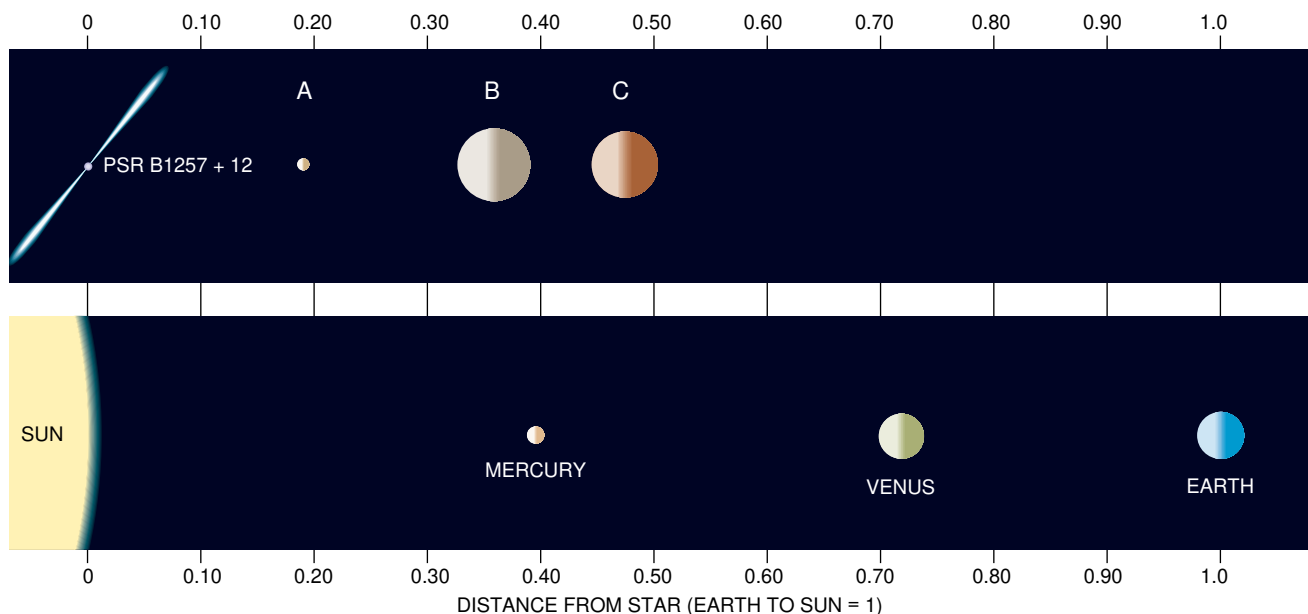


it on Titan? Could life have started on Titan during the centuries following an impact, when lakes of water or water-ice slurries briefly formed? The first close-up examination of Titan—by a Saturn orbiter and Titan entry probe—is scheduled to occur when the ESA-NASA Cassini mission reaches the Saturn system in about 2004.

When we look beyond our solar system, into the gas and grains that populate interstellar space, again we find striking signs of the prevalence of organic chemistry. Astronomers examining microwaves emitted and absorbed by molecules at distinctive frequencies have identified more than four dozen simple organic compounds in interstellar space—hydrocarbons, amines, alcohols and nitriles, some of them having long, straight carbon chains, such as HC_{11}N . When a cloud of interstellar dust grains lies between the earth and some more distant infrared source, it is possible to determine which infrared wavelengths are absorbed by the grains and hence to learn about their composition.

Some of the missing infrared light is widely presumed to have been absorbed by polycyclic aromatics, complex hydrocarbons similar to the compounds found in coal tar. In the part of the infrared spectrum near 3.4 microns, three distinct absorption features are seen. The same patterns appear in the spectra of comets, in tholins made from the irradiation of hydrocarbon ices and in meteoritic organic matter. That infrared fingerprint is probably caused by linked (aliphatic) groups of carbon and hydrogen: $-\text{CH}_3$ and $-\text{CH}_2$. Yvonne Pendleton and her colleagues at the NASA Ames Research Center find that the best spectral fit seems to be with meteoritic organic matter.

The infrared match among comets, asteroids and interstellar clouds may represent the first direct evidence that asteroids and comets contain organic matter that originated on interstellar grains before gathering together in the infant solar system. But the data are also amenable to an opposite interpretation—that some of the organic matter that formed in the early solar nebula accumulated into asteroids and comets, while some was ejected by the sun into interstellar space. If 100 billion other stars did likewise, they could account for a significant fraction of the organic matter in all the interstellar grains in the galaxy. The prevalence of organic material in the outer solar system, in comets that come from far beyond the outermost planets and in interstellar gas and grains strongly suggests that complex organic matter—



EXTRASOLAR PLANETS seem to orbit the star PSR B1257+12, the tiny, dense remnant of an ancient supernova explosion. The spacing of the three surrounding planets—known as A, B and C—resembles the circumstances of our solar system (the

sizes of the planets are not drawn to scale). It is possible that a more distant, habitable planet circles this stellar corpse. There is also increasing evidence that planetary systems orbit many sunlike stars, which offer better prospects for life.

relevant to the origin of life—is widely spread throughout the Milky Way.

Organic molecules on bone-dry interstellar grains fried by ultraviolet light and cosmic rays seem an unlikely habitat for the origin of life, however. Life seems to need liquid water, which in turn seems to require planets. Astronomical observations increasingly indicate that planetary systems are common. A surprisingly large number of nearby young stars of roughly solar mass are surrounded by just the kind of disks of gas and dust that scientists going back to Immanuel Kant and Pierre Simon, the Marquis de Laplace, say is needed to explain the origin of the planets in our system. These disks provide a persuasive though still indirect indication that there is a multitude of planets, presumably including earthlike worlds, around other stars.

George W. Wetherill of the Carnegie Institution of Washington has developed detailed models for predicting the distribution of the planets that should be formed in such circumstellar disks. Meanwhile James F. Kasting of Pennsylvania State University has calculated the range of distances from their suns at which planets can support liquid water on their surfaces. Taken together, these two lines of inquiry suggest that a typical planetary system should contain one and maybe even two earthlike planets circling at a distance where liquid water is possible.

Recently Alexander Wolszczan, also

at Pennsylvania State, unambiguously detected earthlike planets in a place where most astronomers least expected to find them: around a pulsar, the swiftly spinning neutron-star remnant from a supernova explosion. Based on variations in the timing of radio emissions from the pulsar PSR B1257+12, Wolszczan has deduced the presence of three planets (so far called only A, B and C) orbiting the pulsar.

These worlds are closer to their star than the earth is to ours, and PSR B1257+12 emits in charged particles several times as much energy as does the sun in electromagnetic radiation. If all the charged particles intercepted by A, B and C are transformed into heat, these worlds must almost certainly be too hot for life. But Wolszczan finds hints of at least one additional planet situated farther from the pulsar. For all we know, this superficially unpromising system, 1,400 light-years from the earth, may contain a dark but habitable planet. It is not clear whether these planets survived from before the supernova explosion or, more likely, formed afterward from surrounding debris. Either way, their presence suggests that planetary formation is an unexpectedly common and widespread process.

Numerous searches for planets in infant and mature sunlike systems are under way. The pace of exploration is becoming so quick, and so many new techniques are about to be employed, that it seems likely that in the next few

decades astronomers will begin accumulating a sizable inventory of planets around nearby stars.

We have every reason to believe that there are many water-rich worlds something like our own, each provided with a generous complement of complex organic molecules. Those planets that circle sunlike stars could offer environments in which life would have billions of years to arise and evolve. Should not there be an immense number and diversity of inhabited worlds in the Milky Way? Scientists differ about the strength of this argument, but even at its best it is very different from actually detecting life elsewhere. That monumental discovery remains to be made.

FURTHER READING

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