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 62 and 63*]. 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-

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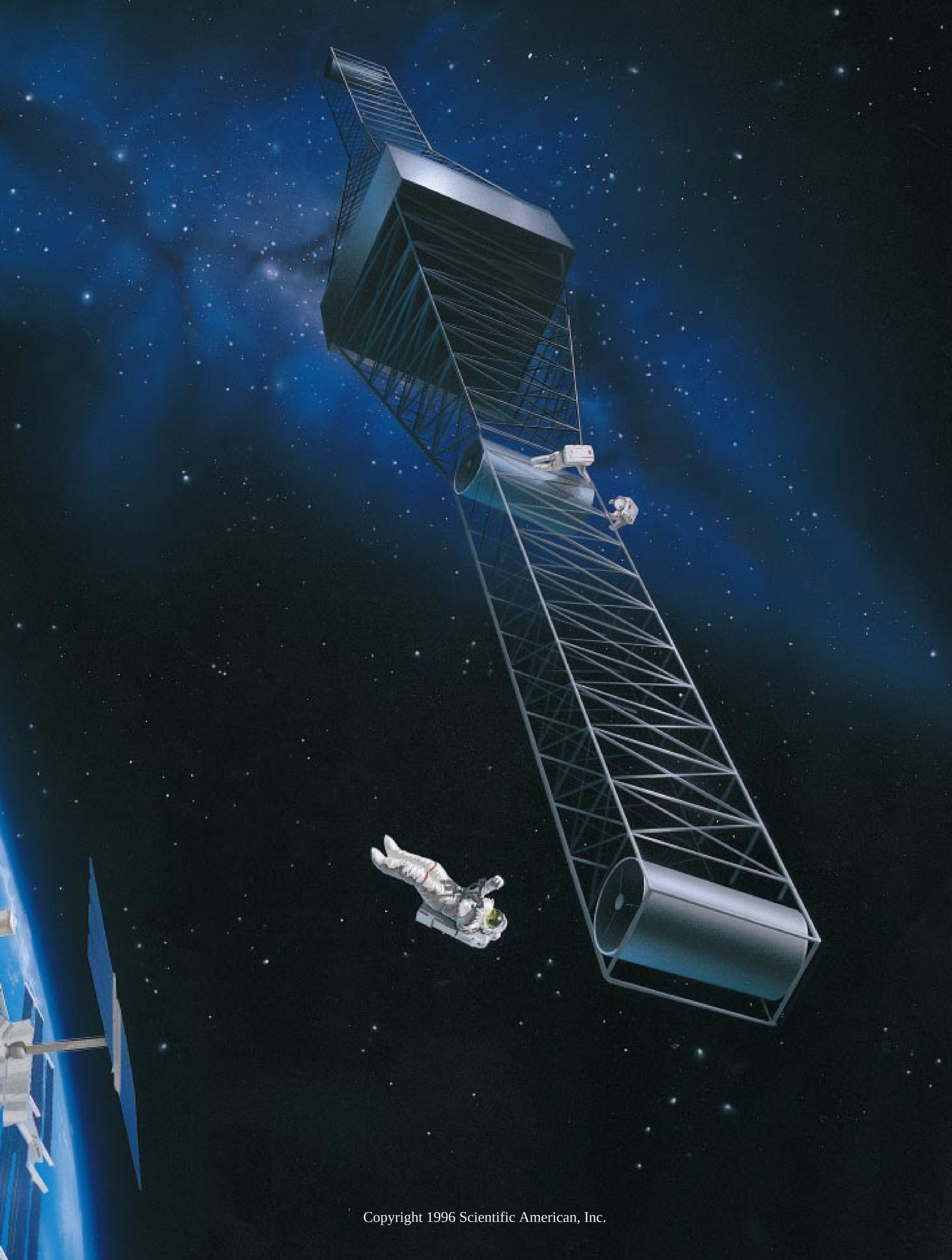
SPACE-BASED TELESCOPE SYSTEM that can search for life-bearing planets has been proposed by the authors. The instrument, a type of interferometer, could be assembled at the proposed international space station (*lower left*). Subsequently, electric propulsion would send the 50- to 75-meter-long device 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]. 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.

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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.

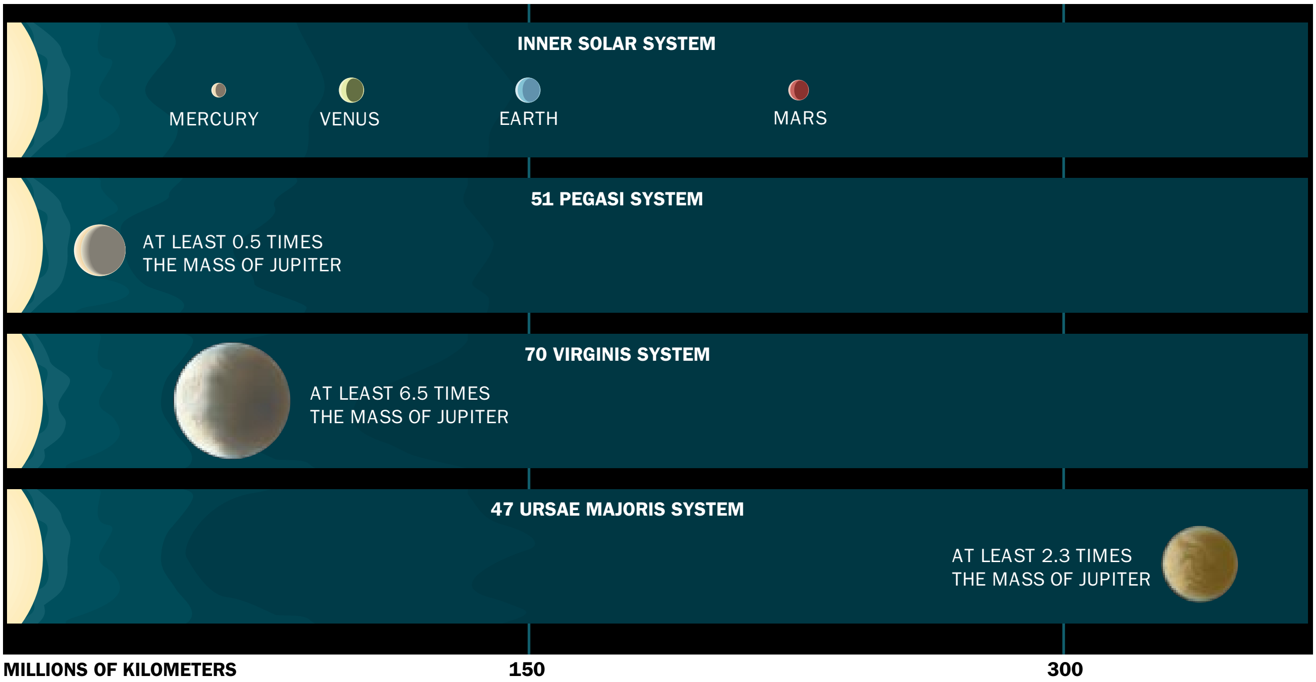
Algae and the Atmosphere

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



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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 canceling 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*

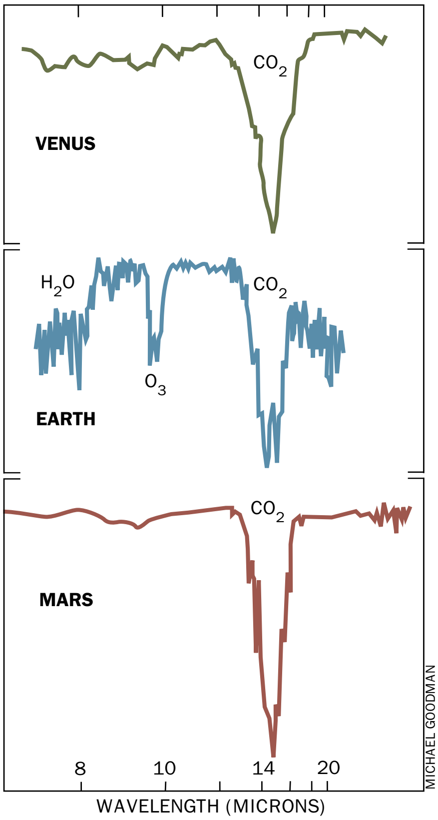
without life, so this possibility must always be explored. In addition, life could be based on some other brand of chemistry that does not produce oxygen as carbon-based life does. But compelling reasons lead us to expect that life on other planets would have a chemistry similar to our own. Carbon is 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



SOURCE: R. Hanel, Goddard Space Flight Center

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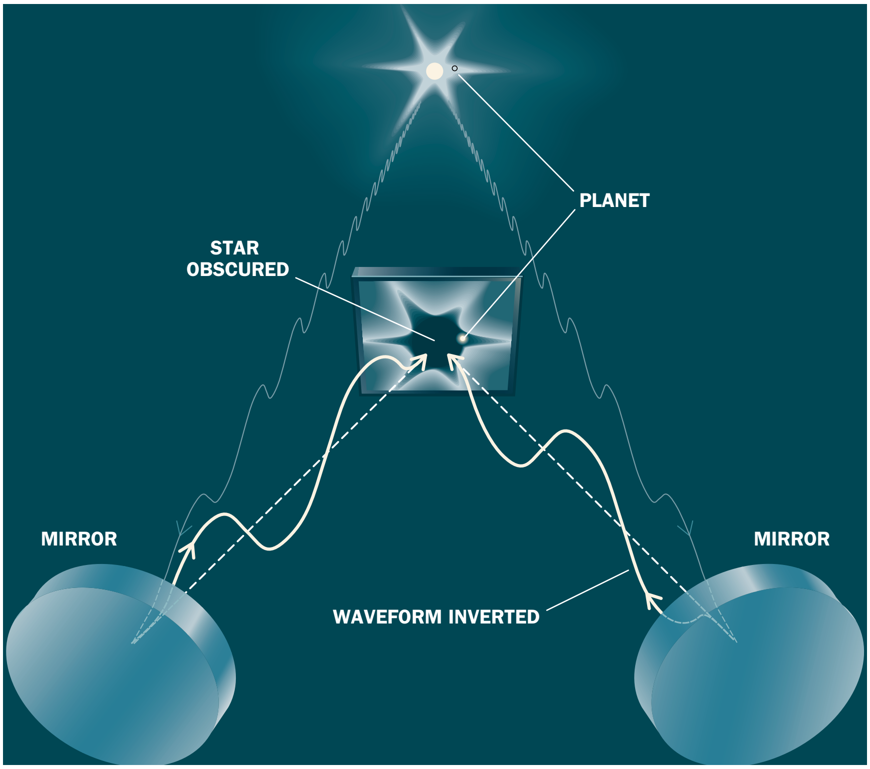
INFRARED SIGNATURE OF LIFE can be seen only on Earth: although Venus, Earth and Mars all have atmospheres rich in carbon dioxide (CO_2), only Earth carries abundant water (H_2O) and ozone (O_3), a form of oxygen usually found high in the atmosphere. Water is a vital ingredient needed to sustain carbon-based 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.



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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.

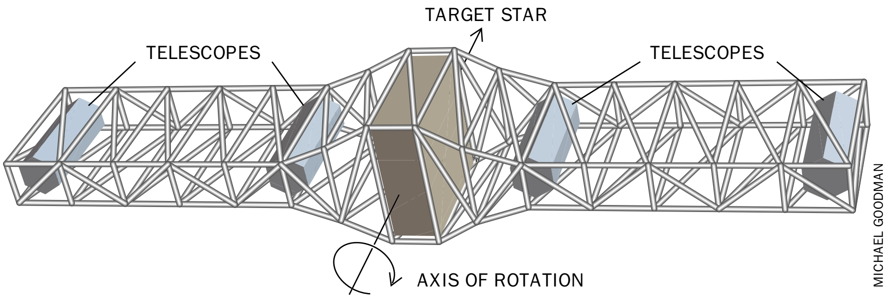
Faced with this quandary, in 1986 we proposed, along with Andrew Y. S. Cheng, now at the University of Hong Kong, that monitoring the mid-infrared wavelengths (longer than visible red wavelengths) emitted by a planet would be a better method for finding planets and looking for extraterrestrial life. 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.

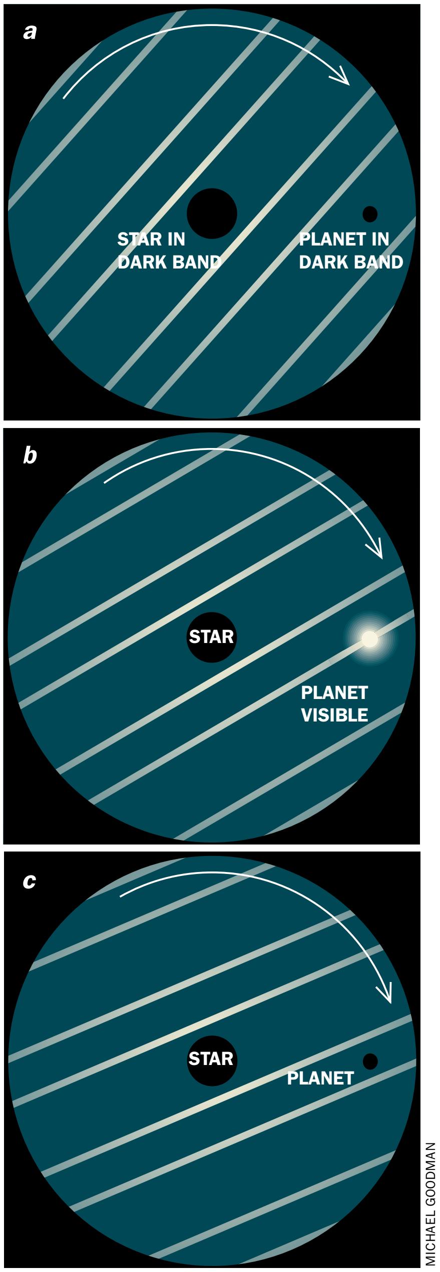
Moreover, three compounds that should appear together on inhabited planets—ozone (a form of oxygen usually located high in the atmosphere), carbon dioxide and water—are easily recognizable by examining the infrared spectrum. Once again, our solar system provides promising support for this technique: 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.

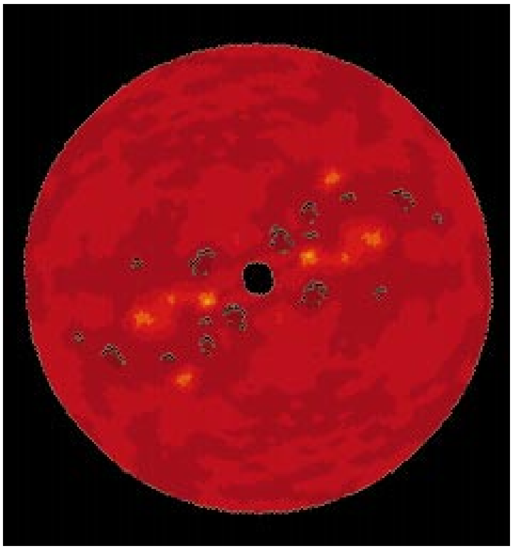


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IMAGE OF DISTANT PLANETS, created from simulated interferometer signals, indicates what astronomers might reasonably expect to see with a space-based telescope. This study displays a system about 30 light-years away, with four planets roughly equivalent 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

A Space Telescope for Infrared Spectroscopy of Earth-like Planets. J.R.P. Angel, A.Y.S. Cheng and N. J. Woolf in *Nature,* Vol. 322, pages 341–343; July 24, 1986.

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