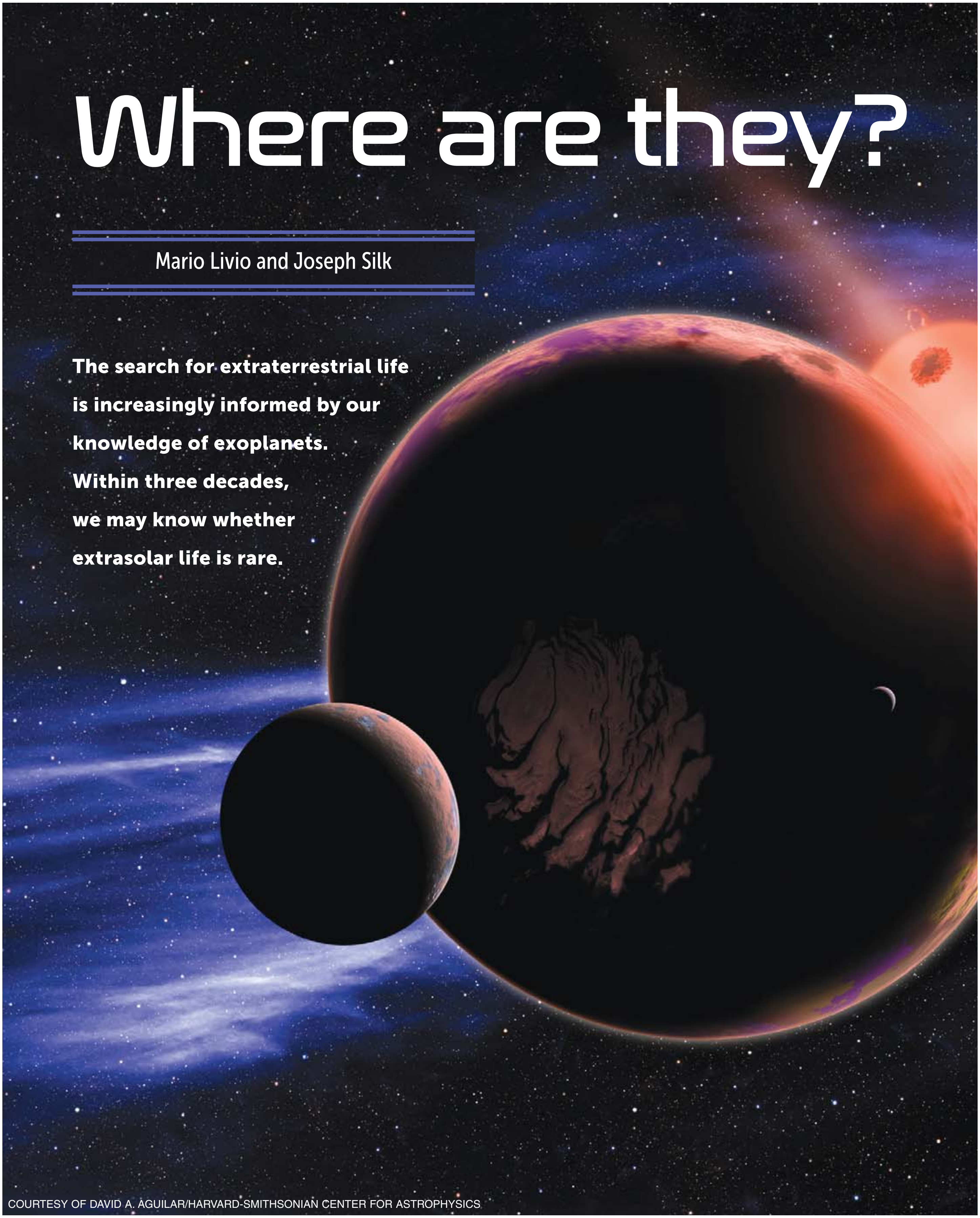
Where are they?

Mario Livio and Joseph Silk

The search for extraterrestrial life is increasingly informed by our knowledge of exoplanets. Within three decades, we may know whether extrasolar life is rare.



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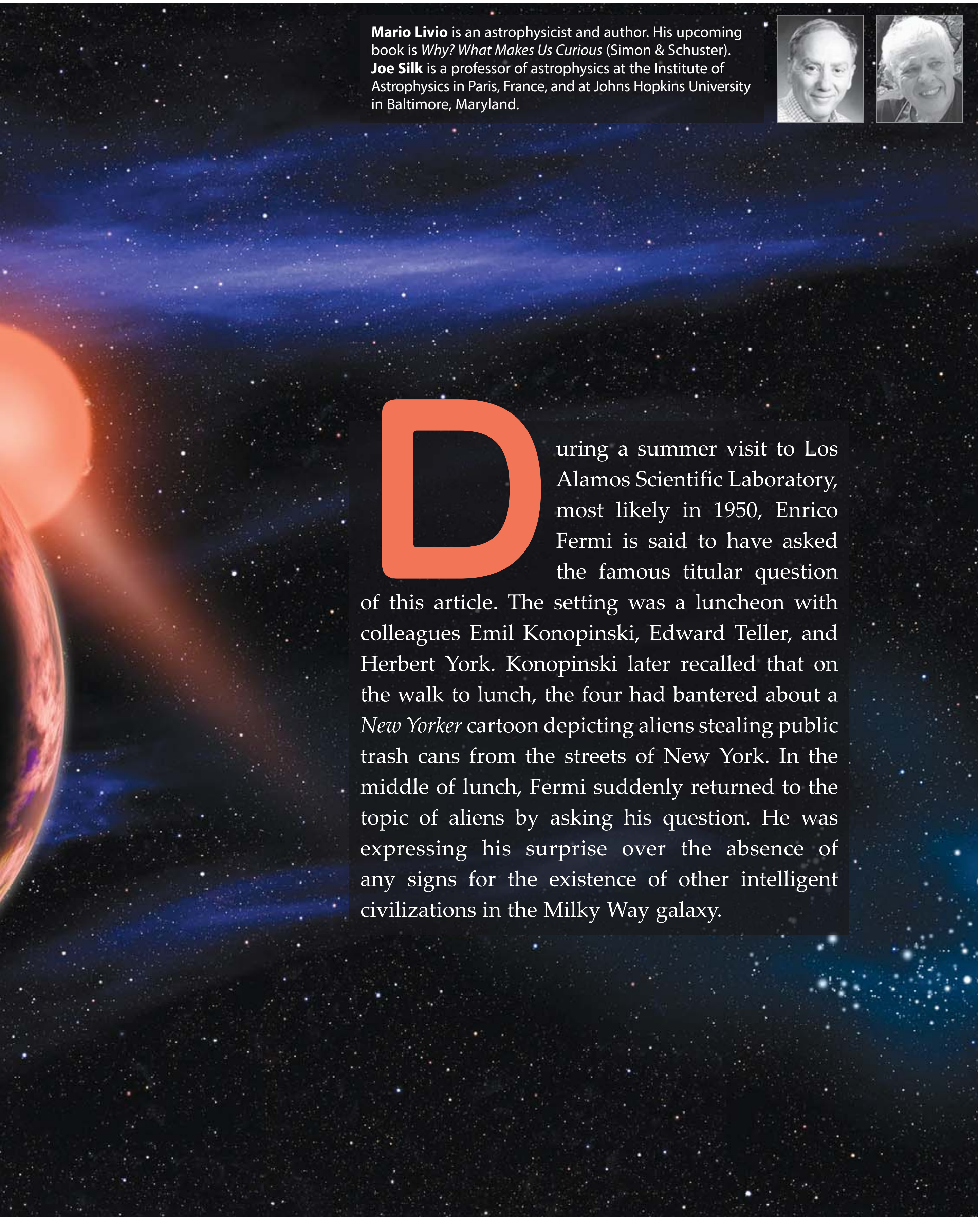

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During a summer visit to Los Alamos Scientific Laboratory, most likely in 1950, Enrico Fermi is said to have asked the famous titular question of this article. The setting was a luncheon with colleagues Emil Konopinski, Edward Teller, and Herbert York. Konopinski later recalled that on the walk to lunch, the four had bantered about a *New Yorker* cartoon depicting aliens stealing public trash cans from the streets of New York. In the middle of lunch, Fermi suddenly returned to the topic of aliens by asking his question. He was expressing his surprise over the absence of any signs for the existence of other intelligent civilizations in the Milky Way galaxy.

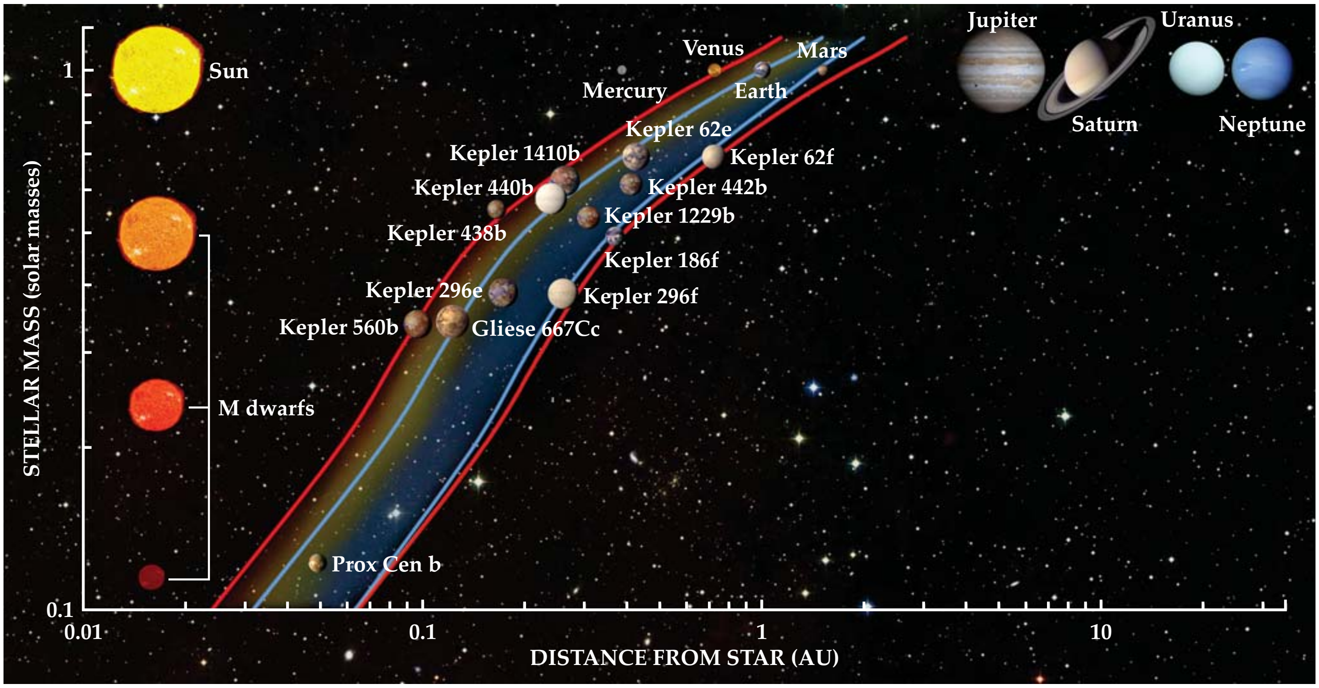

FIGURE 1. THE HABITABLE ZONE, that just-right range of orbital distances around a star that can support liquid water on a rocky surface, lies farther out from a star the more massive, and thus hotter, the star is. Depicted are the planets of the solar system and a collection of habitable-zone exoplanets. Also shown are scaled illustrations of the Sun and three M dwarfs, the most common stars in the galaxy. The red lines represent optimistic estimates for the habitable-zone boundaries based on scenarios in which Venus and Mars were habitable in the past. The blue lines are more conservative estimates based on climate models. (Courtesy of Chester Harman.)

Fermi estimated that for any reasonable set of assumptions, a technological civilization would have reached every corner of the entire Milky Way within a time much shorter than the age of the solar system. Although many potential resolutions to the so-called Fermi paradox have been suggested over the years—the first detailed examination was by astrophysicist Michael Hart in 1975—SETI researchers still have not reached consensus on which one, if any, is correct. Nonetheless, the question of whether we are alone in the Milky Way, or in the universe at large, remains one of the most intriguing questions facing modern humans.

The emergence, evolution, and survivability of extrasolar life, if any exists, involves enormous uncertainties. Despite remarkable progress toward producing life in the lab in recent years, the precise origin of life—the dramatic transformation from chemistry to biology—remains a mystery.

Similarly, even though Darwinian evolution has proven to be an enormously successful paradigm for understanding the diversity of life on Earth, the fact that we have no other examples makes it nearly impossible to say how life might evolve elsewhere. That is true particularly in view of the potentially important play of serendipity throughout the history of life on Earth. For example, Earth is blessed with a relatively large moon that has stabilized the climate. The asteroid belt, on one hand, may have helped to seed life and, on the other, may have been responsible for mass extinctions. Even the location of our solar system—within a minor spur off one of the two main arms of the galaxy, relatively far from the galactic center—has shielded it from the potentially sterilizing effects of gamma-ray bursts.

Given those uncertainties, we attempt in this article to briefly review potential life signatures and future plans to find them; to identify the most generic, remotely detectable signatures of an alien life, both simple and intelligent; and to examine the expected effectiveness of various search strategies.

Extrasolar planets galore

The topic of extrasolar life and how to detect it has become particularly timely. Observations, primarily with the *Kepler* orbiter, suggest that the Milky Way contains no fewer than about one Earth-size habitable-zone planet for every six M dwarfs, the coolest of the red dwarf stars.[1] The habitable zone is that "Goldilocks" region around a star in which liquid water can exist on a planet's rocky surface provided the atmosphere is sufficiently thick. That amounts to more than a billion such planets in our galaxy.

Astrophysicist Adam Frank and astrobiologist Woodruff Sullivan III recently used the *Kepler* statistics on exoplanets to evaluate the prospect that humanity is the only technological civilization to have ever existed in the universe.[2] For that to be true, they concluded, the probability that a habitable-zone planet develops a technological species must be less than 10^{-22}, or one in the expected number of rocky, habitable-zone planets in the observable universe.

The La Silla Observatory in Chile is home to the High Accuracy Radial Velocity Planet Searcher spectrograph. It recently revealed that a planet at least 1.3 times the mass of Earth orbits in the habitable zone of the M dwarf Proxima Centauri.[3] At a distance of 4.2 light-years, Proxima Centauri is the Sun's closest stellar neighbor. Because it has a mass of only 0.12 solar masses and has a luminosity that is only 0.17% of the solar luminosity, Proxima Centauri has a much closer habitable zone than does the Sun (see figure 1). The newly discovered planet completes one orbit in 11.2 days; despite its proximity to its star, it receives an energy flux that is only about 70% of what Earth receives from the Sun.

Searches for life focus on Sun-like and smaller stars because the vast majority of stars are smaller than the Sun: M dwarfs comprise some 70% of all stars in the Milky Way, and a large fraction of them harbor planets. Also, more massive stars have shorter lifetimes and emit intense UV radiation. Both factors make them less hospitable as energy sources for biochemical processes that may require billions of years to unfold and take effect. Stars more massive than about three times the mass of the Sun, for instance, will likely burn out before life has time to emerge and evolve.

In contrast, M dwarfs are more common and live much longer. As an added bonus, planets orbiting in their habitable zones are easier to detect, because M dwarfs are both smaller in size and mass and are less luminous. Consequently, planets can induce a larger reflex motion, the wobble in a star's position as it moves about the star–planet center of mass. Additionally, planets can block a larger fraction of starlight during transits, and the transit probability is higher.

One should note, though, that many red dwarfs exhibit significant flaring activity, a hazard made all the more menacing by the fact that their habitable zones place potentially life-bearing planets close to the stars. Consequently, those planets can experience energetic-particle and x-ray fluxes greatly exceeding terrestrial levels, which may erode atmospheres and create harsh conditions inimical to life. (See PHYSICS TODAY, February 2017, page 24.)

Ideally, therefore, researchers would like to find a star–planet system just like Sun–Earth—Earth 2.0 as it were—because at least we know without a doubt that life emerged here. A program to search for an Earth twin does not guarantee success in finding extrasolar life, but at least it should substantially increase the odds.

Nevertheless, a recent comprehensive examination of the habitability of planets orbiting M dwarf stars concluded that some features of their stellar and planetary environments could confer advantages. For example, synchronous rotation could improve habitable conditions on planets orbiting at the inner edge of the habitable zone. Planets orbiting M dwarfs are also predicted to be more resistant to global glaciation. Therefore, such planets, which are the most numerous and relatively easy to detect, should also definitely be high-priority targets in the search for extrasolar life.[4]

The insistence on the existence of liquid water is again somewhat Earth-centric, but water does have a few special characteristics. It is an excellent solvent; it is less dense as a solid than as a liquid; it is amphoteric, which means it can become an acid or a base by donating or accepting a positive hydrogen ion; and it is abundant across the universe.

Some form of liquid solvent is undoubtedly necessary if chemicals are to be transported into and out of cells and if molecules are to come into contact with one another to form long-chained organic ingredients. A liquid environment would also protect those organic compounds from UV radiation. However, it is not entirely clear whether only water can play that role.

The hunt for biosignatures

The search for extrasolar life has recently received two significant boosts: Breakthrough Listen, a decade-long $100 million project aimed at searching for nonnatural transmissions in the bandwidth from 100 MHz to 50 GHz, and Breakthrough Starshot, whose goal is to send a fleet of tiny probes to α Centauri, the star system nearest the Sun. The recent discovery of an Earth-size planet around Proxima Centauri, one of the three stars in the system, clearly gives extra impetus to Breakthrough Starshot.

One of the stated goals of China's Five-Hundred-Meter Aperture Spherical Radio Telescope, the world's largest filled-in, single-dish radio telescope, is to join the hunt for potential extraterrestrial communications. That's despite the fact that it can access only a limited fraction of the sky. Its construction was completed in July 2016, and the telescope, shown in figure 2, started its commissioning phase in September 2016.

If life can indeed evolve around long-lived, low-mass stars, it may be that the probability for life to exist elsewhere in the universe will be highest some trillions of years from now. Nonetheless, simple life appeared on Earth almost as soon as it cooled sufficiently to support complex and persistent organic chemistry, a crucial precursor to the first water-based organisms. In fact, a recent proposal argues that the cosmic habitable epoch may have started as early as a few tens of millions of years after the Big Bang, after the death of the very first stars.[5]

To be detectable from a distance, life has to evolve to the point where it so dominates the planetary surface chemistry that it significantly alters the atmosphere. Only then will life give itself away through chemical biosignatures that can in principle be detected remotely.[6] Earth itself would probably not have been detectable as a life-bearing planet during the first billion or so years of its existence. Oxygen became an important atmospheric constituent due entirely to life processes but it built up slowly. Any oxygen produced by early organisms first went into oxidizing rocks. Only after the oxidizable rocks became saturated did free oxygen start to enrich the atmosphere.

The evolution of intelligent life involves many more open questions. What are the geochemical constraints on the evolution of complex life? On what time scales do those constraints operate? Is there, as it seems, an impetus toward biological complexification? Are there any evolutionary bottlenecks that make it extremely hard to make the transition to intelligence? Do existential factors limit the likely life span of intelligent life? (Some of those questions are addressed in Charles Cockell's article, "The laws of life," which starts on page 42.)

On Earth, for example, it took 3 billion years for the most basic multicellular life-forms to appear. It took another billion and a half years and an entire series of contingencies, such as plate tectonics and asteroid impacts, to evolve a species capable of rudimentary interstellar communication through radio reception and transmission. We don't know to what extent those time scales reveal any meaningful constraints on the emergence of complex, intelligent life. Nevertheless, they do demonstrate the importance of first establishing whether planetary systems older than the solar system and able to maintain a biosphere are common in the Milky Way. Realistically, near-future searches for extrasolar life will concentrate, after all, on our galaxy.

JEFF DAI (TWAN)

FIGURE 2. THE WORLD'S LARGEST filled-in, single-dish radio telescope, the Five-Hundred-Meter Aperture Spherical Radio Telescope in Guizhou Province, China, entered its commissioning phase last September. Despite the telescope's fixed gaze on a relatively small patch of the sky, the National Astronomical Observatory of China plans to use it to search for potential signals from intelligent life beyond Earth.

The current age of the solar system is about half the age of our galaxy's disk and also half of the Sun's predicted lifetime. We therefore might expect that roughly one-half of the stars in our galactic disk are older than the Sun. That figure by itself, however, is insufficient to judge how commonplace old, biosphere-capable planets are. We need to consider the predicted life span of the biosphere, and not just the lifetime of the host star. Atmospheric scientist Ken Caldeira and geoscientist James Kasting showed that Earth's biosphere will survive for another billion years or so;[7] then Earth will lose all its water within an additional billion years. Both effects are due to the increasing luminosity of the evolving Sun.

The good news is that those limiting effects do not directly apply to M dwarfs, which evolve extraordinarily slowly. For example, the main-sequence lifetime of a star with a mass one-tenth that of the Sun is about 2 trillion years. However, life-hosting planets would still be contingent on geophysical lifetimes because they must be capable of geochemical cycling. For example, the carbon cycle, the movement of carbon from atmosphere to land and oceans and back, plays a large part in determining a planet's temperature.

Intriguingly, a recent examination of cosmic planet-formation history concluded that the solar system formed close to the median age for existing giant planets in the Milky Way. Consequently, about 80% of the currently existing Earth-like planets may have been born before the time of Earth's formation.[8]

The near future

Which detectable biosignature may be considered the most reliable indicator of life on a sufficiently old, rocky planet in the habitable zone of its star? No single biosignature would be absolutely compelling, but an atmosphere that is rich in oxygen—say at a level of a few tens of percent—would probably be the most promising target initially. Figure 3 compares a simulated O_2 transmission signal for a hypothetical Earth-like planet transiting an M dwarf star with the carbon monoxide spectrum detected for the extrasolar giant planet τ Boötis b.

Although the splitting of carbon dioxide by intense UV radiation, the loss of hydrogen from water vapor, and other nonbiological processes can produce oxygen in a planetary atmosphere, only under rare circumstances would they create the high levels of stable oxygen enrichment characteristic of biological activity. Nevertheless, oxygen alone is not definitive evidence for life. Simultaneous detection of oxygen with other potential biosignatures, however, could significantly strengthen the case for a life-based origin for the oxygen. For example, the presence of oxygen and methane together could indicate the kind of extreme thermochemical disequilibrium generated by life. Such considerations moti-

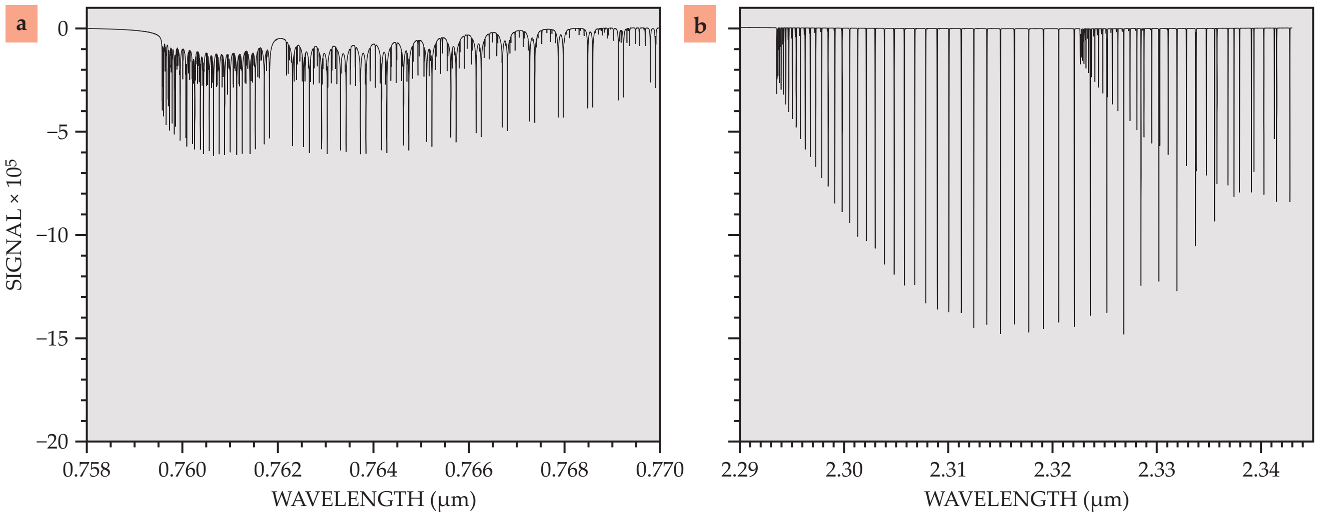

FIGURE 3. ABUNDANT ATMOSPHERIC OXYGEN is one of the most promising signatures of life on an exoplanet. One way to detect that oxygen is to measure the spectrum of a star with a planet in front and subtract the spectrum of the star alone. **(a)** This simulated O_2 transmission signal for a hypothetical Earth-like planet transiting an M dwarf star gives cause for optimism. **(b)** The best fit model for the carbon monoxide signal observed for the hot Jupiter-like planet τ Boötis b is only three times stronger. (Adapted from ref. 10.)

vate spectral observations of extrasolar planets to cover the broadest wavelength range possible.[9]

Consequently, an excellent first step in the quest for extrasolar life in the relatively near future would be to search for planets with atmospheric oxygen in abundance. That could be achieved in principle with a next-generation European Extremely Large Telescope or other large, ground-based arrays of relatively low-cost flux collector telescopes. To perform the search, the telescopes must be equipped with spectrographs whose resolving power $R = \lambda/\Delta\lambda$ is of the order of 100 000 ($\Delta\lambda$ is the smallest wavelength interval that can be distinguished at wavelength λ).[10] Because the oxygen lines in an exoplanet's spectrum will be slightly Doppler shifted relative to oxygen in Earth's atmosphere, it should be possible, though challenging, to detect them. The detection of methane in the IR would naturally have to follow.

In the even shorter term, several upcoming NASA missions will take a first stab at attempting to detect simple signs of life. The *Transiting Exoplanet Survey Satellite* (*TESS*) is expected to be launched no earlier than December 2017. It will likely identify some half-dozen relatively nearby transiting super-Earths—exoplanets with a mass a few times that of Earth—in the habitable zones of M dwarfs. Those will be prime targets for near-IR atmosphere characterization by the *James Webb Space Telescope* (*JWST*), to be launched in October 2018. Unless simple life is extremely ubiquitous and easily detectable, however, the probability for the *TESS*–*JWST* combination, as powerful as it is, to detect life is not very high.

The *Wide-Field Infrared Survey Telescope* (*WFIRST*), expected to be launched in the mid 2020s, will be equipped with a coronagraph, a telescope attachment that blocks out the direct light from a star. Thus *WFIRST* may be able to directly image a few of the super-Earths. Because imaging measures the planet's reflectance, it probes deep into the planetary atmosphere, and thus further constrains atmospheric parameters. Still, the chances that *WFIRST* will actually detect life are also not high.

What would define success for a space mission in search of life? One would want, if such a mission happens to not detect any biosignatures, to at least place a meaningful constraint on the rarity of extrasolar life. According to simulations, to make a statement such as "remotely detectable life occurs in less than about 10% of Earth-like planets in the habitable zone around Sun-like stars" based on nondetection would require the ability to directly image and characterize the atmospheres of at least three dozen or so exo-Earths. Such a yield, in turn, would necessitate a space telescope with an aperture exceeding 8.5 m in diameter even under optimistic assumptions about telescope and coronagraph parameters.[11]

The proposed Habitable Exoplanet Imaging Mission, under discussion for the next astronomy and astrophysics decadal survey in 2020, would have to be designed beyond the upper limit of its current specifications to meet that particular requirement. A more ambitious 9- to 12-m aperture UV/optical/IR space telescope, such as the proposed High-Definition Space Telescope (see figure 4), also under discussion for the next decadal survey, would be a natural candidate to achieve either detection of simple life or an interesting constraint on its rarity.

The hunt for intelligent civilizations

One would ideally like to go beyond simple biosignatures and seek the clearest sign of an alien technological civilization. That could be the unambiguous detection of an information-containing, nonnatural signal, most notably via radio transmission or optical/IR laser beaming. Such a detection is the aim of SETI and other similar programs. One interesting argument to make the search more efficient is that we should concentrate on those directions in which mini-eclipses of the Sun by transiting solar-system planets are detectable. Technological civilizations in those directions, the argument goes, are more likely to discover us and attempt communication.

However, the fraction of the Milky Way that has been reached by radio-communication signals from Earth was recently estimated to be only about 1%. To give ourselves better odds for success, we might want to reach about 50% of the suitable planets before expecting a return signal. That puts

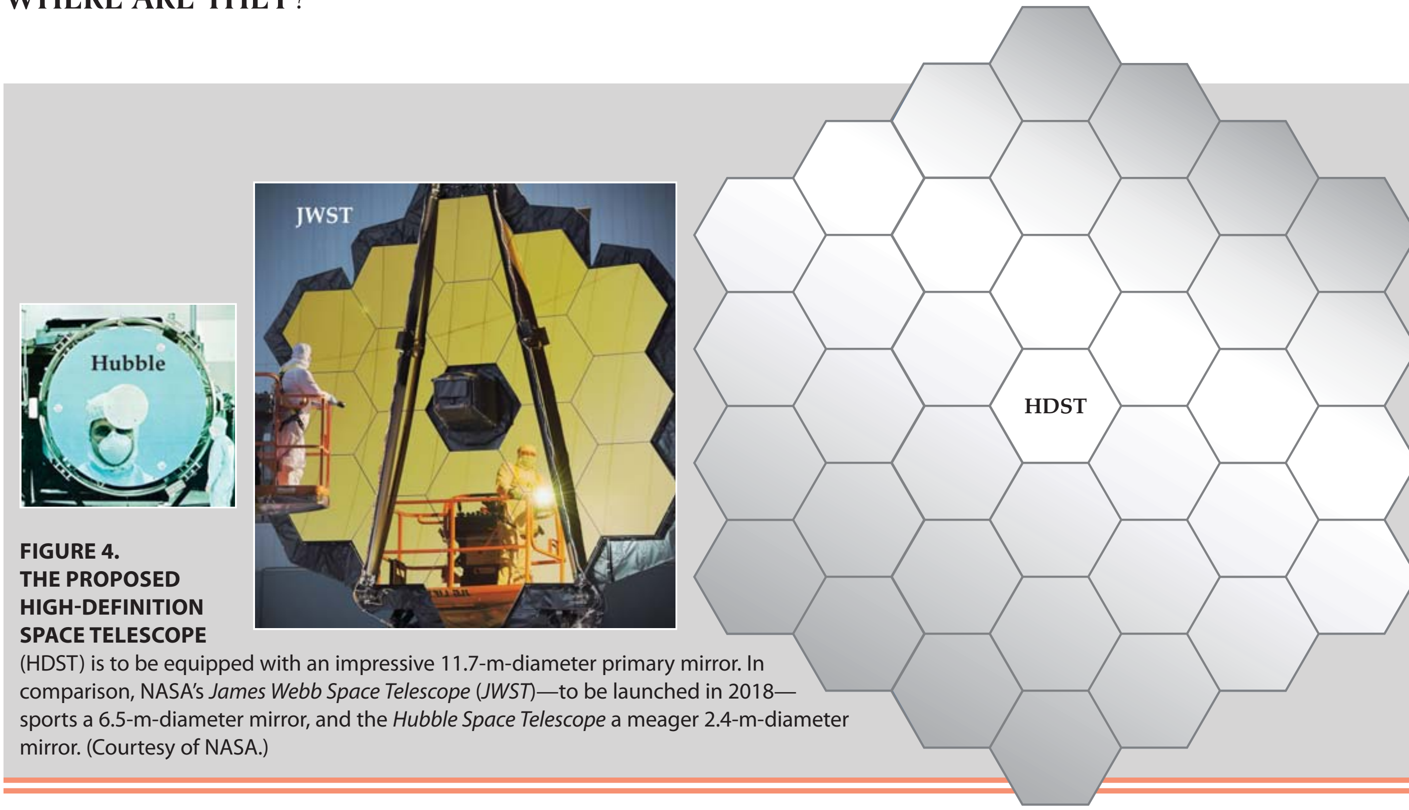

FIGURE 4. THE PROPOSED HIGH-DEFINITION SPACE TELESCOPE (HDST) is to be equipped with an impressive 11.7-m-diameter primary mirror. In comparison, NASA's *James Webb Space Telescope* (*JWST*)—to be launched in 2018—sports a 6.5-m-diameter mirror, and the *Hubble Space Telescope* a meager 2.4-m-diameter mirror. (Courtesy of NASA.)

the more probable time for a reception of a radio signal from another galactic civilization, assuming it exists, some 1500 years into the future.[12]

Similarly, an argument based on Bayesian reasoning, and the possibility that life will emerge in abundance around low-mass stars trillions of years from now, posits that intelligent life on Earth appeared on the cosmic scene rather early. Granting the argument, the very distant future holds much more promise for interstellar communication.

There is, in addition, a distinct possibility that radio communication might be considered archaic to an advanced lifeform. Its use might have been short-lived in most civilizations, and hence rare over large volumes of our galaxy or the universe.

What might then be a more generic signature? Energy consumption, a hallmark of an advanced civilization, appears to be virtually impossible to conceal. One of the most plausible long-term energy sources available to an advanced technology is starlight. Powerful alien civilizations might build a megastructure known as a Dyson sphere[13] to harvest stellar energy from one star, many stars, or even from an entire galaxy. The other potential long-term energy source is controlled fusion of hydrogen into heavier nuclei. In both cases, waste heat and a detectable mid-IR signature would be an inevitable outcome.

Even with the expected higher-efficiency energy production of such an advanced civilization, the second law of thermodynamics ensures that some processes are irreversible. One concern is that even in the absence of technologically advanced aliens, emission from a circumstellar dust belt might confuse any putative signal. The hope is that a natural signal would be distinguishable spectroscopically.

Other potential signatures of technological civilizations that have been suggested, such as various forms of atmospheric industrial pollution and short-lived radioactive products, are necessarily transitory. Basically, we expect that aliens either learn how to clean up after themselves or they destroy themselves. Infrared emission, on the other hand, seems almost unavoidable. Note that the anticipated IR signal should be a nonnegligible fraction of the luminosity of a star and should far exceed typical reflections from terrestrial planetary surfaces and atmospheres.

A recent large survey by the *Wide-Field Infrared Survey Explorer* satellite identified 5—out of about 100 000—red spiral galaxies whose combination of high mid-IR and low near-UV luminosities is inconsistent with simple expectations from high rates of star formation.[14] The UV luminosity, dominated by young stars, typically tracks the star-formation rate, whereas the IR luminosity, dominated by the much more abundant low-mass stars, tracks the total stellar mass. However, a more prosaic explanation for those observations, such as the presence of large amounts of internal dust, has not been ruled out. Such peculiar objects deserve follow-up observations before we make hasty speculations about whether they represent the signature of galaxy-dominating species.

A star that has been in the news for the past 18 months is KIC 8462852, often called "Boyajian's star" (see the Quick Study by Brad Schaefer on page 82). It has shown unusual fluctuations in brightness, sometimes dipping by as much as 21% for periods of a few days, and a gradual decline in brightness by about 19% over a century. One speculation has been that the fluctuations may represent the presence of some megastructure, such as a Dyson sphere, being assembled around the star. More recently, however, a considerably more likely scenario has been suggested. According to the new hypothesis, we are observing a gradual dimming, accompanied by some hiccups, after a brightening that resulted from the star having "swallowed" a planet.[15]

Reflections

To end on a speculative and perhaps pessimistic note, biologically based intelligence may constitute only a very brief phase in the evolution of complexity. What follows could be what some futurists have dubbed the "singularity": the dominance of artificial, inorganic intelligence. If that is indeed the case, advanced species are likely not bound to a planet's surface, where gravity is helpful for the emergence of biological life but is otherwise a liability, but rather floating in space. Even with that imaginative conjecture, one can still argue that any surviving species must be near an energy supply, namely a star. But if such intelligent machines were to transmit a signal, it may well be unrecognizable and nondecodable to our relatively primitive, organic brains.

Perhaps the preponderance of nonbiological intelligence can explain the Fermi paradox. If that scenario holds true, our chances of detecting simple life may far exceed those of discovering intelligent ETs, even if intelligent life is ubiquitous. Still, the ultimate goal of detecting the signature of an advanced intelligence, whether biological or nonbiological, remains the most intriguing option. Therefore, proposed projects for the 2020s that aim in part to search for life—Japan's Space Infrared Telescope for Cosmology and Astrophysics and NASA's Far-Infrared Surveyor to name two—should be welcomed.

The key point is that for the first time in human history, we are perhaps only a few decades away from being able to actually answer Fermi's question. A possible pathway toward that inspiring goal may include the following steps: The detection of potential signs of life with the upcoming generation of space telescopes, followed by the detection of high levels of oxygen from large ground-based telescopes and increasingly reliable detection of biosignatures with the next generation of 10-m-class telescopes in space. Simultaneously, searches for electromagnetic signals from other galactic civilizations should continue, and searches for unusual IR emissions that could indicate energy consumption by remote species should be intensified.

Are we alone? The answer may affect nothing less than our claim for being special in the cosmos. Its importance cannot be overemphasized. Echoing what Giuseppe Cocconi and Philip Morrison said at the end of their seminal 1959 article on searching for extraterrestrials,[16] we shall never know unless we search!

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