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Special Section

Human Uniqueness in the Cosmos

In 1950, the physicist Enrico Fermi is said to have asked "Where are they?"—that is, in a universe teeming with galaxies, and in a galaxy teeming with stars, why have we not yet seen clear evidence of extraterrestrial life? Are we alone, or are there other worlds out there harboring life? Is our universe itself special in some way that makes it conducive to life?

We have asked three scientists to discuss some of the latest research and scholarship regarding the place of life, including human life, in the universe. ***Sara Seager*** *describes the search for Earth-like planets orbiting distant stars and explains what led her to join the hunt.* ***Marcelo Gleiser*** *shows why the findings of physics should help ease our sense of cosmic angst. And* ***Luke A. Barnes*** *explains what it means to say that the universe appears "fine-tuned" for life.*

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Searching for Other Earths

Sara Seager

Look up at the sky on a clear night, somewhere far from the lights of the city, and you will see more stars than you can count. Our own star, the sun, is one of hundreds of billions of stars bound together by gravity in a galaxy—a term that comes from the Greek word for milky, since the night sky is so filled with white starlight that it can look like it is splashed with milk. Our Milky Way galaxy is, in turn, just one of hundreds of billions of galaxies in the universe.

Our sun has eight planets—Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, and Neptune—as well as an asteroid belt; a belt of small icy bodies beyond Neptune (the Kuiper belt); several dwarf planets like Pluto; and numerous planetary moons and other objects. Knowing this, it is only natural to wonder when you look up at the night sky how many of those other stars have planets like ours orbiting them. And are any of those other Earths home to intelligent life forms—perhaps looking out at the stars in their sky, back at our sun, wondering the same thing?

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A few decades ago, astronomers began the systematic search for planets around other stars—what are now called "exoplanets." This fall marks the twentieth anniversary of the announcement of the discovery of 51 Peg b, the first planet confirmed to be orbiting a sun-like star. Since then, astronomers have discovered more than five thousand other confirmed or likely exoplanets.

Perhaps the most striking finding is the sheer variety of types of star-and-planet systems that have been discovered. Some stars have giant planets the size of Jupiter but orbiting much closer in than Jupiter, roughly at the distance Earth would be. Other stars have planets that seem to be about the same size as Earth but are orbiting their stars at a tenth of the distance of Mercury's orbit. Some stars have planets that seem to be rocky like our world but are significantly bigger than it—the so-called "super-Earths." Some stars have systems consisting of several planets all orbiting within the distance of where Venus would be. And there are planets that orbit two suns, in "binary star systems." A hot super-Earth exoplanet called Kepler 10b, discovered in 2010, was the first robustly confirmed rocky exoplanet outside of our solar system and likely has a surface hot enough for melted rock to form lakes made of liquid lava. Another—GJ 1214 b, discovered in 2009—is a planet 2.7 times the size of Earth; it has no counterpart in our solar system and might be a water world, with a layer of an exotic form of water beneath a thick steam atmosphere. The research conducted to date suggests that most of the stars in our galaxy have at least one planet of some sort orbiting them. If you can imagine a kind of planet, as long as the scenario you're imagining obeys the laws of physics and chemistry, it's probably out there somewhere.

No system that we have found so far seems to resemble our own solar system fully, which suggests that the configuration of our solar system is somewhat rare—although the planet-finding techniques available to us today admittedly make finding such copies difficult. And while we can often detect whether a planet is about the same size as Earth and about the same distance from a sun like ours, we cannot yet directly tell whether an exoplanet has Earth-like oceans, continents, and breathable air, or if instead its surface is scorching hot like that of Venus.

Exoplanets and the Search for Life

The idea of searching for extraterrestrial intelligence is a familiar one, thanks largely to movies and television shows depicting scientists, sometimes real and sometimes fictional, scouring the skies for radio signals. But scanning for messages from space is not the only way to look for alien life. The hunt for exoplanets opens up the possibility of another way of searching for life on other worlds, or at least life similar to life here on Earth.

To identify whether an exoplanet might be habitable—meaning that it has the right conditions to harbor life as we know it—we must observe the exoplanet's atmosphere to find out how powerful its greenhouse effect is. Although we usually tend to discuss the greenhouse effect in the context of worrisome human contributions to global warming here on Earth, it is worth remembering that the same effect is what makes our planet warm enough to be habitable in the first place. When it comes to harmful global warming here on Earth, we are concerned about how human industry is changing the chemical makeup of our atmosphere—for example, an increase of around 40 percent of carbon dioxide has been recorded since the beginning of industrialization. Now imagine an exoplanet the size of Earth and roughly the same distance from its sun, and with an atmosphere as dense or denser than ours but with a concentration of carbon dioxide ten or a hundred or even more than a thousand times higher than in our atmosphere. The greenhouse effect would be much more powerful, the temperature would likely be much higher, and, if the surface temperature is very high, the likelihood that such a planet could be a home to life would be low.

Unfortunately, the instruments currently available to astronomers are not capable of studying the atmospheres of small, Earth-sized exoplanets. But since the early 2000s we have been able to study the atmospheres of hot giant exoplanets. Such hot giants, like the exoplanet 51 Peg b mentioned above, are not habitable by life as we know it: like Jupiter they have no solid surface, and since they orbit much closer to their stars than Jupiter, they are also too hot to support life. Still, we have been able to study the atmospheres of a few dozen hot exoplanets, using observatories based in space (mostly the Hubble, Kepler, and Spitzer telescopes) as well as on the ground (such as the European Southern Observatory's Very Large Telescope in Chile, the Gemini South Observatory in Chile, and the Spanish Gran Telescopio Canarias in the Canary Islands).

The general technique we use to study exoplanet atmospheres, spectroscopy, allows us to identify some of the chemicals present in an object based on that object's colors—or, to be more precise, based on the wavelengths of radiation absorbed by the planet's atmosphere.

In the near future, new telescopes will make the study of exoplanets easier, and will make it possible for us to begin studying the atmospheres of small exoplanets. When that day comes, astronomers suspecting that an exoplanet might be habitable will look for several clues. First, we will hope to find water vapor in the atmosphere—vitally important not only because it is a major greenhouse gas but because it would suggest the presence of liquid oceans, and life as we know it requires liquid water. Second, we would like to find carbon dioxide, a gas present on our own solar system's terrestrial planets Venus, Earth, and Mars. And by monitoring the exoplanet's variability in light, we may be able to discern if it has oceans and continents—a mix of features that some evolutionary biologists consider conducive to the development of life.

Our loftiest goal, the prize on which many exoplanet astronomers are fixated, is the prospect of discovering an atmosphere with a gas that does not "belong"—that is, a gas unlikely to be found if life is absent. On Earth, the best example of such a biosignature gas is oxygen. Earth's atmosphere is filled to 21 percent by volume with oxygen, and we humans, like nearly all the known kinds of animals, need oxygen to survive. Yet without plants and photosynthetic bacteria, Earth's atmosphere would have virtually no oxygen. Astrobiologists are busy trying to determine how to tell the difference between planetary scenarios where oxygen may have been produced without life and other scenarios where the presence of oxygen on a planet is a robust sign of life. There are also many other chemicals involved in life processes on Earth, but, as in the case of oxygen, additional clues would be needed before the presence of these gases on an exoplanet could be attributed to life or to other causes (such as volcanoes belching gases into the air). Future telescopes should greatly boost our ability to detect these biosignature gases.

It is worth remembering, of course, that life on other planets could be very much unlike "life as we know it." It could be carbon-based, like life on Earth, but different enough to flourish in an atmosphere significantly different from Earth's. Or it might not be carbon-based at all; it might have a fundamentally different biochemistry. Or, life may exist subsurface or only in oceans. The theories of the young field of astrobiology are informing our study of exoplanets, and the data we astronomers are finding are in turn giving the planetary scientists and astrobiologists much to chew over.

New Tools, New Planets

Looking ahead, the first of the new tools we anticipate aiding the search for small and potentially habitable exoplanets is the Transiting Exoplanet Survey Satellite (TESS), an M.I.T.-led NASA mission scheduled to launch from Cape Canaveral on a SpaceX Falcon 9 rocket in August 2017.

TESS will use four identical cameras to stare at a large strip of the sky for almost a month at a time; over the course of two years, it will have observed 26 such strips, completing a survey of nearly all of the sky. Its quarry will be planets in "transit"—that is, planets that go in front of the star as seen from the telescope. (Think of a transiting planet as akin to an eclipse, but blocking out only a part rather than all of a star.) Transiting planets are the easiest to discover at the present time because the planet does not have to be seen on its own, distinct from the star—an enormous technical challenge. Trying to see directly an Earth-like planet around a sun-like star is like trying to make out a firefly flashing in the air next to a huge searchlight, when the searchlight is in New York and you're in Los Angeles.

Looking for transiting planets makes the problem more tractable: we monitor the brightness of a star over time, watching to see whether there is a tiny (and repeating) drop in brightness, as we would expect if a planet passed in front of the star as seen by the telescope. From the precise shape and duration of the star's change in brightness before, during, and after the planet's transit, a great deal of information about the planet can be gleaned, including information about its size and orbit.

We anticipate detecting tens of thousands of transit-like signals with TESS. My colleagues in the exoplanet-hunting community will then use ground-based telescopes to make follow-up measurements, primarily of planet mass, to determine if the signal is just a false positive or if it is a bona fide planet. TESS is designed to deliver fifty rocky planets with measured masses to the astronomy community. Of those, we will choose perhaps a prize half-dozen or so, and propose to observe their atmospheres with another new tool that will soon be available: the James Webb Space Telescope (JWST), currently scheduled to launch in 2018 from the spaceport in French Guiana. JWST will be larger, in a more favorable orbit, and much more powerful than the famous Hubble telescope that has already for two decades given us unforgettable images of and wonderful information about the universe, and so we hope to use JWST to find signs of habitability or even biosignatures on the exoplanets it helps us to peer at.

What are the chances that we will find signs of life in the atmosphere of a small, rocky exoplanet? With the combination of TESS and JWST, we will for the first time have the capability to detect signs of life in exoplanet atmospheres. But we will have to be very lucky to make any robust discovery amidst the handful of anticipated TESS-discovered habitable planets.

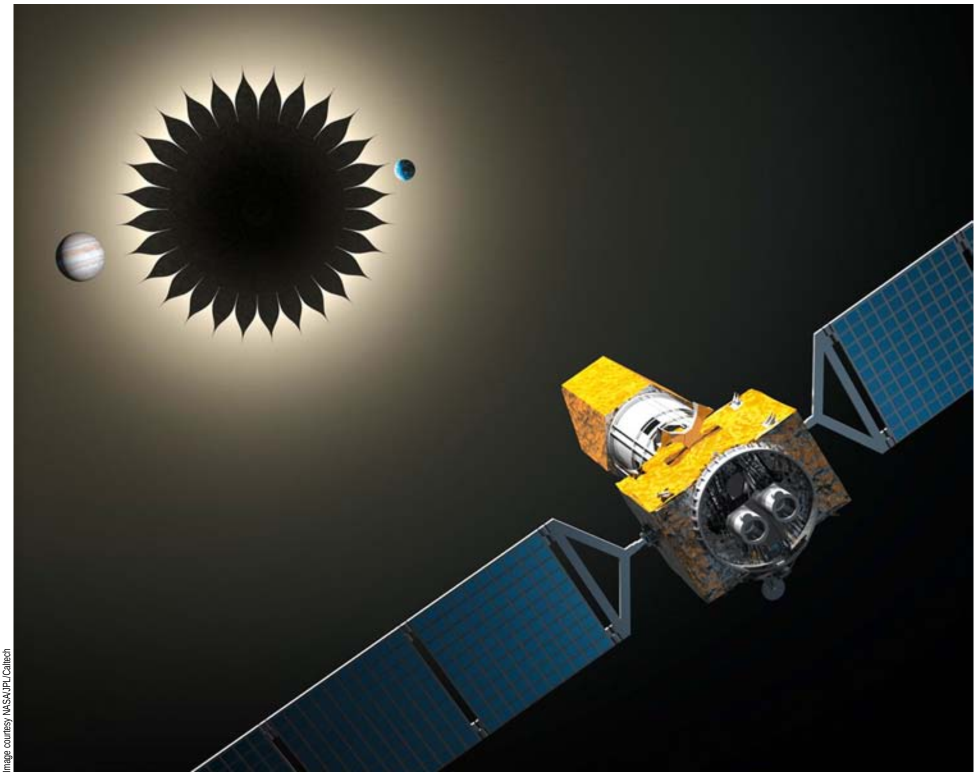
Notwithstanding our high hopes that TESS and JWST will lead to important discoveries, searching for transiting exoplanets will always remain a less-than-ideal technique. For one thing, it requires an exoplanet to be fortuitously aligned between its star and our telescope. A planet in an Earth-like orbit around a sun-like star has only about a one in two hundred chance of transiting its host star from our perspective. And the technique also relies on looking at the star and the planet together, making it more difficult to observe atmospheres of Earth-like planets around a sun-like star.

To be able to search for and identify Earth-like exoplanets orbiting the nearest sun-like stars, we must image the planet directly. Which returns us to the difficulty of our analogy from earlier. Is there any way to make it easier for us to see the firefly fluttering by the searchlight?

This challenge actually involves two problems rolled into one. First, we would have to find a way to block out the bright light of the parent star. (To give a sense of how difficult that is, our own sun is about 10 billion times brighter than the Earth at visible wavelengths.) And then we would have to deal with the problem of diffraction—the bending of light rays as they encounter a surface. A telescope observing a distant star will not see a perfect point of light. Instead the telescope would see a pattern of diffraction rings, which can be up to 100,000 times brighter than an Earth-like planet.

Astronomers and engineers have proposed very clever ways to solve these two problems—and even to make the diffracted light part of the solution. One especially attractive idea involves launching a giant screen to block out the starlight, so that only the light from orbiting planets would enter the space telescope. The screen, called a "starshade," would be in space, flying in formation with a space telescope but at a distance of tens of thousands of miles. In order to deal with the diffraction problem, the screen would not be circular but would look something like a huge flat flower, a concept first suggested in the 1960s by Princeton professor Lyman Spitzer in the same paper that proposed what would become the Hubble Space Telescope, and a shape brought to its modern essence by University of Colorado at Boulder professor Webster Cash. The starshade would make part of the image very dark—dark enough to image exoplanets. (If you think of the diffraction pattern as something like the ripples around a pebble tossed into a pond, the starshade would counter those ripples so that the area around the pebble is smooth.)

In the words of the team tasked by NASA with conceptualizing and analyzing a mission to launch a starshade—a team that I chaired—the



An artist's conception (not to scale) of a starshade—a flower-shaped screen launched into space, flying in formation with a space telescope tens of thousands of kilometers away. With its special shape, the starshade would not only block the bright light of a distant star but would also compensate for the diffraction (i.e., bending) of light, thereby making it possible to glimpse planets orbiting the star.

starshade is the only concept we have that will let us "reach well into the habitable zones of nearby stars to detect and characterize Earth-sized exoplanets using a relatively small space telescope." If properly funded, a starshade mission could be launched in the mid-2020s.

Look Up

Let us take a step back now to ask why we should search for and study exoplanets at all. Hundreds of researchers around the world are dedicating careers to this endeavor, and NASA and the European Space Agency, along with other international partners, are committing precious public funds. Why is it worth the resources and the effort?

The main reason to study exoplanets is to satisfy our scientific curiosity. For instance, the search for exoplanets has already helped us better understand how planets and planetary systems form and develop. Astronomers' theories have been upended by the fact that the most common type of exoplanet we have found so far is one with no analogue in our own solar system: a planet two to three times the size of Earth. (In our solar system, Uranus and Neptune are about four times the size of Earth.) We do not know how what appears to be the most common type of planet in our galaxy forms.

We have already discussed above some of the other fundamental questions that the study of exoplanets might shed some light on, including whether there are planets just like Earth out there, with continents and oceans and thin atmospheres with clouds, and whether any of those other Earths will have signs of life. These are questions of more than just scientific interest—they inspire hope that we might someday more fully understand our own origins and our place in the universe, and they fire the imagination about the possibilities that the future might hold for humankind.

A second reason for studying exoplanets is, admittedly, one that applies also to other areas of science and technology: the possibility of spinoffs. There is a long list of everyday tools that only exist as applications or byproducts of pure research, including the laser (with its ubiquitous applications from surgery to music to medicine), medical imaging, DNA testing for medical and forensic uses, and on and on. Such technological breakthroughs can transform the world. They are, however, unpredictable. We cannot know for certain whether the search for exoplanets will result in major advances in, say, optics or data processing or automation or space operations, or perhaps other unanticipated fields. But by supporting basic research, we increase the likelihood that we will stumble upon some new technology or technique with surprising potential for wider application.

A third reason for supporting the study of exoplanets—and indeed for supporting space science in general—is to help showcase our nation's technical prowess, and to demonstrate U.S. leadership. The details of many of our advanced commercial and defense-related technologies are kept secret; they are either proprietary or raise national-security concerns. But our work in space is on display for the world to see. Consider the James Webb Space Telescope discussed above. Several innovative technologies have been developed and brought together to make this powerful new tool possible, including a folding, segmented primary mirror, adjusted to shape after launch; ultra-lightweight beryllium optics; detectors able to record extremely weak signals; microshutters that enable programmable object selection for the spectrograph; and a cryocooler capable of cooling the mid-infrared detectors to just a few degrees above absolute zero. These kinds of technical advances clearly show the rest of the world our nation's future-oriented stance, and demonstrate how our universities and private industry and public agencies can work together to achieve great goals.

The search for exoplanets can also serve to inspire future leaders, including future innovators in science and technology. In recent years, various space- and planetary-science missions—such as the rovers on Mars, the New Horizons flyby of Pluto, and the brilliant images from Hubble—have captured the public's interest and imagination. The exoplanet hunt, too, offers major opportunities for public engagement. People from all walks of life will surely be drawn in by its complicated space telescopes, its potential for grassroots "citizen science" projects, and its intriguing possibilities for finding strange new worlds. The leaders of the tech revolution of the 1980s and 1990s grew up during the era of the Apollo moon landings; the leaders of the next generation will grow up as we search for other Earths.

For my part, I want to explore. That is what motivates me. I recall from my youth a two-month wilderness canoe trip on the seemingly endless subarctic tundra of Nunavut, Canada. Hundreds of miles from any remote outpost let alone from the nearest town, the trip oscillated between adrenaline-pumped rapids and tediously long lake crossings. Late one day, after my canoe partner and I had not seen other people for weeks, I was getting more and more excited about a person on a very distant shore. Was the person waiting for us? Who could it possibly be? What would we say? As my canoe partner and I paddled slowly down the lake, I was crushed to find not a person but an *inunnguaq*, a rock statue intended to appear like a person from afar. The Inuit created these stunning structures either to keep travelers company or to show the way.

Today I have the same feeling—a sense of adventure, of mystery, and of hope—about our search for exoplanets. Although space is vast, we already know that small planets are very common, and I feel that other Earths are out there, just waiting to be found with our next-generation telescopes. And so I wonder, *What is out there? Who is out there?* In the past few years, as news of our discoveries and our future prospects have filtered into the public consciousness, I have witnessed what I call an "awakening"—a growing realization that finding life elsewhere in our galaxy could be in our near future. This discovery would forever change how we see ourselves and our place in the cosmos. It is a source of great joy and constant wonder to be a part of this historic project of exploration and pursuit of other Earths.