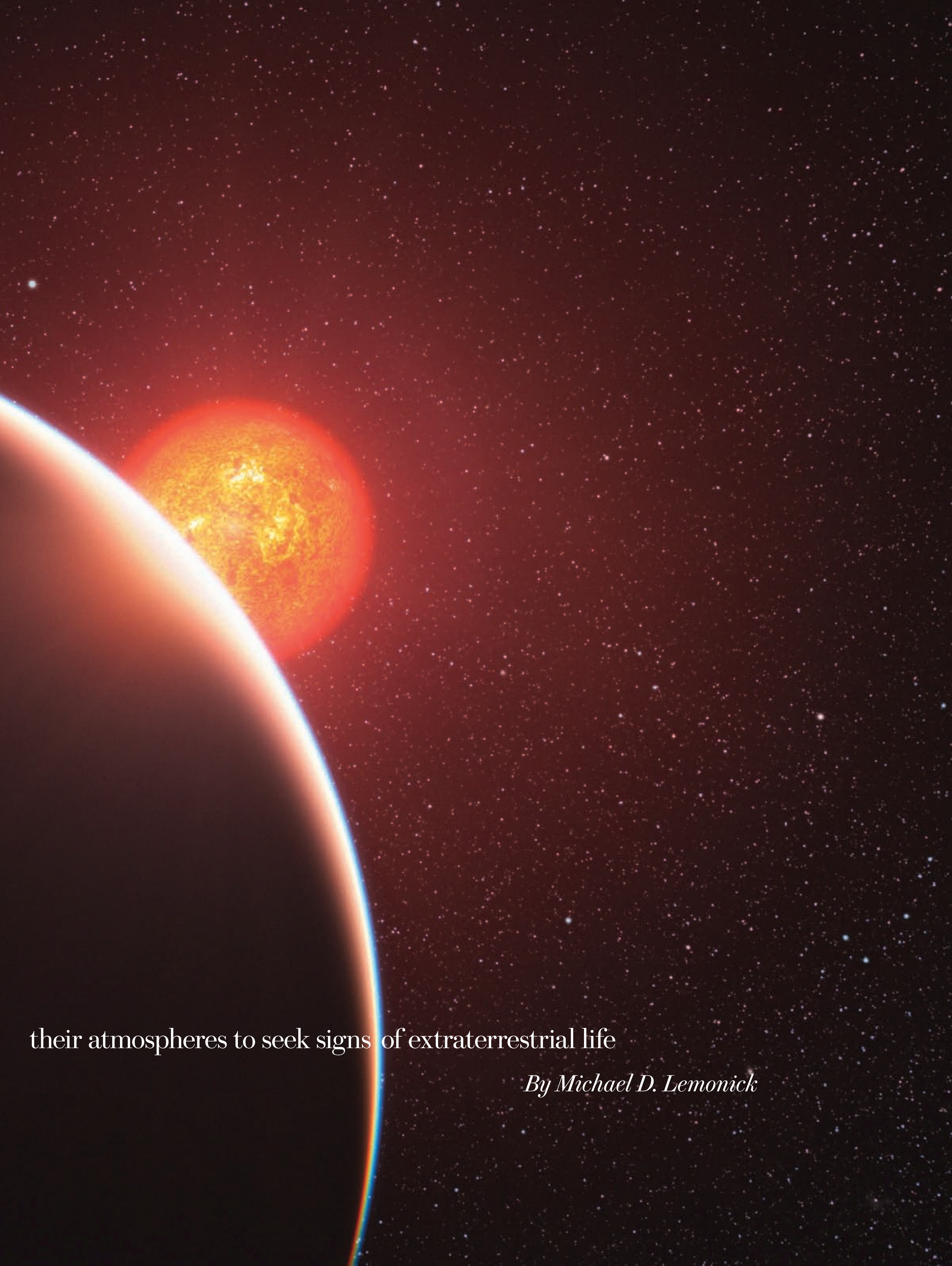
ASTRONOMY

The Dawn of Distant Skies

The galaxy is teeming with planets. Scientists are straining to peer into



their atmospheres to seek signs of extraterrestrial life

By Michael D. Lemonick

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Nobody who was there at the time, from the most seasoned astrophysicist to the most inexperienced science reporter, is likely to forget a press conference at the American Astronomical Society's winter meeting in San Antonio, Texas, in January 1996.

It was there that Geoffrey W. Marcy, an observer then at San Francisco State University, announced that he and his observing partner, R. Paul Butler, then at the University of California, Berkeley, had discovered the second and third planets ever found orbiting a sunlike star. The first such planet, 51 Pegasi b, had been announced by Michel Mayor and Didier Queloz of the University of Geneva a few months earlier—but a single detection could have been a fluke or even a mistake. Now Marcy was able to say confidently that it had been neither. "Planets," he told the crowd, "aren't rare after all."

The announcement shook the world of astronomy. Almost nobody had been looking for planets because scientists were convinced they would be too hard to find. Now, after searching a mere handful of stars, astronomers had discovered three worlds, suggesting billions more waiting to be found.

If Butler and Marcy had merely settled a question on planetary formation theory, their discovery would not have been such a big deal. But it showed unequivocally that so-called extrasolar planets did exist and, with them, the possibility of answering a question that had vexed philosophers, scientists and theologians since the time of the ancient Greeks: Are we alone in the universe?

After the initial celebration, scientists settled down to figuring out exactly how they were going to investigate the prospect of even a rudimentary form of life on a planet orbiting an alien sun. Short of picking up an extraterrestrial broadcast, à la Jodie Foster in the movie *Contact,* the only way to find out would be to search extrasolar planets for atmospheric biosignatures—evidence of highly reactive molecules such as oxygen that would quickly disappear unless some kind of metabolizing organisms were replenishing the supply.

Marcy, Mayor and their colleagues had seen only the gravitational effect the planets had on their parent star; to detect a biosignature, you would need to image an exoatmosphere directly. To do this, NASA planned to launch an increasingly powerful series of space telescopes, a program that would culminate in an orbiting telescope called the Terrestrial Planet Finder Interferometer that would cost billions of dollars and fly sometime in the 2020s. In short, astronomers knew that they wouldn't be learning anything about exoplanet atmospheres anytime soon.

They were wrong. The discovery of those first few exoplanets inspired an entire generation of young scientists to get into what was suddenly the hottest specialty in astrophysics. It convinced many of their older colleagues to switch into exoplanetology as well. This sudden influx of brainpower led to fresh

IN BRIEF

Common wisdom once held that it would be nearly impossible to investigate the atmospheres of distant exoplanets—the glare from their parent star would be too bright.

Yet once scientists began to study exoplanets as they passed behind their star, they realized that the resulting change in stellar brightness could provide clues to what the atmospheres are made of.

Astronomers are now using these advanced techniques to detect atoms and molecules of exoplanetary atmospheres. They hope to soon extend their search to molecules that will provide evidence of distant life.

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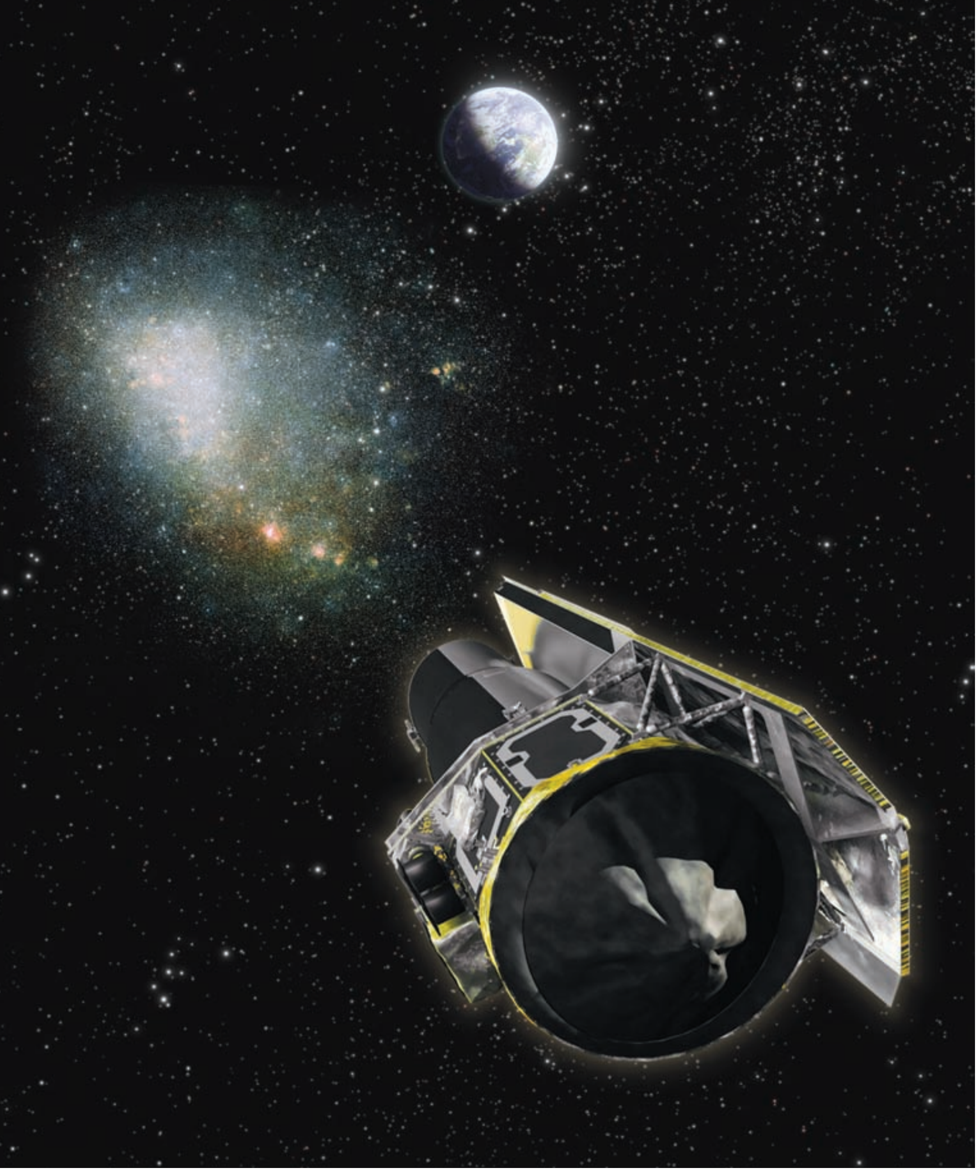


SOLAR ECLIPSE: **The Spitzer Space Telescope can detect the minute change in brightness that happens when a planet passes behind its host star.**

COURTESY OF CALTECH AND NASA

ideas for investigating exoplanet atmospheres and sped things up dramatically. By 2001 observers had identified sodium in the atmosphere of one exoplanet. Since then, they have identified methane, carbon dioxide, carbon monoxide and water as well. They have even found indirect hints, by examining exoplanet atmospheres, that some planets may be partly made of pure diamond. “At this point,” says Heather Knutson, a California Institute of Technology astrophysicist who was involved in many of these pioneering observations, “we've learned something about the atmospheres on the order of 30 to 50 planets—if you count stuff that's not yet published.”

These discoveries are still a long way from providing evidence of life—no surprise, since most of the worlds Knutson is talking about are hot, Jupiter-like planets that hug their star more tightly than fiery Mercury orbits the sun. Increasingly, however, Knutson and other observers have begun to probe the atmospheres of smaller planets, so-called super-Earths, which are between two and 10 times as massive as our home planet—something that nobody could have imagined just a decade ago. The announcement in April that the Kepler space telescope had found two planets less than twice Earth's size, both in orbits where temperatures might permit life to survive, was one more hint that life-friendly worlds are almost certainly plentiful. So while these planets, named Kepler 62e and 62f, are too distant to study in detail, astronomers are convinced it won't be many more years before observers can look for biosignatures in the atmospheres of planets that are essentially twins of Earth.

THE PARKING-LOT PLANET

ASTRONOMERS assumed it would take decades to start looking at planetary atmospheres because the first handful of exoplanets were discovered indirectly, through the influence each had on its parent star. The planets themselves were invisible, but because each star and planet orbit a mutual center of gravity, the gravitational tug of the planet makes the star appear to wobble in place. When a star moves toward us, its light subtly shifts toward the blue end of the visible-light spectrum; when it moves away, the light shifts to the red. The degree of shifting tells observers the star's radial velocity, or how fast it moves toward and away from Earth, which in turn tells us how massive the exoplanet is.

Another option for finding planets was also available, however. If the invisible planet's orbit were perfectly edge-on as seen from Earth, the planet would pass directly in front of its star, in what is known as a transit. Yet at the time of those first discoveries nearly two decades ago, few astrophysicists were thinking about transits at all, simply because the search for planets was itself so far out on the fringe. (A notable exception was William J. Borucki of the NASA Ames Research Center, whose Kepler spacecraft would eventually find transiting objects by the thousands.)

A few years later, in 1999, Timothy W. Brown, then at the National Center for Atmospheric Research, and David Charbonneau, at the time a graduate student at Harvard University, set up a tiny, amateur-size telescope in a parking lot in Boulder, Colo., and saw an exoplanet transit for the first time. The planet was HD 209458b, which had been detected earlier by the radial-velocity technique. Weeks later Gregory W. Henry of Tennessee State University, working with Marcy, watched the same planet transiting its star. Both teams have been given equal credit for the discovery because the two detections were published simultaneously.

The successful detection of transits not only gave astronomers a second way to find exoplanets, it also gave them a way to measure their density. The radial-velocity technique had revealed HD 209458b's mass. Now astronomers knew how physically large it was because the amount of starlight a planet blocks is directly proportional to its size. (Dividing its mass by its size showed HD 209458b to be 38 percent larger than Jupiter even though it is only 71 percent as massive, an unexpected result that Princeton University astrophysicist Adam Burrows calls "an ongoing problem to explain.")

By this time a number of astrophysicists had realized that transits also made it possible to study an exoplanet's atmosphere, in what Knutson calls a "wonderfully clever shortcut." Even before the first transit was reported, in fact, Sara Seager, an astrophysicist at the Massachusetts Institute of Technology, who at the time was Charbonneau's fellow grad student at Harvard, had co-authored a paper with her adviser, Dimitar D. Sasselov, in which they predicted what an observer should see as light from a star passed through a planet's atmosphere when the planet moved across the star's face [see "Planets We Could Call Home," by Dimitar D. Sasselov and Diana Valencia; Scientific American, August 2010]. Physicists have long known that different atoms and molecules absorb light at different wavelengths. If you look at planets in a wavelength that corresponds to the molecule you are searching for, any atmospheres containing that molecule will absorb the light. The wispy planetary atmosphere will become opaque, making the planet appear larger.

Seager and Sasselov suggested that sodium would be especially easy to detect. "Sodium is like skunk scent," Charbonneau says. "A little bit goes a long way." He knows this better than anyone: in 2001 Charbonneau, Brown and their colleagues went back to HD 209458b, their original transiting planet, not with a puny amateur telescope but with the Hubble Space Telescope. Sure enough, the sodium signal was there, just as predicted.

TOTAL ECLIPSE

ASTRONOMERS also realized that there was a second, complementary way to inspect the atmospheres of transiting planets. When a planet passes in front of its star, it presents its nightside to the observer. At other times, it shows at least part of its dayside, and just before the planet goes behind the star, the dayside is facing Earth. Although the star is far, far brighter, the planet itself also glows, mostly in the infrared.

That glow vanishes abruptly, however, when the planet moves behind the star; its contribution to the combined light of planet and star vanishes. If astrophysicists can do a before-and-after comparison, they can deduce what the planet alone would look like [*see box on opposite page*]. "It changes the nature of the problem," Knutson says. "Instead of having to detect a very faint thing close to a very bright thing, all you have to do is measure signals that change with time." As early as 2001, L. Drake Deming, then at the NASA Goddard Space Flight Center, aimed an infrared telescope on Hawaii's Mauna Kea at HD 209458b in an attempt to see this so-called secondary eclipse, but, he says, he couldn't make a detection.

He knew, however, that the Spitzer Space Telescope, scheduled for launch in 2003, would almost certainly be able to make such an observation, as did Charbonneau. Both astrophysicists, unbeknownst to each other, applied for time on Spitzer to make the observations. Both got the time and took their data. Then, one day in early 2005, Deming recalls, he got a voice message: "Drake, this is Dave Charbonneau of Harvard," the voice said. "I hear you made some interesting observations lately. Maybe we should talk."

It turned out that Deming (working with Seager) and Charbonneau had independently made the first secondary-eclipse detections in history, at virtually the same time, using the same observatory. The two groups announced their results for two different stars—the much-worked-over HD 209458b in Deming's case and a planet named TrES-1 in Charbonneau's—simultaneously. A year later Deming's team detected the secondary eclipse of a planet called HD 189733b. "This," wrote Seager and Deming in a 2010 review article, "unleashed a flood of secondary eclipse observational detections using *Spitzer*.... It is accurate to say that no one anticipated the full magnitude and stunning impact of the *Spitzer Space Telescope* as a tool to develop the field of exoplanet atmospheric studies." In fact, Seager says, "we're using the Hubble and the Spitzer in ways they were never designed to be used, going to decimal places they were never designed to reach."

ATMOSPHERIC LAYERS

THOSE STUDIES have shown a couple of things, Seager says. "This sounds trite in a way, but we've learned that hot Jupiters are hot. We've measured their brightness and temperatures," and what scientists have observed is consistent with how they expect stars to heat their planets. "Number two," she continues, "we've detected molecules. Now has [what we've found] been very different from what we expected? You know, not really." Seager notes that physicists can straightforwardly model a ball of gas at some temperature made of some combination of elements and ask what kind of molecules form. "The laws of physics and chemistry are universal," she says.

Seager and other astrophysicists have also learned, however, that despite the overall similarity of exoplanet atmospheres, individual planets can differ in several ways. One has to do with how temperature changes with altitude. Some planets, such as Jupiter and Saturn in our own solar system, show temperature inversions, in which temperature rises with altitude rather than falling. Others do not. "The problem," Knutson says, "is that we don't know what's causing the inversion, and we can't predict, therefore, which exoplanets will and won't have this feature." Some astrophysicists suggest that exoplanets with inversions might have some kind of heat-absorbing molecule, such as titanium oxide, but so far this is just a hypothesis.

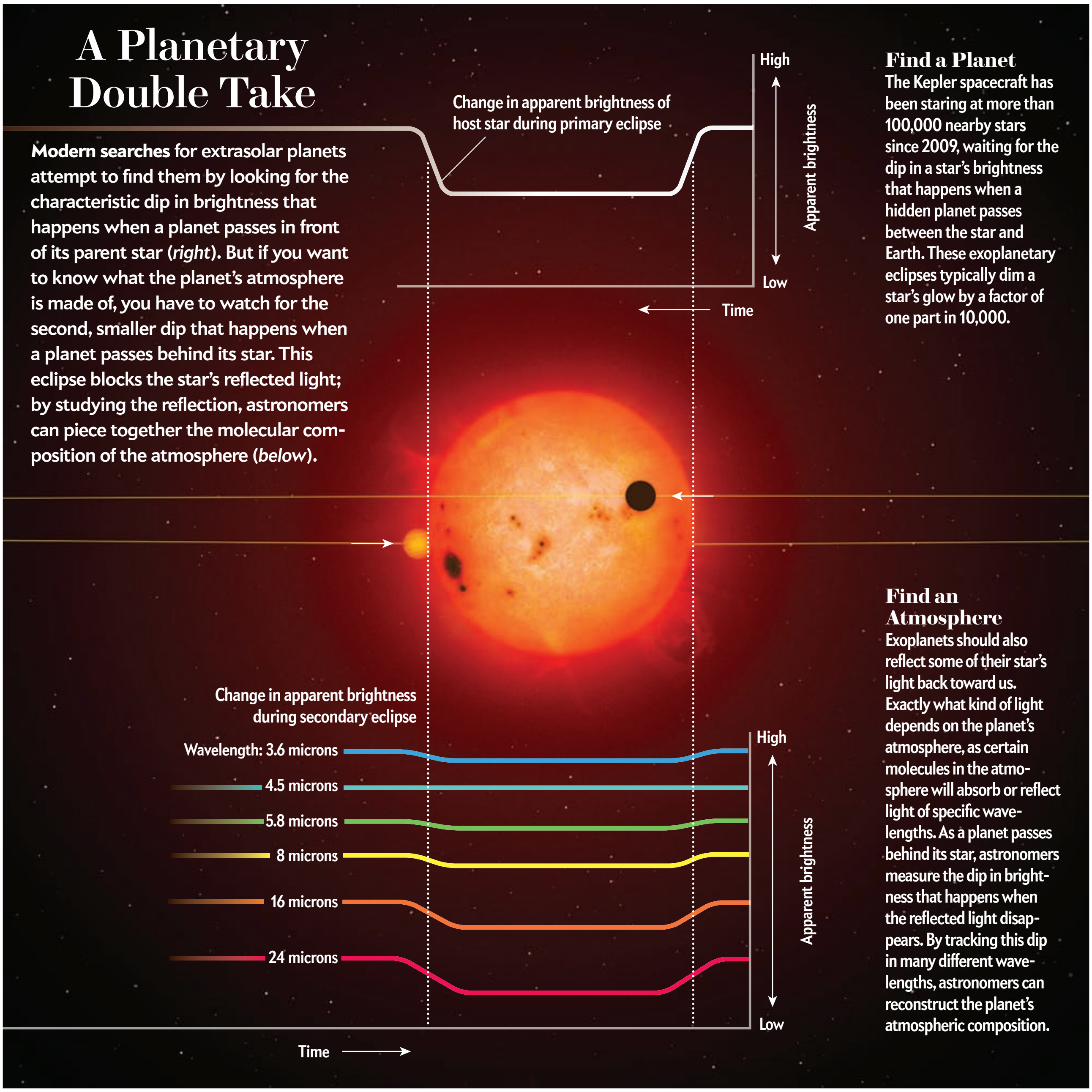
Another question is whether certain planetary atmospheres are made from a different mix of molecules than others. Nikku Madhusudhan, now at Yale University, analyzed the visible and infrared signature of a planet named WASP-12b and deduced that its atmosphere is unusually rich in carbon, with about as much of that element as oxygen.

Theory suggests that a carbon-to-oxygen ratio of more than 0.8, if mirrored in other, smaller planets in the same system (as it presumably would be, given that planets in a solar system are thought to condense from a single disk of gas and dust), would lead to "rocks" made of carbides—carbon-rich minerals—rather than the silicon-rich silicate rocks found in our solar system. If that were true, an Earth-size planet in the WASP-12 system could have continents made of diamond.

Seager and others have written theoretical papers suggest-

A Planetary Double Take

Modern searches for extrasolar planets attempt to find them by looking for the characteristic dip in brightness that happens when a planet passes in front of its parent star (*right*). But if you want to know what the planet's atmosphere is made of, you have to watch for the second, smaller dip that happens when a planet passes behind its star. This eclipse blocks the star's reflected light; by studying the reflection, astronomers can piece together the molecular composition of the atmosphere (*below*).



Find a Planet

The Kepler spacecraft has been staring at more than 100,000 nearby stars since 2009, waiting for the dip in a star's brightness that happens when a hidden planet passes between the star and Earth. These exoplanetary eclipses typically dim a star's glow by a factor of one part in 10,000.

Find an Atmosphere

Exoplanets should also reflect some of their star's light back toward us. Exactly what kind of light depends on the planet's atmosphere, as certain molecules in the atmosphere will absorb or reflect light of specific wavelengths. As a planet passes behind its star, astronomers measure the dip in brightness that happens when the reflected light disappears. By tracking this dip in many different wavelengths, astronomers can reconstruct the planet's atmospheric composition.

SOURCE: NASA/JPL-CALTECH/K. STEVENSON *University of Central Florida (secondary eclipse brightness data)*

ing that there is nothing to rule out planets made largely of carbon or even of iron. In the case of WASP-12, however, it may not be correct. Knutson says that Ian Crossfield of the Max Planck Institute for Astronomy in Heidelberg, Germany, recently found that the light from WASP-12 is contaminated with light from a fainter double star in the background. "His data perhaps seem to cast some doubt on the interpretation for this particular planet," Knutson says.

WATER WORLD

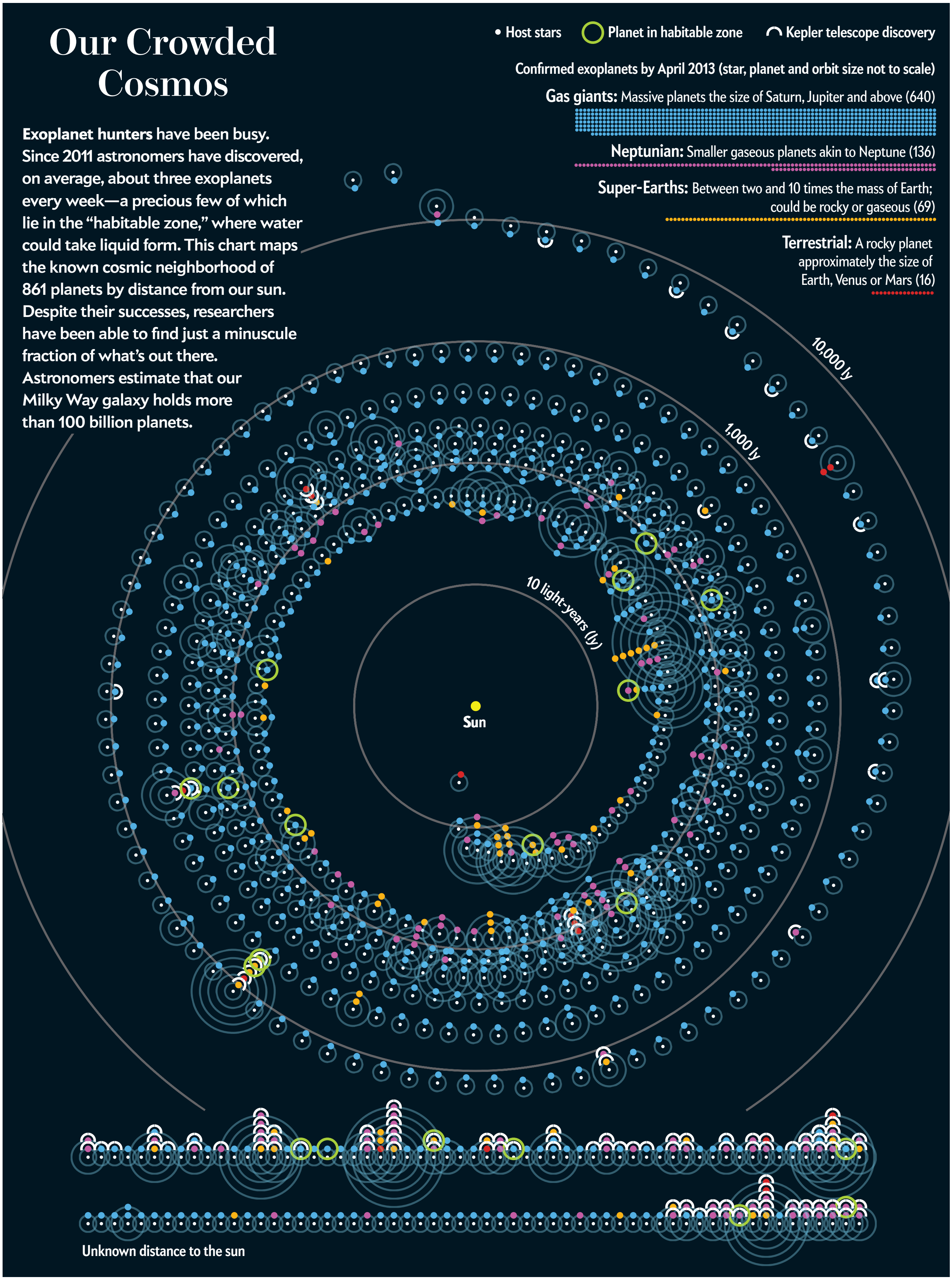
BY FAR THE MOST INTENSE FOCUS of observations has been concentrated on a planet known GJ 1214b, which orbits a small, reddish "M-dwarf" star lying about 40 light-years from Earth. Its proximity makes GJ 1214b relatively easy to study, and its size, just 2.7 times the width of Earth, makes it far closer to being Earth-like than the hot Jupiters found in the first years of planet hunting. "It is everybody's favorite super-Earth," says Laura Kreidberg, a grad student at the University of Chicago who is leading the data analysis on one such observing project.

GJ 1214b was found in 2009 during the so-called MEarth Project organized by Charbonneau to look for planets around M dwarfs. The idea was that small transiting planets would be easier to find around these small, dim stars than around bigger ones, for several reasons. First, an Earth-size planet would block a relatively greater percentage of the small star's light. Such a planet would also exert a relatively greater gravitational pull on

Illustration by Mark A. Garlick

Our Crowded Cosmos

Exoplanet hunters have been busy. Since 2011 astronomers have discovered, on average, about three exoplanets every week—a precious few of which lie in the "habitable zone," where water could take liquid form. This chart maps the known cosmic neighborhood of 861 planets by distance from our sun. Despite their successes, researchers have been able to find just a minuscule fraction of what's out there. Astronomers estimate that our Milky Way galaxy holds more than 100 billion planets.



SOURCE: DATA FROM NASA EXOPLANET ARCHIVE *http://exoplanetarchive.ipac.caltech.edu*

Graphic by Jan Willem Tulp

the star, making it easier to gauge the planet's mass and thus its density. The habitable zone for a small, cool star would also be much closer in than it is for a hot, sunlike star, which makes transits more likely to be spotted (because the orbit of a close-in planet does not have to be so precisely aligned for it to pass in front of the star). Finally, there are vastly more M dwarfs in the Milky Way than there are sunlike stars—about 250 of the former lie within 30 or so light-years of Earth, compared with only 20 of the latter.

GJ 1214b is not quite a second Earth: it is 2.7 times wider and six and a half times as massive as Earth, which gives it an overall density in between that of Earth and Neptune. Unfortunately, as Charbonneau and others realized immediately after the planet was discovered, this density can come about in several different ways. GJ 1214b could, for example, have a small, rocky core surrounded by a huge atmosphere of mostly hydrogen. It could also have a bigger core surrounded by a deep ocean of water, with a thin, water-rich atmosphere on top. It is impossible, given the density alone, to distinguish between those two possibilities—although the possibility of an ocean world is naturally more exciting, given that liquid water is considered a prerequisite for, if not a guarantee of, life as we know it.

Yet when University of Chicago astronomer Jacob Bean observed the planet in various wavelengths, hoping to see a change in its apparent size that would indicate just how thick the atmosphere is, he saw nothing. This could mean one of two things. The planet could have a puffy hydrogen atmosphere but one full of clouds and haze that would make it hard to detect. Or it could have a thin, watery atmosphere but one too thin to delineate with ground-based telescopes. The situation could be analogous to looking at a mountain range from a distance, says Kreidberg, who began working with Bean last year. "There may be peaks," she explains, "but if you're too far away, they might look like a flat line."

To try to resolve the issue, Bean and his colleagues have been awarded 60 orbits of the Hubble; they have already begun to make their observations. It is not the first time astronomers have observed GJ 1214b with the Hubble, but it is by far the most intensive program, and it will take advantage of the new, powerful Wide Field Camera 3, installed during the telescope's final servicing mission in May 2009. With any luck, this observing campaign will finally settle the question of whether GJ 1214b is a water world or not.

THE HUNT FOR OXYGEN

NOW THAT ASTRONOMERS have been in the planet-hunting business for some time, they have begun to find many more planets with long orbital periods. These planets are farther away from their stars and thus cooler than the early population of hot Jupiters. "For a long time we were limited to things that were 1,500 kelvins, 2,000 kelvins, so really quite hot," says Caltech's Knutson. In these conditions, "most of the carbon in the atmosphere gets bound up with oxygen, forming carbon monoxide," she says. "The really interesting thing that happens as you drop below around 1,000 kelvins is that it switches to being incorporated into methane instead."

Methane is especially intriguing because it could be a sign of biological activity—though an ambiguous one, since methane can be produced through purely geophysical processes. Oxygen—and especially ozone, a highly reactive molecule made from three oxygen atoms—would be far more likely to signal the presence of life. It would also be extremely difficult to detect because its spectral signature is subtle, especially so in the relatively small atmosphere of an Earth-size planet.

> **Astronomers are convinced it won't be many more years before observers can look for biosignatures in the atmospheres of planets that are essentially twins of Earth.**

Yet for all the activity around medium-hot super-Earths, astronomers are still focused on the grand prize. "All of this is really just an exercise," Seager says. "I mean, it's interesting in and of itself, but for people like me, it's just a stepping-stone to when we finally get from super-Earths to studying the atmospheres of Earths."

That likely won't happen before the James Webb Space Telescope is launched into orbit, probably in 2018, and a new generation of huge, ground-based instruments, including the Giant Magellan Telescope and the Thirty Meter Telescope, come online by about 2020. Even with those powerful instruments, Seager says, "it's going to take hundreds and hundreds of hours" of observing time. It is not clear even then that it will be possible to detect the signature of life unambiguously; for that, observers might still need the Terrestrial Planet Finder, whose funding has been reduced so drastically that any hope of an actual launch date is pure guesswork at this point.

Yet it is remarkable that, so far ahead of any schedule anyone dreamed of in the 1990s, Seager can even talk about the realistic prospect of finding biosignatures. We are no longer merely hoping that an alien civilization will spot us and point a message our way. We are actively exploring the air above distant worlds, searching their skies for signs that something is home.

MORE TO EXPLORE

Planets We Could Call Home. Dimitar D. Sasselov and Diana Valencia in *Scientific American,* Vol. 303, No. 2, pages 38–45; August 2010.

Exoplanet Atmospheres. Sara Seager and Drake Deming in *Annual Review of Astronomy and Astrophysics,* Vol. 48, pages 631–672; September 2010.

The Kepler exoplanet-detection mission: **http://kepler.nasa.gov**

SCIENTIFIC AMERICAN ONLINE
What kinds of exoplanets have we found? Visit **ScientificAmerican.com/jul2013/exoplanets**