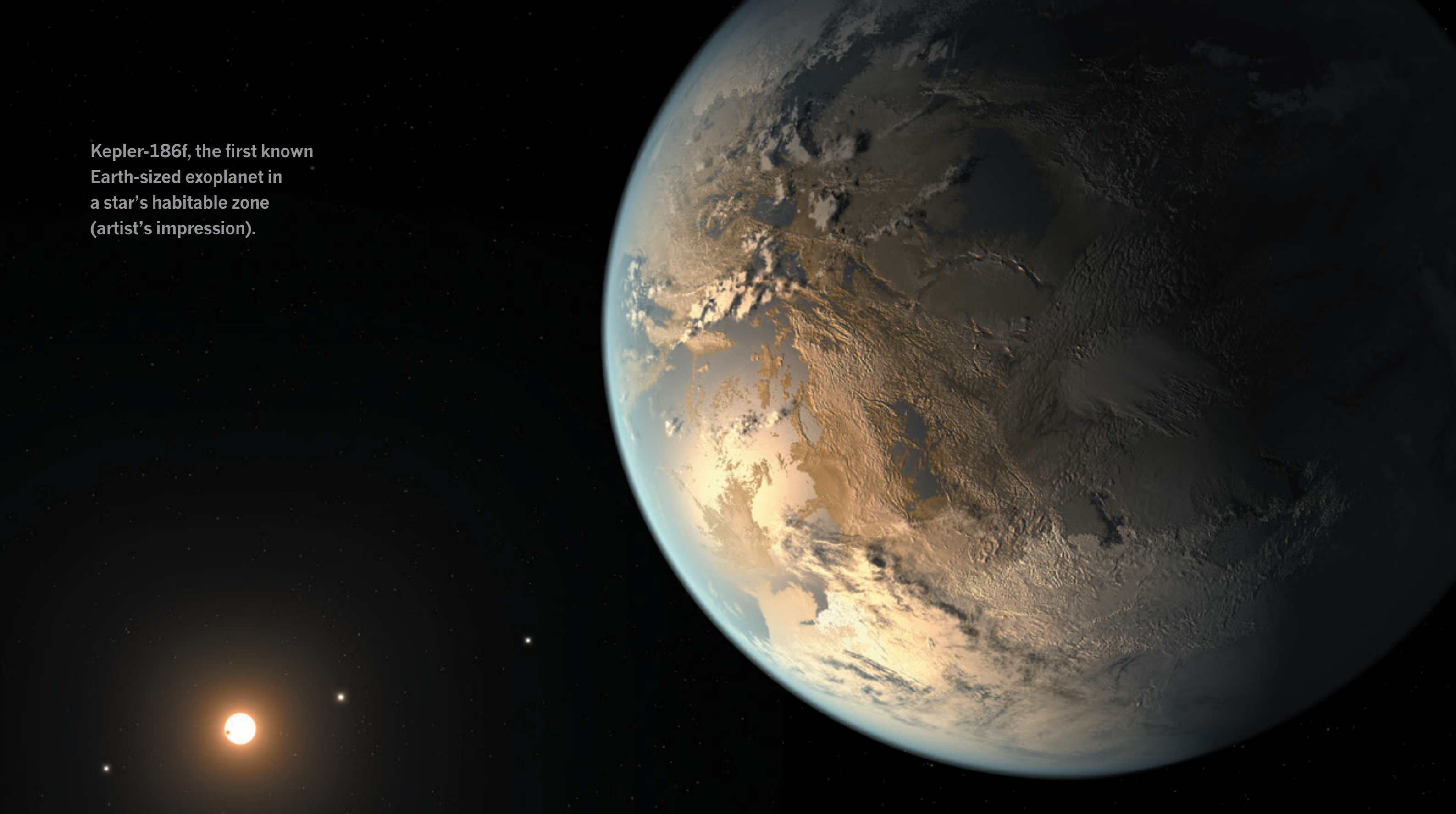


Kepler-186f, the first known Earth-sized exoplanet in a star's habitable zone (artist's impression).

NASA AMES/JPL-CALTECH/T. PYLE

Astronomers are beginning to glimpse what exoplanets orbiting distant suns are actually like.

THE LIGHT OF OTHER WORLDS

BY JEFF HECHT

The trickle of discoveries has become a torrent. Little more than two decades after the first planets were found orbiting other stars, improved instruments on the ground and in space have sent the count soaring: it is now past 2,000. The finds include 'hot Jupiters', 'super-Earths' and other bodies with no counterpart in our Solar System — and have forced astronomers to radically rethink their theories of how planetary systems form and evolve.

Yet discovery is just the beginning. Astronomers are aggressively moving into a crucial phase in exoplanet research: finding out what these worlds are like. Most exoplanet-finding techniques reveal very little apart from the planet's mass, size and orbit. But is it rocky like Earth or a gas giant like Jupiter? Is it blisteringly hot or in deep-freeze? What is its atmosphere made of? And does that atmosphere contain molecules such as water, methane and oxygen in odd, unstable proportions that might be a signature of life?

The only reliable tool that astronomers can use to tackle such questions is spectroscopy: a technique that analyses the wavelengths of light coming directly from a planet's surface, or passing through its atmosphere. Each element or molecule produces a characteristic pattern of 'lines' — spikes of light emission or dips of absorption at known wavelengths — so observers can look at a distant object's spectrum to read off what substances are present. "Without spectroscopy, you are to some extent guessing what you see," says Ian Crossfield, an astronomer at the University of Arizona in Tucson.

But spectroscopy has conventionally required a clear view of the object, which is generally not available for exoplanets. Most new worlds show up only as an infinitesimal dimming of a star as the otherwise invisible planet passes across its face; others are known only from the slight wobble of a star being tugged back and forth by the gravity of an unseen companion. Astronomers often say that trying to study such an object is like staring into a far-off searchlight (the star) and trying to see a firefly (the planet) hovering nearby.

In recent years, however, observers have begun to make headway. Some have extracted the spectra of light passing through the atmospheres of exoplanets as they cross the face of their parent stars — the equivalent of measuring the colour of the firefly's wings as it flits through the searchlight beam. Others have blocked the light of the parent star so that they can see exoplanets in distant orbits and record their spectra directly.

In the past two years, astronomers have begun to record spectra from a new generation of custom-built instruments such as the Gemini Planet Imager on the 8.1-metre Gemini South telescope at the summit of Cerro Pachon in Chile. Exoplanet spectroscopy will be a priority for several spacecraft and ground-based telescopes that are now in development. And astronomers are waiting eagerly for NASA's James Webb Space Telescope (JWST), which will bring unprecedented light-gathering power and sensitivity to the task when it launches in 2018.

These are heady times for those hoping to get a deep understanding of new-found worlds, says Thayne Currie, an astronomer at Japan's Subaru Telescope on Mauna Kea, Hawaii. "We are on the cusp of a revolution."

TRANSIT SPECTROSCOPY

The first exoplanet in orbit around a Sun-like star was discovered in 1995, when astronomers Michel Mayor and Didier Queloz of the Geneva Observatory in Switzerland detected a regular, back-and-forth wobble in the movement of star 51 Pegasi. They concluded[1] that it was caused by the gravity of a planet at least 150 times the mass of Earth — roughly half the mass of Jupiter — orbiting the star every 4 days or so. Other discoveries followed as exoplanet fever took hold, and led telescope managers to make more observing time available for planet-hunting.

The list of finds soon sparked an idea for astronomer David Charbonneau of the Harvard-Smithsonian Center for Astrophysics in Cambridge, Massachusetts. He reasoned that when a planet 'transits', or passes in front of a star, molecules in its atmosphere will absorb some of the starlight, and leave their spectroscopic fingerprints in it. Might it be possible to detect those fingerprints?

To find out, Charbonneau decided to look for sodium. "It's not particularly abundant," he says, "but sodium has very clear spectroscopic features" — excited molecules of it emit two very strong lines of light, which give sodium street lights their familiar yellow-orange colour. When the sodium is backlit, the light that floods through it has dark bands at the same points of the spectrum, and Charbonneau hoped that these would be comparatively easy to spot.

They were: in 2002, Charbonneau and his co-workers announced[2] that they had used the Hubble Space Telescope to detect a sodium signal from a Jupiter-sized exoplanet transiting HD 209458, a star about 47 parsecs (150 light years) from Earth. It was both the first detection and the first spectroscopic measurement of an exoplanet atmosphere. Within a few years, space-based transit observations were recording more complete spectra, and detecting gases such as carbon monoxide and water vapour.

Using this technique means looking for very tiny changes in a star's spectrum, says Charbonneau — maybe 1 part in 10,000. Hubble was and is observers' first choice of instrument: it does not have to contend with absorption of light by gases in Earth's atmosphere, so its spectra are very clean and easy to interpret. But competition for observing time is intense, so astronomers also use ground-based telescopes.

These do have to deal with atmospheric interference, but can overcome it by collecting more light than Hubble can. This allows them to detect fainter objects and to separate individual spectral features more clearly. That pays off because most exoplanets are in star systems that are moving relative to Earth. "So their wavelengths are Doppler-shifted," says Charbonneau, meaning that the radiation coming from them is stretched or squeezed by their movement, displacing the spectral lines slightly from the corresponding lines in Earth's atmosphere. Because the two sets of spectral lines no longer overlap, observers can know for sure how much of the signal comes from the exoplanet. Using this method, astronomers have been able to detect gases making up as little as 1 part in 100,000 of a planet's atmosphere.

An extension of the transit-spectroscopy technique has allowed astronomers to measure the light reflected from a planet's face. They do this after the planet moves across the face of its star, when it will be on the far side of its orbit, with its daylight side facing Earth (see 'Star shades'). Observers will not be able to see it as a separate object — but they will know that its spectrum is combined with that of the star, says Nicolas Cowan, an astronomer at the McGill Space Institute in Montreal, Canada. Shortly afterwards, however, the planet will pass behind the star and be eclipsed — at which point, says Cowan, "you go from a planet and star to just a star. If you measure the difference in flux, you can tell how much light comes from the planet." The process is demanding, he says, but it can measure the infrared spectra of a Jupiter-sized planet in a close orbit even if it is less than 0.1% as bright as the star.

An even more ambitious application of this technique is to follow an exoplanet through a complete orbit. By subtracting the star-only spectrum obtained during the planet's eclipse, observers can get spectra of the planet's atmosphere as its silhouette changes from a thin crescent just after transit to a half-moon shape as it swings to the side, then a full-face view on the far side. This allows them to produce a comparatively fine-grained map of the atmosphere and how it changes over time. Cowan and his co-workers first reported[3] using this technique in 2012, with infrared data from NASA's Spitzer Space Telescope. They showed that the exoplanet HD 189733b was hottest within about 10 degrees of its equator, as predicted. Since then, other researchers have used Hubble and Spitzer[4] to map exoplanet atmospheres in more detail. And Cowan says that with the JWST, "it will be easy to make a 3D map of the atmosphere of a hot Jupiter."

Transit spectroscopy does have its limitations. Some exoplanets have nearly featureless spectra characteristic of clouds, which consist of droplets or fine dust particles that do not leave their imprint on the spectrum in the same way as isolated molecules[5]. The clouds are a big headache, says Charbonneau. "We don't have any direct measurement of what the clouds are made of. We just know they block the light." They aren't necessarily made of water vapour. Charbonneau points out that the cloud-shrouded super-Earth GJ 1214b, 12 parsecs from Earth, is so hot that its clouds could be made of zinc sulfide and potassium chloride. On still hotter worlds, the clouds could contain droplets of iron or rock.

THESE ARE HEADY TIMES FOR THOSE HOPING TO GET A DEEP UNDERSTANDING OF NEW-FOUND WORLDS.

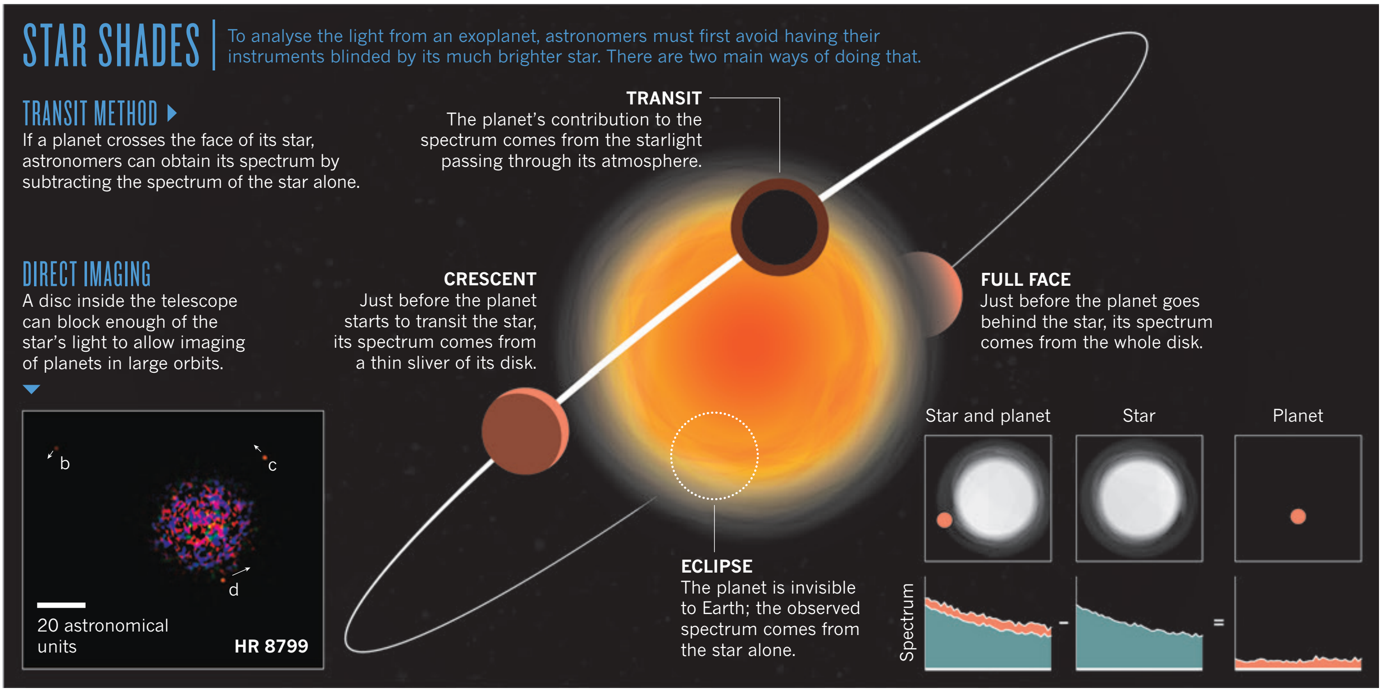
Lisa Kaltenegger, director of the Carl Sagan Institute at Cornell University in Ithaca, New York, points to another limitation of the transit method. "When light hits a transiting planet, it isn't just absorbed," she says. "It also gets bent in the atmosphere", making it impossible for an observer on Earth to see. This bending, known as refraction, increases as the atmosphere becomes thicker. If alien astronomers were trying to get a spectroscopic reading of Earth, she says, refraction would prevent them from probing any deeper than 10 kilometres from the surface[6]. But most of Earth's water is in the lowest 10 kilometres of its atmosphere, she says — so by analogy, "water is going to be one of the hardest things to find in an Earth-like exoplanet".

DIRECT IMAGING

An alternative approach to finding and studying exoplanets is trying to block out the starlight and image them directly, the equivalent of looking for the firefly by holding a hand in front of the searchlight. Early efforts to do this were futile: even the dimmest parent star is much brighter than an exoplanet. The secret of success is to seek brighter fireflies wandering well away from the searchlight — that is, young planets still glowing from the heat of formation, in orbits far from their stars. The first directly imaged exoplanets were announced by two groups simultaneously in 2008. The objects included 3 planets about 60 million years old orbiting the star HR 8799 (ref. 7), and a single planet more than 100 million years old orbiting Fomalhaut (ref. 8), a bright star some 8 parsecs from Earth.

To obtain the spectra of such objects, astronomers turned to adaptive optics, a technology that corrects for the twinkling of a star caused by turbulence in Earth's atmosphere and makes it much easier to spot any exoplanets in its vicinity. Also essential are discs inserted into the telescope's optical pathway to block light from the star, and sophisticated signal processors to digitally sharpen the images.

"Direct-imaging spectra are beautiful and tell you a lot about the



SOURCE: SPECTRUM, NASA/JPL-CALTECH/R. HURT (SSC/CALTECH); DIRECT IMAGING, C. MAROIS *ET AL.*/NRC CANADA

planets and how they formed," says Bruce Macintosh, an astronomer at Stanford University in California and a co-discoverer of the HR 8799 planets. In 2011, he and his colleagues reported[9] the first detection of water vapour on one of those planets using a first-generation direct-imaging instrument that could observe only exoplanets with temperatures higher than 1,000 kelvin. Now, Macintosh is the principal investigator for the Gemini Planet Imager, which, along with the similar Spectro-Polarimetric High-contrast Exoplanet Research (SPHERE) imager at the European Southern Observatory's Very Large Telescope in Chile, is a second-generation instrument built to directly image and take spectra of exoplanets down to about 600 kelvin.

The Gemini instrument launched a multiyear search for Jupiter-like planets orbiting hot, young stars in November 2014. Early observations of 51 Eridani, a 20-million-year-old star about 30 parsecs away, spotted a Jupiter-like world 2.5 times farther from the star than Jupiter is from the Sun[10]. The spectrum showed that this exoplanet, dubbed 51 Eridani b, has an atmosphere containing more methane — a known component of Jupiter's atmosphere — than any other exoplanet. "The really exciting thing with 51 Eridani b and other new exoplanets," says Currie, "is that we see them when their spectra look a little more normal" and Jupiter-like than those of planets that are even younger and hotter, where methane is strangely absent. That could provide crucial insight into planet formation, the current theory of which is based mostly on data from the Solar System.

SPHERE has embarked on a similar survey, but started later, in February 2015, and has less to report. Thus far, says team member Anthony Boccaletti, an astronomer with the Paris Observatory, the most interesting discovery[11] is a group of five gas clumps moving at high velocity away from the young star AU Microscopii, which is known to be unusually prone to flares and other activity. "We don't really know what they are," he says.

STAR SURVEYS

Exoplanet spectroscopy has come a long way from its early days, when practitioners were struggling to extract extremely faint signals from noisy environments. The first results were often problematic. Now, Crossfield says, "for the most part what we are finding holds up and is repeatable".

A coming generation of instruments promises to reveal even more. NASA's Transiting Exoplanet Survey Satellite (TESS), scheduled to launch in August next year, will spend two years searching for exoplanets transiting more than 200,000 of the brightest stars in the solar neighbourhood. Exoplanets will also be targets for the JWST. With its 6.5-metre telescope and advanced instruments, Webb should see many more than the 2.4-metre Hubble. "TESS and Webb will own this space in five years," predicts Macintosh.

Two other planned — but not yet approved — space missions will use exoplanet spectroscopy. NASA's 2.4-metre Wide Field Infrared Survey Telescope, expected to launch in the mid-2020s, would spend most of its time on cosmological questions, but is expected to find and study about 2,600 exoplanets. Currie says that it should be able to image Jupiter-like planets orbiting nearby stars, although smaller, colder bodies similar to Pluto or the hypothetical 'Planet X' speculated to exist at the edge of the Solar System — or Earth, for that matter — will remain out of reach. "We would need a 10-metre-scale telescope in space to do other Earths," says Macintosh.

The second mission is ARIEL, the Atmospheric Remote-Sensing Infrared Exoplanet Large-survey, one of three candidates for a medium-class mission to be launched by the European Space Agency in 2026. The 1-metre telescope would be dedicated to transit spectroscopy and a survey of exoplanets at temperatures higher than 500 kelvin.

In about a decade, astronomers hope to see the completion of three super-giant telescopes: the 24.5-metre Giant Magellan Telescope at the Las Campanas Observatory in Chile, the Thirty-Meter Telescope planned for Mauna Kea, and the European Extremely Large Telescope on Cerro Armazones in Chile. All three will be equipped with adaptive optics systems, and it's a safe bet that they will be doing exoplanet spectroscopy to test models based on the data gleaned up to that point.

Those measurements could be astronomers' first realistic chance to find life in the wider Universe, says Charbonneau. "I'm so excited." ■

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