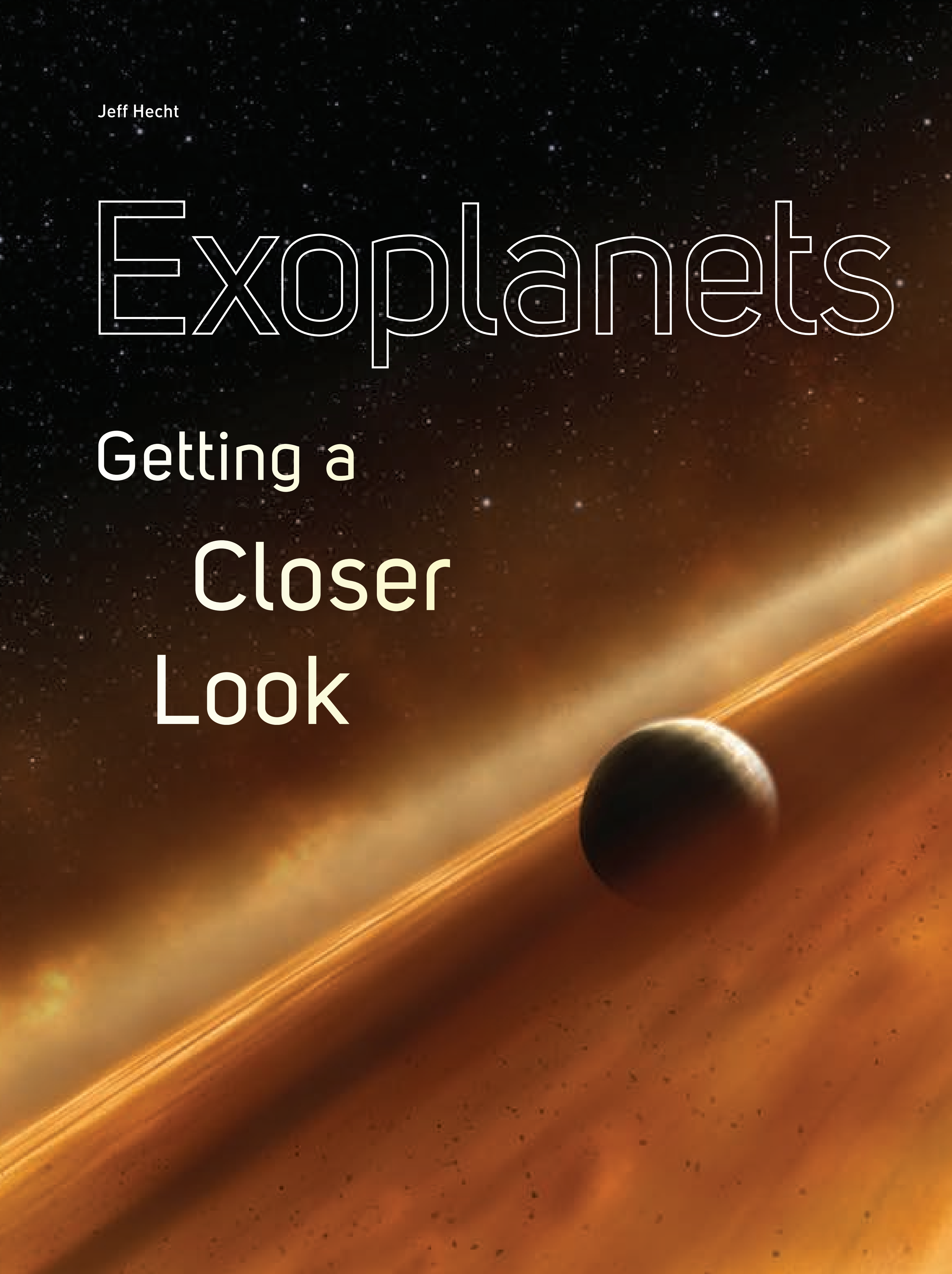
Jeff Hecht

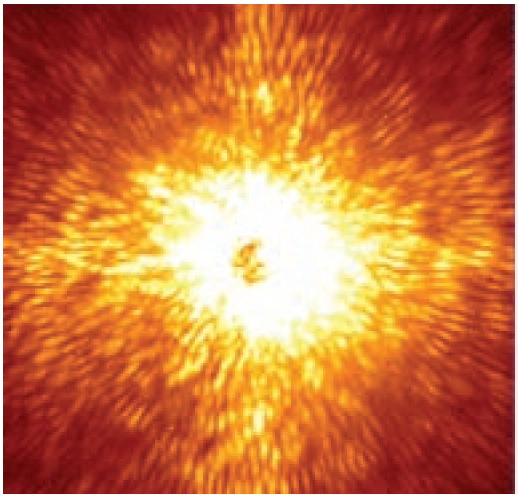
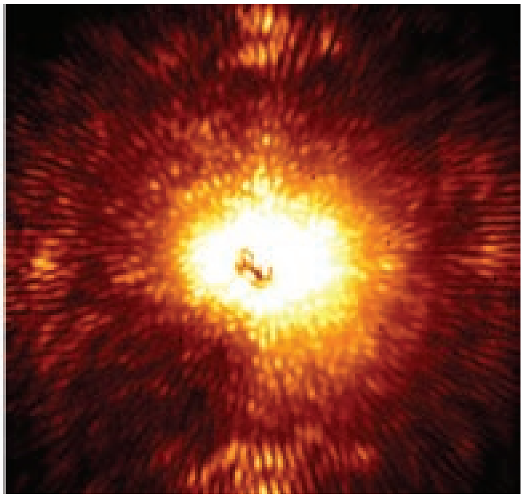
Exoplanets

Getting a Closer Look



Sophisticated new techniques are directly imaging giant planets outside of our solar system and recording spectra that reveal the composition of their atmospheres. And telescopes capable of directly imaging Earth-sized exoplanets are on the technological horizon.

An artist's impression of an exoplanet orbiting Fomalhaut.
NASA

Speckle in a high Strehl ratio telescope.
NASA/Project 1640

For most of the 20th century, astronomers had no solid evidence that planets existed outside of our solar system. The first widely accepted exoplanet discovery came in 1992, when regular variations in the period of pulses from a millisecond pulsar—a rapidly spinning neutron star—showed the presence of two planets. Three years later, the first extrasolar planet orbiting a main-sequence star—a Jupiter-sized giant a mere seven million kilometers from its sun—was discovered from periodic changes in Doppler shifts of stellar spectral lines. And 1999 brought the first successful detection of an exoplanet transit across the face of its host star.

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Since then, the Kepler space telescope has "blown the doors off planet hunting," says Nick Siegler, technology manager of the NASA exoplanet exploration program at the Jet Propulsion Laboratory (JPL), Calif., USA. Launched in 2009, Kepler stared at a fixed field, continually monitoring the brightness of more than 100,000 stars to detect planets transiting across them. As of 5 September 2014, analysis of Kepler data has confirmed 1,743 planets, with an additional 3,514 candidates still being studied.

"Now we know that basically every star that you look at in the night sky has a planet," says Siegler. But such indirect observations cannot tell whether the planets could support life. To find out, he says, "We need to collect photons from the planet itself." And over the past few years, with the help of some clever optical techniques, scientists have started to do just that.

Limits on direct detection

Directly imaging a planet poses a challenge because stars are typically 10^5 to 10^{15} times brighter than planets. Viewed from 10 light years away, the sun would be only two arcseconds from Jupiter and 10^8 times brighter. It would be only 0.4 arcsecond from the Earth, but 10^{10} times brighter. Imagine looking for a firefly (about one-quarter candela) next to the world's largest searchlight (9 billion candelas).

The planet's age also matters, because accreting material heats young planets, and the hotter they are, the brighter they glow. A 100-million-year-old Jupiter would be at about 800K, with a blackbody emission peaking near 4 µm, where it would be 10^6 times fainter than the sun. This would make it easier to detect that the much older and colder Jupiter, which at 4.5 billion years old has cooled to a frigid 165K.

The problem, then, is not resolution, but contrast. Diffraction and scattering of light

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from the star overwhelm the faint light from the planet, so high-contrast imaging is required. "The science does not require significantly greater telescope apertures or a revolution in telescope technology. Rather, the high-contrast sensitivity depends on controlling the residual starlight," wrote Rebecca Oppenheimer of the American Museum of Natural History in a 2009 review.

The biggest obstacle is speckle, produced by minute optical fluctuations and imperfections in the air and optical systems. Oppenheimer observed speckle even in an optical system with an excellent Strehl ratio of 0.85 and found that typical modern instruments produce speckles about one two-hundred-fiftieth as bright as the star at a 0.7 times the resolution limit from the object—more than enough to obscure a Jupiter.

Speckles change continually in time, but their noise properties are correlated, so they do not average out into a uniform background that can be subtracted from an image. Speckle is best known in the air, where turbulence produces the familiar speckles in laser-illuminated spots. Optical systems also suffer speckle in space, where light fluctuations are slower than those caused by air turbulence and, like those in air, do not average out over time.

Overcoming starlight

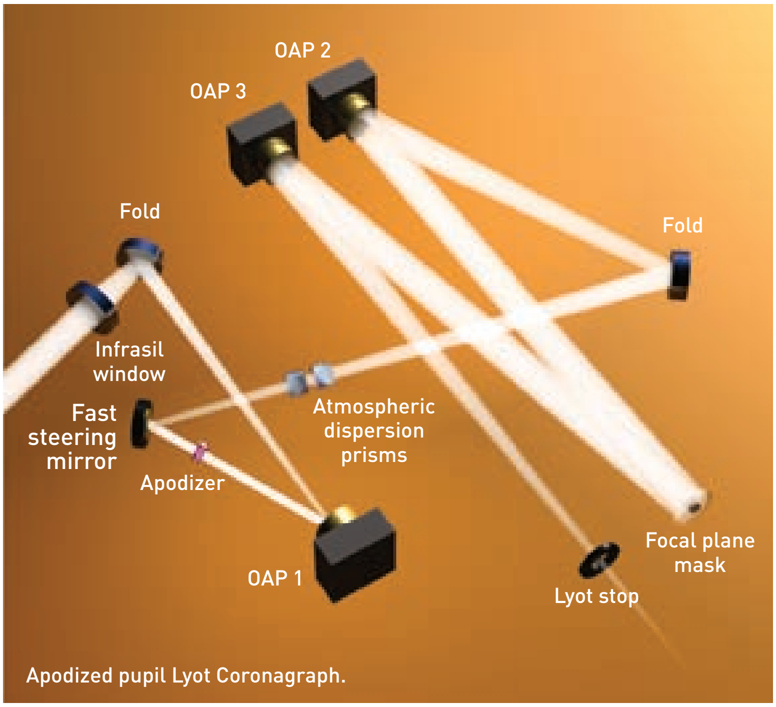
Starlight can be blocked with an instrument called a coronagraph, which astronomer Bernard Lyot invented in the 1930s to observe the solar corona. Coronagraphs focus starlight onto an opaque disk or a hole in an image plane, which either absorbs the light or diverts it away from the final focal plane. This can reveal bright objects close to a star, but exoplanets are so much fainter than stars that other measures are required. The edge of the coronagraph disk may be apodized or softened to reduce diffraction effects, and adaptive optics are used to remove the last traces of scattered and diffracted starlight that remain.

Large ground-based telescopes also use adaptive optics to reduce scattering and improve image quality. The system continually measures the incoming optical wave front and adjusts the shape of a deformable mirror to compensate for air fluctuations and optical imperfections. A two-stage process is used to image exoplanets: A tip/tilt system makes large low-order corrections to the surface, and an array of hundreds or thousands of actuators make faster and smaller corrections to generate the final reflected waveform.

Another way to reduce background starlight is by interferometric nulling using a pair of telescopes. Both scopes focus on the central star, and their optical paths are adjusted to be exactly one-half wave out of phase when they are combined. This destructive interference cancels out the starlight but does not null out the light from the orbiting planet, because that light follows different paths through the two telescopes and so is not precisely out of phase when combined. The Large Binocular Telescope is using nulling to look for dust disks around stars, but it lacks the resolution to see planets. Interferometric nulling "has to be done at very high precision, and is very difficult to do on the ground because of turbulence," says John Monnier of the University of Michigan, USA. But it is more attractive in space, where it is being considered for imaging Earth-like planets.

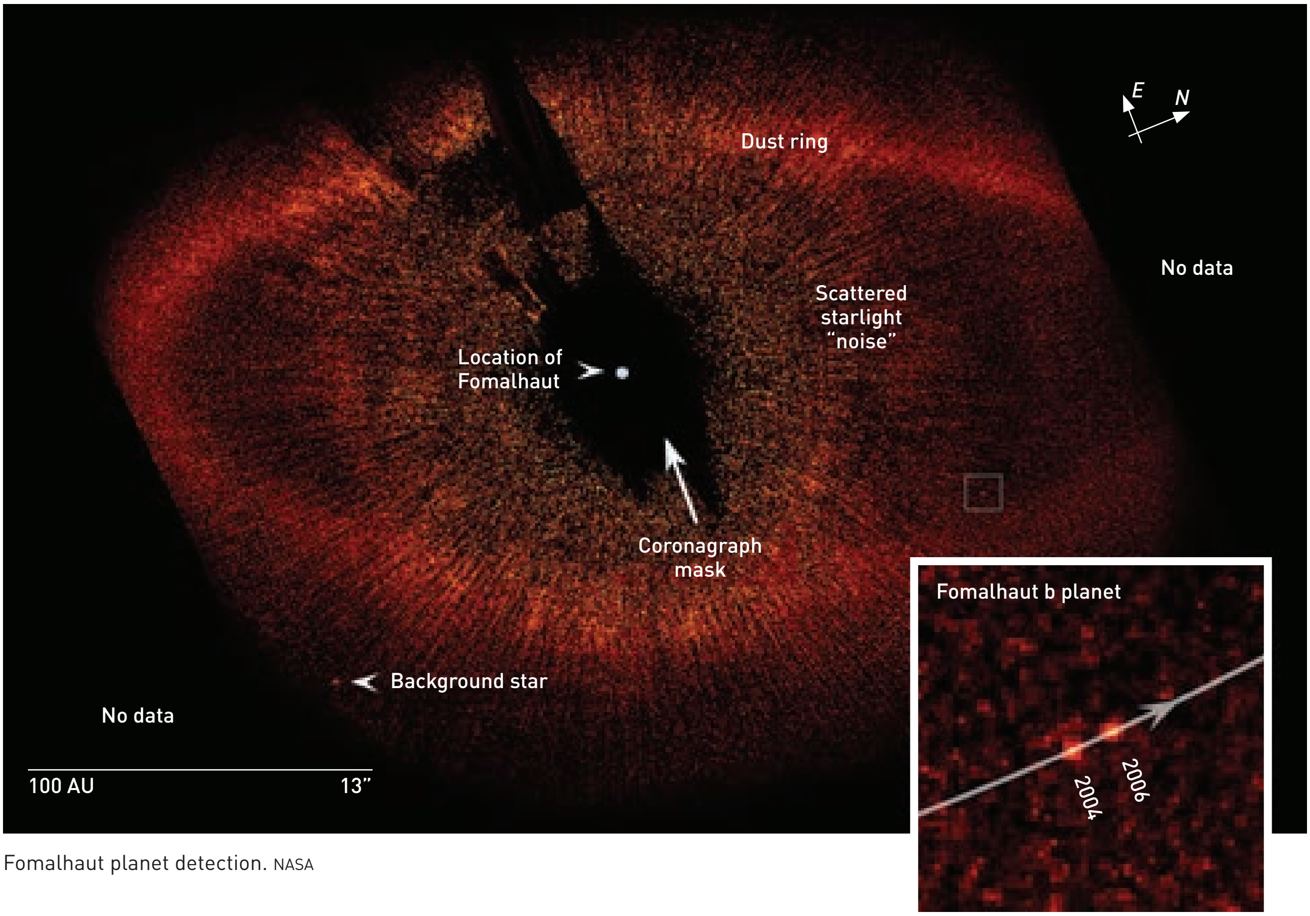
Direct imaging's opening act

Direct imaging of planets evolved from earlier resolution of binary stars. An important step was the 1995 imaging of a brown dwarf orbiting Gleise 229, a nearby red dwarf star, by Shrinivas Kulkarni of Caltech, USA, and colleagues. Detection was easier because the brown dwarf was much brighter than a planet. That success encouraged Oppenheimer, a coauthor, to combine a coronagraph



Apodized pupil Lyot Coronagraph.

Phil Saunders/Adapted from B.R. Oppenheimer et al., Proc. SPIE **7015**, 701519 (2008)



Fomalhaut planet detection. NASA

with a powerful adaptive optic system in a planet-hunting trial on the Air Force 3.6-meter AEOS telescope in Hawaii from 2003 to 2007. That test failed to detect any planets, but laid important groundwork, says Bruce Macintosh of Stanford University, USA.

In 2008, two groups succeeded by focusing on star systems so young their planets were still hot enough to reduce the contrast with their stars. In one study, Paul Kalas of the University of California, Berkeley, USA, and colleagues used the coronagraph on Hubble's Advanced Camera for Surveys to examine Fomalhaut, a bright star about 25 light years away and only 100 to 300 million years old. In 2004 Hubble had spotted a dust disk around the star that looked like it might have been shaped by a planet. A 2006 image revealed movement of one bright spot in the ring, which Kalas found was a planet of three Jupiter masses 12.7 arcseconds from the star. Further observations showed its eccentric orbit has a semimajor axis about six times larger than Neptune's.

In the other 2008 study, Macintosh and colleagues directly imaged three planets orbiting a star called HR 8799 with coronagraphs and adaptive optics on the Keck and Gemini telescopes. Five times brighter than the sun and 128 light years away, HR 8799 is only 60 million years old and, like Fomalhaut, has a protoplanetary disk—a sign of youth and planet-building. The team observed at 1.1 to 4.2 µm, where hot young planets are particularly bright and adaptive optics are particularly effective.

The planets were at 27, 43 and 68 astronomical units from the star, roughly 1, 1.5 and 2 times Neptune's orbit. But because HR 8799 is five times more distant than Fomalhaut, the planets appeared only 0.63, 0.95 and 1.73 arcseconds from the star. Five images taken from 2004 to 2008 showed them moving in their orbits and sharing the star's proper motion. Their masses are now estimated at 7 to 10 Jupiters, and a fourth planet has been found at 14.5 astronomical units.

Sharpening the view from the ground

Adaptive optics on eight- to 10-meter ground-based telescopes yielded the first verifiable exoplanet images. But after imaging the HR 8799 system, "we realized that we were hitting the limits of what these general-purpose systems could do," says Macintosh. "Systems built from the ground up to do exoplanet science should be more powerful." Some of these special-purpose systems are now starting to yield results.

Oppenheimer recycled equipment from her initial system for Project 1640, which she installed on the venerable 200-inch (five-meter) Hale Telescope at Palomar Observatory in 2008. The occulting edges of the coronagraph are "softened" to reduce diffraction. The scientists upgraded the telescope's adaptive optics in 2011 by adding 3,388 small-stroke actuators to the original 241 long-stroke actuators. They also added a sensitive calibration interferometer to control the wave front with a precision of 5 nm, and a multispectral camera to help identify speckle, which is wavelength-dependent.

The first important results, published in 2013, were observations of the HR 8799 planets that yielded the first spectra of exoplanets. Recording data in 35 bands from 995 to 1769 nm, their multispectral camera resolved features of methane, ammonia and/or acetylene, and possibly carbon dioxide and hydrogen cyanide. It's the start of a three-year survey of 200 A- and F-type stars up 150 light years away.

The results intrigued astronomers. "These warm, red planets are unlike any other known object in our universe. All four planets have different spectra, and all four are peculiar," wrote Oppenheimer. One puzzle is why the planets show lines of either methane or ammonia but not both, although both should be present at the observed 1,000 K temperatures. Although the planets are too hot and toxic for life as we know it, their discovery points the way to seeking signs of life on exoplanets.

Other ground-based projects

Macintosh and colleagues used similar technology on the eight-meter Gemini South Telescope in Chile, where their Gemini Planet Imager saw first light in November 2013. "We're still tuning up the system," he says, but it's already an order-of-magnitude improvement over the previous generation of instruments. "In one minute, we are seeing planets that used to take us an hour to detect."

Like Project 1640, the Gemini system uses a soft apodized coronagraph. Its adaptive-optics system uses a spatially filtered Shack-Hartmann wave front sensor and a 64 × 64-element MEMS deformable mirror with 1,493 active elements. A polarimetry mode can map protoplanetary disks, and has already observed a faint one around the very young star HR 4796A.

The Gemini system's observations of a previously known planet orbiting the young star Beta Pictoris improved estimates of its orbital parameters by a factor of three. They are starting a survey of 600 nearby young stars, and hope to find 25 to 50 exoplanets with masses as low as Jupiter that are older than the very young planets of HR 8799, but not as old or cold as planets like Jupiter.

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In June 2014, the European Southern Observatory announced first light for its exoplanet imager, called SPHERE (Spectro-Polarimetric High-contrast Exoplanet REsearch instrument) on the Very Large Telescope in Chile. SPHERE also uses an apodized pupil coronagraph and adaptive optics. In addition, the project, headed by Jean-Luc Beuzit of the Institute of Planetology and Astrophysics of Grenoble, France, will use differential imaging to distinguish starlight from exoplanet light on the basis of its color and polarization.

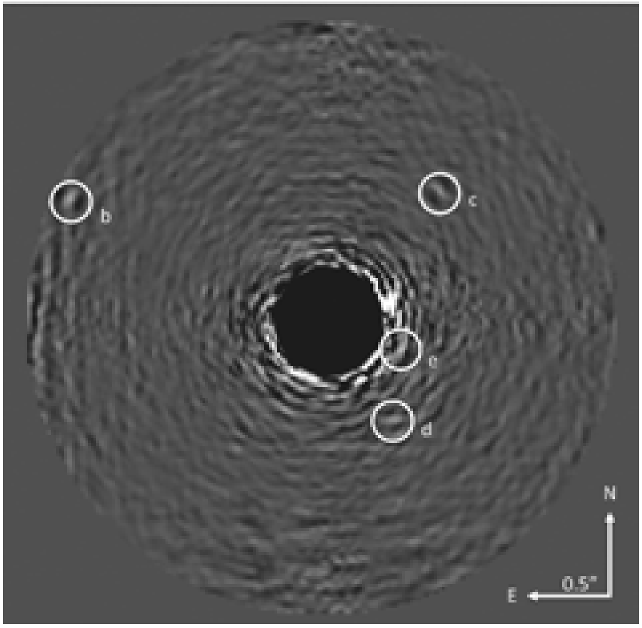
Sitting at the telescope's Nasmyth focus, SPHERE is designed with a Strehl ratio close to 0.90. Its coronagraph feeds three instruments. The main one, the InfraRed Dual-beam Imager and Spectrograph (IRDIS) has a spectral range of 950 to 2,320 nm, and can image in two neighboring spectral channels selected by a set of filters. The Integral Field Spectrograph (IFS) offers multiple channels for speckle correction and spectral data analysis. The Zurich Imaging Polarimeter can detect two perpendicular polarizations simultaneously over a spectral range of at least 600 to 900 nm.

Olivier Guyon of the National Astronomical Observatory of Japan is testing new direct-imaging equipment on the 8.2-meter Subaru Telescope in Hawaii to develop technology for the next generation of super-giant ground telescopes. The Subaru Coronagraphic Extreme Adaptive Optics (SCExAO) system will use high-efficiency coronagraphs with inner working angles as small as the diffraction limit to image planets just 0.04 to 0.5 arcsecond away from a star. It's the most advanced technology in development for ground telescopes, says Macintosh. "It's not intended to do science every night. It's more a new technology to try out at the bleeding edge."

A clearer view from space

For all their power, ground-based telescopes cannot probe the atmosphere of terrestrial planets orbiting other stars. Light scattering in Earth's own atmosphere poses an insurmountable signal-to-noise barrier for a 30-meter ground telescope. Only a space-based telescope, not confounded by the atmosphere, can observe biosignature gases on Earth-like planets in the habitable zones of sun-like stars, says Nick Siegler of JPL.

Space also allows observations deeper in the infrared, where cool, old planets are brighter than in the visible.



HR 8799 exoplanets with starlight optically suppressed and data processing conducted to remove residual starlight. NASA/Project 1640

"The Earth is 10 billion times fainter than the sun in the visible, but only one million times fainter in the infrared, at the 10-micrometer peak of its blackbody emission," says Monnier.

Projects in space have been limited until recently. NASA began planning a space-based exoplanet search called Terrestrial Planet Finder in the early 2000s, but Congress cut the mission from NASA's budget in 2007 because the technology was immature. The upcoming James Webb Space Telescope "has some coronagraph masks on it, but they were never designed to give the contrast needed to detect an exo-Earth," says Siegler. The 6.5-meter Webb will operate from 0.6 to 28 µm, a range where planets are brighter relative to their stars than at visible wavelength. However, infrared operation reduces resolution and the telescope's segmented mirror will scatter some light, so Webb will be limited to studying large, warm planets after its launch in 2018.

Kepler's spectacular success has given a big boost to plans for a new generation of space-based searches for broader ranges of exoplanets. Three classes of technology are under consideration:

Conventional internal coronagraphs. These would resemble the ones used on ground-based telescopes, incorporating an occulting element in the internal optical system to keep starlight from reaching the imaging detector. The actual occulter would be less than 4 mm across. Adaptive optics would help cancel out any starlight bleeding around the occulter and compensate for imperfections in the optics, and could operate much slower than the kilohertz rate needed to correct for atmospheric effects on the ground.

External occulting coronagraphs. These systems would use a large, free-flying disk-like object to occult the star from the viewpoint of the telescope without blocking light from its planets. To do that, it would have to be aligned very precisely with the star and the telescope, and would have to subtend a very small angle at the telescope. NASA's plan is to build a sunflower-shaped occulter called Starshade that would unfold in space to stretch 34 m wide. At a distance of 34,000 km from the telescope, it would cover a spot just 0.2 arcsecond wide in the sky, blocking light from a star, but not from its planets.

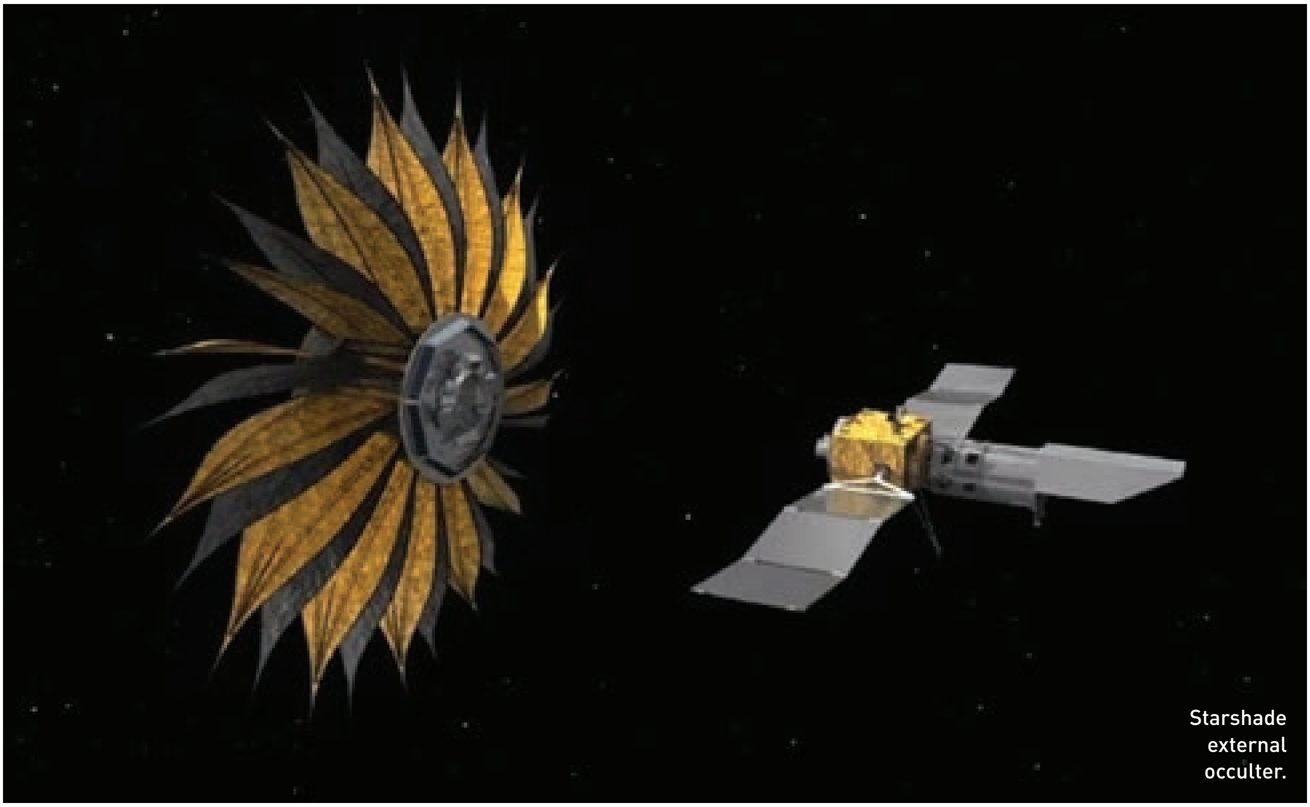
The sunflower-like shape was chosen to reduce diffraction into the region around the star where planets could be orbiting, making them easier to detect, according to Stuart Shaklan, lead engineer for the project at JPL, whose group has built and successfully tested a prototype. The biggest challenges, says Siegler, will come from flying two spacecraft and aligning them with exacting precision so Starshade occults the telescope's view of the star.

Exoplanets are among the goals for the next major space telescope.

Interferometric nulling systems. Interferometry requires precise combination of light from two or more telescopes to null out starlight, so it poses major challenges in space—although fewer than on the ground. "It is not much of a player now, but we expect it will be needed eventually" because it offers the best resolution, says Monnier.

The next big thing

Exoplanets are among the goals for the next major space telescope, which NASA is now planning to follow Webb into space in the early 2020s. A leading candidate is WFIRST-AFTA, based on one of the two surplus Hubble-sized mirrors from the National Reconnaissance Office, which could potentially use a Starshade external occulter. One major science mission would be searching for dark energy, but it also could carry a coronagraph for direct imaging of exoplanets and protoplanetary disks. However,



NASA, Jet Propulsion Laboratory

no firm decisions have been made on planet-hunting with WFIRST, says Siegler.

NASA is also studying alternative dedicated exoplanet missions. The most likely is EXO-C, the Exoplanet Direct Imaging Coronagraph Probe, a 1.5-meter telescope with adaptive optics, an internal coronagraph and response from 450 to 1,000 nm. Also under consideration is a more ambitious version that would work with Starshade, EXO-S.

Although better equipped for exoplanet searches than Webb, neither WFIRST-AFTA or EXO-C would be capable of detecting an Exo-Earth, says Siegler. "WFIRST-AFTA is in the pole position, but we don't believe we can get down to that degree of sensitivity." Adding the extra diffraction inevitable with an internal coronagraph would introduce more obstructions. "We think they can get down to a contrast ratio of one billion rather than 10 billion," says Siegler. "That's still a big deal, amazing science," that would image super-Earths or sub-Neptunes, which Kepler detected but could not image directly.

We'll have to wait longer to search for the biosignatures of life on Earth-like planets. That's a central quest for NASA's proposed Advanced Technology Large Aperture Space Telescope (ATLAST), a giant 10-meter class telescope, envisioned as a "flagship" mission from 2025 to 2035. "ATLAST is way out there," says Macintosh, but it's big enough that with powerful new technology in the developmental pipeline "it could get down to the earth range for a decent population of nearby stars." At last, that would tell us how common life may be in the universe. OPN

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