APPRECIATION 7
Rudolf E. Kalman

Q&A 10
Lockheed Martin's Antonelli on Mars planning

UNMANNED AIRCRAFT 28
The Navy's carrier drone debate

AEROSPACE
★ ★ ★ AMERICA ★ ★ ★

Planet spotting

Getting serious about finding and photographing an Earthly world PAGE 20

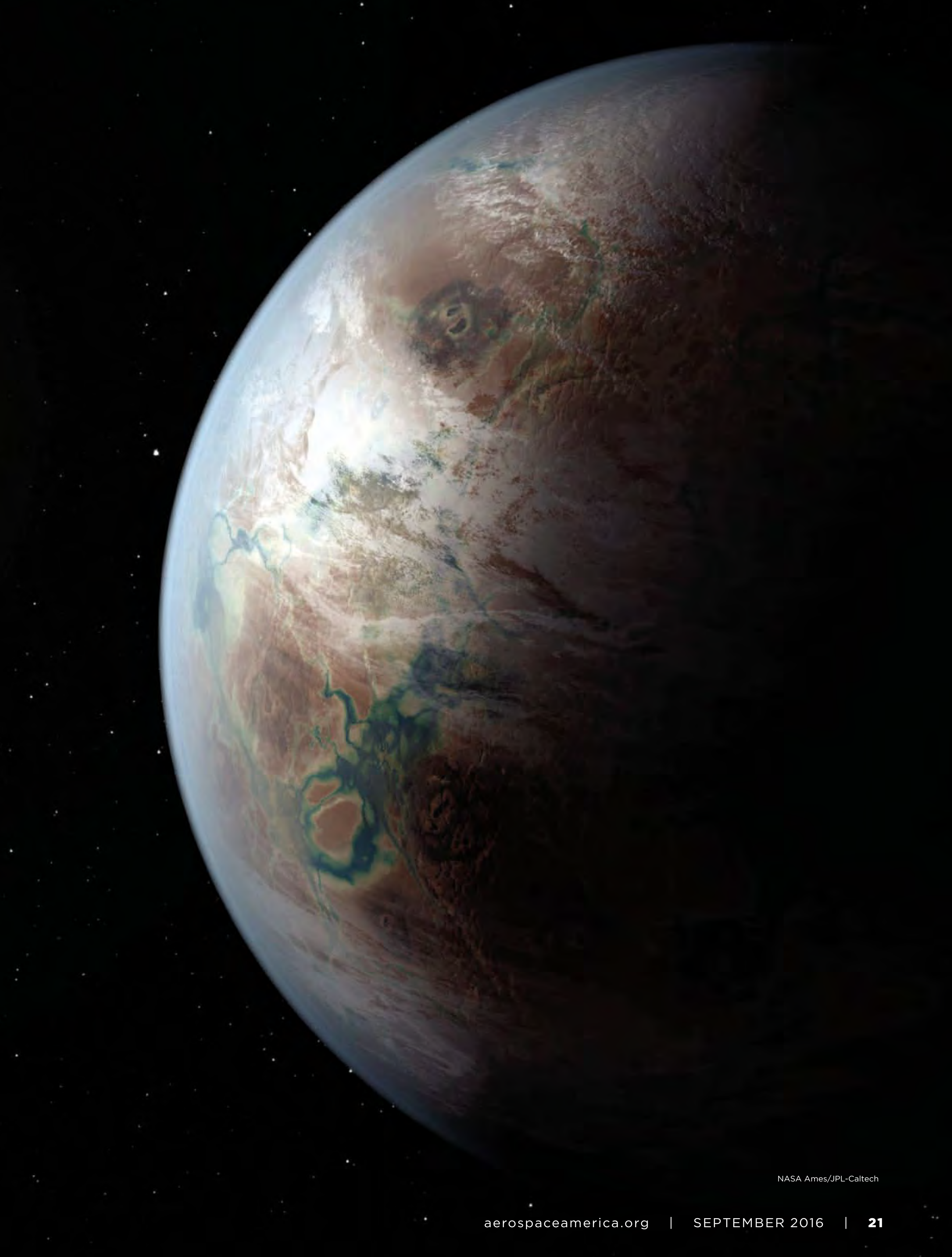
SEPTEMBER 2016 | A publication of the American Institute of Aeronautics and Astronautics | www.aerospaceamerica.org

AIAA
Shaping the Future of Aerospace

8 ★ ★ ★ AEROSPACE AMERICA ★ ★ ★ SEPTEMBER 2016 aerospaceamerica.org

Earthlike exoplanets seem almost certain to exist somewhere in the galaxy, and someday delivering a photograph of one might be astronomy's most amazing achievement. Adam Hadhazy spoke to the technologists who are trying to make that possible.

Planet spotting



NASA Ames/JPL-Caltech

Astronomers have cataloged about 30 planets beyond our solar system that might optimistically harbor life, although none of these worlds is thought to be Earthlike. Researchers are confident that within decades, they'll find what they believe to be a bona fide Earth 2.0.

If such a discovery were made today, it might generate as much frustration as exhilaration. The vast majority of the worlds discovered since 1995 were detected by measuring the gravitational tug on their host stars, or more lately by sensing the dip in brightness of the host star as a planet crossed in front. Right now, no one has the technology to image an Earthlike planet, if one exists. Scientists would have only equations to make the case that their discovery is a planet like ours. What they really want is direct imaging, which would mean gathering photons reflected from the planet's surface and clouds. Such an image would probably look more like a gleaming dot than a Polaroid, but the underlying data would be enough for scientists to deduce the planet's atmospheric conditions.

Not only that, direct imaging could find candidates that the indirect methods might fail to detect. A small planet like Earth would induce only a slight side-to-side ªwobbleº in the star's position, and the planet might not happen to transit the face of its star from our vantage point.

Direct imaging can't be done today for an Earth-sized object because of the daunting optics challenge. The glow of a terrestrial exoplanet could be 10 billion times fainter than that of its host star. Scientists would have to block or occult much of that light to reveal the planet, and they'd have to do it in space to avoid the distorting effects of Earth's atmosphere.

NASA and a host of researchers are determined not to let that status quo stand.

ªWhat's driving all of us is the search for life in the universe,º says NASA's Gary Blackwood, manager of the Exoplanet Exploration Program at the Jet Propulsion Laboratory in Pasadena, California. ªThat's appealed to all of us since we were kids and it still does.º

Engineers at JPL, Princeton University in New Jersey and other facilities have taken up that challenge, and within a decade their work could give astronomers the ability to image an Earth 2.0.

One kind of occulter is a coronagraph, which is a set of filtering optics installed within a telescope's housing. Scientists have photographed the sun's corona or atmosphere this way from the ground since the 1930s.

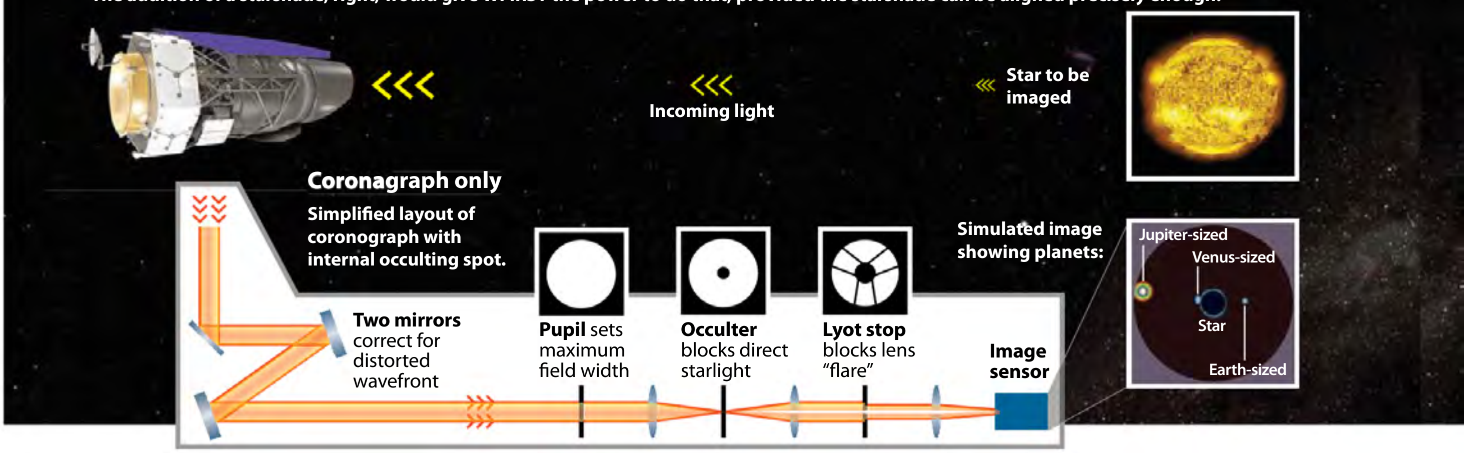
A more spectacular idea would be to block the light from the host star with a sheet of opaque material positioned beyond the telescope in the light path from the star. Dreamed up in the 1960s, starshades have only recently become technologically feasible due in part to the advent of precision-alignment software and microfabrication techniques. A starshade would be deployed thousands of kilometers in front of its companion telescope, shrouding its aperture in deep shadow and letting just the dim light of the stars' exoplanets seep in.

Both occulter types, old and new, have a long way to go before they can suppress starlight sufficiently to reveal Earthly twins, currently as invisible as fireflies encircling a spotlight. A race is underway

"The reality at the moment is we're still working on both coronagraphs and starshades — why would you kill one now when you don't know which will work?"
SARA SEAGER, professor of planetary science and physics at MIT

Revealing Exoplanets

The key to imaging an exoplanet is to block or occult the light from the planet's host star. A coronagraph-only version of NASA's planned Wide Field Infrared Survey Telescope, below, could filter out enough light to image large exoplanets but not dimmer Earth-sized ones. The addition of a starshade, right, would give WFIRST the power to do that, provided the starshade can be aligned precisely enough.



Source: NASA/Jet Propulsion Laboratory

to build two different kinds of next-generation coronagraphs and a starshade to test them in space in the mid-2020s. The coronagraphs would be installed inside the housing of NASA'S Wide Field Infrared Survey Telescope, or WFIRST, the planned successor to the forthcoming James Webb Space Telescope, whereas the starshade would be positioned 50,000 kilometers in front of it.

A lot is riding on that starshade work. WFIRST's 2.4-meter mirror won't collect enough light for its coronagraphs to image a dim Earth 2.0. That ability will have to wait until an even larger telescope is launched in the 2030s. But by flying a starshade in precise formation with WFIRST, the telescope might be able to deliver an Earthly twin by more efficiently suppressing starlight than the coronagraphs. That's because the mirrors and filters of a coronagraph would inevitably lose a large portion of the incoming planetary light. That said, starshades are relatively new to the scene. Researchers must prove that today's small-scale, grounded test versions can suppress light as effectively as has been theorized.

Worldly wheat from chaff

NASA's transit-detecting Kepler space telescope is responsible for the lion's share of the exoplanets discovered so far.

ªThe Kepler mission results have told us the universe is teeming with planets Ð there's at least one for every star,º says Blackwood. ªIf we look, we will find them.º

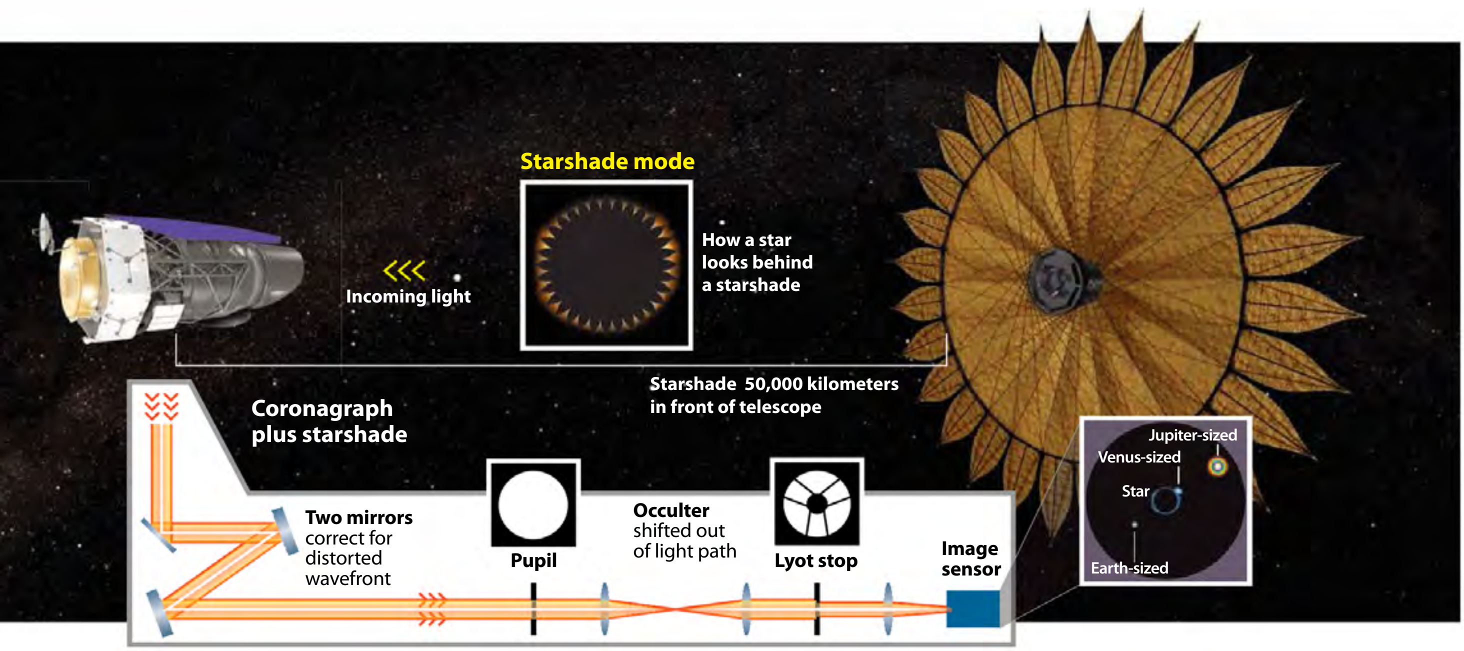
Scientists want an imager, because Kepler's transit detections yield little information beyond the object's mass, size and orbital parameters. Direct imaging has been done to date in only a limited fashion on a handful of worlds, all gas giants, and with only a small portion of the meager light collected from them. Applying the technique to more promising objects could identify telltale signs of alien life such as the right proportion of oxygen, carbon dioxide and methane. Or an imager might examine the closest stars within 100 light-years or so and find an Earthlike planet on its own, perhaps even in the Alpha Centauri star system four light-years away.

ªDirect imaging is how we're going to get Earths,º says aerospace engineer Jeremy Kasdin of Princeton University.

That will require occulters, and they must be more than an outstretched hand crudely eclipsing a star. They must also reduce the spreading, or diffraction, of lightwaves. Like water flowing around a rock in a stream, light changes course in response to its surroundings, diffracting when it hits an impediment's edges, like the rim of a telescope's aperture and the optical components inside.

Typical coronagraphs consist of lenses, masks and mirrors installed inside a telescope. The light from an observed star enters the telescope and bounces off its primary mirror to a secondary mirror that directs the light into the coronagraph. The light is tightly focused on an opaque occulting mask the size of a pinhead. This mask blocks out most of the starlight, but some light still diffracts around it. This remaining starlight goes through a series of other mirrors, lenses and masks to continue filtering it out. Meanwhile, the light from an object beyond the periphery of the star, such as an exoplanet, passes unimpeded through the optics to a camera.

A starshade deals with diffraction differently. If the starshade were simply a dark disk, starlight would



John Bretschneider

Adam Hadhazy

Experiments inside a 77-meter tube at Princeton University will test a protoype starshade made by NASA's Jet Propulsion Laboratory.

inconveniently diffract around its hard edges. Instead, a starshade has petals radiating off a central disk, like a sunflower. The shape of those petals causes the light diffracting around them to form interference patterns that overlap and largely cancel out each other. The starshade therefore casts a central, ultra-dark shadow where the telescope sits. The starshade can be positioned relative to a star so that the telescope captures only the light shining from its exoplanets.

Drawing board to reality

In two NASA reports released last year, one called ªExo-Cª for exoplanet coronagraph and another called ªExo-Sº for starshade, technologists described how these occulters might each be deployed for under a billion dollars. The ªExo-C ª report assumed a telescope with a small mirror of 1.1 meters, while ªExo-Sº looked at 1.4- and 2.4-meter mirrors. Extensions to these studies were published in April 2016 to explicitly consider WFIRST's 2.4-meter primary mirror. That mirror was one of two spare mirrors and telescope housings given to NASA in 2012 by the National Reconnaissance Office, the agency that buys and operates U.S. spy satellites. The larger diameter means the telescope's housing Ð which NASA will modify significantly Ð has enough volume for NASA to include two different kinds of coronagraphs as a technology demonstration.

NASA doesn't see a need to choose between coronagraphs and the starshade technology, especially not before each has been battle tested in space.

ªWe see both starlight suppression methods as promising and worthy of investment,º explains John Gagosian, program executive for the WFIRST mission and the Exoplanet Exploration Program at NASA headquarters. ªNASA is committed both to performing the coronagraph flight demonstration on WFIRST and to maturing starshade technologies to enable a possible starshade flight demonstrationº during the WFIRST mission.º

Of course, WFIRST is not all about planet hunting. The telescope will map galaxies to study dark energy, the strange force that might explain why the universe is expanding at an accelerated pace instead of slowing due to gravity. Currently, less than 10 percent of the $3 billion WFIRST project is ultimately projected for its coronagraph development and operations covering a six-year mission length. For the starshade, concept work is underway now to identify the necessary components and their costs, which are expected to be relatively modest, says Kevin Grady, the WFIRST project manager at NASA's Goddard Space Flight Center in Maryland.

Researchers continue to make strides on starshades with NASA funding. A few years ago, JPL demonstrated in the lab how a starshade might be stowed small for launch and then unfurl its petals in space. Meanwhile, Northrop Grumman has run tests in the Nevada desert. Last year, the company positioned a mini-starshade on a pedestal between the 2.1 meter mirror in the McMath-Pierce Solar Telescope in Arizona and a camera to practice imaging around bright objects, such as Jupiter and the star Vega. In April, NASA formally declared the starshade a ªtechnology development activity.º The move brought various starshade-related initiatives under one roof with the goal of fostering the technology for endorsement in the National Academy of Sciences' next Astronomy and Astrophysics Decadal Survey, scheduled for release in 2020. These recommendations about priorities from scientists and technologists carry enormous weight in Congress, at NASA and the White House. Kasdin has a unique perspective on coronagraphs and starshades because, as he puts it, ªI'm the only person in the community who works on both.º A contributor to the ªExo-Sº report, Kasdin is also the lead scientist for WFIRST's coronagraph.

ªI don't view this as a competition,º Kasdin goes on. ªEach of them has hard things. Coronagraphs have had a little bit more time spent on them, so we know where the warts are, but we're making a lot of progress with starshades.º

While the coronagraph and starshade research communities are indeed largely separate, neither views its efforts as zero sum.

NASA/Tim Jacobs

NASA's Kepler space telescope has found the lion's share of the several thousand exoplanets that astronomers have cataloged over the last two decades.

ªThe reality at the moment is we're still working on both coronagraphs and starshades Ð why would you kill one now when you don't know which will work?º says Sara Seager, a professor of planetary science and physics at MIT.

She and Blackwood are co-chairs of NASA's StarShade Readiness Working Group formed in January to build on the work of the Exo-S science and technology definition team, which Seager chaired. Even so, Seager is quick to point out the scientific advantages of each approach. Coronagraphs would be more efficient at finding exoplanets, Seager says, because they look wherever the telescope housing points. Starshades, on the other hand, can cast dark shadows onto smaller, nearer-term, less expensive telescopes. But because starshades must be moved in sync with the telescope for each exo-solar system to be studied, they cannot cover as many systems as coronagraphs.

ªIdeally, you have both,º Seager says. ªThe coronagraph does the survey, finds the planets we want, then the starshade goes inº for a closer look.

Testing a starshade

In a long hallway underneath Princeton's Frick Chemistry Lab, a yard-wide, sealed steel tube runs nearly the length of a football field. Its interior is painted pitch black and represents the darkness of space.

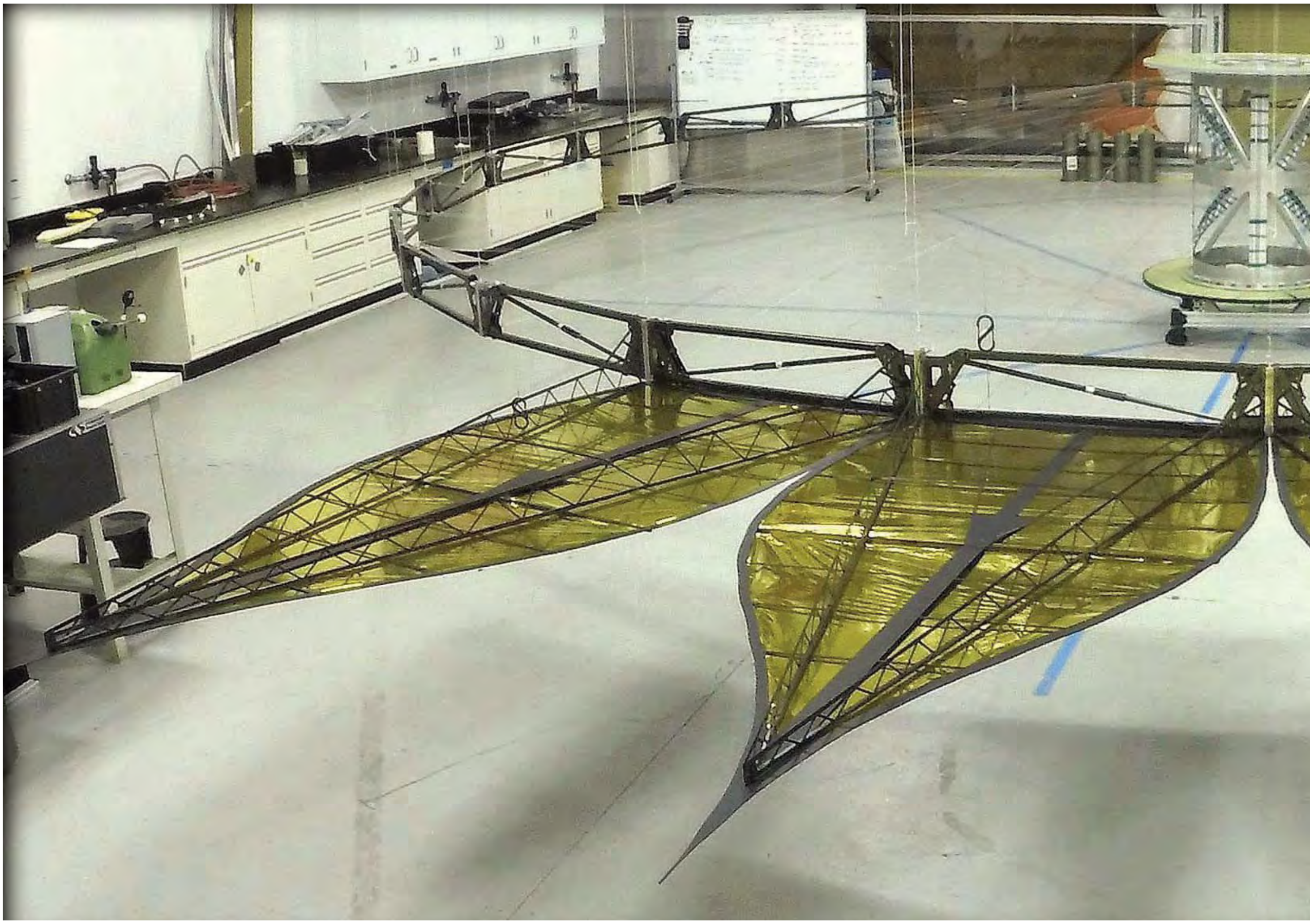
ªIt's fun to put your head down the tube,º says Kasdin. ªIt's very black, very existential.º

The tube is bookended by large boxes. One contains a camera, representing a space telescope; the other, a 21-megawatt, helium-neon laser, representing a star. In between, the metal tube passes through a third box, where a one-inch-wide slice of silicon with 16 petals Ð a micro-starshade, manufactured by JPL Ð intersects the laser beam.

In tests likely to run through early next year, Kasdin's team of colleagues and students will shine laser light through the tube to see how well the starshade suppresses the laser light. Next year, they'll install a communications link between the camera and the starshade mount to investigate formation flying, keeping the instruments synced when one or the other is moved.

ªThis experiment is a scaled version of the real flight version so we can ensure that the starshade can work in space,º says Yunjong Kim, one of Kasdin's post-doctoral researchers.

Depending on how these tests and others go ahead of the decadal survey, NASA may well be in a position to give a green light to a starshade for a future mission. If that mission is to be WFIRST, starshades will probably not be considered technologically developed enough for a simultaneous launch and deployment with the telescope. The likelier scenario would be a rendezvous mission, in



A mockup starshade tested by NASA's Jet Propulsion Laboratory. The yellow petals are micro-starshades that radiate out from a central disk. The petals' shape causes the light diffracting around them to form interference patterns that overlap and cancel out each other.

which the starshade launches subsequent to WFIRST and pairs with it in space. To enable this meet-up, mission planners must decide by mid-2017 whether WFIRST will be designed as ªstarshade ready,º with components including a crosslink for formation flying and data transfer with its late-arriving, occulting partner.

ªWith just a few more dollars of investment in being starshade ready, we can be available for the next technological step of this external occulter,º says Grady, the WFIRST manager. ªI think it's just a great story in further leveraging our investment for this telescope.º

Should a starshade with a 40-meter diameter indeed end up paired with WFIRST, it might be able to obtain images of more than three dozen planets over the mission's duration, including a few Earths.

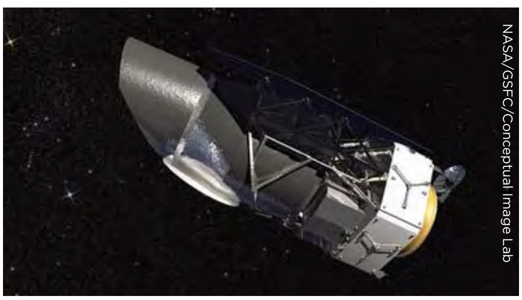
Improved coronagraphs

Astronomers have more modest science ambitions for the coronagraphs in development for WFIRST. It is hoped they can provide deep-enough contrast to behold gas giants like Jupiter, Neptune-like ice giants, maybe even a super-Earth or two, the enigmatic worlds several times more massive than our own and without analogs in our solar system.

To achieve this, the two coronagraph types slated for WFIRST must dramatically improve on the rudimentary devices flown on Hubble, Spitzer and in 2018, the James Webb Space Telescope. These new coronagraphs will include sophisticated, active wavefront control, which corrects for optical aberrations that reduce the high contrast needed to observe exoplanets. For maximum light suppression, actuators move deformable mirrors to keep a star centered in the coronagraph. Although such mirrors have never flown in space, the technology behind them is well-understood from their use on ground-based observatories offsetting the distortion caused by Earth's atmosphere.

Because the WFIRST telescope was inherited by NASA and not initially planned to accommodate a coronagraph, engineers are having to cleverly address certain inherent design limitations. A key one is WFIRST's ability to stay precisely pointed at target stars. For the clean, deep observations scientists desire for studying exoplanets, WFIRST's coronagraphs will require exquisite stability of 0.4 milliarcsecond, meaning the telescope cannot waver more than about half the apparent width on the sky of a typical,

A race is underway to build two kinds of next-generation coronagraphs in time to test them in the mid-2020s on NASA'S Wide Field Infrared Survey Telescope, the planned successor to the forthcoming James Webb Space Telescope.



point-like star as seen from Earth. The challenge is that WFIRST will naturally jitter as much as 11 milliarcseconds. To solve that problem, the coronagraphs will have what Feng Zhao, the WFIRST coronagraph instrument manager, likens to an anti-shaking feature found on expensive, terrestrial cameras. A sensor in the coronagraph will detect the telescope's jitter and then feed that information to a fast steering mirror that will immediately shift to compensate and keep the incoming light centered. The wavefront control system must also compensate for diffraction and fragmentation of observations caused by the six struts, or ªspider arms,º supporting WFIRST's secondary mirror.

ªDespite all that, WFIRST is still a really good opportunity to see a bunch of exoplanets,º says Wesley Traub, the project scientist for the WFIRST mission at the JPL. By working through these issues, the coronagraphs on WFIRST should pave the way for future instruments designed hand-in-glove with their telescope architectures.

Earths in abundance?

Early planning has begun for WFIRST's successors. Two concepts, the Large UV/Optical IR surveyor, or LUVOIR, and HabEx, short for the Habitable Exoplanet Imaging Mission, could have primary mirrors from eight to 12 meters and come outfitted with both coronagraphs and starshades for direct imaging. If WFIRST has not already spotted Earth 2.0, these instruments should finish the job, and then some.

ªWith LUVOIR, and HabEx, now it's getting really exciting,º says Blackwood. ªWe'll be able to survey many, many systems and look for the signs of life in planets' atmospheres.º

When it comes to finally answering the question of whether we are alone in the universe, Blackwood adds: ªI'm as impatient as you are.º ★