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# Unveiling EXOZODIACAL light

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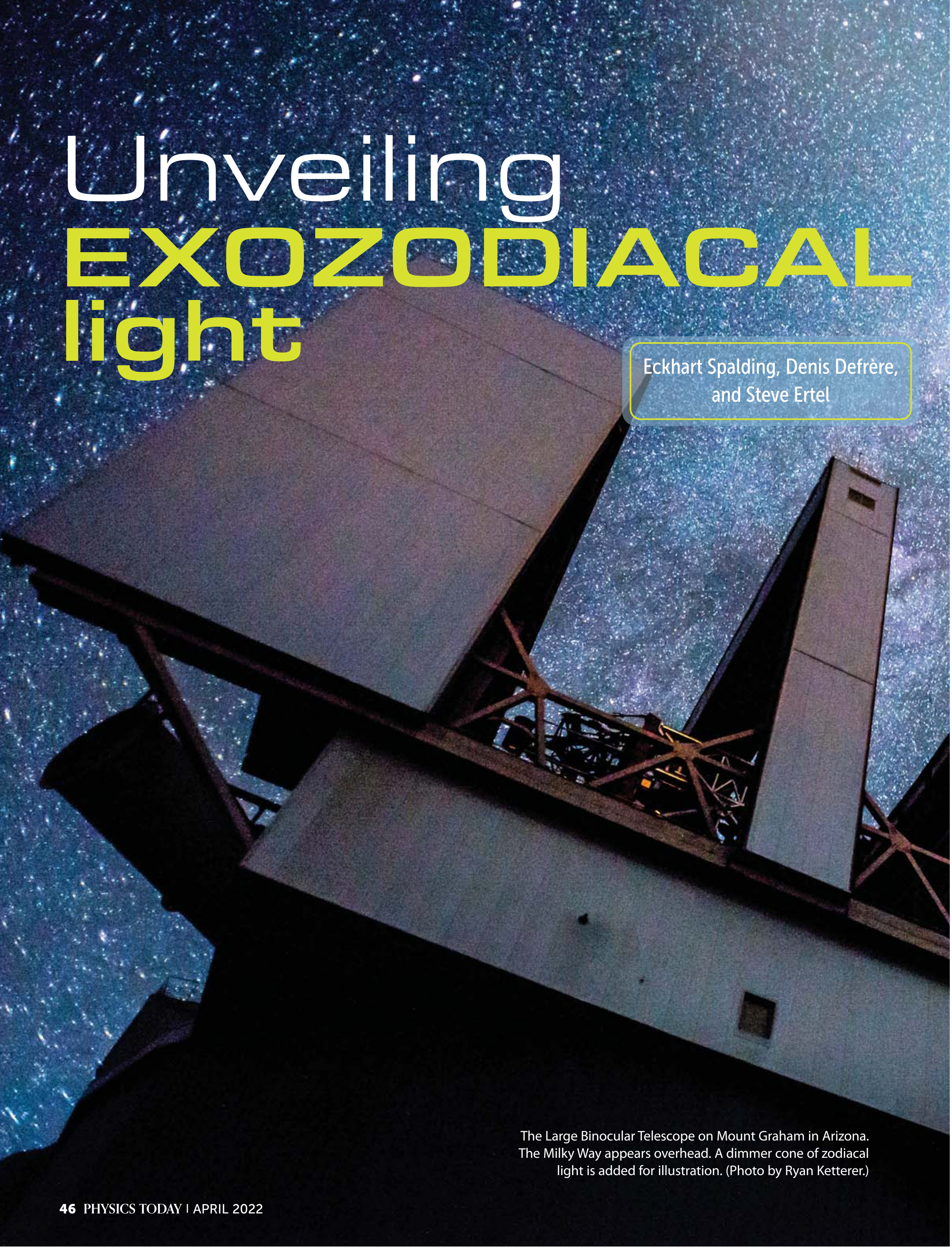

The Large Binocular Telescope on Mount Graham in Arizona. The Milky Way appears overhead. A dimmer cone of zodiacal light is added for illustration. (Photo by Ryan Ketterer.)

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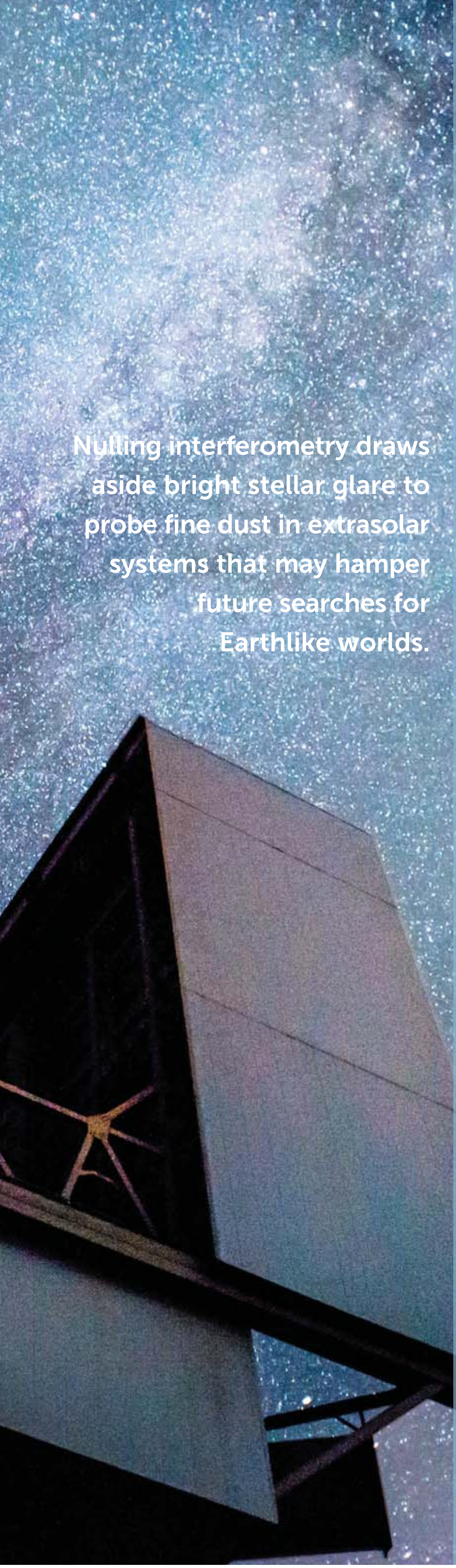

Nulling interferometry draws aside bright stellar glare to probe fine dust in extrasolar systems that may hamper future searches for Earthlike worlds.

Under a dark sky and with the proper celestial orientation, stargazers can see the plane of the Milky Way as a soaring thoroughfare of glowing stars and the silhouettes of dust clumps and tendrils. If the season is right and the eyes adjust enough, a dimmer cone of light emerges that intersects the Milky Way at an angle of about 60 degrees. That cone is zodiacal light: sunlight scattered by small dust grains orbiting the Sun in the ecliptic plane. The dust begins a few solar radii from the Sun and stretches out to the asteroid belt. It is optically thin, with a total mass about $10^{-9}$–$10^{-8}$ times that of Earth and originates mostly from the residue of comet tails and asteroid smashups.

Until recently, the demography of equivalent dust populations around other stars—exozodiacal disks—was unknown. Yet such disks are of paramount importance in understanding exoplanetary systems whose architectures and dynamics leave imprints in the disks' shapes, thicknesses, and compositions. Exozodiacal disks also carry environmental signatures of a star's habitable zone (HZ), commonly defined as the region around the star where liquid water can be expected to exist on the surfaces of Earth-sized exoplanets with atmospheres. The HZ environment influences a rocky planet's ultimate fate: It can cause the planet to remain an uninhabitable rocky orb, evolve into a steamy water world with a punishing greenhouse effect, or end up a balmy habitable middle ground, among other possibilities.

Roughly 5000 exoplanets are known to date from various detection methods. The transit method has uncovered most of them, but it requires a planet to pass in front of the host star and is best suited for planets with tight, short-period orbits that enable repeated observations. Direct imaging has uncovered just a few tens of exoplanets. The method's strength lies in its ability to characterize the atmospheres of exoplanets, particularly those with wide orbits, without requiring the planetary system to be close to an edge-on orientation relative to Earth's line of sight.

Direct imaging can also peer deeper into exoplanet atmospheres and pick out absorption lines of species that include water, oxygen, and methane. In certain combinations, high signal-to-noise detections of such chemical species could provide strong evidence of a biosphere.[1] Although an exozodiacal disk can strongly influence a planet's habitability, it can also snarl observations by acting as a noise source.

## Probing extrasolar systems

The greatest obstacle for directly imaging an exoplanet is not the planet's dimness but the host star's blinding glare, which is particularly challenging for ground-based instruments that collect light waves after they have been aberrated by Earth's turbulent atmosphere. Although ground-based instruments continue to

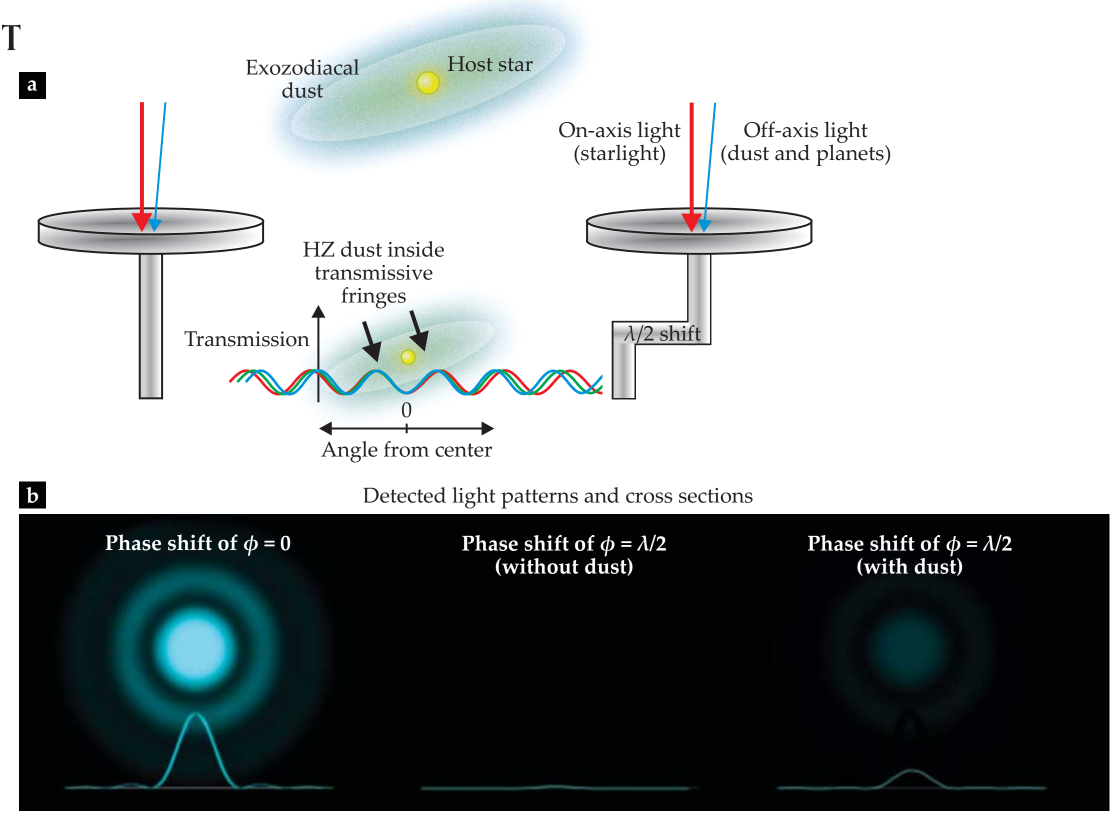

**FIGURE 1. INTERFEROMETRIC NULLING** separates a star's overpowering light from the dim glow of circumstellar material. **(a)** Light from a star and its surrounding material is collected by two apertures. One beam undergoes a half-wavelength phase shift, and combining the beams produces a destructive transmission fringe over the on-axis host star. Light from circumstellar material remains because it is off-axis and seeps through constructive transmission fringes. (Adapted from ESA 2002/Medialab.) **(b)** Imaging a star with a telescope produces a circular Airy pattern (left). If the star were bare, nulling would remove the entire signal except for trace leakage from phase noise or the star's nonzero angular diameter (center). But if the star has circumstellar material in its habitable zone (HZ), a dim signal remains (right).

reach ever-greater sensitivities and produce valuable results, the atmosphere imposes so much noise that large space telescopes remain the most promising route to directly imaging and characterizing Earth-sized exoplanets.

Space telescopes are colossally expensive, so mission planning must maximize the scientific return to justify the price. The best-informed mission plans inescapably require some foreknowledge of exozodiacal dust because such dust could well be the greatest obstacle to the mission's sensitivity. For a given amount of smoothly distributed dust, an observation's signal-to-noise ratio will depend on the integration time and the diameter of the telescope's primary mirror. A clumpy dust distribution can introduce additional noise and further complicate the analysis.[2] Even if exozodiacal dust is optically thin, as zodiacal dust is, the total light from such a disk may make it orders of magnitude brighter than a planet. Those factors have significant consequences for the size, lifetime, operational cadence, and cost of a mission.

Whatever the precise nature of exozodiacal light, one contribution is almost certainly Poynting–Robertson drag, whereby an orbiting particle's angular momentum diminishes as it absorbs stellar photons and reemits them. Over time it causes dust particles to creep inward from cold primordial outer rings, such as the solar system's Kuiper belt. As the dust spirals inward, collisions grind the grains down to sizes small enough for radiation pressure from the host star to blow them out of the system.

Minor bodies can also produce exozodiacal dust. A planet's gravitational pull can scatter an object from a distant debris belt onto an orbit that brings it sufficiently close to the host star. Increased exposure to the star's light causes volatiles to outgas, thereby depositing dust in the inner system.

Scientists face the same fundamental challenge when imaging exozodiacal disks and exoplanets: detecting a faint signal separated by a tiny angle from a blazingly bright star. In a copy of the solar system 10 parsecs (approximately 3.26 light-years) away, Earth would sit just 0.1 arcsecond from the Sun—roughly the diameter of a quarter held 30 miles away. And the Sun would be 10 million times brighter than Earth at IR wavelengths. In principle, a stellar interferometer with a baseline length of 15–20 m can obtain that spatial resolution at an observing wavelength of around 10 μm—the wavelength at which HZ dust at around 300 K is expected to be most emissive. From the ground, however, the atmospherically induced perturbations that make stars twinkle are essentially prohibitive for imaging an exo-Earth.

## The first IR nulling

In 1978, when exoplanets had yet to be discovered and the *Hubble Space Telescope* was little more than a vision, Roland Bracewell at Stanford University proposed that a space-based interferometric array twirling about an axis could detect exoplanets in the IR.[3] A schematic of the technique, known as nulling interferometry, is shown in figure 1.

In nulling interferometry, light is collected by two apertures at the ends of the interferometer arms. A half-wavelength phase shift is applied to one arm, and the two beams are combined to create a transmission pattern composed of alternating constructive and destructive interference fringes. On-axis light from the star is multiplied by a destructive transmission fringe, thereby effectively subtracting it from the combined signal. But light from an exoplanet or circumstellar dust, which enters the apertures at an angle relative to the starlight, is multiplied by a constructive transmission fringe and is therefore not sieved out with the starlight. The amplitude of the residual light rises and falls with time, either because the optical path length changes or because an asymmetric structure around the star flits in and out of view as the sky rotates overhead. An exoplanet's signature would appear as a characteristic ripple in the observed brightness.

In the 1990s Roger Angel and Nick Woolf at the University of Arizona in Tucson were aware that exozodiacal dust could

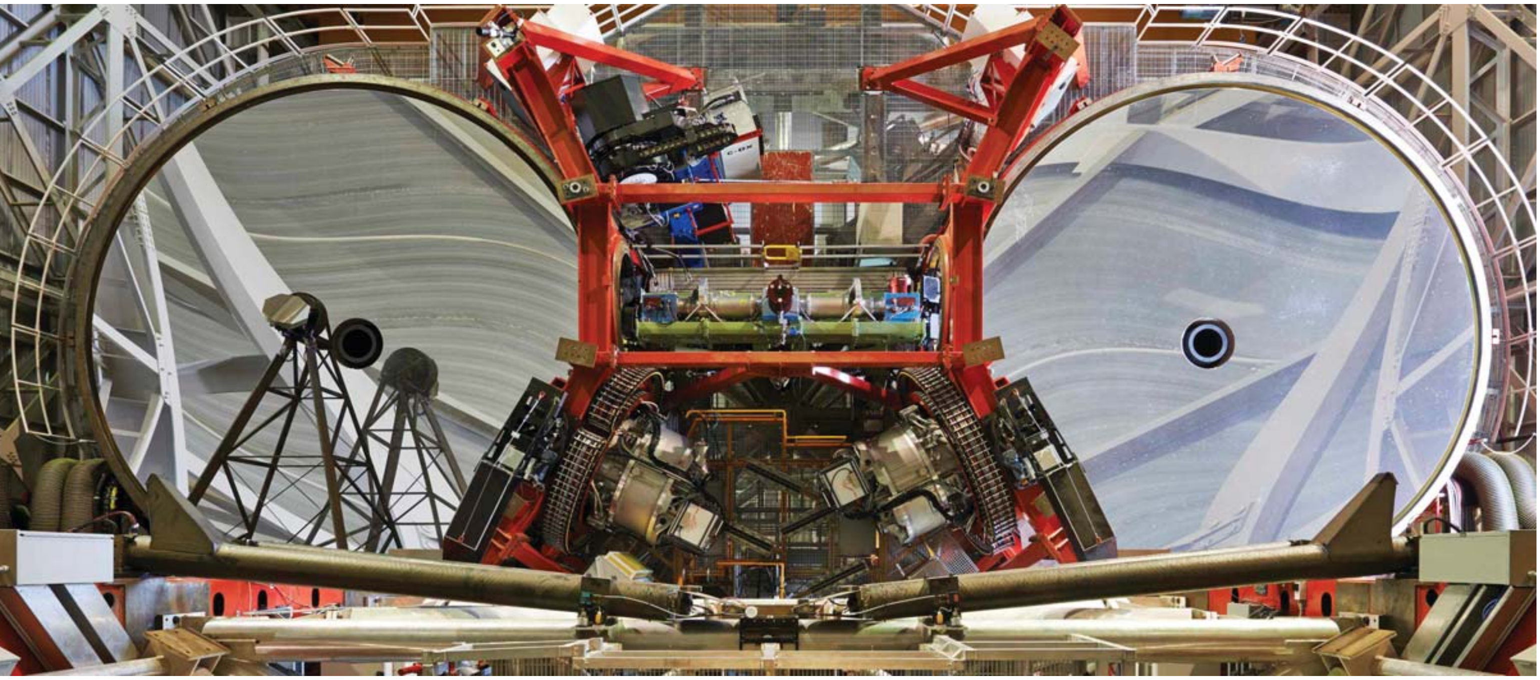

**FIGURE 2. THE TWIN APERTURES** of the Large Binocular Telescope sit 14.4 m apart, center to center. The green structure between them is an interferometer that enables the telescope to be used for nulling. (Courtesy of LBTO–Enrico Sacchetti.)

be a limiting source of noise for space missions attempting to image exo-Earths. They also knew that the planned Large Binocular Telescope would be able to characterize the dust from Earth using nulling interferometry. The LBT, shown in this article's opening image, was slated to have a unique configuration of large twin primary mirrors on a single mount,[4] shown in figure 2. (Angel also innovated a new mirror casting technique that used a rotating furnace to produce the 8.4-m-diameter mirrors—the largest monolithic mirrors for astronomy, then and now. He and coauthors Buddy Martin and John Hill describe the advances in mirror design in an article in PHYSICS TODAY, March 1991, page 22.)

While the LBT was under construction, Angel's then graduate student Philip Hinz, with assistance from William Hoffmann, Donald McCarthy, and others in the department, built a nulling instrument with a 5 m baseline between two mirrors of the Multiple Mirror Telescope (MMT). The detector was sensitive to light in the 8–28 μm range, which includes HZ dust emission.

The researchers placed a narrow null over the star Betelgeuse and measured the transmitted light from its dust nebula down to within 0.2 arcsec of the star. The resolution was better than that from the full MMT aperture; in that case, a perfect wavefront would have delivered a characteristic resolution of 0.3 arcsec. Although the turbulent atmosphere induced rapid changes in the optical path length between the two arms of the interferometer, the researchers used a series of rapid readouts to quantify the null depth—the excess light above that expected from perfect stellar light suppression, which originates from circumstellar emission—to within the limits imposed by phase noise.

Hinz and coworkers produced the first nulling constraints on circumstellar structure[5] in 1998. The project's primary objective was not to complete a full exozodiacal survey—the sensitivity was not yet good enough—but to provide a proof of concept for using null measurements to fit physical models of dusty disks around young stars.

## Scaling up sensitivity

The same atmospheric turbulence that causes stars to twinkle also degrades the resolution of any large rigid, single-aperture ground-based telescope to that of a much smaller telescope just a few centimeters across. Increasing the sensitivity of nulling interferometry at the MMT therefore required at least partial correction for Earth's roiling atmosphere. To overcome atmospheric effects, scientists built adaptive optics (AO) systems with sensors to measure aberrations in the wavefront, compute a full wavefront reconstruction, and deform mirrors to cancel the aberration, typically at hundreds of Hz to roughly 2 kHz.

Serious development of AO began in the 1970s behind the curtain of classified US defense research, but it was still a relatively new technology in the civilian astronomical community[6] in the 1990s. The first telescopes to be upgraded with AO had to be retrofitted with additional optics between the telescopes' optical trains and their detectors.

When the MMT was outfitted with an AO system in 2002, the implementation was based on a novel design funded by the US Air Force: a deformable secondary mirror, integrated with the telescope's optics, that removed the need for additional optics and thereby minimized thermal noise.[7] The secondary mirror also benefited nulling observations by consolidating photons from an object onto a smaller area of the detector, thereby further reducing background noise, and by deblurring the object and straightening transmissive fringes.

Even with substantial wavefront correction, there was still enough atmospherically induced slope in the wavefront phase to cause the two beams from the subapertures to retain differential phase noise. The noise caused the on-sky transmission pattern to jitter, which in turn caused contaminant stellar light to flicker in the data.

For a time, the team at the MMT resorted to a slow, makeshift form of phase correction: They manually tuned an electric field over a piezoelectric ceramic mount to move an internal mirror and change the optical path length. By doing so, Hinz, with then graduate students Wilson Liu and Nathan Stock, resolved dust around young stars ensconced in gaseous envelopes and protostellar disks. They derived upper limits for the amount of HZ exozodiacal dust around a few older main-sequence stars, and, by incorporating complementary data from elsewhere, they determined that a bright debris disk around the star $\beta$ Leonis consists of multiple rings of material.

As IR nulling ramped up at the MMT and construction of the LBT continued, scientists began using other facilities to observe extremely dusty systems so they could characterize the brightest end of the exozodiacal luminosity function. Space-based data came from the *Spitzer Space Telescope*'s infrared spectrograph in the 5–37 μm band, from its multiband imaging photometer in the 24 μm and 70 μm bands, and from the *Wide-Field Infrared Survey Explorer* (*WISE*) in the 12 μm band. Data from 1.6 μm to 2.2 μm came from ground-based interferometers, including the Infrared Optical Telescope Array on Mount Hopkins in Arizona, the array and instruments at the Center for High Angular Resolution Astronomy at Palomar Observatory on Mount Wilson in California, and the Very Large Telescope Interferometer on Cerro Paranal in Chile.

Although those interferometric observations did not involve nulling, they exploited the instruments' high angular resolutions to detect emission from thick, hot dust clouds close to the clouds' host stars. Models suggest that such dust comes predominantly from continual replenishment by a rain of infalling comets.[8] The Sun's F-corona scatters light from small amounts of dust at a similarly close separation, and Sun-grazing comets deliver small amounts of dust, but our solar system has no direct analogue to that thick, hot dust.

Those ground-based interferometric observations were not sensitive enough and were at wavelengths that were too short to detect the more tenuous dust near a star's HZ. The space-based photometry, for its part, could not suppress the target star's light enough to reveal faint circumstellar emission. Such measurements need ground-based mid-IR nulling interferometry.

For future space missions to image exoplanets, HZ exozodiacal dust would have to be characterized down to a sensitivity approaching the level of a few zodis. (One zodi equals the brightness of the zodiacal disk.) In 1997 NASA began funding the project to optically connect the twin Keck telescopes on Mauna Kea in Hawaii, thereby creating an interferometer. Operating in a nulling mode, the telescope became the Keck Interferometer Nuller (KIN) and was used to measure the exozodiacal luminosity function—that is, the number of exozodiacal systems per luminosity interval.

The KIN had multiple baselines: 4 m across the two halves of each individual telescope and an 85 m baseline between the two telescopes.[9] Between 2008 and 2011, the KIN collected a data set of 44 systems in multiple wavelength channels ranging from 8 μm to 13 μm. Based on the 8–9 μm measurements, the survey put an upper limit on the median brightness of exozodiacal disks around Sun-like stars at 60 times the thickness of the zodiacal disk,[10] or 60 zodis.

As the KIN survey came to an end, the LBT was getting up and running. Its twin monolith telescopes have center-to-center separation of 14.4 m, a number chosen so that baselines up to the nearly 23 m distance between the outer edges of the mirrors can be continuously sampled. The LBT's two sub-telescopes are each 8.4 m wide, and either one would be a large research telescope by today's standards. Both are crammed with a twin menagerie of instruments built and operated by a consortium of institutions and use adaptive secondary mirrors based on the pioneering tests conducted at the MMT.

## The HOSTS survey

Because the LBT has a squat configuration, a compact baseline, and adaptive secondary mirrors, it can avoid the added complexity and thermal emission of long optical trains when it combines the beams from the sub-telescopes. The LBT Interferometer (LBTI) thus has less instrumental noise and achieves greater sensitivities than other facilities with longer baselines.

The LBTI group, headed by Hinz, who once led the early nulling experiments at the MMT, embarked on a new exozodiacal disk survey in the spring of 2014. The Hunt for Observable Signatures of Terrestrial Planetary Systems (HOSTS) survey targeted A-, F-, G-, and K-type stars. Those stars were subdivided into two subsamples: One contained A- and F-type stars, which are particularly hot and bright and consequently have HZs at larger radii from the stars. The LBTI would have the greatest sensitivity to dust in those systems. The other subsample included close Sun-like analogues that would be of greatest interest for future space-based missions. The full target list comprised 68 stars within 30 parsecs, close enough that emission from the inner HZ should be detectable.[11]

For their observations, the researchers

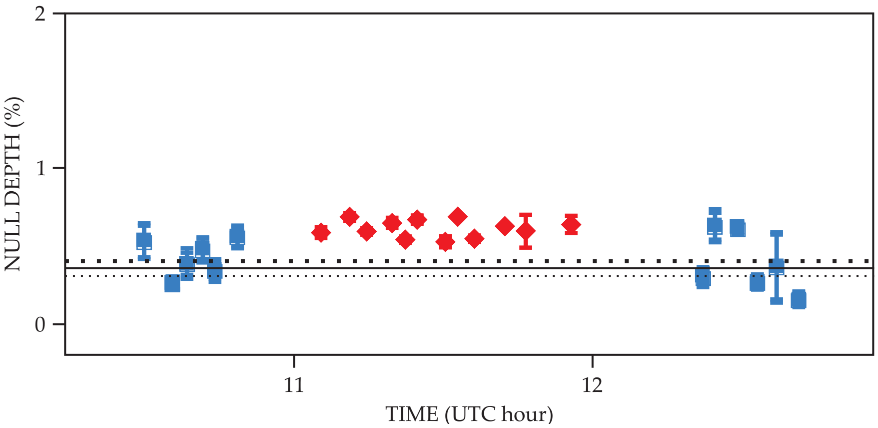

**FIGURE 3. THE NULL DEPTH** embodies the amount of circumstellar emission detected through nulling interferometry. The offset between the data for Vega (red), a star from the Hunt for Observable Signatures of Terrestrial Planetary Systems survey, and those for calibration stars (blue) indicates a glow from exozodiacal dust in Vega's habitable zone. The dotted lines represent the one-sigma uncertainty of the null floor.

alternated placing the central null over science stars—the targets of the investigation—and calibration stars. The offset in the null level between the two types of targets indicated light from circumstellar dust (see figure 3). The interferometer's tiny field of view minimized the probability of background sources, such as distant galaxies, masquerading as HZ dust.

The star $\eta$ Corvi was chosen as an early proof-of-concept target because it was already known to be particularly dusty. But when the LBTI observed the star in early 2014, it found that the null depth corresponded to excess light of only about 4%, smaller than expected, given the 23% total disk-to-star flux ratio measured by *Spitzer*. Subsequent modeling suggested that much of the dust must be close to the star,[12] constrained to within 0.5–1.0 AU.

The LBTI group had developed a software loop to track the differential phase between the two sub-telescopes and send commands to an internal mirror to correct one of the beams. The team members improved their phase-tracking system after the $\eta$ Corvi observation, but the improvements did not translate to better observational sensitivity when they looked at another system, $\beta$ Leonis. They finally solved the problem with a data-reduction technique, nulling self-calibration, that was developed for the Palomar Fiber Nuller by Bertrand Mennesson of NASA's Jet Propulsion Laboratory in California and Charles Hanot of the University of Liège in Belgium. The algorithm uses the statistical distribution of the interferometric output signal to calculate the true astrophysical null. Applied to the LBTI data set, nulling self-calibration provided 5–10 times better null accuracy.

The high luminosity of $\beta$ Leonis and its proximity to Earth have enabled dust in its HZ to be particularly well resolved, and the use of different aperture radii in the data analysis provides details about the dust's structure. The data are most consistent with a composition of silicates and organics, and with a modeled grain-size distribution, they suggest the existence of a two-component outer dust disk. The material that makes up the inner component was found to be so dense that collisions between dust and rocks would have ground down most of the particulates over the age of the star. The dust must therefore have been replenished from an external source, such as disintegrating comets.[13]

The survey's criterion for success was to observe 35 stars, and by the spring of 2018, the LBTI had observed 38. Figure 4 shows the measured exozodi levels around the stars. Ten had detections of dust, ranging in thickness from 38 to 2600 zodis, with typical uncertainties of a few tens of zodis. Particularly dusty systems, such as $\eta$ Corvi, were already known to be the exception and not the rule, but analysis of the HOSTS results mercifully revealed that even systems at tens of zodis are unusual.

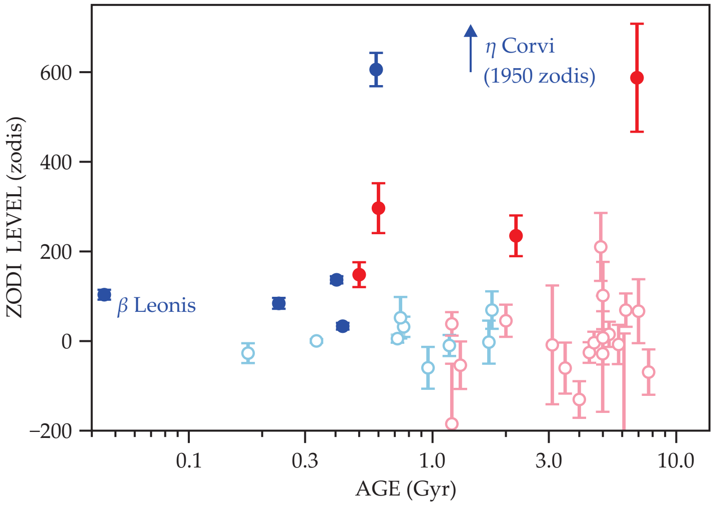

**FIGURE 4. THE BRIGHTNESS** of exozodiacal disks observed in the Hunt for Observable Signatures of Terrestrial Planetary Systems survey is measured in zodis, where one zodi is the brightness of the zodiacal disk. Filled data points indicate detections of exozodiacal light, and unfilled data points are nondetections. The majority of systems observed were nondetections, which suggests that the amount of light from exozodiacal dust in most stellar systems is similar to that in our solar system. (Adapted from ref. 14.)

Figure 5 shows the constraints that the LBTI and *WISE* placed on the exozodiacal luminosity function. To within 95% confidence, the analysis shows that the median surface brightness of exozodiacal disks around Sun-like stars is 27 zodis or less, with a best fit to the data of only 3 zodis, which suggests that our solar system may actually be typical.[14] Exozodiacal dust should therefore not pose a serious challenge for directly imaging Earth-like planets from space, as it would if typical dust levels were beyond 20 zodis or so.

## Next steps for HOSTS

The LBTI currently has the best sensitivity to HZ exozodiacal dust of any instrument, and the HOSTS results will form the basis for planet-yield estimates when planning future space missions for imaging exo-Earths. The possible presence of HZ dust still poses a challenge for detecting faint planets, but the exozodiacal luminosity function traced out by HOSTS indicates that space-based designs will not need to have significantly expanded apertures, as would have been necessary for dustier scenarios. Such modifications could have easily incurred additional costs on the order of billions of dollars for a single mission.

Even after the success of HOSTS, a better understanding of exozodiacal dust would still be valuable. More data could help elucidate disk morphologies and constrain the dust's composition and dynamics—and, thus, its origin. Clumps or disk-shape asymmetries could suggest perturbations from planets. The shape of the dust's radial surface density could also indicate the clearing out of planetary material, a smooth funneling of dust from outer belts, or the fitful deposition of material from bodies such as comets and asteroids. Such processes will provide critical context once rocky HZ planets can be imaged and studied directly. In addition, if tighter constraints can be placed on dust levels around stars with HOSTS nondetections, smaller and cheaper space-based apertures could potentially be deployed and obtain a sufficient signal-to-noise ratio to image planets.

The LBTI group has plans in place to use the interferometer for a deeper study of detected disks, in which observations will be taken at multiple wavelengths and use more on-sky rotation as targets move overhead. The sensitivity of the LBTI is currently limited by detector noise; imperfect background subtraction; and instrumental vibrations, particularly from the telescope swing arms that hold the secondary mirrors. The group is currently working to improve all three factors. NASA has allocated funding for the LBTI's efforts over the next three years through an Exoplanets Research Program grant.

## Nulling's future

Nulling will continue to be used in exoplanet science. It has the potential to find planets at smaller angles to their host stars than coronagraphy, the technique of successive optical masking to remove on-axis stellar light. In recent years, research groups have tested new nulling techniques with simulations, in labs, and on telescopes. Recently the Palomar Fiber Nuller was used to make the first detection of a faint companion star by rotating a null fringe around the primary star.[15]

An upcoming project, Hi-5, will turn the Very Large Telescope Interferometer into a giant four-aperture nuller.[16] It will benefit from the observatory's state-of-the-art infrastructure, the scientists' experience from past nulling projects, and improved software control and data processing. Hi-5 will also have integrated optics—miniaturized optical components in photonic analogues of integrated circuits—to provide increased optical stability and beam-combination flexibility. In addition to its main goal of detecting young giant planets in the HZs of nearby planetary systems, Hi-5 has an ambitious slate of science objectives that includes studying the multiplicities of stars in different evolutionary states to better constrain star formation models and detecting exozodiacal disks at wavelengths between the sweet spots of other nulling instruments.

Atmospherically induced noise remains prohibitive for observing habitable rocky planets from the ground for all but a handful of the closest stars, even with future 30-m-class telescopes. Nulling observations of such planets must wait for space-based missions in the decades ahead. Ambitious space nulling projects from years ago, such as the *Terrestrial Planet Finder*, never advanced beyond the development stage. But new designs have recently emerged with the benefit of an additional decade's worth of progress. A European team is proceeding with the study phase of the space-based *Large Interferometer For Exoplanets*, a proposed nuller with up to four mirrors on long baselines.[17] The researchers predict that it could detect hundreds of small rocky planets around nearby stars, including possibly dozens of Earth-sized planets in their stars' HZs.

Even if planets in HZs are common, the distances between the nearest Sun-like stars remain staggeringly vast on any human scale. Still, there is no physical reason why the distances to the nearest stars cannot be traversed in future centuries, with technological analogues of the outrigger sailing craft of Pacific Islanders who millennia ago set out on expeditions to the remotest of islands and navigated by the stars. Should that come to pass, nulling observations will help furnish the navigational charts to the most suitable destinations.

Or perhaps Earth-like worlds, glassy with ocean glint and speckled with clouds, are truly vanishingly rare. The evolution of life may also be so unusual that atmospheric studies of habitable exoplanets in our own century will provide no reason to suspect they are anything more than serene but deserted outposts, with nothing and no one to hear the wind and the waves. With time we will begin to know.

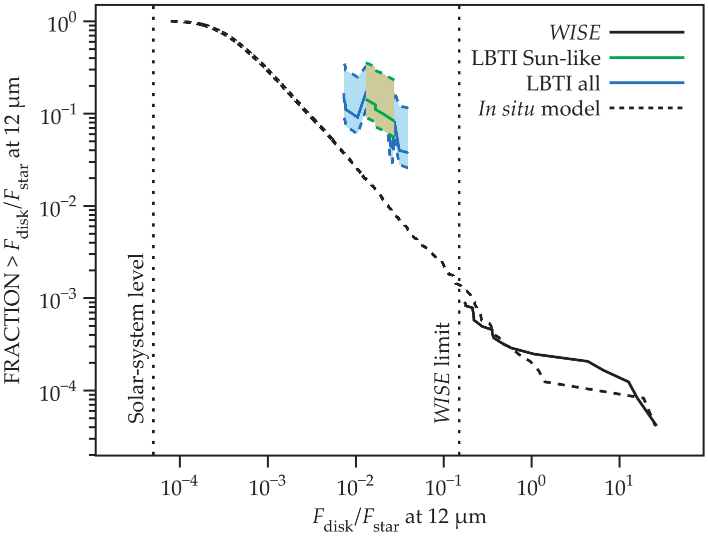

**FIGURE 5. THE EXOZODIACAL LUMINOSITY** function is constrained by data from the Large Binocular Telescope Interferometer (LBTI; blue and green lines) and the *Wide-Field Infrared Survey Explorer* (*WISE*; solid black line). The shaded regions around the LBTI data indicate uncertainties. The dashed line shows a model extrapolation of the *WISE* results. This plot is a reverse-cumulative distribution of the ratio of flux from the disk to flux from the star. Like luminosity, the flux ratio is independent of distance. It's measured at 12 μm, where habitable-zone dust is especially emissive. The green color shows the LBTI constraint from only Sun-like stars (F, G, and K types), and the blue is from all observed stars, including hot A types. The finding that the LBTI data have a shallower slope than the *WISE* extrapolation suggests the presence of additional physical processes that produce small levels of dust. (Adapted from S. Ertel et al., *Astron. J.* **155**, 194, 2018.)

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