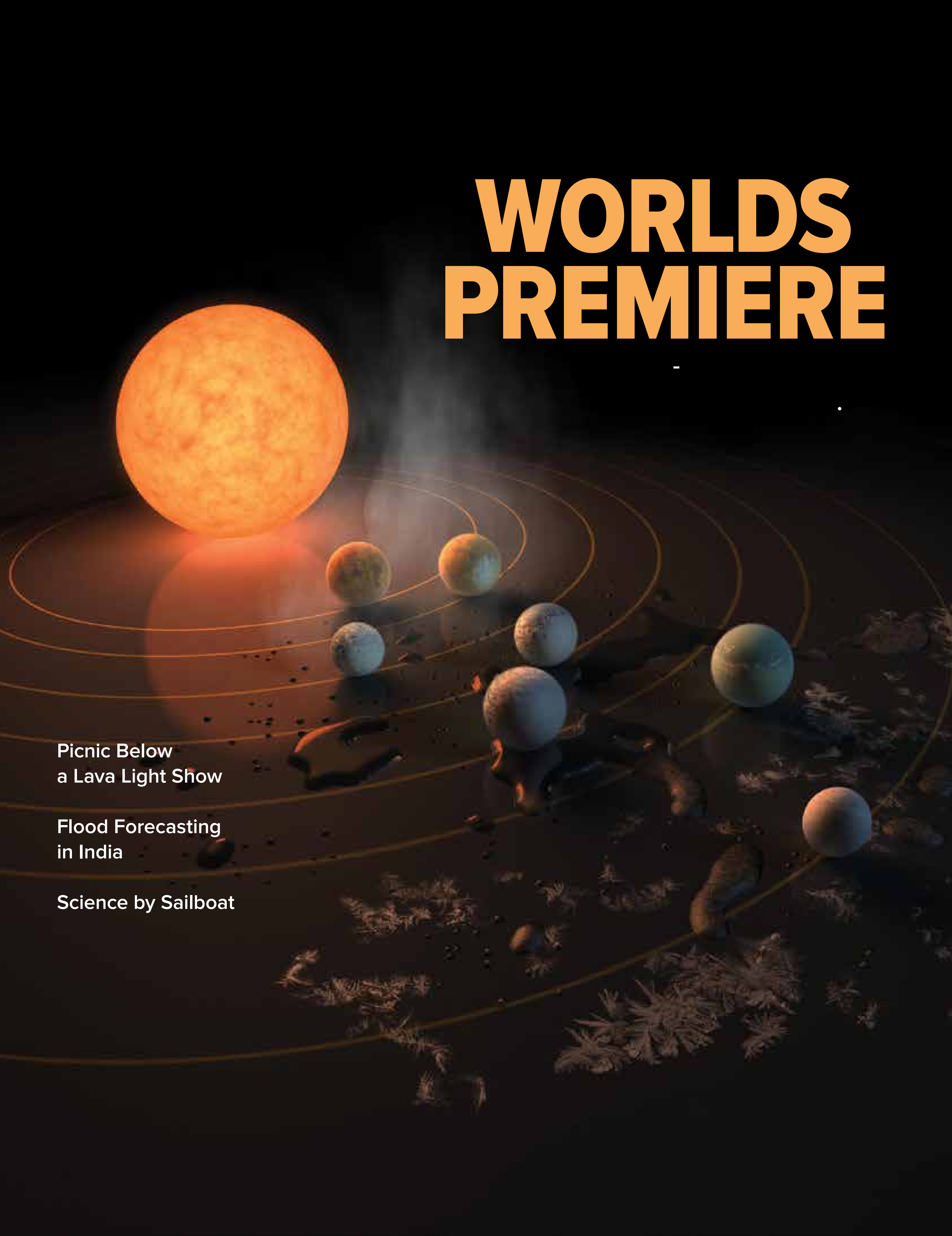

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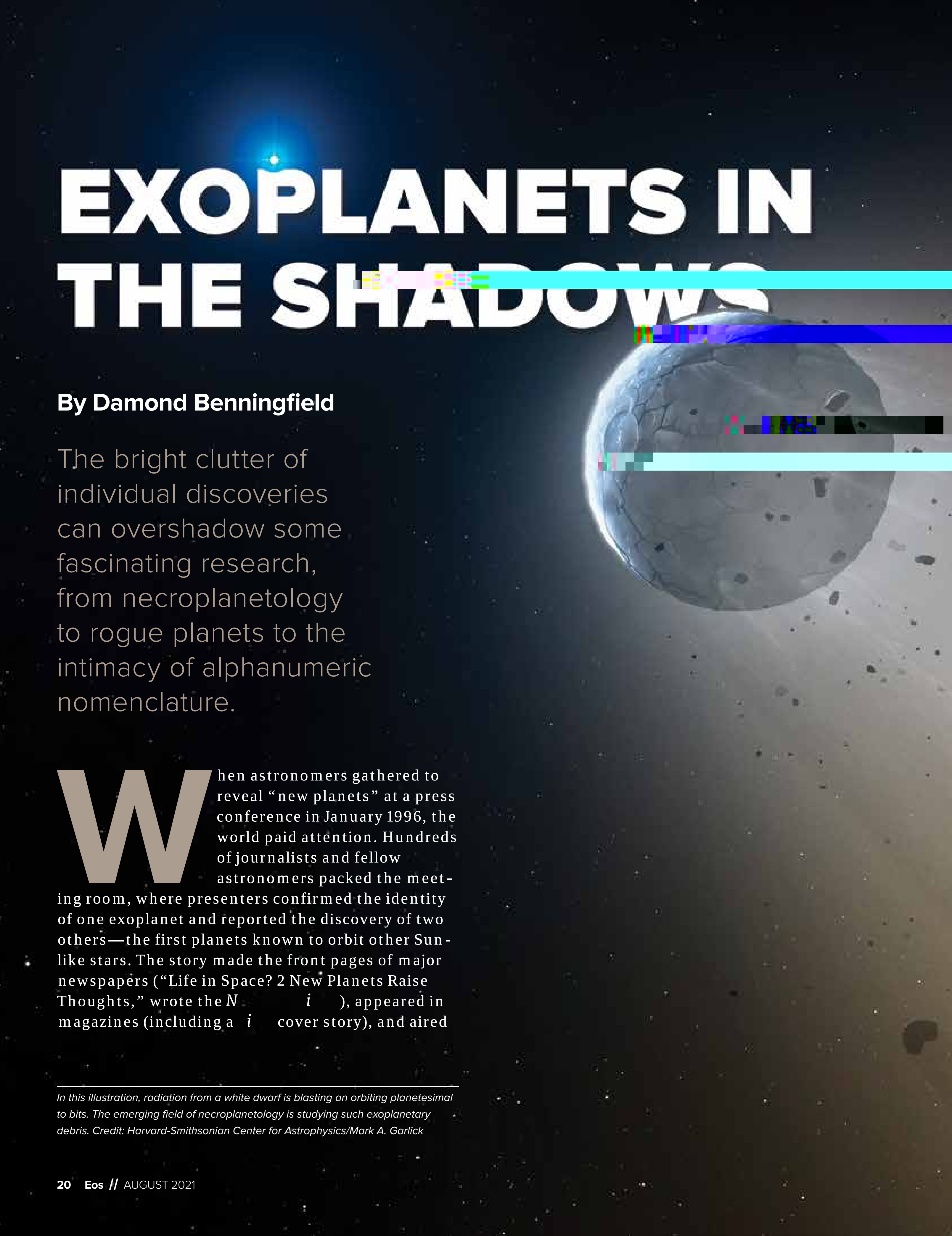
EXOPLANETS IN THE SHADOWS

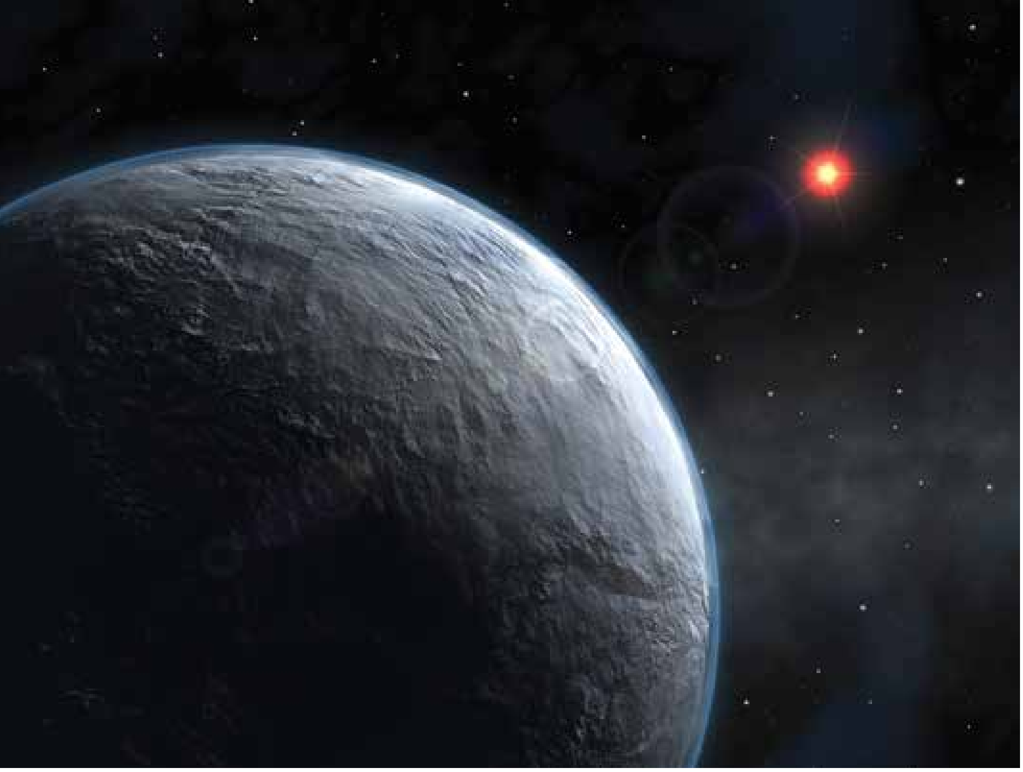
By Damond Benningfield

The bright clutter of individual discoveries can overshadow some fascinating research, from necroplanetology to rogue planets to the intimacy of alphanumeric nomenclature.

When astronomers gathered to reveal "new planets" at a press conference in January 1996, the world paid attention. Hundreds of journalists and fellow astronomers packed the meeting room, where presenters confirmed the identity of one exoplanet and reported the discovery of two others—the first planets known to orbit other Sun-like stars. The story made the front pages of major newspapers ("Life in Space? 2 New Planets Raise Thoughts," wrote the *N* *i*), appeared in magazines (including a *i* cover story), and aired



In this illustration, radiation from a white dwarf is blasting an orbiting planetesimal to bits. The emerging field of necroplanetology is studying such exoplanetary debris. Credit: Harvard-Smithsonian Center for Astrophysics/Mark A. Garlick



An artist's rendering of OGLE-2005-BLG-390L b, which was discovered through gravitational microlensing. It is one of the most remote exoplanets yet seen, at a distance of about 20,000 light-years. Credit: ESO

on television news (including CNN) soon after.

A quarter of a century later, exoplanets still generate headlines—sometimes. With the number of confirmed planets well beyond 4,000 and more being added to the list almost weekly, however, a sort of exoplanet fatigue has set in. Only the most spectacular discoveries show up in our daily newsfeeds: potentially habitable planets, for example, or "extreme" worlds—those that are especially hot or young or blue or close to our solar system.

Yet some of the topics in the penumbra of exoplanet discussions are just as fascinating as those in the spotlight. They remain in the shadows in part because they involve objects that are rare or that are difficult to find and study with current technology. The recently named field of necroplanetology, for example, studies planets orbiting dead or dying stars, providing the only direct look at the innards of exoplanets. Gravitational microlensing allows astronomers to detect planets at greater distances than once thought possible. Several groups of researchers are developing instruments or small spacecraft to look at Earth as an exoplanet analogue, showing us what our planet would look like to an astronomer many light-years away. And the International Astronomical Union (IAU) has begun the long process of bestowing proper names on exoplanets—a process that simply may not have had enough time to filter into the consciousness of either professional astronomers or the public.

"We've discovered a lot of weird things," said Laura Mayorga, an exoplanet researcher and postdoctoral fellow at the Johns Hopkins University Applied Physics Laboratory (APL). "When we first started studying exoplanets, we found that they got stranger and stranger. They put all of our understanding to the test.... Finding something new throws everything up in the air, and it has to resettle. That makes this a really exciting time."

Death of a Planet

Although it sounds like something from a Syfy channel original movie, necroplanetology is the newest branch of exoplanet studies—a novelty that involves intrinsically rare targets. The term was coined by Girish Duvvuri, then a student working with Seth Redfield at Wesleyan University in Connecticut, in a 2020 paper. "We're proud of the name," said Redfield. "It's a great way to describe the systems we're studying. It has a small number of practitioners, but the larger community is just starting to look into this topic."

The name was originally applied to the study of dead or dying planets around white dwarfs, which are the hot but dead cores of once normal stars. A typical white dwarf is at least 60% as massive as the Sun but only about as big as Earth. The size of white dwarfs makes it easier to detect the remains of pulverized planets as they transit, passing across the face of the star and causing its brightness to dip a tiny bit.

Starlight filtering through an exoplanet's atmosphere during a transit would reveal its composition. (Astronomers have used the same technique to measure the atmospheres of planets transiting much larger main sequence stars, which are in the prime of life.) "What we started finding first was not whole planets but planetary debris," Redfield said.

In particular, using early observations from the K2 mission of the planet-hunting Kepler space telescope, they found WD 1145+017, a white dwarf about 570 light-years from Earth. The star's light dipped several times in a pattern that repeated itself every few hours. The researchers concluded that they were seeing the debris of a planet that had been shredded by its star's gravity—probably chunks or piles of rock surrounded by clouds of dust.

Observations with large ground-based telescopes revealed calcium, magnesium, iron, and other heavy elements in the white dwarf's spectrum. Such heavy elements should quickly sink toward the core of a white dwarf, where they wouldn't be detected. Their discovery suggested that the elements had been deposited quite recently, as rubble from a disrupted planet (or planets) spiraled onto the white dwarf's surface.

"All those clues made it clear that planets can exist around white dwarfs," said Redfield. "They can be destroyed by white dwarfs as well. The tidal forces are quite extreme, so they can break apart and grind up a planet.... As that material accretes onto the white dwarf, we're actually learning about the innards of the planets."

Such a planet may have been born far from its host star and migrated close enough to be destroyed. Astronomers know that such migrations are possible because they have discovered a few hundred "hot Jupiters": worlds as massive as the largest planet in the solar system but so close to their stars that their upper atmospheres are heated to hundreds or thousands of degrees. Some of these planets are being eroded by stellar radiation and winds, perhaps marking the beginning of the end for worlds that could be subjects for future necroplanetologists.

Stars That Take a Dip

Despite expectations of a bounty of such white dwarf systems, Redfield said, they seem to be rare. (A recent study found evidence of one intact giant planet around one white dwarf.) Astronomers have found evidence of similar processes at work around main sequence stars, though.

The best-known example is KIC 8462852 (also known as Boyajian's Star), about 1,470 light-years from Earth. Large, but irregular, dips were discovered in the brightness of the star, which is bigger, hotter, and brighter than the Sun. Possible explanations for the decrease included the panels of a "mega-structure" built by an advanced civilization orbiting the star—an idea (since abandoned) that generated plenty of headlines.

Astronomers have discovered other examples of "dipper" stars as well. Edward Schmidt, a professor emeritus at the University of Nebraska–Lincoln, reported 15 slow dippers, whose light varies over long timescales, in a study released in 2019. He said he plans to publish details on 17 more in an upcoming paper.

The stars all have similar masses and temperatures, which suggests that their dipping patterns share a common explanation, Schmidt said. "It could be caused by disintegrating planets—that looks promising so far." He's looking through published spectra of the stars to see whether their surfaces are polluted by the residue of planets, which could solidify the idea.

A couple of systems discovered by Kepler seem to add credence to the hypothesis. Kepler-1520b, for example, shows dips in luminosity of up to 1.3%. A ground-based study found that the dimming is caused in part by clouds of dust grains, providing "direct evidence in favor of this object being a low-mass disrupting planet," according to a 2015 paper. And K2-22, discovered in Kepler's K2 mission, appears to be a disintegrating planet more massive than Jupiter but only 2.5 times the diameter of Earth.

Another study suggested a slightly altered explanation for Boyajian's Star and other dippers: disintegrating exomoons. Researchers suggested that one or more moons could be snatched away as a planet falls into its star. "The planet essentially hands its moons to the star—they're orphaned exomoons," said Brian Metzger, one of the study's authors and a physicist at Columbia University and senior research scientist at the Flatiron Institute.

Stellar radiation could be eroding the surviving moons, releasing solid grains of material that then form a clumpy disk around the star. So the young field of necroplanetology may need a new subfield: necro a ology.

A Second Chance at Life

For some planets, though, the death of a star isn't necessarily the end—it may be the beginning. The first confirmed exoplanets, discovered 3 decades ago, orbit a pulsar, a dead star whose composition is more exotic than a white dwarf. A pulsar is a rapidly spinning neutron star, the collapsed core of a massive star that exploded as a supernova. As the neutron star spins, it emits pulses of energy that form an extremely accurate clock. The gravitational tug of a companion alters the timing of the pulses a tiny bit, revealing the presence of an orbiting planet.


This artist's view shows a brilliant aurora on one of the planets of the pulsar PSR 1257+12, energized by the pulsar itself (top left). The system's other two confirmed planets also are in view. Credit: NASA/JPL-Caltech

The first identified pulsar planets orbit PSR B1257+12. Astronomers have since discovered a handful of others, but most searches have come up empty. An examination of more than a decade of observations made by the North American Nanohertz Observatory for Gravitational Waves (NANOGrav), a project that is using pulsar timing to hunt for gravitational waves, for example, found no evidence of planets around a set of 45 fast rotating pulsars. The search could have revealed planets as light as the Moon in orbital periods of 1 week to almost 5 years, said Erica Behrens, a graduate student at the University of Virginia who conducted the study during an internship at the National Radio Astronomy Observatory.

"Since we've seen so few, it seems like they're pretty rare," Behrens said, which may explain why they've received so little attention since the early discoveries. "They must have formed after the star has blown up. No planet that existed while the star was still living would be able to survive the supernova."

Theoretical work hints that instead of supernova survivors, pulsar planets may be "zombies," born from the debris of companion stars.

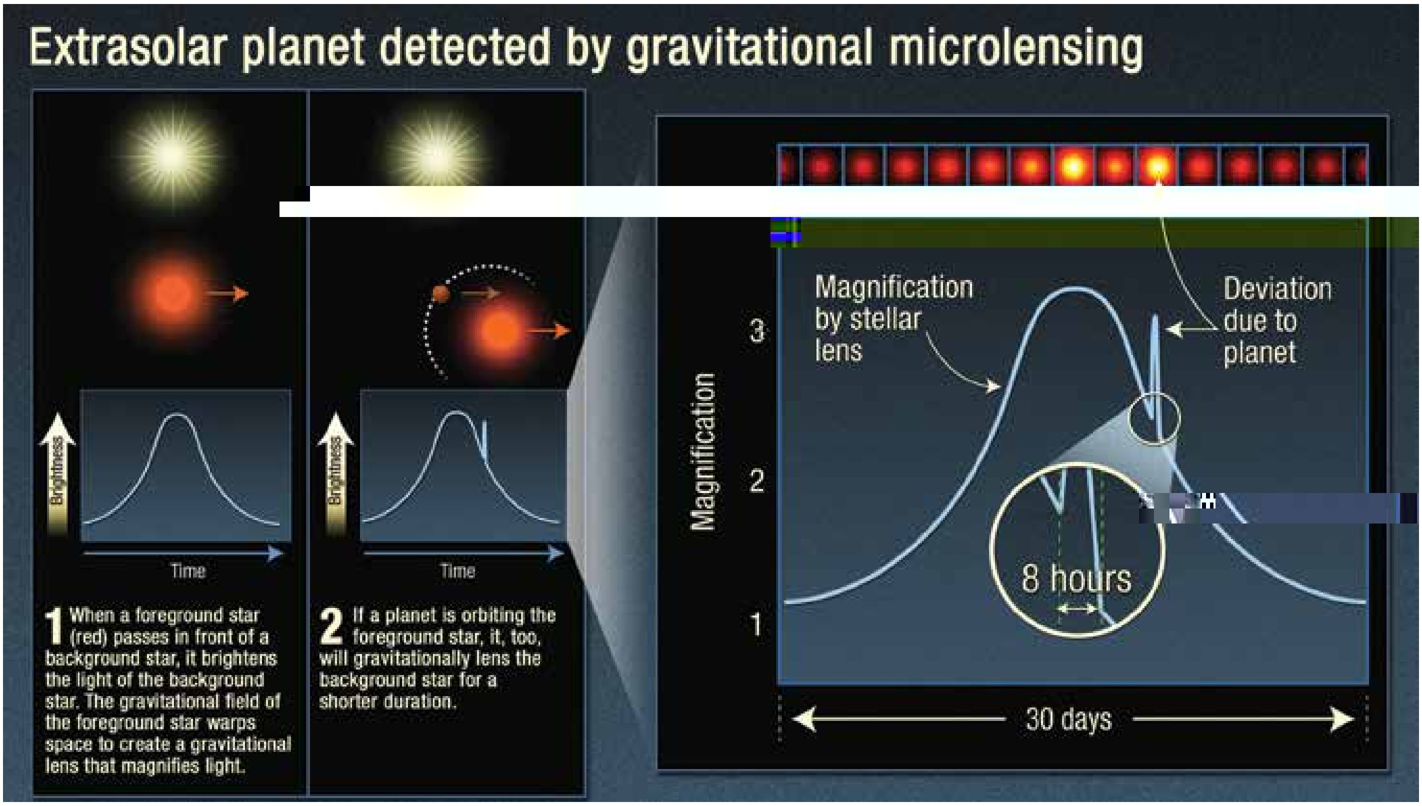
Metzger and Ben Margalit, also of Columbia, have suggested, for example, that the companion could be a white dwarf. The extreme gravity of the neutron star tears the white dwarf apart—perhaps in a matter of seconds—and the debris forms a disk around the pulsar. Some of the material in the disk falls onto the neutron star while the outer edge of the disk expands and cools. Solid material in those precincts may condense to form solid bodies, which then merge to make planets.

The scenario would explain the frequency of pulsar planets, which is roughly equal to the frequency of neutron star–white dwarf binaries, Metzger said. It would not, however, explain the birth of a pulsar planet that's been discovered in a globular cluster, where the density of stars is extremely high. "You'd have to invoke more exotic interactions," which scientists are still trying to model, he said.

A Rogues' Gallery of Exoplanets

Although most exoplanets have been discovered through transits or radial velocity measurements, which detect a back-and-forth shift in the wavelengths of starlight caused by the pull of orbiting planets, a few stragglers have been found through other methods. Such methods are difficult to apply, or they're looking for objects or phenomena that are rare, so they've yielded far fewer discoveries than the most favored methods.

Astrometry, for example, precisely measures a star's position to detect tiny wobbles



This diagram shows how microlensing reveals a planet orbiting a star. Credit: NASA, ESA, and K. Sahu (STScI)

caused by the gravitational tug of orbiting planets. Such measurements are hard to make and have yielded only one or two discoveries. However, astronomers expect observations by the Gaia spacecraft, which is plotting the positions and motions of more than 1 billion stars, to yield thousands of new Jupiter-sized exoplanets in relatively wide orbits, which would create a whole new population for study.

The most successful of the lesser known techniques, however, has been gravitational microlensing which has revealed more than 100 planets. “It’s very complementary to other techniques,” said Matthew Penny, an astronomer at Louisiana State University. “You get an instant detection of some very distant planets that would take decades to find with other techniques.”

Gravitational microlensing relies on general relativity, which posits that if a star or planet passes in front of a more distant star, the intervening object’s gravity bends and magnifies the background star’s light, creating a double image. If the alignment is perfect, it creates a bright circle of light known as an Einstein ring. (The same technique is used on a larger scale to study galaxies and quasars billions of light-years away.)

The length and magnification of a lensing event allow astronomers to calculate the intervening object’s mass and, in the case of a planet, its distance from its star. Astronomers have measured planet-star separations of up to more than 10 astronomical units (AU), which is far wider than with other techniques.

Microlensing can reveal planets that are thousands of light-years away (the current record holder, according to the NASA Exoplanet Archive, is at 36,500 light-years, many times farther than planets discovered with other techniques). Microlensing allows astronomers to study planets in regions of the Milky Way well beyond our own stellar neighborhood, including the central galactic bulge.

Perhaps most important, microlensing is the only technique that can reveal rogue planets, which travel through the galaxy alone, unmoored to any star.

Rogues might form as stars do, from the gravitational collapse of a cloud of gas and dust. That process would form only massive planets—a minimum of 5 times the mass of Jupiter, Penny said. “So far,” however, he explained, “the main results are that there are not a lot of free-floating giant planets out there,” with only a handful of confirmed discoveries to date.

Most rogues probably form from the disk of material around a star, then escape. “It could be an interaction between planets,” Penny said. “If you form a lot of planets in a disk, the disk keeps order until it dissipates. But once the damping effect of the disk is gone, all hell breaks loose,” and gravitational battles can sling planets into interstellar space. There may be billions of these smaller castaway worlds.

Although three searches are dedicated to finding planetary microlensing events, they’re restricted by daylight, clouds, and the other disadvantages of looking at stars from the ground.

As with astrometry discoveries and the Gaia mission, though, a space telescope may greatly expand the numbers of confirmed exoplanets. The Nancy Grace Roman Space Telescope, which is scheduled for launch later in the decade, could find 1,400 bound exoplanets and 300 rogues during its lifetime, Penny said. The telescope's mirror will be the same size as that of Hubble Space Telescope, but with a field of view 100 times wider. That field of view will allow Roman to see a large area toward the