Science & Technology

Brave New Worlds

Columbia astronomers are going beyond our solar system to understand exoplanets, find exomoons, and explore all sorts of surreal estate.

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UPDATE: Columbia astronomers David Kipping and Alex Teachey have found new evidence of the existence of an exomoon.

The sun, veiled by the mist of a soggy Manhattan morning, was undetectable outside David Kipping's thirteenth-floor office window in Pupin Hall on the Morningside Heights campus. But Kipping, an assistant professor of astronomy, was contemplating another celestial object anyway, one far more obscure — TrES-2b, the darkest world in the galaxy.

“It absorbs 99 percent of its sun’s light,” Kipping says. “That’s less reflective than black paint.” An artistic rendering of TrES-2b, hanging on the wall opposite the window, reveals a disk coal-dark, streaked with scorched red swirls.

In space, nothing is close, but TrES-2b is unthinkably distant, 750 light years away, about four and a half quadrillion miles from Earth.

TrES-2b is an exoplanet, a world outside our solar system, one of 3,529 verified by NASA as of October 2017. “But that,” says Kipping, “is the tip of the iceberg. There are so many worlds, it’s mind-blowing.” Exoplanets are everywhere, scattered through the Milky Way like Motel 6 on the freeway. Scan the night sky, pick out any star, and it probably has planets; most all of the two hundred billion stars in our galaxy do. “On average, it’s a few planets per star,” says Kipping. That’s approximately a trillion exoplanets.

Since the fall of 2015, Kipping’s Cool Worlds lab, part of the Department of Astronomy at Columbia, has studied these extrasolar planetary systems. Cool Worlds searches for exoplanets, exomoons, and all sorts of surreal estate; six graduate students currently work in the lab. “We look for things mostly within the habitable zone,” says Kipping. That’s the sweet spot in any system, where planets are not too hot or too cold — a place where temperatures might be right for liquid water, a place where Earth-like worlds might exist. A place, Kipping says, “where life starts to become possible.”

Kipping was eleven when astronomers found the first exoplanet orbiting a sun-like star — 51 Pegasi b — in 1995. Before that, most scientists regarded exoplanet searches as pseudoscience, like looking for UFOs, crop circles, or Roswell aliens; exoplanet hunters were considered eccentrics. “They were mavericks and radicals,” Kipping says, “and not accepted for the science they were doing.” Still, over the next decade, astronomers would discover a few hundred exoplanets, and in 2009 NASA launched the Kepler space telescope to find more. From seventy-five million miles out in space, Kepler surveyed the stars between the constellations Cygnus and Lyra, and swiftly spotted exoplanets all over the place.

NASA / JPL-CalTech

Suddenly a fringe specialty became the most intriguing subject in astronomy. Initially, scientists looked for firsts: the first oxygen-rich exoplanet (Gliese 1132b), the first potential water world (Gliese 1214b), and the first Earth-size planet in the habitable zone (Kepler-186f). In March 2016, the Cool Worlds lab announced the discovery of Kepler-167e, one thousand light years away, the size of Jupiter and about as cold — 220 degrees below zero Fahrenheit. “The exhilaration you feel from an act of discovery is joyous,” says Kipping. “Whether it’s some little thing nobody else knew or an entirely new planetary system, you want to go out in the world and tell everyone. It’s like being in love.”

But the obsession with discovering new exoplanets — “a gold rush,” in Kipping’s words — has already died down. “We’re past that,” he says. “Now we’re trying to fill out the missing details. We want to understand the stories of these exoplanets.” Certainly astronomers already know basic things about them — their size, how long they take to orbit their stars — but little else. “We’re now asking more meaningful questions,” says Kipping. “What are their atmospheres? How much water do they have? What would it be like to walk on the surfaces of these worlds?” And of course, maybe the most tantalizing question ever, and surely the tease of the galaxy: do they have life?

The Kepler telescope, the size of an SUV and fortified with forty-two camera sensors, has scrutinized about 150,000 stars — an astoundingly slight patch of sky, about one ten-thousandth of 1 percent of the Milky Way. Go outside, make a fist, and extend your arm skyward; your fist represents roughly the portion of sky Kepler has seen.

Even from such a trifling sample, Kepler has generated a daunting assortment of data, as many as two million data points per star. Columbia is among the hundreds of universities and research centers worldwide that download and decode the data. “It’s a treasure trove of discoveries,” says Emily Sandford ’17GSAS, a fourth-year graduate student on the Cool Worlds team. “It’s more data than we know what to do with.” Discovery is within the data — the exoplanet’s radius, mass, shape, reflectivity, temperature, orbital period, atmosphere — markers that may signal if life is possible. The secrets of the galaxy, or at least some of them, are now stowed on Cool Worlds desktops. “Sometimes I think, ‘My eyes are the only ones that have ever seen this,’” says Tiffany Jansen, a second-year graduate student.

Seeing is one thing. Deciphering is quite another. Simply put, Kepler collects the data by photographing stars and recording pixels of their light. Viewed on a computer screen, the stars appear as inscrutable bright globs. Orbiting exoplanets, if there are any, are not visible. But the pixels contain a critical piece of information that kickstarts every discovery: “They measure the star’s brightness,” says Sandford.

Within the billions of minutes of light measurements, Cool Worlds researchers can drill down to search for an eclipse-like event — a transit. That occurs when an exoplanet passes between its parent star and Kepler. “A planet passing by will block some of the star’s light,” says Moiya McTier, a second-year graduate student. “And the data will show that as a dip in the light.” That dip, should it repeat at precise intervals, suggests an exoplanet is there.

ESO / M. Kornmesser

From that dip, researchers can create a transit light curve, a graph replete with additional data. “By studying the light curve,” McTier says, “we can figure out the physical characteristics of an exoplanet.” As technology develops, they will be able to detect specific surface features, like oceans, vegetation, or polar ice caps. “Finding out things through the transit method, the limit is your imagination,” says Kipping.

Turning the raw data into decipherable computer files is a formidable process. “It’s just a long list of meaningless numbers,” says Sandford. “You can’t scroll through it and learn anything. To comb through the entire volume of data by hand would take ten years.” Sandford’s days are spent coding — converting the gibberish into information both manageable and coherent. “It’s basically computer programming,” she says. Write good code and your computer could take hours to crack what otherwise takes a decade. But writing good code isn’t easy. “For someone starting out,” says Jansen, “a lot of time is spent just figuring out what’s wrong with your code.”

Nearly nothing is known about the topographical features of exoplanets; Cool Worlds is just now scratching those surfaces. Unquestionably, space theoreticians have long ruminated on exoplanet landscapes. They simply calculate a planet’s density and then take a smart guess. Molten glass rains down on HD 189733b; flurries of rubies and sapphires fall on HAT-P-7b; boiling lava coagulates on Kepler-78b; diamonds cover WASP-12b. None are outlandish claims, but they are all speculations. Iron, for instance, is one of the densest common elements in the universe. Hence, a dense planet might contain an abundance of iron. But maybe not. “There’s lots of leeway in the interpretation of data,” says Sandford. “It’s possible to infer a planet is partially made of carbon. And carbon is what makes up diamond. So a diamond planet is a possibility. But it’s not the only possibility. The uncertainties are quite large.”

What is known is that exoplanets come in two basic categories. “We can say some exoplanets are gaseous, and some are rocky,” says Jansen. “But that’s really the extent of our knowledge.” The rocky planets, like Earth and Mars, have solid surfaces. The gas giants, like Jupiter, Saturn, Uranus, and Neptune, may not sustain any solid surface at all. Plunge past their atmospheres, and instead of hard ground one could conceivably find a nebulous, plasma-like interior.

Jansen is surveying both types of exoplanets. Looking at their light curves, she searches for one thing: reflectivity. A highly reflective exoplanet suggests a surface that could be coated with ice. That presents the scientists with a fun extrapolation: ice signals the presence of liquid water, the quintessential biosignature, “a molecular fingerprint for life,” says Jansen. So let evolution augment the water with organic molecules, wait while they mingle and wallow for a billion years, and microbes might emerge. That’s extraterrestrial life, but Jansen cautions about getting carried away. Deducing the presence of water (much less life) based only on a planet's reflectiveness is "very difficult," she says. After all, trees and asphalt, two very different substances, mirror light at about the same intensity. Before reaching anything close to certainty, Cool Worlds must learn more.

McTier, meantime, will spend the next several years looking for mountains. "It's going to be really difficult," she says. "No one has ever found a mountain on a planet outside our solar system." But mountains cast shadows; McTier theorizes that shadows should show in the data. "They will cause jaggedness in the light curve," she says.

If McTier discovers a mountain, the suppositions will begin. Here's one: on Earth, plate tectonics made mountains possible — also hills, canyons, valleys, lakes, rivers, and oceans — all topographical antecedents that led to life. Perhaps a mountainous exoplanet has tectonic plates? If so, does that mean life is more likely there? "We can learn a lot," says McTier, "just based on shadows."

Exoplanets give off one-billionth the light of a star. Exomoons orbiting them are even fainter. No astronomer has officially discovered one, but Cool Worlds has a candidate — a possible exomoon orbiting Kepler-1625b, a gas giant at least six times the size of Earth and about four thousand light years away. The Kepler data is promising but inconclusive; Kipping obtained time on NASA's Hubble space telescope this past October, hoping to corroborate his findings and proclaim a discovery. A final confirmation won't happen until spring. Beyond that he says little else: "We're being very cautious. We're waiting to see what the data gives us."

Discovering the first exomoon would surely be a spectacular find. But nobody will be startled. Exomoons, like exomountains, are expected. Stranger things have already been seen. "Look at the exotica coming out of exoplanets," says Kipping. Hot Jupiters like TrES-2b (gargantuan, superheated, typically ten times closer to their stars than Earth is to the sun) are ubiquitous. "And nobody expected to find them," he says.

Astronomers once thought our solar system was a template for the rest of the galaxy. Every inference about exoplanets was built on it. "But our solar system," says Kipping, "is not typical." With eight major planets and millions of asteroids, the solar system covers ten trillion miles. Yet compact systems seem more common. The seven TRAPPIST-1 planets, discovered this past February, are crammed in space; they occupy a congested area of barely six million miles — one-sixth the distance between the sun and Mercury, its closest planet.

About half the exoplanets have wildly eccentric orbits. But in our solar system, the planets' orbits are basically elliptical; Earth's is almost a circle. Our sun is categorized as a yellow dwarf star, middle-aged and relatively hot; but three-quarters of stars are red dwarfs — "older and dimmer," says Kipping, and often one-tenth the size.

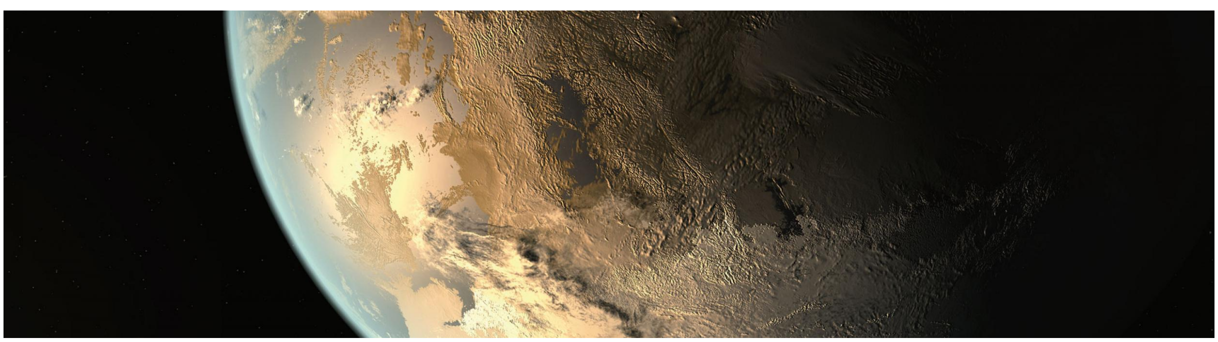
Hardly an analog to the rest of the galaxy, our solar system is actually an anomaly. "We're not the freak of the universe — but we are a very poor approximation," Kipping says. To Cool Worlds researchers, that might be the most startling discovery of all.

When astronomy was first taught at Columbia University (then King's College) in 1754, little was known about the planets. The British astronomer William Herschel wouldn't find Uranus for another twenty-seven years, and Neptune's reveal was ninety years away. Telescopes surveyed land more frequently than stars. In 1776 George Washington, then the Continental Army's commander in chief, supposedly persuaded the College to loan him a telescope — the school's only telescope — as a way to monitor British troop movements during the Battle of Long Island. Washington promptly lost both the telescope and the battle. There the story ends, and it may be apocryphal anyway. Whether Washington ever wondered about exotic worlds or extraterrestrials is unclear. But John Adams, Washington's presidential successor, did. The universe, he said, is "both infinite and eternal," and at twenty — almost the age of the Cool Worlds graduate students — he wrote this in his diary: "All the unnumbered worlds that revolve around the fixed stars are inhabited."

Well, surely not all. But some? "I would be shocked if life was not elsewhere in the galaxy," says McTier. Concurs Sandford: "The odds of us being the only planet with life are kind of ridiculous." Jansen remembers a Caribbean vacation at age nine: "My mom goes, 'You've got to come outside and see the stars.' I'm like, 'Oh, fine.' And then I saw this dome of stars. There were so many. I just looked at them — and then I thought, if every one of those stars has planets, there's no way we're the only living creatures in the universe. That was very specifically the moment I thought astronomy was amazing. I'll never forget it."

Of the trillion or so exoplanets estimated in the Milky Way, about 10 percent — one hundred billion — may hold water and reside in the habitable zone. Any life out there might scale from primordial microbes to technologically advanced aliens. “You’re looking at vast opportunities for life,” says Kipping. How much, what kind, where located? “I can’t even speculate,” he says. “There’s just no information to go on. Working with a single data point, we are completely stuck.” That single data point is us. Earth is the only example of life anyplace.

Although there’s now Proxima b, an exoplanet discovered in August 2016 and a potential analog of Earth — about the same size, in the habitable zone, and as a bonus, only four light years, or some twenty-four trillion miles, away. Celestially speaking, that’s just across town. Cool Worlds researchers, captivated by Proxima b, are contributing to Breakthrough Starshot, the initiative founded by the celebrated physicist Stephen Hawking and Facebook CEO Mark Zuckerberg. The proposed project is an outrageous venture: somehow develop and ultimately dispatch an uncrewed nanocraft to snap flyby photographs of Proxima b. The preferred cruising speed for the probe is approximately 37,200 miles per second, one-fifth the speed of light. Travel time should be twenty-one years. Getting the probe ready to go could take at least that long. But imagine what might be in those photos. Oceans? Vegetation? City lights? Not much of anything? Who knows. “There’s a chance,” says Kipping, “that when I’m retired I might see a photo beamed back.” That image could forever change the way we see not only the exoplanets, but ourselves.



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Picturing Planets

The images you see of these alien worlds are imaginative renderings created by multimedia artists in collaboration with NASA astronomers. The depictions are largely speculative, drawing a fine line between scientific precision and artistic inspiration. Typically, the designers have minimal information to go on — the exoplanet’s size, if it’s rocky or gaseous, the distance from the star it orbits, and perhaps a rough idea of its temperature. Scientists work with the artists to rein in creative overreach and ensure as much accuracy as possible. Color choice is critical. Generally, shades of blue or green are eschewed, since blue may be too suggestive of an exoplanet with abundant water, and green can suggest plant life. Rocky worlds with visible surface features are the most difficult to design, and often require several days’ work. Gas giants, blistering balls of fire, usually take less. Either way, these otherworldly illustrations, seen in virtually all media worldwide, continue to captivate millions.

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