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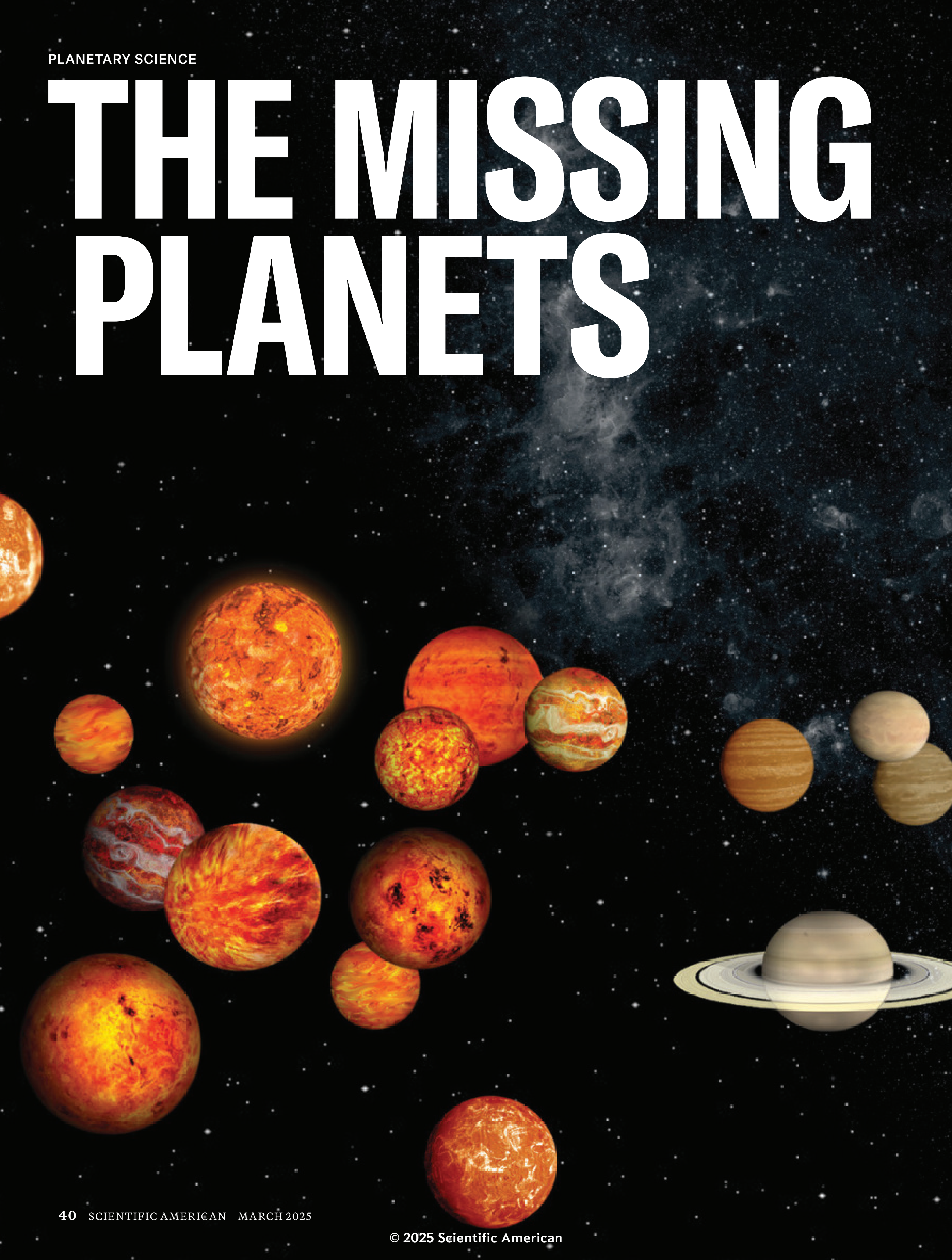
THE MISSING PLANETS



Exoplanet demographics reveal a puzzling lack of worlds in a certain mass range throughout the galaxy

BY DAKOTAH TYLER

ILLUSTRATION BY RON MILLER

F**OR CENTURIES** our solar system was the only planetary system known to humans. We had no proof other worlds existed beyond those in our own cosmic backyard, and we imagined that if other planetary systems were out there, they would mirror ours: small, rocky worlds orbiting close to their stars, with giant planets similar to Jupiter and Saturn farther out. Scientists studied the history of our sun and its satellites with all the tools they had, and they used the knowledge they gained to shape our understanding of how planets form and evolve. But about three decades ago astronomers discovered exoplanets circling stars that were not our own. In the years since, we have found thousands of them, shattering what we thought we knew about planets.

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It turns out that planetary systems in our galaxy exhibit remarkable diversity—some have tightly packed planets in exotic configurations; others are dominated by gas giants skimming their stars. Now a new era of planetary science has emerged: exoplanet demographics. By analyzing patterns in the sizes, orbits and compositions of the planets they detect, scientists are uncovering the real processes that shape planetary systems. What we are finding is not a simple narrative but a puzzle: striking trends in planet populations that challenge our understanding of how planets are born and grow.

These trends offer new clues about the answers to fundamental questions: Why are there very few planets in particular size ranges—most notably a swath of "missing planets" somewhat larger than Earth? Why does our solar system lack the most common types of planets in the galaxy—those larger than Earth but smaller than Neptune? And perhaps most important, how do these findings affect our search for habitable worlds?

Unraveling these mysteries isn't just about studying individual planets—it's about seeing the big picture. By investigating the patterns in exoplanet demographics, we're learning not only what makes planetary systems tick but also where our solar system fits into this galactic context. Ultimately, we want to know whether our planet is rare—or whether the conditions that allowed life to arise here might be plentiful out there.

THE FIRST CONFIRMED exoplanets were discovered in 1992 orbiting a pulsar—a radio-wave-emitting, rapidly rotating neutron star formed from the aftermath of a massive star turned supernova. It's still unclear whether these pulsar planets survived the supernova explosion or formed from its debris. In either case, they are outliers in the known exoplanet dataset.

The real breakthrough came in 1995 with the discovery of 51 Pegasi b, the first exoplanet found orbiting a sun-like star. This world defied all expectations. Rather than a distant gas giant like Jupiter, 51 Pegasi b was a behemoth half the mass of Jupiter but orbiting astonishingly close to its star, whipping around it once every 4.2 days. At such proximity the planet would broil at around 1,800 degrees Fahrenheit, hot enough to vaporize some metals. Although 51 Pegasi b has only about half Jupiter's mass, this extreme temperature causes the gas to inflate, giving the planet a radius twice as big as Jupiter's. Astronomers dubbed this strange new class of planets "hot Jupiters."

The existence of hot Jupiters threw a wrench into the leading planet-formation models. Theories had been based on the structure of our solar system, where rocky worlds orbit close to the sun, and gas giants stay much farther out in colder regions where they can accumulate hydrogen and helium gas. But here was a Jupiter-mass world that somehow occupied the searing-hot inner reaches of its planetary system. If massive planets could form so close to their stars—or form farther out and move there later—what other unexpected arrangements might exist?

Astronomers discovered 51 Pegasi b by detecting a wobble in its star's motion caused by the gravitational tug of the orbiting planet—a technique called the Doppler (or radial velocity) method. As a planet orbits, it pulls its star slightly toward it. From our perspective on Earth, that star moves closer toward and then away from us (if the orbit is at the right angle from our line of sight), causing the star's light to alternately redshift and blueshift, similar to the way the pitch of an ambulance siren rises as it approaches and falls as it passes by. The more massive the planet and the closer its orbit, the greater the stellar wobble and the easier it is to detect.

That's why the first exoplanets found with this method were hot Jupiters—and why this strategy has a strong detection bias for large planets in close orbits. As more planets were discovered with the radial velocity method, patterns began to emerge. By 2008, after surveying hundreds of stars, researchers found that about 10 percent of sun-like stars host giant planets within a few times the Earth-sun distance (called an astronomical unit). Yet these early demographic patterns were clouded by our observation biases.

A major step forward in planetary demographics came when NASA launched its Kepler Space Telescope. By staring continuously at more than 150,000 stars for four years, Kepler detected thousands of planets, using what's called the transit method. It searched for the slight dimming of a star's light that occurs when a planet passes in front of it from our point of view. The results were startling: Erik A. Petigura, my Ph.D. adviser at the University of California, Los Angeles, analyzed the Kepler data and showed that approximately half of all sun-like stars host at least one planet between Earth and Neptune in size. These planets, which don't exist in our solar system at all, seem to make complete orbits around their stars in weeks or months rather than years. In retrospect, it had been shortsighted to think our solar system was the galactic template. As a rule of thumb in astronomy, however, it's usually safe to assume our perspective is average and not special, so I think we can be forgiven.

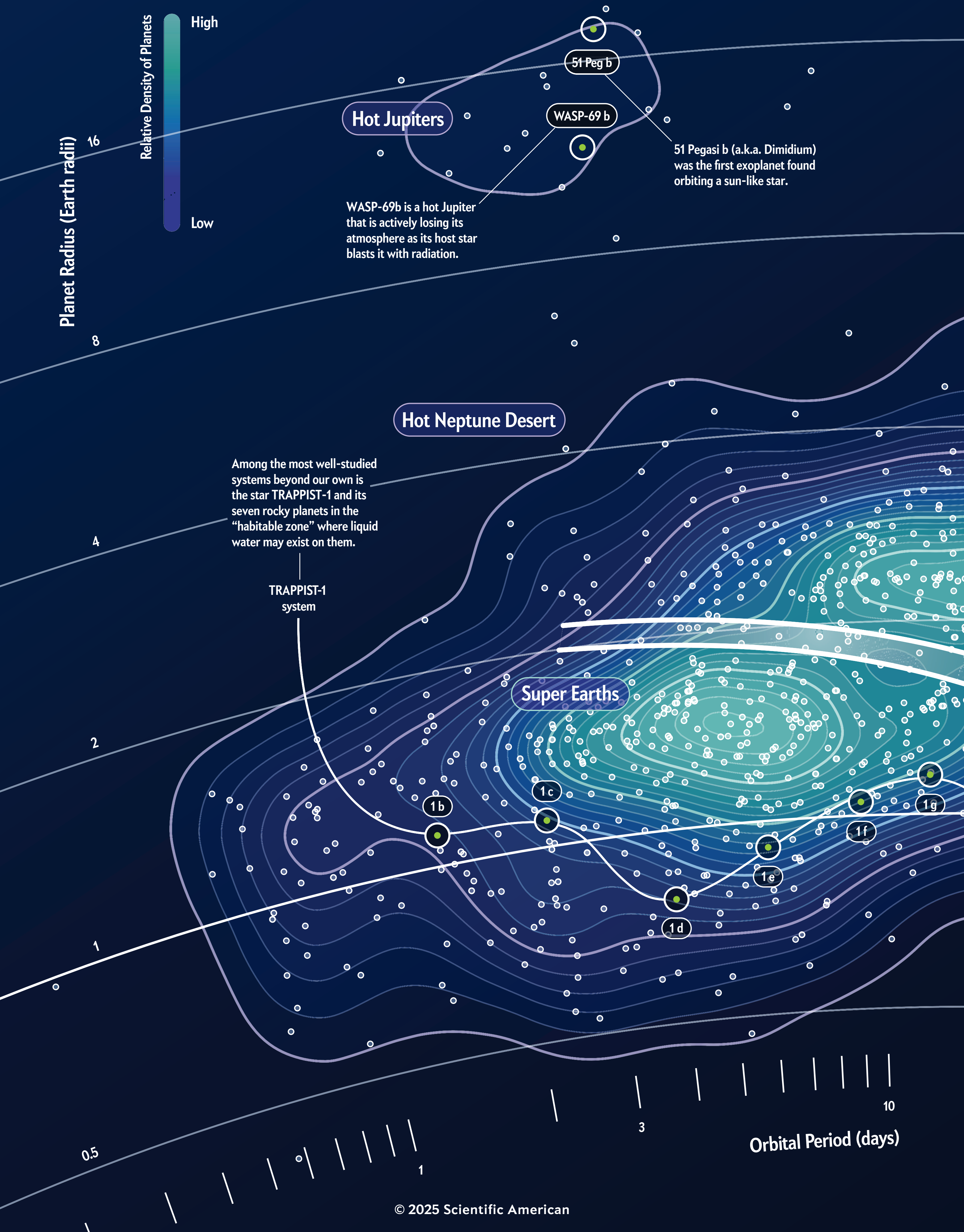
We want to know whether our planet is rare—or whether the conditions that allowed life to arise here might be plentiful.

As the Kepler sample grew, a mystery became more and more apparent. Astronomers saw a striking dearth of planets with sizes around 1.6 to 1.9 Earth radii, which they called the radius gap. This finding was no detection-bias fluke—after researchers had accounted for all the selection effects and biases in the observations, the gap remained. Something about planet formation or evolution must actively prevent planets from maintaining this intermediate size, most likely a process that strips atmospheres from planets in this range.

Adding further intrigue to this puzzle is a phenomenon known as the "hot Neptune desert." Planets the size of Neptune are conspicuously absent on orbits shorter than about three days. The reasons for this scarcity are still under investigation, but extreme radiation from stars at this distance and tidal forces probably contribute to this trend. Just as we see with smaller planets that have masses near the radius gap, short-period Neptunes are especially vulnerable to atmospheric loss. Over time their thick gaseous envelopes may be completely stripped away, leaving behind bare, rocky cores that we might classify as super Earths—scaled-up versions of our rocky world. Scientists think the hot Neptune desert is therefore a more extreme case of the same processes shaping the radius gap. (As we gathered more observations, some theories even predicted these features as a consequence of the radiation streaming from stars.)

Follow-up radial velocity observations with ground-based telescopes added another crucial piece to the puzzle. By measuring the masses of known exoplanets, astronomers found that the radius gap corresponds to a transition in composition. Planets with masses below the gap are dense and rocky like Earth, whereas those above it have lower densities, indicating substantial atmospheres. The smaller planets appear to be super Earths. The larger ones are "mini Neptunes" with rocky cores enshrouded by thick layers of hydrogen and helium.

This demographic pattern poses fundamental questions. Do all small planets start with substantial atmospheres, and do some lose them over time? Or do they form with different compositions from the beginning? Recent observations of planets actively losing their atmospheres suggest gas loss plays a significant role.



51 Pegasi b (a.k.a. Dimidium) was the first exoplanet found orbiting a sun-like star.

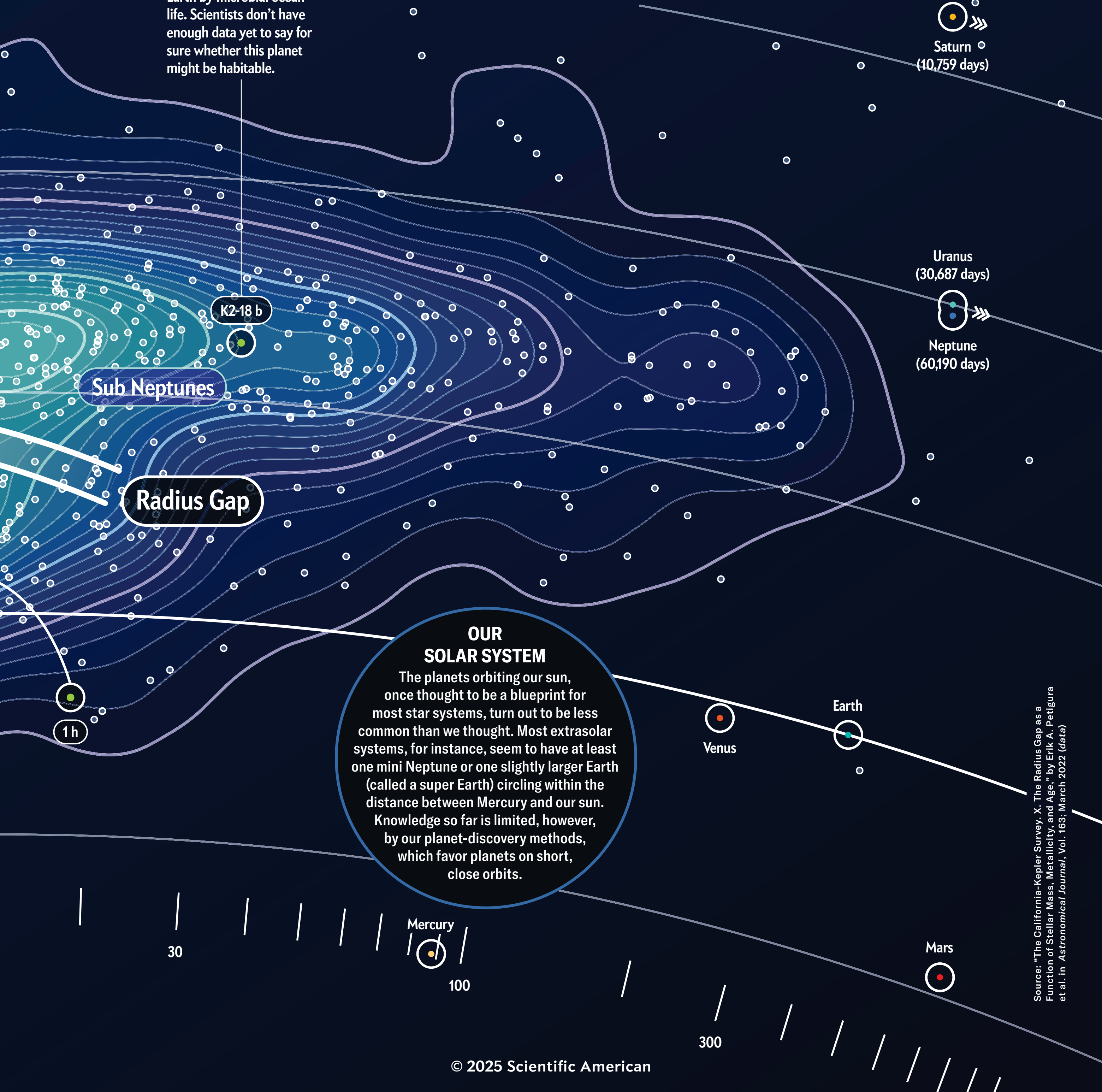
WASP-69b is a hot Jupiter that is actively losing its atmosphere as its host star blasts it with radiation.

Among the most well-studied systems beyond our own is the star TRAPPIST-1 and its seven rocky planets in the "habitable zone" where liquid water may exist on them.

Exoplanet Demographics

Astronomers have discovered more than 5,000 planets around other stars so far. Some puzzling large patterns have emerged, such as a lack of planets with radii somewhat larger than Earth's but a fair bit smaller than Neptune's—a mysterious absence called the radius gap. There also seem to be almost no "hot Neptunes"—Neptune-size worlds orbiting close to their stars. Scientists suspect processes that strip gas off planets after they form, such as the wind caused by the strong radiation streaming off stars, can explain these gaps. A catalog of nearly 1,000 known exoplanets is shown here.

GRAPHIC BY NADIEH BREMER



K2-18b is a sub Neptune where researchers made a controversial potential detection of dimethylsulfide, a chemical produced on Earth by microbial ocean life. Scientists don't have enough data yet to say for sure whether this planet might be habitable.

OUR SOLAR SYSTEM

The planets orbiting our sun, once thought to be a blueprint for most star systems, turn out to be less common than we thought. Most extrasolar systems, for instance, seem to have at least one mini Neptune or one slightly larger Earth (called a super Earth) circling within the distance between Mercury and our sun. Knowledge so far is limited, however, by our planet-discovery methods, which favor planets on short, close orbits.

Source: "The California-Kepler Survey. X. The Radius Gap as a Function of Stellar Mass, Metallicity, and Age," by Erik A. Petigura et al. in *Astronomical Journal*, Vol. 163; March 2022 (data)

ASTRONOMERS THINK there are several processes that can rip atmospheres off planets or limit their formation in the first place. The two leading contenders are photoevaporation and core-powered mass loss. Together they may explain the radius gap and the hot Neptune desert.

Photoevaporation is one of the best explanations for the radius gap. When young stars ignite, they unleash extreme ultraviolet and x-ray radiation, along with powerful winds of charged particles. Planets that orbit too close to their host stars find themselves bathed in this radiation, which heats their atmospheres to the point where particles can escape into space.

Imagine two newly formed planets orbiting at the same distance from their respective stars, each starting with a rocky core and a substantial hydrogen-helium gas envelope. Planet A has a lower mass and weaker gravity, so it can't hold on to its atmosphere as the star pumps energy into it. It quickly loses all its gas to space and becomes a dense, rocky super Earth. When we observe this system, the atmosphereless planet appears smaller in size. Planet B, however, has a higher mass and stronger gravity, which allows it to retain most of its atmospheric envelope. When we observe this system, the planet appears large because of its light and puffy primordial cocoon.

The photoevaporation theory makes several predictions that match observed patterns. For example, the radius gap should slope downward with orbital period because planets closer to stars experience more intense radiation and need to be more massive to survive with their atmospheres intact. Similarly, we see a lack of Neptune-size planets with orbits shorter than three days, the so-called hot Neptune desert. This region is where atmospheric escape is so efficient that only rocky cores can survive.

The second mechanism for the disappearance of planet atmospheres is core-powered mass loss, which is caused by the heat generated within a planet. After planets form, they hold on to significant amounts of heat from the process of pulling mass into themselves. This residual internal energy can warm the base of the atmosphere as the planet cools, lifting up the primordial envelope from below and helping gas to escape, along with the pull from stellar radiation.

Core-powered mass loss suggests that smaller and less massive planets, with weaker gravity and less insulating gas, lose their atmospheres from below as they cool over hundreds of millions of years. Larger planets, in contrast, have enough gravitational strength to retain their envelopes despite the internal heating. This mechanism also aligns with the radius gap, given that intermediate-size planets are most susceptible to atmospheric loss through this process.

Our solar system, once thought to be the blueprint for all planetary systems, now stands as just one of countless possibilities.

Ultimately, hot planets cool off, and stellar irradiation heats up atmospheres. Astronomers think both mechanisms are at work, but the jury is still out on which theory has its thumb pressed more heavily on the planetary-evolution scale. It's likely the outcome depends on the specific conditions of the planet in question.

Other processes may also contribute. The rapid boil-off theory, for instance, posits that during a planet's early years, shortly after its star has formed, the debris disk circling the star—which contains the raw ingredients that were used to build the planets—gets cleared out. The resulting rapid drop in pressure around the planet may drive a sudden boil-off phase for its atmosphere.

In other cases, planets may form in gas-poor environments. These worlds would naturally lack thick atmospheres from the start, leading to a rocky composition. Finally, massive impacts between young planets could strip away their atmospheres, leaving behind bare, rocky cores in what's called collisional stripping. Although this process is probably rare, it may explain some planetary populations.

RECENT OBSERVATIONS have begun to catch some of these situations in action, providing direct evidence of atmospheric escape. Because planets are most likely to let go of mass when they're young, most small planets we can observe aren't undergoing significant loss. There is, however, a favorable scenario for observing an atmosphere escaping in real time: a gas giant on a close-in orbit, also known as a hot Jupiter.

A compelling example is the planet WASP-69b, which my group observed using the telescope at the W. M. Keck Observatory in Hawaii. WASP-69b is a Jupiter-size, Saturn-mass gas giant orbiting so close to its star that a full trip around it takes the planet only 3.8 days. In a paper we published in 2024, we reported outflows of material around the planet that indicate it is actively losing helium. In this case, the mass-loss mechanism must be photoevaporation. The planet is too massive to lose mass to internal heating; instead it's getting blasted with high-energy radiation from its host star. Our observations revealed that WASP-69b is losing about 200,000 tons per second, or one Earth mass per billion years. Furthermore, there have been dramatic variations in the shape of the outflow of escaping gas: sometimes it has a cometlike tail stretching over 350,000 miles, and at other times it appears far less prominent.

This variability in outflow probably stems from changes in the host star's activity. Much as our sun cycles through periods of heightened and decreased activity during its magnetic cycle, stars can experience periods of more or less intense radiation and flaring. Stretches of heightened stellar activity might boost atmospheric escape rates and change the shape of any material rushing off the planet. This dynamic interplay between star and planet illustrates that atmospheric loss may not be a steady, uniform process even in more mature planets. Rather it's an ongoing battle shaped by both the properties of the planet and the mood of its star.

Our findings and others show how photoevaporation can help explain both the radius gap and the hot Neptune desert by demonstrating this mass-loss process in real time. For a given orbital distance, planets require a minimum mass to hold on to their atmospheres amid the onslaught of high-energy stellar radiation. The radius gap separates the planets that are massive enough from those that are not. The hot Neptune desert demonstrates how this concept is amplified as a planet gets nearer to the star and the stellar irradiation increases exponentially. At sufficient proximity to a star, *only* hot Jupiters have the mass required to retain an atmosphere—all other planets get stripped to their bare, rocky core.

THE NEXT DECADE should be an exciting stage for refining our understanding of planetary demographics. Although most astronomers agree that atmospheric mass loss is the primary reason we don't see slightly bigger Earths or hot Neptunes on close orbits, the finer details remain unresolved. Is photoevaporation, driven by stellar radiation, the dominant factor? Or does core-powered mass loss, fueled by a planet's internal heat, play a larger role? Untangling the contributions of these mechanisms requires a new generation of telescopes and instruments capable of precisely measuring planetary masses, compositions and atmospheres.

We hope to better understand how the radius gap depends on stellar type. For low-mass stars, such as M dwarfs, the radius gap appears to shift—smaller planets around these stars are able to retain atmospheres more often because they are exposed to less radiation than larger stars put out. The radius gap is usually less defined because low-mass stars put out different kinds of radiation than larger stars. The planets around these stars also tend to have greater core-composition diversity, and these systems may have an increased rate of major collisions.

Planets around M dwarfs also tend to orbit much closer, where stellar activity such as flares and winds can have a big effect on atmospheric retention. Close inspection of these worlds has revealed hints that some of them might harbor significant amounts of water, potentially in the form of deep global oceans underneath hydrogen-rich atmospheres. These "water worlds" would occupy a unique position in planetary demographics, challenging simple models of rocky super Earths and gas-rich mini Neptunes.

New ground-based instruments such as the Keck Planet Finder, which recently went online at the Keck observatory, and other high-precision radial velocity tools will be indispensable in testing our theories. By enabling us to measure planetary masses across a wide range of star types, these advances will help us determine whether the masses of super Earths and sub Neptunes align with predictions from our various models. In multiplanet systems, these kinds of data can help disentangle the effects of stellar irradiation history, allowing researchers to compare planets that formed under similar conditions.

NASA's Transiting Exoplanet Survey Satellite mission is conducting extended monitoring over long timescales that could reveal planets with slightly wider orbits around their stars than most known worlds have. By filling out this sparsely populated region of small exoplanets with longer orbital periods, these discoveries will provide crucial data for understanding how atmospheric loss and composition vary across a broader range of planetary environments.

The big leap forward should come when some big-ticket telescopes come online in the next decades. Ground-based super telescopes, such as the European Southern Observatory's Extremely Large Telescope, are expected to see first light in the late 2020s. These instruments will excel at observing young, luminous planets still glowing with the heat of their formation. Such gigantic telescopes will offer critical insights into the chaotic early stages of planetary evolution, when atmospheres are most vulnerable to loss.

The Habitable Worlds Observatory, a NASA flagship space telescope, is planned to launch in the 2040s. It is being designed to detect and study Earth-like planets in the habitable zones of sun-like stars. The aim is to use the observatory to directly image these worlds and analyze their atmospheres to search for signs of oxygen, methane and water vapor—key indicators of habitability.

What we learn from all these new tools will reach far beyond planetary demographics. By studying how planets lose or retain their atmospheres, we are unlocking the secrets of habitability, diversity and the forces that sculpt worlds across the galaxy.

Our solar system, once thought to be the blueprint for all planetary systems, now stands as just one of countless possibilities—a unique configuration in a cosmos teeming with variety. Most stars host planets unlike anything in our cosmic neighborhood, reminding us that the universe is richer and more surprising than we have imagined. By untangling the forces that shape these distant worlds, we inch closer to answering some of humanity's oldest questions: How common are planets like Earth? Is there other life among the stars? And what does our place in this vast and intricate universe truly mean? ●

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Life as We Don't Know It. Sarah Scoles; February 2023. ScientificAmerican.com/archive