THE PLANETARY SOCIETY

THE PLANETARY REPORT

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INSIDE THE ICE GIANTS

AFTER VOYAGER, BOTH URANUS AND NEPTUNE HAVE CHANGED THEIR FACES

THE SKIES OF MINI-NEPTUNES ✲ CHANGE COMES TO WASHINGTON ✲ PORTRAIT OF MU69

EMILY STEWART LAKDAWALLA *is editor of* The Planetary Report.

IT'S ONE AMONG millions. Nothing special drew New Horizons to 2014 MU69 (nicknamed "Ultima Thule"), except that it was in the right place at the right time for the fast-flying spacecraft to zip past it. And yet, merely by visiting it, we made 2014 MU69 special, turning it from a dot in the sky so faint that it's only visible to Hubble into the double-lobed world in this photo. New Horizons will spend another year returning all its data from the encounter, and scientists will spend years—perhaps decades—debating how this odd little binary thing formed and evolved. In the meantime, data artists like Thomas Appéré will help us imagine what 2014 MU69 would look like if we could only travel the more than 6 billion kilometers (4 billion miles) that separates Earth from it.

—Emily Stewart Lakdawalla

NASA/JHUAPL/SwRI/Thomas Appéré

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THE PLANETARY SOCIETY

ON THE COVER: The moons Triton (right) and Proteus look down upon one of Neptune's deep blue storms, a cloud whorl thousands of kilometers across. White clouds of methane ice crystals swirl above the maelstrom, drifting over sporadic lightning. Artist Michael Carroll painted this work in acrylic, and then added digital enhancements. *Credit: Michael Carroll*

CONTACT US
The Planetary Society
60 South Los Robles Avenue
Pasadena, CA 91101-2016
General calls: 626-793-5100
Email: *tps@planetary.org*
Internet: *planetary.org*

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Editor EMILY LAKDAWALLA
Art Director LOREN A. ROBERTS for HEARKEN CREATIVE
Copy Editors NICOLE YUGOVICH, KELLY BEATTY, and JASON DAVIS
Technical Editor JAMES D. BURKE
Science Editor BRUCE BETTS
Chief Operating Officer JENNIFER VAUGHN

BILL NYE *is chief executive officer of The Planetary Society.*

Space for Everyone

What We Do—and What We Want to Do

I DON'T KNOW about you, but for me, the last 5 years have flown by. Normally, I would include a joke here about how the flying would have been silent because we're in outer space, but actually, it's been a bustling buzz here at The Planetary Society, which is still firmly on Earth.

With these 5 years behind us, it was time to create another 5-year plan. We call it "Space for Everyone." Check it out at **planetary.org/spaceforeveryone**. For me, the key to our future is you. You are the doers. You are the people who will find life elsewhere, protect Earth from an incoming massive asteroid or comet, and reach into outer space to explore other worlds.

As I'm pretty sure you know, our staff—your staff—has been helping us grow the organization by keeping you informed, responding to your needs, and connecting more of the world's citizens to the adventure of space exploration than ever before. Guided by our last strategic plan, our membership—which comprises people like you—grew more than 20 percent to 50,000. Together, we flew our LightSail 1 spacecraft. We are leaders in planetary defense and solar sailing. We established international relationships and guided the creation of a Planetary Science Caucus in the U.S. Congress. Our presence in Washington, D.C. is now full time. We hope to someday have a similar presence near the headquarters of every space agency in the world.

With you in mind, we set some ambitious but achievable goals for the next 5 years. We want to have 75,000 members who carry out 1 million actions for space by 2023. We want you to sign petitions, volunteer in your communities, crowdfund space technology, share space stories, help recruit new members, and get involved in citizen science. Our mission is to enable you to participate in the advancement of space exploration and science. With more members and more actions, The Planetary Society proves public support for space exploration. That proof helps fuel future exploration.

I strongly believe that we are on the verge of finding life elsewhere. Such a discovery would be historic and on the scale of discoveries made by people like Copernicus and Galileo. It would be profound. It would change the way each of us feels about being a living thing in the cosmos. This discovery will not be made by an individual but by a species—our species—on its planetary home world. By the way, the cost to any one of us will be almost unnoticeable because planetary exploration is an amazingly good bargain. In many ways, the same is true with regard to giving an incoming impactor a nudge to save our world. It will be extraordinary and inspirational for all humankind.

As your CEO, it's my job to make sure we put our time, our treasure, and especially our staff's remarkable talents to best use. I'll do my very best. So, watch this space for firm plans to connect more of you more strongly to outer space as we get this ball rolling or rocket nozzle thrusting. The Planetary Society has worked the last 39 years to make space an adventure to be shared by people all over this planet. Thanks for your continued support. Let's go!

Space for Everyone

A STRATEGIC FRAMEWORK FOR THE PLANETARY SOCIETY

NASA/JPL-Caltech/MSSS/Seán Doran

Our new 5-year framework will guide decision making as we build on our past to create an inspiring future. Here are some examples:

SUCCESS!
The LightSail project sparked the imaginations of millions of people and is propelling other innovative space projects. We plan to build on this success and invest more in science and technology projects.

GROWTH!
We will strengthen our international presence as advocates with the world's space agencies and as a worldwide network for space professionals and enthusiasts. We want Planetary Society members to feel part of a global community.

SUCCESS!
We have dramatically increased citizen engagement in policy and advocacy and are cultivating relationships with key decision makers. We now have "a seat at the table" and will push governments to increase funding for space exploration.

GROWTH!
We are on the verge of answering some of humankind's deepest questions: "Where did we come from?" and "Are we alone?" The Planetary Society considers answering these questions to be a fundamental goal of space exploration. We will fund more projects, educate the public, and advocate with policymakers for the search for life.

SUCCESS!
For decades, we have funded near-Earth asteroid detection, tracking, and research. We will protect our planet from dangerous space rocks by supporting asteroid deflection technology and international response strategies.

GROWTH!
We've been listening to you, our members, and will invest in new ways to enhance your connection to space exploration. We aspire to provide a high-quality member experience, unite our members through a digital community, and organize more in-person activities.

Together, we will advance space science and exploration in pursuit of our shared vision: to know the cosmos and our place within it. See the full story at planetary.org/spaceforeveryone.

CASEY DREIER *is chief advocate and senior space policy adviser for The Planetary Society.*

Change Comes to Washington

A Wave Election Wiped out Congress' Top Space Supporters

THE ONLY CONSTANT in politics is change, so the saying goes. Change in the United States Congress tends to be incremental and even predictable due to regular staff turnover, jockeying for leadership positions, and shifting constituent demands. However, every now and then, Congress changes abruptly, disrupting our continuous mental model with an abrupt discontinuity that inverts political dynamics. We call these political discontinuities "wave elections." In the fall of 2018, the United States Congress experienced a wave election, one requiring policy advocates everywhere to step back and rebuild their plans.

ABOVE *The 116th Congress convened in January, beginning an era of divided government. The 2018 midterm elections saw the Democratic Party regain control over the House of Representatives while the Republican Party maintained its majority in the Senate. In the turnover, some of Congress' strongest space supporters lost their bids for reelection.*

The wave was a gain of 40 seats in the House of Representatives by the Democratic Party, which captured control of the chamber for the first time since 2010 with the largest popular vote margin for a minority party since 1942. Additionally, Congress experienced a large number of retirements, adding to the turmoil. Together, these effects created a freshman legislative class of 111 new members—an unusually high turnover rate of 21 percent.

The wave washed out Congress' most dedicated supporters of space exploration. John Culberson (R-TX-07), chair of the powerful House commerce, justice, and science appropriations subcommittee, lost his seat after serving for 18 years. Culberson was the prime mover behind the hundreds of millions of dollars directed annually to the Europa Clipper and lander missions. He was also the co-chair of the Planetary Science Caucus. In the Senate, Bill Nelson (D-FL), the only sitting member of Congress to have flown in space, also lost his reelection bid. Many other members of NASA's oversight committees and the Planetary Science Caucus lost their seats as well.

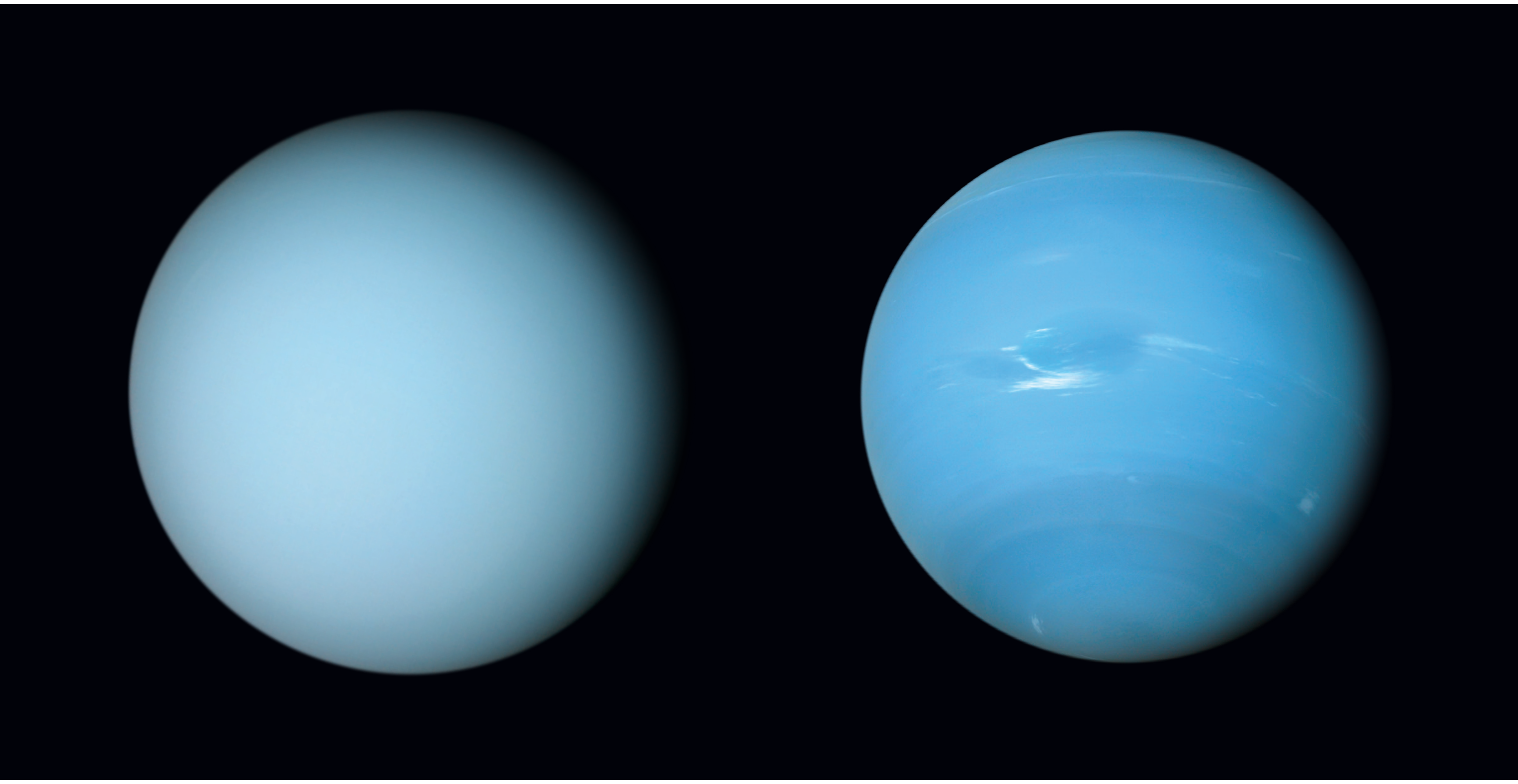
Caucuses are ephemeral institutions bound to a specific Congress. They must be rechartered every 2 years. The Planetary Society's new chief of Washington operations, Brendan Curry, has been hard at work meeting with new members and working to rebuild the caucus membership. Already Rep. Steven Palazzo (R-MS-04) has stepped up to serve as co-chair with Rep. Derek Kilmer (D-WA-06), maintaining its bipartisan nature.

That is just the beginning. Many key congressional committees have new leadership, bringing with them new priorities. Unfortunately, none of them appear eager to take the mantle of chief advocate for exploring Europa, though we will work hard to get them on board. That requires ongoing efforts to forge relationships with hundreds of legislators—no easy task for a small policy team like ours.

Fortunately, we can depend on you—our members—for help. In the first week of March, more than 100 of your fellow Planetary Society members from 25 states trekked to Washington, D.C. as part of our annual Day of Action. They met with members of Congress old and new to promote space science and exploration. Their remarkable commitment to space advocacy will ensure that The Planetary Society can safely surf these waves of change instead of getting washed out to sea.

Getty Images

AMY SIMON *leads the Hubble Space Telescope's Outer Planet Atmospheres Legacy program.*



NASA/JPL-Caltech/Björn Jónsson

The Realm of the Ice Giants

What Exploring These Planets Teaches Us

IMAGINE 2 ICY WORLDS far from the Sun. Their serene, blue atmospheres. Huge, ominous-looking storms. Tantalizing glimpses of moons with exotic, icy terrains. Delicate sets of encircling rings.

Speeding toward its eventual escape from the solar system, Voyager 2 visited Uranus in 1986 and Neptune in 1989. These historic flybys gave us our first detailed views of these intriguing worlds along with the rings and moons that surround them. No other spacecraft have ventured there since. Uranus and Neptune reside in a largely unexplored corner of the Sun's realm, yet they are members of the most populous planetary mass range (50 to 100 Earth masses) based on our current knowledge of extrasolar systems.

The brief Voyager flybys revealed these 2 worlds to be quite different from Jupiter and Saturn, sometimes called the gas giants. Given their large distances from the Sun, Uranus and Neptune are much colder and have a higher abundance of atmospheric water and other ice-forming molecules, earning them the

ABOVE *Only Voyager 2 has visited the ice giants, Uranus (left) in 1986 and Neptune (right) in 1989. These Voyager portraits are newly reprocessed to show the 2 planets at correct relative size and color. Since Voyager, planetary astronomers have studied the ice giants from Earth and have seen their faces change.*

AMY SIMON *is a planetary scientist at NASA's Goddard Space Flight Center who has studied the atmospheres of the giant planets for 25 years. She has served on the science teams of multiple NASA missions (Galileo, Cassini, OSIRIS-REx, and Lucy) and leads the Hubble Space Telescope's Outer Planet Atmospheres Legacy program.*

nickname "ice giants." Ice giants are mostly water, probably in the form of a supercritical fluid; the visible clouds likely consist of ice crystals with different compositions. Despite their cold temperatures, they still support giant storms, much like Jupiter's Great Red Spot or Saturn's large, seasonal outbreaks.

OBSERVING FROM EARTH

With the Voyager flybys long since passed, today we're stuck with studying the ice giants from the ground. Well-equipped amateur astronomers with larger telescopes can often identify localized storms of bright clouds crossing the planets' tiny disks. (In 2019, Uranus and Neptune will be best positioned for telescopic viewing in October and September, respectively.)

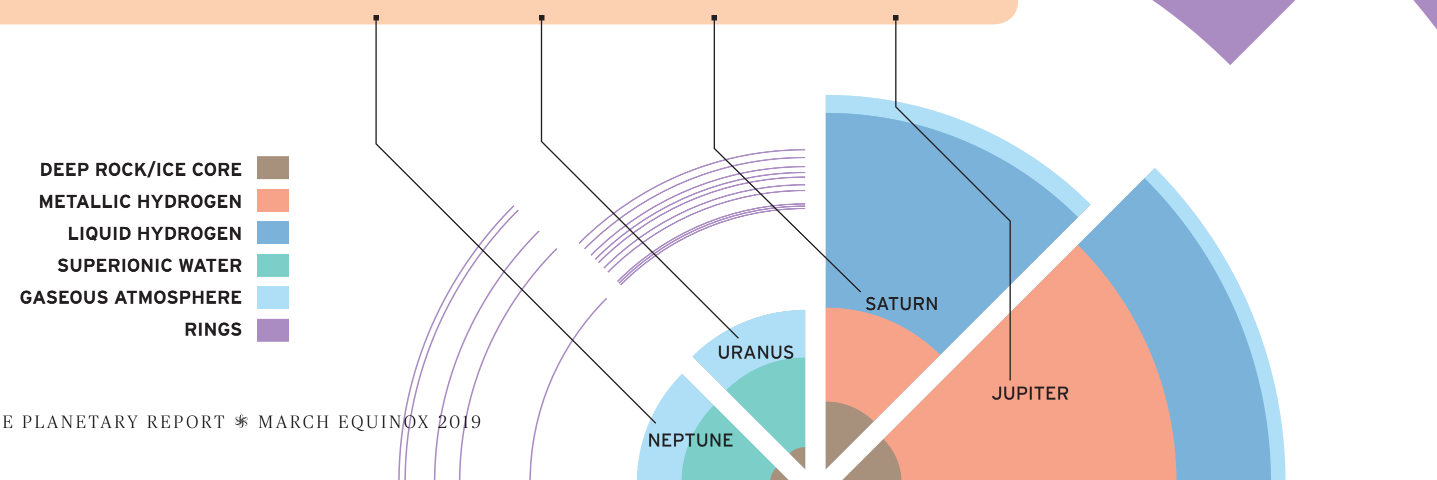
Planetary scientists primarily study these worlds using large, ground-based telescopes, such as Keck Observatory, Gemini Observatory, and Europe's Very Large Telescope, all of which use adaptive optics to sharpen the view. The Hubble Space Telescope is also used to track storm and cloud activity over time, and even the Kepler spacecraft observed the ice giants as they passed through its field of view.

Uranus and Neptune have some obvious similarities. Roughly 4 times Earth's diameter, they are almost identical in size (to within 3 percent), and their deep interiors have comparable rotation rates: 17 and 16 hours, respectively. However, the length of a "day" in their atmospheres varies a lot depending on latitude because both sport high-speed winds up to 400 meters per second (900 miles per hour)—even faster than those on the gas giants.

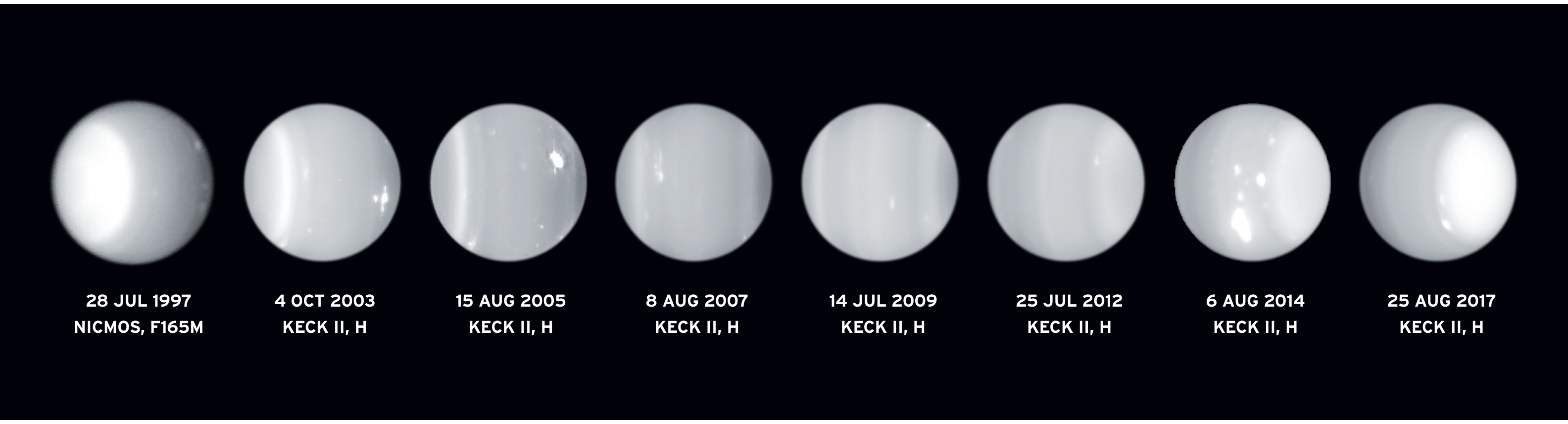
Both planets appear pale blue. Their blue color arises from the strong absorption of sunlight's red wavelengths by minor amounts of methane (CH_4) in their atmospheres. Neptune's blue is deeper than Uranus' blue, either because Uranus has more haze or because Neptune's atmosphere has another unidentified constituent that absorbs longer wavelength light even more strongly. Both also have complex magnetic fields that are offset from their centers and angled askew, which create asymmetrically shaped magnetospheres. Both have rings and satellite systems with dozens of moons.

BELOW *The 4 largest planets are all covered with a gaseous envelope of hydrogen and helium mixed with icy materials that make colorful clouds. All 4 are encircled by rings. Under the surface, they are very different. Here, the interior structures of the 4 worlds are shown to scale with each other. The table describes the planets' physical properties as compared to Earth.*

	EARTH	NEPTUNE	URANUS	SATURN	JUPITER
Mass	1	17.1	14.5	95.2	317.8
Diameter	1	3.88	4.01	9.45	11.21
Density	1	0.297	0.230	0.125	0.240
Day length	1	0.671	0.718	0.444	0.414
Distance from Sun	1	30.05	19.20	9.58	5.20
Orbital period	1	164.8	84.0	29.4	11.9
Regular satellites	1	7	18	24	8
Irregular satellites	0	7	9	38	71



Emily Lakdawalla/Loren A. Roberts for The Planetary Society



Larry Sromovsky and Pat Fry (Univ. of Wisconsin-Madison) with observations contributed by Imke de Pater (Berkeley) and Heidi Hammel (AURA)

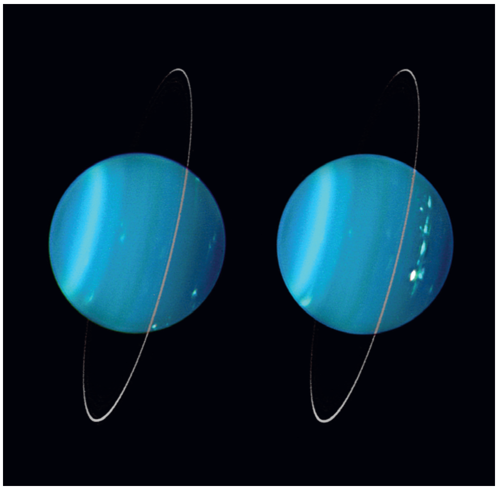
However, as you'll discover below, the ice giants also differ from each other in significant ways, presenting unique extremes for studying this class of planet.

URANUS

Uranus has the largest obliquity (axial tilt) of any planet, a substantial 98 degrees, so its globe is essentially rolling on its side. Given its distance from the Sun (averaging 19.2 AU), this planet takes 84 years to complete an orbit, leading to very long seasons that keep each pole bathed in continuous sunlight or darkness for decades. Uranus radiates no more energy than it receives from the Sun–it's the only outer planet without excess internal heat. This may be due to when and how it formed. It may also result from sluggish atmospheric convection in an atmosphere that's effectively a super cold -220 degrees C (-365 degrees F).

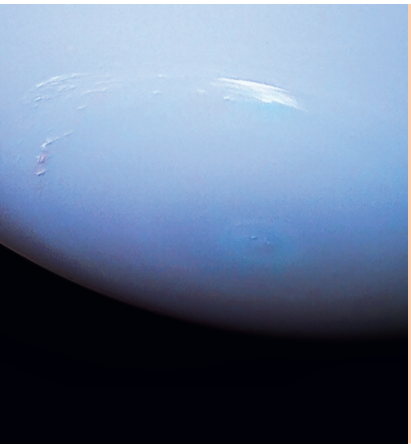
When viewed by Voyager 2, Uranus presented a bland atmosphere, virtually devoid of detail. However, though not as stormy as Neptune's atmosphere, Uranus' atmosphere is far from inactive. In recent years, ground-based observations and the Hubble Space Telescope have revealed distinct clouds and storms. A dark spot appeared in 2006, presaging widespread activity associated with the northern spring equinox in 2007. Yearly monitoring by Hubble continues to show small, bright clouds–likely condensations of methane or hydrogen sulfide ice–appearing and disappearing. Most recently, ground-based infrared observations identified hydrogen sulfide gas in the Uranian atmosphere, while none of this gas is seen in the upper atmospheres of Jupiter and Saturn, and researchers had presumed that any hydrogen sulfide must lie deeper down and hidden from view.

Uranus has many medium-sized moons but no single large one akin to Saturn's Titan. These companions appear to have formed in place during or after whatever event tilted Uranus onto its side, and they orbit in its equatorial plane. The moons contain slightly more ice than they do rock, with some unknown material darkening their surfaces. They also show the spectral signature of frozen carbon dioxide ("dry ice"). Ariel's surface has structures that look like flow features, and Umbriel has a bright polar ring, perhaps ice lying exposed on a crater floor. Another small moon, Mab, may be generating a tenuous, blue-toned ring, like Enceladus does for Saturn's E-ring, though its source currently remains a mystery. Many of the small moons tumble and interact throughout the main Uranus rings, which are much darker and narrower than Saturn's yet more opaque than Jupiter's.



ABOVE *Uranus' serene atmosphere is punctuated by possibly seasonal storms, which appeared both before and after its equinox in 2007. The south polar haze dimmed, and the north polar haze brightened with the change of seasons.*

LEFT *Uranus has a dainty ring system. It is best seen in a wavelength of infrared light that is strongly absorbed by atmospheric methane. The methane absorption makes Uranus' atmosphere dark, so the rings and high-altitude storm clouds appear comparatively bright.*



What Does "Ice" Mean?

In the strictest definition, ice is the solid form of water. However, planetary astronomers often use "ice" to refer to the solid form of any condensable molecule. These tend to be highly reflective, form clouds, and (unlike minerals) can readily change between liquid, solid, and gas states at relatively low temperatures. Frozen water and carbon dioxide ("dry ice") are the most familiar ices on Earth, but methane, ammonia, hydrogen sulfide, and phosphine (PH_3) can all freeze in the atmospheres of Uranus and Neptune. (In fact, due to the extremely cold temperatures, most of the clouds we observe there are likely condensations of methane or hydrogen sulfide ice.)

ABOVE *As Voyager 2 flew past Neptune, it saw high, white clouds swirling around a faint vortex at the planet's south pole. The clouds cast shadows on the blue atmosphere below. The serene faces of the solar system's ice giants mask high-speed winds in atmospheres as dynamic as those of Saturn and Jupiter.*

NASA/JPL-Caltech/Daniel Macháček

NEPTUNE

Neptune resides 30 AU from the Sun, taking 165 years to complete an orbit. Despite being much farther out than Uranus, its average temperature is similar (-230 degrees C or -380 degrees F), and Neptune's interior is emitting more than twice the radiation it receives from the Sun. It's certainly a mystery why Uranus and Neptune differ in this regard. One complication is that the overall reflectivity of Neptune varies with time, absorbing more or less sunlight at a wide range of wavelengths. That might have an effect on its energy balance.

Compared to Uranus' extreme obliquity, Neptune has a much more reasonable 28-degree tilt, similar to that of Earth, Mars, or Saturn. Voyager 2 showed Neptune to have many bright clouds and storms, including a particularly large anticyclonic storm not then visible from the existing Earth-based facilities. Similar to Jupiter's Great Red Spot, it was named the Great Dark Spot, but it was apparently no longer present when Hubble first viewed Neptune in 1994.

Since then, several candidate new dark spots have been observed, though none lasted longer than a few years. A small one, discovered in Hubble images in 2015, was accompanied by high, thick, and white clouds easily visible from Earth-based telescopes. Another outbreak of bright storms occurred in 2017, and the most recent 2018 Hubble images show a new dark spot as large as the one imaged by Voyager 2. Unlike storms on Jupiter, Neptune's large storms are not confined in latitude and can move toward the poles or equator, which likely contributes to their short life spans. Some research suggests that the "weather layer" in Neptune's atmosphere–and Uranus' too–may be no more than about 1,000 kilometers (600 miles) deep.

Neptune has at least 14 moons, most of which were spotted by Voyager 2 or by intensive telescopic searches. Its best-known satellite is Triton, which at 2,706 kilometers (1,681 miles) across is 20 percent smaller than Earth's Moon but 10 percent larger than Pluto. Triton circles Neptune in the retrograde direction, implying that it is a captured dwarf planet, likely taken from the Kuiper belt. Voyager 2 only glimpsed part of Triton, amazing scientists with its views of an intricately patterned, nearly craterless surface and active, geyser-like jets shooting dark material many kilometers above the south pole. Neptune's rings are also unlike those of any other planet, sometimes appearing in clumps and as partial arcs rather than complete rings. The weak gravity of a small moon, Galatea, may be shepherding the rings into this configuration.

TERRA INCOGNITA

There is a long list of things that we don't know about these local ice giants and what they have to tell us about our solar system. Among the big questions, we seek to understand how the planets formed and why they have their current orbits. For example, some dynamicists suspect that Uranus and Neptune formed much closer to the Sun and then migrated outward due to countless gravitational interactions with small bodies in the primordial solar nebula.

Likewise, we seek to understand the configurations of extrasolar planet systems, many of which look very different from ours, with planets tightly packed close to their stars.

Hubble and ground-based telescopes can help us monitor the changing clouds on Uranus and Neptune, but to figure out which models of solar system formation are closest to the truth, we need to follow up the reconnaissance of Voyager 2 with visits by modern spacecraft.

For example, the nebula from which the Sun and planets formed had compositional gradients that changed as material was swept up or blown off, such that each planet's unique composition pinpoints when and where it formed. While some constituents can be detected remotely, only an atmospheric probe can measure the noble gases (helium, neon, argon, xenon, and krypton) in each planet's atmosphere, as these do not chemically react or change over time.

The addition of a satellite system that formed in place (Uranus) and one that was captured (Neptune) further constrains the gravitational interactions that occurred early on among the outer planets. Orbiting spacecraft could scrutinize more regions of these satellites, recording crucial details of geologic features as well as surface composition.

As we strive to understand the hundreds of like-sized extrasolar planets, we need detailed understanding of atmospheric processes on our own planets. Uranus and Neptune provide especially important cases for understanding atmospheric dynamics in cold atmospheres and over a range of seasonal extremes. Do the heat balances of Uranus and Neptune vary over time? Are the emissions from their interiors actually more similar than indicated by Voyager 2? To get answers, we need additional measurements of the reflected (illuminated hemisphere) and emitted (unlit hemisphere) power for each of these planets.

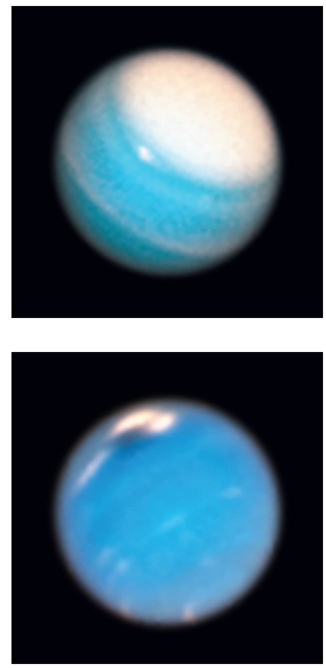
Even better would be detailed measurements of interior structure to understand atmospheric layering and how that affects convection of heat upward from the deep interior. This can be achieved by using orbiters to map the gravity fields close to each planet, as well as by probing deep beneath the cloud tops using radar, microwave sounding, and possibly even Doppler seismology. Atmospheric probes can measure how the temperature, pressure, and winds in these atmospheres change with altitude. This is crucial for knowing how the clouds we observe from Earth fit in global circulation models.

We also seek to understand how ocean worlds—large moons with vast subsurface reservoirs of water—came to exist and how common they may be in our solar system or elsewhere. The discoveries of subsurface oceans on Europa, Ganymede, and Enceladus provide new potential habitats for life. Does Triton also conceal an ocean under its frozen crust? Spacecraft passing near other large moons could map surface features, magnetic field deflections, and maybe even active geysers and plumes, any of which could indicate large liquid reservoirs hidden below the surface.

New missions to Uranus and Neptune can provide timely answers to many of our pressing scientific questions. The ideal scenario involves sending orbiters to both planets that could dispatch instrumented probes to plunge into their atmospheres and obtain critical measurements. If such missions were still active in 2050 (at Uranus) and 2046 (at Neptune), they'd see equinoxes at both planets, with the shifting of seasons and illumination of both poles of both the planets and their moons.

Other bodies could become additional targets of potential ice giant missions. For example, a Neptune orbiter with probe(s) could maximize its science return by also flying past a Centaur asteroid en route and then exploring Triton (a captured Kuiper belt object) after its arrival. A spacecraft heading outward to conduct a Kuiper belt flyby tour could first go past Uranus and deliver an atmospheric probe along the way.

For now, such missions are little more than engineering concepts, but that doesn't diminish their scientific potential. Let's go explore the ice giants in our solar system and see what secrets they hold!



ABOVE *New storms appeared in both Uranus' (top) and Neptune's (bottom) north polar regions in 2018. The Uranus storm was visible to ground-based telescopes as a bright spot, while the dark Neptune spot was only visible to the Hubble Space Telescope. Hubble can see at blue wavelengths at higher resolution than ground-based telescopes can.*

NASA/ESA/Amy Simon (GSFC) and the OPAL Team/Joseph DePasquale (STScI)

A Kepler Orrery

by Ethan Kruse

AS OF MISSION END on 30 October 2018, Kepler had detected 1,815 planets or planet candidates in multi-planet systems. All 726 such systems are drawn here. (More than 2,000 additional single-planet systems are not pictured.) The sizes of the planet orbits are to scale with each other, including the orbits of the planets in our own solar system out to Uranus (dashed lines). Current exoplanet discovery techniques are more likely to yield planets in tighter orbits around their stars. The sizes of the planets are at correct relative but not absolute scale. The colors of the planets denote their estimated equilibrium temperatures. For an animated version of this image, go to **planet.ly/keplerorrery**.

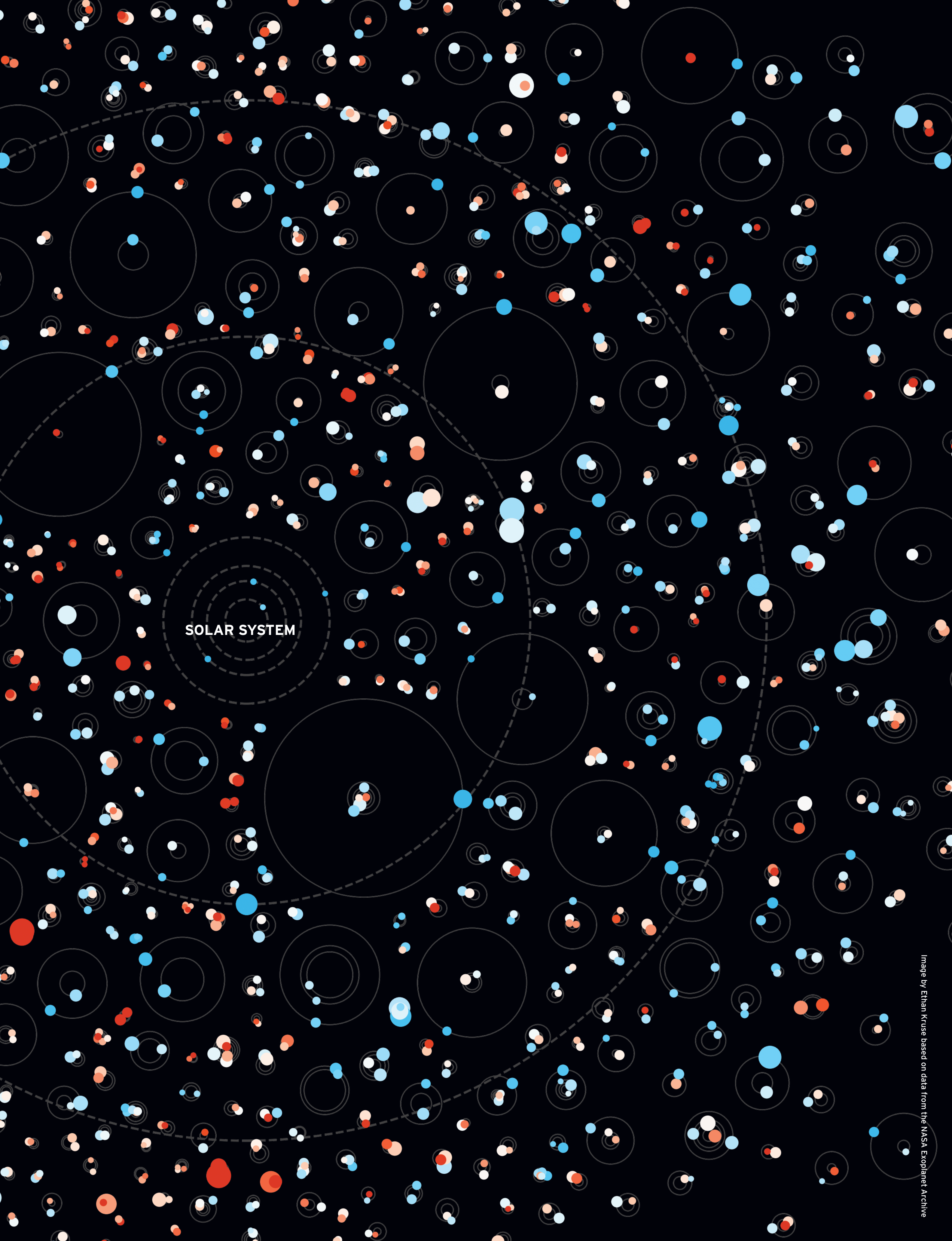
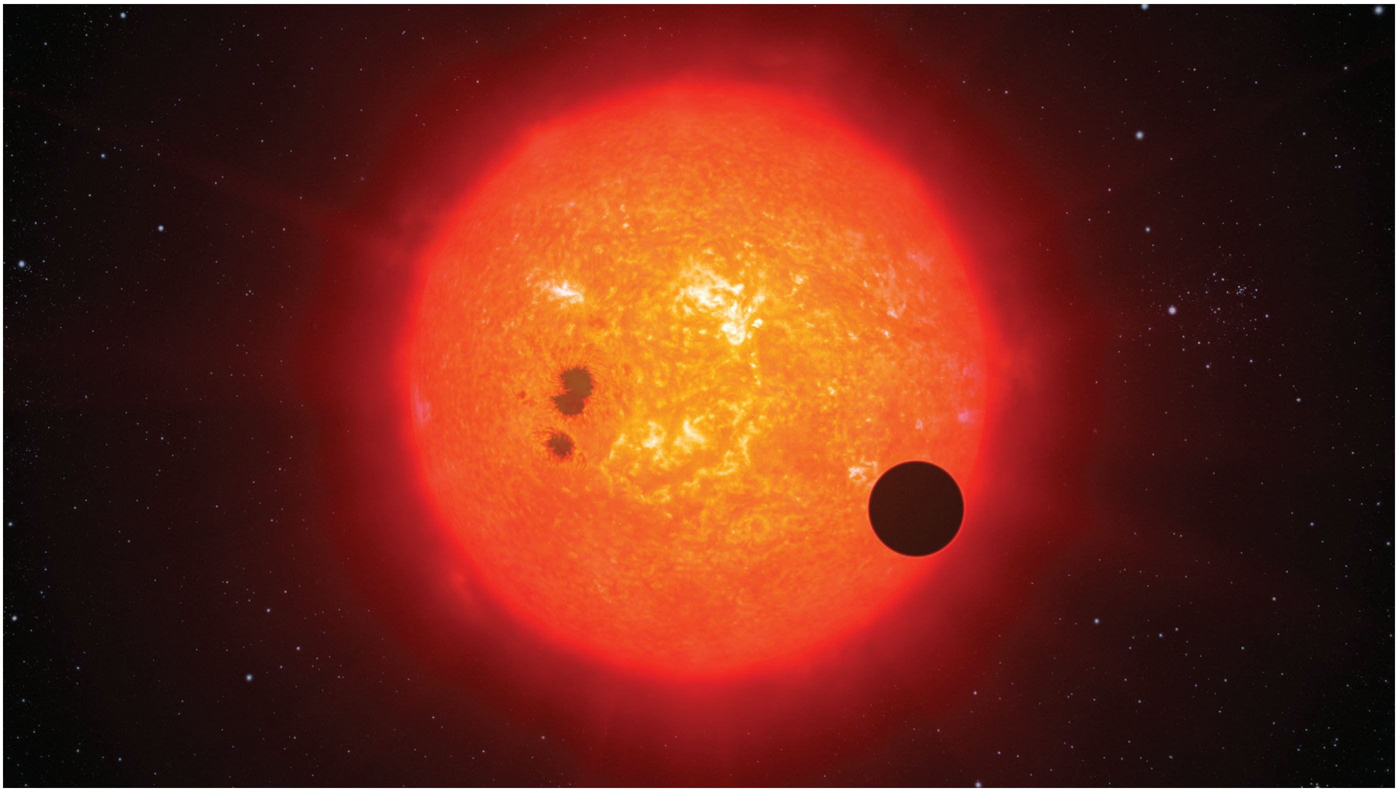


Image by Ethan Kruse based on data from the NASA Exoplanet Archive

HANNAH WAKEFORD *is the Giacconi Fellow at the Space Telescope Science Institute in Baltimore, Maryland.*



ESO/L. Calçada

The Skies of Mini-Neptunes

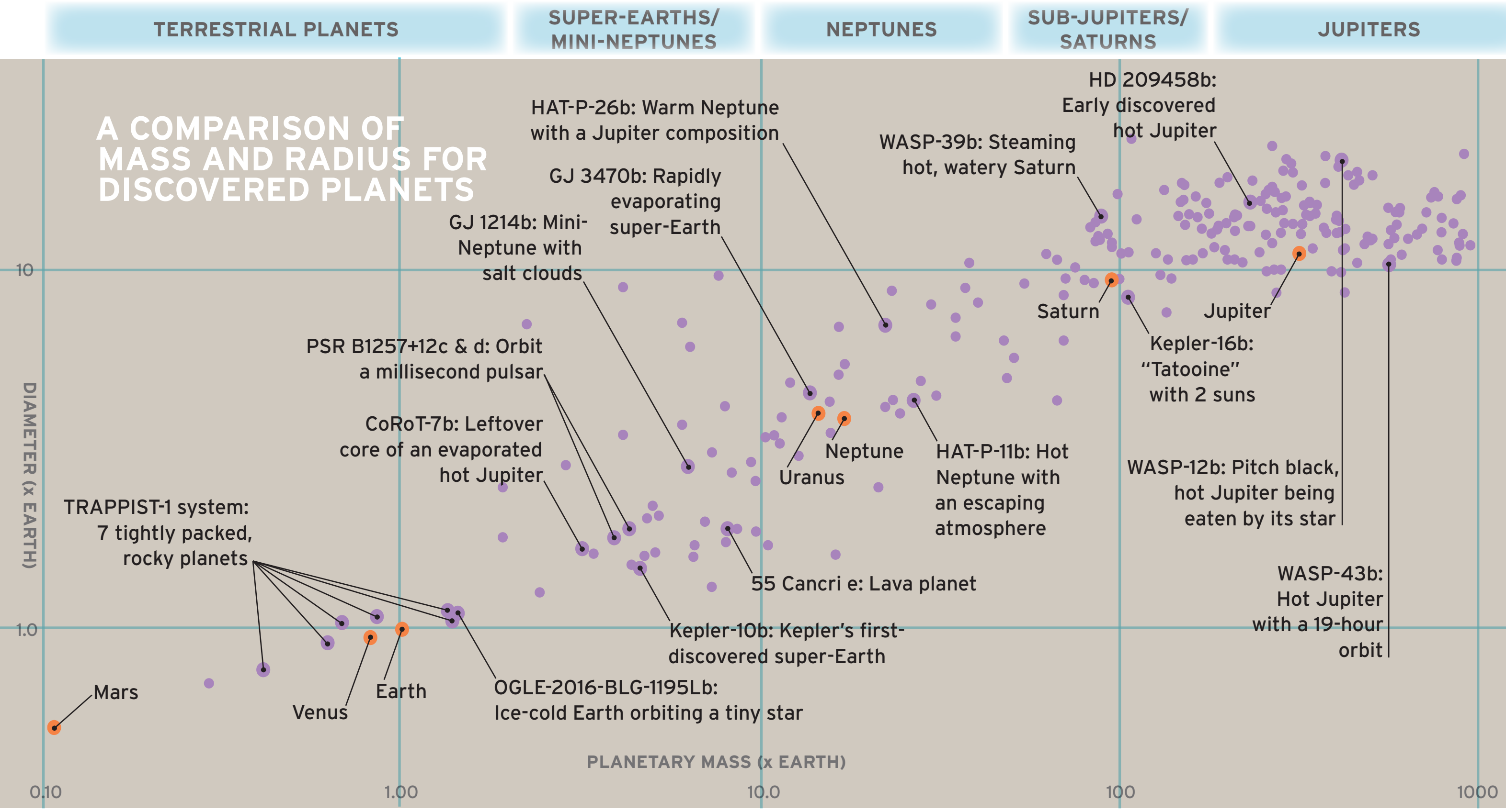
Sniffing the Air of Other Worlds to Learn How Planets Formed and Evolved

ABOVE *Artist's impression of a recently discovered super-Earth that orbits the nearby star GJ 1214. Discovered with the European Southern Observatory's 3.6-meter telescope at La Silla, GJ 1214b is the second super-Earth exoplanet for which astronomers have determined the mass and radius, giving vital clues about its structure. It is also the first super-Earth around which an atmosphere has been found.*

A GREAT QUEST is underway to discover Earth-size worlds in their stars' habitable zones. Along the way, astronomers have been surprised to learn that the most typical size of planet in our galaxy is one with no counterpart in our own solar system.

These planets are called super-Earths or mini-Neptunes. They populate an unfamiliar regime of worlds. They are larger than Earth, the Sun's biggest rocky world, yet smaller than Neptune or Uranus, which are about 4 Earths in diameter. In fact, an exoplanet detected as it transits across the disk of its host star is 4 times more likely to have a size in the super-Earth/mini-Neptune regime than to be bigger than Neptune. These discovery statistics are telling us something–but what?

The ice giants of our solar system, Uranus and Neptune (see "The Realm of the Ice Giants," page 7), represent a transition from a hydrogen-dominated mass, such as that seen in Jupiter and Saturn, to a mass defined more by solid or liquid ices deeper in the atmosphere formed of "heavy" elements (atoms more massive than helium). Such planets still have a hydrogen-helium outer envelope, but their mass is dominated by a deep, fluid ocean made of heavy, icy material and potentially a rocky core. By contrast, terrestrial planets have rock and metal compositions and rela-



tively thin atmospheres containing little to no hydrogen or helium.

At what point does a planet stop being mostly rock and transition to one that's mostly hydrogen and helium? For now, the answer is unknown, but we are trying to figure it out.

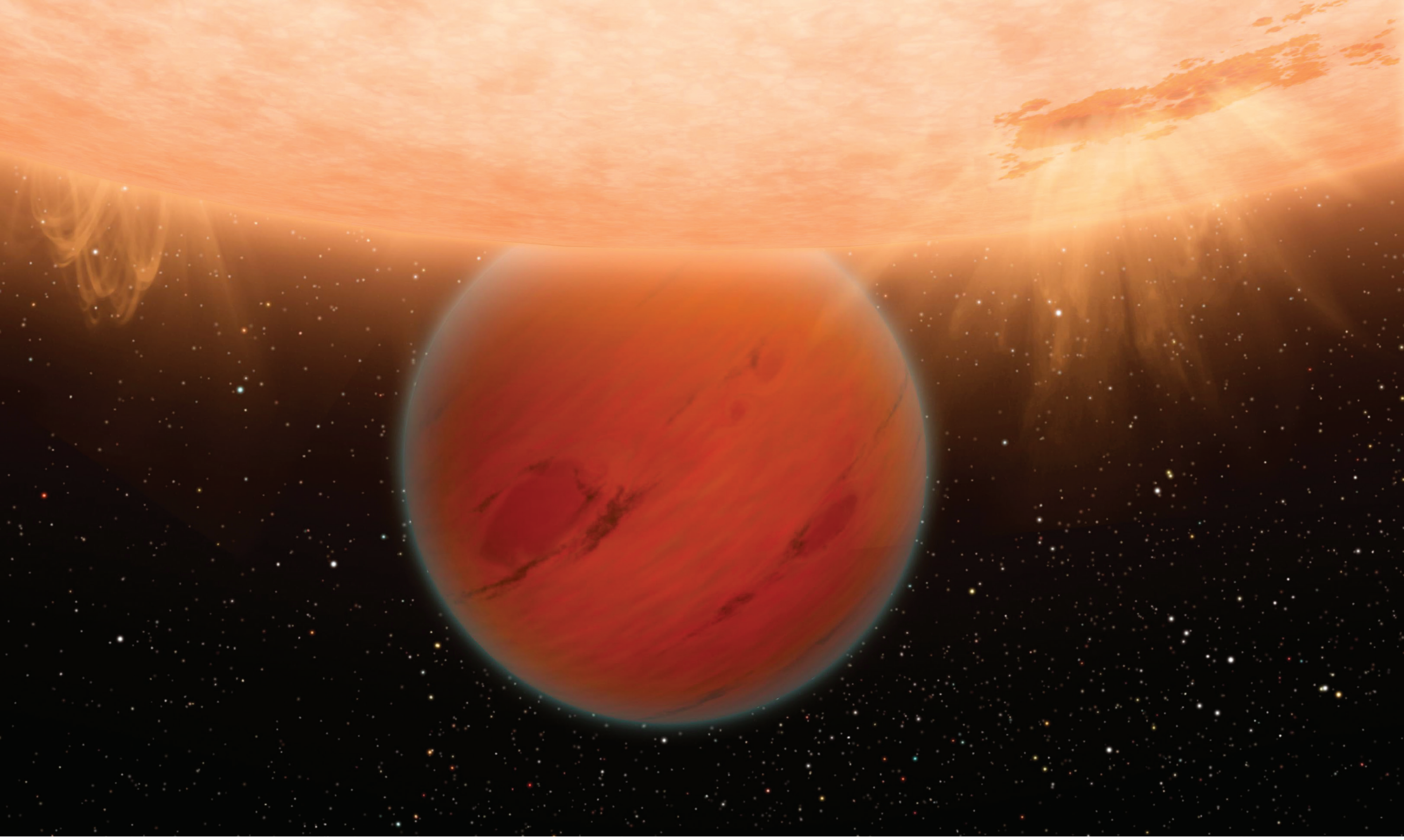
NASA's Kepler spacecraft, whose impressive 9-year mission ended in November 2018, was launched to observe 150,000 Sun-like stars continuously in order to discover Earth-sized planets on year-long orbits. It used a detection method called the transit technique, which looks for the dimming of a star's light caused by a planet passing in front of the star from our point of view. The use of this method to search for extrasolar worlds was suggested in the 1600s by Dutch astronomer Christiaan Huygens. He reasoned that just as we can see the Galilean moons pass in front of Jupiter, we should be able to see planets do the same thing by looking toward the stars.

Over the course of its mission, Kepler collected data on more than 500,000 stars and revealed that there must be more planets in our galaxy than stars. Moreover, Kepler found a hugely diverse population of planets—more than 2,500 in all—orbiting any and all types of stars, from planetary debris falling onto hot, dense, white dwarfs to small, rocky worlds orbiting small, cool stars (known as M dwarfs) and everything in between. Of the roughly 4,000 exoplanets known at the end of 2018, more than half of the ones with a measured diameter fall in the super-Earth/mini-Neptune regime. These objects have diameters 1.6 times to 4 times that of Earth.

To characterize the atmospheres of one of these strange new worlds and find out of what it is made, we primarily measure the absorption spectrum of its atmosphere, called a planetary transmission spectrum. As a planet passes in front of its star, some of the starlight we record filters through the planet's atmosphere before it reaches us. Imprinted on the starlight are the spectral fingerprints of the molecules that make up the planet's atmo-

ABOVE *This graph displays all exoplanets with measured diameters and masses. Rocky planets form a tight line (lower left), but super-Earths/mini-Neptunes have widely varying atmospheres and densities. At Jupiter's size, increasing mass no longer increases the diameter of a planet (upper right). Most of Kepler's discoveries would be in the super-Earth/mini-Neptune region, but few of them have measured masses, so they do not appear here.*

Emily Lakdawalla and Loren A. Roberts for The Planetary Society based on data from exoplanets.org



ABOVE *An artist's impression of the Neptune-sized world GJ 436b. Measurements from Hubble and Spitzer indicate that this planet's atmosphere is highly enriched in heavy elements, which is deeply puzzling; no theorist predicted the existence of a hydrogen-rich planet with such a large amount of heavy elements.*

NASA/JPL-Caltech

sphere. Each molecule absorbs specific wavelengths of light, changing the amount of light we measure from the star. If we detect these specific changes, the molecules can be identified using databases of molecular absorption signatures and models. For example, water vapor has distinct absorption signatures in the near-infrared, which can also be measured in Earth's atmosphere.

For this measurement to succeed, the star needs to be bright enough to emit many photons toward the planet, and the planetary atmosphere has to be extended enough for as many of those photons as possible to pass through the planet's atmosphere–where some of those photons are absorbed, scattered, or reradiated by different molecules–before they complete their journey to our telescopes.

CASE STUDIES

One of the most famous super-Earths/mini-Neptunes, designated GJ 1214b, was discovered by the ground-based MEarth project (pronounced "mirth") in 2009, even before Kepler entered the science phase of its mission. GJ 1214b is a small, gassy world 2.6 times the size of Earth but just a third of its density, and at the time it was thought to be a rarity in exoplanets. Given its mass and diameter, this planet could potentially consist of a rocky core with a hydrogen-helium atmosphere hundreds of kilometers deep, or it could be a world covered in a deep ocean and atmosphere of steam.

To find out what this puffy little planet is made of, astronomers have scrutinized it with numerous ground- and space-based telescopes. These measurements show that the planet's atmosphere is very effective at blocking its star's light. Observers expected to find strong spectral fingerprints from water vapor in the atmosphere, but instead they saw a complete absence of any such features. The absence of such features doesn't necessarily mean water is absent, but the question is:

HANNAH WAKEFORD *is the Giacconi Fellow at the Space Telescope Science Institute in Baltimore, Maryland. Her work focuses on characterizing the atmospheres of exoplanets through observations, primarily with Hubble, and theoretical models of exotic cloud species for hot giant planets.*

what could be blocking starlight so uniformly across all wavelengths? The answer: clouds.

Clouds are prevalent around all bodies in our solar system that have an atmosphere. They probably are just as prevalent on exoplanets and challenge our ability to characterize them. In some cases, clouds can help us study the dynamics and temperature of an atmosphere, but their opacity makes it difficult to accurately determine the abundances of other compounds in a planet's air.

To really understand a planet's composition—and thus to determine if it belongs in the "rocky" or "gassy" category—we need to measure the amounts of different materials in its atmosphere. Our best approach is to look for gaseous materials in a planet's atmosphere—since diffusion would distribute these materials equally everywhere. By identifying a molecule and—where possible—its abundance, we can understand more: the planet's energy budget (how it deals with incoming and outgoing radiation), its chemistry (what reactions are occurring and whether there's more or less of something than we'd expect), and its dynamics (how all of these interact with one another). Each of these supplies clues to the formation and evolution of the planet.

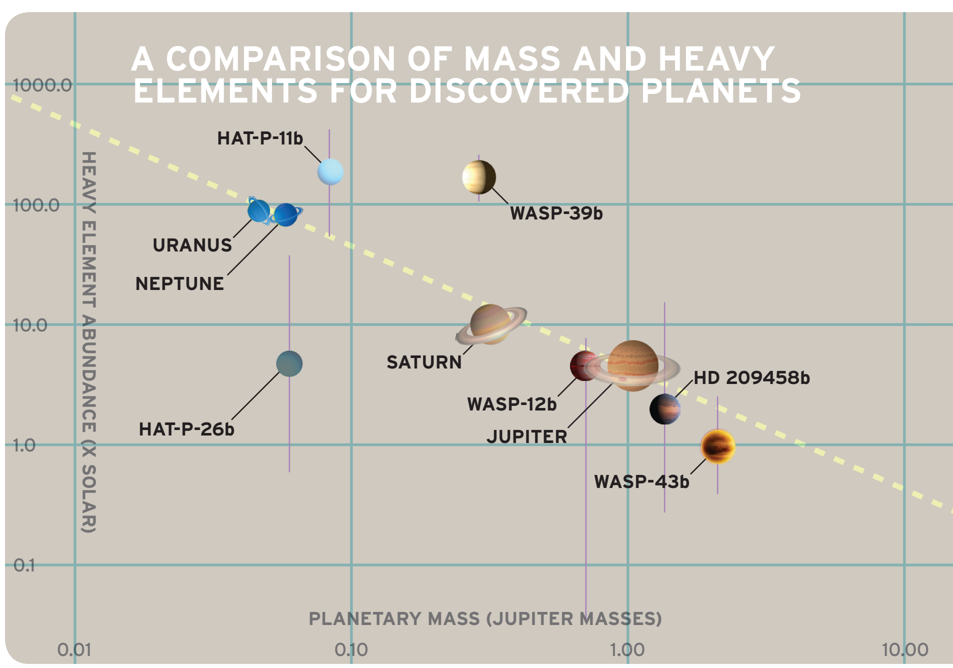
Water is the most useful of these molecules. Water is the third-most abundant molecule in the universe, trailing only molecular hydrogen (H_2) and carbon monoxide (CO). It is very stable and exists in all phases in a vast array of astrophysical contexts. Of course, it is essential for life as we know it. Water's abundance remains relatively constant under equilibrium conditions at all temperatures (as long as more oxygen than carbon is present), so it's likely to be well mixed throughout hot, giant-planet atmospheres. The Hubble Space Telescope makes it relatively easy to detect water vapor in the atmospheres of giant exoplanets, resulting in its identification in 80 percent of the planets that we've observed. However, determining water's abundance is still difficult: only 5 percent of Hubble's measurements yield definitive constraints on how much water is present.

Here in our own solar system, there's an interesting trend among the outer planets: an atmosphere's proportion of heavy elements increases as the planet's mass decreases. For example, compared to their relative abundance in the Sun, Jupiter has 4 times more heavy elements, Saturn has 10 times, and Neptune and Uranus have about 100 times. If we use water vapor in an exoplanet's atmosphere to estimate the abundance of oxygen (and thus all heavy elements), then we can determine whether this trend applies in other planetary systems.

The first definitive measurement of this type was conducted on WASP-43b, a world with twice the mass of Jupiter. Its heavy elements have relative abundances matching the Sun's, fitting the expected trend.

Subsequent observations with Hubble revealed water vapor in the atmospheres of smaller exoplanets, such as the Saturn-mass world WASP-39b and the Neptune-mass worlds HAT-P-11b and HAT-P-26b. However, these planets didn't fit the solar system pattern. The "warm Saturn" WASP-39b has an atmosphere with, proportionately, 150 times more

BELOW *In the 4 largest planets of our own solar system, the amount of carbon in their atmospheres is directly related to their sizes, with less-massive planets having relatively more carbon. When we measured water in exoplanet atmospheres—which should, theoretically, show the same relationship—we were surprised to discover no strong correlation between water abundance and planet mass.*



Loren A. Roberts for The Planetary Society based on data from Hannah Wakeford

ABOVE *Scientists were excited to discover water vapor in the atmosphere of a relatively small planet, about the size of Neptune, using the combined power of NASA's Hubble, Spitzer, and Kepler space telescopes. The planet, called HAT-P-11b, is probably gaseous with a rocky core, much like our own Neptune. Observing HAT-P-11b was the first time that astronomers were able to detect anything measurable in the atmosphere of a planet in this size range.*

heavy elements than the Sun. Meanwhile, the atmosphere of Neptune-mass HAT-P-26b comes in at between 1 times and 30 times the Sun's value, but that of the somewhat smaller world HAT-P-11b has anywhere between 90 times and 700 times the solar abundance of heavy elements!

These results suggest that our solar system's pattern isn't necessarily relevant elsewhere—particularly in the lower-mass regime of the ice giants—and that exoplanet atmospheres are likely far more diverse than our backyard examples. Using our planetary system to assess others is proving not to be the apples-to-apples comparison we hoped it would be. Every measurement we make of exoplanet atmospheres just serves to expand the diversity of the population of worlds we've studied.

BACK TO THE DRAWING BOARD

As of now, astronomers can only discuss which molecular species are present in exoplanet atmospheres. In the coming years, we hope that our observations will establish definitive constraints on the abundances of those species. Only then will astronomers be able to push further and further into the super-Earth/mini-Neptune regime.

NASA's Transiting Exoplanet Survey Satellite (TESS), launched in April 2018, could discover hundreds of new planets around bright stars—perfect candidates for follow-up observations on their atmospheres. Meanwhile, we await the 2021 launch of the James Webb Space Telescope, which should be able to measure and constrain both water and carbon-bearing species in those planets. Our study of exoplanet atmospheres will advance by leaps and bounds!

Super-Earths and mini-Neptunes occupy crucial positions in the continuum of planetary atmospheres. As we look forward to detecting a plethora of smaller planets with the transit technique, we'll also be surveying smaller, cooler stars whose attendant planets will also likely span a wider range of temperatures. Smaller, cooler planets allow us to explore the effects that a planet's mass has on the chemical reactions in its atmosphere as well as the relative abundance of carbon-bearing molecules to hydrogen and helium.

For now, however, definitive detections of carbon-based species remain elusive. Photometric observations by the Spitzer Space Telescope aren't good enough to identify their molecular absorptions with certainty. For its part, Hubble has yet to find a planet with definitive evidence of methane in its atmosphere. However, we are constantly learning new things with each observation, and there are plenty of giant exoplanet atmospheres left to explore. The big question we hope to answer is: what can we learn about our own solar system—its architecture, formation, and evolution—by looking out to these strange new worlds?

RICHARD CHUTE *is The Planetary Society's chief development officer.*

LEFT *Eleanor Masin donates in memory of her son Jonathan, who took this photo of Messier 31, the Andromeda Galaxy, in August 2011.*

Up for a Challenge?

The Grand Dames of Planetary Defense

CURIOUS ABOUT OUR matching gift challenges? Our appeal letters often feature challenges from generous Planetary Society members. Some allow us to identify them by name, but some, out of modesty, often prefer to remain anonymous. I'm excited to lift the curtain on two of these mysterious donors who generously support our Shoemaker NEO grant program.

Allow me to introduce you to Connie (still too modest to share her last name!) and to Eleanor Masin. Together, they have taken up the cause of protecting our planet from near-Earth objects. Through their matching gift challenges over the past several years, they have powered our Shoemaker NEO grants to new heights. Through gifts exceeding $53,000 over 5 years, they have attained more than $100,000 for amateur astronomers dedicated to finding, tracking, and characterizing dangerous near-Earth objects.

Connie, a member for 19 years, says that The Planetary Society is one of her highest philanthropic priorities. At age 89, Connie does not feel computer savvy, so she keeps up with the Society through *The Planetary Report*. Living on the east coast of Florida, Connie eagerly anticipates the launch of LightSail 2 later this year.

For Eleanor, The Planetary Society came into focus when she and her husband, John, wanted to make gifts in memory of their son, Jonathan, who passed away in 2014. She introduced Jonathan, an accomplished amateur astronomer and photographer, to the night skies as a young boy. Through her challenge gifts, Eleanor honors his memory by supporting amateur astronomers as part of the Shoemaker NEO grant program.

Are you up for a challenge? Watch for our Shoemaker NEO appeal later this year!

PLANETARY SOCIETY VOLUNTEERS

Coming Together for Space

by Kate Howells, The Planetary Society's global community outreach manager

FOR 2018's WORLD Space Week, Wael Bazzi, outreach coordinator for the Middle East and North Africa, connected with various universities and space societies across Lebanon to help organize a series of events to celebrate space.

Among them was the astronomy club at the American University of Beirut, represented by psychology student Rayan Abdel-Baki, a recently appointed point of contact with SGAC (Space Generation Advisory Council).

As Abdel-Baki describes, "The major challenge facing World Space Week Lebanon was simple: students across the country lacked context and engagement when it came to the significance of space in our everyday lives."

With Bazzi's mentorship, these space-interested groups came together under one banner. They organized an ambitious, week-long series of events across the country. Seminars on exoplanets, galaxy mapping, astrophotography, and the search for extraterrestrial life delivered in-depth information to students, while space-themed arts and crafts workshops and stargazing trips engaged nonstudents and younger children.

"The World Space Week celebration was a sign that Lebanon is ready to be involved once more with the ever-evolving discussion about our place in space," says Bazzi. "It is important to continue cultivating that discussion."

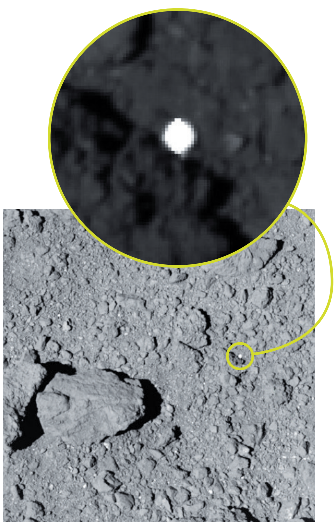
ABOVE *Around the world, The Planetary Society's volunteers connect directly with their communities to spread awareness and appreciation of space.*

Jonathan Masin; Wael Bazzi

BRUCE BETTS *is chief scientist for The Planetary Society.*

Scientific Progress

Projects Keep Moving Forward at The Planetary Society



ABOVE *Hayabusa2 target marker on the asteroid Ryugu. The marker includes the names of all Planetary Society members as well as others who wanted to send their names to an asteroid.*

RIGHT *Honeybee Robotics' Planetary Deep Drill prepares to drill during 2018 testing at a gypsum quarry in southern California.*

NAMES OF MEMBERS ENCOUNTER ASTEROIDS AND 2014 MU69

New Horizons just completed a thrilling flyby of Kuiper belt object 2014 MU69 (nicknamed "Ultima Thule"), and Planetary Society members' names did too. The Planetary Society has long flown members' names on spacecraft. In the last few months, member names have participated in many deep-space encounters. In addition to New Horizons, we've gone into orbit around the asteroid Bennu on board the OSIRIS-REx spacecraft and landed on the asteroid Ryugu on target markers dropped on the surface to guide Hayabusa2 to its own landing. Learn more about the names on these and other missions at **planetary.org/namesinspace**.

PLANETARY DEEP DRILL TESTS

Planetary Deep Drill is a technology concept being developed to drill hundreds of meters or more into planetary ices like those at the poles of Mars and the surface of Europa. Honeybee Robotics successfully completed testing of Planetary Deep Drill in December 2018 at a gypsum mine in southern California. This round of tests followed up on tests sponsored by The Planetary Society that were conducted in 2015 at the same mine. Why a gypsum mine? Gypsum has similar mechanical properties to water ice at extremely cold temperatures.

What began as a single drill project has now evolved into two variants. The current round of tests incorporated a miniaturized version of an actual spacecraft flight instrument: the

Mars 2020 rover's Scanning Habitable Environments with Raman and Luminescence for Organics and Chemicals (SHERLOC). SHERLOC is an ultraviolet spectrometer that can search for organic molecules.

Planetary Deep Drill's next test will happen in Greenland in summer 2019. It will be drilling into an actual ice sheet. Learn more about the tests at **planet.ly/deepdrilltest2**.

Thanks! Planetary Society members have helped make these projects—and many others—possible! Thank you.

Hayabusa target marker: ISAS/JAXA; Planetary Deep Drill: Honeybee Robotics

PLANETARY DEFENSE

The Planetary Society is proud to once again be a primary sponsor of the biannual Planetary Defense Conference, which brings together experts on all aspects of the asteroid threat to Earth. The week-long conference will be held in spring 2019 in Washington, D.C.; we will cohost an affiliated public event at the University of Maryland. At the conference, we will present papers and report on the presentations of others. We will also announce a new call for proposals for our Gene Shoemaker Near-Earth Object grant program that supports highly skilled amateur astronomers around the world in their efforts to track and characterize near-Earth objects. Proposers will then have until 30 July to submit proposals to upgrade their observatories. Learn more about all our planetary defense efforts at **planetary.org/defense**.

LIGHTSAIL 2 STILL AWAITING LAUNCH

As of this writing, we still await a new launch date for our solar sail spacecraft, LightSail 2, on a SpaceX Falcon Heavy rocket. The completed LightSail 2 spacecraft remains in clean room storage at Cal Poly San Luis Obispo, where we periodically recharge its batteries. In January, LightSail 2 underwent a successful required bake-out, spending several hours at high temperature to make sure any components that might release gases do so on Earth rather than in space.

When a launch date draws near, LightSail 2 will be taken to the Air Force Research Laboratory in Albuquerque and will be reintegrated with the Georgia Tech spacecraft Prox-1. They will then travel to Florida for integration with the Falcon Heavy rocket. When the launch draws closer, the team will hold another operational readiness test to practice procedures to be used in orbit. Learn more, including any updates on the launch date, at **sail.planetary.org**.

Observatorio Cerro Mamalluca: Miguel Carvajal

Eclipse and Aurora Tours With Society Members!

TAHITI TOTAL SOLAR ECLIPSE
25 JUNE - 4 JULY 2019
WITH OPTIONAL BORA BORA EXTENSION TO 7 JULY

Discover the magic of one of the most beautiful places on Earth, the islands of French Polynesia, with leader Bob Nansen. See the total solar eclipse on 2 July from a chartered aircraft near the remote Gambier Islands. Enjoy this marine wonderland of coral reefs and exquisite islands and immerse yourself in Polynesian culture.

CHILE TOTAL SOLAR ECLIPSE
26 JUNE - 6 JULY 2019
WITH OPTIONAL EASTER ISLAND EXTENSION 21-26 JUNE

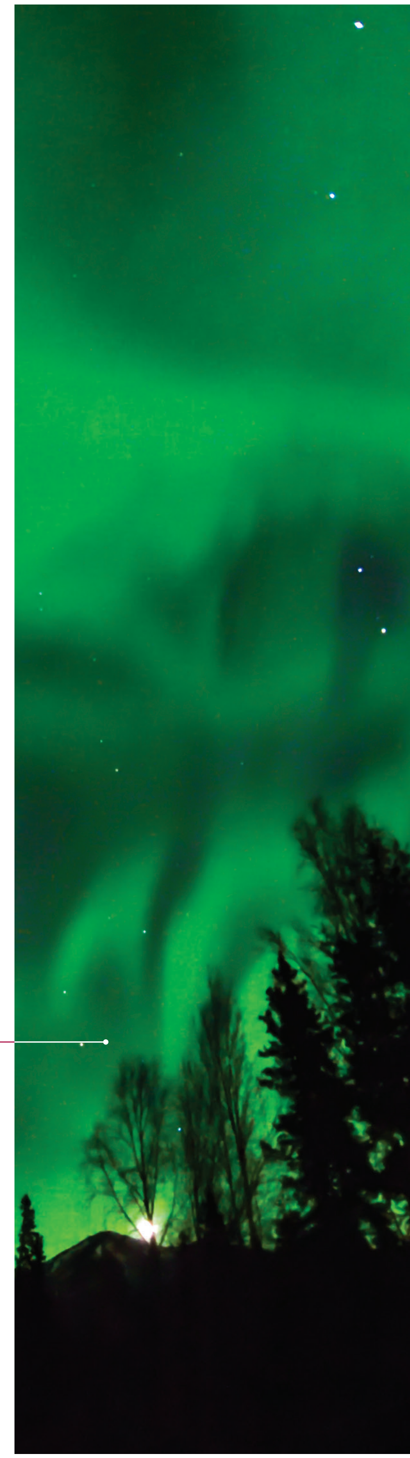
Join us as we explore Chile, where you'll experience the total solar eclipse on 2 July. Visit astronomical observatories with popular dark-sky guide Tyler Nordgren. Explore the archeology of the Valle del Encanto and discover the unique cloud forest and coastal beauty of Parque Nacional Fray Jorge.

SINGAPORE ANNULAR ECLIPSE
18-27 DECEMBER 2019
WITH OPTIONAL ANGKOR WAT PRE-TRIP 15-20 DECEMBER

Discover the amazing island city of Singapore and see the annular solar eclipse from Bintan Island, Indonesia on 26 December with leaders Bob Nansen and Chris Carpenter. The Angkor Wat pre-trip in Cambodia allows you to explore the finest archaeological site in Asia.

ALASKA AURORA BOREALIS
27 FEBRUARY - 3 MARCH 2020

Join astronomer Tyler Nordgren on our expedition to see Alaska's northern lights. You'll see Alaska's wildlife—from grizzlies to musk oxen—in their winter habitat. Then, you'll travel by train from Talkeetna—past 20,310-foot Mt. Denali—to Fairbanks, where you'll delight in the night sky's dazzling aurora borealis.



We invite you to join these wonderful adventures! Space is limited, so please contact us right away for reservations. Phone Betchart Expeditions Inc. at (800) 252-4910 or email: *betcharttaunya@gmail.com*.

IN THE SKY

In late March and early April, in the pre-dawn East there is a line of 3 planets, from super-bright Venus low down, to yellowish Saturn to its upper right, to bright Jupiter farther to the upper right. Venus gets lower in April and is joined by Mercury near the horizon. As weeks pass, Jupiter and Saturn get higher in the sky before dawn. In the evening sky, reddish Mars gets lower in the West as the weeks pass. Through April, it is not far from the brighter reddish star Aldebaran in Taurus. Mercury joins Mars very low in the West in June; they are very close on the 18th. By June, Jupiter is rising in the East in the early evening.

RANDOM SPACE FACT

The most distant object ever encountered was the Kuiper belt object 2014 MU69 (unofficially nicknamed "Ultima Thule") during the 1 January 2019 New Horizons flyby. The spacecraft was 6.6 billion kilometers (4.1 billion miles) from Earth during the encounter. The previous record holder was Pluto, which New Horizons encountered at a distance of 4.8 billion kilometers (3.0 million miles) from Earth.

TRIVIA CONTEST

Our June Solstice contest winner is Gary Green of Old Town, Maine, United States. Congratulations! The question was: ***What was the first human-made object to hit another world besides Earth?*** The answer: ***The Luna 2 spacecraft. It impacted the Moon in September 1959.***

Try to win a copy of *Astronomy for Kids: How to Explore Outer Space with Binoculars, a Telescope, or Just Your Eyes!* by Bruce Betts and a *Planetary Radio* T-shirt by answering this question:

On what planet in our solar system have the fastest wind speeds been measured?

Email your answer to *planetaryreport@planetary.org* or mail your answer to *The Planetary Report*, 60 S. Los Robles Ave., Pasadena, CA 91101. Make sure you include the answer and your name, mailing address, and email address (if you have one). By entering this contest, you are authorizing *The Planetary Report* to publish your name and hometown. Submissions must be received by 1 June 2019. The winner will be chosen in a random drawing from among all the correct entries received.

For a weekly dose of "What's Up?" complete with humor, a weekly trivia contest, and a range of significant space and science-fiction guests, listen to *Planetary Radio* at *planetary.org/radio*.

Where We Are

An At-A-Glance Spacecraft Locator

SINCE I LAUNCHED this column, I've had to report uncertainty on the status of the Opportunity rover. It is with great sadness that I say this will be the last time I'll mention Opportunity here, as NASA has declared the mission at an end. The twin MarCO spacecraft have also communicated their last signals to Earth—after venturing farther than any other SmallSats have before. However, the solar system remains a busy place, even with these losses.

I recently learned from amateur radio operators that China's Chang'e-5 T1 spacecraft is still communicating with Earth from a stable lunar orbit. Yutu-2 has wandered off from Chang'e-4, exploring Von Kármán crater on its own—as documented in photos from Lunar Reconnaissance Orbiter. And Israel is now on its way to the Moon with the Beresheet lander, which launched on 22 February. Their landing attempt is on 11 April. If they stick the landing, SpaceIL will become the fourth organization in history to soft-land a spacecraft on the Moon.

This quarter, our view happens to catch Parker Solar Probe very close to the Sun just 3 days before perihelion. It will experience another perihelion on 1 September. A Venus flyby on 26 December will shrink its orbit, dropping its next close approach even closer. BepiColombo will eventually be in Parker's neighborhood but will spend all of 2019 far from the Sun, cruising toward an April 2020 Earth flyby.

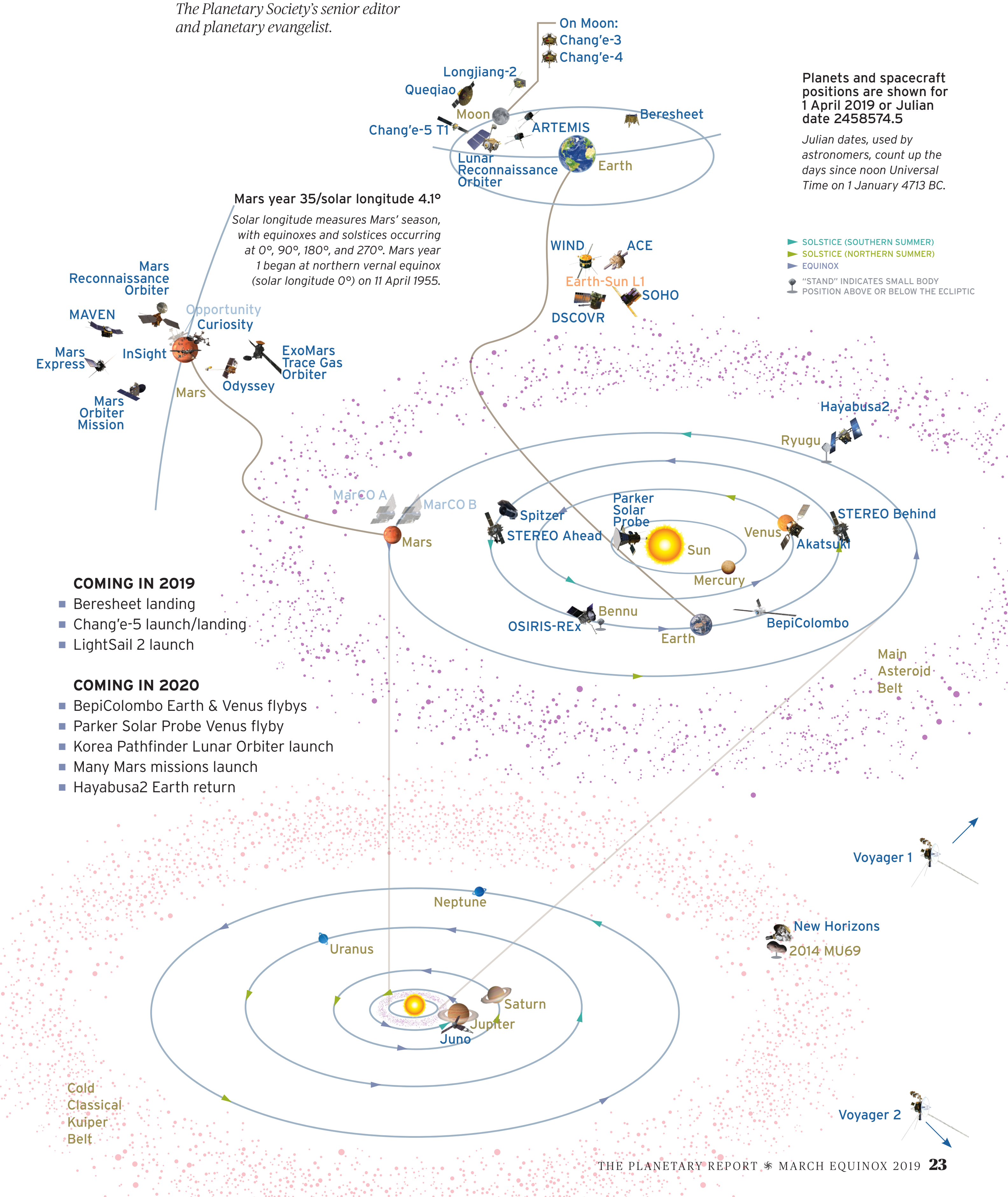
Japan's Hayabusa2 successfully grabbed a sample from asteroid Ryugu on 21 February. It will depart for Earth return late this year. OSIRIS-REx will spend the rest of 2019 surveying Bennu and plans to capture its sample in 2020.

At Mars, InSight has finished deploying its seismometer and is at work on the installation of its heat probe, while 6 spacecraft are in orbit above it. Curiosity has finally descended the slope of Vera Rubin Ridge and will likely spend the rest of the year—possibly longer—exploring the clay-filled swale beyond it.

New Horizons has now left 2014 MU69 behind but is still doing Kuiper belt science, studying the faint light from other tiny worlds and preparing to search for a future flyby target.

Loren A. Roberts for The Planetary Society after a concept by Olaf Frohn

EMILY STEWART LAKDAWALLA *is The Planetary Society's senior editor and planetary evangelist.*



Planets and spacecraft positions are shown for 1 April 2019 or Julian date 2458574.5

Julian dates, used by astronomers, count up the days since noon Universal Time on 1 January 4713 BC.

Mars year 35/solar longitude 4.1°

Solar longitude measures Mars' season, with equinoxes and solstices occurring at 0°, 90°, 180°, and 270°. Mars year 1 began at northern vernal equinox (solar longitude 0°) on 11 April 1955.

COMING IN 2019

- Beresheet landing
- Chang'e-5 launch/landing
- LightSail 2 launch

COMING IN 2020

- BepiColombo Earth & Venus flybys
- Parker Solar Probe Venus flyby
- Korea Pathfinder Lunar Orbiter launch
- Many Mars missions launch
- Hayabusa2 Earth return

THE PLANETARY SOCIETY
60 SOUTH LOS ROBLES AVENUE
PASADENA CA 91101-2016 USA

PRINTED ON RECYCLED PAPER

astronomical art

Ron Miller, Black Cat Studios
Ice World Canyon

The Planetary Report challenged astronomical artists to submit artwork on the theme "ice giants." Illustrator and author Ron Miller submitted this work inspired by the discovery of exoplanet OGLE-2016-BLG-1195Lb, a world 13,000 light years away that has mass and orbit similar to Earth. This Earth-like planet orbits a very faint star, however, so it is likely ice-covered.

Miller placed a hypothetical Earth-sized ice world in orbit around a gas giant. He writes: "Covered with glaciers as deep as Greenland's ice cap, the landscape is one of vast, canyon-sized cracks and fissures. With its sun only a distant, tiny star much smaller and dimmer than Earth's, its future explorers would have to contend with temperatures falling below −200 degrees Celsius (−400 degrees Fahrenheit)."