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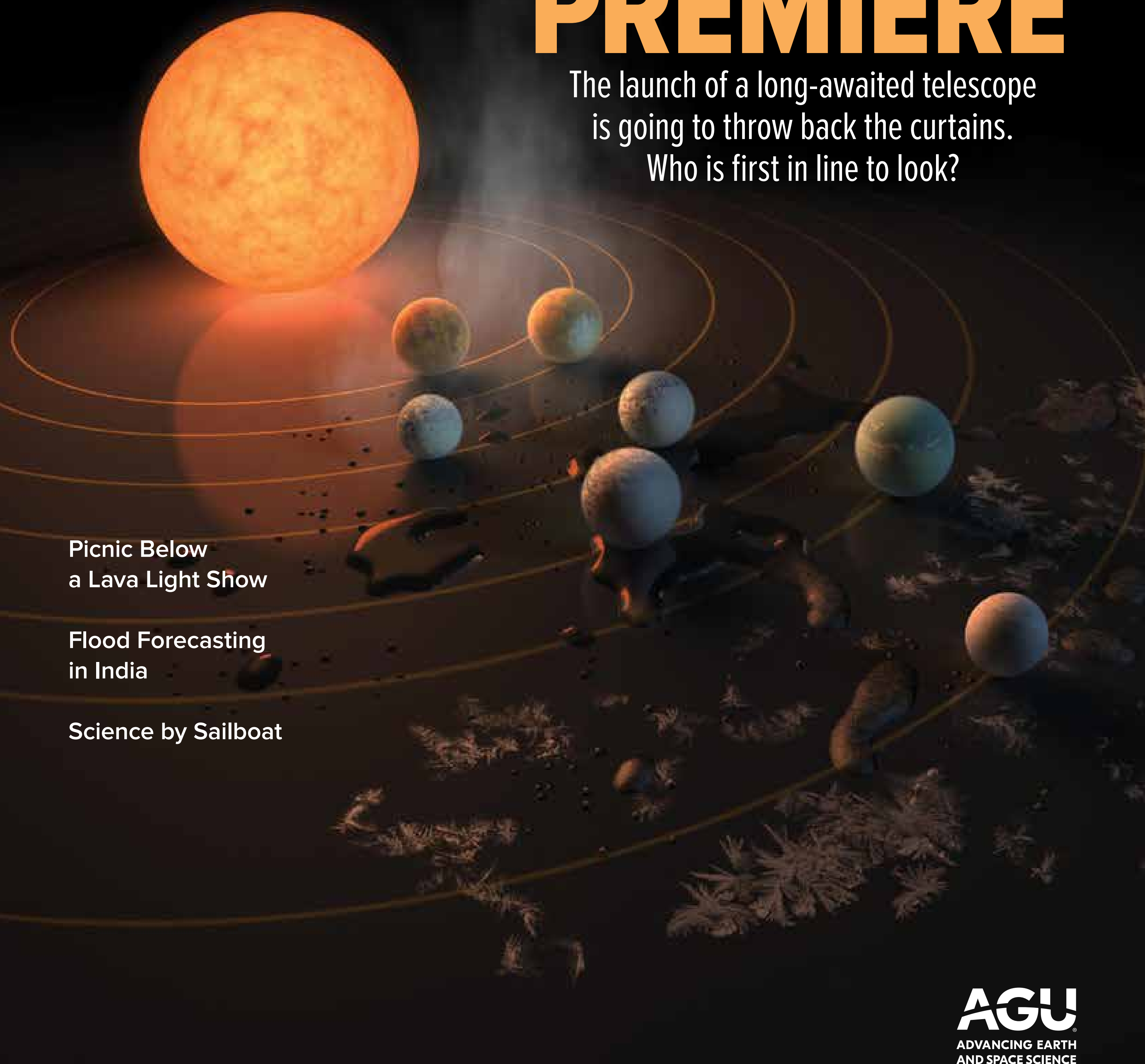
SCIENCE NEWS BY AGU

WORLDS PREMIERE

The launch of a long-awaited telescope is going to throw back the curtains. Who is first in line to look?



AGU
ADVANCING EARTH AND SPACE SCIENCE

Unveiling the Next Exoplanet Act

The whole field of exoplanet study is frustratingly tantalizing. We now know for sure there are alien worlds. We can see them! Kinda. We see their shadows; we can see their fuzzy outlines. We are so close to the tipping point of having enough knowledge to truly shake our understanding—in the best way, says this space geek—of Earth's place in the universe.

The first light of the James Webb Space Telescope (JWST) may be what sends us over that exciting edge. In just a few months, the much-delayed launch will, knock on wood, proceed from French Guiana and take around a month to travel to its destination at the second Lagrange point (L2). "This is certainly an exciting time for exoplanet science, with current missions like Hubble and TESS [Transiting Exoplanet Survey Satellite] providing us with new discoveries and future missions like JWST, which promises to provide incredible new data that will answer some of our current questions and also create many new ones," said Sarah Hörst of Johns Hopkins University, *Eos*'s Science Adviser representing AGU's Planetary Sciences section who consulted on this issue. "The field is moving very quickly right now."

That's why our August issue is all about exoplanets—what we know and what awaits us over the launch horizon. Who gets the first peek through JWST? In March, the proposals selected for the first observing cycle were announced. Meet the slate of scientists who will be pointing the telescope at other worlds, and read what they hope to learn in "Overture to Exoplanets" on page 26.

As with all new instruments, the data collected from JWST will be pieced together with observations from ongoing missions and other facilities around the world. "Over the last decade, we've gotten gorgeous images from the ALMA interferometer in Chile and have seen loads of fine-scale structure, tracing pebbles in planet-forming disks," says astronomer Ilse Cleeves in our feature article. Hörst found this synergy with ALMA (Atacama Large Millimeter/submillimeter Array) especially intriguing: "Although I've thought a lot about what we'll learn about individual planets, I hadn't really thought much about what we'll be able to learn about planet formation process by studying the disks themselves."

In "The Forecast for Exoplanets Is Cloudy but Bright," on page 34, we learn the immense challenge posed by exoplanet atmospheres, when researchers are still struggling to understand the complex dynamics of clouds on our own planet. And in "Exoplanets in the Shadows" on page 20, we look at the rogues, the extremes, and a new field being coined as necroplanetology.

What awaits us when the first science results start coming in from JWST and all the coordinated missions next year? "I'm really excited for the unexpected," says Hörst. "I'm excited for all the 'well, that's weird' moments. Those are my favorite things in science because that's when you know that new discoveries are going to be made. I'm also really happy for all of my colleagues who have worked so tirelessly for so many years to make JWST happen."

We're pretty happy, too, for the scientists long awaiting this day and for the rest of us who eagerly await a wide new window on our mysterious universe.

Heather Goss, Editor in Chief

Eos

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Randy Fiser, Executive Director/CEO

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The seven small, potentially rocky worlds of the TRAPPIST-1 system orbit an M dwarf star, shown in an artist's rendering. Credit: NASA/JPL-Caltech

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Gaps in Exoplanet Sizes Shift with Age

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Twenty-six years ago, astronomers discovered the first planet orbiting a distant Sun-like star. Today thousands of exoplanets are known to inhabit our local swath of the Milky Way, and that deluge of data has inadvertently revealed a cosmic mystery: Planets just a bit larger than Earth appear to be relatively rare in the exoplanet canon.

A team has now used observations of hundreds of exoplanets to show that this planetary gap isn't static but instead evolves with planet age—younger planetary systems are more likely to be missing slightly smaller planets, and older systems are more apt to be without slightly larger planets. This evolution is consistent with the hypothesis that atmospheric loss—literally, a planet's atmosphere blowing away over time—is responsible for this so-called "radius valley," the researchers suggested.

Changes with Age

In 2017, scientists reported the first confident detection of the radius valley (bit.ly/gap-radius). (Four years earlier, a different team had published a tentative detection; bit.ly/tentative-detection.) Defined as a relative paucity of exoplanets roughly 50%–100% larger than Earth, the radius valley is readily apparent when looking at histograms of planet size, said Julia Venturini, an astrophysicist at the International Space Science Institute in Bern, Switzerland, not involved in the new research. "There's a depletion of planets at about 1.7 Earth radii."

Trevor David, an astrophysicist at the Flatiron Institute in New York, and his colleagues were curious to know whether the location of the radius valley—that is, the planetary size range it encompasses—evolves with planet age. That's an important question, said David, because finding evolution in the radius valley could shed light on its cause or causes. It's been proposed that some planets lose their atmospheres over time, which causes them to change size. If the timescale over which the radius valley evolves matches the timescale of atmospheric loss, it might be possible to pin down that process as the explanation, said David.

In a new study published in the *Astronomical Journal,* the researchers analyzed planets originally discovered using the Kepler Space Telescope (bit.ly/exoplanet-size-distribution). They focused on a sample of roughly 1,400 planets whose host stars had been observed spectroscopically. Their first task was to determine the planets' ages, which they assessed indirectly by estimating the ages of their host stars. (Because it takes just a few million years for planets to form around a star, these objects, astronomically speaking, have very nearly the same ages.)

"There's a depletion of planets at about 1.7 Earth radii."

The team calculated planet ages ranging from about 500 million years to 12 billion years, but "age is one of those parameters that's very difficult to determine for most stars," David said. That's because estimates of stars' ages rely on theoretical models of how stars evolve, and those models aren't perfect when it comes to individual stars, he said. For that reason, the researchers decided to base most of their analyses on a coarse division of their sample into two age groups, one corresponding to stars younger than a few billion years and one encompassing stars older than about 2–3 billion years.

A Moving Valley

When David and his collaborators looked at the distribution of planet sizes in each group, they indeed found a shift in the radius valley: Planets within it tended to be about 5% smaller, on average, in younger planetary systems compared with older planetary systems. It wasn't wholly surprising to find this evolution, but it was unexpected that it persisted over such long timescales [billions of years], said David. "What was surprising was how long this evolution seems to be."

These findings are consistent with planets losing their atmospheres over time, David and his colleagues proposed. The idea is that most planets develop atmospheres early on but then lose them, effectively shrinking in size from just below Neptune's (roughly 4 times Earth's radius) to just above Earth's. "We're inferring that some sub-Neptunes are being converted to super-Earths through atmospheric loss," said David. As time goes on, larger planets lose their atmospheres, which explains the evolution of the radius valley, the researchers suggested.

Kicking Away Atmospheres

Atmospheric loss can occur via several mechanisms, scientists believe, but two in particular are believed to be relatively common. Both involve energy being transferred into a planet's atmosphere to the point that it can heat to thousands of degrees kelvin. That input of energy gives the atoms and molecules within an atmosphere a literal kick, and some of them, particularly lighter species like hydrogen, can escape.

"You can boil the atmosphere of a planet," said Akash Gupta, a planetary scientist at the University of California, Los Angeles not involved in the research.

In the first mechanism—photoevaporation—the energy is provided by X-ray and ultraviolet photons emitted by a planet's host star. In the second mechanism—core cooling—the source of the energy is the planet itself. An assembling planet is formed from successive collisions of rocky objects, and all of those collisions deposit energy into the forming planet. Over time, planets reradiate that energy, some of which makes its way into their atmospheres.

"Age is one of those parameters that's very difficult to determine for most stars."

Theoretical studies have predicted that photoevaporation functions over relatively short timescales—about 100 million years—while core cooling persists over billions of years. But concluding that core cooling is responsible for the evolution in the radius valley would be premature, said David, because some researchers have suggested that photoevaporation can also act over billions of years in some cases. It's hard to pinpoint which is more likely at play, said David. "We can't rule out either the photoevaporation or core-powered mass loss theories."

It's also a possibility that the radius valley arises because of how planets form, not how they evolve. In the future, David and his colleagues plan to study extremely young planets, those only about 10 million years old. These youngsters of the universe should preserve more information about their formation, the researchers hope.

By **Katherine Kornei** (@KatherineKornei), Science Writer

Chasing Magma Around Iceland's Reykjanes Peninsula

Icelandic Meteorological Office seismologist Kristín Jónsdóttir stands on solidified black basalt that glows red from erupting Fagradalsfjall volcano behind her. Credit: Kristín Jónsdóttir

In December 2019, Reykjanes Peninsula, which juts into the Atlantic Ocean southwest of Iceland's capital city of Reykjavík, began experiencing intense seismic swarms. Since then, scientists at the Icelandic Meteorological Office have been tracking and monitoring deformation of Earth's surface as magma intruded into the shallow crust. Three initial intrusions occurred near Mount Thorbjörn, just outside the town of Grindavík. A fourth slightly inflated the peninsula's westernmost tip, and a fifth leapfrogged back east, beyond Grindavík, to Krýsuvík, according to Sara Barsotti, an Italian volcanologist and coordinator for volcanic hazards at the Icelandic Meteorological Office.

More than a year after this unrest began, on 24 February 2021, a large earthquake measuring magnitude 5.7 jolted the peninsula between Keilir and Fagradalsfjall volcanoes, "marking a turning point," Barsotti said.

Soon thereafter, the Icelandic Meteorological Office's seismic network recorded more than 50,000 earthquakes on the peninsula. Using the monitoring tools at their disposal, scientists found a corridor of magma between Keilir and Fagradalsfjall, said Barsotti. This magma flowed underground for approximately 3 weeks, with earthquakes defining the edges of the subterranean chamber. Then both seismicity and deformation plummeted.

At that point, some scientists hypothesized that the intrusion would freeze within the crust, said Kristín Jónsdóttir, a seismologist at the Icelandic Meteorological Office. "Then," she said, "the eruption started."

Keeping Crowds Safe

On 19 March, lava began to erupt from the edge of the intrusion near Fagradalsfjall, and Icelanders flocked to the mountains above the fissure to picnic, play football, or simply

Against a gray sky, orange lava pours and pops out of Fagradalsfjall on the second day of the eruption. In the foreground, cooling lava glows against the black basalt that's already solidified. Credit: Toby Elliott/Unsplash

observe nature's lava light show. "Icelanders…feel this is part of their life," said Barsotti. "They really want to enjoy what their country is capable [of giving] them."

Because crowds continue to visit the eruption, the Icelandic Meteorological Office meets daily with Iceland's Department of Civil Protection and Emergency Management to ensure the safety of volcano watchers, Barsotti explained. A rescue team is always present, and they use handheld sensors to detect gases that could be dangerous.

"The big challenge," Barsotti said, is "[foreseeing] the opening of new vents." What began as a single vent now boasts a fissure swarm, cones, and lava fields. "People should be [able] to go, but [we must keep] them far away from what we consider to be hazardous."

The Icelandic Meteorological Office keeps vigil over this volcano with a variety of techniques. For example, InSAR (interferometric synthetic aperture radar), a satellite-based method, allows scientists to measure differences in topography at centimeter scale. GPS stations help track how the ground itself moves. Passive satellite imagery can trace the progress of toxic clouds, like sulfur dioxide.

Seismic Monitoring of the Future

Geoscientists from across Europe have been exploring distributed acoustic sensing, or DAS, to monitor seismicity near Mount Thorbjörn. In April, Sebastian Heimann, a scientist at Helmholtz Centre Potsdam in Germany, presented the latest results from the ongoing study at the 2021 Annual Meeting of the Seismological Society of America.

At a molecular level, DAS works because fiber-optic cables contain impurities, explained Hanna Blanck, one of Heimann's coauthors and a doctoral student at the University of Iceland. A laser pulse sent through a cable will encounter these impurities, she said. When that happens, the light scatters, and a small portion returns toward the laser source. By continuously measuring the returning signal, scientists can look for changes that indicate the cable has moved. Earthquakes have distinct signatures that help differentiate them from, for example, the rumble of a passing car.

DAS provides several advantages to traditional seismic networks, including higher spatial resolution, said Blanck. Traditional seismic networks are spaced kilometers apart, whereas the spatial resolution Heimann used along the 21-kilometer-long cable was a scant 4 meters.

"We caught more small earthquakes compared to the conventional methods [likely because] we have many more records along the fiber," said Philippe Jousset, a coauthor and a geophysicist at Helmholtz Centre Potsdam, describing previous work using the same cable near Mount Thorbjörn (bit.ly/imaging-cables). In that study, Jousset and his colleagues, including Blanck, compared the catalog of earthquakes recorded by both DAS and traditional seismic stations.

"Propagating magma increases the pressure in the surrounding crust, causing many small earthquakes," said Blanck. More data mean detecting more small earthquakes, which should yield a better picture of magma movement.

However, "[DAS] is still in its research phase," said Jónsdóttir, "so it's not being routinely used by monitoring agencies." In the future, she said, it will likely complement more established methods in seismology.

Nevertheless, seismologists and volcanologists often investigate secrets of Earth that cannot be seen, Jónsdóttir said, so holding a freshly formed piece of basalt as lava spews in the background—after hypothesizing the existence of an intrusion in that very location—provides incredible validation.

By **Alka Tripathy-Lang** (@DrAlkaTrip), Science Writer

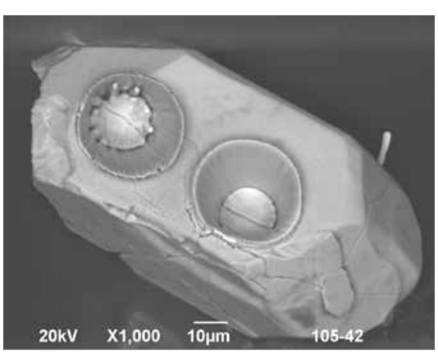
Vestiges of a Volcanic Arc Hidden Within Chicxulub Crater

About 66 million years ago, an asteroid hurtled through Earth's atmosphere at approximately 20 kilometers per second—nearly 100 times the speed of sound—and slammed into water and limestone off Mexico's Yucatán Peninsula, catalyzing the demise of the dinosaurs. The solid rock hit by the asteroid momentarily behaved like a liquid, said University of Texas at Austin geophysicist Sean Gulick. Almost instantaneously, a massive transient crater extended to the mantle, and rocks from 10 kilometers deep rushed to the sides of the hole. They slid back toward the crater's center and shot 20 kilometers into the air before collapsing outward again. As the rock flowed outward, it regained its strength and formed a peak ring, resulting in mountains encircling the center of the 200-kilometer-wide Chicxulub crater.

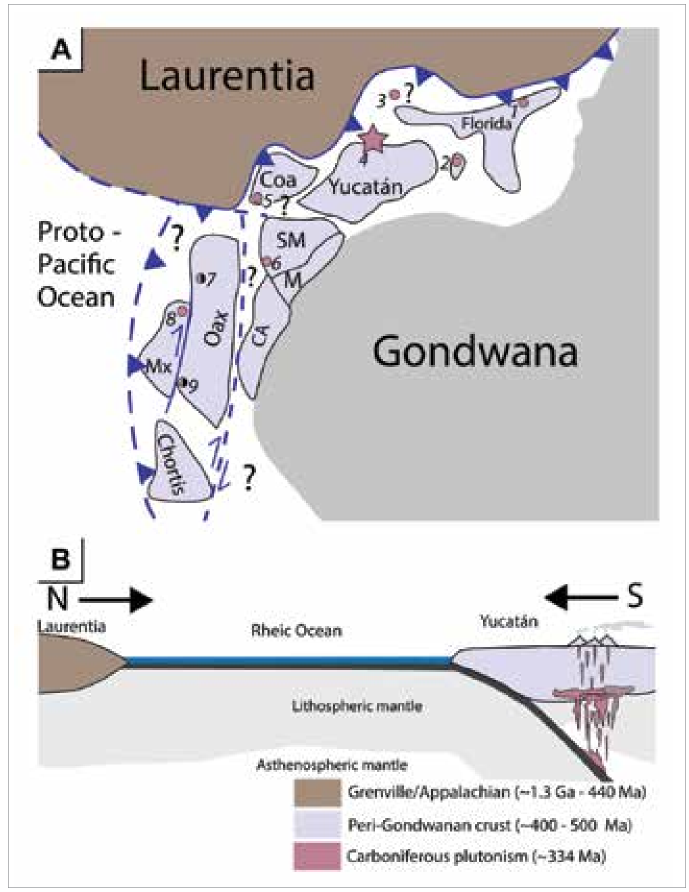
The story of these rocks "turned out to be completely separate from the story of the impact crater."

In 2016, at a cost of $10 million, scientists participating in International Ocean Discovery Program Expedition 364, in collaboration with the International Continental Scientific Drilling Program, extracted an 835-meter-long drill core from the Chicxulub crater. The core includes 600 meters of the peak ring, said Gulick, who serves as co-chief scientist of Expedition 364.

In a recent study published in the *Geological Society of America Bulletin,* Catherine Ross, a doctoral student at the University of Texas at Austin; Gulick; and their coauthors determined the age of the peak ring granites—334 million years old—and unraveled an unexpected history of arc magmatism and supercontinent reconstruction (bit.ly/arc-magma). The story of these rocks, said Gulick, "turned out to be completely separate from the story of the impact crater." The tale is told by tiny crystals of zircon—small clocks within rocks—that record various chapters of Earth's history.



Zircons, like this one with laser ablation points, record the storied history of the Chicxulub crater. Credit: Catherine H. Ross



(a) The amalgamation of Pangea. Laurentia, in brown, lies to the north. Gondwana, shown in gray, lies to the south. Numerous terranes, shown in purple, were caught between the ancient continents of Laurentia and Gondwana. The Yucatán lies in the midst of these terranes, and a pink star indicates the Chicxulub impact site. CA = Colombian Andes; Coa = Coahuila; M = Merida terrane; Mx = Mixteca; Oax = Oaxaquia; SM = Southern Maya. (b) A simplified cross section through Laurentia, the Rheic Ocean, and subduction off the edge of the Yucatán crust. The Rheic Ocean must subduct below the Yucatán to create the arc magmatism responsible for the zircons Ross analyzed. Ga = giga-annum; Ma = mega-annum. Credit: Ross et al., 2021, https://doi.org/10.1130/B35831.1

Getting Past a Shocking Impact

As a melt solidifies, said Ross, zirconium, oxygen, and silicon atoms find each other to form zircon. Trace atoms of radioactive uranium easily swap places with zirconium while excluding lead (the product of uranium decay). By measuring both uranium and lead, geochronologists like Ross can calculate when lead began to accumulate in the crystal. In zircons of granitoids, this date typically records when the grain crystallized from the melt.

The drill core granites, however, harbor an incredible amount of damage caused by the impact's shock wave. "The energy of Chicxulub is equivalent to 10 billion times the size of a World War II era nuclear bomb," said Gulick. Highly damaged zircons from the peak ring yield the impact age, he said, but "once you go below those highest shocked grains, you more faithfully record the original age and not the impact age."

The zircons that Ross and colleagues targeted lacked microstructures that indicate shock, said Maree McGregor, a planetary scientist at the University of New Brunswick who was not involved in this study. "A lot of people would overlook this material when they're trying to understand impact cratering," she said, because past studies focused heavily on the impact age and not the history of the target rocks.

Ross incrementally bored into 835 individual zircons with a laser, measuring age as a function of depth to differentiate age domains. "Being able to visualize the data and separate [them] in that way is...critical when you're trying to establish different ages for different regional tectonic events," said McGregor.

"The energy of Chicxulub is equivalent to 10 billion times the size of a World War II era nuclear bomb."

Ancient Ocean, Volcanic Arc

In addition to the 334-million-year-old Carboniferous zircons, Ross found three older populations. Crystals with ages ranging from 1.3 billion to 1 billion years ago fingerprint the formation of the supercontinent Rodinia. After Rodinia fragmented, 550-million-year-old zircons place the Yucatán crust near the mountainous margins of the West African craton, which was part of the supercontinent Gondwana. Zircons between 500 million and 400 million years old document deformation as these crustal bits moved across the ancient Rheic Ocean toward Laurentia, which today corresponds to the North American continental core, Ross said.

As the Rheic oceanic slab subducted, fluids drove partial melting that powered a volcanic arc on the edge of the Yucatán crust, said Ross. Using trace element geochemistry from individual grains, she found that in spite of their tumultuous impact history, Carboniferous zircons preserve volcanic arc signatures.

This research, said coauthor and geochronologist Daniel Stockli, is very tedious micrometer-by-micrometer work. But ultimately, he said, these finely detailed data illuminate processes at the scale of plate tectonics.

By **Alka Tripathy-Lang** (@DrAlkaTrip), Science Writer

Indian Cities Prepare for Floods with Predictive Technology

Chennai, India, was pummeled by more than 483 millimeters (19 inches) of rain in a single day in 2015. Credit: Veethika, Wikimedia, CC BY-SA 4.0 (bit.ly/ccbysa4-0)

Urban floods in India have caused fatalities, injuries, displacement, and enormous economic losses. Cities across the country are now investing in high-tech tools to better model and forecast these natural hazards.

In 2015, the metropolis of Chennai faced devastating floods responsible for the deaths of more than 500 people and displacement of more than a million more. Financial losses reached around $3 billion. The extent of the damage prompted the Indian government to approach scientists to develop a flood forecasting system for the city.

Subimal Ghosh, a professor of civil engineering at the Indian Institute of Technology Bombay, led the efforts. Chennai's topography makes it particularly vulnerable, Ghosh said. In addition to being a coastal city, Chennai has many rivers and an upstream catchment area from which water flows when there is heavy rainfall.

Forecasting in Chennai

The city's topography determines where inundation occurs and made the development of a flood forecasting system complex. The system had to include the hydrology of the upstream region; river, tidal, and storm surge modeling; and a high-resolution digital elevation map of the city, Ghosh said.

A consortium of scientists from 13 research institutes and government organizations worked on these separate aspects and together developed India's first fully automated real-time flood forecasting system, launched in 2019.

"We generated 800 scenarios of flood and tide conditions," Ghosh said. "When the model receives a weather forecast from the National Centre for Medium Range Weather Forecasting, it will search and find the closest scenario. If there is a chance of flood, the model will predict the vulnerable sites for the next 3 days."

Sisir Kumar Dash is a scientist at the National Centre for Coastal Research (NCCR) in Chennai, which is responsible for the operation of the model. "We analyze daily rainfall data, and if there is a probability of inundation, the model is run and alerts are sent to the state disaster management department," he said.

Since the tool was implemented, however, Chennai has not experienced heavy rainfall, so it has not been put to a strong test.

Forecasting in Bengaluru

Bengaluru, formerly known as Bangalore, has seen some success with its own flood forecasting system, according to scientists at the Indian Institute of Science (IISc) in Bengaluru and the Karnataka State Natural Disaster Monitoring Centre. The organizations developed the system together.

P. Mujumdar, a professor of civil engineering at IISc who led the work, said that "short-duration rainfall forecasts from various weather agencies were combined with our hydrology model—which has high-resolution digital elevation maps of the city—and information on drainage systems and lakes."

Real-time rainfall data are obtained through a network of 100 automatic rain gauges and 25 water level sensors set up on storm water drains at various flood-vulnerable areas across Bengaluru. The model, however, is unable to make reliable predictions if the rainfall is sudden and didn't appear in the forecast, Mujumdar added.

Scaling Up

Raj Bhagat Palanichamy is a senior manager at the Sustainable Cities initiative of the World Resources Institute who was not involved in flood forecasting in Chennai or Bengaluru. He had a sober view of the projects. "A good model is not about the tech or visualization that come with it," he said. Instead, it's "about the ability to help in the decisionmaking process, which hasn't been successfully demonstrated in India."

Shubha Avinash, scientific officer at the Karnataka State Natural Disaster Monitoring Centre, said the forecasting model was still an effective tool: "The forecast model has served as a better decision support system for administrative authorities in disaster preparedness, postflood recovery, and response actions in heavy rain events faced by the city in recent years." Avinash oversees the operation of the Bengaluru flood model.

Avinash added that the alerts help city officials take timely, location-specific action. For instance, the city power company (Bangalore Electricity Supply Company Limited, or BESCOM) makes use of the wind speed and direction forecasts to ascertain which areas would have a probability of fallen electric lines and shuts down power supply to ensure safety.

The tool also has a mobile application, Bengaluru Megha Sandesha (BMS), which can be accessed by officials and residents for real-time information about rainfall and flooding.

Mujumdar added that "short-duration, high-intensity floods are increasing in Indian cities and happen very quickly—within 15–20 minutes—due to climate change and urbanization. Similar models should be developed for all cities."

Last year, India's Ministry of Earth Sciences developed a flood warning system for the Mumbai region, iFLOWS-Mumbai, which is likely to be operational this year.

"Cities need to have a proper road map," Bhagat said, "with not just the model as the target but an integrated response plan (both short term and long term). It should start with the creation and seamless sharing of related data in the public domain."

By **Deepa Padmanaban** (@deepa_padma), Science Writer

Climate Clues from One of the Rainiest Places on Earth

The Pacific Ocean off the coast of Nuquí, Chocó, Colombia, is one of the rainiest spots on Earth. Credit: Andreas Philipp, CC BY-NC-ND 2.0 (bit.ly/ccbyncnd2-0)

A jet stream known as the Chocó low-level jet (the ChocoJet) connects the Pacific Ocean with western Colombia. It helps dump more than 9,000 millimeters of rain each year, making the area offshore of the Colombian town of Nuquí one of the rainiest places on the planet.

"The ChocoJet—this low-level flow—is a physical bridge between the sea surface temperatures and sources of moisture in the Pacific, and the climate patterns of western South America," said John Mejia, an associate research professor of climatology at Nevada's Desert Research Institute and lead author of a new paper on the phenomenon.

In addition to its regional impact, the ChocoJet plays a role in the El Niño–Southern Oscillation (ENSO), a climate pattern whose variations can signal droughts and floods for Colombian farmers. ENSO also has significant impacts on Europe, Africa, Asia, and North America.

"In the atmosphere, we are all connected," Mejia said, and the ChocoJet "is part of the engine that redistributes the heat from the tropics to higher latitudes."

Rainy Puzzle

In 2019, after 6 months of preparations, Mejia and his team were able to get enough helium tanks and sonde balloons to this remote region, which is accessible by only sea or air. They launched the balloons up to four times a day over 51 days, resulting in new data on temperature, winds, and other atmospheric conditions.

They detailed their findings in a recent paper published in the *Journal of Geophysical Research: Atmospheres* (bit.ly/rainy-chocojet). The new data contribute to a better understanding of the dynamics and thermodynamics of the ChocoJet's processes, which have implications for regional wildlife and agriculture, as well as for natural hazards. Mejia said the main contribution of the field campaign in Nuquí and the resulting data was to find out why and how these precipitation mechanisms produce one of the rainiest places on Earth, with the added benefit of building on the very scant climate data gathered previously. "This is a field experiment that can help test climate models.... Figuring this out can make global models more accurate," Mejia said.

Students from Institución Educativa Ecoturistica Litoral Pacifico in Nuquí prepare to launch a sonde balloon during the fieldwork campaign. Credit: Organization of Tropical East Pacific Convection (OTREC) participants/John Mejia

Alejandro Jaramillo, a hydrologist at the Center for Atmospheric Sciences at the National Autonomous University of Mexico, said that more observations will allow for a better model, which will lead to better prediction of rainfall and major weather events, like hurricanes. Jaramillo was not involved in the new research.

"If you better understand the processes that are causing this high rainfall, you can find better ways for climate models to fill in the gaps where there [aren't] hard data," Jaramillo said.

Impacts Beyond Climate

According to Germán Poveda, a coauthor on the recent study and a professor at the National University of Colombia, the project not only aimed to understand the dynamics and thermodynamics that explain the rainiest region on Earth but also was an opportunity to train Colombia's next generation of climate scientists.

Juliana Valencia Betancur, for instance, was an undergraduate environmental engineering student at Colegio Mayor de Antioquia in Medellín during the Nuquí field campaign. She and a half dozen other undergraduate students helped prepare and launch balloons as part of their undergraduate research experience.

"I hadn't had much interest in atmospheric science, but after Nuquí, with all the marvelous things I learned, my outlook changed completely, and my professional career changed course," she said, adding that she is now looking for graduate opportunities in atmospheric science.

Johanna Yepes, a coauthor and researcher based at Colegio Mayor de Antioquia, said that Nuquí's local schoolchildren also benefited from the project's outreach activities. During the field campaign, the researchers visited Nuquí's only school and, with enthusiastic support of the principal, presented their project to students in the fourth to seventh grades. The students were also invited to visit the launch site and got a chance to launch a sonde balloon themselves.

"For me, it was the most beautiful part, putting what we were doing in very simple words and seeing how the children understood the daytime cycle of rain, sometimes even better than we did ourselves," Yepes said.

By **Andrew J. Wight** (@ligaze), Science Writer

Studying Arctic Fjords with Crowdsourced Science and Sailboats

In June 2017, Nicolas Peissel led the 13-meter sailboat *Exiles* out of port in St. John's, Newfoundland and Labrador, Canada. The vessel sailed north to Greenland and into the remnants of Tropical Storm Cindy. Peissel and several other crew members are aid workers for Doctors Without Borders, but they were on a 3-month scientific—not medical—expedition aboard *Exiles*.

The expedition explored the feasibility of crowdsourced science using sailboats to expand data collection in fjords affected by the melting Greenland Ice Sheet. Daniel Carlson, an oceanographer at Germany's Helmholtz-Zentrum Hereon and science officer for the expedition, sailed on *Exiles* for a month. After he left, the crew of nonscientists continued collecting data. The expedition log and preliminary results were published in *Frontiers in Marine Science* (bit.ly/arctic-sailing).

"Scientific work was historically, and should continue to be, undertaken by members of the general public."

Exiles, whose crew collected data on fjords in the Arctic, anchors near a receding glacier in 2017. Credit: Daniel Carlson

The melting ice in Greenland is increasing the amount of fresh water in fjords, which changes the salinity and mixing of ocean water. Scientists don't fully know what impact these changes will have on the marine ecosystem.

To study what contributes meltwater to the ocean, scientists measure the conductivity, temperature, and depth (CTD) of the water column, but reaching these remote fjords to take measurements on research ships is expensive and treacherous. Ships also often carry several research teams with conflicting experimental needs and schedules. These limitations leave gaps in our understanding of the changing Arctic waters.

"Since you're spending so much money on a research cruise, there's usually a push to visit as many fjords as possible," Carlson said, "but with the sailboat, you're able to just stop and investigate things you find interesting." Sailboats also require much less fuel, lessening the environmental impact of Arctic research.

Together, the *Exiles* crew took 147 CTD measurements. Carlson also took aerial photographs of icebergs with a drone to estimate the rate at which they melt. He said this wouldn't have been possible on a research cruise with tight schedules and timelines.

Crowdsourcing Science in the Arctic

Carlson collected much-needed data on changes occurring in fjords as a result of melting ice. The expedition also demonstrated that crowdsourced science is a viable option for expanding Arctic oceanography research.

"We were extremely happy that we could collaborate with a professional scientist in a scientific institution," said Peissel, who is a coauthor on the paper. "But we also wanted to be the citizens that could produce raw, reliable scientific data, and we proved that." The crew took 98 CTD measurements after Carlson left.

Caroline Bouchard, a fisheries scientist at the Greenland Institute of Natural Resources who wasn't involved in the study, also uses sailboats for Arctic research. She appreciates their affordability and versatility and would like to see more people with sailboats taking part in research. "It's not like you can just make your own thing—you need the instruments—but I think there would be interest from citizen scientists," Bouchard said.

Although it takes experienced sailors to navigate in the Arctic, more sailboats than ever have been heading north, which could bring new opportunities for amateur scientists. Peissel said that sailors in the Arctic usually have an intense connection to the sea and nature. "These are the people who are more than likely to say, 'Hey, why don't you put your instruments on board?'"

Following their study's success, Carlson and Peissel are planning another expedition to the Arctic in 2022. "The scientific discipline, just like humanitarianism, does not uniquely belong to the scientist or the humanitarian," Peissel said. "Scientific work was historically, and should continue to be, undertaken by members of the general public."

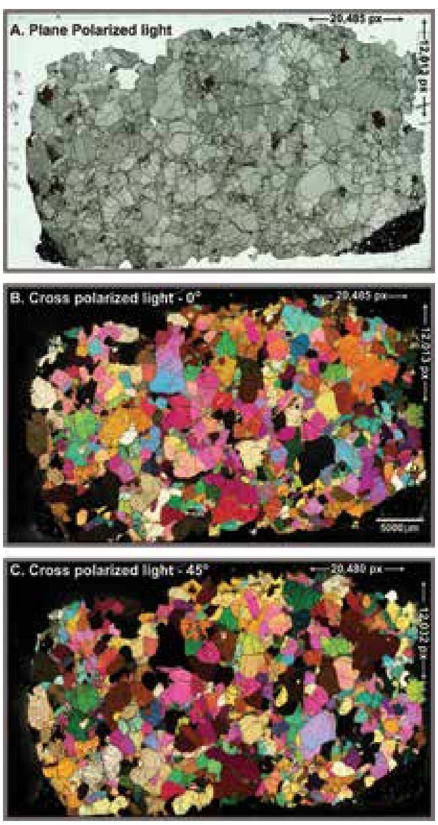
By **Andrew Chapman** (@andrew7chapman), Science Writer

A New Tool May Make Geological Microscopy Data More Accessible

It all started with a problem many geoscientists faced in 2020.

Alex Steiner, a doctoral student at Michigan State University, had research to do working on thin sections—slivers of geological materials that are usually analyzed under a microscope. But he and the two undergraduate students on the project were not allowed to access the lab or the geological samples they were working on because of the pandemic.

It was out of this necessity that Steiner helped develop a new tool that could automatically take pictures of entire thin sections and stitch them into digital panoramic microscope images that could be analyzed anywhere.



These image mosaics of a fragment of Earth's mantle were collected in optical arrangements with the PiAutoStage: (a) plane-polarized light, (b) cross-polarized light, and (c) cross-polarized light at 45° of rotation. Three sets of images permit students to examine minerals and rock textures in a way that replicates the experience of using a petrographic microscope. Credit: Steiner and Rooney, 2021, https://doi.org/10.1029/2021GC009693

A technical report on the device, named PiAutoStage, was recently published in *Geochemistry, Geophysics, Geosystems* (bit.ly/pi-auto-stage).

Because thin sections are also commonly used for instruction in geoscience lab courses, PiAutoStage could also provide instructors a new, affordable resource to digitize and use specimens and literary materials they already have curated in their curriculum.

"I think this is a really nice approach to a problem that I heard a lot of people talking about last year when everything moved online," said Anita Marshall, a geologist at the University of Florida who was not involved in the study. "Anybody that had any sort of microscope work in their courses really struggled to move that work online."

Getting Microscopy Online

PiAutoStage consists of an open-source mechanism that moves the sample around the microscope, attached to a high-resolution integrated camera and an inexpensive Raspberry Pi computer. The researchers wrote computer code to take hundreds of high-resolution images of an entire microscope sample and combine them into a single panorama.

This technique allowed two undergraduate students—one at Michigan State University in East Lansing and another at Wayne State University in Detroit—to work collaboratively on the same project at the same time using the same thin sections of a flood basalt sequence, said Tyrone Rooney, a geologist at Michigan State University and senior author of the paper.

And for the most part, the students enjoyed working with the microscope images online, Steiner said. "Because the interface behaves the same way as things like Google Earth or things like that. It's just zoom in, zoom out, click and drag around. So they picked it up real quick. I don't think anyone had any complaints, even with the very first lab we ran this year.

One downside to long-distance microscopy, however, is its difficulty in replicating the collegiality that comes with the ability of "students to be able to shout across [the room] to another student, 'Hey, what's this?'" said Rooney. The researchers tried to replicate this interaction by allowing students to share panorama views with one another.

The software also does not replicate all the different functions of a microscope, Rooney said. "You don't have the ability to use a lot of the advanced tools that are in a microscope that help students identify ambiguous crystals."

Despite these limitations, "from the perspective of a broad teaching tool, we think it's useful and in fact is different to a microscope," Rooney added. "Previously, students would not have actually been able to see the entire area of a microscope slide in a panoramic image."

"In a postpandemic world, devices like this could still be used for teaching. It allows students to have access to samples, for example, that might be very valuable and can't be left in the lab, or there aren't enough thin sections for an entire group."

More Accessible Geoscience

"In a postpandemic world, devices like this could still be used for teaching," Rooney said. PiAutoStage "allows students to have access to samples, for example, that might be very valuable and can't be left in the lab, or there aren't enough thin sections for an entire group."

Although resources that can image microscope samples already exist, they are often prohibitively expensive: Microscopes with built-in or add-on cameras can cost tens of thousands of dollars.

By contrast, because the PiAutoStage mechanism is entirely 3D printed, it would cost less than $200 to make the device, said Steiner, who was lead author of the report. "You don't have to order the parts from anybody or anything like that. You can literally make all of the hardware—it's all printed and assembled, [and] basically, it snaps together."

The system is also open source and made to be adaptable to almost any microscope. The researchers have set up a PiAutoStage

A crystal-rich lava from northern Kenya was captured in cross-polarized light. The lava contains abundant, chemically zoned clinopyroxene crystals that record a history of magma interactions. Credit: Steiner and Rooney, 2021, https://doi.org/10.1029/2021GC009693

website detailing examples, instructions, and FAQs to help others build their own device.

The new technique could make future research into thin sections more accessible, Rooney said. "With more of these devices out there, more innovations will happen simply because more people are trying to use it. I don't know what will happen. All I can say is, when we introduce a new tool, usually data follows."

The images produced by PiAutoStage have one additional benefit.

"Just looking at the thin section imagery that I've taught with for years in a different way, I've seen them in a different way," Rooney said.

"All the petrologists that have seen what this is have also responded with, 'This is so cool.' In fact, that word seems to be one that is used quite an awful lot," he added.

By **Richard J. Sima** (@richardsima), Science Writer

Forecasters Navigate a Highway to Success Around Lake Victoria

With the sight of a color-coded flag or the touch of a mobile phone button, fishers and fish traders along the vast shores of Lake Victoria now know when it's ideal to postpone a fishing trip or to buy less fish for the day.

Four years of testing an early-warning system (EWS) to inform fisherfolk in East Africa of approaching high-impact weather events on Lake Victoria recently concluded. The High Impact Weather Lake System (HIGHWAY) project successfully demonstrated how improved weather, water, and climate services can save lives and livelihoods, as well as support socioeconomic development of vulnerable communities.

In 2017, the HIGHWAY project started on Lake Victoria, the largest of the African Great Lakes and the largest inland fishery on the continent. Lake Victoria's 7,145-kilometer-long shoreline is shared by Kenya, Tanzania, and Uganda. Fisheries employ between 500,000 and a million people from those countries as well as from neighboring nations Burundi and Rwanda and harvest about a million metric tons of fish every year.

A man raises a red flag, signaling severe weather, on the shores of Lake Victoria. Credit: Samuel Gatei/WMO

Lake Victoria's size (it is the world's second-largest freshwater lake, behind only Lake Superior in North America) allows it to generate its own weather patterns, sometimes suddenly and with human and economic casualties. According to its website, HIGHWAY aimed to "enhance the resilience of African people and economic development to weather and climate related shocks, with an initial focus on the Lake Victoria Basin." The project was funded by £4.5 million from the U.K. Department for International Development, under Weather and Climate Information Services for Africa.

"HIGHWAY was an ambitious project that spanned the entire weather and climate services value chain—improving surface-based observations, developing products to improve forecasting quality, and providing training on impact-based forecasts and warnings in the Lake Victoria basin," said Jay Wilson, head of the Project Management and Implementation Division at the World Meteorological Organization (WMO).

"Thanks to the strong commitment, partnership, and collaboration from all international and regional partners, we succeeded in increasing access to and use of co-designed early warnings that improved the lives of communities living in the Lake Victoria basin," said Wilson.

"This early-warning system is a good thing for Lake Victoria, because according to Red Cross statistics, about 5,000 people were dying annually [due to storms, strong winds, and large waves] prior to the year 2016. This figure does not include all the deaths that occur on the lake given that not all incidents are reported," said Paul Oloo, Kisumu County director of meteorology and assistant director of the Kenya Meteorological Department.

> **"Thanks to the strong commitment, partnership, and collaboration…we succeeded in increasing access to and use of codesigned early warnings that improved the lives of communities living in the Lake Victoria basin."**

Making the System

As part of the project, the National Meteorological and Hydrological Services (NMHSs) of Kenya, Rwanda, Tanzania, and Uganda cooperated in generating regular Lake Victoria weather forecasts and severe weather warnings.

HIGHWAY supported the increase in availability of meteorological data and observations throughout the Lake Victoria basin. Of note, the project contributed to the rehabilitation of upper air stations in Lodwar and Nairobi, Kenya; Entebbe, Uganda; and Dar es Salaam, Tanzania.

The project also contributed to the availability of such enhanced tools as high-resolution modeling, as well as products, including Rapidly Developing Thunderstorm (which detects, tracks, characterizes, and forecasts convective cells) and Convective Rainfall Rate (an algorithm based on the assumption that high clouds with a large vertical extent are more likely to be raining). Such products improve the accuracy of severe

Fisherfolk are among those most threatened by severe weather on Lake Victoria. Credit: Samuel Gatei/WMO

weather forecasting in the basin, explained Wilson.

Practical Outcomes

Because of the HIGHWAY enhancements, the Uganda National Meteorological Authority is able to provide updates on thunderstorms and heavy rain over Lake Victoria in real time. In Kenya and Tanzania, marine weather forecasts are now being disseminated specifically to fishing communities twice per day. The forecasting offices of all three NMHSs also share their published forecasts through a WhatsApp group.

A three-color traffic light flag system and notice boards are also used on beaches around the lake to describe the conditions expected during the forecast period.

The flag signals help people without smartphones, said Ibrahim Mengo, a fisherman in Uganda. "When I look at the forecast and see the flag is green, then I know it's OK to go, but when [the flag is] red or orange, I know where I'm going is not safe and I decide whether or not to go."

Communication and Cooperation

Efforts supported by HIGHWAY addressed improving communication and cooperation in sharing meteorological data among organizations and communities. Severe weather forecasts, participants said, could be inconsistent: In some cases, fisherfolk did not receive any weather warning. In other cases, the fisherfolk did not take received weather information seriously, and sometimes they did not understand the message itself, Oloo said.

In contrast, "the early-warning information passed currently to them is in a language and format that they can understand. Weather warnings were co-designed with them, standard weather messages developed jointly, and the weather information passed directly in its original format using the WhatsApp platform," Oloo said.

"The early-warning information passed currently to [fisherfolk] is in a language and format that they can understand. Weather warnings were co-designed with them, standard weather messages developed jointly, and the weather information passed directly in its original format using the WhatsApp platform."

Innovations also included a "quick reference guide developed for translating standard weather terms to local languages," he added.

Training sessions for forecasters, observers, and users in fishing communities have built trust in the forecasts. "Communities are more confident in using the weather information to plan fishing trips and other journeys on the lake," said Wilson.

In establishing the regional early-warning system, standard operating procedures and impact-based warning methods were developed jointly by partner states. Representatives from those states joined daily teleconferences so they could agree on severe weather warning information, but each partner state disseminated weather advisories in its area of jurisdiction.

"We receive weather messages on our phones, and when you get an update, you send it to other people and put it on your WhatsApp status so that it can reach many fishermen," said Mildred Shihanga, a fish trader in Kenya.

Saving Lives and Livelihoods

"I think the EWS for Lake Victoria is a very good and important step to protect the lives and livelihoods of the communities that live around the lake," said Nairobi-based climate scientist Abubakr Salih Babiker of the Intergovernmental Authority on Development's Climate Prediction and Applications Centre, which provides climate services to 11 East African countries but is not part of the HIGHWAY project.

"The boats used by fishermen are small and have no access to weather forecasts, especially when they are in the water. Now the EWS gives them the forecast before and while they are in the water using mobile technology," Babiker said. "It also helps farmers to plan better. It will help in saving lives and livelihoods."

Rumelia Joshua, a fish trader in Tanzania, agreed. "The information helps us because when we get notified about bad weather, we buy fish in small quantities and save money," she said.

Scaling Up

WMO and other supporters of the HIGHWAY project plan to scale it up to encompass regional forecasting for all of East Africa, said Wilson.

Babiker said HIGHWAY owes its success to the cooperation of the partner states as well as to forecast products that focus on the lake itself as opposed to national systems. "In this way, you get better products and better user services. If you are a fisherwoman on the lake, you basically need the same information regardless of your country," he said.

By **Munyaradzi Makoni** (@MunyaWaMakoni), Science Writer

"Earth Cousins" Are New Targets for Planetary Materials Research

Are the processes that generate planetary habitability in our solar system common or rare elsewhere? Answering this fundamental question poses an enormous challenge.

For example, observing Earth-analogue exoplanets—that is, Earth-sized planets orbiting within the habitable zone of their host stars—is difficult today and will remain so even with the next-generation James Webb Space Telescope (JWST) and large-aperture ground-based telescopes. In coming years, it will be much easier to gather data on—and test hypotheses about the processes that generate and sustain habitability using—"Earth cousins." These small-radius exoplanets lack solar system analogues but are more accessible to observation because they are slightly bigger or slightly hotter than Earth.

Here we discuss four classes of exoplanets and the investigations of planetary materials that are needed to understand them (Figure 1). Such efforts will help us better understand planets in general and Earth-like worlds in particular.

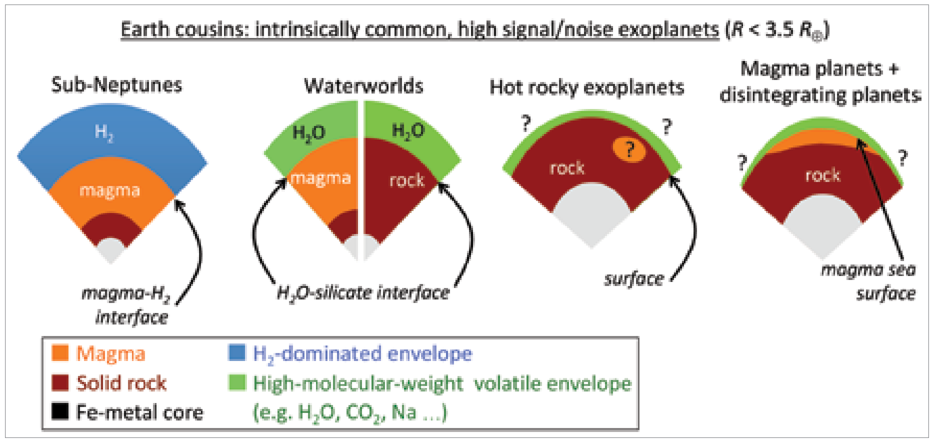


Fig. 1. Shown here are four common exoplanet classes that are relatively easy to characterize using observations from existing telescopes (or telescopes that will be deployed soon) and that have no solar system analogue. Hypothetical cross sections for each planet type show interfaces that can be investigated using new laboratory and numerical experiments. CO_2 = carbon dioxide, Fe = iron, H_2 = molecular hydrogen, H_2O = water, Na = sodium.

What's in the Air?

On exoplanets, the observable is the atmosphere. Atmospheres are now routinely characterized for Jupiter-sized exoplanets. And scientists are acquiring constraints for various atmospheric properties of smaller worlds (those with a radius *R* less than 3.5 Earth radii), which are very abundant [e.g., *Benneke et al.*, 2019; *Kreidberg et al.*, 2019]. Soon, observatories applying existing methods and new techniques such as high-resolution cross-correlation spectroscopy will reveal even more information.

For these smaller worlds, as for Earth, a key to understanding atmospheric composition is understanding exchanges between the planet's atmosphere and interior during planet formation and evolution. This exchange often occurs at interfaces (i.e., surfaces) between volatile atmospheres and condensed (liquid or solid) silicate materials. For many small exoplanets, these interfaces exhibit pressure-temperature-composition (*P*-*T*-*X*) regimes very different from Earth's and that have been little explored in laboratory and numerical experiments. To use exoplanet data to interpret the origin and evolution of these strange new worlds, we need new experiments exploring the relevant planetary materials and conditions.

Studying Earth cousin exoplanets can help us probe the delivery and distribution of life-essential volatile species—chemical elements and compounds like water vapor and carbon-containing molecules, for example, that form atmospheres and oceans, regulate climate, and (on Earth) make up the biosphere. Measuring abundances of these volatiles on cousin worlds that orbit closer to their star than the habitable zone is relatively easy to do. These measurements are fundamental to understanding habitability because volatile species abundances on Earth cousin exoplanets will help us understand volatile delivery and loss processes operating within habitable zones.

For example, rocky planets now within habitable zones around red dwarf stars must have spent more than 100 million years earlier in their existence under conditions exceeding the runaway greenhouse limit, suggesting surface temperatures hot enough to melt silicate rock into a magma ocean. So whether these worlds are habitable today depends on the amount of life-essential volatile elements supplied from sources farther from the star [e.g., *Tian and Ida*, 2015], as well as on how well these elements are retained during and after the magma ocean phase.

Volatiles constitute a small fraction of a rocky planet's mass, and quantifying their abundance is inherently hard. However, different types of Earth cousin exoplanets offer natural solutions that can ease volatile detection. For example, on planets known as sub-Neptunes, the spectroscopic fingerprint of volatiles could be easier to detect because of their mixing with lower-molecular weight atmospheric species like hydrogen and helium. These lightweight species contribute to more puffed-up (expanded) and thus more detectable atmospheres. Hot, rocky exoplanets could "bake out" volatiles from their interiors while also heating and puffing up the atmosphere, which would make spectral features more visible. Disintegrating rocky planets may disperse their volatiles into large, and therefore more observable, comet-like tails.

Let's look at each of these examples further.

Unexpected Sub-Neptunes

About 1,000 sub-Neptune exoplanets (radius of 1.6–3.5 Earth radii) have been confirmed. These planets, which are statistically about as common as stars, blur the boundary between terrestrial planets and gas giants.

Strong, albeit indirect, evidence indicates that the known sub-Neptunes are mostly magma by mass and mostly atmosphere by volume (for a review, see *Bean et al.* [2021]).

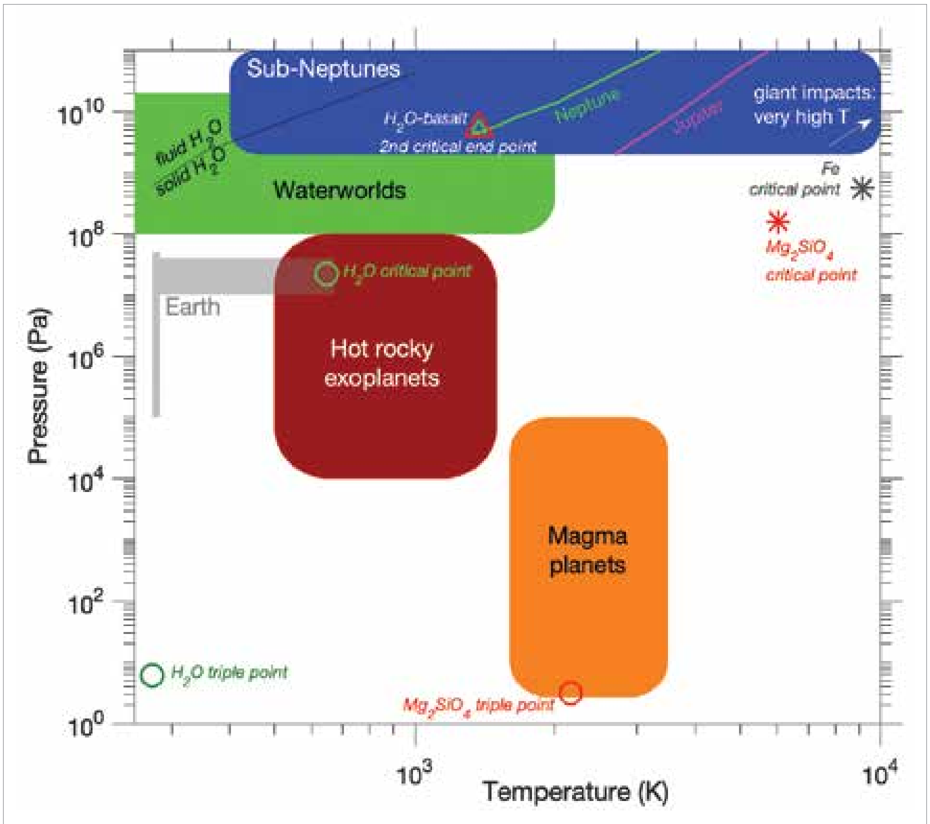


Fig. 2. Ranges of plausible conditions at the interfaces between silicate surface rocks and volatile atmospheres on different types of worlds are indicated in this pressure–temperature (P-T) diagram. Conditions on Earth, as well as other relevant conditions (critical points are the highest P-T points where materials coexist in gaseous and liquid states, and triple points are where three phases coexist), are also indicated. Mg_2SiO_4 = forsterite, an igneous mineral that is abundant in Earth's mantle.

This evidence implies that an interface occurs, at pressures typically between 10 and 300 kilobars, between the magma and the molecular hydrogen (H_2)-dominated atmosphere on these planets. Interactions at and exchanges across this interface dictate the chemistry and puffiness of the atmosphere. For example, water can form and become a significant fraction of the atmosphere, leading to more chemically complex atmospheres.

Improved molecular dynamics calculations are needed to quantify the solubilities of gases and gas mixtures in realistic magma ocean compositions (and in iron alloys composing planetary cores, which can also serve as reservoirs for volatiles) over a wider range of pressures and temperatures than we have studied until now. These calculations should be backed up by laboratory investigations of such materials using high-pressure instrumentation like diamond anvil cells. These calculations and experiments will provide data to help determine the equation of state (the relationship among pressure, volume, and temperature), transport properties, and chemical kinetics of H_2-magma mixtures as they might exist on these exoplanets.

Because sub-Neptunes are so numerous, we cannot claim to understand the exoplanet mass-radius relationship in general (in effect, the equation of state of planets in the galaxy) without understanding interactions between H_2 and magma on sub-Neptunes. To understand the extent of mixing between H_2, silicates, and iron alloy during sub-Neptune assembly and evolution, we need more simulations of giant impacts during planet formation [e.g., *Davies et al.*, 2020], as well as improved knowledge of convective processes on these planets. Within the *P-T-X* regimes of sub-Neptunes, full miscibility between silicates and H_2 becomes important (Figure 2).

Beyond shedding light on the chemistry and magma-atmosphere interactions on these exoplanets, new experiments may also help reveal the potential for and drivers of magnetic fields on sub-Neptunes. Such fields might be generated within both the atmosphere and the magma.

Hot and Rocky

From statistical studies, we know that most stars are orbited by at least one roughly Earth-sized planet (radius of 0.75–1.6 Earth radii) that is irradiated more strongly than our Sun's innermost planet, Mercury. These hot, rocky exoplanets, of which about a thousand have been confirmed, experience high fluxes of atmosphere-stripping ultraviolet photons and stellar wind. Whether they retain life-essential elements like nitrogen, carbon, and sulfur is unknown.

On these hot, rocky exoplanets—and potentially on Venus as well—atmosphere-rock or atmosphere-magma interactions at temperatures too high for liquid water will be important in determining atmospheric composition and survival. But these interactions have been only sparingly investigated [*Zolotov*, 2018].

Many metamorphic and melting reactions between water and silicates under kilopascal to tens-of-gigapascal pressures are already known from experiments or are tractable using thermodynamic models. However, less well understood processes may occur in planets where silicate compositions and proportions are different than they are on Earth, meaning that exotic rock phases may be important. Innovative experiments and modeling that consider plausible exotic conditions will help us better understand these planets. Moreover, we need to conduct vaporization experiments to probe whether moderately volatile elements are lost fast enough from hot, rocky planets to form a refractory lag and reset surface spectra.

Exotic Water Worlds?

Water makes up about 0.01% of Earth's mass. In contrast, the mass fraction of water on Europa, Ceres, and the parent bodies of carbonaceous chondrite meteorites is some 50–3,000 times greater than on Earth. Theory predicts that such water-rich worlds will be common not only in habitable zones around other stars but in closer orbits as well. JWST will be able to confirm or refute this theory [*Greene et al.*, 2016].

If we could descend through the volatile-rich outer envelope of a water world, we might find habitable temperatures at shallow depths [*Kite and Ford*, 2018]. Some habitable layers may be cloaked beneath H_2. Farther down, as the atmospheric pressure reaches 10 or more kilobars, we might encounter silicate-volatile interfaces featuring supercritical fluids [e.g., *Nisr et al.*, 2020] and conditions under which water can be fully miscible with silicates [*Ni et al.*, 2017].

We still need answers to several key questions about these worlds. What are the equilibria and rates of gas production and uptake for rock-volatile interfaces at water world "seafloors"? Can they sustain a habitable climate? With no land, and thus no continental weathering, can seafloor reactions supply life-essential nutrients? Do high pressures and stratification suppress the tectonics and volcanism that accelerate interior-atmosphere exchange [*Kite and Ford*, 2018]?

As for the deep interiors of Titan and Ganymede in our own solar system, important open questions include the role of clathrates (compounds like methane hydrates in which one chemical component is enclosed within a molecular "cage") and the solubility and transport of salts through high-pressure ice layers.

Experiments are needed to understand processes at water world seafloors. Metamorphic petrologists are already experienced with the likely pressure-temperature conditions in these environments, and exoplanetary studies could benefit from their expertise. Relative to rock compositions on Earth, we should expect exotic petrologies on water worlds—for example, worlds that are as sodium rich as chondritic meteorites. Knowledge gained through this work would not only shed light on exoplanetary habitability but also open new paths of research into studying exotic thermochemical environments in our solar system.

Magma Seas and Planet Disintegration

Some 100 confirmed rocky exoplanets are so close to their stars that they have surface seas of very low viscosity magma. The chemical evolution of these long-lived magma seas is affected by fractional vaporization, in which more volatile materials rise into the atmosphere and can be relocated to the planet's darkside or lost to space [e.g., *Léger et al.*, 2011; *Norris and Wood*, 2017], and perhaps by exchange with underlying solid rock.

Magma planets usually have low albedos, reflecting relatively little light from their surfaces. However, some of these planets appear to be highly reflective, perhaps because their surfaces are distilled into a kind of ceramic rich in calcium and aluminum. One magma planet's thermal signature has been observed to vary from month to month by a factor of 2 [*Demory et al.*, 2016], implying that it undergoes a global energy balance change more than 10,000 times greater than that from anthropogenic climate change on Earth. Such large swings suggest that fast magma ocean-atmosphere feedbacks operate on the planet.

To learn more about the chemical evolution and physical properties of exoplanet magma seas, we need experiments like those used to study early-stage planet formation, which can reveal information about silicate vaporization and kinetics under the temperatures (1,500–3,000 K) and pressures (10^{-5} to 100 bars) of magma planet surfaces.

Exoplanets and exoplanetesimals that stray too close to their stars are destroyed—about five such cases have been confirmed. These disintegrating planets give geoscientists direct views of exoplanetary silicates because the debris tails can be millions of kilometers long [*van Lieshout and Rappaport*, 2018]. For disintegrating planets that orbit white dwarf stars, the debris can form a gas disk whose composition can be reconstructed [e.g., *Doyle et al.*, 2019].

To better read the signals of time-variable disintegration, we need more understanding of how silicate vapor in planetary outflows condenses and nucleates, as well as of fractionation processes at and above disintegrating planets' surfaces that may cause observed compositions in debris to diverge from the bulk planet compositions.

Getting to Know the Cousins

In the near future, new observatories like JWST and the European Space Agency's Atmospheric Remote-sensing Infrared Exoplanet Large-survey (ARIEL, planned for launch in 2029) will provide new data. When they do, and even now before they come online, investigating Earth cousins will illuminate the processes underpinning habitability in our galaxy and reveal much that is relevant for understanding Earth twins.

From sub-Neptunes, for example, we can learn about volatile delivery processes. From hot, rocky planets, we can learn about atmosphere-interior exchange and atmospheric loss processes. From water worlds, we can learn about nutrient supplies in exoplanetary oceans and the potential habitability of these exotic environments. From disintegrating planets, we can learn about the interior composition of rocky bodies.

Laboratory studies of processes occurring on these worlds require only repurposing and enhancing existing experimental facilities, rather than investing in entire new facilities. From a practical standpoint, the scientific rewards of studying Earth cousins are low-hanging fruit.

Acknowledgments

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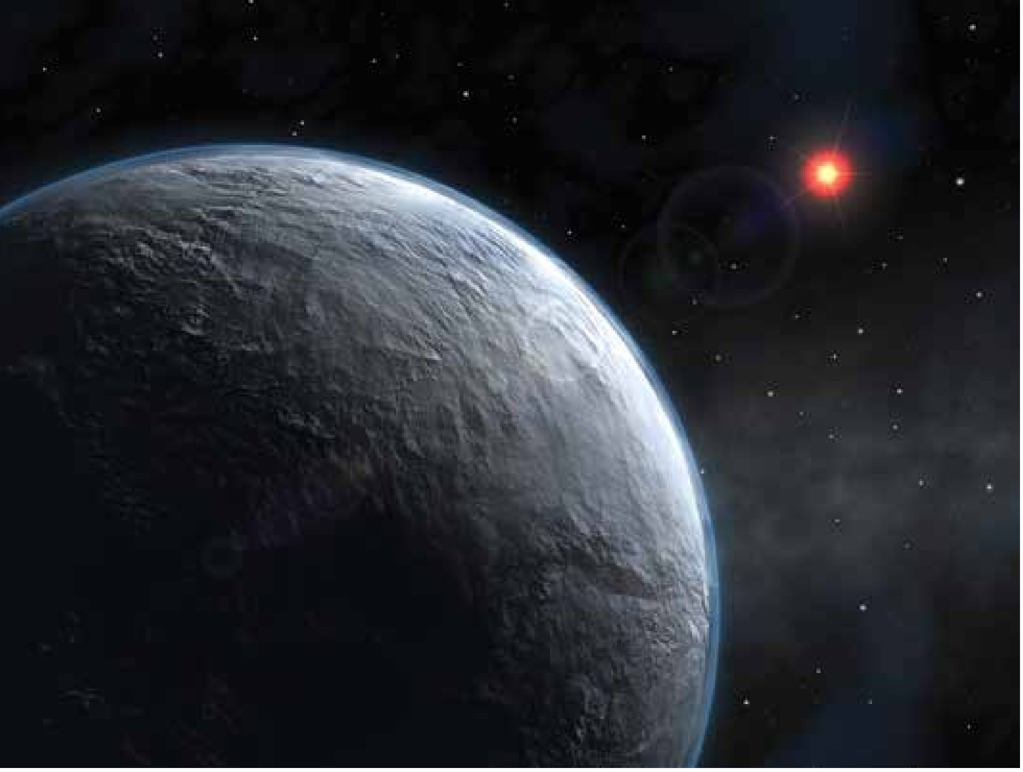
EXOPLANETS IN THE SHADOWS

By Damond Benningfield

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

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

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



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

on television news (including CNN) soon after.

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

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

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

Death of a Planet

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

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

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

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

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

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

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

Stars That Take a Dip

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

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

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

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

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

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

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

A Second Chance at Life

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

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

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

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

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

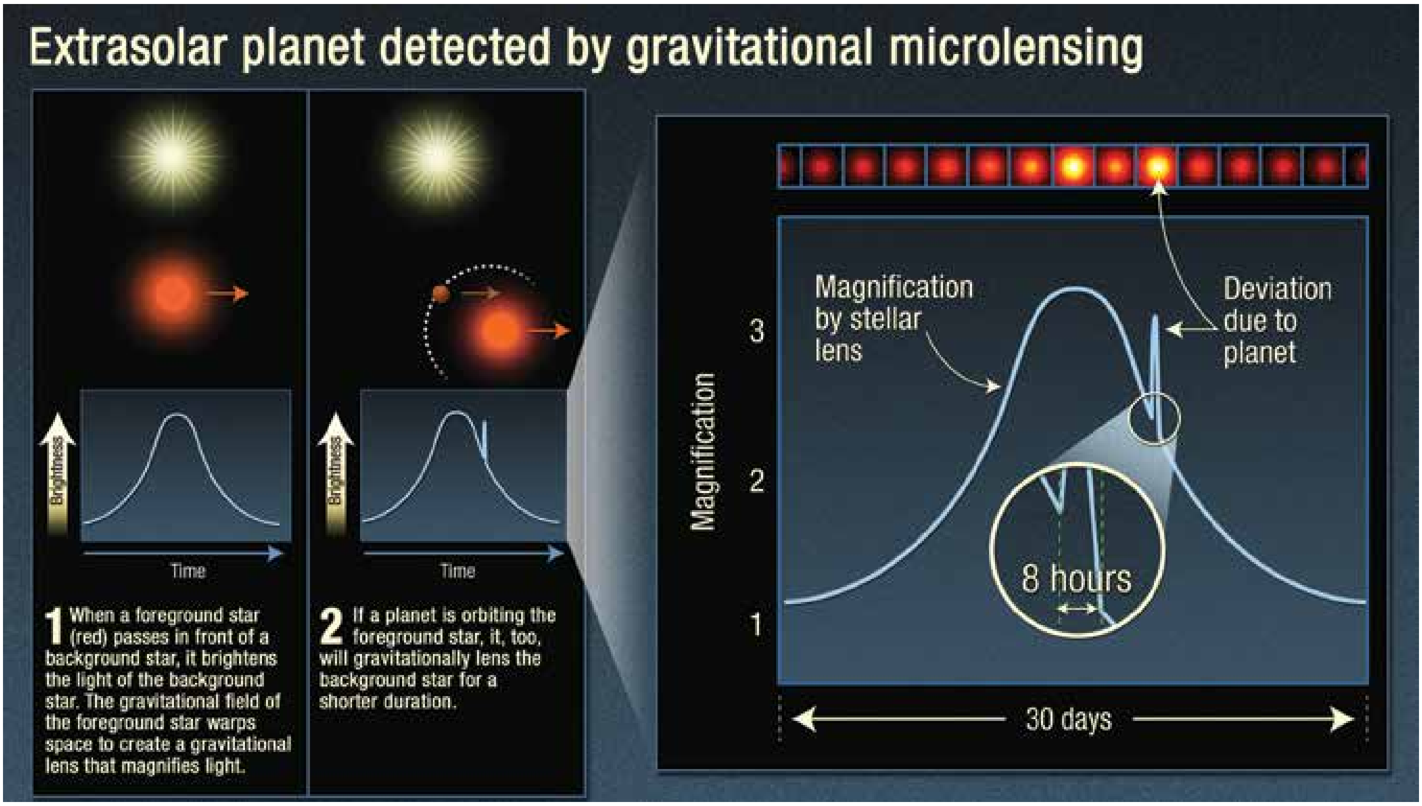
Metzger and Ben Margalit, also of Columbia, have suggested, for example, that the companion could be a white dwarf. The extreme gravity of the neutron star tears the white dwarf apart—perhaps in a matter of seconds—and the debris forms a disk around the pulsar. Some of the material in the disk falls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

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

A Rogues' Gallery of Exoplanets

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

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



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

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

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

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

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

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

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

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

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

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

As with astrometry discoveries and the Gaia mission, though, a space telescope may greatly expand the numbers of confirmed exoplanets. The Nancy Grace Roman Space Telescope, which is scheduled for launch later in the decade, could find 1,400 bound exoplanets and 300 rogues during its lifetime, Penny said. The telescope's mirror will be the same size as that of Hubble Space Telescope, but with a field of view 100 times wider. That field of view will allow Roman to see a large area toward the galactic bulge—the preferred target for microlensing planet searches. Current plans call for it to scan the region six times for 72 days per session.

"It's the ideal platform for doing microlensing because you can never predict when a lensing event will occur, and planetary events are very short," Penny said.

One Telescope, Many Exoplanet Studies

Roman is expected to help with other exoplanet studies as well. As a technology demonstration, it will carry a coronagraph, which blocks the light of a star, allowing astronomers to see the light of planets directly. "It'll try to get down to Jupiter-like exoplanets that are closer than Jupiter is now," said Mayorga. "It might get as close as 1 AU for a Sun-like star."

Current images of exoplanets, whether from telescopes in space or on terra firma, generally cover a single pixel. To better understand those pictures, scientists use the planets of our solar system as exoplanet analogues. In essence, they take the beautiful pictures of Earth and the other worlds that fill Instagram pages and squish them down to a pixel. "That sets a ground truth for the weird things we find in the universe," Mayorga said. "It allows us to connect that disk-integrated light to the underlying cloud bands or continents or oceans. It's the only place we can make that connection."

Mayorga and colleagues used Cassini images snapped during a flyby of Jupiter as one analogue. They saw how the planet's brightness and color changed as viewed under different Sun angles or as the Great Red Spot rotated in and out of view.

Several teams are developing missions or instruments that would use Earth as an exoplanet analogue. Mayorga, for example, is involved with a concept known as Earth transit observer, a proposed CubeSat mission that would watch Earth from L2, a gravitationally stable point in space roughly 1.5 million kilometers beyond Earth. Transits of the Sun would reveal the composition of our planet's atmosphere, including its many "biomarkers," such as oxygen, ozone, and methane.

Another mission, LOUPE (Lunar Observatory for Unresolved Polarimetry of Earth), would monitor Earth in both optical and

A rogue planet glides through the galaxy alone in this artist's impression. Credit: NASA/JPL-Caltech

polarized light from an instrument that hitches a ride on a lunar orbiter or lander.

"Measuring the linear polarization of a planet over a range of time yields a wealth of information about atmospheric constituents and clouds, as well as surface features like vegetation, water, ice, snow, or deserts," said Dora Klindžić, a member of the mission team and a graduate student at Delft University of Technology and Leiden Observatory. "By observing Earth from a distance where we can reasonably pretend we are an outsider looking at the Earth, such as from the Moon, we can learn how a planet richly inhabited with life and vegetation appears when observed from another faraway planet. In a way, we are looking at ourselves to know others."

Interstellar Probe could provide that type of understanding from an even more distant perspective. The proposed spacecraft could travel up to 1,000 AU from the Sun to study interstellar space and would look back toward the planets of the solar system. "Ten, 20, 30 years into the mission, we would have observations of the solar system from outside looking in, as if we were flipping the telescope and taking a look at a planetary system we do know," said Michael Paul, project manager for the mission study at APL. "Tying that with in situ data we have for Mercury, Venus, Mars, Earth, Jupiter, Saturn will better inform the models we have of other planetary systems."

No Tatooines Here

Give an object a good name, and people are likely to pay attention. "The fact that [Boyajian's Star] has this special name means that there aren't many other objects like it," said Redfield. Perhaps with catchier names, the "unsung" planets and techniques, which can produce some of the most thought-provoking discoveries, will gain their share of the spotlight.

The three exoplanets discussed at the January 1996 press conference, for example, were designated 51 Pegasi b, 47 Ursae Majoris b, and 70 Gamma Virginis b—the names of the parent stars followed by the letter b. Astronomers have used that naming scheme ever since, with extra planets in a system assigned the letters c, d, e, and so on, on the basis of the order of discovery.

The system works well, although the names get a little confusing when the star has only a long catalog designation; no one's going to be enchanted by 2MASS J21402931+1625183 A b, for example. And such "telephone book" designations are hardly going to appeal to the public, which regularly sees planets with names like Tatooine and Vulcan and Gallifrey in movies and TV shows.

So the IAU has conducted two international competitions that have produced proper names for more than 140 exoplanets. In the most recent project, 112 countries held individual contests, with each country proposing the name for one planet and its star.

"It was great to tap into the public imagination," said Eric Mamajek, cochair of the naming campaign steering committee and deputy chief scientist for NASA's Exoplanet Exploration Program. "I was blown away by the ones that made it through the campaign. The names all have stories."

Astronomers have been slow to adopt the names, though. The names don't show up in most of the major online catalogs, for example. "Those phone book names take on the intimacy of a proper name for most astronomers," said Redfield. "I know that HD 189733 b [an exoplanet he's studied] is just a bunch of numbers, but for me it has the power of a proper name. I call it '189.' We're on a nickname basis."

"I think it will be a long process," said Mamajek. "It may take a new generation—people who grew up reading these names in textbooks."

Perhaps that new generation will recognize the first exoplanet confirmed around a Sun-like star not as 51 Pegasi b but as Dimidium or the first pulsar planets not as PSR B1257+12 b and c but as Draugr and Poltergeist.

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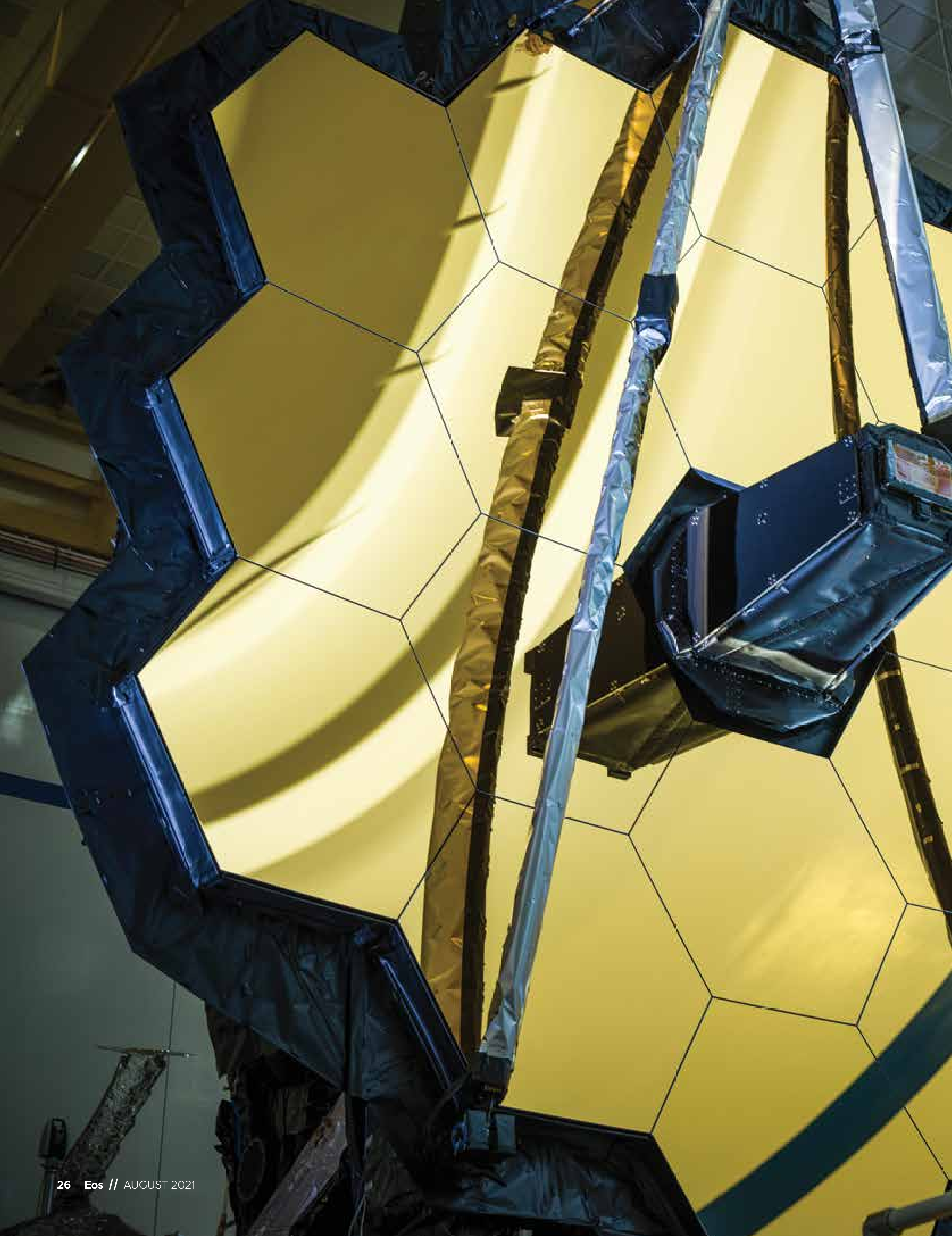

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OVERTURE TO EXOPLANETS

BY KIMBERLY M. S. CARTIER

THE CURTAIN IS ABOUT TO RISE ON THE JAMES WEBB SPACE TELESCOPE. LET'S SEE WHAT'S IN STORE FOR ITS OPENING ACT.

The James Webb Space Telescope's iconic hexagonal golden mirrors allow it to collect a broad range of infrared light, perfect for uncovering the secrets of exoplanets. Credit: NASA/Chris Gunn, CC BY 2.0 (bit.ly/ccby2-0)

The long-awaited launch of the James Webb Space Telescope (JWST) is finally in sight. Astronomers around the world are anticipating the wealth of information the flagship will gather on everything from the oldest galaxies in the universe to the birthplaces of stars and planets.

"It really is a Swiss army knife telescope with a huge range of applications," said Elisabeth Matthews, an astronomer at Observatoire de Genève in Switzerland.

JWST, built by a team of more than 1,200 people from 14 countries, will collect infrared (IR) light across a broad range of wavelengths. That makes it ideally suited to studying exoplanets, which bury most of their secrets deep in the infrared spectrum. In this way, among many others, JWST will build on the legacies of the Hubble and Spitzer space telescopes, both of which astronomers have used to make revolutionary leaps in our understanding of distant worlds, although neither telescope was designed to do so. JWST's instruments, on the other hand, were designed with exoplanets in mind.

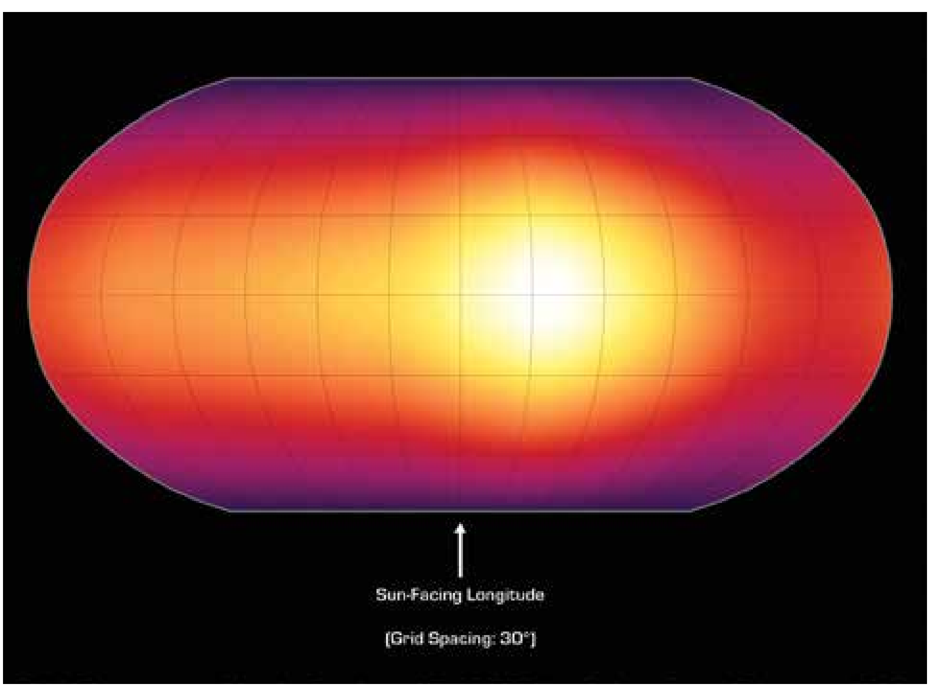
The observatory is scheduled to launch by the end of this year, and exoplanet scientists have long been planning what they want to look at first. In 2020 they submitted their proposals to the telescope's science team, and the selections for JWST's first observing cycle were announced in March. (An observing cycle is 1 year, or 8,760 hours, of observing time.) More than 20% of JWST's time during its first observing cycle will be dedicated to understanding exoplanets.

The unifying theme across the exoplanet observing programs? "One word: diversity," said Stefan Pelletier, an astronomy doctoral student at Université de Montréal. "All bases are being covered in terms of science cases as well as instrument and observing configurations."

The list of principal investigators (PIs) and coinvestigators on the accepted programs is also more diverse across many axes of identity than space telescope programs have been in the past. Compared with a recent round of Hubble proposals, a higher percentage of PIs who are women and also PIs who are graduate students will make the first JWST observations.

It's a testament to the hard work by the team at the Space Telescope Science Institute, Matthews said, "both in making sure [members of] the exoplanet community are able to understand the telescope and design good science experiments for it and also in ensuring that the proposals for these science experiments have been carefully and equitably judged."

Andrew Vanderburg, an astronomer at the University of Wisconsin–Madison, added, "It's awesome that the [dual anonymous] peer review—where the reviewers don't know who wrote the proposals, and vice versa—makes it possible for young scientists with good ideas to be awarded time on the world's most powerful observatory from day one."



In 2007, astronomers used the Spitzer Space Telescope to create the first global temperature of an exoplanet, the hot Jupiter HD 189733 b. With JWST, astronomers plan to make a map of this planet's hot spots (yellow) and cold spots (blue) not just in 2D, but also in 3D. Credit: NASA/JPL-Caltech/H. Knutson (Harvard-Smithsonian cfa)

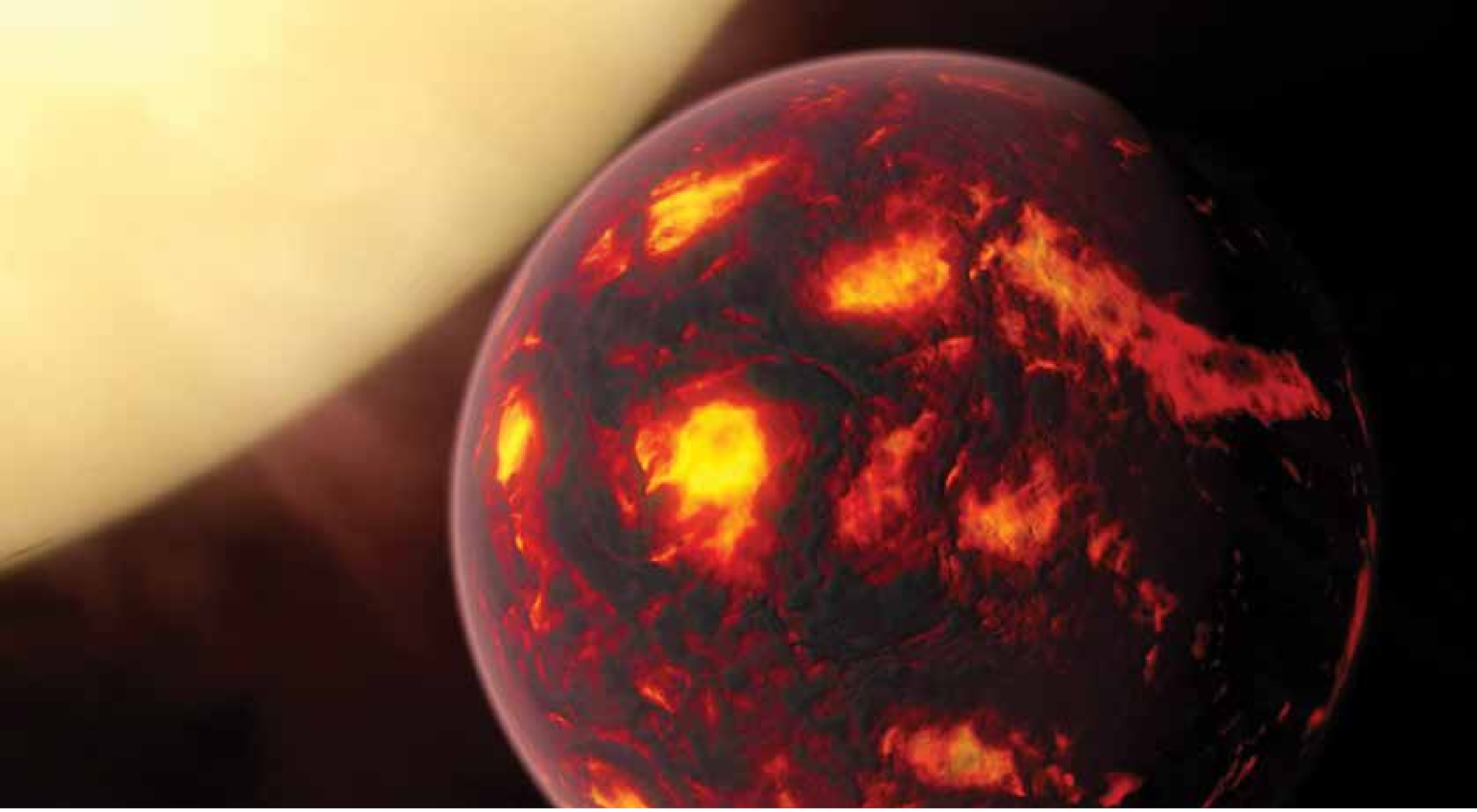
Prologue: A Shakedown Cruise

JWST promises to be a game changer for understanding how and what types of planets form and what makes them habitable, but for this first cycle it's unknown how the telescope's performance will measure up to expectations. "The reviewers very much wanted a robust 'shakedown cruise,'" said Peter Gao, an exoplanet scientist at the University of California, Santa Cruz. "Several proposals focused on new and interesting observing methods and science cases that are sure to be the testing grounds for similar, larger, and more elaborate proposals in the next cycles."

The selected exoplanet observations tend to stay well within the telescope's expected limitations. "JWST time is very precious, so for the first cycle it is understandable that emphasis was put on programs that are 'safe' in that they are almost guaranteed to generate good results," said Alexis Brandeker, an astronomer at Stockholm University. Some observations might be "risky" in that the scientists aren't sure what they'll find, but if they do find something, they'll get a good look at it.

On the science side, there's variety both in the types of planets targeted for observations and in the types of observations being made. "These include the measurement of mineral cloud spectral features as a way to probe the composition of exoplanet clouds, exploring asymmetries in the dawn and dusk limbs of exoplanets during transits, eclipse mapping, and getting a sense of which rocky exoplanets host atmospheres," Gao said.

And on the target side, "there is a nice balance between some of the first exoplanets to be characterized, like HD 189733 b, and weird exoplanets whose observations were difficult to interpret, like 55 Cancri e," said Lisa Đặng, a physics graduate student at McGill University in Montreal. Instead of making limited observations of a wide range of planets, most of the selected exoplanet programs seek to observe one or a few planets in great detail.



The surface of 55 Cancri e is probably molten, as seen in this artist's illustration. Astronomers will use JWST to better understand how the surface heats up. Credit: ESA/Hubble, M. Kornmesser, CC BY 4.0 (bit.ly/ccby4-0)

Lights Up on a Familiar Scene

In this first observing cycle, "we are going after a lot of known exoplanets that we have observed in the past, so there aren't many unexplored targets," Đặng said. "This makes absolute sense since it will be the first time we are going to use these instruments in space and we don't really know what challenges we will have to deal with yet."

"There are some really interesting planets...that we already have tantalizing glimpses of from Hubble and Spitzer data," said Hannah Wakeford, an astrophysicist at the University of Bristol in the United Kingdom. Wakeford, for example, will be targeting a well-studied, but still mysterious, hot Jupiter, HD 209458 b. "The data we currently have from Hubble tell us there is something in this atmosphere, and my program aims to show that it is clouds made from magnesium silicates (glass)," she said.

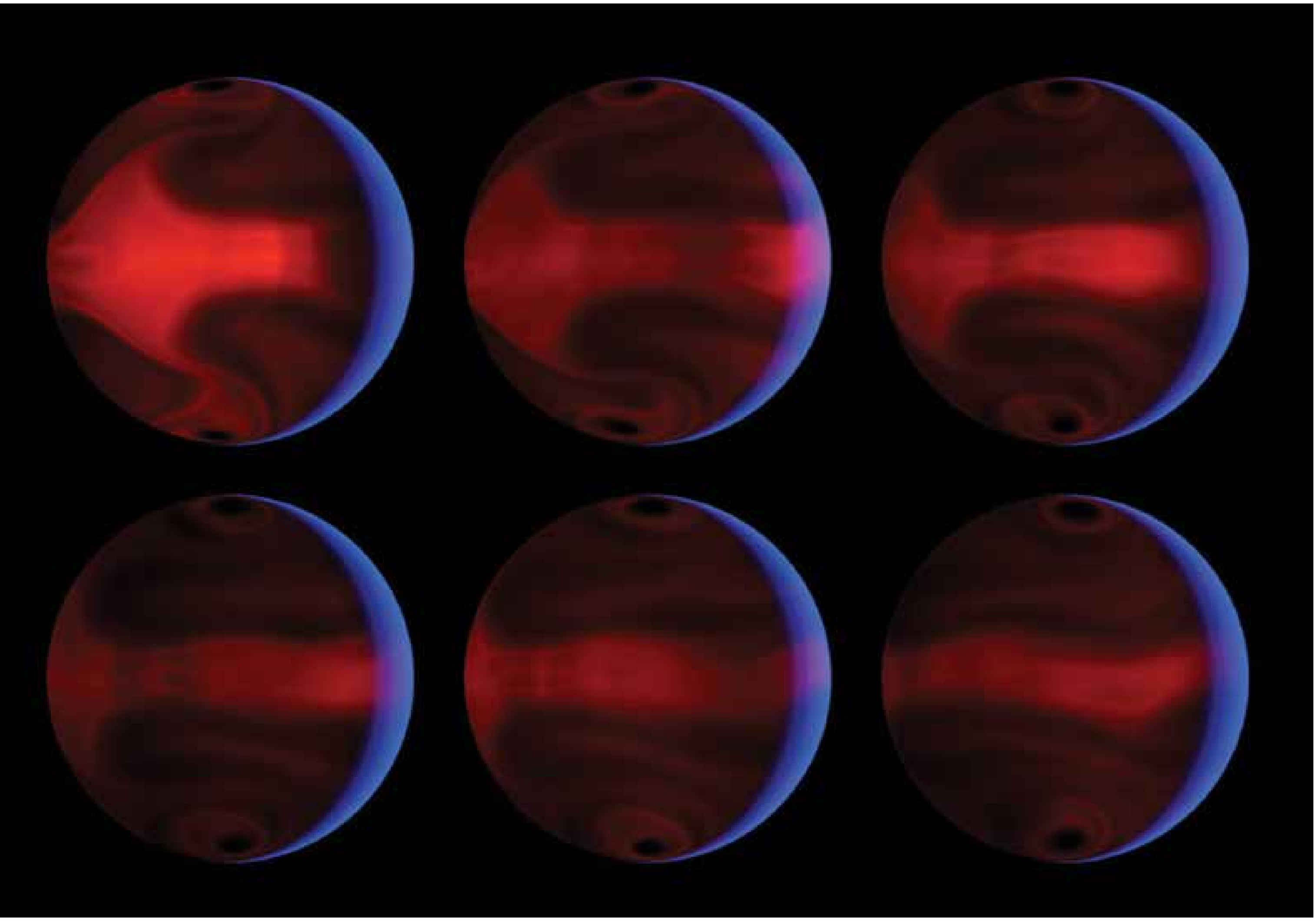
Tiffany Kataria, a planetary scientist at NASA Jet Propulsion Laboratory in Pasadena, Calif., is part of one of the five programs studying HD 189733b, a hot Jupiter so normal that it's called canonical. "This planet was one of the first exoplanets whose atmosphere was observed with the Spitzer and Hubble space telescopes, yet there is still much we don't know about the properties of its atmosphere," she said. Kataria will make a 3D map of the planet's glowing dayside to study its wind and temperature patterns, "which tells us a great deal about the physical processes taking place in the atmosphere."

JWST WILL BUILD ON THE LEGACIES OF THE HUBBLE AND SPITZER SPACE TELESCOPES, BOTH OF WHICH ASTRONOMERS HAVE USED TO MAKE REVOLUTIONARY LEAPS IN OUR UNDERSTANDING OF DISTANT WORLDS.

Néstor Espinoza's target is hot Jupiter WASP-63 b and, more specifically, its sunrise and sunset. The program "aims to try to detect, for the first time, the infrared atmospheric signatures of the morning and evening limbs of a hot gas giant exoplanet.... It goes in the direction of exploring atmospheric structure of these distant exoplanets in 3D." Espinoza is an astronomer at the Space Telescope Science Institute in Baltimore, Md.

Plenty of smaller planets reside among the old favorites that JWST will study, including the Earth-sized lava world 55 Cancri e. Brandeker's program will examine changes in light when the glowing, molten planet passes behind its star. "We hope to see if consecutive eclipses show the same or different faces of the planet," he said. Planets that orbit close to their stars are assumed to be tidally locked, having the same hemisphere always facing the star. If 55 Cancri e rotates faster or slower than it orbits, "this assumption, often taken for granted, can be questioned also for other planets. This in turn has major implications for how planets are heated, i.e., one side versus all sides."

Another old favorite is the sub-Neptune GJ 1214 b, the target of one of Eliza Kemp-



The flash heating that HD 80606 b experiences once every 111 days likely creates intense storms and unexpected weather patterns, which JWST will monitor. These computer models of those weather patterns are based on Spitzer data taken during a 2007 flash heating event. (Blue represents colder bulk atmosphere, and red represents warmer winds.) Credit: NASA/JPL-Caltech/G. Laughlin (UCO/Lick Observatory)

ton's observing programs. "Through a combination of mid-IR transmission spectroscopy, plus thermal emission and secondary eclipse observations, we aim to get a clearer picture of the atmospheric composition and aerosol properties of this enigmatic world," she said.

"The overlap with existing observations is not a main motivator because we expect JWST to perform so much better than existing facilities," said Kempton, an exoplanet astronomer at the University of Maryland in College Park. "But it will certainly be reassuring to see that the JWST data do agree with prior observations, and the level of agreement will help us to contextualize all data taken previously with facilities like Hubble and Spitzer."

Newest among the old favorites soon to be studied by JWST is the TRAPPIST-1 system, which excited astronomers and the public alike when it was discovered to have seven possibly rocky Earth-sized planets.

A grand total of eight different programs will look at these planets' atmospheric properties. "With this program," said Olivia Lim, an astronomy doctoral student at Université de Montreal and PI for the program, "we are hoping to determine whether the planets have an atmosphere or not, at the very least, and if they do host atmospheres, we wish to detect the presence of molecules like [carbon dioxide, water, and ozone] in those atmospheres. This would be an important step in the search for traces of life outside the solar system."

"JWST has a small chance of finding biosignatures on TRAPPIST-1 planets," said Michael Zhang, "but a very good chance of telling us which molecules dominate the atmosphere and whether there are clouds." Zhang is an astronomy graduate student at the California Institute of Technology in Pasadena.

Planetary Plot Twists

Some exoplanets just don't fit inside the box as neatly as other exoplanets do, and astronomers are really hoping that JWST will help them understand why that is. Kataria leads the program to study one of these oddballs, HD 80606 b.

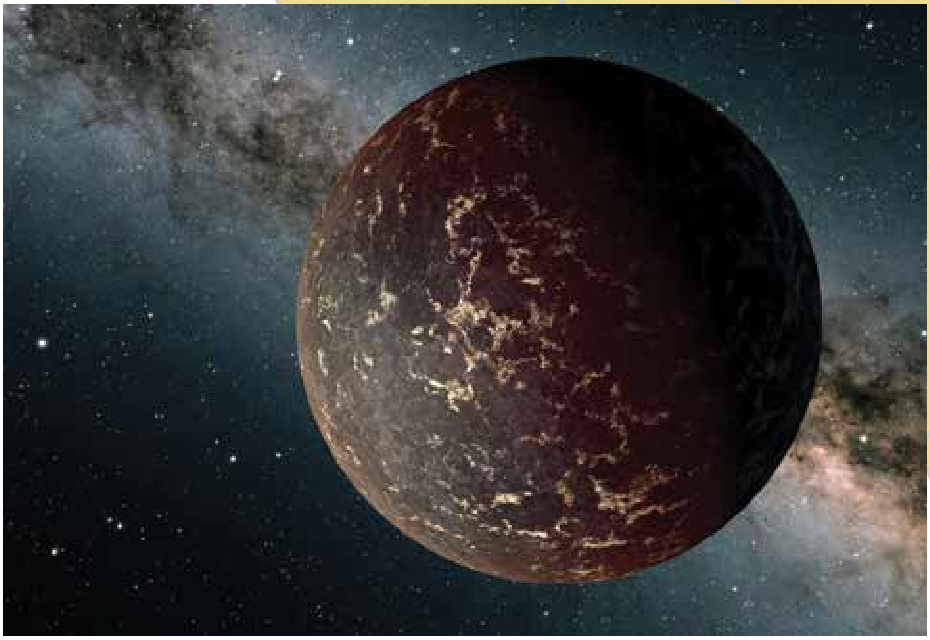
"HD 80606 b is an extreme hot Jupiter, and that's saying something, given that hot Jupiters are pretty extreme to begin with!" Kataria said. "This Jupiter-sized exoplanet is on a highly eccentric, or elliptical, orbit and experiences a factor of greater than 800 variation in flux, or heating, throughout its 111-day orbit."

"Most of the time it spends at relatively temperate distances," Brandeker added, "but once every 111 days it swooshes very closely by the star in a few days so gets 'flash heated.'"

Studying HD 80606 b's atmosphere as it heats and cools "will really help us examine the pure physics behind atmospheric energy transport, which is important for all worlds," Wakeford said.

Kataria is also a coinvestigator on a program to make a 3D atmospheric map of a different oddity, WASP-121 b, a gas giant so hot that it bleeds heavy metals into space and orbits so close to its star that it's shaped like a football. WASP-121 b is one example of a "super-puff" planet: These planets are roughly the size of Jupiter but far less massive, which makes their density closer to that of cotton candy. Pelletier will be looking at another super-puff, WASP-127 b. "Our hope is to gain a better understanding of the carbon budget on a planet vastly different from anything we have in our solar system," he said.

What's the most important thing to learn about super-puff planets? "Basically anything!" according to Gao, whose program will target super-puff Kepler-51 b. "All previous attempts at characterizing super-puff atmospheres have yielded featureless spectra and therefore very little information. If our observation is anything but a flat line, then we will have learned so much more than what we now know about these mysterious objects. It really is a fact-finding mission."



The small rocky planet LHS 3844 b depicted in this illustration has been confirmed to have no atmosphere, so JWST will be able to study its surface composition. Credit: NASA/JPL-Caltech/R. Hurt, IPAC

M Dwarfs' Breathtaking Aria

M dwarf stars are the smallest and most common stars in the universe, and astronomers have found that they host plenty of planets. Rocky habitable planets around these stars are easier to find using the two most prevalent methods—transits and radial velocity—but whether those planets can host atmospheres is still debated.

"I think the Cycle 1 observations will teach us a ton about whether rocky planets around M dwarfs can keep their atmospheres," said Laura Kreidberg, director of research into the atmospheric physics of exoplanets at the Max Planck Institute for Astronomy in Heidelberg, Germany. "This is one of the most fundamental questions about where life is most likely to arise in the universe. There are tons of these small planets around small stars"— more than 1,500 are known so far—"but they experience more high-energy radiation over their lifetimes, so it's not known whether they can keep their atmospheres. No atmosphere [is] bad news for life!"

"JWST HAS A SMALL CHANCE OF FINDING BIOSIGNATURES ON TRAPPIST-1 PLANETS BUT A VERY GOOD CHANCE OF TELLING US WHICH MOLECULES DOMINATE THE ATMOSPHERE AND WHETHER THERE ARE CLOUDS."

Both of Kreidberg's observing programs will target rocky planets around M dwarfs. "One of the planets [LHS 3844 b] is already known to not have an atmosphere, so the goal of this program is to study the planet's surface composition—what type of rock it's made of—and search for any hints of volcanic activity, which could produce trace amounts of sulfur dioxide."

Kreidberg is also looking at TRAPPIST-1 c, "which is very close to Venus in temperature. For that planet, I'm searching for absorption from carbon dioxide, to test whether the planet has a thick, Venus-like atmosphere or whether the atmosphere has been lost."

"While we have made many models of atmospheric loss for small planets," Gao said, "this will be our first real test of these theories. Will we find out that most characterizable rocky planets don't actually have atmospheres and that our modeling efforts for their climates and habitability are futile? Or will we see a much more diverse set of atmospheric states? The results of these studies will be interesting and informative for future cycles regardless of what we find."

Small-Planet Showstoppers

About half of JWST's exoplanet-specific observing time will be dedicated to studying worlds smaller than Neptune. "This tells me without a doubt that the community is overwhelmingly interested in the little guys," Gao said. These planets might be rocky (if they're small enough) or could have a rock-ice core and a thick atmosphere.

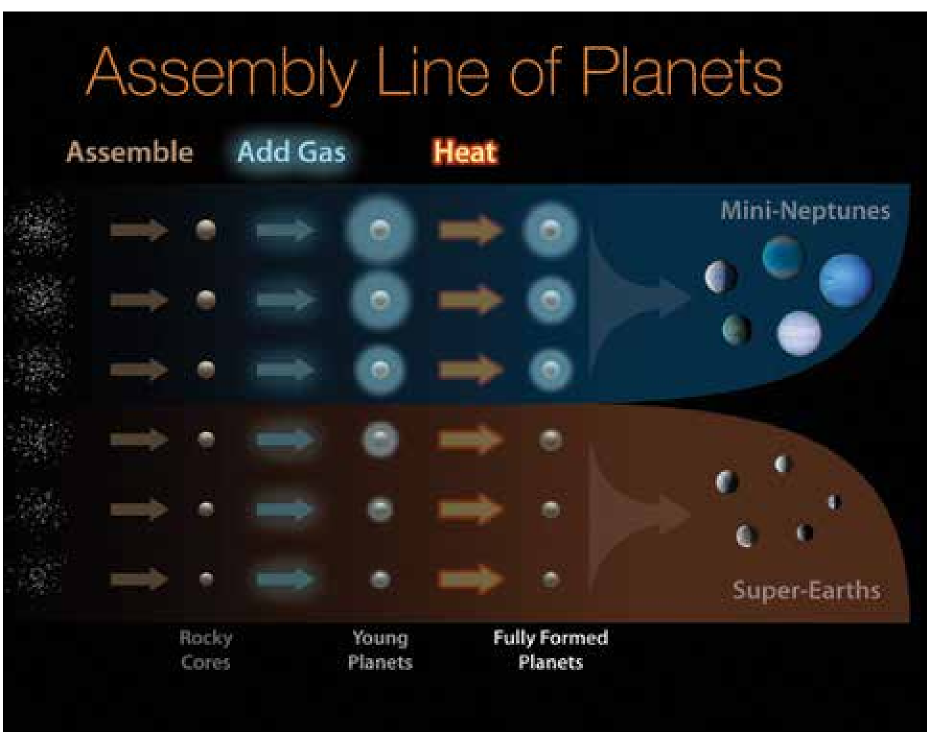
"The large program on sub-Neptune and super-Earth atmospheres led by Natasha Batalha and Johanna Teske is especially exciting to me because it will provide us with a systematic survey of a class of planets that is not present in our solar system and was not readily observable with previous facilities," Kempton said. "The potential for this program to unlock greater insight into the atmospheres of small planets is quite high."

"THIS PLANET ORBITS CLOSE ENOUGH TO THE WHITE DWARF THAT IT COULD NOT HAVE ORIGINALLY ORBITED THERE BEFORE THE STAR'S DEATH. SO HOW DID IT GET THERE?"

"These planets are so small that they're beyond the reach of current technology, so anything JWST discovers will be a big improvement on what we know," Zhang said. "For small planets like GJ 367 b, my target, and 55 Cancri e, we basically don't know anything, so we'll learn the first thing about them. Do they have atmospheres? If so, are they carbon dioxide, oxygen, or exotic metal atmospheres made of sodium and silicon oxide?"

One of Espinoza's programs will focus on super-Earth K2-141 b, a planet only slightly larger and more massive than Earth but much, much hotter. "Depending on the properties of this exoplanet like the presence or not of an atmosphere, the flux change during its orbit around the star should give rise to very different signals, which will enable us to infer what this exoplanet's exterior is made of," said Espinoza.

If K2-141 b does have an atmosphere, it might not be the one it started with. Lisa Đặng aims to find out. Rocky planets as hot as that one "are thought to have lost any primordial atmosphere but, instead, could sustain a thin rock vapor atmosphere [that] outgasses from the mantle," she said. Does the atmosphere stick around or rain back down? "With our observations we are hoping to detect molecular signatures of the atmospheric constituents and also obtain a map of the planet's atmosphere and surface."



Small planets all start from a collection of dust and gas. How much material a future planet starts with determines how much additional gas it can attract and how much of that gas it will keep when it heats up. Planets that end with a large gaseous envelope are termed mini-Neptunes, and those with only a small amount of gas are deemed super-Earths. Credit: NASA/Ames Research Center/JPL-Caltech/R. Hurt

Ballad of Planets and Disks

JWST should build upon discoveries made not only by space telescopes like Hubble and Spitzer but also by ground-based observatories like the Atacama Large Millimeter/submillimeter Array (ALMA). These observations will probe the birthplaces of planets: the disks of dust and gas around young stars. "Over the last decade, we've gotten gorgeous images from the ALMA interferometer in Chile and have seen loads of fine-scale structure, tracing pebbles in planet-forming disks," said Ilse Cleeves, an astronomer at the University of Virginia in Charlottesville. "Some of the structures likely trace planets in formation, and so it'll be very exciting to see what JWST uncovers, both in terms of patterns in the disk and perhaps even the drivers—protoplanets—themselves!"

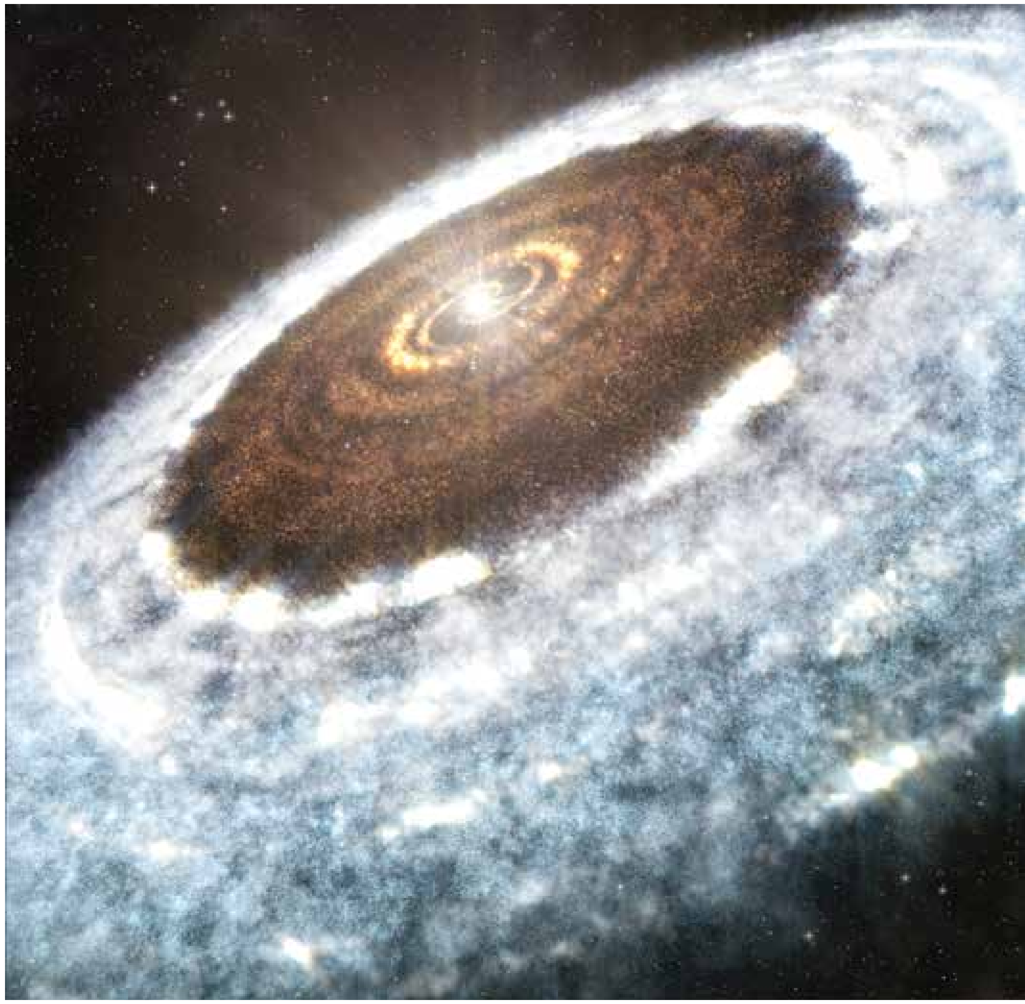
Matthews added that "if JWST is able to successfully detect planets in these disks, it will be an important confirmation of our understanding of how planets interact with disks." If no planets appear in the disks, astronomers will have to rethink how, and whether, planets shape disks.

Cleeves will be studying planet-forming disks to understand how they give rise to habitable planets. "How common are habitable planets? Availability of water is a natural place to start, but we don't have great observational constraints on how much water is present or the distribution of water in disks. We are looking forward to mapping out water ice in a nearby disk that happens to be posing in front of a host of background stars." If a star's light passes through a part of the disk that has ice, the ice will imprint a spectroscopic signal on the light. With so many background stars, Cleeves said, they'll be able to say not just whether ice is present, but also where.

The makings of a world well suited for life go beyond the presence of water, however, and Melissa McClure's three observing programs will look for them. We'll "trace how the elemental building blocks of life—like carbon, hydrogen, oxygen, nitrogen, and sulfur—evolve between molecular clouds, where they freeze out on dust grains as ices, and protoplanetary disks, where these ices are incorporated into forming planetesimals and, ultimately, planets," she said. "I think that within a few years we will have an understanding of how much water terrestrial planets typically have and whether they inherited that water from their birth locations in their disks or if cometary delivery was necessary." McClure is an assistant professor and a Veni Laureate at Leiden Observatory in the Netherlands.

A perhaps underrecognized component of JWST's observing capabilities is the coronagraph that will allow direct imaging of exoplanet systems, meaning that the telescope will see light emitted by the planet itself. Coupled with JWST's infrared capabilities, the telescope will be able to observe planets much older and colder than is currently possible. That's Matthews's aim. "Eps Indi Ab is similar in age to the solar system and is similarly far from its star as Jupiter is from the Sun. Because JWST is able to image much further into the infrared than Earth-based telescopes and because old planets are brighter at these very long wavelengths, our project provides a unique opportunity to study a truly Jupiter-like planet outside the solar system," she said.

Sometimes planets survive their star's demise, as is the case of WD 1856+534 b, a gas giant planet that orbits the slowly cooling corpse of a star, also known as a white dwarf. In this case, the planet's survival presents a puzzle. "This planet orbits close enough to the white dwarf that it could not have originally orbited there before the star's death. So how did it get there?" asked Andrew Vanderburg, whose program will target this system.



A few of the first observations with JWST will seek to map out how planet-forming disks distribute their water and other materials that are essential for life. This artist's illustration shows where water ice may exist in a planet-forming disk. Credit: A. Angelich (NRAO/AUI/NSF)/ALMA (ESO/NAOJ/NRAO), CC BY 4.0 (bit.ly/ccby4-0)

Bridge to Act II

Once the "shakedown cruise" is complete, Hannah Wakeford would like to see JWST used to study more worlds the size of Jupiter, Saturn, and Neptune. "There is so much we can learn that we can't even get from our own solar system giant planets," she said, "so it is, in my opinion, a low-risk, high-reward scenario."

On Vanderburg's wish list: "Disintegrating planets. These will be great probes of the interior compositions of planets, so I hope we will get observations of them in the future."

Cleeves called the first cycle "a great place to start. I have a feeling, though, that the most interesting next projects are those that we haven't anticipated yet, so I'm really looking forward to the first couple of years with JWST, grappling with the data and finding those unexpected puzzles."

Espinoza agreed. "I'm almost convinced features will show up in the data that we will perhaps not be able to explain right away," he said. "As such, the very first exoplanetary observations to be made by JWST are going to be a big jump into the known unknown.... As the title of an album of one of my favorite rock bands would say, 'Expect the unexpected.'"

Author Information

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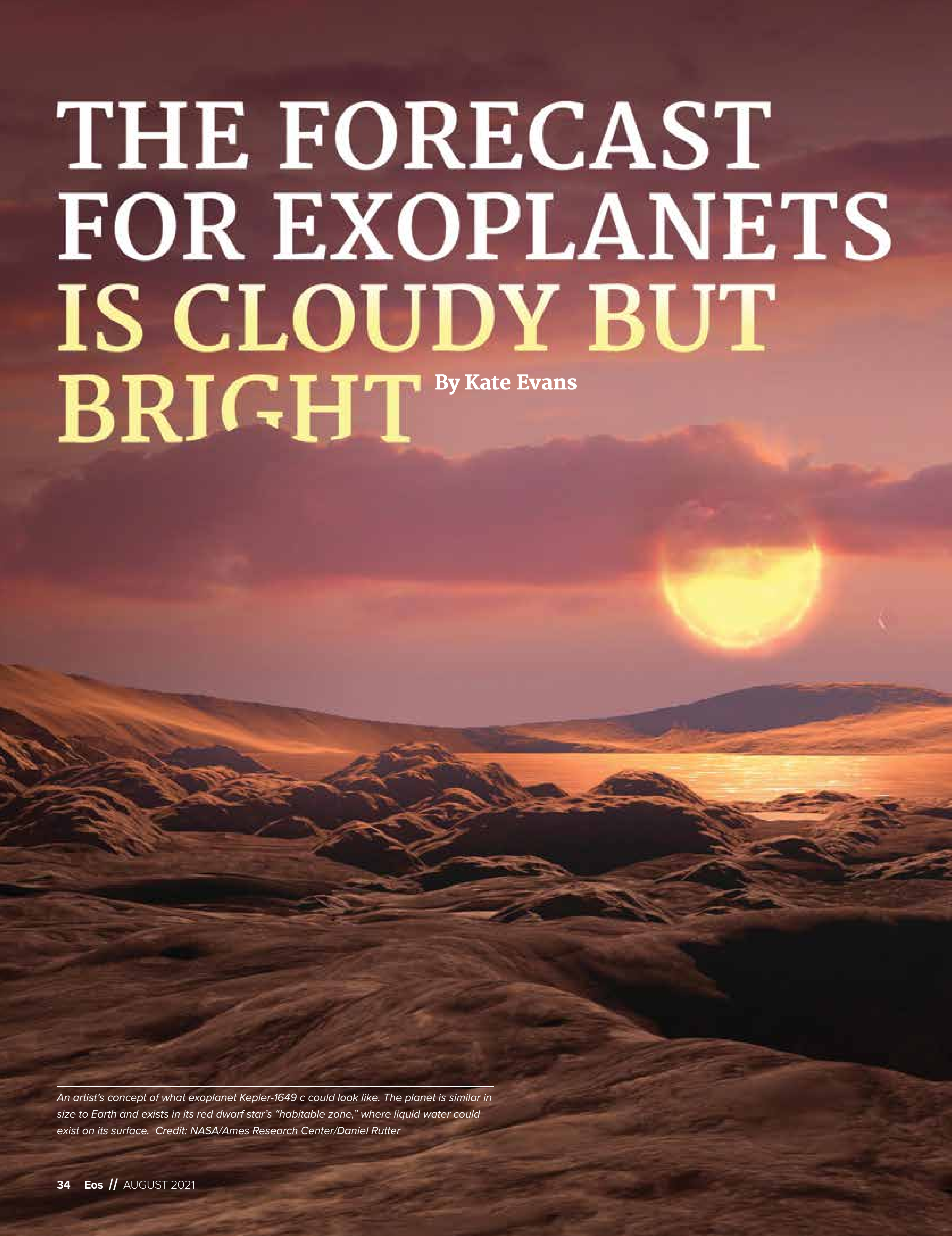
THE FORECAST FOR EXOPLANETS IS CLOUDY BUT BRIGHT

By Kate Evans



An artist's concept of what exoplanet Kepler-1649 c could look like. The planet is similar in size to Earth and exists in its red dwarf star's "habitable zone," where liquid water could exist on its surface. Credit: NASA/Ames Research Center/Daniel Rutter

Clouds make climate modeling on Earth difficult. Identifying—and even defining—atmospheric phenomena on other planets is the next big exoplanet challenge.

The first time scientists measured the atmosphere of an exoplanet—a planet outside our solar system—they found something unexpected in the signal. It was 2001, and the Hubble Space Telescope was trained on HD 209458 b, a recently discovered gas giant roughly the size of Jupiter.

When astronomers looked for the presence of sodium in light waves shining through the planet's atmosphere as it crossed in front of its star, there was a lot less of it than they thought there would be, said Hannah Wakeford, a lecturer in astrophysics at the University of Bristol in the United Kingdom. "From the very first measurement of an exoplanet atmosphere, there was evidence that something else was happening, something else was there blocking the light."

On Earth, clouds take many forms, like these cirrus and stratocumulus clouds. Their variety and ubiquity make them difficult to account for in climate models. Credit: NASA

The most compelling theory for what that something could be? Massive banks of dark, hot clouds. "Clouds are essentially liquid or solid droplets or particles that are suspended in a gaseous atmosphere," said Wakeford. But because the planet is so hot—5 times hotter than Earth—those droplets couldn't be made of water, as they are on Earth.

In the 2 decades since analyzing the atmosphere of HD 209458 b, astronomers have discovered more than 4,000 exoplanets. Using spectroscopy, they have measured the atmospheres of more than 100 of those objects, and it looks like many of them are cloudy. The way those extraterrestrial clouds behave and the exotic things they could be made of—liquid sand, iron, even rubies—are stretching scientists' ideas of what terms like clouds, rain, and snow even mean in the context of the universe.

"Clouds are everywhere," said Laura Kreidberg, an astronomer at the Max Planck Institute for Astronomy in Germany. "And to have any hope of understanding what's going on in [exoplanet] atmospheres, we have to understand the clouds."

Mushballs and Methane Lakes

The trouble is, clouds are complicated. Even on Earth, clouds are difficult to model (one reason weather forecasts can still lack accuracy.) Their complexity arises partly because they are simultaneously very small and very large: made up of microscopic water droplets yet so vast they can cover more than two thirds of Earth's surface. Another reason is that there are so many kinds of clouds, and they behave in complex ways, explained atmospheric physicist David Crisp at the Jet Propulsion Laboratory, California Institute of Technology.

Clouds are "ubiquitous; they can form in many different kinds of environments, and there are many processes associated with their formation," Crisp said.

And they're not made only of water, either. Most cloud particles start growing on condensation nuclei—a speck of dust or a grain of salt. And although most earthly cloud droplets are spherical and liquid, those that make up cirrus clouds are hexagonal ice crystals.

Clouds can frustrate scientists' ability to see clearly, whether they are gazing at the heavens from the ground or peering back at Earth from space. In the 1980s, Crisp helped build the camera in the Hubble Space Telescope and now leads a NASA team that uses orbiting satellites to measure the dangerous levels of carbon dioxide accumulating in Earth's atmosphere. "I've learned to hate clouds from both sides now," he joked.

Clouds mess with models predicting future climate change, he said, because they simultaneously warm and cool the planet, depending in part on whether their droplets are mainly liquid or mainly ice. In general, low-lying, mostly liquid clouds provide shade and reflect solar energy back into space, whereas high-altitude, frozen cirrus clouds trap infrared radiation emitted by Earth's continents and oceans and intensify surface heating. This duality has long frustrated exoplanet cloud watchers, too—scientists scrutinize cloud signals to better understand how or whether clouds are heating the atmosphere below them.

Scientists are still trying to understand whether, at a global level, those cooling and warming effects cancel each other out and how that balance could change in the future. (One recent study even suggested that at carbon dioxide levels of around 1,200 parts per million, global cloud cover could become unstable and dissipate, dramatically accelerating warming.)

Despite the uncertainties, we know a lot more about Earth's clouds than we do about those on other planets and moons of our solar system. It was only in the 1970s, for instance, that scientists figured out that Venus is enveloped in clouds of sulfuric acid. "This stuff will strip paint—and just about anything else," said Crisp. Space missions to Venus have dropped mass spectrometers into the planet's atmosphere that, "even though sulfuric acid is not very nice to our mass spectrometers," have managed to send back data about the chemical makeup and concentrations of several cloud layers.

Jupiter's atmosphere has been sampled too, and has been found to contain swirling ammonia clouds. Recent flybys of the tops of these clouds by NASA's Juno mission identified mushballs—Jovian hailstones formed out of water-ammonia slush enrobed in an ice crust—that fall through the planet's atmosphere. On the way down, these mushballs collide with upward moving ice crystals and electrify the clouds, causing shallow, high-altitude lightning visible from space.

Thanks to the Cassini spacecraft, we know that the atmosphere on Titan, the largest of Saturn's moons, is largely made up of nitrogen, like Earth's. There are seasons, monsoons, and wild windstorms. But Titan's mountains are made of solid ice, and instead of a water cycle, it has a hydrocarbon cycle: On Titan, the rain, rivers, and lakes are made of methane and ethane.

But many questions remain when it comes to solar system weather. For example, we don't know how deep into Jupiter the mushballs fall before they evaporate and rise again, said Wakeford. There are mysterious long-chain hydrocarbons floating high in the atmosphere of Titan too. "We have absolutely no idea how they got there; it's baffling."

What knowledge we do have is drawn from the briefest of snapshots, added Crisp. "We've dropped a few dozen probes into the atmosphere of Venus. But you know, if you measured Earth's atmosphere with only a dozen instruments, how much would you know about the Earth? These planets are big places, and they have complicated climates—quite as complicated as ours."

An artist's impression of the gas giant HAT-P-7 b. Astronomers detected strong winds and catastrophic storms and suspect that the clouds could be made of corundum, the mineral that forms rubies and sapphires. Credit: Mark Garlick/ University of Warwick

A Lead Blanket or Gems and Jewels

The challenges of analyzing extraterrestrial clouds are magnified when it comes to exoplanets. We can't send a probe laden with instruments to any of them or record detailed images of their surfaces.

All we have is light, said Heather Knutson—the light coming from a far-off star. "We know there's a planet in orbit around it, and we can indirectly infer some basic things about that planet, but it's really a sort of poor man's camera," said Knutson, an astronomer at the California Institute of Technology

When an exoplanet passes in front of its star—an event called a transit—astronomers can measure the way light passes through the planet's atmosphere on its way to us. Measuring how opaque the atmosphere is at different wavelengths of light (transit spectroscopy) offers clues to its composition. Kreidberg used an X-ray analogy to explain how it works: "Our bodies are opaque in optical light. If you shine a flashlight at a person, you can't see through them. But if you look in the X-rays, you can see through the skin, but not through the bones."

In the same way that our skin differs from our bones, molecules in planetary atmo-

"We've dropped a few dozen probes into the atmosphere of Venus. But you know, if you measured Earth's atmosphere with only a dozen instruments, how much would you know about the Earth?"

spheres are opaque or transparent at different wavelengths. "Whether it's water or methane or oxygen or carbon dioxide, they have distinct opacity at different wavelengths of light," said Kreidberg. "So if the planet looks a little bit bigger at a particular wavelength, then we can work backward from that to try to infer what's in its atmosphere."

But clouds get in the way of that process, said Knutson. "If we're going with the X-ray analogy, clouds are sort of like a lead blanket over the planet. You see something that looks very featureless."

Still, on the basis of the planet's average atmospheric temperature—something astronomers can estimate from the brightness of the star and the planet's distance from it—it's possible to infer what those clouds are likely to be made of because of the varying temperatures at which different molecules condense from gas into liquid.

An imagined movie poster for the exoplanet HD 189733 b, a cobalt-blue hot Jupiter with winds approaching 8,700 kilometers per hour and rain of molten glass. Credit: NASA

And the vast range of possible temperatures is something that distinguishes exoplanets from those in our solar system, said Nikku Madhusudhan, an astrophysicist and exoplanet scientist at the University of Cambridge. "Because of that vast range, you allow for a much wider range of chemical compositions [than in the solar system]. A lot more chemistry can happen."

Here on Earth, with an average temperature of 290 K, clouds are made mostly of water. The atmospheres of some exoplanets, between 400 K and 900 K, are warm enough to condense salts and sulfides into clouds. At around 1,400–2,000 K (a third as hot as the Sun), we would expect to see clouds of molten silicates—the material that makes up the volcanic sand on some of Earth's beaches and is used in the production of glass. On an even hotter planet like WASP-76b, which is estimated to reach 2,400 K, clouds are likely made of liquid iron. And the atmospheres of the hottest known exoplanets—giant, 2,500+ K ultrahot Jupiters orbiting very close to their stars—are the right temperature for clouds made of corundum, a crystalline form of aluminum oxide that forms rubies and sapphires on Earth.

"These are quite literally the gems and jewels that we have here on Earth forming clouds and lofted high into the atmospheres of Jupiter-sized worlds that are lit glowing from their star," said Wakeford. She remembered walking through the Hall of Gems in London's Natural History Museum after learning this, trying to imagine the crystals molten and forming clouds. "It just blew my mind."

Metallic Monsoons

WASP-76 b made headlines in 2020 when a team of European researchers published a paper suggesting it had not only clouds of iron but iron rain as well.

Like our own Moon and many planets that orbit very close to a star, WASP-76 b is tidally locked, meaning one side of the planet always faces the star (dayside) and the other always faces away (nightside). Researchers found evidence of iron atoms in the atmosphere of WASP-76 b's hotter dayside but not on the cooler nightside, which they argued meant that the iron must be condensing into liquid droplets as wind carries the atoms around the planet. "We see the iron, and then we don't see the iron. So it has to go somewhere, and the physical process that we expect is rain," said Kreidberg, who was not involved in the study. "This is some of the most convincing evidence I have ever seen for exoplanet weather."

But Caroline Morley, an astrophysicist at the University of Texas at Austin, cautioned that the phenomenon could be more complex. Recent studies, including one coauthored by Kreidberg, have examined the microphysics of how iron droplets form, finding that the substance's high surface tension means that it doesn't easily condense from a gas to a liquid. There might be some other processes involved in WASP-76 b's iron phenomenon, Morley said—perhaps the iron interacts with some other chemicals in the planet's atmosphere, which helps it form a cloud.

"Statistically, I believe that there are exoplanets where it is raining right now," she said. "But I think that we have not seen smoking gun evidence for rain on other planets yet."

Crisp agreed. "Clouds we've detected. Rain and snow have not yet been detected—but I'd be surprised if they weren't there. Those are logical outcomes of the systems we see."

Metaphorical Meteorology

So when astronomers talk about possible rain on exoplanets, is it really what we would think of as rain? What do the concepts of rain and clouds even mean in the context of distant space? To some extent, it's all a metaphor, said Wakeford.

On Earth, the terms rain, clouds, and snow all apply almost exclusively to one substance: water. "Water is one of the most amazing materials in the universe," Wakeford said, but not all substances behave like water when experiencing differences in pressure or temperature. "So when we frame these very alien clouds and rain and snow in that [water-based] context, it puts things in our minds that aren't exactly what the physics is."

For instance, words like snow and hail can be a bit misleading when you talk about solid particles in an atmosphere that's hotter than a lava flow. "I tend to use rain instead of snow," Wakeford said, "because snow to us evokes a temperature, a coldness. Rain is something that can define many different types of conditions, whereas snow for us is very much a cold thing. And this is not what's happening here on some of these planets that are so incredibly hot."

Still, Wakeford thinks a smattering of poetic license is justified to bring the public along on the journey and capture people's imaginations. "If you start by saying, 'It's raining drops of glass on these planets'—that's a starting point. I can use that; I've got [your attention] now. Then we can build on that and get a deeper understanding."

When it comes to actually doing the research, though, scientists should be both circumspect and open-minded, said Madhusudhan. Although it can sometimes help to extrapolate from what we're discovering about Earth's clouds to these faraway planets, for instance, it's important to remember that these worlds are so exotic that it's possible there are processes going on in their atmospheres that we haven't even considered. "The biggest mistake we could make is to try to simplify the complexity of exoplanetary systems just to fit a narrative."

We may go on to discover kinds of weather we don't even have words for, said Madhusudhan. "We have to be open to the fact that the complexity in nature may greatly surpass our imagination at the present time."

Peering into the Infrared

So far, everything we know about clouds on exoplanets has been based on what Madhusudhan calls indirect inference: "It's a bit more real than philosophical but a bit less real than an actual observation." But the launch of the international James Webb Space Telescope (JWST) near the end of this year promises to give astronomers the chance to make direct observations of exoplanet clouds for the first time.

JWST will keep Earth between it and the Sun and is designed to look at the longer wavelengths of infrared light. "Planets are easier to study in the infrared," said Knutson. The telescope will make faraway objects look brighter than they do in visible light and will be better able to detect molecules in exoplanet atmospheres. It should also advance our understanding of alien weather.

"When you go to midinfrared, the composition of a cloud droplet starts to matter—the way that it scatters light is different for different cloud species," said Knutson. "So we might, for the first time, directly measure what the clouds are made of."

Morley is leading a team that will use JWST to examine a cold exoplanet called WISE J085510.83-071442.5 to test for the presence of water ice clouds and see whether they are changing as the planet rotates, implying that there are storm systems and weather. "That would give us real evidence, for the first time, that there's water ice forming in a planet outside of the solar system," Morley said.

Wakeford, meanwhile, will have a chance to train the telescope on HD 209458 b, the very first planet that 20 years ago was assumed to have clouds of magnesium silicate. JWST will give her a chance to prove (or disprove) that assumption with direct measurements.

Overall, "I think we think about clouds more broadly than anybody has thought about clouds in human history," said Morley. "And we're just on the cusp of being able to get a huge amount of really detailed information about those clouds. It's a really exciting time to be in this field."

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▶**Read the article at bit.ly/Eos-exo-clouds**

> **"We see the iron, and then we don't see the iron. So it has to go somewhere, and the physical process that we expect is rain."**

In Appreciation of AGU's Outstanding Reviewers of 2020

AGU Publications recognizes a number of outstanding reviewers for their work in 2020, as selected by the editors of each journal.

Peer review is central to communicating and advancing science. While there have never been more ways to distribute ideas and research outputs, a robust peer review ensures that we maintain the highest integrity in our scientific discourse. The peer review process is organized by our journal editors, but every article decision relies on dedicated individuals who take time out from their own research to volunteer their time and expertise. The work of these reviewers ensures proper evaluation of thousands of articles each year. We are truly thankful for their efforts.

As the uses for scientific literature have grown, so has the complexity of papers, which now typically include more authors bringing more techniques, data, simulations, and results. This increase in complexity has increased the challenge and role of reviewing. The outstanding reviewers listed here have provided in-depth evaluations, often through multiple revisions, that greatly improved the final published papers. Their contributions helped raise the quality of submissions received from around the world, providing valuable feedback that elevates the prominence of our journals to the high standards aligned with the AGU tradition.

Every article decision relies on dedicated individuals who take time out from their own research to volunteer their expertise.

Many Reviewers: A Key Part of AGU Journals

While we note these few outstanding reviewers here, we also acknowledge the broad efforts by many AGU reviewers in helping ensure the quality, timeliness, and reputation of AGU journals. We also welcome new and first-time reviewers who have joined the family of integrity stewards and have been providing authors valuable evaluations. In 2020, AGU received more than 18,100 submissions, which is up from the 16,700 submissions received in 2019, and published more than 7,163, up from 7,000 articles in 2019. Many of these submissions were reviewed multiple times—in all, 19,227 reviewers completed 42,564 reviews in 2020 compared to the 39,368 reviews completed in 2019.

This increase has happened in the past year while each AGU journal worked to shorten the time from submission to first decision and publication or consistently maintained industry-leading standards. Several AGU journals regularly return first decisions within 1 month of submission, and most others do so now within 2 months. Reviewers represent a key part of this improvement. We look back at 2020 here, but we have already seen that in 2021, during the pandemic and unrest, members of our amazing community have continued to accept invitations to peer review article submissions.

Editorials in each journal (some already published, some upcoming) express our appreciation along with recognition lists. Our thanks are a small recognition of the large responsibility that reviewers bear in improving our science and its role in society.

Additional Thanks

We are working to highlight the valuable role of reviewers through events (though they may be virtual) at Fall Meeting and other meetings.

Each reviewer also receives a discount on AGU and Wiley books. We will continue to work with the Open Researcher and Contributor Identification network (ORCID) to provide official recognition of reviewers' efforts, so that reviewers receive formal credit there. As of 5 May we have over 71,700 ORCIDs linked to GEMS user accounts as compared to 59,962 at this time last year.

Getting Your Feedback

We are working to improve the peer review process itself, using new online tools. We conducted a full survey in 2020, and we continue to provide a short questionnaire for feedback after each review is completed.

We value your feedback, including ideas about how we can recognize your efforts even more, improve your experience, and increase your input on the science.

We look forward to hearing from you. If you'd like to respond directly, feel free to take our survey.

Once again: Thanks!

By **Matt Giampoala** (mgiampoala@agu.org), Vice President, Publications, AGU; and **Carol Frost,** Chair, AGU Publications Committee

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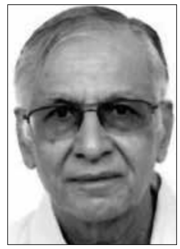

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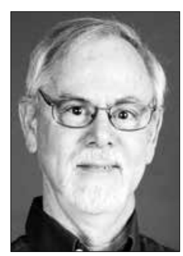

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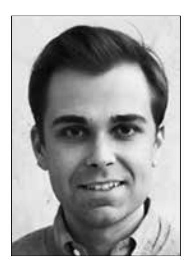

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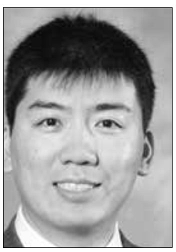

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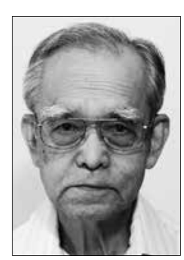

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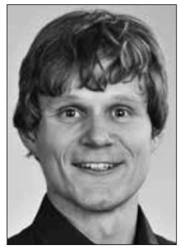

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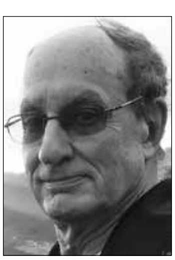

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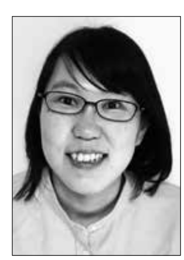

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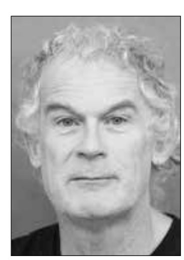

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South Pole Ice Core Reveals History of Antarctic Sea Ice

Tracking seasonal changes in sea ice over millennia can give scientists a better understanding of just how much variation is natural, as well as how these yearly variations interact with long-term climate patterns. Although annual fields of reflective ice are carefully monitored today, it is difficult to accurately discern the extent of summer or winter sea ice from times before satellite imagery. Therefore, the question remains, How can scientists follow these data back tens of thousands of years?

In a new study, *Winski et al.* track sea salt levels from the South Pole Ice Core project to follow sea ice patterns over more than 11,000 years. According to a chemical transport model, storms carry sea salt from sea ice inland to the core's location. Although most of the sea ice itself melts away each year, the core's chemical profiles can indicate how much sea ice existed from season to season across an entire epoch.

The researchers discovered an increase in wintertime sea ice between 8,000 and 10,000 years ago, followed by an abrupt decrease 5,000–6,000 years ago. The sudden decrease, concentrated in the South Atlantic region, accompanied an increase in sea ice in the Northern Hemisphere. According to the authors, this moment likely marks a change in sea currents affecting local and global climate.

Changes in sea ice can lead to rapid climate change, which affects the entire planet. This study fills in the details on this ephemeral but vital indicator, the authors say. (*Geophysical Research Letters*, https://doi.org/10.1029/2020GL091602, 2021) **—Elizabeth Thompson,** *Science Writer*

Carbonate Standards Ensure Better Paleothermometers

Anna-Nele Meckler, a researcher at the University of Bergen, Norway, works with a loading instrument for clumped isotope analysis. Credit: Eivind Senneset

The climate of ancient Earth left telltale signs in the geochemical record. On the basis of chemical properties of carbonate minerals, scientists can calculate what a site's temperature was hundreds of millions of years ago. Such a "paleothermometer" provides a peek not just into past climates but also into geological processes like elevation changes to Earth's surface. Analyses by different research groups, however, don't always agree.

A new study by *Bernasconi et al.* describes a community effort, InterCarb, to standardize the chemical analysis known as carbonate clumped-isotope thermometry, using common carbonate standards.

Carbonate clumped-isotope thermometry relies on a thermodynamic tendency for rare heavy isotopes of oxygen and carbon to bond, or clump together, in carbonate molecules. At lower temperatures, the molecules are more likely to form with clumped isotopes; scientists can use this fact to calculate temperatures on ancient Earth.

For analyses, researchers treat carbonate samples, from seafloor mud to megalodon teeth, with acid to produce carbon dioxide gas. They then use mass spectrometers to compare the tiny amounts of heavy isotopes in that gas with the abundances expected by random chance, based on a set of carbon dioxide gases. This standardization, known as the absolute reference frame or carbon dioxide equilibration scale, corrects for differences between individual mass spectrometers and partially enables interlaboratory comparisons. The correction, however, doesn't account for differences in sample preparation.

The authors of this new study propose standardization using carbonate reference materials, which require processing with acid, just like the samples being investigated, instead of with gases. To validate the approach, 22 laboratories analyzed three reference carbonates and four unknown carbonate samples. When measurements of the unknown samples were corrected using average values for the references, discrepancies between laboratories reflected expected uncertainty rather than dramatic differences due to sample preparation as reported in previous studies.

The approach proposed by the authors—the InterCarb-Carbon Dioxide Equilibrium Scale (I-CDES)—will support standardization between laboratories and facilitate future investigation by the clumped-isotope community to understand Earth's past. (*Geochemistry, Geophysics, Geosystems*, https://doi.org/10.1029/2020GC009588, 2021) **—Jack Lee,** *Science Writer*

‘Oumuamua May Be an Icy Fragment of a Pluto-Like Exoplanet

In October 2017, for the first time in history, astronomers spotted an interstellar object on its journey through our solar system. The interloper? ‘Oumuamua, a shiny object with a flattened body about half a city block long.

Since then, scientists have followed many clues in attempts to determine what ‘Oumuamua is made of—and where it might have begun its journey. Some have hypothesized that it is made of hydrogen ice or water ice.

Now *Jackson and Desch* present a new analysis that suggests the mysterious object is made primarily of nitrogen ice and may have been ejected from the surface of a Pluto-like body orbiting a star in another solar system.

The new analysis takes into account ‘Oumuamua’s size, its shininess, the conditions it has been exposed to in interstellar space, and the component of its acceleration that is not due to gravity. Using these characteristics, the researchers narrowed down a list of potential materials. They found that the substance that best fits all of the clues is nitrogen ice.

Nitrogen is not an exotic material in our own solar system, the authors note. For instance, Pluto and Triton, the largest moon of Neptune, are swathed in nitrogen ice. Therefore, ‘Oumuamua could have originated from a Pluto-like exoplanet that ejected numerous icy fragments from its surface.

Further calculations suggest that ‘Oumuamua may have been launched into space about half a billion years ago in a solar system potentially located in the Perseus arm of the Milky Way. Ejection from the exoplanet could have resulted from orbital instabilities similar to those seen early in our own solar system’s history. (*Journal of Geophysical Research: Planets*, https://doi.org/10.1029/2020JE006706, 2021) **—Sarah Stanley,** *Science Writer*

A 50,000-Year History of Current Flow Yields New Climate Clues

From 50,000 to 15,000 years ago, during the last ice age, Earth’s climate wobbled between cooler and warmer periods punctuated by occasional, dramatic ice-melting events.

Previous research has suggested that these oscillations were likely influenced by changes in the Atlantic Meridional Overturning Circulation (AMOC), a pattern of currents that carry warm, tropical water to the North Atlantic, where it cools, sinks, and flows back south. However, the precise role played by the AMOC in ancient climate fluctuations has been unclear.

Now *Toucanne et al.* have reconstructed the historical flow of a key current in the upper part (the northward flow) of the AMOC, the Glacial Eastern Boundary Current (GEBC), shedding new light on how the AMOC can drive sudden changes in climate.

An iceberg floats off of Baffin Island, Nunavut, Canada, in the North Atlantic Ocean, a region that plays a key role in ocean circulation. Credit: National Snow and Ice Data Center, CC BY 2.0 (bit.ly/ccy 2-0)

The GEBC flowed northward along Europe’s continental margin during the last ice age (it persists today as the European Slope Current). To better understand the GEBC’s role in the AMOC, the researchers collected six seafloor sediment cores off the coast of France. Analysis of grain sizes and isotope levels in the core layers revealed the current’s strength when each layer was deposited, yielding the first high-resolution, 50,000-year historical record of the current.

This new historical record shows that the GEBC flowed faster during warmer intervals of the last ice age but weakened during the coldest periods. The timing of these changes aligns well with previously established records on AMOC speed and the southward return flow of deep waters to the west.

Comparing the history of the GEBC with other records also shows that major ice-melting events, in which ice age glaciers released huge amounts of fresh water into the Atlantic, correspond with periodic weakening of the current and of the AMOC in general.

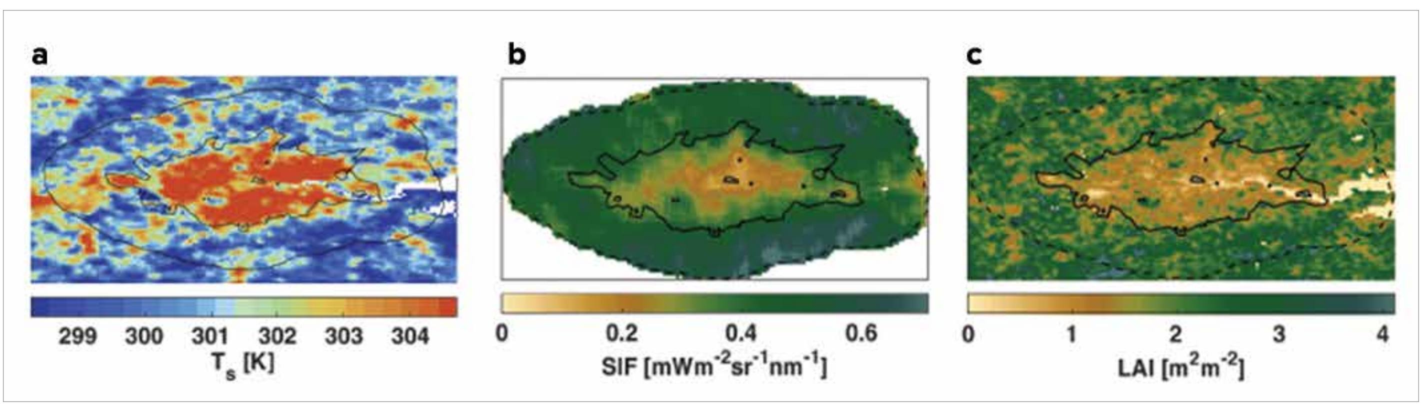
Drawing on these findings, the researchers outline a mechanism by which the GEBC could have carried cold glacial meltwater northward and contributed to changes in the AMOC that may have driven warm-cold climate oscillations in the North Atlantic. (*Paleoceanography and Paleoclimatology*, https://doi.org/10.1029/2020PA004068, 2021) **—Sarah Stanley,** *Science Writer*

Dune Aurora Explained by Combined Satellite–Ground Observations

Auroral dunes are seen in the sky in this photo taken from Aura, Finland, on 20 January 2016. Credit: Grandin et al., 2021

Grandin et al. present new observations of auroral dunes, a phenomenon that has been photographed over northern Europe by amateur astronomers. Their features are similar to those of typical aurorae in terms of their light emission characteristics, but their structure is more banded. The authors suggest that the underlying mechanism for this banded structure is modulation of the atmospheric density by a horizontally propagating atmospheric bore, following a waveguide formed by a temperature inversion detected in the upper mesosphere. Auroral particle excitation of the bore's trailing wave pattern results in the appearance of the dunes. Combining surface and satellite observations, the authors derive a wavelength and propagation speed for the dune feature, relating the latter to characteristics of the upper mesosphere. Strong horizontal neutral winds and electron precipitation play roles. (https://doi.org/10.1029/2020AV000338, 2021) **—Mary Hudson**

Urban Vegetation a Key Regulator for Heat Island Intensity



Maps of London show the average (a) surface daytime temperature, (b) vegetation activity, and (c) leaf area index during summer. Solid lines show the boundaries of the city clusters, and dashed lines, the boundaries of the rural surrounding. Credit: Paschalis et al., 2021

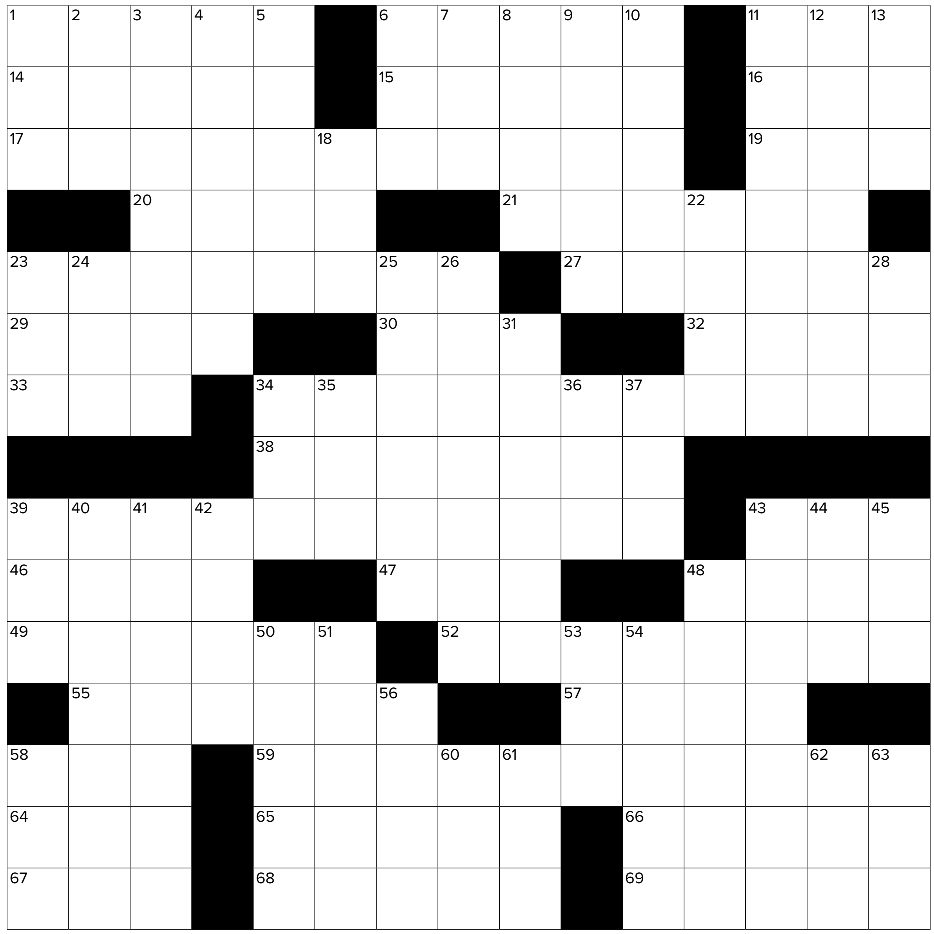
High temperatures in urban areas expose many people to potentially dangerous heat stress. *Paschalis et al.* used state-of-the-art satellite data for 145 city clusters to disentangle the drivers of surface urban heat island intensity (SUHI) and to quantify urban–rural differences in vegetation cover, species composition, and evaporative cooling.

They found that daytime SUHIs are highly correlated with vegetation characteristics and the wetness of the background climate. The magnitude and seasonality of daytime SUHIs are controlled by urban–rural differences in plant transpiration and leaf area, explaining the dependence of SUHIs on wetness conditions. Urban vegetation is the most important factor in regulating SUHIs. A reduced fraction of forested areas in cities leads to a strong decrease in leaf area index and weaker evaporative cooling.

These results highlight the importance of preserving urban forests as natural reserves for reducing the daytime surface urban heat island effect, rather than simply for "greening" cities. (https://doi.org/10.1029/2020AV000303, 2021) **—Donald Wuebbles**

Distant Wanderers

By Russ Colson, Minnesota State University Moorhead



ACROSS

1 A core group
6 Relating to a hose-like feature—and rhyming with ruble
11 What the gravity of one exoplanet might do to another, revealing its presence
14 Said not just in your head
15 Clear, as a file
16 Cellular messenger (abbr.)
17 Hydrogen- and helium-rich exoplanet more than 10 times more massive than our own world with a rocky or metal core
19 It transports energy (abbr.)
20 Type of type—or a chalk-eating urge
21 Start for "-logical"
23 A good thing to do with a job tip
27 Monkey type
29 Dendritic growth common in forests
30 Apple seed
32 Oil platforms
33 Word in ppm
34 Exoplanets up to twice the size of our own world
38 Ellipticals and ____ (galaxies)
39 Rocky (silicate) exoplanets similar in size to our own world or smaller
43 Baseball or hub, e.g.
46 Medication
47 Affirmative
48 Snowball world of *The Empire Strikes Back*
49 Native tribe of the Mississippi Valley whose first five letters spell a type of garment
52 A planet with an axis of rotation not perpendicular to its plane of ecliptic? Or well-spiced
55 Planets that have not cleared their orbit, like Pluto
57 One measure of the size of an exoplanet that, with 58 across, hints at planet composition
58 One measure of the size of an exoplanet (abbr.) that, with 57 across, hints at planet composition
59 Gas giant–type exoplanets orbiting near their stars
64 Piggy's play pen?
65 Planet that has left its star
66 They might emerge when many lamps are rubbed?
67 "The" in Avignon
68 Stone obelisk
69 Higher than tenors

DOWN

1 Preserve, as garden produce
2 Ginger ____
3 Method used to discover exoplanets in which shifts in wavelengths of light with time are measured
4 Titanium ore mineral
5 Education Company (abbr.)
6 Place to start a drive
7 Internet address (abbr.)
8 Something on a hook
9 One who questions
10 Something specific on a hook
11 Method used to discover exoplanets in which variations in light intensity with time are measured
12 Soft, as in "camping with temperature control is so ____"
13 Fulton ____: a range of sizes in which few exoplanets exist, yielding clues to planetary formation
18 Nope
22 Monsieur in Mainz
23 Protocol for moving files (abbr.)
24 Raw resource
25 On a high horse
26 South Dakota capital and a former Canadian prime minister
28 What the punctured tire says?
31 Envy is a kind of ____ —John Gay
34 157.5 deg.
35 Ending for sit, set, cut, and mash
36 Seen in the middle of Ireland
37 Language for the eyes (abbr.)
39 Abbr. for a planetary dynamical timescale
40 Scholarly
41 Landing strips
42 Ending for "geo-" that yields the name of a U.S. state
43 Government's just power derives from this—U.S. Declaration of Independence
44 What the fox did to the Gingerbread Man
45 Terminal degree (abbr.)
48 Low-cost lodging facility
50 Units of academic time load (abbr.)
51 "The game is ____"
53 Increase (with "up")
54 Endangered antelope
56 "All the wrld's a ____, and all the men and women merely plyrs"
58 Internet access option
60 Apr, May, Jun, ____
61 Fictional United Earth Alliance (abbr.)
62 Word in John Wayne movie titles (with Grande, Lobo, or Bravo)
63 A type of sib

See p. 50 for the answer key.

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