Space News
LIZ KRUESI
A rundown of some of the most exciting developments in space and time.

A Wealth of Water
NOLA TAYLOR TILLMAN
Spacecraft visiting the outer planets have revealed multiple planetary objects hold water oceans below their surfaces.

Discovering the Dark Universe
LIZ KRUESI
Most of the Universe is undetectable, and yet astronomers have learned an incredible amount about this invisible and mysterious part of the cosmos in the past five decades.

2021 ASP Awards Announced
The Astronomical Society of the Pacific is proud to announce this year’s awards for astronomy research and education.

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on the cover
Front: MACS J0717.5+3745 is the site of a gigantic collision between galaxy clusters. The pink glow in this image is X-ray data from the Chandra X-ray Observatory, and the blue glow is a calculated map of dark matter. [X-ray: NASA/CXC/Ecole Polytechnique Federale de Lausanne, Switzerland/D. Harvey & NASA/CXC/Durham U./R. Massey; Optical & Lensing Map: NASA, ESA, D. Harvey (Ecole Polytechnique Federale de Lausanne, Switzerland) and R. Massey (Durham University, UK)]

Back: On September 18, 2021, a SpaceX Dragon capsule carrying four civilian-astronauts safely slashed down in the Atlantic Ocean. This completed the Inspiration4 mission, which launched September 15 and orbited Earth for three days. [SpaceX]
I hope that during this year you have enjoyed looking back at a sampling of the most fascinating astronomical discoveries of the past five decades. (And don’t worry, there’s still one more celebratory issue to come this year.)

It continues to astonish me how much scientists have learned about the Universe and our place within it, since 1972 when the Astronomical Society of the Pacific (ASP) launched Mercury. One of these days, presumably after the pandemic has ended, I hope to dig around the ASP archive room and look at how early issues of Mercury reported on these incredible discoveries.

The issue you’re currently reading has been a fun one to put together, because it touches on such a wide range of topics. The two science features capture some of the most exciting research areas in astronomy: oceans at worlds other than Earth, and the discovery and investigation of dark matter and dark energy. Both of these pieces are part of the 50-volumes-of-Mercury celebration.

This issue also features the winners of this year’s ASP awards for astronomy research and astronomy education excellence. If you haven’t yet read about these deserving awardees, please do take a look at pages 36–40. I’m especially excited about the winners of both the 2020 and 2021 Robert J. Trumpler awards, which honors exceptional doctoral theses. It’s inspiring to see where astronomy is going and the technology that will take us there.

And now, a few questions to you as a reader: Are there topics you wish Mercury would include more often? Thinking about the past couple years of issues, are there articles you especially enjoyed? If so, please email me at editor@astrosociety.org.

Now that summer has gone and autumn is just beginning (it feels like it here, as the leaves have started falling and there’s a chill in the air), sit back with a mug of tea or hot chocolate, and dig into this issue of Mercury.

Liz Kruesi
Editor, Mercury
Celebrating Unseen Influences

In Memory of Vera Rubin, one of history’s great astronomers.

“… I became an astronomer because I could not imagine living on Earth and not trying to understand how the Universe works.”


I first met Vera Rubin when I was an undergraduate student. She had afternoon coffee with a small group of young women including me who all were considering careers in astronomy. She shared many stories of her own early career challenges (including having Princeton University reject her application to graduate school because the astronomy program didn’t admit women), and she answered all our questions. She also listened as we each expressed our fears and concerns about entering a field still dominated by men. In fact, when I went to professional astronomy conferences, Rubin was one of only a handful of women I would see among several thousand researchers. Seeing her there was comforting to me and gave me confidence — if she could make a successful career for herself despite the explicit sexism she endured, maybe I could too. It wasn’t until graduate school that I fully understood how groundbreaking her work was to science. Her observations sparked a revolution in astronomy as great as the paradigm shift Johannes Kepler had led and that her work would directly challenge.

Between 1609 and 1619, Kepler published his three elegant and simple laws of planetary motion. As applied to the known planets in our Solar System at that time, these are: Planets orbit in an ellipse with the Sun at a focus; the line connecting the Sun and planet sweeps out equal areas over the same period of time; and planets farther from the Sun will take more time \( T \) to complete their orbits and do so in a way that obeys a simple mathematical relationship, \( T^2/a^3 = \text{constant} \), where \( a \) is the semi-major axis of the elliptical orbit.

Kepler’s laws, published between 1609 and 1619, were not immediately embraced. Astronomers were slow to abandon the idea of circular orbits. In fact, Kepler himself was not comfortable with elliptical orbits either, and it took him many years of objective...
analysis to finally trust and believe his own data. Widespread acceptance of Kepler’s laws came a decade or two later when they were used to successfully predict the transits of Mercury (1631) and Venus (1639). To observe these tiny inner planets marching across the face of the Sun, you need extremely accurate information about where these planets are in their orbits and how fast they are moving. Get it wrong, and you’ll miss the event. Kepler’s laws made these predictions possible, and in the case of Mercury, the 1631 transit was the first observed one in history.

Astronomers can use Kepler’s laws to describe all kinds of orbits — the paths of comets orbiting the Sun, moons orbiting their planets, and artificial satellites orbiting the Earth. Kepler’s laws applied everywhere, or did they? In 1968, Vera Rubin found a remarkable exception, leading to a shift in our understanding of the cosmos as deep and profound as the revolution Kepler introduced.

In the late 1960s, how stars orbited inside galaxies was unknown. Rubin and her colleague, Kent Ford, used telescope sat Arizona’s Kitt Peak National Observatory and Lowell Observatory to collect data from stars and glowing regions inside the spiral-shaped Andromeda Galaxy. If you go only by what you see, it looks like most of Andromeda’s mass is in its very dense, massive core. You would expect the billions of stars orbiting Andromeda’s central bulge to follow Kepler’s laws – moving more slowly on the outskirts compared to the ones closer to the center. That was not the case at all. Rubin and Kent found the studied areas in the Andromeda Galaxy orbited with about the same speed no matter how far they were from the galactic center. This shocking discovery was not only true of Andromeda, but as the decades passed, Rubin found the same rotation curves in other galaxies. What’s the reason? Stars inside galaxies appear to not follow Kepler’s laws because detectable matter is only a fraction of the mass comprising a galaxy. The stuff you can’t detect — called “dark matter” because it isn’t visible in any part of the spectrum — must be responsible for what looks like a clear violation of Kepler’s laws.

Rubin didn’t invent the concept of dark matter, but she confirmed its existence. (See “Discovering the Dark Universe” on pages 28–35 for more about this discovery.) Rubin’s groundbreaking confirmation of dark matter completely transformed our understanding of the universe. Dark matter makes up almost 85% percent of the universe’s mass. It’s literally everywhere in the cosmos, influencing the motion of everything. For her groundbreaking discovery, Vera Rubin has been honored with numerous awards, including the ASP’s most prestigious award, the Catherine Wolf Bruce Gold Medal, in 2003.

In this issue of Mercury and here at the ASP, we celebrate her contributions to astronomy. We also celebrate the influence she has had on so many women, like me, who consider her among a remarkable generation of women who, like dark matter itself, are an unseen influence driving the direction of our lives. 🌙

LINDA SHORE is the Chief Executive Officer of the Astronomical Society of the Pacific.
The year 2021 marks a milestone in the history of a great figure in ancient Greek astronomy. It was in 480 BCE, 2,500 years ago, that Anaxagoras arrived in Athens, making him the first of the pre-Socratic philosophers to live there. Of course, with ancient sources one must use caution, but the biographer Diogenes Laertius in the third century CE stated Anaxagoras began philosophy in Athens at age 20, in the same year the Persian king Xerxes attacked Greece. That was 480. While he was successful at first with the destruction of Athens, the forces of Xerxes were defeated at the great battles of Salamis and Plataea. It is against this military backdrop that Anaxagoras began his career.

In astronomy, Anaxagoras is a figure of the utmost importance. Here I will describe his work relating to the Moon. On 17 February 478 BCE, there was an annular eclipse of the Sun visible across most of Greece. Ancient Greek writer and historian Herodotus described an eclipse at the time Xerxes left Anatolia for his Greek invasion, but there was no eclipse visible from there in 480; it may be that Herodotus picked the 478 eclipse to mark this great event. Modern scholars have written that such an annular eclipse “would have shocked the Greeks and Anatolians as an ominous sign.” It was almost certainly this eclipse that led Anaxagoras to make the astounding claim that he measured the size of the Sun.

To be more precise, he related the size of the Sun to the size of Peloponnesus, which is the peninsula comprising the lower portion of Greece. Various ancient sources offer quotes such that Anaxagoras “said the Sun was a fiery molten mass and greater than the Peloponnesus,” or conversely the Moon “is as large as the Peloponnesus.” Whether he developed it or not, it seems certain Anaxagoras possessed a theory that correctly explained solar and lunar eclipses, even though he held to the opinion that Earth was a thin disk. As for the size estimate, why did he...
relate it to the size of that particular area of Greece? In a 2007 study of this issue, Daniel Graham and Eric Hintz (professors of philosophy and astronomy, respectively, at Brigham Young University in Utah) noted that it was known by 478 that the Moon blocks the Sun’s light in proportion to the width of the Moon. Thus a measure of the shadow could lead to a size estimate. This appears to be what Anaxagoras did. The annular eclipse, in which 95 percent of the Sun was covered, cast a shadow that “covered the whole breadth of the Peloponnesus, except the extreme northwest,” Graham and Hintz state. Thus Anaxagoras equated the terrestrial size with the lunar size, and concluded the Sun was even larger.

His attribution of a fiery nature for the Sun seems to derive, suggest Graham and Hintz, from his view of the heavenly bodies “as being massy (i.e. rocky) and held aloft by a strong vortex motion of the upper heavens, and perhaps fiery as a result of friction.” Anaxagoras realized the Sun generated its own light and wrote, “it is the Sun that puts brightness into the Moon.” As the Moon merely shone by reflection, attributing a fiery nature to a rocky Sun was a natural step.

But what of the origin of the Moon itself? The philosopher daringly suggested the Moon was also a large rock, flung into space by Earth, thus presaging the fission hypothesis of lunar origin proposed by George Darwin in the nineteenth century.

Galileo Galilei was not the first to get in trouble for daring hypotheses about the nature of heavenly bodies. At that time in Greece, the Moon and Sun were regarded as deities. As a friend of the Athenian leader Pericles, the divinity denier Anaxagoras was a perfect target for the opponents of Pericles. Anaxagoras was sentenced to death, but Pericles saved him from that fate. Pericles was unable, however, to prevent his friend Anaxagoras from being exiled to a town in modern-day Turkey, though. He died there in 428 BCE, age about 72.

This only touches on the intellectual reach of Anaxagoras, who gave a complete account of the universe, including the light of the Milky Way, the formation of comets, and meteorological phenomena. Graham and Hintz sum up his career “as a genuine scientist—perhaps the first empirical astronomer.”

CLIFFORD J. CUNNINGHAM was recently seen in Tucson, Arizona, chatting with Charlie Duke, who walked on the Moon during the Apollo 16 mission.
**That Ol’ Gamma Moon**

50 years ago, Apollo 15 and 16 set out to measure the Moon’s gamma-ray emission

_When is the Moon brighter than the Sun? The joke answer would be “at nighttime, of course.” But another answer to this riddle is when the Moon is viewed in the gamma-ray waveband of the electromagnetic spectrum._

Gamma rays are the most energetic form of light, at least 100,000 times more energetic than optical light, which is that sliver of the electromagnetic spectrum that our eyes detect with an energy range roughly between 1 and 10 electron volts (eV). In astronomy, gamma rays are defined as photons higher than 100,000 eV (100 keV). They can have an energy of a million (MeV), billion (GeV), trillion (TeV), and possibly quadrillion (PeV) electron volts.

To be clear, the Sun is the brightest object in the sky from radio waves through X-rays and, actually, in the higher region of the gamma-ray realm, above 1 GeV, when it releases a solar flare. But there’s a generous swath of the electromagnetic spectrum in which the Moon is the star — between 20 MeV and 1 GeV.

And so, the next question might be, how can our cold and lifeless Moon generate gamma rays? In two ways: Natural radioactivity from elements on the lunar surface such as uranium and thorium produce gamma rays; and cosmic rays originating from beyond our Solar System bombard the lunar surface with such force as to emit gamma rays with a spectrum specific to the elements they interact with.

Two NASA missions that brought humans to the Moon also were the first to measure these gamma rays in depth. Apollo 15 and 16 were launched on July 26, 1971, and April 16, 1972, respectively. Apollo 15 is perhaps better known as the mission that introduced the Moon buggy; Apollo 16 gave scientists their best view of the so-called lunar highlands.

Lesser known, however, is the fact that both Apollo missions carried a gamma-ray spectrometer. The full instrumentation was approximately 4.2 inches (10 centimeters) in diameter and 8.9 inches (22 cm) long, located on a boom extended from the Apollo orbiting capsules, and built primarily by researchers at the University of California, San Diego. With this simple instrument, researchers were able to map about 20 percent of the lunar surface, providing the first chemical abundance maps of the Moon.

Although these experiments were built primarily to study the Moon’s radioactivity — important to understand if we ever plan to spend time there — we also got a peek at two cosmic phenomena only then recently discovered.
While in transit to and from the Moon, Apollo 15 measured the diffuse cosmic gamma-ray background. Many decades would pass before we understood the primary source of these cosmic gamma rays to be quasars and similar active galactic nuclei (AGNs) powered by supermassive black holes.

For its contribution to gamma-ray astronomy, Apollo 16 caught a glimpse of a gamma-ray burst, the first GRB to be captured by two spacecraft, the other being Vela 6. The unique multiwavelength spectra — with lower-energy gamma rays detected by Vela and higher-energy ones by Apollo — would be a mystery that took another 30 years to solve, ultimately by the multiwavelength NASA Neil Gehrels Swift Observatory.

The Moon’s gamma rays cannot reach us on Earth, and our atmosphere protects us from this radiation. But should we venture back to the Moon, we’ll certainly need to wear protection. The Moon is “sunny” with gamma rays both day and night, regardless of your location on its rotation. 

CHRISTOPHER WANJEK is a Baltimore-based science writer who has revisited his fascination with the Apollo missions in his book *Spacefarers* (HUP, 2020).
Interpreting Change

Time and our limited perceptions frequently obscure the impermanence of the world.

On a recent hike in the coastal redwoods, a solitary old-growth tree stood. A short fence surrounded it, and a nearby sign announced it as an example of what once had blanketed the slopes and valleys. Without this tree, a casual visitor may not have noticed the forest was filled with second- or even third-growth trees, although they may have noticed all the stumps. Redwood lumber is prized for its ability to withstand rotting, enduring for years beyond a fir or pine structure. Redwoods grow fast, springing from the stumps and downed “nurse” logs without the need for replanting. A 50-year-old forest with sizable trees may obscure the fact of past harvesting of the trees unless you are conversant with the other characteristics of an old-growth forest. Forests such as this may give us the illusion of a nature that self-corrects with little action on our part other than leaving it alone for a few years.

As visitors to natural areas we anticipate seeing the same features and views we first saw reading National Geographic as a child. And usually nature cooperates, with landscapes little altered other than human intrusions. Visiting Yosemite Valley we may notice the scars of rockslides on the valley walls, and maybe even see one ourselves. Most people would see those slides as a rare occurrence without realizing much of the topography is a result of downslope movement of one kind or another. In the visitor’s mind, the landscape is
timeless, looking much as it did when the early popularizers such as John Muir first described the setting.

In school, we learn about how the world was very different in the past, although you have to go quite far in the past to find a time when it would have appeared appreciably different — much longer than what human history can hold. Even a clearcut in the coast redwoods starts looking as it once did within a single human lifespan, visual evidence of how nature really does stay the same even when we interfere. Apparently.

Relative timespans
Humans are able to recognize change within their own lives as they age and experience various stages of growth. We are even able to note the aging of our parents as they become someone different than the people we grew up with, although the changes took place so slowly we were barely aware of them. Maybe it is the same phenomenon that makes me continue to see my unchanged self when looking in the mirror. My aging has crept up on me without any apparent drastic changes to my appearance. Even the events of our lives don’t appear to create too many distinctions. The marriages of two of my children and the birth of a grandchild remind me I have aged, however the visage in the mirror remains a younger self who isn’t possibly old enough to have grandchildren.

The slow changes in our landscape and global systems are perhaps similar: The changes are too slow and incremental and taking place elsewhere for us to notice. Even the increasing occurrence of large events such as polar vortexes, unprecedented wildfires, and the melting of the polar ice caps are tangential to our own lives, at least for most of us, and our immediate environment continues to show little to no change. Scientists attempt to use data to demonstrate the magnitude of the climate changes taking place, however these don’t match with our daily experience or expectation of the permanence of the world. As noted previously, humans struggle to think in the time scales on which most global changes take place. When presented with actual images of locations taken many years apart most people are able to pick out the differences, even in places such as redwood forests and the cliffs of Yosemite. But the basic background is much the same. Going back still further, we have only renderings of what we imagine it must have looked like, using data from tree rings or ice cores or accumulated sediments to argue for the truth of what we present. In the same way, renderings of potential future impacts are frequently used to project what eventual outcomes may look like.

One of the things educators do to engage students when they are unable to bring an actual phenomenon into the learning environment
is to bring in an analogous one. When used appropriately, these analogues can stand-in for the actual phenomenon we wish the learners we are interacting with to understand enough to explain using evidence they collect themselves. This requires creating concrete learning opportunities that are open-ended enough to allow students to form their own conclusions, and not just to participate in confirmation activities.

Climate change education tends to use the same data sets, asking students to recreate the same graphs they see in the media. Having every student in every classroom using the same data points to create the same graphs does nothing to create even a momentary cognitive dissonance as they struggle to make sense of their experience. The outcome is predetermined with no room for individual thought. In an extreme point of view it is almost indoctrination, where critical thinking and dissent is disallowed. What we want is for young learners to have the opportunity to examine a phenomenon, not just a data set, gather evidence, then make an argument explaining the phenomenon based on their own evidence. Ideally the phenomenon is one they encounter in the context of their own lives.

Change is all around us. And it always proceeds at its own pace, usually at one we are unable to observe at a single glance, or even within the constraint of a single human life span. Even then other factors may obscure the perception of change. The solution for educators is surely not simple, and it may involve looking at how learners experience the world over their entire school career. Some standards encourage the observation of patterns decipherable over the course of a single year. The ones we as science educators concerned with the state of our planet must bring into student experience are those we can only decipher over many. A singular experience is not enough to convince someone of the impact of slow change. To truly understand, many experiences over a lifetime and more are necessary.

BRIAN KRUSE manages the formal education programs at the ASP.

The interacting galaxy pair known as Arp 87 beautifully displays the millions-years-long dance of such collisions. These astronomical events occur on time frames completely unfamiliar to human lifetimes. [NASA, ESA, and The Hubble Heritage Team (STScI/AURA)]
This is Not Your Mother’s Astronomy Course

The past five decades have seen enormous changes in not just the science of astronomy but also in how astronomy is taught.

One of the marvels of astronomy is how much our knowledge of the universe expands and evolves over time. Even over the course of a human lifetime, our understanding of the cosmos has changed. Take a look at our Solar System. Just 50 years ago, back when *Mercury* magazine was starting out, what did we know about our Solar System? We knew that it contained one star, nine planets (back when Pluto still held planetary rank), dozens of moons, a swarm of asteroids and comets, but that was pretty much it. Pluto was the edge of the observable Solar System, so remote that even its largest moon Charon wouldn’t be discovered for another eight years. Astronomers knew comets had to come from somewhere, though, and both Kenneth Edgeworth and Gerard Kuiper had even theorized Pluto’s territory might be filled with icy objects. Unfortunately, this realm was still only theoretical.

If your mother had taken a Solar System astronomy class in the early 1970s, it would have been very different from the one your students see, not only in content, but also in format. Like our knowledge of astronomy, our understanding of astronomy education has come a long way. Even back in the ’70s, enrollment in introductory astronomy courses was high, where “over 50,000 students per year take general education courses in introductory astronomy.” There was a Kuiper Belt of sorts — a theoretical outer expanse of astronomy education that instructors knew should exist, but that they had no actual experience with. Just as today, educators noted a disconnect between the general public and science, stating that “it is necessary to explain to the public that science affects our lives in a much more basic manner than just through gadgets.” There was also concern that “an anti-science reaction is developing in this country, particularly among high school and college students.”
To combat these issues, instructors encouraged one another to try a radical approach: engage your students. Many argued that passive learning wasn’t enough, that students needed to be engaged in their learning. But by their definition, “the quasi-active techniques include those in which the student works primarily, although not exclusively, on his own. Except for laboratory exercises, the quasi-passive activities are generally done at the institution, either with teaching fellows or with a professor, whereas the quasi-active activities are normally done outside of school.”

What was a “quasi-active” activity, you ask? Essentially anything the student had to do on their own. Reading the textbook qualified, as did answering homework questions, writing papers, or completing lab activities.

Others argued that students could be engaged with a really good lecture. In his 1971 essay, “Science education: a case for astronomy,” plasma astrophysicist and astronomy instructor Donat Wentzel wrote, “I call a good lecture one that is fairly self-contained and gets across one or two ideas that the student can remember and appreciate days, weeks, and hopefully months later.” He went on to explain, “I feel that one can present a fair amount of descriptive material, always on condition that the value of this material be stated quite explicitly. With this proviso, I find that even the more apathetic students are willing to learn a fair amount of astronomy.”

These days, assertions like these might wind up in the reject pile of job applicants for a teaching position, as we now understand that a strong teaching statement should encompass more than the promise of “really good lectures.” But 50 years ago, these words were innovative. Wentzel, as it turns out, would later be honored for a lifetime of service to astronomy. Like any good astronomer, he knew the importance of following the data, and soon understood that a good lecture was just the beginning. In a sense, a good lecture was like knowing the basic properties of Jupiter as observed from Earth. To know more, you need to make better observations.

You need to fly past Jupiter.

**A bigger picture**

In 1972 and 1973, the Pioneers 10 and 11 spacecraft launched, followed in 1977 by Voyagers 1 and 2. Solar System exploration and astronomy education research were about to greatly expand their horizons. Here on the ground, technology was steadily improving through the 1970s and 1980s. We no longer had to use Clyde Tombaugh’s blink comparator to find motions of Solar System...
objects. We had computers and digital detectors, in the form of CCDs (charge-coupled devices). Searches became digitized, and in a cosmic blink of the eye, Kuiper Belt Object 1992 QB₁, now known as 15760 Albion, was discovered. It wasn’t long until more followed.

On the education front, researchers were getting a clearer picture of exactly why the best lectures were never enough. If you teach well...anything, and you haven’t yet seen the award-winning documentary *A Private Universe*, stop what you are doing and watch it. To see Harvard graduates struggle with the basic concept of seasons is to fully grasp why the best lectures will never unseat the strongest preconceived notions. Astronomy educators began digging into these preconceptions, trying to find their roots. More important, those educators were trying to figure out how to replace the preconceptions with what the universe is really doing. That replacement process, it turns out, requires constant, in-person engagement. Students couldn’t be expected to go home, read the book, and magically change the picture they’d held on to for so long. They needed interaction, and lots of it. They needed to confront those preconceptions head on, and they needed instructors who could help them do it.

By the early ’90s, astronomy education as a self-contained discipline was growing, and instructors were exploring different methods of active learning. Around the time that 15760 Albion (known then as 1992 QB₁) was discovered, the baton was being handed to the next generation of astronomy educators, who developed cooperative learning activities that could be completed during class time. Lectures were abbreviated and classes were flipped. Novice astronomy instructors were soon attending workshops about incorporating strategies like Think, Pair, Share questions and Concept Mapping into their courses. While not new to the field of K–12 education, cooperative learning strategies were just starting to find a foothold within the realm of university science education. Students were now being encouraged to work together with one another, rather than compete against one another for high grades. Structured student interactions within the classroom, not just outside of it, were starting to pop up in astronomy classrooms, just like the KBOs being discovered in space.

**Decades of progress**

…Which brings us to now. More than 2,000 KBOs have been discovered, and in 2015, astronomers finally observed multiple KBOs up-close and personal with the New Horizons mission that had raced past Pluto. In the past half century, it’s as though an entirely new branch to the Solar System has formed. Our previous knowledge
barely scratched the surface, and Pluto itself became a member of a new class of objects.

The past 50 years have brought similar advances in astronomy education. We have a better understanding of not just the psychology behind student preconceptions, but the types of activities that can be done to tackle them. A wealth of materials now exists to guide students away from common misunderstandings in introductory astronomy classes. In fact, so much has been done in astronomy education that there are dedicated conferences, workshops, publications, and poster sessions. Universities even offer graduate degrees in astronomy education now.

On the other hand, there are countless journal articles discussing actual observations of the over 2,000 known Kuiper Belt Objects. It’s definitely not your mother’s astronomy class. And it’s a pretty safe bet that your descendants’ astronomy class will be even further afield than we can imagine.

C. RENÉE JAMES is a science writer and professor of physics and astronomy at Sam Houston State University, where she has taught introductory astronomy since 1999. She is the author of two books, “Seven Wonders of the Universe That You Probably Took for Granted” (2010) and “Science Unshackled” (2014).

SCOTT T. MILLER is a Professor of physics and astronomy at Sam Houston State University, where he has taught introductory astronomy for non-science majors and engaged in astronomy education research since 2008.
First Mars Samples Stored

The Perseverance rover, which has been at Mars since February 18, has successfully drilled its first two core samples and stored them in titanium tubes. The NASA mission first tried to collect a sample in August, but the rock crumbled, said the space agency. The second attempt from September 6, which used a different rock, was a success. It was so successful, in fact, that Perseverance collected its second sample from the same rock. These demonstrate the rover’s complex, multi-day, sample-collection process works.

The captured samples come from a briefcase-size rock on a ridge in Jezero Crater, the site the rover has been exploring for months. Once the team selected the sampling site, the rover began its collection process September 1. First, Perseverance’s drill ground away the top layer of the rock, then the drill cut a pen-size core. The rover placed that core in one of its 42 remaining titanium tubes. Perseverance then transferred the tube (with its sample) to the rover’s underside, where a suite of instruments imaged and inspected the freshly captured material. Finally, the process was completed September 6 when the tube was sealed, to wait for a future day when it returns to Earth for further analysis. Perseverance followed the same steps two days later for another sample from the same basalt rock. Preliminary analysis of both found crystalline minerals and evidence of past volcanic activity.

The Mars 2020 mission has the capacity to collect and store dozens more samples, and the team expects many of those to come from Jezero Crater’s delta region. While the rover is staying relatively near (within a couple miles of) its landing site, it will eventually move farther north and west to an area marks a once-river and a once-lake met. On Earth, the beds of ancient bodies of water hold fossilized signs of life. The Perseverance team will look for similar signs and other evidence of astrobiology at Mars. — Liz Kruesi
Peculiar Gamma-ray Burst Found

Explosive signals called gamma-ray bursts (GRB) are the most energetic blasts detected. For decades, astronomers have cataloged these bursts into two classes: long-duration, lasting 2 seconds up to a few minutes and signaling a massive star’s explosion-then-collapse into a black hole; and short-duration, a gamma-ray blast less than 2 seconds and signaling a collision between two compact objects (neutron stars or black holes). In both cases, the initial gamma-ray signal is from a jet of radiation and high-speed material beamed out of the source and aimed at Earth’s telescopes. A GRB signal detected last year, however, looks a bit like both types at the same time. Two papers in the July 26 issue of *Nature Astronomy* describe this weird GRB, and what it might mean for understanding such bursts.

In August 2020, multiple space-based gamma-ray detectors collected roughly 1 second of gamma rays, the most energetic form of light, signaling a GRB. Over the next several hours, telescopes sensitive to other types of light helped triangulate the GRB’s location and further study the source. They saw fading X-rays and a varying radio signal, both of which are typical in the so-called “afterglow” of a long-duration GRB. (The afterglow is a result of the jet passing through intervening material, energizing it and making it glow.) But with the short initial gamma-ray spike, this burst, known as GRB 200826A, has surprised astronomers.

For years, some scientists have suspected GRBs detected with modern instruments aren’t all being catalogued correctly. And that might mean some of the short-duration bursts seen over the past decade are actually from massive-star collapse and not from mergers. In fact, one of the research teams who studied GRB 200826A wrote in their *Nature Astronomy* paper: “This burst confirms the existence of short-duration GRBs with stellar core-collapse origin, and presents some challenges to the existing models.”

The other team argues in their paper this GRB “appears to sit on the brink between a successful and a failed collapsar.” Perhaps long-duration GRBs are the result of a collapsing massive star with powerful jets, and some of the short-duration variety arise when the jets aren’t strong enough to sustain themselves. — L. K.
Dust Shrouded and Dimmed Betelgeuse

When the star Betelgeuse dimmed in late 2019 to early 2020, the astronomy community began to wonder if the star would soon explode as a supernova. It’s a red supergiant star, which is a late evolutionary stage of a star some 8 to 30 times the mass of the Sun. And Betelgeuse is destined to explode as a supernova; perhaps this was the start? But the star brightened again. Crisis averted.

Most stars are too far away from us, too small, or too faint (or some combination of the three) for telescopes to resolve them. But Betelgeuse, the bright orange star at constellation Orion’s shoulder, is only about 700 light-years away and a supergiant star. Astronomers for over a decade have been able to resolve some details of Betelgeuse’s surface, and that ability let researchers learn what was happening with this star during its “great dimming” of 2019–2020.

A new study, published in June in the journal Nature, suggests this dimming was the result of an enormous cloud of dust shrouding roughly one quarter of the star’s surface. This study used multiple instruments at the European Southern Observatory’s Very Large Telescope (VLT) in Chile. The researchers hypothesized and computationally modeled several scenarios that could have explained the dimming. They determined the most likely scenario is that convection in the star’s stellar plasma material brought up a large bubble of cooler gas, which was ejected from the star. Once the bubble cooled enough, it condensed to dust.

In late 2019 to early 2020, the star Betelgeuse dimmed then rebrightened. [ESO/M. Montargès, et al.]

A previous study published in The Astrophysical Journal used the Hubble Space Telescope to study Betelgeuse. Those researchers suspected a similar scenario. — L. K.
Hubble Telescope Averts Scare

For more than a month, astronomy's most famous telescope had ceased observations. On June 13, the Hubble Space Telescope suspended science operations due to an issue related to the payload computer. This main payload computer controls, coordinates, and monitors Hubble's science instruments. When the fault arose, the science instruments went into safe mode. After nearly a month of testing, the mission team announced on July 13 it had identified the problem.

The payload computer resides in the Science Instrument Command and Data Handling (SI C&DH) unit, which also houses the Power Control Unit (PCU). The PCU provides a steady 5 volts to power the Hubble payload computer hardware. If the voltage either drops below or rises above that value, a secondary circuit tells the main payload computer to suspend operations. The Hubble team believes either the voltage is not at 5 volts or this secondary circuit no longer functions as it should.

Hubble's SI C&DH unit also has a backup payload computer and backup PCU, and the team successfully switched to both the backup PCU on July 15. On July 17, the telescope's science operations were back online. “I’m thrilled to see that Hubble has its eye back on the universe, once again capturing the kind of images that have intrigued and inspired us for decades,” said NASA Administrator Bill Nelson in a press statement a couple days later. (See page 41 for one of the first images released after Hubble was back online.)

In this photo from the Space Shuttle Atlantis crew in 2009, the Hubble Space Telescope appears to float above Earth. [NASA]

In the observatory’s 31 years of operation, there have been several other scary shutdowns. In fact, in 2008, there was a similar switch to a backup module on the SI C&DH. The 2009 servicing mission then replaced the entire SI C&DH. The mission team anticipates Hubble will continue operating normally for years. — L. K. ☺
A Wealth of Water

Spacecraft visiting the outer planets have revealed multiple planetary objects hold water oceans below their surfaces.

By Nola Taylor Tillman
Earth’s sparkling blue color clearly identifies it from space as a world of water. And while it’s the only blue marble in the Solar System, Earth is not the only ocean world in our planetary system. Several of the moons around the giant planets are thought to contain water beneath their rocky and icy crusts. Even tiny Pluto boasted a liquid ocean beneath its surface in the recent past, and other objects toward the edge of the Solar System may also be hiding their aqueous treasures out of sight. The abundance of water, thought to be a key ingredient for life as we know it, provides an optimistic hope for one day finding life somewhere other than Earth.

Planets form from the material leftover after a star is born, and moons often form from the planetary leavings. Other satellites develop later in a planet’s evolution, when an impact hurls heated material from the world into space, where it can coalesce into a new object. With hydrogen the most abundant material in the universe, it makes sense that water (made up of hydrogen and oxygen) could be a common ingredient in most newborn worlds and their moons.

But when a planet and its moons are far from the heat of the Sun, that liquid water tends to freeze as the hot, young planet cools. Maintaining a liquid layer as a permanent part of the environment requires an additional source of heat. The giant planets can provide that in the form of gravitational tides, which is why most of the known ocean moons can be found orbiting Jupiter and Saturn.

**Jupiter’s Galilean moons**

In 1610, the Italian astronomer Galileo Galilei spotted four unusual objects orbiting Jupiter, the first moons identified around another world. While nearly a hundred moons have been since discovered around the largest planet in the Solar System, the four Galilean moons — Europa, Ganymede, Callisto, and Io — are the largest of the bunch. Io reigns as the most volcanic object in our planetary system and may contain a magma ocean; the other three are thought to boast a layer of water beneath their crusts, making them ocean worlds.

At only a little smaller than Earth’s Moon, Europa has captured a great deal of interest. Since 1985, scientists have pondered the possibility that it could shelter a liquid ocean due to interactions with Jupiter’s gravitational field. In 1998, NASA’s Galileo spacecraft reported fluctuations of Jupiter’s magnetic field around both Europa and Callisto, potentially in response to salty subsurface oceans. Other Galileo observations confirmed a salty sea beneath the crust of Ganymede.

These oceans would have formed early in the Solar System’s history, when the moons themselves were born. Internal heat would have...
helped them to sustain their liquid interior. As the innermost Jovian moon, Io feels the greatest tug from Jupiter as it orbits the planet. Europa is next in the line of Galilean moons and also feels a strong gravitational pull from the planet along with gravitational interactions with the other moons. These tugs, known as “tidal heating,” are strong enough to keep the interior of both inner satellites liquid, although in Io’s case the ocean is made of magma rather than water.

Next in line is Ganymede. “Ganymede is very interesting because it’s the biggest moon in the Solar System, like a mini planet,” says Olivier Witasse, project scientist for the European Space Agency’s (ESA’s) JUpiter ICy moons Explorer (JUICE) mission. Larger than Mercury, the moon may host a magnetic field that could shield the planet from the worst of Jupiter’s radiation. Its surface shows signs of past eruptions of water bursting from the crust and freezing over, and its atmosphere hosts water vapor.

At the outer edge of the Galilean moons is Callisto, whose surface is one of the most cratered crusts in the Solar System, suggesting an older, stagnant surface. But the Galileo spacecraft revealed a magnetic field that fluctuated in time with Jupiter’s rotation; an ocean could be hiding beneath the deceptively boring surface in the same way magnetic field fluctuations at Europa and Io hint at salty water oceans.

Of the trio of Galilean oceans, Europa’s is considered one of the most interesting for several reasons. First, it is closer to the surface, buried beneath only a few tens of kilometers rather than the hundreds of kilometers that shield the water of Ganymede and Callisto. Furthermore, Europa’s ocean lays on top of a rocky crust, where it
can interact chemically with the ground beneath it. On Earth, hydrothermal systems at the bottom of the ocean have proved surprisingly habitable for life, and scientists are optimistic that similar systems could evolve where salty water and rock meet on Europa.

In 2016, the Hubble Space Telescope caught a tantalizing glimpse of plumes of material erupting from the surface of Europa. Although not as consistent as the better-known eruptions of Saturn’s moon Enceladus, Europa’s fountains may provide an opportunity to probe beneath its icy layer. When NASA’s Europa Clipper mission begins to orbit the planet in 2030, it will study the moon’s icy surface to gain an idea of the environment and how common such plumes might be. Clipper’s radar will probe beneath the ice to find regions where liquid water may pool in small lakes beneath the surface but above the ocean layer, and perhaps even catch a glimpse of the surface of the ocean below. The spacecraft will also study the properties of the ocean layer.

“[Europa] is the best place, in my opinion to look for life beyond Earth,” says Cynthia Phillips, project staff scientist for the mission. “Europa could be habitable today — I’m so excited to see what the Europa Clipper mission discovers there!”

Saturn’s Enceladus excites
When NASA’s Cassini spacecraft reached Saturn in 2004, it didn’t take long to reveal plumes of liquid material jetting into space from the southern pole of Enceladus. Suddenly this small icy moon, something of an afterthought, became far more intriguing. Fountains of liquid burst from crevices known as “Tiger Stripes,” and with a little adaptation to its original mission, in 2008, Cassini was able to fly through and take a sample of the underground ocean.

The spacecraft found that Enceladus’s plumes contain a mixture of carbon, hydrogen, oxygen, and nitrogen (CHON) molecules, including organic compounds that are the building blocks for life on Earth. “The coexistence of some of these CHON molecules, like the two ends of a battery, can generate chemical energy to power a biosphere perhaps [similar to] the more sparsely inhabited oceans.
and lakes on Earth,” says Marc Neveu, an astrobiologist at NASA’s Goddard Space Flight Center.

Confirming a global ocean, rather than a local subsurface sea or lake, took longer. Gravitational measurements made over the course of three Cassini flybys of the moon revealed that the material supplying the plumes came from a global ocean, not just from a local reservoir at the southern pole. In 2016, scientists reported that Enceladus has a slight wobble resulting from its ice shell gliding atop a frictionless layer of liquid water. Together, the details confirm that Enceladus is an ocean world.

While the plumes weren’t enough to confirm the global ocean, they certainly played an important role in identifying it. “The fact that Enceladus has those spectacular eruptions was one of the reasons we paid so much attention to it and bothered to make those measurements in the first place,” says Douglas Hemingway, a planetary scientist and Chief Scientist of Civil Space Capture at Maxar Technologies. “If we had enough money, we could make similar observations at all kinds of other bodies in order to study their interiors, and possibly identify more internal oceans.”

And Enceladus’s more than 100 identified plumes may provide the best hope of identifying life beyond Earth. Whereas the Jovian moon Europa’s plumes are faint and irregular, Enceladus’s eruptions are constant. “While each ocean world has its own pros and cons to their potential to harbor life, Enceladus is unique among them because of
its access to ocean material,” says planetary scientist Terry Hurford of NASA’s Goddard Space Flight Center.

**And Titan thrills**

One of the most intriguing Solar System moons is Saturn's largest moon, Titan. Of all the worlds beyond Earth, only Titan has rainfall. Unlike our planet, however, Titan’s rain is made up of hydrocarbons, resulting in a methane rain that fills the surface with methane lakes and seas. Organic molecules cover the surface, blown around by the wind and potentially interacting with one another.

“Titan is an organic sedimentary world wonderland,” says planetary scientist and Titan researcher Michael Malaska, of NASA’s Jet Propulsion Laboratory (JPL).

Like many of the large moons, Titan also hides a subsurface ocean of liquid water. Formed early in Titan’s life, the ocean lies under the rocky surface, with an ever-growing crust of [methane/water] ice piling up as a barrier between the two as the moon cools over time. If powerful impacts early in the Solar System’s history managed to pierce the crust of titan, material and potentially even life from the surface could have migrated into the ocean, where it might have been able to survive.

New research, however, suggests that organics could have migrated up from the core. Malaska references a recent presentation at the American Geophysical Society meeting from Kelly Miller of the Southwest Research Institute, who suggested that there could be more organics in Titan’s ocean than in Earth’s. “That’s a lot!” notes Malaska. Because of where they formed in the Solar System, both Titan and Enceladus could have collected ammonia in their subsurface oceans, which could provide a dose of organic molecules.

According to Malaska, pressures in the ocean would have been at least 10 times higher than the deepest part of Earth’s ocean. Working with researchers at the University of Illinois at Chicago, he is exploring how life could thrive under extreme pressures. “We are seeing how microbes adapt to very high-pressure conditions,” he says.

Unlike Enceladus and Europa, any life hidden beneath the crust of Titan may remain hidden for a long time. “To search for extant life, Infrared vision can see through Titan’s thick atmosphere to its surface, which hosts lakes of methane and ethane. Below that surface, though, lies a water ocean. [NASA/JPL/University of Arizona; illustration: Chuck Carter and James Tuttle Keane/Keck Institute for Space Studies]
we will have to go very deep to get into the crustal ice and deeper subsurface ocean, and that is very challenging to do,” Malaska says.

**Water water everywhere**

Although the surfaces of the Solar System tend toward dry barrenness, water is clearly abundant around the Sun. Europa, Enceladus, Titan, Ganymede, and Callisto are some of the most well-known worlds thought to have hidden oceans beneath their crusts but they are likely not the only ones. Neptune’s moon Triton may host another hidden ocean. Originally formed in the Kuiper Belt, the icy outer region that Pluto calls home, Triton was captured by Neptune. Tides from the giant ice planet could have melted any subsurface ice.

NASA’s New Horizon mission also revealed that Pluto had a subsurface ocean in its past, though it has most likely frozen relatively recent — in astronomical time frames. Although both Pluto and its largest moon Charon are small worlds, the gravitational tides produced as they orbit each other likely melted water ice to liquid. Charon is very close to the same size as its parent, and the pair are often referred to as a double planet system.

Pluto and Charon aren’t the only so-called “binaries” in the Kuiper Belt — in fact, a large percentage of the objects in the belt may come in pairs. Pluto’s ocean opened the door to the idea that the largest of these binaries could potentially have housed oceans melted by their companions at some point in their past. And this isn’t the only belt in the Solar System that may hold ocean worlds. Some scientists think Ceres, the largest body in the Asteroid Belt between Mars and Jupiter, may contain a subsurface ocean.

The past couple decades have revealed an unbelievable wealth of oceans in the Solar System, and the forthcoming missions of JUICE and Europa Clipper promise to discover more detail.
Discovering the Dark Universe

Most of the Universe is undetectable, and yet astronomers have learned an incredible amount about this invisible and mysterious part of the cosmos in the past five decades.

By Liz Kruesi

The collisions between clusters of galaxies, like MACS J0025.4–1222 shown here, display evidence that dark matter exists. The more-dispersed hot gas, the magenta pink X-ray glow in this image, was slowed by friction during the collision; while the blue in this image traces the mass distribution of dark matter (calculated from warped images of background galaxies). [X-ray (NASA/CXC/Stanford/S. Allen); Optical/Lensing (NASA/STScI/UC Santa Barbara/M. Bradac)]
Humans understand the world around us via observation. By interpreting the glowing dots in the night sky, early observers began to understand the greater cosmos. Eventually they learned those pricks of light are stars, some a few light years away and others far more distant and making up galaxies. Observers later could see other types of light, like penetrating X-rays and other high-energy radiation, which are released during explosive cosmic events. And they could detect the radio hum from a spinning compact star.

Such observations over the centuries have taught us about the Universe and our place within it. But these observations can also reveal what we don’t know — because we cannot see all.

That’s how scientists in the past few decades learned that everything they can see, all the material they understand and detect, makes up only about 5 percent of the Universe. Of the remaining 95 percent of the cosmos, about one-third is an invisible matter, and the remaining is something even more mysterious. To uncover this majority of the Universe, researchers have developed new experiments, detection methods, and theoretical explanations.

**Early observations**

The first evidence of invisible dark matter came in the 1930s, when astronomer Fritz Zwicky looked at the motions of galaxies within a cluster of galaxies. He analyzed the motions of several member galaxies in the Coma cluster and calculated the mass required to keep the galaxies gravitationally bound together. It was substantially more than his calculation of the galaxy cluster’s mass based on its luminous galaxies. That meant, “it would have the surprising result that dark matter is present in the universe in far greater density than visible matter,” he wrote in his 1933 paper in *Helvetica Physica Acta* (this quote has been translated from the original German paper).

Fast forward to the crucial results of the 1970s, which finally convinced scientists of this missing matter. Just two years before the Astronomical Society of the Pacific launched *Mercury*, two astronomers — Vera Rubin and W. Kent Ford — published their results from studying the motions of stars and glowing gaseous regions in the nearest large galaxy to us, the Andromeda Galaxy (M31). They were using these objects’ spread-out light, their spectra, to measure how

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In the 1970s, multiple groups of astronomers used both optical and radio telescopes to measure the velocities of stars and bright nebulas in the Andromeda Galaxy (M31). The findings suggested the existence of an unseen type of matter. [Vera Rubin and Janice Dunlap]
fast those stars and emission regions were moving around the center of their galaxy. Their orbiting motions should follow the same type of motions that govern how the eight planets orbit the Sun (closer-in to the center of mass means moving faster). But when the astronomers looked at the speeds of the objects located in the middle of Andromeda’s disk, things looked odd. Those stars and gaseous regions were moving faster than expected. Some type of mass the astronomers couldn’t see seemed to gravitationally hold those objects to the galaxy. This result echoed Zwicky’s Coma cluster findings.

A few years later, in 1975, astronomers Mort Roberts and Robert Whitehurst published their findings of the Andromeda Galaxy. Their radio observations extended how far out from the galaxy’s center researchers could see. The bright regions’ velocities stayed constant. Throughout that decade, more researchers looked at additional galaxies, and they found the same story. By the early 1980s, most astronomers realized the majority of the Universe’s material was dark and undetectable directly.

A cosmic glue

Physics, and its laws, describes how everything in the Universe operates under four fundamental forces: the gravitational force (we are very familiar with this one, but it’s actually the weakest force), the electromagnetic force (optical light and other forms of radiation), the strong nuclear force (it holds atomic nuclei together), and the weak force (it’s responsible for radioactive decay). The latter three forces work in conjunction with the elementary particles that physicists know to comprise the so-called “Standard Model;” the gravitational force doesn’t fit within that same framework, and summarizing that discrepancy is worth an entire other article.

Scientists’ understanding of everything they can detect and interact with is based upon the Standard Model and the general theory of relativity, the latter of which tells us how gravity works. Astronomers have looked for direct signals of dark matter for decades, but they’ve seen signs of this material interacting with the ordinary cosmos through only the gravitational force.

This force affects anything with mass, whether it emits light or it’s invisible. It governs how cosmic structure grew and evolved. Scientists know dark matter influenced cosmic structure, because it is and always has been the dominant form of matter. It is a sort of cosmic glue, says University of California, Irvine researcher Gopolang Mohlabeng. “It’s an unobserved type of matter that binds our galaxies together.”

In the early Universe, higher densities of matter formed what astronomers call “gravitational wells,” which attract anything with mass. Matter would fall in, and they would become trapped in these wells. The region’s density would continue to increase, and eventually the ordinary matter in that well would, because it interacts via the electromagnetic force, heat up and release radiation. Stars were born. Galaxies were born. Cosmic structure was born.

“If you think about it,” says Mohlabeng “without dark matter actually trapping normal matter to form our Milky Way Galaxy, the Solar
System would not have formed, the Earth would not have formed, and we actually wouldn’t be here.”

After decades trying to learn more about dark matter, astronomers unfortunately are confident of only two things: It exists, and it interacts via gravity.

**Detecting the invisible**

“The hardest part about searching for dark matter is that it can be a lot of things;” says NASA astrophysicist Regina Caputo. Researchers want to directly detect this mysterious matter — that means watching it bump into special underground detectors, seeing its interaction signatures in nearby space, or perhaps even creating dark matter in Earth’s most-powerful physics experiments. For decades, scientists have designed, built, and run complex, and some less-complex, detectors. They’ve created advanced computer simulations to guide them. But it’s complicated, because there are many theories of what dark matter could be and each idea requires a specific technique to find it.

One of the leading theories for what dark matter could be is a class of particles known as Weakly Interacting Massive Particles (WIMPs). Theorists in the 1980s first presented such a hypothesis; and it was one that particle physicists, astronomers, and cosmologists thought could explain dark matter. And so, experimentalists built detectors and placed them underground, observers used telescopes to look toward galaxies, particle physicists tried to create it in massive colliders — all to find these WIMPs.

But those searches and experiments have all came up empty. And it doesn’t mean WIMPs aren’t still an option, it just means they can’t be all of dark matter.

“You always look at the easiest thing first, right, and we did that, and we didn’t see it;” says Caputo, an astrophysicist who’s been looking for gamma-ray signals corresponding to WIMP interactions in the Milky Way and nearby galaxies. “And so now we have to just keep diving deeper to try to figure out what [dark matter] is.”

Astronomers are now looking to more complex and varied models. “[Imagine] you’re looking at individual blades of grass to try to figure out … what makes up the soccer field,” says Caputo. “Is the grass the same on the other side of the field as it is on my side of the field?” Meaning, all the dark matter doesn’t have to be the same everywhere. Ordinary matter, after all, isn’t only one type of particle.
Instead, there’s a dozen elementary particles and a handful of force-carrier particles, interacting with one another in multiple ways. Dark matter could be just as complex — if not more. This invisible matter is some 80–85 percent of the total mass in the Universe.

“The fact that it doesn’t interact with light, it doesn’t interact with everyday things that we see and touch,” says Mohlabeng, “makes it very difficult for us to actually know where to begin to search.” As a dark matter phenomenologist, he looks at the data astrophysicists have and then conceives new models that could explain dark matter. Observational and experimental researchers then develop ways to test those models.

And it’s a field that is becoming ever more creative, as dark matter researchers investigate other possible candidates for the Universe’s missing matter, some 26 percent of the total Universe. That amount added to normal matter makes up 31 percent. The remaining roughly 69 percent is something even more mysterious, more elusive, and far less understood than dark matter.

**Serendipitous findings**

Astronomers categorize objects all the time to understand similarities and the physics behind them. In the 1980s, astronomers discovered exploding stars called “supernovas” come in two main classes. Within one of those broader categories is a subclass called “Type 1a,” and these, it turns out, are crucial tools for understanding the Universe.

Type 1a supernovas all have similar intrinsic brightnesses whenever or wherever they explode, and those similarities mean astronomers can use them to measure distances across the Universe. By comparing how a Type 1a supernova’s light changes over time, scientists can figure out how much energy it is emitting and thus how far away from Earth it is.

In the following decade, two teams detected dozens of these supernovas at different distances from us. In astronomy, a farther distance translates to further back in time. Scientists have known since the 1930s that the Universe is actually expanding, and the supernova researchers used the brightness-distance relationship to study the rate the Universe was expanding. Saul Perlmutter led one team, and Brian Schmidt and Adam Riess led the other. They expected to measure how much the expansion had slowed due to the gravitational pull of all the matter in the Universe, but instead, as the teams announced in the late 1990s, they found the expansion has actually sped up. The supernovas were fainter and thus farther away than expected, and that happens because something is pulling the Universe apart. Enter “dark energy,” that mysterious something that seems to be counteracting gravity.

“If these results are confirmed, it will require a major change in our picture for the universe,” stated astrophysicist Robert Kirshner in a
The Universe’s 13.8-billion-year history

The Cosmic Microwave Background carries information about the first several hundred thousand years of cosmic history. From that information, scientists know how structures evolved, how dark matter influences regular matter, and how much dark energy exists. [ESA – C. Carreau]
“We will be forced to add another constituent to our best model for the universe, a form of vacuum energy that drives the expansion.”

One could argue the brightness calculations weren’t correct, or maybe there’s a whole lot of dust and other material making the supernova blasts appear fainter and redder. But scientists over the decades since have investigated these options and ruled them out. They’ve now measured hundreds of Type 1a supernovas, confirming these results over and over again, and they’ve also employed other probes to measure cosmic expansion.

**Fossil signals**

One of these observational techniques uses a pervasive fossil radiation, the residual glow from early in the Universe’s history. When the cosmos first came into existence 13.8 billion years ago, it was incredibly dense and extraordinarily hot. All of the current Universe’s matter and radiation was crammed together at that time, and then the cosmos expanded rapidly. At the beginning, the ordinary matter and radiation moved together until about 400,000 years later, when the light was no longer linked with matter, and it could travel freely. All that once-high-energy radiation has rode along with cosmic expansion since, which has pulled that blazing light to cool microwaves. Now, this cool radiation is everywhere in the Universe, known as the Cosmic Microwave Background (CMB).

Astronomers have studied this leftover radiation with many detectors over the past several decades, and they can read much of the information it carries. That includes the seeds of today’s largest structures — cosmic scaffolding of galaxies and clusters of galaxies — and evidence that the Universe is dominated by a dark energy component. In fact, it’s the CMB that reveals 69 percent of the cosmos is dark energy.

That’s not the only additional tool astronomers have used. By mapping the large structures across the sky, like clusters of galaxies across time, scientists can tell how dark energy has counteracted gravity.

While astrophysicists have confirmed this mysterious energy exists and measured how it behaves, they have essentially no idea what it is. One theory is it’s the energy of the vacuum of space itself. “In quantum physics, the vacuum should have energy, thanks to Heisenberg’s uncertainty principle,” says University of Queensland astrophysicist Tamara Davis. “You can never actually be sure that nothing is there.”

Particles appear for very short amounts of time and then disappear, and these “virtual” particles would give energy to the vacuum.
“Vacuum energy should have exactly the property we expect dark energy to have: In particular, it would have repulsive gravity” she says. But there’s a big mismatch in the amount of vacuum energy needed to explain dark energy and the amount of it actually expected to exist. “That mismatch is up to 120 orders of magnitude. That’s about $10^{120}$ times more than we actually see.”

“We talk about dark energy as though it’s a thing,” adds Davis. “It could also be that our theory of gravity is incomplete and to explain dark energy what we need is a correction to our theory of gravity.”

What’s next?
Planned telescope surveys and space missions will constrain more details of dark energy, further measuring how it affects the Universe. And while that will help scientists understand this puzzle, it won’t reveal what dark energy actually is. That’s because observation and experiment are only one part of the equation. “We can keep measuring its properties in ever more detail, using many different methods, to understand how it behaves,” says Davis. “However, to understand what it is, we need new theoretical breakthroughs — which is the hard part.”

It’s a similar story for dark matter: Theoretical innovations are necessary to lead the observers and experimentalists in their quest to understand invisible material.

“When we first started thinking about particles and what makes up the fundamental building blocks of the Universe, it took a hundred years at least to figure that out,” says Caputo. Now, scientists are trying to understand 95 percent of the Universe, and they have far fewer tools to use. They cannot see dark matter and they cannot detect dark energy. They can only use how these mysterious entities affect the remaining 5 percent of the cosmos.

LIZ KRUESI is the Editor of Mercury. She has told the stories of the Universe since 2005, and is especially interested in the research that reveals the dark side of the cosmos.
The Astronomical Society of the Pacific is proud to announce this year's awards for astronomy research and education.
In August, the Astronomical Society of the Pacific (ASP) announced the recipients of its 2021 awards. These awards recognize individual achievements in astronomy research, technology, education, and public outreach each year. Recipients of our awards have included luminaries such as Edwin Hubble, Vera Rubin, Isaac Asimov, Margaret Burbidge, Carl Sagan, and Katherine Johnson.

Nominees are welcome from ASP Members and members of the broader astronomical community through March 1 of each year. The Awards Committee appointed by the ASP Board of Directors reviews the nominations, and then the Board of Directors makes the final selections.

The ASP holds an Annual Awards Gala in honor of and to recognize the ASP Awards Recipients for their leadership in and advancement of astronomy and space science. We had to take a pause in 2020, but we are happy to be resuming our awards and forthcoming celebration — although virtual — later this year.

Catherine Wolfe Bruce Gold Medal
The Astronomical Society of the Pacific’s Catherine Wolfe Bruce Gold Medal, which is the ASP’s most prestigious award, was established in 1898 by Catherine Wolfe Bruce, an American philanthropist and patroness of astronomy. The ASP presents the medal annually to a professional astronomer in recognition of a lifetime of outstanding achievement and contributions to astrophysics research.

This year, the ASP’s Catherine Wolfe Bruce Gold Medal is awarded to Bruce Elmegreen in recognition of his pioneering work on dynamical processes of star formation. Over four decades of innovative research, Elmegreen has fundamentally changed our understanding of star formation. He studied widespread hierarchical structure in young stellar regions, discovered that star formation is rapid following turbulent compression and gravitational collapse of these regions, explained the formation of stellar clusters, and discovered the largest scales for these processes in galaxies beyond our own, spanning a wide range of cosmic time.

Elmegreen was born in Milwaukee, Wisconsin, and received his bachelor’s degree in Physics and Astronomy from the University of Wisconsin, Madison. He earned his doctorate at Princeton University under the guidance of Lyman Spitzer, Jr. (Bruce Medal awardee, 1973), studying the ionization of the local interstellar medium. His interests turned to interstellar dynamics as a Junior Fellow at Harvard University, where, together with colleague Charles Lada, he proposed that ionization from one generation of stars can compress residual gas and form another generation. He followed that with observations of interstellar filaments as further evidence for triggered collapse and proposed the same process on the scale of spiral arms. General observations and acceptance of these ideas would take decades.
After six years on the faculty of Columbia University in the City of New York, Elmegreen moved to IBM Research in 1984 where he began studies of galactic spirals, making the first digitized color images of galaxies and examining their symmetries to find spiral modes. He proposed that interstellar compression from turbulence produces a hierarchy in space and time for young stellar structures, with bound clusters forming in the densest parts of the hierarchy.

Elmegreen has authored more than 750 publications, which have amassed over 27,000 citations. In 2001, Elmegreen received the Dannie Heineman Prize for Astrophysics jointly from the American Astronomical Society (AAS) and the American Physical Society, and, in 2016, an IBM Research Outstanding Accomplishment Award for Research in Star Formation. From 2015-2018, he was President of the International Astronomical Union (IAU) Division on Interstellar Matter and Local Universe and Chair of the Resolutions Board, and he served as National Representative of the AAS to the IAU. He was Publications Board Chair for the AAS in 1998 and currently serves on the Publications Board of the ASP. Elmegreen was elected Fellow of the American Association for the Advancement of Science in 2013, and an Inaugural Fellow of the AAS in 2020.

Robert J. Trumpler Award

The Robert J. Trumpler Award is presented to a recent recipient of a doctoral degree in astronomy or physics, whose research is considered unusually important to astronomy. The ASP is presenting awards both for 2020 and 2021 this year.

The recipient of the 2020 Robert J. Trumpler Award is Guðmundur Kári Stefánsson, who completed his doctorate in astronomy at The Pennsylvania State University in 2019. His dissertation, Extreme Precision Photometry and Radial Velocimetry from the Ground, is described by one of his nominators as “the broadest and deepest demonstration of expertise in precision astronomical instrumentation I have seen.” Another nominator called Stefánsson “a multidimensional talent who has demonstrated ability and depth in astronomical instrument hardware, data analysis, and observational astrophysics.” Stefánsson is currently a Henry Norris Russell Postdoctoral Fellow at Princeton University.

Stefánsson's thesis characterized and developed a revolutionary innovation for achieving high precision differential photometry from the ground where Earth’s atmosphere and limitations inherent in the astronomical detectors used make precise measurements of stellar brightness exceedingly difficult. In differential photometry, the brightness of a star is simultaneously compared to the brightness of other nearby stars. Stefánsson's Engineered Diffuser — a nanofabricated piece of optic — is capable of molding the image of a star into a broad and stabilized shape on the detector, substantially improving brightness measurements. One nominator called his breakthrough “startling in its simplicity,” adding that “this operational simplicity is very important since it allows widespread adoption.” Currently, Stefánsson's Engineered Diffuser is being used by an increasing number of telescopes around the world to better study extrasolar planets including at the Apache Point Observatory in New Mexico, Mount Palomar Observatory in California, the Nordic Optical Telescope on the Canary Islands, and by the Las Cumbres Network located across the planet.

Guðmundur Kári Stefánsson has won the 2020 Robert J. Trumpler Award. [Emily Perkinson]
The recipient of the 2021 Robert J. Trumpler Award is Jane Huang, who earned her doctorate at Harvard University in 2020. Her dissertation, *Rings and Spirals in Protoplanetary Disks: The ALMA View of Planet Formation*, was described by one nominator as an “iconic work, masterfully done, by a student who is writing her ticket to the top of a fast-growing field.” Another called her dissertation “a once-in-a-decade thesis in millimeter astronomy as well as in protoplanetary disks and planet formation studies.”

Huang’s research took advantage of the sensitivity and precision of the Atacama Large Millimeter/Submillimeter Array (ALMA) to image protoplanetary disks with amazing detail to uncover the surprising amount of substructure within. These ubiquitous structures, which include multiple rings, spirals, and other features, are images of new solar systems being formed. Huang’s work further revealed how the radial gas and dust substructures are key to understanding the formation and chemical composition of young planets. Her landmark work will help theorists develop better models of planet formation and inform how researchers will use the next generation of infrared and optical instruments to study distant solar systems as they form.

Huang is currently a NASA Hubble Fellowship Program Sagan Fellow at the University of Michigan.

**Klumpke-Roberts Award**

The Klumpke-Roberts Award is presented to an individual or individuals who have made outstanding contributions to the public understanding and appreciation of astronomy. For 2021, this award goes to Lars Lindberg Christensen, Head of Communications, Education and Engagement at National Science Foundation’s NOIRLab since 2019. For more than 30 years, he has brought science to the public and increased public awareness of the universe. Prior to joining the NOIRLab, Christensen was Head of Education and Public Outreach for the European Southern Observatory (ESO), spending two decades with the observatory organization.

Christensen’s leadership in the field of astronomy communication to the public began with a keen interest in astronomy and vision for science communication. By spearheading the communication and education of large science organizations — such as the European Space Agency’s Hubble operation, ESO, and the IAU — and his efforts of building a global community of astronomy communicators through outreach, technology, and global connections, Christensen has given people the ability to make educated decisions “regardless of nationality, age, gender, or socio-economic status.”

Throughout his career, he has been a proponent of open public access. Adding to his already listed accomplishments and as Press Officer at the IAU for more than 15 years, Christensen also focused on the developing world. One nominator added “Lars’ organizational and networking skills were exemplary in dealing with groups in the many countries. He has a gift for presenting education in terms of the local culture, so it makes sense for people to understand.”

Lars Lindberg Christensen has won the 2021 Klumpke-Roberts Award. [NOIRLab/NSF/AURA/J. Pollard]
Christensen is author of a dozen books and more than 200 publications, video producer of documentaries and planetarium shows, international project leader, and local grassroots developer. He has also contributed to public education and science awareness leading him to one of his largest accomplishments: as the global manager of the IAU's International Year of Astronomy 2009. Planetariums, network television, and top vodcasts, have all benefited from Christensen's innovative approach, and as commented by a nominator, “…speaks volumes to Lars’ vision of making scientific educational material of the highest quality available, for free, to anybody in the world with a computer, an internet connection, and the desire to learn more about astronomy.”

**Thomas J. Brennan Award**
The Thomas J. Brennan Award is given to an individual demonstrating excellence in the teaching of astronomy at the high school level in North America.

This 2021 award goes to Christine Hirst Bernhardt, Albert Einstein Distinguished Educator Fellow, mentor, curriculum developer, and education leader. Bernhardt’s enthusiasm and passion for all things astronomy have led her to be a role model to students in the classroom, mentor to her fellow colleagues, and astronomy ambassador in the community and abroad. Her dedication and enthusiasm have no doubt created future educators, researchers, and lifelong astronomers. One of Bernhardt’s former students and a current University of California, Santa Barbara, astrophysics major confirms — “I can say with complete certainty that I wouldn’t be where I am today, as an astrophysics major pursuing what I love, without her influence and inspiration.”

As a teacher, Bernhardt has developed a hands-on high-altitude ballooning project where students design experiments to be carried into the stratosphere and launch from the school's outdoor stage. She has mentored students in her astronomy club; founded a community space program bringing to them activities, telescopes, and NASA speakers; volunteered her time at elementary schools and with STEM programs focused on girls; and has mentored students how to write science proposals aboard both the International Space Station and NASA Stratospheric Observatory for Infrared Astronomy aircraft missions and participate in her student space symposium.

Enthusiasm reaches far beyond the classroom as Bernhardt also develops curriculum, both as a teacher and as an ambassador connecting teachers to resources through developing curriculum and on the newly formed National Astronomy Education Committee through the International Astronomical Union. Her educational leadership includes designing and facilitating a program to integrate Earth and Environmental concepts into Next Generation Science Standards (NGSS) including best practices, pedagogy, and progression toward full implementation of NGSS in the greater Los Angeles area. Bernhardt, as a **National Astronomy Education Coordinator**, plans to develop impactful professional development for teachers wishing to implement astronomy-based lessons, and connecting teachers to unique learning opportunities in astronomy.

Congratulations to all the award winners. The ASP will present these awards at a virtual celebration, the **2021 ASP Awards Gala** on November 19, 2021. This celebration takes place during the ASP's Annual Meeting.
reflections
By Liz Kruesi

Peculiar Galaxies Photographed

On July 17, the Hubble Space Telescope stared at the interacting galaxies collectively known as ARP-MADORE2115-273. The telescope had just returned to science operations after being offline for a month (see news story on page 20).

These interacting galaxies are part of A Catalogue of Southern Peculiar Galaxies and Associations, compiled by Halton Arp and Barry Madore. The object shown here, ARP-MADORE2115-273, is one of the many targets in astronomer Julianne Dalcanton’s Hubble observing program to capture never-before-seen views of these peculiar galaxies across the sky. So far, the program has observed more than 170 galaxies. These new images reveal fine details of the objects, like dust blocking gas and stars and striking structural features. [NASA, ESA, STScI, Julianne Dalcanton (UW); Image Processing: Alyssa Pagan (STScI)]