LOWELL OBSERVATORY

125 YEARS | 1894 - 2019

ANNUAL REPORT

2019

2019

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TRUSTEE'S UPDATE

By W. Lowell Putnam

2019 was an extraordinary year for Lowell Observatory. As you will read in this report, our scientists were very successful and productive in their research and our outreach and program staff were busy engaging with a very receptive public audience at all levels. The opening of the GODO was the largest on-campus event we have ever hosted and showed how the combination of our astronomers, educators and volunteers creates unmatched experiences.

That combination and the experiences that result also lead to the largest amount of gifts the Observatory has ever received. One other factor in that record is the recognition of how effectively and efficiently our team came together to build the Giovale Open Deck Observatory. We went from concept to ground-breaking to opening in just over 2 years. It certainly impressed the Marley Foundation board as well as the Karis family and helped persuade them to making their gifts to build our new visitor center.

We also received a number of bequests this past year from longtime supporters many of which have helped build the endowments in the Lowell Observatory Foundation. We are sorry to lose those friends, but are very grateful for their ongoing support.

All of this happens because so many of you believe in what we are doing and are so generous on an ongoing basis. I hope, as you read about the work done this past year, you will remember that it is your support that helps make this happen. ▪

DIRECTOR'SUPDATE

By Jeffrey Hall

As I believe this report will amply demonstrate, 2019 was a pretty good year for Lowell Observatory. Accomplishments aside, it had an air of excitement as the 125th anniversary of our founding or, as the vocabulary of Deputy Director for Marketing and Communications Danielle Adams reminded us, our quasquicentennial

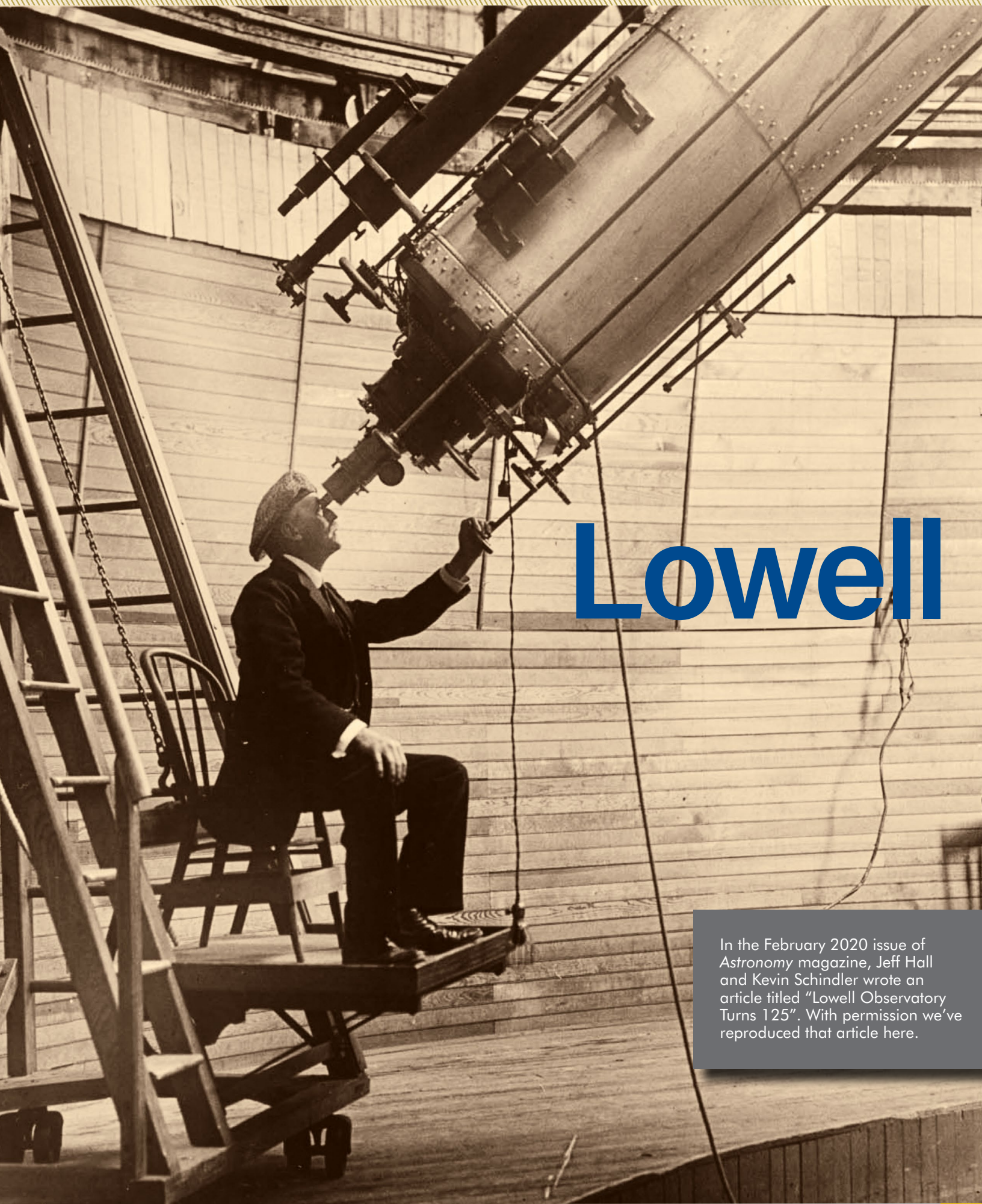
The excitement began literally at the stroke of New Year's Day with the New Horizons spacecraft's flyby of the little Kuiper Belt Object that had recently been named Arrokoth. Once again, amazing images of a new world graced our television and computer screens, with the excitement and relevance of discovery amply on display.

Dr. Will Grundy's ongoing involvement with New Horizons is just one example of the wide-ranging and prolific science conducted at Lowell, the summaries of which fill the bulk of this report. I hope you enjoy perusing the many interesting programs of our research staff, which include not only pure research but a variety of instrumentation projects that have added some excellent new capacity to our observing arsenal.

Our outreach mission also saw major milestones in 2019, including the completion of the wonderful new Giovale Open Deck Observatory (GODO) and the fabulous success of our development team in raising well over $20 million toward the construction of the new Astronomy Discovery Center. The opening of the GODO brought the largest one-day crowd ever to Mars Hill, and yet I was struck at how open and peaceful the campus seemed as everyone enjoyed our newly expanded facilities. (Getting them all parked, however, was another matter!)

As the days grew short and the nights increasingly cold, we toasted a year well done and looked ahead to all the challenges of 2020. It of course was not in our awareness that half a world away, a few people in Wuhan, China had come down with an acute new illness. As I write this introduction in mid-2020 with a certain amount of hindsight, I can only be even more impressed with the team and the accomplishments presented in this report, which provide a steady foundation of mission excellence and financial reserves that have given us resilience as 2019 gave way to the turmoil of 2020.

Enjoy reading about these accomplishments, and I hope everyone will be able to come see us on Mars Hill before too much longer. ▪



Lowell

In the February 2020 issue of *Astronomy* magazine, Jeff Hall and Kevin Schindler wrote an article titled "Lowell Observatory Turns 125". With permission we've reproduced that article here.

A worker takes a break atop Mars Hill in Flagstaff, Arizona, during construction of the Clark Telescope Dome on May 5, 1894. LOWELL OBSERVATORY ARCHIVES

Within the dome protecting the 24-inch Clark refractor at Lowell, many historic observations were made, including Percival Lowell's viewings of Mars. DAVID J. EICHER

Observatory TURNS 125

More than a century after opening its doors, "America's Observatory" remains a hotbed for scientific discovery and public outreach. BY JEFFREY HALL AND KEVIN SCHINDLER

Percival Lowell, founder of historic Lowell Observatory, targets Venus during the daytime from the observer's chair of the famous 24-inch Clark Telescope on October 17, 1914.
LOWELL OBSERVATORY ARCHIVES

On May 28, 1894, wealthy Boston businessman, mathematician, and astronomer Percival Lowell stepped off the train in Flagstaff, a hamlet of 800 people in the Arizona Territory, and headed up a hill just west of town. He would spend the rest of his life on what came to be known as Mars Hill, where he fastidiously studied martian features he thought were intelligently designed structures, and exhaustively calculated the predicted location of an undiscovered hypothetical world called Planet X.

In the 125 years since Percival's arrival in Flagstaff, his observatory has evolved considerably. Known to many as America's Observatory, the site now boasts a research faculty of 14 Ph.D.-level astronomers and an informal outreach program that draws more than 100,000 visitors to the campus each year.

Telescopes then and now

Lowell Observatory has long benefited from ownership of some of the finest tools of the astronomer's trade. And while a comprehensive description of all of them could fill a book, two are especially distinguished: The famed Clark Telescope and the Discovery Channel Telescope.

Percival Lowell observes Venus through the Clark refractor, built by Alvan Clark & Sons of Cambridgeport, Massachusetts, in 1897. LOWELL OBSERVATORY ARCHIVES

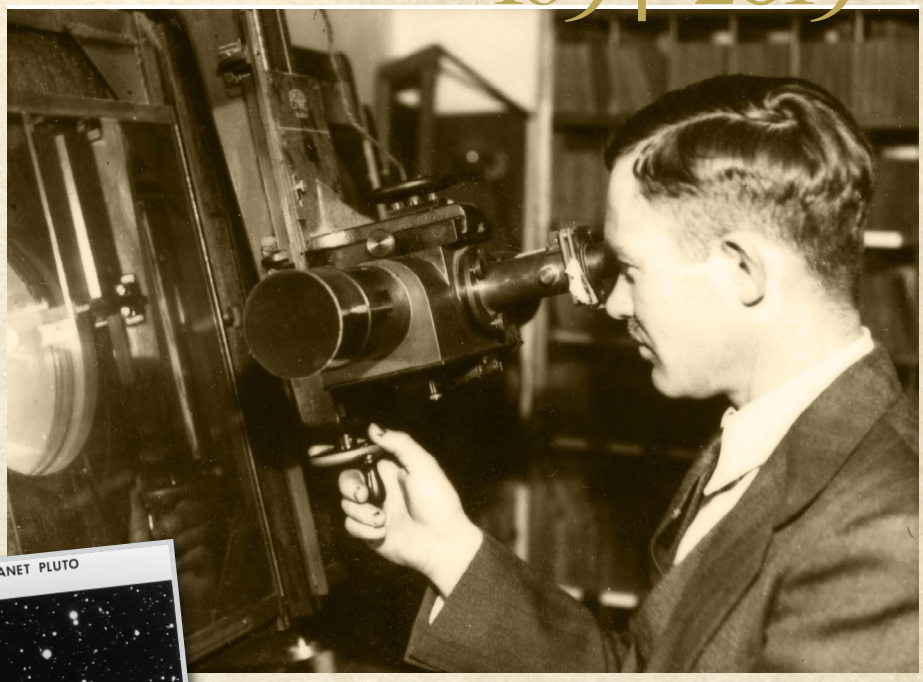
Shortly after founding the observatory, Lowell commissioned a 24-inch refractor from Alvan Clark & Sons in Boston for the princely sum of $20,000, which equates to about $600,000 today. The telescope still graces its historic dome overlooking Flagstaff. It is now used solely to give the public spectacular views of the universe, but it has played a role in some of the most important observations of the 20th century.

For instance: In 1912, Percival Lowell directed astronomer Vesto M. Slipher to observe so-called spiral nebulae with the Clark. The first object he observed was the Andromeda Galaxy (M31). To his surprise, he found Andromeda was hurtling toward our solar system at some 670,000 mph (1.1 million km/h). In a one-page notice in the *Lowell Observatory Bulletin* the following year, Slipher penned one of the greatest understatements in astronomical literature: "It might not be fruitless to observe some of the more promising spirals … Extension of the work to other objects promises results of fundamental importance." His later observations with the Clark revealed the first cosmological redshifts — the stretching of light waves that's a result of the expanding universe. Perhaps the recently renamed Hubble-Lemaître Law should be further amended to the Hubble-Lemaître-Slipher Law?

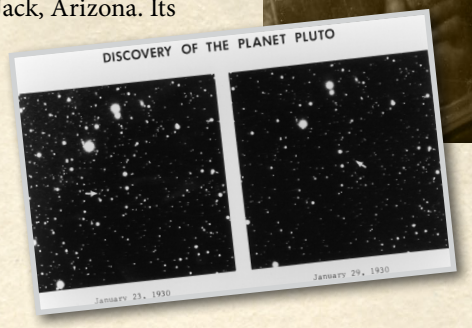
The Discovery Channel Telescope (above) is located in Happy Jack, Arizona, and provides Lowell astronomers with the freedom to explore almost any research project that intrigues them. LOWELL OBSERVATORY

The modern bookend to the historic Clark telescope is Lowell's 4.3-meter Discovery Channel Telescope (DCT), taking its name from the well-known media company. Discovery founder and former CEO John Hendricks has long been a member of the observatory's Advisory Board. And Discovery, Hendricks, and his wife, Maureen, made gifts totaling $16 million toward the $53 million cost of the project. These were gifts, not purchases: Discovery has no ownership of the telescope, nor any direction regarding the research it conducts. In return for their contributions,

Vesto M. Slipher uses a spectrograph built by John Brashear. Slipher relied on this spectrograph to discover the first evidence of an expanding universe. LOWELL OBSERVATORY ARCHIVES



ABOVE: Clyde Tombaugh uses a Zeiss Blink Comparator to compare differences between two images. This tool allowed him to quickly identify any objects that moved between two images of the same part of the sky taken at different times, which is how he discovered Pluto. LOWELL OBSERVATORY ARCHIVES



LEFT: The discovery images of Pluto, taken six days apart in January 1930, are seen here with arrows identifying the position of Pluto. LOWELL OBSERVATORY ARCHIVES

they received naming rights and first right of refusal for use of images in educational broadcasts. The research carried out with DCT proceeds as it would at any other professional telescope.

Groundbreaking for the DCT occurred on an especially hot day in July 2005. The first-light gala celebration was almost exactly seven years later, featuring a marvelous keynote address by Neil Armstrong — his final public appearance before his death several weeks later. Today, the fully commissioned telescope operates night in and night out at an elevation of about 7,800 feet (2,400 meters), some 40 miles (64 km) southeast of Flagstaff in Happy Jack, Arizona. Its finely figured thin meniscus primary mirror, held in shape by a 156-element active optics system, regularly delivers impeccable seeing — a measure of the sharpness of a telescope's image — to any of its five instruments at the Ritchey-Chrétien focus. The DCT can switch between any of these instruments in about a minute, making it uniquely suited for observing programs that target quickly evolving cosmic objects, such as gamma-ray bursts and supernovae. Boston University, the University of Maryland, the University of Toledo, Northern Arizona University, and Yale University have joined Lowell as partners with access to the DCT, and the consensus of its users is that the DCT is one of the best-performing and most efficient 4-meter telescopes they have experienced. It is a testament to the outstanding engineers who built and maintain it, and it will be Lowell's research flagship for decades to come.

A scientific haven

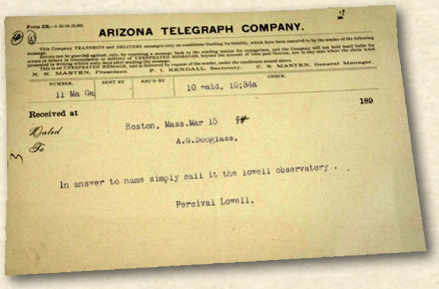
The core of Lowell's research philosophy is to provide outstanding telescopes and instrumentation and then let its faculty use them to do whatever science they find interesting. Astronomers coming to Mars Hill are handed, in effect, an academic blank check. Lowell welcomes projects that take longer to complete than the three-year cadence of a typical research grant. Also welcomed are ideas that might be given the slightly derisive term "fishing expeditions." Sometimes such pursuits are indeed dead ends — though dead ends can also be decidedly revealing — but sometimes you catch some very interesting fish. Perhaps the most dramatic example is Slipher's spectroscopic observations of "spiral nebulae," which Lowell pushed for to see if their compositions matched those of the solar system's gas giants. Unlike Slipher's measurements of Andromeda, many of these objects showed recessional velocities, which proved to be the first evidence of the expanding universe.

Today, Lowell's programs include extensive studies of the outer solar system's icy moons, as well as comets and asteroids. Researchers at Lowell explore the characteristics and variations of stars ranging from Sun-like dwarfs to massive supergiants, as well as investigate the formation and characteristics of exoplanets around those stars. Farther afield, the formation and evolution of dwarf galaxies and the characteristics of galaxy clusters are topics of interest. And tomorrow? We'll let the curious minds on Mars Hill chart that course.

The great demotion

Slipher's redshift observations are arguably the most fundamental astronomical observations ever made at Lowell, but surely one of the best known is the discovery of Pluto. Spurred on by perturbations found in Uranus' orbit in the late 19th century, Lowell spent the latter years of his life searching for a possible ninth planet whose gravitational pull could explain Uranus' orbital oddities. He dubbed the predicted world Planet X.

Ninety years ago, on February 18, 1930, Clyde Tombaugh walked into Slipher's office and said, with what must have been trembling excitement, "I have found your Planet X." Eventually, the


ARIZONA TELEGRAPH COMPANY.

Received at Boston, Mass. Mar 15

Dated

To A.G.Douglass.

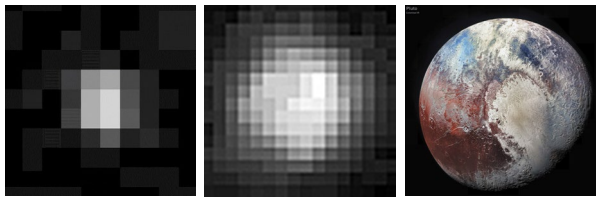
In answer to name simply call it the lowell observatory . .

Percival Lowell.

Percival Lowell sent this telegram establishing his famed observatory's name on March 15, 1894. It reads: "In answer to name simply call it the lowell observatory." LOWELL OBSERVATORY ARCHIVES

Giovale Open Deck Observatory is a 4,300-square-foot plaza with six permanently mounted telescopes available for public use. The $4 million site, which opened its doors last fall, aims to increase the roughly 100,000 visitors Lowell Observatory draws in each year. LOWELL OBSERVATORY

distant and diminutive world showed it was not gravitationally assertive enough to be the Planet X Percival Lowell had in mind. Instead, it was an enigmatic little object revealed in detail only in July 2015 during the historic New Horizons flyby — a mission in which current and former Lowell astronomers have played a pivotal role.



Our evolving view of Pluto is seen in this series of images, showing how the dwarf planet appeared to Tombaugh in 1930 (left), Hubble's Faint Object Camera in 1994 (middle), and the New Horizons spacecraft in 2015 (right). LEFT: LOWELL OBSERVATORY/C. TOMBAUGH. MIDDLE: NASA/ESA/A. STERN/M. BUIE. RIGHT: NASA/JHUAPL/SWRI/Z. DOYLE

As we all know, the Pluto of 2006 was classified as a "dwarf planet," which is not — through logic one could find a bit head-scratching — a planet. The famous (or, depending on your point of view, notorious) "demotion" of Pluto to a dwarf planet by the International Astronomical Union in 2006 has encouraged ongoing curiosity about the outskirts of the solar system. This curiosity reached a fever pitch during New Horizons' 2015 flyby of Pluto, and again on January 1, 2019, when the spacecraft briefly encountered the Kuiper Belt object Arrokoth (2014 MU_{69}).

Consider the Pluto of today, as further revealed by New Horizons, for which Lowell scientist Will Grundy leads the surface composition team. Pluto, we now know, is a place with five moons, a complex atmosphere, variegated terrain and surface regions, and patently active geology. Holding all this up to the idiosyncrasies of the other planets and non-planets in the solar system, as well as to the strange and new planetary characteristics and system architectures being revealed around most planet-harboring stars, one could argue it might be a reasonable time to reexamine this matter. Perhaps we would arrive at a more thoughtful taxonomy than we currently have.

Bringing science to everyone

Percival Lowell was much more than just an impressive businessman and academic. He was also an avowed popularizer of astronomy. His controversial ideas about Mars were often aired to the irritation of the professional community. But he also inspired many with his belief that the excitement of scientific discovery should be shared with everyone, making them "co-discoverers" of the objects, laws, and phenomena that make up our weird and wonderful universe.

Lowell Observatory continues that commitment today as an integral part of its mission. The observatory's modest, one-room operation of the early 1990s expanded dramatically in 1994 with the opening of the Steele Visitor Center. Visitation at Lowell then held steady at 60,000 to 70,000 people per year until the New Horizons flyby, when it rose sharply and has since remained at 100,000 or more.

In response to this example of a good problem to have, Lowell is now in the advanced stages of design and fundraising for a new $29 million,

What we know about the universe pales in comparison to what we don't.

32,000-square-foot (3,000 square meters) visitor facility.

As a nonprofit institution, Lowell relies increasingly on philanthropy to support research as well as outreach. And in June 2019, the observatory staff was thrilled to announce the naming of the Kemper and Ethel Marley Foundation Astronomy Discovery Center, the result of a $14.5 million pledge from the eponymous foundation to fund 50 percent of the center's cost. Lowell is now proceeding full steam ahead with the remaining fundraising, and our goal is to open the new center in 2023. Our vision is for it to be the premier facility in the world for communicating the marvels of the universe to all.

In the meantime, to alleviate crowding and long lines, in the fall of 2019, Lowell opened the $4 million Giovale Open Deck Observatory, a suite of six permanently mounted telescopes under a roll-off building. Among the instruments are a 0.8-meter Starstructure Dobsonian, 0.6-meter and 0.5-meter PlaneWave reflectors, and a strikingly beautiful 0.2-meter Moonraker refractor. Exhibits, a classroom, a huge planisphere, and our own version of Stonehenge will further enhance the experience. The technical description of this new public observing plaza — at least, according to many of our visitors — is "way cool."

Why?

For all of us who love our calling, it's fun to talk about *what* we do. But it's perhaps trickier, albeit equally or more important, to understand and discuss *why* we do it.

Lowell's employees often speak of their mission as encompassing dual pillars of research and outreach, but they are, in fact, both related components of the unified goal of communicating science. Whether our audience is a professional astronomer reading an *Astrophysical Journal* article by a Lowell researcher or a 12-year-old asking one of Lowell's educators about the workings of a black hole, the observatory communicates the wonders of the universe and promotes scientific, evidence-based curiosity and thinking.

Any way you choose to interact with Lowell Observatory, the goal is to have you come away with the simple pleasure of knowing something you didn't before, such as a perspective or idea about our universe that provides you with a new insight into how this vast physical system works.

Those at Lowell want you to feel *curious*. You don't need to visit the observatory or read a research paper to find out the mass of Jupiter or to get a list of the names of all the planets; you can get this information off the internet. More important is wondering about the greater whole that might come into focus after learning about the smaller parts. What can humans deduce from the store of knowledge with which we've armed ourselves?

Lowell Observatory wants everyone to feel *comfortable* with the unfamiliar. What we know about the universe pales in comparison to what we don't. We live in a cosmic sea of uncertainty, a universe governed by the strikingly counterintuitive rules of relativity and quantum mechanics. It's a place where our perceptions are often well out of sync with reality. However, all too often, our public discourse and policy decisions are ruled by absolute certainty in the correctness of our point of view and the feeling that those who hold different points of view are idiots — or, worse, enemies.

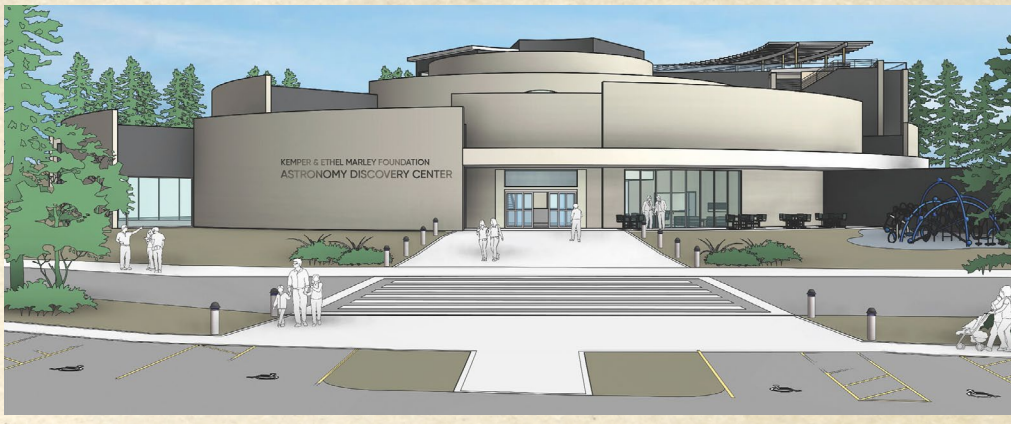
Science, in contrast, is about deeply exploring data, taking pleasure in the power of codifying and understanding physical principles in the beautiful language of mathematics, and maintaining open-mindedness to challenges to long-held beliefs. Imagine the beauty of a world in which all of us do not reject the unfamiliar, but instead embrace it.

And Lowell Observatory wants everyone to feel *humble*. A good scientist should always hold the sentence, "I might be wrong," front and center in their mind. Experiencing the universe in all its vast weirdness encourages us to wonder, to feel humble, and to be willing to change our minds when the data demand that we do.

Some years back, an email arrived from a mom in a state far from Arizona. She and her family had visited Lowell, and afterward, their son was so excited by what he had experienced that he promptly went home and wrote a school report about Clyde Tombaugh and his discovery of Pluto. She wrote in her email that Lowell educators had "amazed, challenged, and opened a young mind."

That is why we do what we do. For young and old, amateur astronomers and professionals, everyone who wonders about the incredible sights that wheel overhead every night, we want to amaze and challenge, and to show how much fun it is to be part of the uncertainty and excitement of discovery.

And this is not merely doing well by doing good. In today's rapidly evolving, technical, and often fraught world, it is a societal and national imperative. We welcome all to join us on the journey.



The Kemper and Ethel Marley Foundation Astronomy Discovery Center, seen here in this artist's concept, is expected to open in 2023 and help boost annual attendance to more than 250,000 guests. LOWELL OBSERVATORY

Jeffrey Hall *studies solar-stellar activity cycles and, since 2010, has served as Director of Lowell Observatory, where* **Kevin Schindler** *is the historian.*

ASTRONOMER **SCIENCE**HIGHLIGHTS

The cover of the May 17 issue of Science magazine, featuring the first published results from the New Horizons flyby of Arrokoth, just four and a half frenetic months after the flyby. (American Association for the Advancement of Science / Science Magazine)

Dr. Will Grundy

Will Grundy researches icy outer solar system planets, planetesimals, and satellites, using a combination of laboratory, theoretical, and observational techniques, plus direct exploration by robotic space probes. His research was fully funded by grants during 2019. Grundy was an author on 18 peer-reviewed scientific papers, articles, and book chapters published during the year.

Grundy is currently a co-investigator on three NASA space missions. 1.) New Horizons explored the Pluto system in 2015. At the opening of 2019, the spacecraft explored the small Kuiper belt object (486958) Arrokoth, a billion miles beyond Pluto. This leftover planetesimal from the early stages of planet formation was revealed as having a peculiar bi-lobed shape resulting from its formation from the gravitational collapse in the protoplanetary nebula. The sparseness of impactors so far from the Sun has left it little changed from when it formed. Grundy participated in sharing these exciting new results with the public via numerous media interviews, press briefings, and public talks. 2.) The Lucy mission is to be launched in 2021 to explore Jupiter's co-orbiting Trojan asteroids. Grundy is the Instrument Scientist for Lucy's infrared imaging spectrometer system. The instrument and spacecraft both passed their critical design reviews during 2019, and construction was already well advanced by the end of the year. 3.) The Trident mission is one of four mission concepts selected through a competition in 2019 as candidates for the next launch opportunity in NASA's Discovery mission program. If it is selected for flight in the next proposal stage, Trident will re-visit Neptune's large moon Triton, a Pluto-like, geologically active icy world with a probable interior ocean. Triton was last explored by the Voyager II spacecraft back in 1989, using 1970s-vintage technology. A half-century of miniaturization, microchip development, and infrared detectors has enabled modern instruments to be far more capable.

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During 2019, Grundy was involved in observational projects using ground- and space-based telescopes including Hubble, Keck, DCT, and IRTF. These projects ranged from spectroscopic, photometric, and thermal emission observations, to high spatial resolution imaging to discover satellites of small bodies and determine their orbits.

Grundy does laboratory studies of low temperature materials at Northern Arizona University, collaborating with Lowell's Dr. Jennifer Hanley, plus NAU faculty members. The thermodynamic complexity of low temperature mixtures is emerging as a major theme in need of deeper investigation. These materials enable the spectacular geological activity seen on Pluto and other small, icy planets and moons across the outer solar system. Many students are involved in the research, including summer students hosted through the National Science Foundation's Research Experience for Undergraduates (REU) program, along with NAU undergraduate and graduate students.

Grundy serves on the DPS Committee, the leadership body for the largest professional society of American planetary scientists. He also serves as an editor for ***Icarus***, the leading scientific journal in planetary sciences. Grundy also reviewed manuscripts in 2019 for other scientific journals including *Monthly Notices of the Royal Astronomical Society, Nature Astronomy,* and *Astrophysics & Space Science*. He reviewed proposals for a NASA Research & Analysis funding program and reviewed telescope time proposals for three different Hubble Space Telescope time allocation competitions. ▪

ASTRONOMER **SCIENCE**HIGHLIGHTS

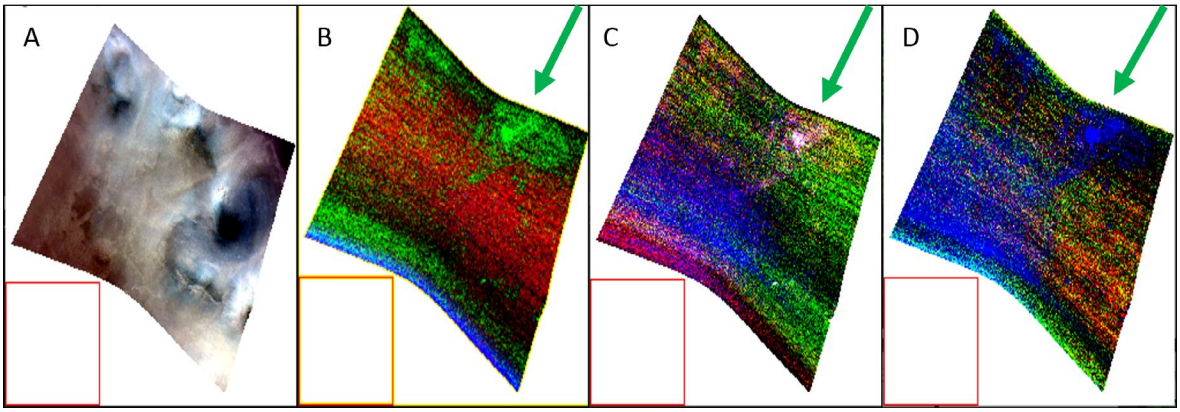

Image from the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) showing different parameters of the same image, highlighting a potential chlorine salt deposit (green arrows).

Dr. Jennifer Hanley

Jennifer Hanley's main research topic is understanding liquid stability across the Solar System. One way to affect stability of water on Mars and Europa is by adding salt. Chlorine salts in particular (chlorides, perchlorates and chlorates) can lower the freezing point of pure liquid water from 273 K (0°C) down to 204 K (-68°C). This past year, Hanley worked with several undergraduate students, from Northern Arizona University, Amherst College, and Fort Lewis College, to study the spectral characteristics of the chlorine salts and to identify them across Mars. This work builds on the newly created parameters, and resulted in identifying interesting features on the surface of Mars that might be chlorine salts.

In addition, Hanley was PI of an observing campaign to investigate whether these chlorine salts are found on the surface of Jupiter's moon Europa, and if so, what the distribution is. She used IGRINS, a high-resolution near-infrared spectrometer that was visiting the Lowell Discovery Telescope (LDT) in early 2019, along with NIHTS (Near-Infrared High Throughput Spectrograph) on the LDT, to obtain spectra of Europa across various longitudes to determine spatial variations.

Another focus of Hanley's research is the mechanical and spectral properties of cryogenic liquids and ices on outer Solar System bodies. Continuing her work in NAU's Astrophysical Materials Laboratory, Hanley focused on the stability of nitrogen, methane and ethane liquids under Titan conditions. Over the summer she worked with an undergraduate student from Arizona State University, in addition to her new NAU graduate student Anna Engle, to further explore these strange phenomena.

In 2019, Dr. Hanley was invited to participate in a panel at the Women in Planetary Science Conference in Tempe, AZ. She also presented her work at various conferences and workshops, including the Astrobiology Science Conference in Seattle, WA, the European Planetary Science Conference-AAS Division of Planetary Science joint meeting in Geneva, Switzerland, and the Titan after Cassini workshop in Madrid, Spain. ▪

ASTRONOMER **SCIENCE**HIGHLIGHTS

DDO 43 is one of the LITTLE THINGS dwarf irregulars. Ultraviolet, blue, and green images combined into a color picture of the stars in DDO 43. The blue blobs are clusters of young stars.

Dr. Deidre Hunter

Dwarf Irregular galaxies are disk-shaped. They are thicker than spiral disks but even so, they are more like a plate than a ball. In disk galaxies the gas, stellar, and star formation mass densities decrease with distance from the center of the galaxy. Hunter and her collaborators used the LITTLE THINGS multi-wavelength data on nearby dwarf irregulars to examine the properties of the stellar disk, the gas disk, and the young stars and in particular how the densities fall off with radius in order to see how they are related to each other. This was motivated by the fact that atomic hydrogen gas densities in dwarfs are too low to form the clouds that make new stars, according to models, and yet the galaxies do form stars. So they wanted to understand what the relationship is between the gas and the young stars.

They found that in most dwarfs the atomic gas has a radial profile that is relatively flat in the center and then falls off rapidly with radius (see the figure) while the young stars are more concentrated to the center of the galaxy. They suggest that in the central regions the missing atomic gas has turned into molecular clouds that form new stars as in spiral galaxies. Molecular clouds are mostly made of the hydrogen molecule, but that molecule cannot be observed directly, so other molecules are used as tracers. But the molecular gas in dwarf galaxies has come to be known as "dark gas" because it is not generally visible with these common tracers. When Hunter's colleague Bruce Elmegreen determined the amount of molecular gas implied by the current star formation activity and added that to the atomic hydrogen, they found that this total gas density falls off with radius more like the mass density of older stars does, reinforcing the view of missing gas.

Hunter received a grant from NSF in the Fall of 2019 to fund additional work on the molecular gas content of dwarf irregulars. Haylee Archer will be joining the graduate program at ASU in the Fall of 2020 and working with Hunter on this for her PhD dissertation.

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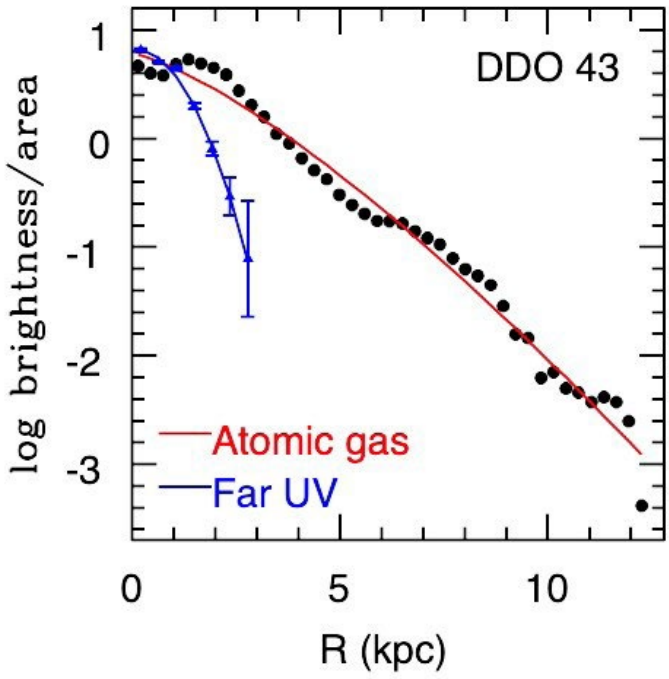
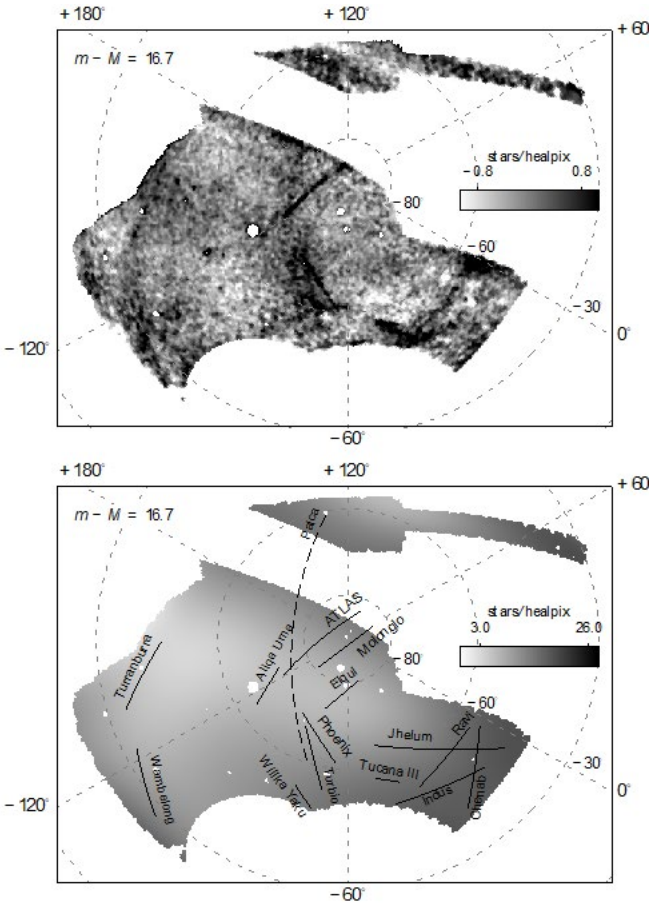
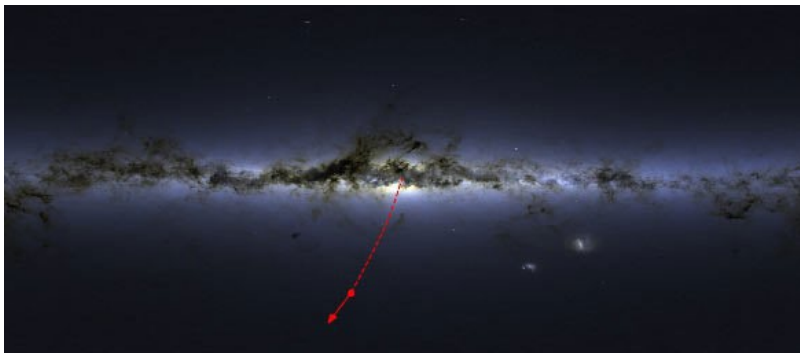
Unrelated to the missing gas in the central regions, the fall off of the stellar mass densities of older stars often abruptly changes slope in the outer disk. The team examined possible explanations for what changes at the break. They found that the break often occurs at the radius where the rotation speed of the rotating galaxy levels off or increases more slowly. The break is also more tightly correlated with the mass density of the older stars than with that of the gas. The break does not seem to be related to any change in star formation activity, both in dwarfs and in spirals. In addition to Hunter, this study involved three LITTLE THINGS team members (Bruce Elmegreen – IBM, Kim Herrmann – Penn State Mont Alto, Se-Heon Oh – Sejong Univ), two MIT Field Camp undergraduates (Esther Goldberger, Hannah Taylor), one MIT Field Camp graduate student counselor (Anton Ermakov), and three NAU undergraduates (Bradley Malko, Brian Barandi, Ryan Jundt). The paper presenting these results will be submitted for publication shortly. ▪

Atomic hydrogen gas density and far ultraviolet emission from hot young stars, showing how these drop off with distance from the center of the galaxy. The lines are fits to the data points.



ASTRONOMER **SCIENCE**HIGHLIGHTS





Left: Some of the stellar streams discovered by the Dark Energy Survey. Credit: N. Shipp/DES Collaboration

Top Right: Artist's rendering of S5-HVS1 being ejected from the neighbourhood of the black hole at the center of the Milky Way. Credit: James Josephides/Swinburne Astronomy Productions

Bottom Right: The path of S5-HVS1 away from the center of the galaxy. Credit: Sergey Koposov/S5 Collaboration

Dr. Kyler Kuehn

During 2019, Kyler Kuehn continued his collaboration with several groups that are following up on the data acquired by the Dark Energy Survey – particularly the MagLiteS Survey, the DELVE Survey, and the Southern Stellar Stream Spectroscopic Survey. The latter survey (which Dr Kuehn helped to found) has been searching for globular clusters or dwarf galaxies in the halo of the Milky Way that have been pulled apart by our Galaxy's gravity. That search has yielded some especially interesting results, including the serendipitous discovery of a hyper-velocity star (S5-HVS1) that was ejected at high speed from the neighbourhood of the black hole at the center of the Milky Way galaxy. Dr Kuehn has time scheduled on the LDT in 2020 to make observations with EXPRES of the northern hemisphere counterparts of the streams observed by S5.

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In addition, Kyler has begun setting up a new laboratory at Lowell, seeking to apply photonic technologies to astronomy. The most interesting novel technology uses microscopic silicon rings as filters to eliminate the infrared emission from the night sky, allowing infrared telescopes to be much more efficient. Initial on-sky tests of the technology performed in Australia in 2018 were promising, and he hopes that his new laboratory will be operational in time for further tests in 2020 that will bring the technology one step closer to becoming a regularly-used part of astronomical instruments.

Finally, Kyler has worked with his colleagues at Australian Astronomical Optics in Sydney to plan for the future of the Starbug fiber positioner technology – especially on the MANIFEST fiber feed facility, one of the first generation of instruments planned for the Giant Magellan Telescope. ▪

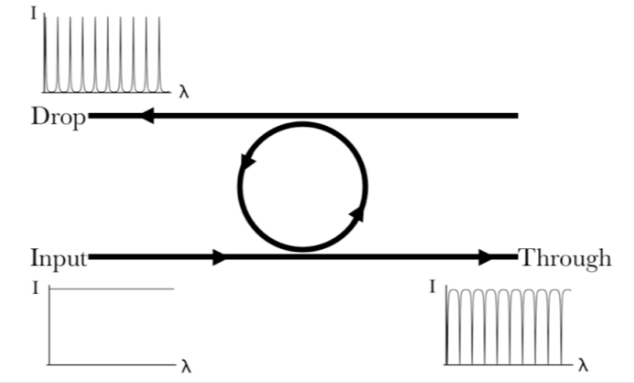
Links:

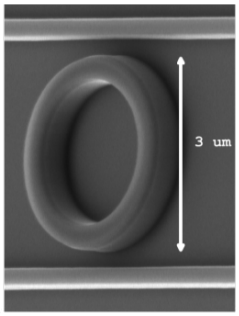
S5 Collaboration: https://s5collab.github.io

Scientific journal article on ring resonators: https://doi.org/10.1364/OE.25.015868

MANIFEST, a fiber feed facility for the Giant Magellan Telescope: https://www.gmto.org/resources/facility-fiber-optics-positioner-manifest/

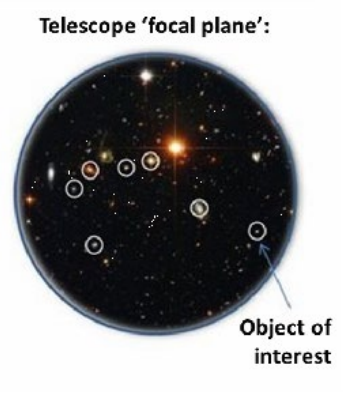
Starbugs in action: https://www.youtube.com/watch?v=xrumMTsFkPY

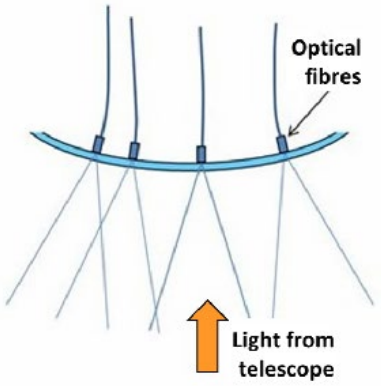




Left: (Left) a schematic of the filter created by a ring resonator, showing the dips in intensity of transmitted light as a function of wavelength (Right) a microscope image of a 3um diameter ring resonator and adjacent waveguides. Credit: S. Ellis et al.

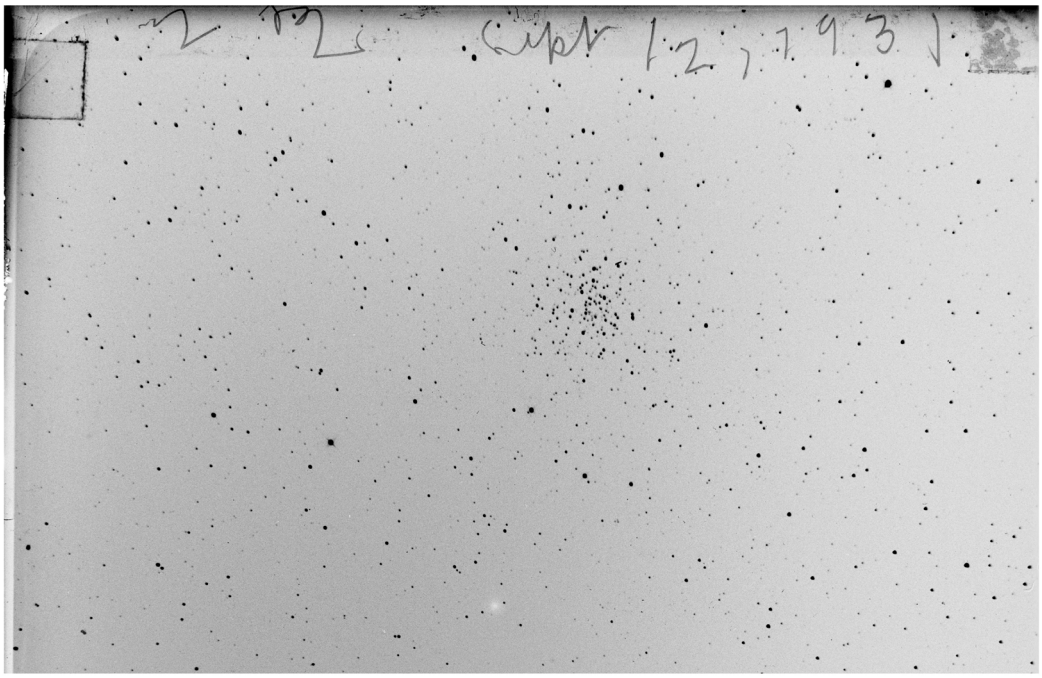
Right: A Starbug fiber positioner, with piezoceramic actuators arranged around an optical fiber used to collect starlight at a telescope's focal plane. Credit: Australian Astronomical Optics/Macquarie University





(Left) A representation of the telescope field of view, with Starbug targets circled. (Right) Starbugs deployed at the telescope focal plane, showing the area that each Starbug can view. Credit: Australian Astronomical Optics/Macquarie University

ASTRONOMER **SCIENCE**HIGHLIGHTS



A portion of one plate from the archives showing the open cluster NGC 2420. This plate was taken in September, 1931 by Carl Lampland using the 40-inch reflector. Some of the plates taken at Lowell between 1930 and 1951 were scanned by Buie et al (2015, AJ, 1499, 22) and the DASCH project to help support navigation of the New Horizons mission to Pluto.

Dr. Stephen Levine

Stephen Levine's research interests include large astrometric surveys and numerical simulation of the dynamics of astrophysical disk systems, with an emphasis on understanding the structure and evolution of lopsided disk and irregular galaxies. He is also interested in understanding the importance of passing stellar systems on the evolution of the outermost reaches of our own solar system. He maintains an active interest in stellar occultation studies of outer solar system objects.

Levine continues collaborating on the construction of the AAVSO Photometric All-Sky Survey (APASS) which will greatly simplify photometric calibration over the entire sky in the under-served magnitude range from 10 to 17. The survey covers the entire sky in five colors, and provides an empirical link between the earlier Johnson B and V, and the Sloan Digital Sky Survey g', r' and i' passbands. Levine is also working on a project to find and characterize all the known Solar System objects observed as part of the APASS survey.

Levine began work with L. Amundson on a project to digitize the Lowell archive of astronomical photographic images (see figure for an example) and spectra. The long term goal will be to preserve these data and make them available to the broader community over the internet.

During 2019, Levine continued to serve as the Lowell Discovery Telescope (LDT, formerly the DCT) Scientist, working with the LDT observing, instrumentation, operations and engineering communities to get the best out of the facility. ▪

ASTRONOMER **SCIENCE**HIGHLIGHTS

Left: The 2019 solar eclipse photographed from the Atacama Desert, Chile.

Right: The Lowell Observatory Solar Telescope (LOST) observes the Sun next to its big sibling, the Lowell Discovery Telescope.

Dr. Joe Llama

Joe Llama's primary research is to detect and characterize exoplanets. This year marked an exciting milestone with the commissioning of the EXtreme PREcision Spectrograph (EXPRES) on Lowell's Discovery Telescope. Built by Yale University, EXPRES is the first in the newest generation of spectrographs capable of measuring the gravitational wobble of a star caused by the presence of an orbiting Earth-sized exoplanet. With EXPRES, Dr. Llama is conducting an essential followup of planetary candidates found by NASA's Transiting Exoplanet Survey Satellite (TESS). TESS is a space-based telescope that measures the brightness of stars searching for periodic dips in light caused by a planet. While TESS is capable of detecting planet-sized objects, it is not able to measure their masses, a fundamental step in confirming that a planet indeed causes the signal.

One of the main hurdles in finding an Earth-sized exoplanet orbiting in the habitable zone of a star like our Sun with EXPRES comes from the star itself. Stellar activity can completely down out the signal of such a tiny planet. To better characterize the impact of stellar activity on the data collected by exoplanet surveys, Dr. Llama is building the Lowell Observatory Solar Telescope (LOST) that will feed sunlight directly into EXPRES. This tiny telescope will observe the Sun every clear day in just the same way that the LDT is used at night to search for exoplanets. Commissioning began in Summer 2019, and we achieved first light in December 2019.

As part of the visiting scientist program, Dr. Llama was delighted to host Professor Moira Jardine and Professor Andrew Collier-Cameron from the University of St Andrews in January 2019. They continued their collaborative work on modeling the observable signature of radio emission induced by an exoplanet, which can be used as an indirect method to detect exoplanetary magnetic fields.

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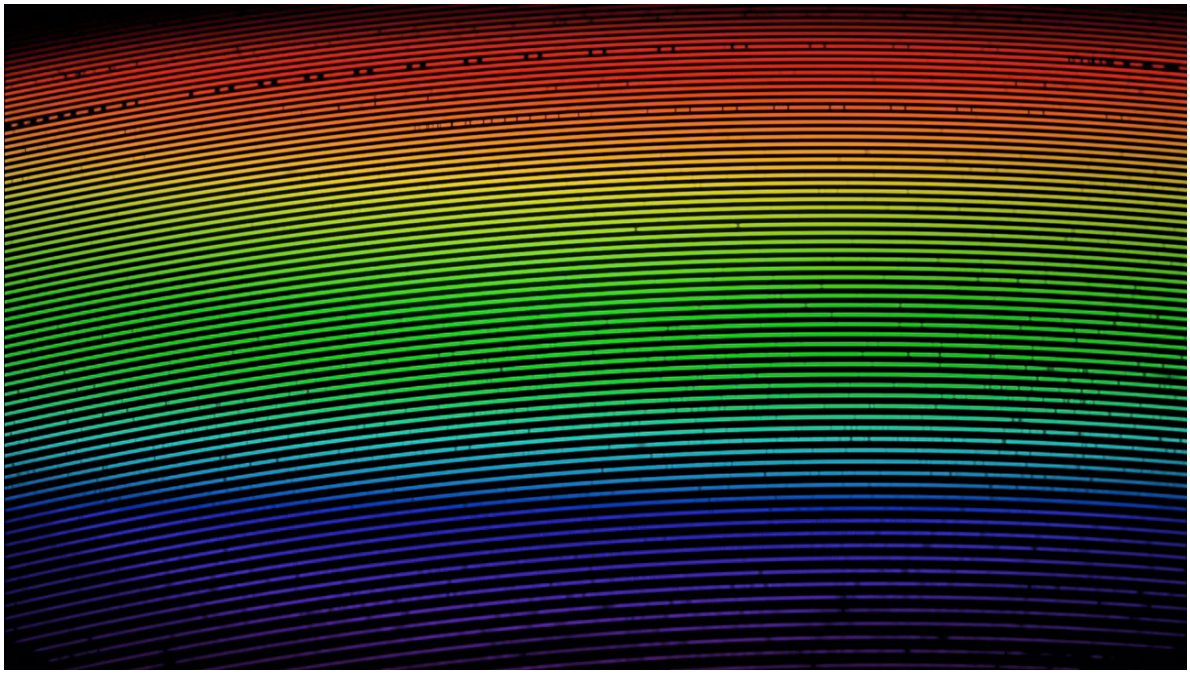
He presented this work at an International Astronomical Union meeting in Chile in the summer that coincided with the solar eclipse (Photo attached) and also at Extreme Solar Systems IV in Reykjavik, Iceland. Dr. Llama also continued his collaboration with former Lowell Astronomer Dr. Evgenya Shkolnik in several projects, including the Star-Planet Activity Research CubeSat (SPARCS). SPARCS is a CubeSat about the same size as a family-sized box of cereal that will launch in the next few years and will make unprecedented measurements of the ultraviolet radiation from low-mass stars. As a member of the science team, Dr. Llama is working hard on simulating the data SPARCS will obtain to best plan the observing and analysis strategy to maximize the scientific yield from this exciting mission. ▪



The first light solar spectrum from LOST observed using EXPRES.

ASTRONOMER **SCIENCE**HIGHLIGHTS

Star trails above the UKIRT 3.8-m telescope (at far right). Credit: U.K. Infrared Telescope, Mauna Kea Observatory, Hawaii

Dr. Phil Massey

Red supergiants (RSGs) like Betelgeuse and Antares represent the end-point in a massive star's life—or do they? During a sabbatical visit to Lowell Observatory in 2013, the Swiss stellar evolutionary theorist Georges Meynet demonstrated that if we were seriously underestimating the amount of mass such stars lose, they might not blow up as supernovae, but instead first evolve back to warmer temperatures. During relaxed conversations with Lowell astronomer Phil Massey, he argued that current observations did not really constrain the mass-loss rates of stars like RSGs very well—that the actual rates could be 10 times or even 25 times higher. If so, the implications would be staggering to stellar astronomers, meaning that perhaps half of the yellow supergiants in the sky were actually in the process of getting hotter rather than cooler.

For the next several years, Massey and Lowell Research Associate Kathryn Neugent attempted to obtain observing time with the 3.8-meter United Kingdom Infra-Red Telescope (UKIRT) telescope high atop Mauna Kea on the Big Island of Hawaii. They knew that the key to testing this remarkable suggestion was to measure the relative number of RSGs as a function of luminosity in a "mixed age" population of massive stars, such as one would find in the nearby Andromeda Galaxy. They needed to observe in the infrared, as this would result in far more accurate measurements of the stars' luminosities. They were eventually successful, and the observations were obtained in early 2018 (proving that persistence pays!). By then, Neugent was enrolled in the PhD program at the University of Washington during her thesis work on RSGs under the mentorship of Emily Levesque, and took the lead on the project.

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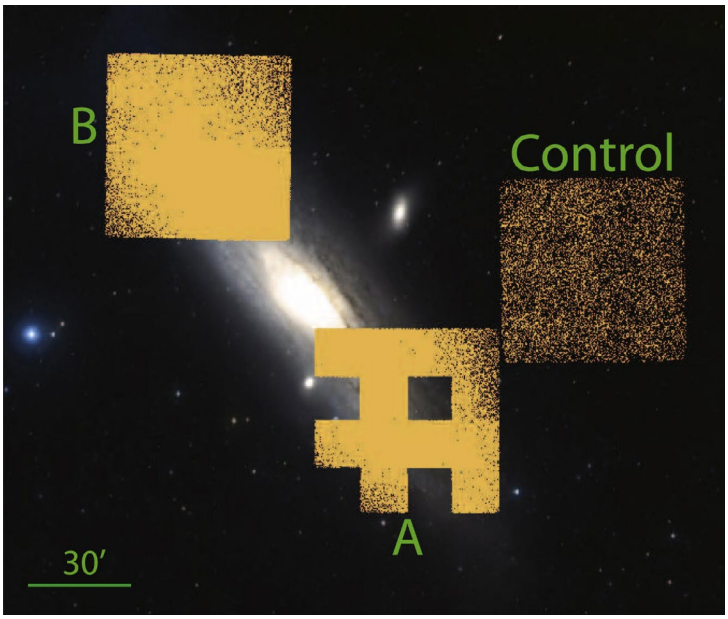
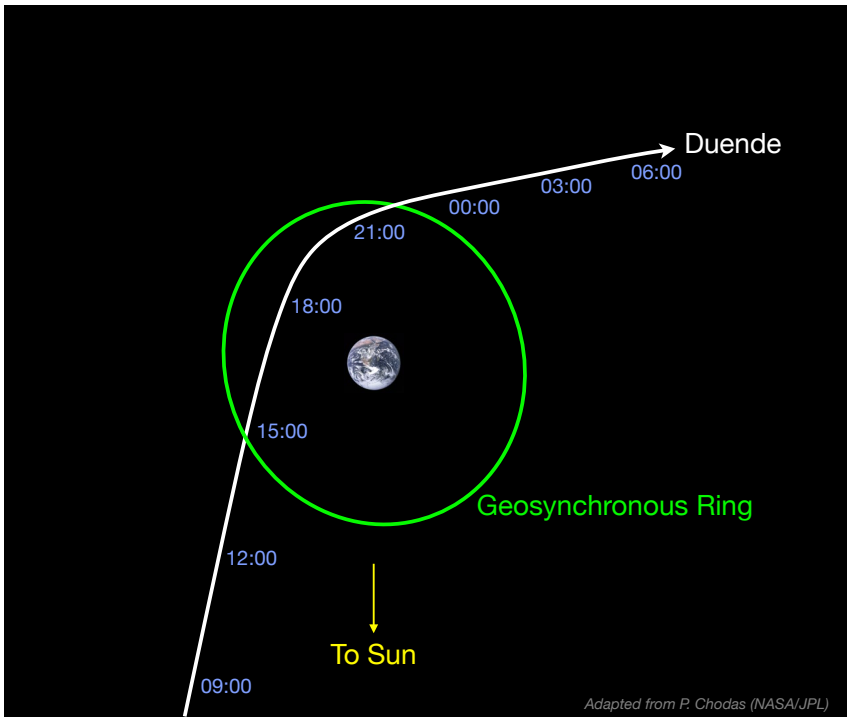
Infrared photometry is not quite as straightforward as optical work, and Massey drafted the assistance of Lowell astronomer Michael Mommert. Although Mommert's work is primarily centered on small solar-system bodies, such as asteroids, he was a frequent UKIRT user. With Mommert's advice, Massey was able to produce the first deep luminosity function for red supergiants. That summer Neugent traveled to Geneva, Switzerland, to work with members of Meynet's group on the interpretation of these data.

What they found was that the luminosity function of RSGs in the Andromeda Galaxy could be used to completely rule out the extremely high mass-loss rates that would have turned things topsy-turvy. Meynet's group had recently revised the mass-loss prescription used in their calculations. This revision was quite significant, particularly for the highest mass RSGs, and the work by Neugent, Massey, and Levesque confirmed that this revision gave near-perfect agreement with the observations. The older, more commonly adopted law, gave a poorer fit. Their results were published in the *Astrophysical Journal*. ▪



The two fields (labeled A and B) plus the control field used to obtain the luminosity function of red supergiants in M31. The yellow dots all represent a star with infrared photometry. The strange shape of field A was due to a telescope error in the dither pattern resulting in only partial coverage. From Neugent et al. (2020, Astrophysical Journal, 889, 44) and used with permission.



Schematic of the February 15, 2013 flyby of asteroid Duende projected on to the ecliptic plane. The three-hour time ticks are in UTC.

Dr. Nicholas Moskovitz

In 2019 Dr. Nicholas Moskovitz continued to carry out investigations related to asteroids, comets, and meteors. This work was conducted with numerous collaborators including Lowell postdoc Maxime Devogèle, NAU graduate student Annika Gustafsson, and several NAU undergraduates. One highlight from 2019 was the publishing of a pair of articles representing the culmination of 8 years of work focused on a remarkable near-Earth encounter by an asteroid named Duende.

Back in February of 2012 the asteroid Duende was discovered. This was a fairly ordinary near-Earth asteroid with a diameter of about 40 meters. However, it was soon realized that on the 15th of February 2013 it would experience an extraordinarily close encounter with the Earth at distance from the surface of 27,700 km (about 17,000 miles or a little over 4 Earth radii). This flyby would be inside the ring of geostationary satellites (Figure 1) and was the first time that such a close encounter was known more than just a few days in advance. This provided an opportunity for detailed study of Duende during the flyby to investigate the influence of Earth's gravitational field on a minor planet, a phenomenon modeled for decades (in fact dating back to the mid 1800's with pioneering work by the French astronomer Édouard Roche) but rarely tested.

In the weeks surrounding the flyby Moskovitz led an extensive observational campaign that employed 20 different telescopes distributed around the globe. The primary focus of these observations was to collect information about the rotation of Duende and to determine whether the Earth encounter could cause a change in Duende's rotation state. These were challenging observations, in part because of Duende's rapid motion across the sky which saw it approach the Earth from deep in the southern sky, flyby, and then recede from far in the north, thus requiring the use of telescopes in both hemispheres. In the days before the flyby an improbable confluence of unforeseen complications made these observations even harder: one observatory was struck by lightning, one CCD camera had an electronic failure, wild fires caused one telescope to close, and heavy precipitation prevented several telescopes from operating. An additional distraction, and making for an exciting 24 hours, was the unexpected and entirely unrelated impact of a large meteoroid over the city of Chelyabinsk, Russia on the same day as the Duende flyby.

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Despite these factors Moskovitz and his colleagues were able to collect extensive data on Duende. It was found that Duende is in a state of complex rotation, known as a non-principal axis rotation. This means that rather than spinning neatly like a top, Duende is spinning about multiple axes appearing to tumble through space. This was unexpected, tumbling asteroids the size of Duende are rare, and this posed a problem: only a few people in the world know how to interpret data of a tumbling asteroid, let alone figuring out if the complex tumbling somehow changed during the planetary encounter. Hence began several years of analysis that required development of new techniques and new models. Working with colleagues Conor Benson (graduate student) and Dr. Daniel Scheeres at the University of Colorado Boulder, tools were developed to interpret the Duende data.

Ultimately, Moskovitz and this team produced a physical model of Duende that fits the observational data and provides the possible interpretation that Duende's rotation slowed down due to gravitational interactions with the Earth during the flyby. This interpretation, if correct, would be the first time such gravitationally induced changes have been detected in real time, and provides important clues about the hidden interior structure of Duende. As current and future asteroid discovery surveys find increasingly more objects like Duende, the opportunities to conduct such real time experiments in planetary geophysics will increase, thus providing additional fodder for the methods that Moskovitz and his colleagues developed to explain what happened to Duende. ▪

ASTRONOMER **SCIENCE**HIGHLIGHTS

Lisa Prato and collaborator Christopher Johns-Krull (Rice University) at the June, 2019 AAS Meeting press conference presenting results on their team's direct detection of the youngest known exoplanet around the star CI Tau.

Dr. Lisa Prato

Team DEFT (Disks and Exoplanets Flagstaff Team) and Lisa Prato made significant progress on several exciting science projects in 2019; the work appeared in 16 refereed publications and conference papers throughout the year and is supported by over $1M in new and continuing NSF and NASA grants. Former Lowell/Northern Arizona University (NAU) master's student, Laura Flagg, now at Rice University, Joe Llama, Prato, and others at Lowell, published results in the Astrophysical Journal revealing warm CO gas in the atmosphere of a giant planet orbiting the young star CI Tau! This result, important because it confirmed the initial identification of CI Tau b and showed that young planets are relatively bright, was followed by a poster and a press conference at the June 2019 American Astronomical Society (AAS) meeting in St. Louis, Missouri (see photo). Current Ph.D. student Lauren Biddle spent the year in extensive development of computer code tailored to model the complex environment around young stars like CI Tau where forming planets modulate the brightness variability of the central stars, providing a unique signpost for planet formation. Brian Skiff has tirelessly accumulated data at the 31-inch telescope and analyzed light fluctuations in support of Biddle's computational work. In December, a new NAU Ph.D. student, Shih-Yun Tang, joined Team DEFT after successful completion of his master's degree at Taiwan's National Central University. Stay tuned for the Annual Report on Tang's and Biddle's important 2020 accomplishments.

Prato worked with former undergrad REU student-turned-intern Kendall Sullivan (now in the University of Texas at Austin Ph.D. program) on her publication of the properties of the enigmatic extremely young and variable stars in two close binaries; Sullivan and Prato were awarded time on the 3-meter IRTF telescope in August, 2019, and obtained four excellent nights of spectra to study these systems in greater detail. NAU undergraduate intern Sean Graham and Prato also were successful with an IRTF program to assess the possible triple nature of a mysterious young binary system, UY Aur, with spectral variability that all but obliterates the spectral signatures of the cooler star. Also from NAU, 2019 REU and now undergraduate intern Cody Huls joined the group and took over from former intern Kyle Lindstrom, now a graduate student in Physics at the University of Minnesota, the complicated development of a grid of synthetic spectra for characterizing young binary star properties. Huls also took on the measurement of radial velocities in the young triple system AS 205 in order to determine the masses of the stars in the close binary component.

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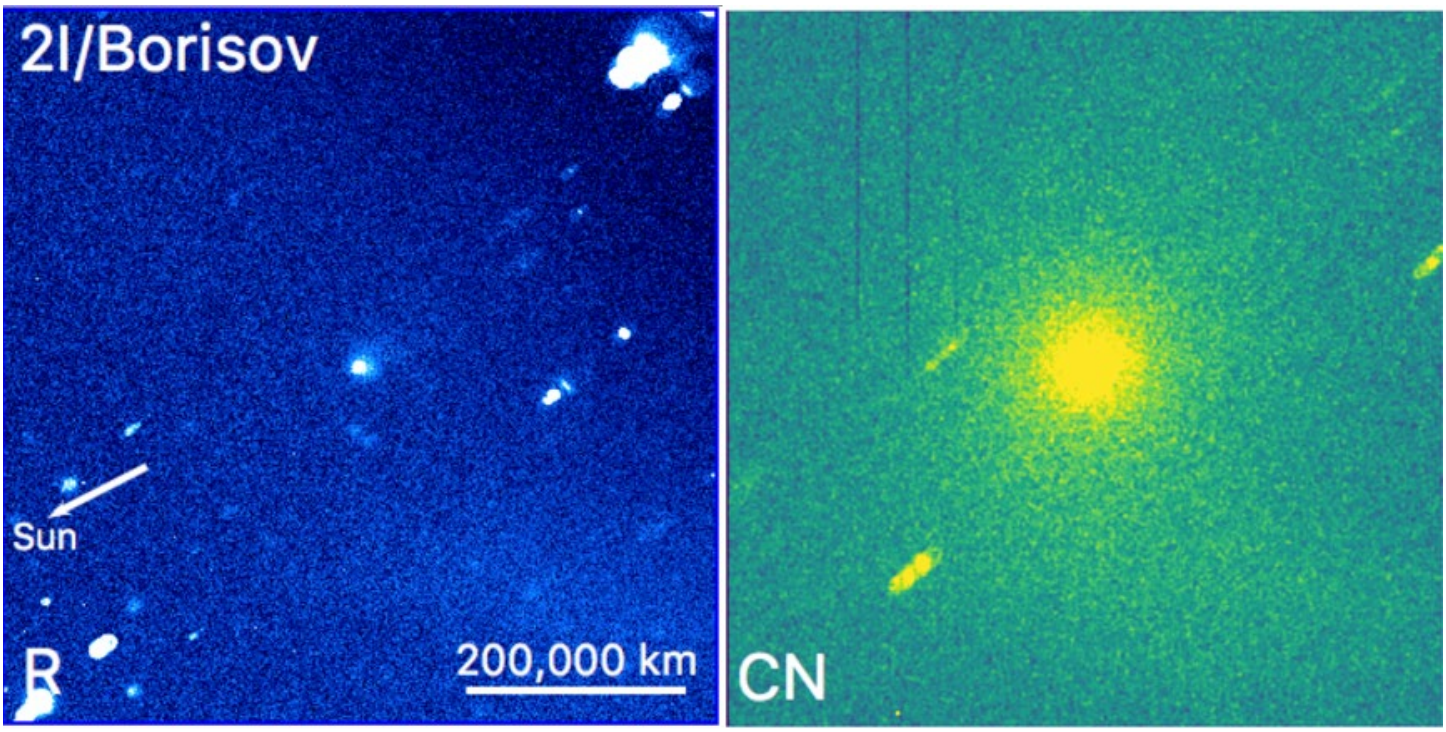
In addition to time on the IRTF (student PIs Graham, Sullivan, Flagg), Prato was awarded several nights as PI at the 10-meter Keck II telescope and several weeks at the McDonald Observatory 2.7-meter. Prato organized a successful proposal team (PI Ben Tofflemire, UT) awarded highly competitive ALMA array time. Prato was active in NAPSA (Northern Arizona Planetary Science Alliance) leadership, presented talks and posters at local and international conferences and workshops, served on time allocation committees and National Science Foundation panels, and gave public talks at the Grand Canyon Star Party (full house!), Festival of Science, Ask an Astronomer Webinar, McDonald Observatory, and a KNAU radio interview. ▪



Early images of Comet 2I/Borisov obtained on 2019 September 25 using the Lowell Discovery Telescope (formally the Discovery Channel Telescope). Only a very faint dust coma and even fainter tail (pointing towards the upper-right) are visible in the broad-band, false-color image on the left, while the cyanogen gas coma is readily evident in the narrow-band CN filter image shown on the right. (Star trails are evident in both images.)

Dr. David Schleicher

The primary research topic for Dr. David Schleicher in 2019 was Comet 46P/Wirtanen, which made its closest known approach to Earth in late 2018, approaching to within 0.08 AU (about 7 million miles). Working with former post-doc Dr. Matthew Knight (University of Maryland) and colleagues Drs. Tony Farnham and Lori Feaga (also at UMD), cyanogen (CN) gas jets were detected early in the apparition, and their motion with time was used to determine that the nucleus was rotating with a period of about 9.0 hrs. Due to the comet's rapid passage by the Earth, in early 2019 the sense of rotation of the spiral jets had reversed to become counter-clockwise as the comet was now viewed from the opposite direction (see last year's Report for an example image). As Wirtanen retreated from the Sun (and from the Earth), it progressively got fainter, but not before the team determined that its rotation period had increased to about 9.1 hrs, with the increase caused by the action/re-action associated with the gas jets that act like rockets on the comet's surface. Much of the remainder of the year was then spent attempting to interpret images of the comet's jet morphology obtained throughout the apparition. A preliminary model solution by Schleicher indicates that each of the two source regions that produce the jets are located near the comet's equator but separated by about 150° in longitude; however, the modeling is complicated by the changes in the rate of rotation that took place simultaneously with the changing viewing geometry.

Another major project involved studies of the first inter-stellar comet, 2I/Borisov. Discovered in late summer, the object's extremely high velocity (nearly 50% greater than the escape velocity from the Sun) made it evident within weeks that it did not originate in our own solar system but rather came "from far, far away." [Note that the first inter-stellar object, 1I/'Oumuamua, was only discovered two years earlier, but exhibited none of the expected cometary activity such a coma or tail, and is now thought to have been an inter-stellar asteroid rather than a comet.] Using a variety of telescopes with

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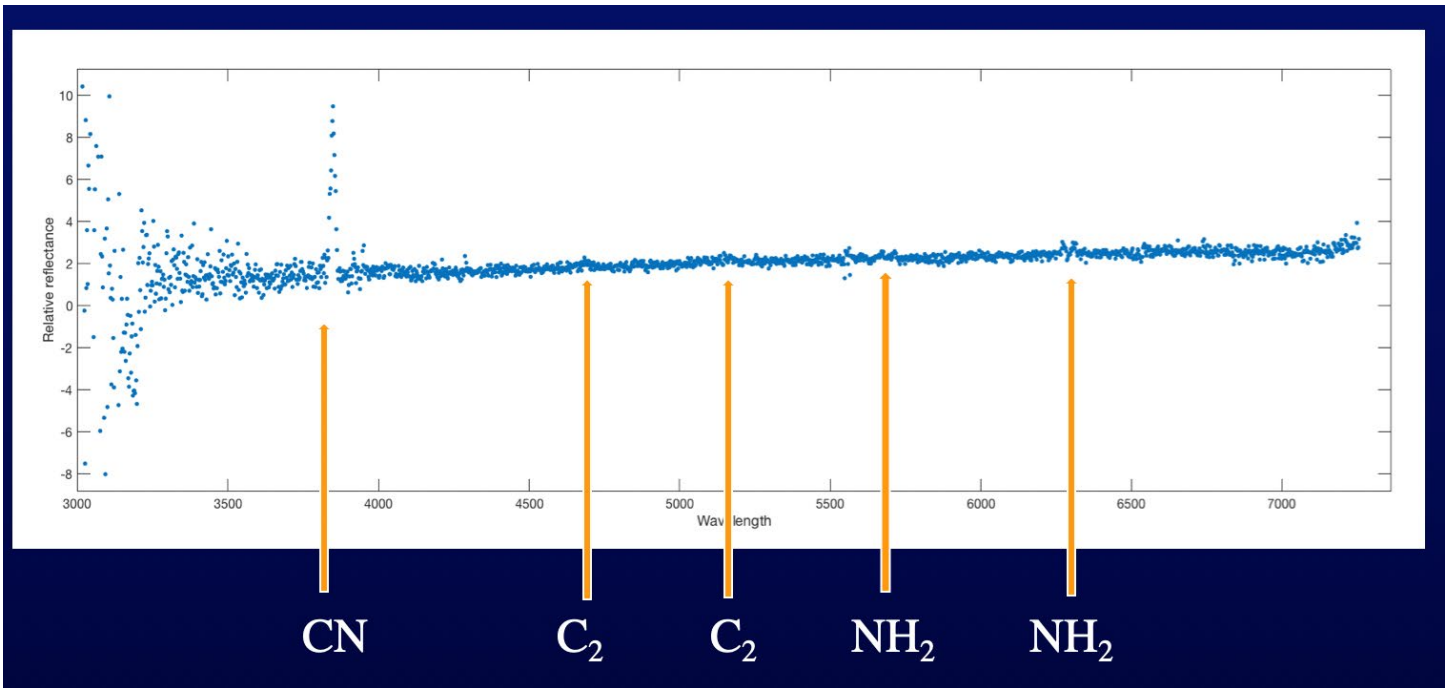
differing instruments, Schleicher and several colleagues including Brian Skiff, Dr. Maxime Devogele (Lowell), and Knight, obtained images, spectra, and photometry to characterize the comet's physical properties and chemical composition, in spite of it being quite faint (~17th in September and ~15th magnitude at its peak in December). The composition of Borisov proved most interesting. Cyanogen was most easily detected (see figures) while only a marginal detection of OH (the direct byproduct of water) was made, resulting in somewhat high but not unusual CN-to-OH abundance ratio. Based on data from Lowell and researchers at other institutions, diatomic carbon (C2) was strongly depleted in September but reached near-normal levels by December – highly unusual behavior. Most surprisingly, NH – the byproduct of ammonia – was significantly enhanced as compared to most comets in the Lowell compositional database of over 200 objects. Bottom line: while Borisov contained the same chemical components as comets originating in our solar system, its composition appears to be unique, as one would expect for a comet "from beyond."

Schleicher and Research Associate Allison Bair also continued analyses of photometric measurements obtained over a four decade span, in particular investigating the physical and compositional changes that comets exhibit as they approach and recede from the Sun. Also, for those comets in relatively small orbits (where they go out to near the distance of Jupiter and back every 5-8 years), Schleicher and Bair have discovered a few cases where the comets apparently are slowly running out of material to vaporize and are progressively becoming fainter with each passage. ▪



A sample spectrum of Comet 2I/Borisov obtained on October 27 using the Lowell Discovery Telescope. While the CN emission feature is quite strong, and, as usual, the NH2 bands faint but clearly evident, the C2 bands (normally as strong as the CN band) are barely detectable. Our and other researchers' observations indicate that the relative abundance of C2 molecules with respect to CN molecules changed dramatically as this interstellar object heated up as it approached the Sun – a behavior not seen in comets originating in our own solar system.

ASTRONOMER **SCIENCE**HIGHLIGHTS

Three mobile AstroHaven 16-1 domes in view at the NPOI site.

Dr. Gerard van Belle

The $3.26M PALANTIR (Precision Array of Large-Aperture New Telescopes for Image Reconstruction) upgrade project for the Navy Precision Optical Interferometer (NPOI) is nearing first fringes at Anderson Mesa. All three PlaneWave PW1000 1-meter telescopes are on site, as well all three AstroHaven 16-1 trailer-mounted domes; two of the PW1000's are now deployed in their domes. The NPOI Anderson Mesa site saw substantial infrastructure work in support of PALANTIR, including tree topping/trimming/removal (for maneuvering the mobile domes around the site), assembly of two AstroHaven domes, installation of the 2nd PW1000 in its dome, and welding of telescope stands for telescope support. These activities were supported by Dr. van Belle's four NAU undergraduate student interns, including Wyatt Clark (Mech E), Bradley Kingsley (Mech E), Nick Green (Mech E), and Adam Schilperoort (Comp Sci). Van Belle is continuing his tenure at NPOI as the Chief Scientist for the facility. As part of his duties in this regard, he produced an Astro2020 White Paper looking a possible future development of the facility (see below).

At the DCT, the POKÉMON (Pervasive Overview of Kompanions of Every M-dwarf in Our Neighborhood) survey has been completed by van Belle and Lowell-NAU graduate student Catherine Clark. This large survey of every low-mass star down to the hydrogen fusion limit covers 1,263 targets out to 15 parsecs. They have been successful in supplementing the POKÉMON survey with additional time from the WIYN telescope on Kitt Peak via NASA's NN-EXPLORE program. Initial survey results indicate the detection of more than 30 previously unknown companions, which represents a ~10% increase over the previously know companions. These detections will have a substantial impact upon our understanding of, and expectations for, stellar multiplicity at the lowest end of the stellar mass scale. This work is enabled by the visiting Differential Speckle Survey Instrument (DSSI) speckle, in partnership with Lowell adjunct Dr. Elliott Horch, and graduate student Mr. Zachary Hartman, visiting from Georgia State University and in residence at Lowell. The four researchersare extending DSSI's capability at DCT with the completion of the Quad-channel Wavefront-sensingSpeckle Survey Instrument (QWSSI) upgrade to DSSI. QWSSI is expected to deploy to telescopes at Anderson Mesa and Happy Jack in mid-2020.

Lowell adjunct Dr. Kaspar von Braun has been collaborating with van Belle on the PALANTIR and QWSSI projects, and has been the Los Angeles local point-of-contact for PlaneWave. Von Braun has also been assisting van Belle with the development of the 20-inch Titan Monitor (TiMo) telescope on Mars Hill (located behind the Lampland dome).

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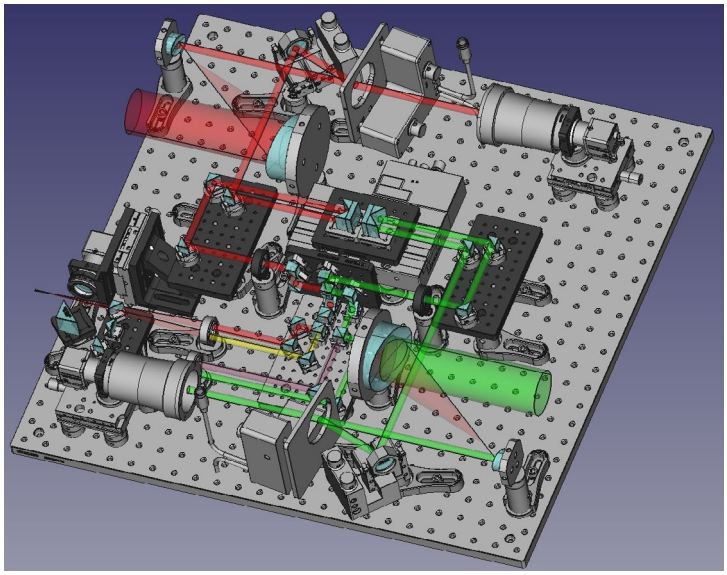
Van Belle's NASA-funded Small Business Innovation Research (SBIR) research project with industry partner Made In Space transitioned from a completed Phase I to significantly larger Phase II effort. This concept is exploring the possibility of flying a space-based optical interferometer based upon MIS's in-space manufacturing techniques. For this effort, he is designing and building a prototype beam combiner instrument at Lowell that will be integrated into a MIS testbed (representative of the manufactured support booms) at MIS's Jacksonville labs in Fall 2020 (Photo TBD). An update for the Optimast-SCI concept was presented at the January 2020 Winter AAS meeting in Honolulu.

van Belle also authored multiple White Papers for the Astro2020 Decadal review, including "High Angular Resolution Astrophysics - Fundamental Stellar Parameters" (2020) van Belle et al., "The Navy Precision Optical Interferometer" (2020) van Belle et al., along with co-authoring 14 more. ▪



CAD design for the Optimast optical payload prototype, which is slated to be built by Dr. van Belle at Lowell in early 2020.

ASTRONOMER **SCIENCE**HIGHLIGHTS

A halo around the Sun (created by ice crystals in the atmosphere) on one of the rare winter mornings when our star peeked above the horizon in Haukijärvi, Finland.

Dr. Michael West

Michael West divided his time between research, public outreach and leadership duties as Deputy Director for Science.

Michael was selected as a U.S. Fulbright scholar for 2020-2021. The Fulbright Program is the U.S. government's flagship international educational exchange program. Its goal is to increase mutual understanding between the American people and people in 125 other countries. As a Fulbright scholar, Michael will spend two months in Finland in 2020 and again in 2021 to develop and teach a course on Communicating Science with the Public. While there, he will also research Finnish approaches to science communication as practiced at leading science centers and universities throughout the country. The knowledge gained will benefit Lowell's science and outreach mission.

Michael devoted a lot of time and energy to writing. He spent a month at a writer/artist residency at the Arteles Creative Center in Haukijärvi, Finland, where he continued work on an astronomy-themed book. He was one of a dozen writers and visual artists chosen from an international pool of over 200 applicants. Additionally, he continued to write his regular columns for the observatory's monthly What's Up at Lowell newsletter and his Dispatches from the Universe column for the quarterly Lowell Observer, as well as his popular AstroAlerts, which go out to nearly 4,000 subscribers.

He also continued to serve as Secretary of the International Astronomical Union's commission on Communicating Astronomy with the Public. The IAU is the largest organization of professional astronomers in the world, with 13,533 members in 107 countries. The commission's raison d'être is to explore and facilitate new ways of communicating astronomy with the public, guided by the belief that, "It is the responsibility of every astronomer to play a role in explaining the interest and value of science to our fellow citizens."

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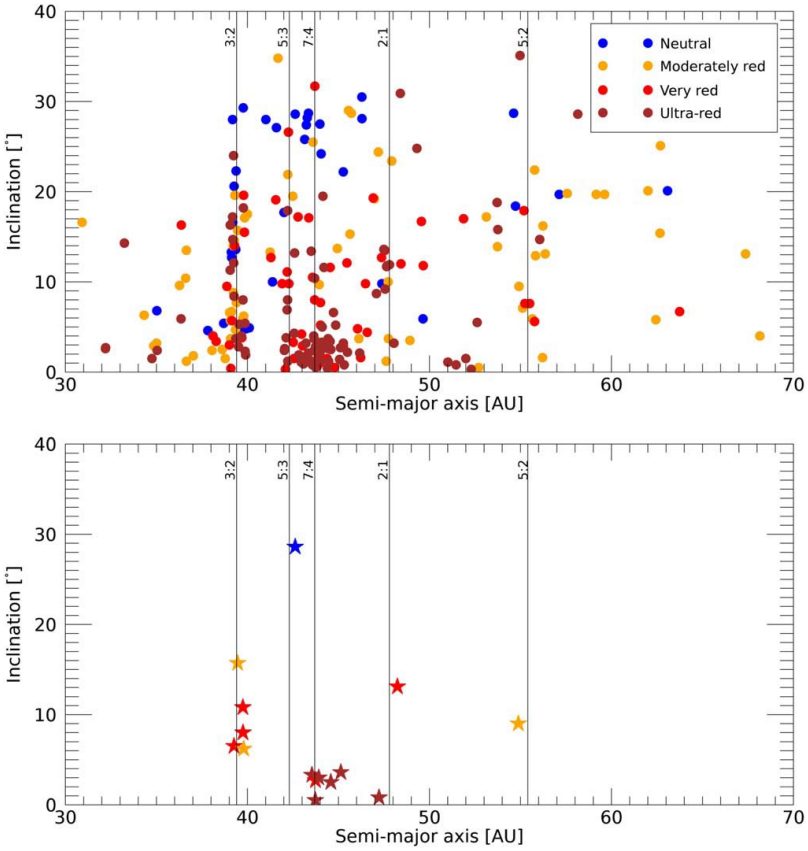
On the research front, Michael worked with Roberto De Propris (University of Turku) and a team of collaborators at Harvard, MIT and UC Berkeley to study how environment influences galaxy properties. One of the most intriguing examples of this is the tendency for the largest galaxies to share the same orientation as their surroundings. This remarkable coherence of structures over millions of light years suggests that the birth and evolution of giant galaxies have been influenced by the filamentary distribution of matter on the largest scales – the 'cosmic web.'

Additionally, he and Michael Gregg (UC Davis) used Hubble Space Telescope to examine the properties of rare elliptical galaxies found in void regions of space. Galaxies, especially ellipticals, are a gregarious bunch - wherever there's one there are usually others. This makes hermit galaxies cosmic oddities. This project aims to determine whether the properties of elliptical galaxies in voids differ from those of their counterparts in more populous regions of the universe, which will yield new insights into the processes that have shaped galaxies over billions of years. ▪

The galaxy cluster MACS J0416.1–2403 has a highly elongated distribution, and the orientations of its brightest member galaxies reflect this arrangement.



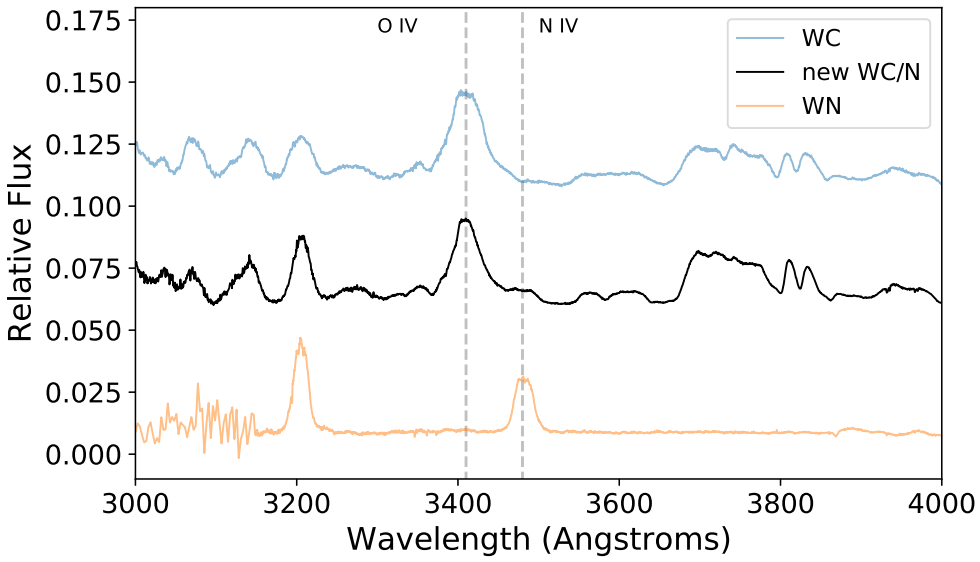
Color distribution in the trans-neptunian belt: We plotted all TNOs with known colors (upper plot), and the stars in the lower plot represent the contact binaries reported so far. Vertical lines are mean motion resonances with Neptune. The dynamically cold classical TNOs are located at low inclination (<5 deg) between the 3:2 and 2:1 mean motion resonances.

Dr. Audrey Thirouin

Audrey Thirouin's research focuses on the small icy trans-neptunian objects (TNOs) at the edge of our Solar System. In 2019, she was an author on 11 peer-reviewed scientific papers and 2 chapters for the book entitled "*The Trans-Neptunian Solar System*". Thirouin was also involved in community service works, including the review of several manuscripts for Nature Astronomy, Icarus, Monthly Notices of the Royal Astronomical Society and AAS Journals, as well as the review of telescopes proposals.

Over the past few years, her research has been focused on binary systems, and more specifically on contact binaries which include objects with a peanut shape or bilobed shape, two objects touching in one point, and two objects with a small separation. Thirouin and colleague are using the 4.3-meter Lowell Discovery Telescope and the 6.5m Magellan Telescope in Chile to know where, how many and how the contact binaries have formed in the trans-neptunian belt. One tracer to identify where the contact binaries may have formed is the color of their surfaces. The team obtained the colors of these binaries and discovered that several contact binaries trapped in mean motion resonances with Neptune were not formed in-situ. In fact, several contact binaries in resonances display the typical colors of the dynamically cold classical population, suggesting that these contact binaries now trapped in resonances were originally cold classical TNOs (see Figure). These objects, known as escaped dynamically cold classical TNOs, can form in the main reservoir of the cold classical region or form once they are trapped in resonances. However, as our team noticed that the dynamically cold classical population has a deficit of contact binaries, it seems that the formation of contact binaries happened from dynamical interaction during or after their escape from the main reservoir of dynamically cold classical TNOs.

Results from this work have been presented at the Europlanet Science Congress-Division for Planetary Science (EPSC-DPS) meeting in Geneva, Switzerland. In late 2019, Thirouin was interviewed for a special article about binaries across our Solar System, with a special focus on the recent flyby of Arrokoth by the NASA's New Horizons spacecraft, by the *Sky and Telescope* magazine. This article entitled "*Binary Worlds*" was published in the February 2020 edition. ▪



Left: The ultraviolet spectra of a WC, WN, and our new transition star denoted as a WC/N star. The nitrogen (N IV) line is show next to a prominent oxygen line (O IV) in the different Wolf-Rayet subtypes.

Image 2 caption: Erin Aadland in front of the Lowell Discovery Telescope.

Erin Aadland

Erin Aadland is finishing her 2nd year in the Astronomy and Planetary Science graduate program at Northern Arizona University, working with Dr. Philip Massey on massive stars at Lowell Observatory. Her thesis project is evaluating the physical parameters of Wolf-Rayet stars in order to better understand their evolution. The outer layers of these massive stars have mostly been stripped away revealing the stars' cores. The primary stripping mechanism is unknown. There are two proposed mechanisms: either the stars are undergoing mass-loss via stellar winds and/or they have a close companion star stripping off material. One way to determine this is to model the star's spectra. This modeling process allows the star's chemical composition and other physical parameters to be determined. The parameters can then be compared to evolutionary models, which will help identify what the primary stripping source is.

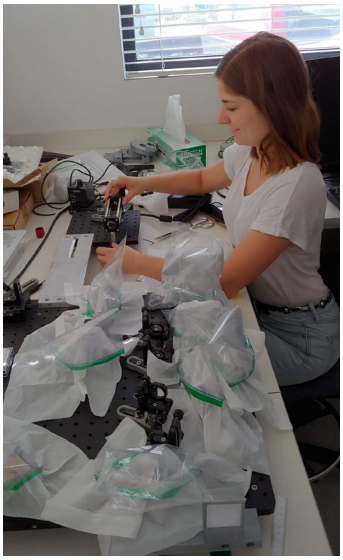
Wolf-Rayet stars have three subtypes: WNs, WCs, and WOs. The subtype is determined by what spectral lines are observed, indicating different chemical compositions. WNs have strong helium and nitrogen lines (products of H-burning). WCs have strong carbon lines (produced from He-burning) and the WOs which have strong oxygen lines (produced from carbon and helium).

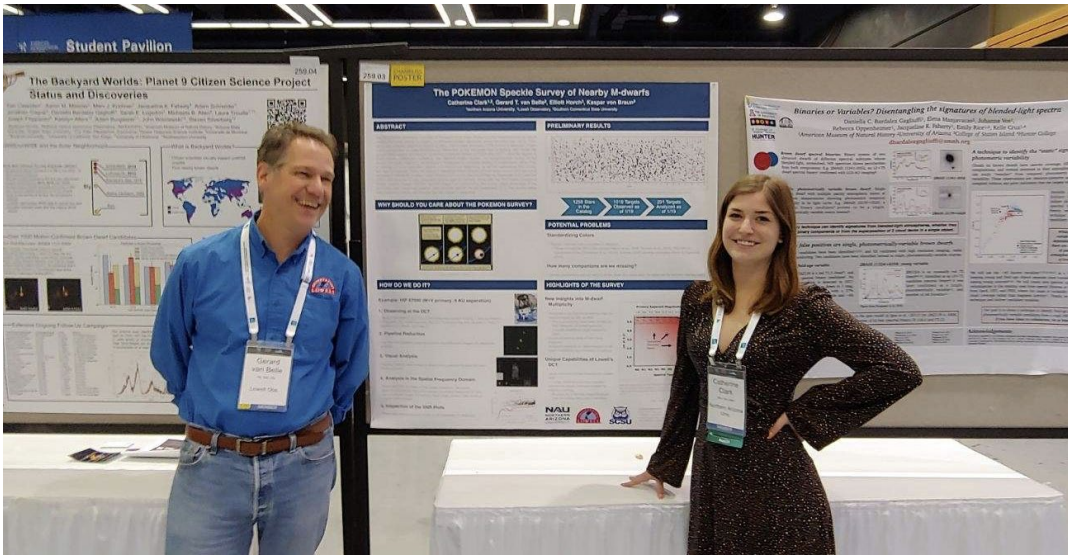
To evaluate which stripping mechanism is primarily responsible, Erin is currently modeling the spectra of 4 WC stars and comparing the results to the evolutionary models. They have found that the modeled WC stars' physical parameters agree with those needed for the stripping to occur via the stars' own stellar winds.

In addition to working with Dr. Massey, Erin has been working with Dr. D. John Hillier from University of Pittsburg. Their team discovered that one of the WC stars has nitrogen in its spectra, which is unheard of! In a typical WC star, the nitrogen has been completely stripped away. Finding residual nitrogen in one of the WCs suggests this star could be a transition star between the WC and WN subtypes (see left image). There is a previously defined transition star called WN/C star. However, this transition star has a different spectra than what we have observed in our star, as the WN/C star has a spectra similar to a WN star but contains a carbon line. Therefore, we have possibly discovered a new transition phase for these massive Wolf-Rayet stars.

She also had time on the LDT this past fall to observe Galactic Wolf-Rayet stars to compare to the Wolf-Rayet stars observed in the Large Magellanic Cloud, one of the closest galaxies and only visible from the southern hemisphere. By comparing stars that formed in these two different environments, she will be able to determine what role metallicity plays in the evolution of Wolf-Rayet stars. ▪

RESEARCH ASSISTANT **SCIENCE**HIGHLIGHTS





Left: Catherine Clark building QWSSI. *Right: Gerard van Belle and Catherine Clark at AAS 233.*

Catherine Clark

In 2019 Catherine Clark continued working with Dr. Gerard van Belle on her PhD research. So far, this research has produced the Pervasive Overview of Kompanions of Every M-dwarf in Our Neighborhood (POKEMON) speckly survey of nearby M-dwarfs. This survey has inspected, at diffraction-limited resolution, every low-mass star our to 15 pc, and additional brighter targets to 25 pc. The primary emphasis of this survey is the detection of low mass-companions to these M-dwarfs for refinement of the M-dwarf multiplicity rate, and to determine the multiplicity rate by subtype for the first time. This survey has resulted in ~30 new companions to these M-dwarf primaries. This survey has implications not only for stellar astrophysics, but for exoplanet studies as well.

In order to complete the observations for the POKEMON survey, Clark observed three nights at the 3.5-m WIYN telescope using the NN-Explore Exoplanet Stellar Speckle Imager in January 2019. She also observed seven nights at the 4.3-m Lowell Discovery Telescope (LDT) using the Differential Speckle Survey Instrument (DSSI) in September 2019. During this observing run, she was able to complete the observations for the POKEMON survey, and assist other observing programs as well.

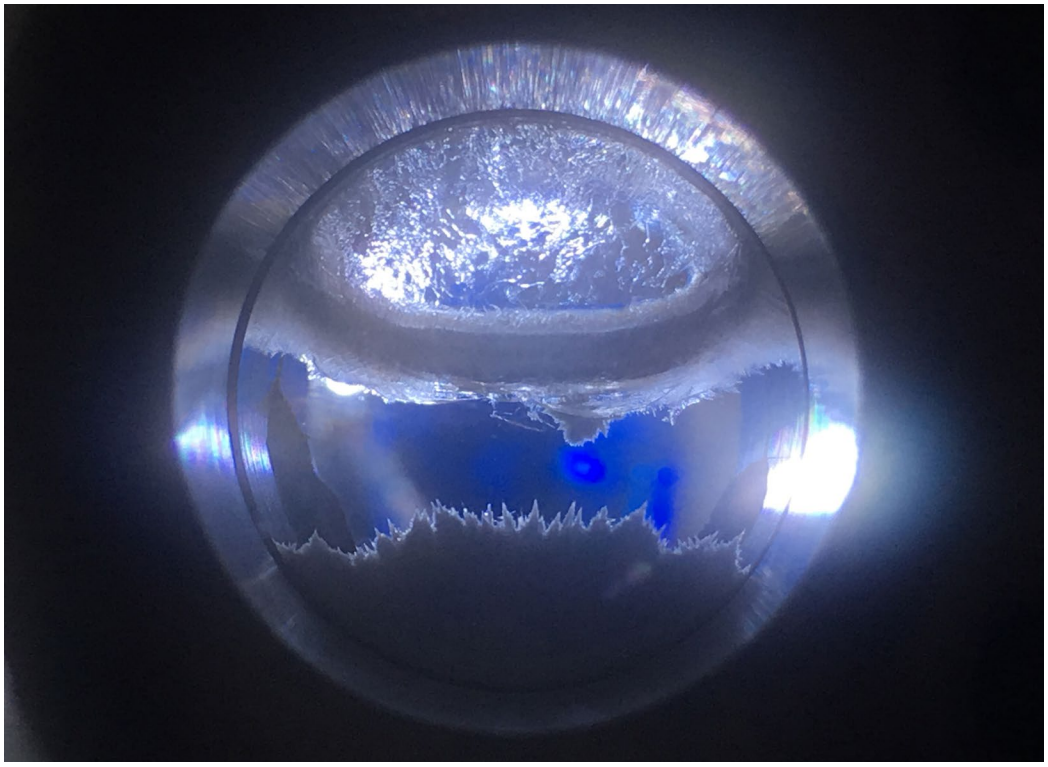
During the September observing run, Clark also began following up TESS Objects of Interest using DSSI. Once these observations are complete, she will be able to compare the non-planet-hosting POKEMON M-dwarfs to the planet-hosting TESS M-dwarfs to see whether there is a meaningful difference between their multiplicity rates.

Clark and van Belle have also been working on the upgrade to DSSI, known as the Quad-camera Wavefront-sensing Stellar Speckle Interferometer (QWSSI). While DSSI observes at two wavelengths, QWSSI will observe simultaneously at six wavelengths, including two in the near-infrared. QWSSI will also include simultaneous wavefront sensing. QWSSI will soon be tested on the 1-m telescopes located outside Flagstaff at Anderson Mesa, and will then be moved to the LDT for commissioning. QWSSI represents a new frontier in high-resolution speckle imaging, and brings with it the promise of many new and exciting projects.

In order to share the results from her research, Clark traveled to three conferences in 2019: the American Astronomical Society meeting in Seattle, the first TESS science conference at MIT, and the Extreme Solar Systems conference in Reykjavik. She received a travel grant to attend the TESS conference. She presented a poster at each of these meetings, and generated interest both in her current research and upcoming projects. She also attended the Women in Space conference at ASU to learn more about equity and inclusion for female and nonbinary scientists.

In addition to her work as a graduate research assistant, Clark finished her PhD classes and continued her classes for her Graduate Certificate in Science Communication. In September, she passed her written qualifying exam, and in December, she passed her oral qualifying exam. She is now a PhD candidate. ▪

RESEARCH ASSISTANT **SCIENCE**HIGHLIGHTS



Left: Anna Engle and Johns Hopkins University student Junellie Gonzalez visiting the LDT.

Right: In NAU's Astrophysical Materials Lab, showing a mixture of methane and ethane at its eutectic point and is forming methane-rich ice on top of the sample and ethane-rich ice on the bottom.

Anna Engle

In 2019, Anna Engle began her first year as a PhD student working with Drs. Jennifer Hanley and Will Grundy in the Astrophysical Materials Lab located at Northern Arizona University. Anna started her work with the Astro Mat Lab in 2017 as an REU (Research Experience for Undergraduates) student, which developed into a Research Specialist position in 2018 before transitioning into her current position as a graduate student. Her work with the Astro Mat Lab in 2019 focused on experimentally constructing the methane-ethane phase diagram at cryogenic temperatures with an emphasis on evaluating the solid phase transitions in pure ethane. While previous studies on the methane-ethane system have emphasized the conditions in which they are found on Earth—namely at high pressures and high temperatures—the work Anna is completing at cold temperatures provides insight into how the two species behave in the outer Solar System, especially in the context of Saturn's moon Titan.

Titan has the most substantial atmosphere of any satellite in the Solar System and is unique in its ability to harbor stable liquids on its surface. The average temperature range is between 89 and 95 K and has a substantial reserve of methane and ethane. While the two are often found together, it is important to consider pure ethane, especially since the species has the potential to experience three separate solid phases all between 89 and 90 K. The existence of these solid phases could impact crystalline configurations within the methane-ethane system, leading to implications for the lakes, the geology, and possibly even in the atmosphere. The work completed on pure ethane was presented as a poster at the 50th Lunar & Planetary Science Conference in The Woodlands, TX, as well as at the Northern Arizona Planetary Science Alliance STEM Poster Session in Flagstaff, AZ.

In addition to conducting and presenting research, Anna also attended the Women in Space conference held in Tempe, AZ, and aided in the instruction of the Astro Mat Lab's 2019 REU summer student. Looking forward to 2020, Anna will continue to take classes, work with outer Solar System materials in the lab, and start on her second-year project that will focus on the movement of ions through polymers in super-capacitors. ▪

TECHNICALSUPPORTHIGHLIGHTS

Left: IGRINS being removed from LDT after its final observing run. Credit: K. Kuehn

Above: (Left) Dr. Kyler Kuehn, Deputy Director for Technology, (Top right row) Dave Shuck and Juan Alaniz, Facilities Group, (Bottom right row) LaLaina Shumar and Haylee Archer, Telescope Operators.

By Dr. Kyler Kuehn, Deputy Director for Technology

The Technology Group had a busy year in 2019. The former Deputy Director for Technology, George Jacoby, departed, and was replaced by Kyler Kuehn, who relocated from the Australian Astronomical Observatory in Sydney. Additionally, long-time staff members Ted Dunham and Ralph Nye both retired in 2019. With the departure of such experienced employees, the group was reorganized and Lowell's Instrument Maker Jeff Gehring was appointed the new Technical Facilities Manager. Near the end of the year, Dave Shuck and his Facilities team also moved into the Technology group. Several new LDT Telescope Operators were also hired, including LaLaina Shumar and Haylee Archer.

In addition to the staffing changes, the Technology Group reconstituted its Safety Committee, and the IT group has begun work on its portion of the Mars Hill Master Plan. In particular, the IT staff are preparing for the new facilities such as the ADC and upgrading the infrastructure to accommodate an increase of many thousands of visitors annually, as well as the increasingly specialized needs of a larger staff. They have already deployed several new security cameras on campus, as well as extending the existing network access to the GODO and other buildings.

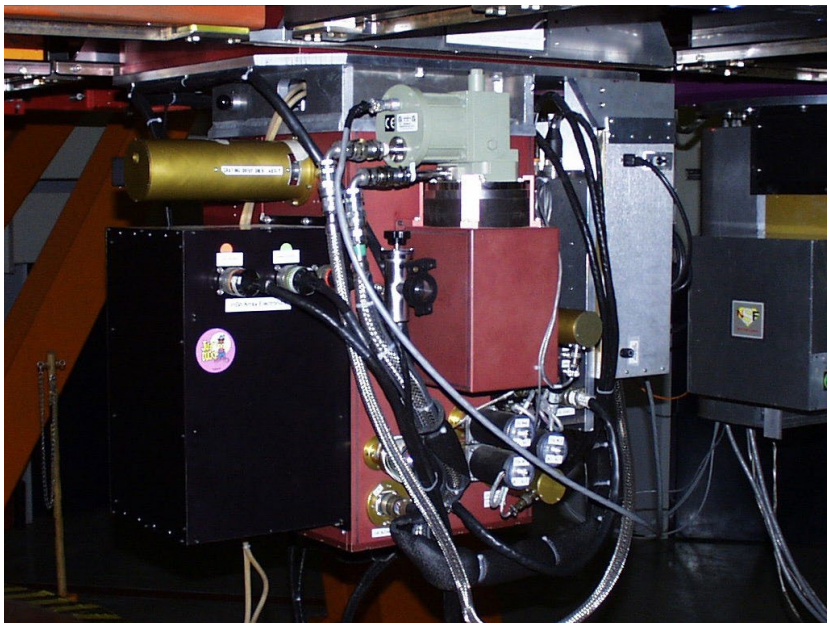
The technical staff continue to support the 1m telescope project designed to improve the performance of the Navy Precision Optical Interferometer. In addition, the group is making plans for large-scale improvements to NPOI, to be funded by a new Congressional appropriation for the Navy. We expect this "Plus-up" work to commence in 2020 and be completed within 3-5 years. The new capabilities for NPOI will make it a world-leading facility in optical interferometry.

Speaking of world-class facilities, the Discovery Channel Telescope (renamed in early 2020 to the Lowell Discovery Telescope) continued to operate throughout 2019. EXPRES, commissioned in 2018, had its first full year of regular operations, while IGRINS finished its scheduled period of operation at LDT and was removed partway through the year. In addition to the 300+ nights of scheduled science observations undertaken by the operations staff, there were numerous improvements made behind the scenes by the instrumentation, engineering, and software teams. The telescope simulator environment was upgraded, allowing improved training of new telescope operators, as well as testing of software changes and new instrument interfaces.

TECHNICALSUPPORTHIGHLIGHTS

In addition to the regular operation and maintenance activities of the instrumentation group, they also began several new instrumentation projects in 2019. SETH is an optical communication system for the LDT, designed to receive laser signals from a NASA spacecraft to be launched in late 2024. The CSHELL infrared spectrograph was received by Lowell from the IRTF in Hawai'i, and a study is underway to determine the best way to refurbish and install the instrument on the 42" Hall telescope. The Technology group, in conjunction with the Lowell astronomers and science partners, have also developed a list of potential new instrument capabilities for LDT, to be designed and built in the coming years.

Finally, the Technology group has determined the requirements for the new Technical Services Building, to be built within the next few years as part of the overall Mars Hill Master Plan. This will include a new machine shop, clean room, optics laboratory, and other facilities required for the design, construction, testing, and maintenance of our current and future instruments. The entire group is looking forward to the possibilities that this new facility will afford, both to the group and to the observatory as a whole. ▪



The CSHELL Infrared Spectrograph. Credit: IRTF, U of Hawaii

DEVELOPMENTHIGHLIGHTS

By Lisa Actor,
Deputy Director for Development

and the Development Team

Lowell Observatory received $25,648,688 gifts and commitments in 2019 setting a new record for fundraising. While many of these gifts were for the Giovale Open Deck Observatory and for the future Kemper and Ethel Marley Foundation Astronomy Discovery Center (ADC), gifts for general operating through the Annual Fund and Membership also exceeded previous years. Funds from grants and bequests added significantly to the total as well.

Some of the 2019 highlights include:

A $14.5 million commitment from the Kemper and Ethel Marley Foundation to name the Astronomy Discovery Center.

A $6 million commitment from the Richard F. Caris Memorial Trust to name the Astronomy Discovery Center's Dark Sky Planetarium.

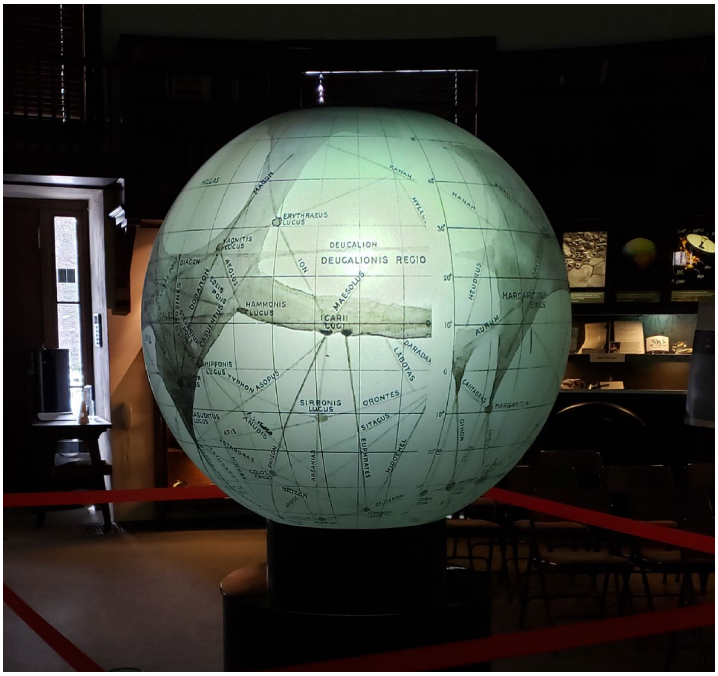
DEVELOPMENTHIGHLIGHTS

The completion and dedication of the Giovale Open Deck Observatory. *Credit: Joe Llama*

A $1 million gift from David and Edith Lowell to build a loop road and new warehouse building.

The $25.6 million does not include an additional $1.5 million challenge gift from the Caris Trust for the ADC. This challenge will match all gifts to the ADC dollar for dollar up to $1.5 million, helping propel the ADC campaign toward groundbreaking in 2021. ▪

PUBLICPROGRAM**HIGHLIGHTS**



Percival Lowell's Mars map displayed on the 48-inch diameter OmniGlobe in the Rotunda Museum. Credit: Sarah Burcher

By Samantha Gorney, Deputy Director for Education

Lowell Observatory's outreach team had a remarkable year in 2019. In addition to doing all the work required to keep the observatory's robust suite of high-quality outreach programs running, the team juggled several complex projects and hosted a number of high-profile events. Projects tackled include the integration of a new display system in the Rotunda Museum, the fit-up and commissioning of the Giovale Open Deck Observatory, and the development of an Interpretive Master Plan. Special events consisted of a live question-and-answer session with an astronaut, a celebration of the 125th anniversary of the observatory, programs commemorating the 50th anniversary of the Apollo 11 Moon landing, the grand opening of the Giovale Open Deck Observatory, and a Mercury transit viewing party. Despite the furious pace and intense workloads experienced behind the scenes, the quality of outreach programs never suffered. That outcome is a testament to the capability and dedication of public program staff and volunteers.

An exciting new educational tool arrived in mid-March in the form of a 48-inch diameter OmniGlobe. This digital globe and associated kiosk replaced an outdated display system in the Rotunda Museum. Guests can interact with the globe on their own during the day and take in shows facilitated by educators during the evening. The OmniGlobe software allows users to format images for display on the globe and add the formatted files to an extensive, built-in content library. Percival Lowell's maps of Mars were, aptly, the first files added to the content library.

Lowell's impressive new Giovale Open Deck Observatory came together in record time thanks to the hard work of staff from every department. While the effort put forth by each member of the outreach team was significant, the workloads carried by Public Program Manager Sarah Burcher and Senior Educator Jim Cole were herculean. Jim spent several months testing and preparing the scopes and mounts for installation. Sarah and Jim both put many hours into the installation and commissioning of the Giovale Open Deck Observatory telescopes and instruments. They also managed to train more than 20 people on the operation of the moving building and the facility's many different telescopes in just under two months.

In early March, a group of 600 Flagstaff students participated in a live question-and-answer session with an astronaut onboard the International Space Station as part of the NASA Downlink program. The event was made possible by a team of Flagstaff educators, including Lowell Observatory's Master Teacher Todd Gonzales. They drafted a compelling application that earned Flagstaff's students one of the highly sought-after Downlink spots and spent many hours preparing for the event in the weeks leading up to it.

PUBLICPROGRAM**HIGHLIGHTS**

The observatory ushered in the Giovale Open Deck Observatory with a grand opening event held on Saturday, October 6, 2019. More than 1,800 visitors participated in festivities that day, setting the record for one-day attendance. The staff and volunteers present on campus that evening were witness to a paradigm shift. A once-bustling Rotunda plaza grew quiet, and the west side of campus sprang to life. Although hundreds of guests were on site that evening, the infamously long Clark Telescope line never manifested. Visitors waiting in lines at the Giovale Open Deck Observatory were awed and entertained by a previously unavailable, wide-open view of the night sky. In fact, they appeared to be almost as enamored with naked-eye views of the night sky as they were with the views afforded by telescopes.

A new afterschool STEM program fostered by Event Coordinator Jelena Lane launched in the Fall. This program, developed in partnership with program coordinators at Clark Homes, brings astronomy-themed, hands-on activities to children at the nearby low-income housing complex. Activities, led by Lowell educators, were offered to children at Clark Homes every other week throughout the second half of the school year.

Working in collaboration with leaders from the Girl Scouts Arizona Cactus-Pine Council, Programming and Scheduling Coordinator John Compton developed a workshop designed to help Girl Scouts earn their Space Science badge. The pilot workshop, held at Lowell in 2019, drew in several local and regional Girl Scout troops and was deemed very successful. At the request of the Arizona Cactus-Pine Council, Lowell is designing a Girl Scouts patch specific to the observatory that will be available to Girl Scouts who participate in future workshops.

Lowell Observatory Camps for Kids (LOCKs) programs were offered to children throughout the year at both on- and off-site locations. On-site, attendance reached record levels for both elementary and middle school camps. Off-site, a record number of children attended LOCKs programs at the Flagstaff Family Food Center, and additional classrooms in Cave Creek, Arizona, adopted the LOCKs - Preschool curriculum.

The incredible night sky over GODO on grand opening night. Credit: Danielle Adams

PUBLICPROGRAM**HIGHLIGHTS**

Left: One of the 5th grade classes in the 2018-19 school year and their Mars landscape. Mr. Brown, their partner, assigned "landing sites" for each group's robot. Each group then programmed their robot to reach the same destination from their different starting points.

Right: 4th graders demonstrating the effects of wind on sand dunes using a hair dryer.

By Dr. Deidre Hunter

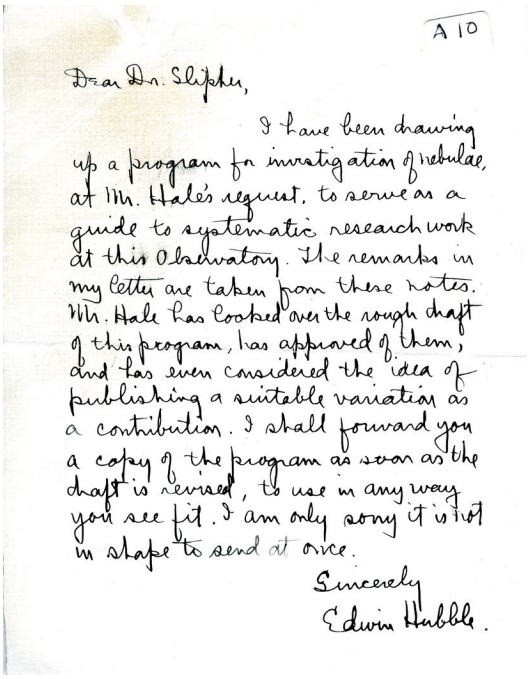
Native American Astronomy Outreach Program

In 2019 the Native American Astronomy Outreach Program (NAAOP) finished the first year and began the second year of our three-year collaboration with the Kayenta Unified School District. In the second half of the 2018-19 school year we held a school-wide star party at which students shared their project posters with their parents. The classes also came to Lowell on their field trips that included posters sessions with Lowell staff, meeting engineers from Gore and Raytheon, and touring either NPOI or LDT. In the 2019-20 school year, we partnered with the 7 4th-7th grade teachers that we worked with in the first year and added 8th grade. The 8th grade curriculum unit is on the chemistry of frost on the highlands of Venus and the rust on Mars.

We also held week-long residential summer camps for rising 6th and 7th graders. There was an Engineering Day that consisted of a visit by several Gore engineers who had designed activities related to their type of medical engineering. Dr. Will Grundy gave the students a tour of the ICE lab, the cryogenics laboratory at NAU where he and his colleagues make and study ices relevant to the outer Solar System, such as Pluto. A tour of the Grand Canyon was about geology of the Earth and was conducted by a professional group. Book Club aims to instill a love of reading. The 6th graders read *The Boy Who Harnessed the Wind*, an autobiography about a boy who invented and built a wind turbine that saved his people from starvation, and the 7th graders read a science fiction book about Earth in the future. The class activities built on the 5th and 6th grade curriculum units that the students participated in during the school year. One of the activities was to build a giant model of a human habitation on Mars. On the last night of camp, the students camped out under the stars complete with viewing the night sky and eating S'mores. ▪

One of the 6th grade field trips to Lowell. Poster of energy cycle under the ice on Titan.

PUTNAMCOLLECTION**CENTER**HIGHLIGHTS



A 10

Dear Dr. Slipher,

I have been drawing up a program for investigation of nebulae, at Mt. Hale's request, to serve as a guide to systematic research work at this Observatory. The remarks in my letter are taken from these notes. Mt. Hale has looked over the rough draft of this program, has approved of them, and has even considered the idea of publishing a suitable variation as a contribution. I shall forward you a copy of the program as soon as the draft is revised, to use in any way you see fit. I am only sorry it is not in shape to send at once.

Sincerely
Edwin Hubble.

Left: One of the letters from the collection of correspondence between V.M. Slipher and Edwin Hubble.

Right: The Lampland Diaries exhibit opened in May.

By Lauren Amundson, Librarian and Archivist

In 2019, the Lowell Observatory Library and Archives continued its mission of collecting, preserving, and providing access to current research and historical resources. Archivist and Librarian Lauren Amundson, Collections Assistant Stacey Christen, and a dedicated team of volunteers and interns worked on a variety of projects throughout the year.

In the spring, NAU History graduate student Megan Nolan completed an internship in the archives. She processed the papers of emeritus astronomer Dr. Wesley Lockwood, who retired in 2008 and donated his collection in 2018. Zachary Peach, a graduate student in the Library and Information Science program at the University of Arizona, completed an internship in the archives in the fall. He created the finding aid for the Lockwood papers and improved the finding aid for Percival Lowell's papers. He also digitized correspondence between V.M. Slipher and Edwin Hubble and uploaded the letters to Omeka, our publicly-available digital collections platform.

On May 11, collections staff unveiled a new exhibit in the Putnam Collection Center (PCC) titled The Lampland Diaries. The exhibit focuses on the life and career of Lowell astronomer Carl Otto Lampland, who worked at the observatory from 1902 to 1951. The exhibit showcases his daily diaries, logbooks, astronomy photographs, and equipment. Volunteer Karen Kitt created an accompanying online exhibit with letters, photographs, and the digitized diaries.

In commemoration of the observatory's 125th anniversary, staff and volunteers created a new digital collection on the Arizona Memory Project called Flagstaff It Is - The Founding of Lowell Observatory. The collection consists of early correspondence between Andrew Douglass and Percival Lowell, as Douglass scouted sites for an observatory in the Arizona Territory.

Amundson and Lockwood continued conducting oral history interviews. They interviewed former Lowell and NAU astronomer Barry Lutz and former Lowell groundskeeper Jerry McGlothlin. There are now almost thirty recordings in our collection.

Staff welcomed three in-person researchers and received approximately fifty requests from authors, editors, filmmakers, publishers, and researchers for reproduction and use of archival materials.

PUTNAMCOLLECTION**CENTER**HIGHLIGHTS

Amundson supervised a team of ten volunteers and their projects, which included collections processing, cataloging, and digitization; humidifying and flattening architectural drawings and blueprints; and moving manuscripts, photographs, and glass plate negatives to the PCC.

Lowell Observatory joined other museums, archives, and libraries in the northern Arizona region to form the Northern Arizona Heritage Response Coalition. Its purpose is to provide support for one another in the event of a disaster such as fire or flood. The group is currently working to finalize a Mutual Aid Agreement.

In October, Lowell partnered with NAU Cline Library Special Collections and Archives, the Arizona Historical Society, and the Museum of Northern Arizona to offer a free public workshop on Preserving Family Collections. Archivists from each institution welcomed members of the public and provided advice on preserving their family documents, photos, and videos.

Social media remains an important part of collections outreach, with a WordPress blog (*A Signal from Mars*) and Twitter account (@asignalfrommars). Topics include "This Day in Lowell History," announcements about new exhibits and collections, events, project updates, and fun items we find in the archives. ▪

MARKETING&COMMUNICATIONSHIGHLIGHTS

The 125th anniversary logo created by Senior Creative Specialist, Sarah Gilbert

Percival Lowell's seal recreated by Creative Specialist, Alex Elbert.

By Dr. Danielle Adams,
Deputy Director for Marketing and Communications

Many people think of marketing as advertising and promotion, which are some of its outputs, but the full picture of marketing begins with inputs like guest insights and feedback concerning their desired visitor experience. In 2019, the former Communications team developed into a complete Marketing & Communications team, with the addition of Dr. Danielle Adams at the end of December 2018 as the team's first Deputy Director and the redefinition of Miriam Robbins' role from Gift Shop Manager to Visitor Experience Manager. Generously donated DON funds were used to remodel an additional room in the White House (the former residence of Lowell astronomer Dr. Nat White) to serve as Miriam's office.

At the Steele Visitor Center, Retail Associates were reimagined as Visitor Experience Associates, with core job functions of welcoming and orienting guests at the start of their experiences at Lowell Observatory, converting many of them to members, and helping them commemorate their experiences at the gift shop. Miriam and Danielle studied up on current best practices for guest experience matters at annual conferences for the Museum Store Association and the Visitor Experience Group. Miriam also served as project manager to select and integrate a new admissions point-of-sale system from ACME Technologies.

Within the gift shop, Visitor Experience Supervisor Kimberley Denune directed the beautification of displays and the curation of merchandise to make the gift shop a more inviting experience for our guests. These efforts paid off, as gift shop revenue increased from $595,646 in 2018 to $698,417 in 2019, with the average spend in the gift shop increasing from $5.71 to $6.73 per guest. Throughout 2019, 1634 guests purchased or renewed annual memberships at the Steele Visitor Center on the days of their visits, an increase of about 200 over 2018.

Borrowing from cultural anthropology, Danielle worked with Heather Craig to institute a new program of qualitative sentiment analysis and the creation of the Net Reviewer Score, which enabled the team to discern trends in guest experiences and uncover actionable data that could improve our public program. Such analysis informed, among other things, the increase of admissions pricing at the opening of the Giovale Open Deck Observatory (GODO), a change whose value was affirmed in guest comments following the GODO's grand opening.

Promotional efforts were refined in 2019 with the introduction of guest personas and segmented marketing tactics. Sarah Gilbert created a new 125th anniversary logo that was applied to new signage throughout campus and advertising on all channels to highlight the quasquicentennial of the observatory on May 28, 2019. Donors Kyle and Rachel Dilger generously donated hours of aerial drone video footage through their newly established company, Corvid Aerial Solutions, which Molly Baker used to create a new "Experience Wonder" promotional video. Later in the year, new team member Alex Elbert painstaking made a digital version of an old seal that Percival Lowell starting using shortly before he died, which read, "Lowell Observatory - Worlds Revealed."

MARKETING&COMMUNICATIONSHIGHLIGHTS

Promotional exhibits included the AAS winter meeting, the Northeast Astronomy Forum (NEAF), the IPW international travel trade show, SpaceFest, and several Good Morning Flagstaff chamber of commerce events. At the end of the year, Sarah designed a new traveling booth that features 125 years of Lowell history as an exhibit around the booth's exterior.

Building on its 2018 start, the Flagstaff's Lunar Legacy campaign, originated by Historian Kevin Schindler, generated record-breaking national and international media coverage for Lowell Observatory, including articles by the New York Times, the Los Angeles Times, and the Associated Press that listed Flagstaff among the top places to celebrate the 50th anniversary of the Moon landing. Throughout the year, Kevin gave 137 programs, special tours and media interviews and produced 34 publications, many of these highlighting the observatory's role in mapping the Moon and training astronauts for the Apollo missions. The Lunar Legacy campaign culminated in the celebration of the 50th anniversary of the Apollo 11 Moon landing, which drew 1237 guests to the observatory on July 20, 2019. This community-wide campaign garnered numerous awards, including the Friend of the Humanities Award to Kevin Schindler from Arizona Humanities, the Arizona Governor's Tourism Award for Outstanding Tourism Partnership (Rural), the Destination Marketing Association West award for Outstanding Achievement (Best Idea Program), and the Stars of the Industry Award from the Arizona Lodging and Tourism Association. Additionally, NASA used the Lunar Legacy program as a model for engagement in other communities.

In the midst of the Lunar Legacy celebrations, Lowell's Marketing and Communications team began to promote the opening of the Giovale Open Deck Observatory (GODO). The "Stargazing Reimagined" campaign, a concept originated by Heather Craig and designed by Sarah Gilbert and Alex Elbert, drew a highest-ever single-day attendance of 1813 people to the Grand Opening of the GODO on October 5, 2019. Lowell's media blitz continued with national and regional buzz surrounding the GODO, including a highlight by USA Today, and was bolstered by social media posts by Alex and new team member Madi Mooney. Altogether, 103,831 visitors came to Lowell Observatory in 2019.

Beyond the three major events of the observatory's 125th anniversary, the 50th anniversary of the Apollo 11 Moon landing, and the Grand Opening of the GODO, Dave Sawyer and Heather Craig set up the Flagstaff chapter of Astronomy on Tap, which filled the Southside Tavern every month with science lovers who came for astronomy talks and trivia. The end of 2019 saw the development of the first-ever "I Heart Pluto Festival," which was conceived to set off a 10-year campaign that will culminate in the 2030 centennial celebration of Pluto's discovery in 1930.

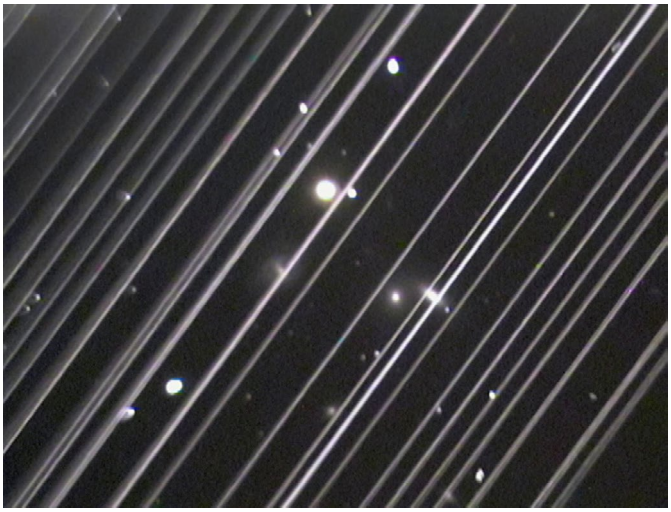
MARKETING&COMMUNICATIONSHIGHLIGHTS

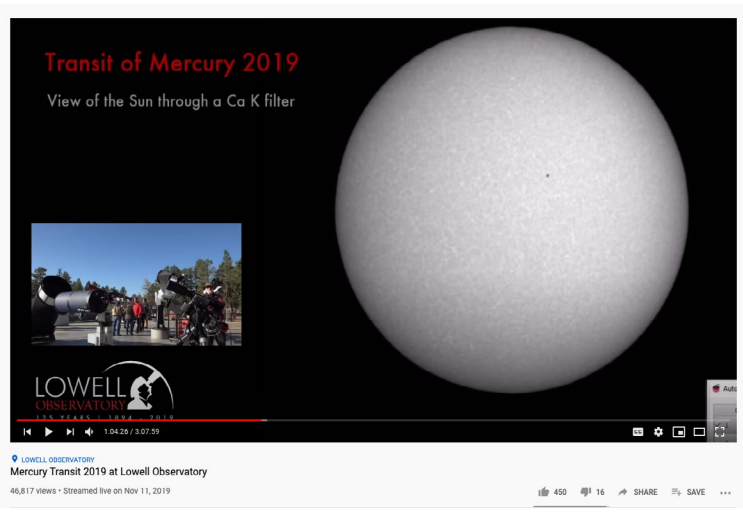
The year 2019 was punctuated by several unexpected and remarkable events. On May 25, during a Meet an Astronomer event with Deputy Director for Technology Dr. Kyler Kuehn, Lowell Educator Victoria Girgis snapped an image of a galaxy cluster that was crossed by some 25 Starlink satellites. This image was quickly picked up by national and international media as an exemplar of the impact that satellite constellations can have on astronomical imaging. Throughout the year, this image recirculated after every Starlink launch.

In July, sitting United States Senator Martha McSally toured the observatory by day and enjoyed it so much that she returned for stargazing in the evening. During her visit, Lowell staff and Sole Trustee Lowell Putnam spoke with her about the congressional bills that would finalize the 1910 conveyance of a plot of land known as Section 17 to the observatory and provide badly needed funding for maintaining and operating NPOI.

In August, Lowell Putnam, Jeff Hall, and Danielle Adams met with executives from Discovery Communications to reboot the relationship between Lowell Observatory and Discovery. Months of conversation and review of the expired DCT agreement ultimately led to the signing of a new cooperative content marketing agreement that also renamed the Discovery Channel Telescope (DCT) as the Lowell Discovery Telescope (LDT).

On November 12, the observatory hosted its first ever YouTube live-stream for the transit of Mercury. Conceived as a practice run for a coming Lowell42 live stream, this broadcast unexpectedly generated more than 30,000 views during the 4-hour event, plus another 15,000 views afterwards. ▪





Left: The image of the NGC 5353/4 galaxy group taken by Victoria Girgis on May 25, 2019. The diagonal streaks of light are from approximately 25 Starlink satellites.

Right: The Transit of Mercury live-stream on YouTube.

VOLUNTEERHIGHLIGHTS

Left: Recipients of asteroid citations, front row (left to right): Andy Odell, Jonna Peterson, Klaus Brasch. Back row: Glenda Hill, Gary Tallman, Pat Benson, Kris Naylor, Gene Hill, Rich Comnick.

Right: A group of volunteers gathers at Cinder Lake Crater Field as Kevin Schindler (second from left) begins the tour.

By Mary DeMuth,
Volunteer Coordinator

Throughout Lowell's 125th anniversary year, volunteers continued to serve the observatory in many capacities: educating the public about astronomy and Lowell history, preserving and digitizing Lowell's extensive and valuable archives, assisting the Development department with membership recruitment and donor support, and helping the business office with weekly tasks. During the 2019 calendar year, fifty individuals (including 10 new volunteers) gave just over 4,300 hours of service to the observatory.

In recognition of their dedication to Lowell, nine volunteers whose tenure with Lowell surpassed five years as of the end of 2017 had asteroids named for them. On April 26, a luncheon was held in the Tombaugh Apartment and the nine (very surprised!) volunteers were presented with citations approved by the International Astronomical Union (IAU) showing their asteroid's orbit within those of Earth, Mars and Jupiter, the IAU citation as published, and specifics about their asteroid including an estimate of its size. Sadly, just two weeks after receiving his citation, long-time public program volunteer Andy Odell passed away unexpectedly, leaving behind many Lowell friends and colleagues.

Flagstaff and Lowell Observatory honored the 50th anniversary of the first manned Moon landing with an 18-month-long salute to northern Arizona's role in carrying out the Apollo missions. The Lunar Legacy festivities included special lectures, tours, VIP appearances, movies, music, food, and drink. In celebration of National Volunteer Month and the half-century Apollo 11 milestone, lucky Lowell volunteers were treated to a private presentation by Lowell Historian and Lunar Legacy coordinator Kevin Schindler about the events that led up to the Apollo 11 and subsequent Moon landings, which highlighted the contributions of the northern Arizona residents who worked toward the success of those missions. Following the presentation, Kevin led volunteers on a tour of Cinder Lake Crater Field 1, where they trekked through the manmade moonscapes NASA used to train Moon-bound astronauts in the 1960s and 1970s. Back in Flagstaff, the group made a stop at the United States Geological Survey's Shoemaker Astrogeology Building to see and pose for pictures with Grover, the vehicle the astronauts used for lunar driving lessons. The day's celebration ended with an informal lunch at the Trustee's Residence.

The following month, the volunteer program was front page news in the Arizona Daily Sun's June 6 edition as part of the community newspaper's coverage of Lowell's 125th anniversary: https://bit.ly/2W2A8aT.

It was a year of new beginnings as the much-anticipated Giovale Open Deck Observatory was completed and made its public debut in early October. Public program volunteers were eager to train on the new telescopes and beginning in late fall, both seasoned and new volunteers enjoyed hands-on practice with the telescopes and the thrill of introducing visitors to Lowell's fabulous new facility. ▪

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CONFERENCEPROCEEDINGS & **ABSTRACTS**

For a complete list of 2019 conference proceedings and abstracts see:

lowell.edu/research/recent-publications

STATEMENT OF FINANCIAL POSITION

Combined Statements of Financial Position

(with comparative totals for the year ended December 31, 2018)

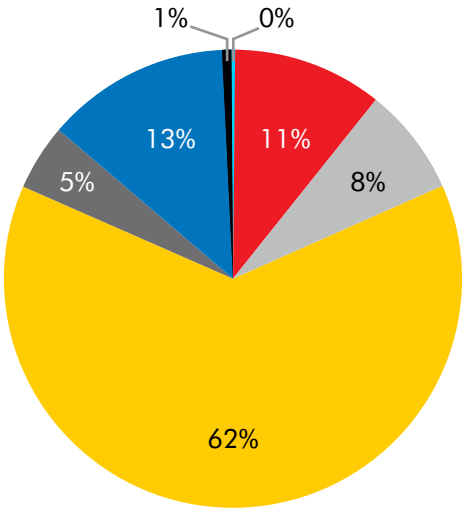
ASSETS	2019	2018
Current Assets		
Cash and cash equivalents	$ 156,179	$ 265,651
Restricted cash	790,973	206,178
Restricted certificates of deposit	403,582	-
Investments without donor restrictions	849	8,893
Research grants receivable	319,429	360,146
Contributions receivable, current portion	2,788,205	1,265,726
Inventory and other assets	341,900	338,767
Total Current Assets	**4,801,117**	**2,445,361**
Property, plant and equipment, net	48,356,606	45,626,539
Contributions receivable, net of current portion	10,389,449	364,302
Collection item	400,000	400,000
Investments with donor restrictions	22,787,049	25,990,107
Total Noncurrent Assets	**81,933,104**	**72,380,948**
Total Assets	**$86,734,221**	**$74,826,309**
LIABILITIES AND NET ASSETS		
Current Liabilities		
Accounts payable	$ 375,473	$ 427,401
Accrued expenses and other current liabilities	52,661	90,636
Total Current Liabilities	**428,134**	**518,037**
Note payable, bank	2,595,000	7,453,421
Deferred research grant revenue	44,576	85,454
Deferred access fee revenue	7,470,403	7,761,824
Total Liabilities	**$10,538,113**	**$15,818,736**
Net Assets		
Unrestricted	$ 27,563,416	$ 28,770,277
With donor restrictions	48,632,692	30,237,296
Total Net Assets	**76,196,108**	**59,007,573**
Total Liabilities and Net Assets	**$86,734,221**	**$74,826,309**

STATEMENT OF FINANCIAL ACTIVITIES

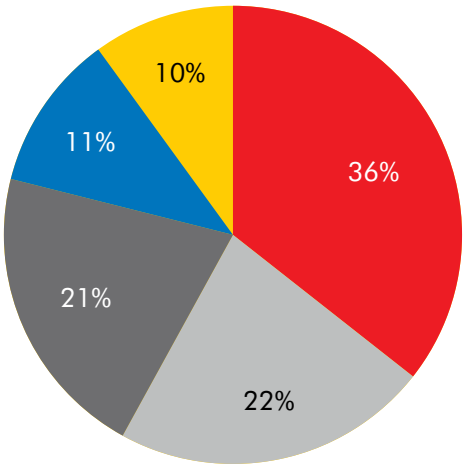
Combined Statements of Financial Activities for the year ended December 31, 2019

(with comparative totals for the year ended December 31, 2018) (before depreciation)

REVENUE & SUPPORT	2019		2018	
Grant and contract revenue	$ 3,276,144	11%	$ 3,649,780	36%
Telescope access fees	2,376,660	8%	2,343,970	23%
Contributions	19,501,430	62%	4,711,035	46%
Public program revenue	1,434,428	5%	1,374,743	13%
Investment income (loss) net	4,013,478	13%	(1,930,770)	-19%
Other income	194,861	1%	69,684	1%
Gain on sale of assets	56,500	0%	-	0%
Total Support and Revenue	**$30,853,501**		**$10,218,442**	



EXPENDITURES	2019		2018	
Program services:				
Research	$ 4,172,506	36%	$ 3,842,835	36%
Technology	2,617,092	22%	2,731,196	25%
Public program	2,445,484	21%	1,935,954	18%
	9,235,082		8,509,985	
Support services:				
Management and general	1,292,400	11%	1,018,522	10%
Fundraising	1,183,757	10%	1,215,339	11%
	2,476,157		2,233,861	
Total Expenditures	**$11,711,239**		**$10,743,846**	
Gain on interest rate swap	-		-	
Change in net assets	$ 19,142,262		$ (525,404)	



The above Statement of Financial Activities reports the results of Lowell Observatory and the Foundation excluding the effect of depreciation expense. Depreciation is the assigning of a tangible asset's cost, such as buildings, furniture, fixtures, and equipment, over the years that the asset is likely to be used. Recording depreciation has no effect on the liquidity or cash flow of the Observatory. It reflects an estimate of using up the monetary value of long-lived assets. In the financial statements it reduces the carry basis of Property, Plant and Equipment and the Change in Net Assets.

It is customary for non-profits, such as Lowell Observatory, to look for capital contributions to provide for the addition or replacement of these long-lived assets instead of expending the funds out of operations. Therefore, the financial performance for not-for-profits is best appraised by analyzing operating results excluding the effects of depreciation. Depreciation expense recognized in the Observatory's records for 2019 and 2018 was $1,954,000 and $1,932,000.

Auditor's Opinion

Lowell Observatory has received an unqualified opinion from its auditors, Beach Fleishman, on the audit of its financial statements for the year ended December 31, 2019. Copies of the audited financial statements are available at lowell.edu/about/governance_and_financials/

LOWELL OBSERVATORY

125 YEARS | 1894 - 2019

ANNUAL REPORT

2019

Front Cover: The grand opening of the Giovale Open Deck Observatory | Credit: Danielle Adams
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