



ANNUAL REPORT

2020

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TRUSTEE'S UPDATE

By W. Lowell Putnam



For all of us, 2020 has been a year of challenge and response. Thanks to our supporters and the incredible and innovative efforts of the staff, Lowell Observatory can look back and view this past year as a successful one, if not quite what we had originally planned.

As you read through this you can see that our research efforts have continued unabated and the number of peer-reviewed publications is one indication of the respect the science community has for the work of our astronomers. Our outreach and education efforts were impacted, but the teams were able to find ways to keep communicating and engaging. We were able to keep our construction projects moving, albeit at a slower pace. Donor support (thanks to all of you!) has remained strong and our financial position has continued to improve.

The public interest in astronomy is at an all time high, and we look forward to a phased re-opening of visitors to Mars Hill in 2021. Meanwhile we hope you will be able to plan a visit to us at your earliest convenience, and know that we are working hard to keep Percival Lowell's vision and mission active and growing. ■

Thank you,

A handwritten signature in black ink, appearing to read "W. Lowell Putnam".

DIRECTOR'S UPDATE

By Jeffrey Hall



In early January 2020, a number of us set forth into the airways as we always do at that time of year, heading for the annual winter meeting of the American Astronomical Society. None of us imagined that just over two months hence, on Percival Lowell's birthday on March 13, we would shutter our outreach programs and discharge the staff from Mars Hill to work from isolated rooms at home.

But so events turned out, and one can do little but work as positively as possible with the situation one is given. Happily, communications systems have advanced to the point that bandwidth-intensive teleconferencing enabled us to keep our mission moving forward online, whether via scientific conferences and research collaboration, discussions about the content and exhibits for the Astronomy Discovery Center, or many new educational live streams for the public. And equally happily, scientists who in recent years have been studying the physiology of immunity via mRNA were able to deliver an answer to the pandemic in astonishingly short order.

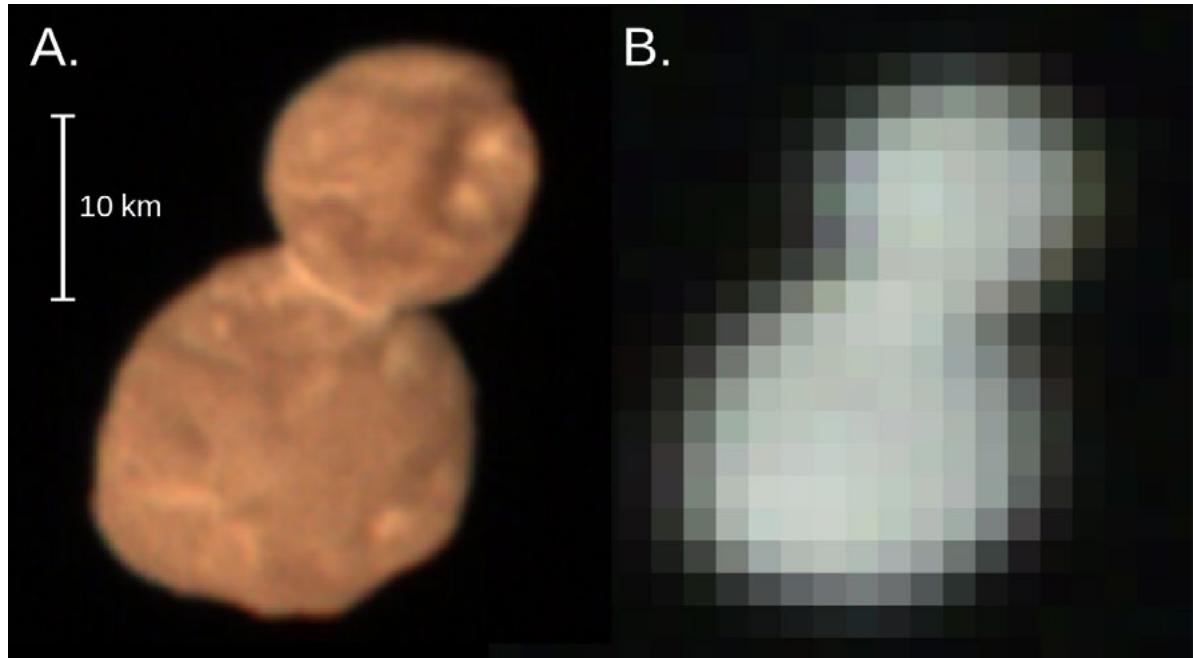
In my less-upbeat moments, I've been appalled at the medieval rejection of science that has made the COVID-19 pandemic worse and more protracted than it needs to be. But this has only increased my resolve to ensure Lowell Observatory elevates its mission to the highest level. That mission, paraphrased from our formal mission statement, is to communicate our science and discoveries, specifically about astronomy and planetary science, and generally about evidence-based thinking and the scientific

method. We communicate with equal dedication to professional and lay audiences, and it is vital that we – and all institutions of science – continue to do so. Hyperbole abounds these days, but it is hard to underestimate the need to restore critical and evidence-based thinking to our society and populace. My freshly grown-and-flown sons are beginning careers that will flourish if we can somehow do this; I have a dimmer view of the events that await them, and all who will succeed us, if we do not.

We can't solve all these problems from here on Mars Hill, but we'll continue to do our best to do our part. ■

A handwritten signature in blue ink that reads "Jeffrey Hall". The signature is fluid and cursive, with "Jeffrey" on top and "Hall" on the bottom, both starting with a capital letter.

ASTRONOMER / PLANETARY SCIENTIST HIGHLIGHTS



Arrokoth as seen by New Horizons at visible wavelengths (A.) and at infrared wavelengths (B.). The reddish visible wavelength color is due to the presence of complex organic macromolecular material called tholin. The infrared data indicates a relatively uniform composition across Arrokoth's surface. Methanol ice (CH_3OH) was the only compound detected.

Dr. Will Grundy

Dr. 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 2020. Grundy was an author on 18 peer-reviewed scientific articles and book chapters published during the year.

Grundy is a co-investigator on two NASA space missions:

1.) New Horizons explored the Pluto system in 2015 and, a billion miles beyond Pluto, the small Kuiper belt object (486958) Arrokoth in 2019. Grundy leads the surface composition science theme team for New Horizons.

2.) Lucy will be launched in 2021 to explore Jupiter's co-orbiting Trojan asteroids. Grundy is the instrument scientist for Lucy's infrared imaging spectrometer system which, despite the pandemic, was built during 2020.

During 2020, Grundy was involved in observational projects using ground- and space-based telescopes including Hubble, Keck, LDT, 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 investigates low temperature materials in the laboratory at Northern Arizona University, collaborating with Lowell's Dr. Jennifer Hanley, plus NAU faculty members and undergraduate and graduate students. Shaelyn Raposa joined the team in 2020 as a new graduate student.

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ASTRONOMER / PLANETARY SCIENTIST HIGHLIGHTS

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The complexity of low-temperature mixtures is emerging as a major theme in need of deeper investigation. These materials enable the spectacular geology seen on Pluto and other small, icy planets and moons across the outer solar system.

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 international scientific journal in planetary sciences. Grundy reviewed manuscripts during 2020 for many other scientific journals as well, including *Science*, *Monthly Notices of the Royal Astronomical Society*, *Philosophical Transactions of the Royal Society A, Astronomy & Astrophysics*, *American Chemical Society Earth & Space Chemistry*, *Planetary & Space Science*, *Earth & Planetary Science Letters*, *Accounts of Chemical Research*, and *Planetary Science Journal*. He reviewed proposals for NASA Research & Analysis funding programs and reviewed telescope time proposals for Gemini and Hubble. ■

ASTRONOMER HIGHLIGHTS

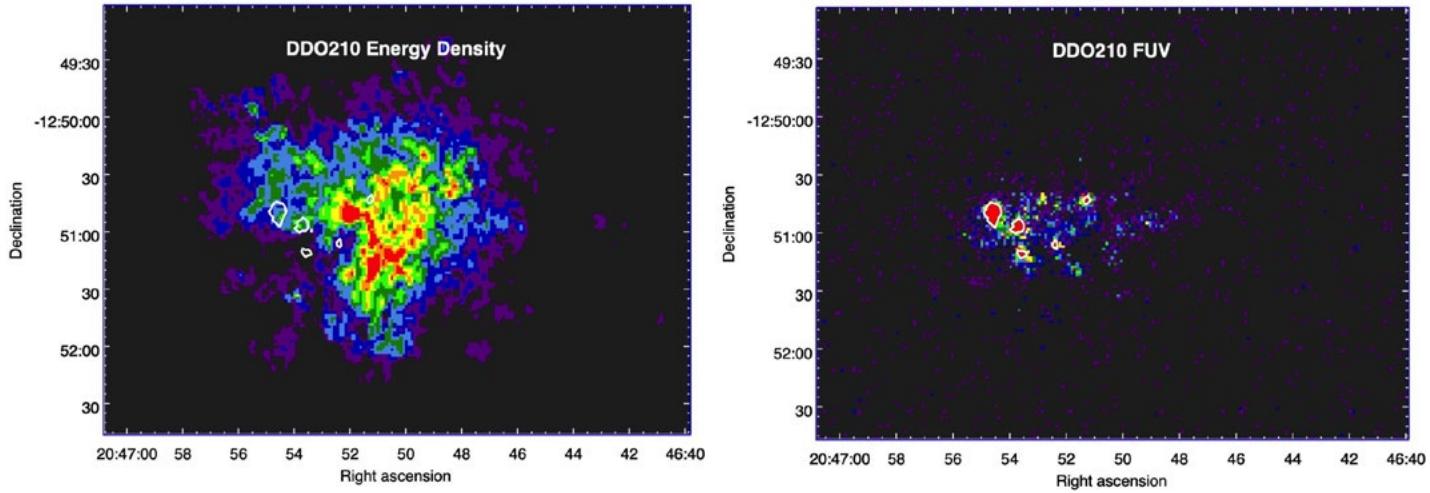


Dr. Jennifer Hanley

2020 was a year like no other. It started with two international conferences back-to-back in January. The first was in Ushuaia, Argentina (see image) for the *Seventh International Conference on Mars Polar Science and Exploration*. Dr. Hanley presented her research studying the properties of salts and water on Mars' surface. A reporter from Forbes who was attending the conference wrote up a story about her research on the extreme temperatures liquid water can exist at in the presence of salts at Mars' poles. From there, Hanley flew to Galveston, TX to give an invited, keynote talk at the *Challenging the Perceptions of the Requirements for Life on Earth and Other Worlds Gordon Research Conference*. The talk was entitled "Salts Across the Solar System: A Guide to Finding Life." Then, along with the Lunar and Planetary Science Conference being cancelled in late March 2020, everything changed.

The Astrophysical Materials Laboratory at Northern Arizona University was shut down, and did not reopen until September, with heavy modifications and safety measures in place. The Research Experience for Undergraduates was shifted to remote, forcing a pivot in research topics. Observing at the LDT was remote. Caregiving responsibilities increased. Through all the challenges, there were some bright notes. REU student Sanya Mittal analyzed orbital spectra of Gale Crater, Curiosity's landing site, and found interesting hydrated features. PhD student Anna Engle submitted her first, first-author paper on the methane-ethane system and its applications to Titan. Hanley was awarded a NASA Solar System Workings grant to continue her research on the lakes and seas of Titan. And most importantly, everyone survived, if a little worse for wear. ▀

ASTRONOMER HIGHLIGHTS



DDO 210 is an extreme example of the lack of alignment between the KED (left image) and the FUV (right image). In these images the color indicates the intensity with red being peaks in the quantity being imaged. The peaks in the FUV image are outlined by a white contour that is reproduced on the KED image. The peak regions of hot young stars are off to the left of the peak regions of kinetic energy in the gas in this galaxy.

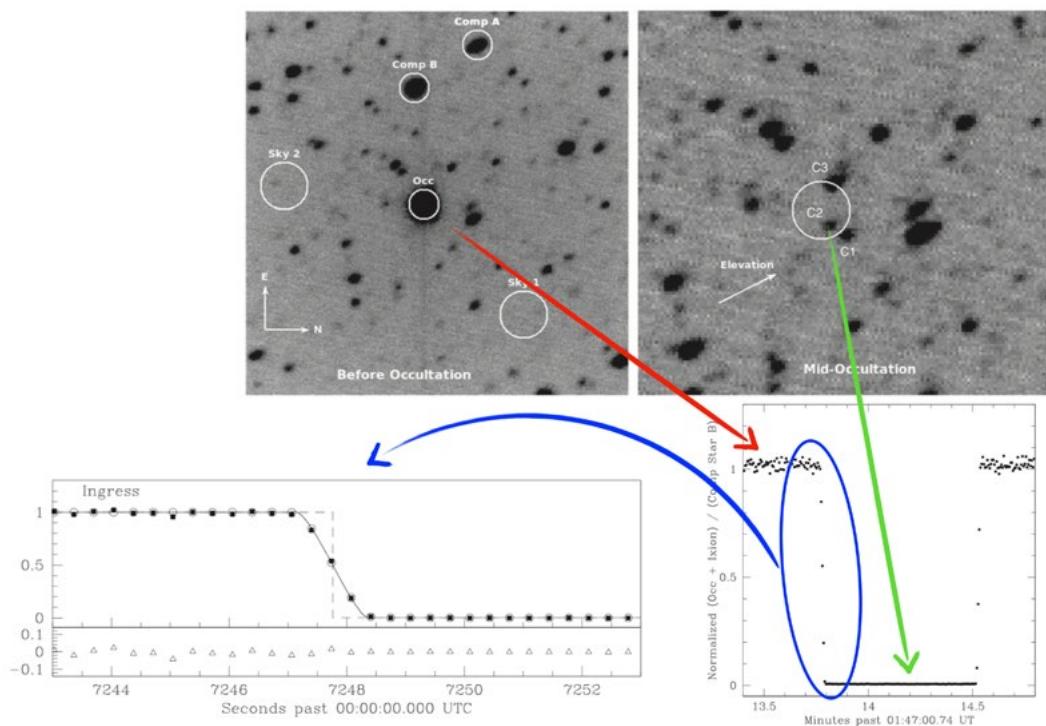
Dr. Deidre Hunter

The gas densities in tiny dwarf irregular (dIrr) galaxies are so low that the gas is stable against breaking up into clouds the way the gas does in giant spiral galaxies. It is these clouds that contract under the force of their own gravity and ultimately produce new stars. Dwarf irregular galaxies are forming stars, so how do they make the gas clouds that form stars?

Turbulence in the gas has the potential for creating clumps in the gas density that initiate cloud and then star formation. To study the connection between turbulence and star formation, Dr. Hunter and her collaborators, including post-undergraduate Haylee Archer who was paid by DON, looked for relationships between young stars traced by far-ultraviolet images and gas turbulence traced by images of the kinetic energy density (KED) in the LITTLE THINGS sample of nearby dwarf irregular galaxies. KED is just the energy in the turbulent plus thermal motions of the atomic hydrogen gas that pervades galaxies.

They performed 2-dimensional cross-correlations between FUV and KED images to see how well the peaks in the star formation aligned with peaks in the KED. They also measured cross-correlations in annuli to produce a measure of the correlations as a function of radius, and plotted excess KED against star formation on a pixel-by-pixel basis in each galaxy. They found that the star formation and KED are poorly correlated. This implies that turbulence is not an important way to make star-forming clouds in dIrrs. This also limits the ability of star formation itself to be a contributor to large-scale turbulence in the gas, contrary to expectations. ■

ASTRONOMER HIGHLIGHTS



The upper panels show the occultation field of view as imaged by the LDT guide camera. The left side shows the field before the star in the center was occulted by Ixion. The right side shows a zoomed in view of the area during the occultation; the star normally would be visible inside the white circle. Several faint stars (C1, C2, C3) that were otherwise lost in the glare of the brighter star are clearly visible. The elongation seen in the stellar images is due to atmospheric refraction, which was quite pronounced because of the low elevation of the field during the event (which meant that the line of sight passed through substantially more atmosphere than if the field

had been overhead). The amount of light from the star measured by the LDT guide camera versus time is shown by the light curve in the lower right. The red arrow indicates the portion of the light curve before the occultation and the green arrow the total amount of light measured during the occultation. The lower left panel gives a magnified view of the light curve showing how the star faded as Ixion passed in front of it. The relatively slow fading of the star was a direct indication that projected size of the star at Ixion was large enough to be measured. (From Levine, S., et al. 2021, AJ, 161, 210, "Occultation of a Large Star by the Large Plutino (28978) Ixion on 2020 October 13 UTC").

Dr. Stephen Levine

Dr. 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.

Levine maintains an active interest in stellar occultation studies of outer solar system objects. During 2020, Levine and Lowell staffers Amanda Bosh and Michael Collins successfully observed occultations of the trans-Neptunian Objects (50000) Quaoar and (28978) Ixion. For the latter, they were able to measure the diameter of Ixion (roughly 710 km), determine that it had no atmosphere, and measure the diameter of the star that it occulted. The star was a red giant 130 times the diameter of our Sun.

Levine supervised the bachelor's thesis of J. Lertprasertpong (MIT Physics department). He investigated how well JASMINE (Japan Astrometry Satellite Mission for INfrared Exploration) will be able to determine the kinematic structure of the central bulge region of our Milky Way galaxy. This was the outgrowth of a project started in January 2020 as part of the MIT Astronomy Field Camp.

Levine is working with Lowell librarian/archivist Lauren Amundson on a project to digitize the Lowell archive of astronomical photographic images and spectra. The long-term goal will be to preserve these data and make them available to the broader community over the internet.

During 2020, Levine continued to serve as the Lowell Discovery Telescope Scientist, working with the LDT observing, instrumentation, operations and engineering communities to get the best out of the facility. ■

ASTRONOMER HIGHLIGHTS



LOST installed on the roof of the LDT auxiliary building.

Dr. Joe Llama

Dr. Llama works on detecting and characterizing exoplanets using high-resolution spectroscopy. In particular, he is interested in how the variability of the host star that arises from dark spots, bright flares, and coronal mass ejections impacts our ability to detect the smallest of exoplanets.

Breaking the trend of astronomers having to stay up all night observing with the LDT, in 2020, Llama oversaw the installation of the Lowell Observatory Solar Telescope (LOST). This 0.007-meter telescope begins observing at daybreak, sending sunlight through a fiber into the EXtreme PREcision Spectrograph (EXPRES), an instrument capable of searching for Earth-sized exoplanets. EXPRES, built by our partner Yale University, is designed to search for Earth-sized exoplanets orbiting within the habitable zone of our nearest stellar neighbors.

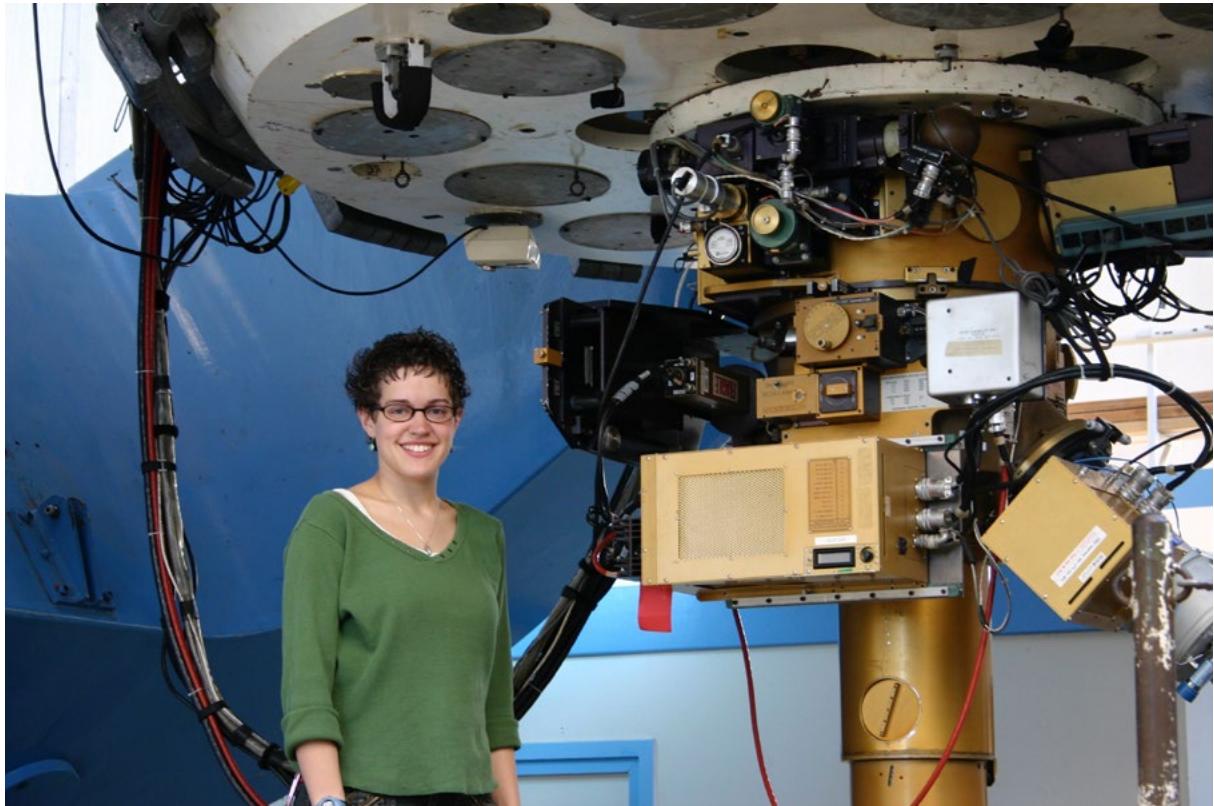
Llama is particularly interested in one unsolved hurdle that currently limits our ability to detect exoplanets like Earth. Variability arising from magnetic activity on the star's surface can completely drown the signal from an orbiting planet. This variability makes it incredibly challenging to detect Earth-sized planets. Without knowledge of the stellar surface, it is difficult to determine if the signal is coming from a planet or the star itself.

The Sun is the only star astronomers can image at high resolution and all wavelengths. By feeding sunlight into EXPRES, LOST observes the Sun just like LDT observes other stars at night. By combining these observations with data from spacecraft that are imaging the Sun's surface in unprecedented detail, we will revolutionize our ability to characterize the jitter induced from stellar activity.

During the summer of 2020 and overseen by Lowell's talented and dedicated technical team, LOST was installed in its permanent location on the rooftop of the auxiliary building at the LDT site (see images below). Since the installation of LOST, we have obtained almost 10,000 observations of the Sun over six months. This data will be one of the most precise and extensive datasets of sun-as-a-star observations ever obtained.

Adding LOST to Lowell's telescope suite means that science observations are happening 24 hours a day at Lowell Observatory. Stay tuned next year for updates on Lowell's most miniature telescope and how it is helping us tease out the tiny signals from Earth-sized exoplanets! ▀

ASTRONOMER HIGHLIGHTS



Emily Levesque at the Kitt Peak 2.1-meter telescope in 2004.

Dr. Phil Massey

Although it's really hard to think back to it, one of the most interesting things that was happening astronomically in early 2020 was the fact that Betelgeuse was getting fainter and fainter. Betelgeuse is, of course, one of the brightest stars in the sky. It's visible from both hemispheres, and is possibly the best known star to the general public, making up one of Orion's shoulders. The "Great Dimming," as it has come to be called, started in December of 2019, and continued until mid-February.

Now, like all red supergiant stars, Betelgeuse is always a bit variable in terms of its brightness, but what was happening in early 2020 was unprecedented: it had faded by a factor 4 in brightness. You could see this visually: it no longer rivaled Rigel down at Orion's foot, but rather was as dim as Bellatrix, the star that made up the other shoulder of Orion. The popular press had picked up on the fact that stars like Betelgeuse are nearing the end of their lives, and speculation was rampant that Betelgeuse was going to undergo a supernova explosion, which would certainly have been cool. However, among astronomers there were two schools of thought about what was happening. Stars like Betelgeuse have giant "star spots," regions where the surface is somewhat cooler than the surrounding material. Maybe one of these giant convection cells had formed and was reducing a lot of the light. The other possibility was dust.

This was all very intriguing to Dr. Massey. Sixteen years ago, he and his then summer student Emily Levesque and his colleague in Chile, Knut Olsen, had set out to measure the temperatures of red supergiants using spectrographs at Kitt Peak National Observatory and Cerro Tololo Inter-American Observatories. Among the other stars they had measured was Betelgeuse. And a few years after that,

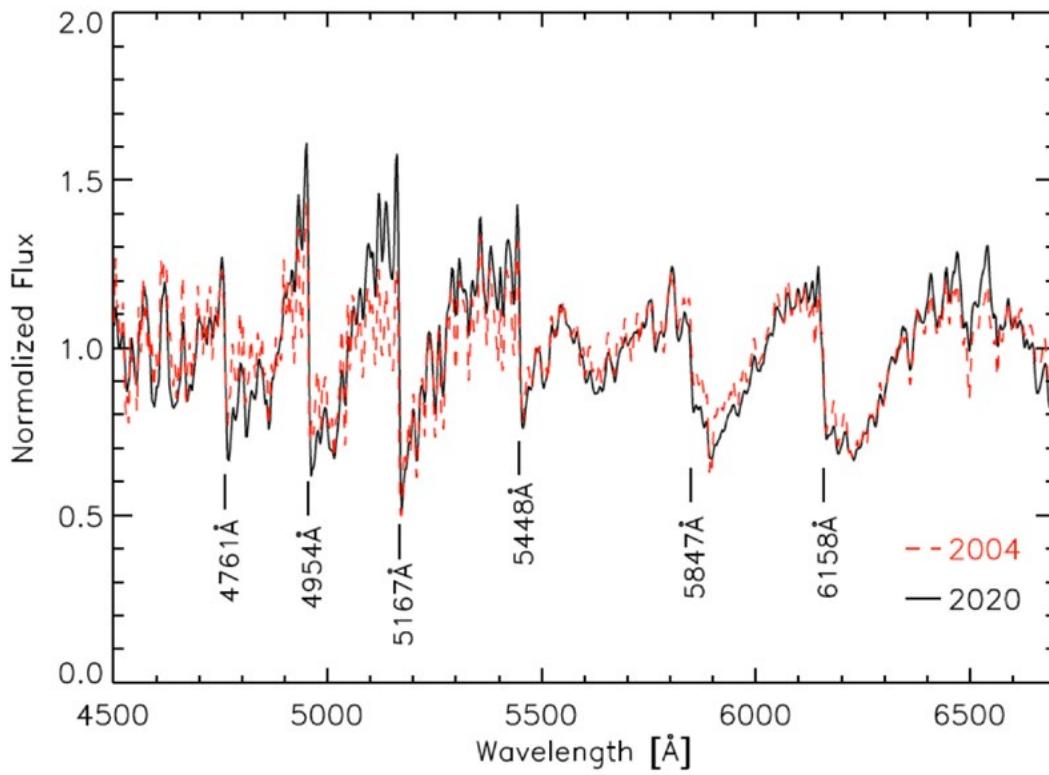
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the same team had established that red supergiants were indeed "smokey," that their stellar winds created dust. Levesque, now a professor at the University of Washington, and Massey conferred and decided they should repeat the Betelgeuse measurement using the same technique on the LDT. (The DeVeny spectrograph is a close relative of the spectrograph they had originally used.) Their reasoning was thus: if Betelgeuse had faded because there was a big star spot, they should find a cooler temperature than they had sixteen years ago. If instead the Great Dimming was due to dust, the temperature should be about the same. Fortunately, Massey already had time assigned on the LDT for another project using the DeVeny, and on the night of February 14, 2020, he was able to get a new spectrum of the star. Even though Betelgeuse had faded, it was still ridiculously bright for a 4.3-meter telescope, and it required some careful work to observe it. But by the time he wrapped up his other project at midnight he had reduced the data, emailed it to Levesque, and had gotten the answer back from her: it was the same temperature as what they had measured previously! They wrote the paper and it was accepted the next week in the *Astrophysical Journal Letters*.

As it happened, that night Betelgeuse had been at its faintest, and during the next month it continued to get brighter, finally reaching its normal brilliance in mid-April. But, by then we all had plenty of other things on our minds. ■



The spectrum of Betelgeuse on February 14, 2020 is compared to that obtained in 2004. The strong spectral features are due to titanium oxide. Red supergiants are so cool that their outer layers can actually have molecules.

ASTRONOMER HIGHLIGHTS



Six-camera LO-CAMS array (sans dome) located on the roof of the Mars Hill instrument shop.

Dr. Nicholas Moskovitz

In 2020 Dr. Moskovitz carried out a number of projects related to minor planets in the solar system. He performed numerous observations to characterize the physical properties of near-Earth asteroids. This included obtaining key data in support of the upcoming Double Asteroid Redirect Test (DART) spacecraft mission — NASA's first-ever planetary defense experiment that will investigate how to deflect a near-Earth asteroid in its orbit. He also led a small team at Lowell in further developing the ASTORB database — a compilation of all known asteroids in the solar system — and its associated website at asteroid.lowell.edu. 2020 was a noteworthy year for ASTORB as the minor planet catalog eclipsed one million known objects. But the biggest focus for Moskovitz in 2020 was a project referred to as LO-CAMS, the Lowell Observatory Cameras for All-Sky Meteor Surveillance.

LO-CAMS is a network of cameras that autonomously record video to detect and characterize meteors. The basic configuration involves multiple cameras co-located in a single enclosure to provide a fly's-eye view of the night sky. These sets of cameras, or stations, are deployed at locations ~50-100 miles apart so that the trajectory of a meteor detected by more than one station can be triangulated to determine its three dimensional vector through the atmosphere. This trajectory can be propagated back into space to infer where in the solar system the meteor originated, and in the event of large meteoroids, propagated down to the ground to enable a search for freshly fallen meteorites.

In 2020, the LO-CAMS project was awarded a five-year NSF CAREER grant that kick-started a wide range of activities related to meteor science and public outreach.

Thanks to various contributions from Lowell staff, including major effort from research assistant Megan Gialluca, two new LO-CAMS stations (Mars Hill and LDT) were deployed in 2020 and several more were prepared for installation in early 2021. These stations leveraged heritage from the Global Meteor Network project, but represent a unique approach that delivers a highly modular and easily deployable system. In the coming years, more than a dozen new stations are expected to be installed at locations throughout the southwest, including on the roofs of high schools, museums, and community colleges.

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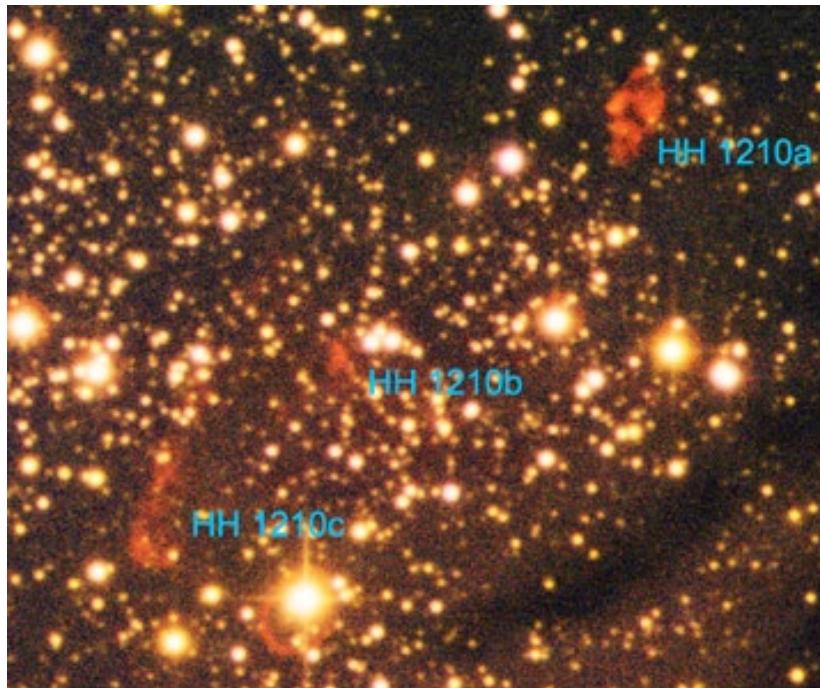
Early performance of these new systems proved to be impressive: the diminutive 1/3-inch sensors see down to a stellar limiting magnitude of 6.5 and the network as a whole started yielding several hundred meteor trajectories every night. On nights of major meteor showers this yield increased by an order of magnitude.

Moskovitz and his collaborators are looking forward to continued expansion of this network and the installation of two interactive, touchscreen exhibits (developed in collaboration with the Advanced Media Lab at Northern Arizona University), one at Meteor Crater and one in the Steele Visitor Center at Lowell. These exhibits will receive daily updates from the LO-CAMS cameras so that recent meteors will be viewable to visitors just hours after they have been recorded. Stay tuned in 2021 for the premier of these exhibits. ▀



Stack of all 490 moving objects detected by one LO-CAMS camera during the peak of the Geminid Meteor Shower. Residual background stars and flashing satellites are seen across the image. The Geminid radiant is clearly located just off frame to the right as the majority of meteors point back to that position.

ASTRONOMER HIGHLIGHTS



Dr. Lisa Prato

Dr. Lisa Prato and Team DEFT (Disks and Exoplanets Flagstaff Team) weathered the uniquely challenging 2020 with numerous significant scientific advances. The year began on a high note as Team members Prato and Cody Huls attended the Honolulu American Astronomical Society (AAS) meeting to present research on young binary star systems. Prato also collaborated with Lowell Historian Kevin Schindler on a AAS e-poster and associated presentation about Vera Rubin's observational work at Lowell Observatory that led to the discovery of dark matter. Following the AAS meeting, in late January Team DEFT hosted colleagues and collaborators from Rice University for a mini-workshop on our joint young star programs.

Team DEFT students and research interns worked on numerous projects and manuscripts, most of which are coming to fruition or have already been published in 2021. Graduate student Lauren Biddle submitted a paper demonstrating that small changes in the brightness of the young planet-hosting star CI Tau occur on the same timescales as much larger brightness variations, confirming the role of the short period planet orbiting the star driving streams of circumstellar disk material onto the star's surface. Graduate student Shih-Yun Tang collaborated with Rice University graduate student Asa Stahl on software to extract high-precision radial velocities to identify planets orbiting young stars using the IGRINS data accumulated at the LDT between 2016 and 2019. Undergraduate students Sean Graham and Cody Huls worked on analysis of young binary stars to understand better their high degrees of variability and to determine their fundamental properties; both students graduated from NAU in December. Huls made huge progress on creating a multi-dimensional grid of synthetic spectra for the characterization of young stars; he also completed solutions to the orbits for two young star binary systems, AS 205B and V562 Ori, and is preparing this work for publication. Lowell Educator Hannah Zigo joined the team a year ago and has been working part time on the reduction and analysis of standard star spectra for a reference publication. Team interns and students showed terrific discipline, grit, and good-natured agreeability over the many long months of zoom Team and individual meetings.

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Prato worked with colleagues on several publications covering a broad topical range, from the analysis of CI Tau's magnetic field, to a study of the enigmatic young triple star T Tauri, to jet outflows from young stars in the Circinus dark clouds (see figure), to the characterization of a high-mass X-ray binary. Prato was fortunate to obtain observing time at multiple facilities, from the 10-meter Keck to Lowell's own 31-inch, and several facilities in between such as the McDonald Observatory 2.7-meter, the 3-meter IRTF, and the 4-meter Mayall Telescope in Chile (the first program back on after the pandemic closure). Unfortunately, as a result of the pandemic, Prato's observations on the Steward 90-inch and with the ALMA millimeter array were canceled or postponed. Prato also collaborated with Deputy Director for Technology Dr. Kyler Kuehn and the expert Lowell technical team on testing the CSHELL spectrograph and planning its future deployment. Prato continued to receive grant support from NASA and the NSF for these and other programs, to serve on numerous NASA and NSF committees and reviews, to co-chair the AAS Publications Committee, and to participate in the AAS Strategic Planning. The 2020 highlight? To see Team DEFT students cope masterfully with the stresses of the pandemic, to excel in their research, and to evolve into strong independent scientists. ▀

ASTRONOMER HIGHLIGHTS



Comet NEOWISE as seen from the Giovale Open Deck Observatory in mid-July of 2020. As always, the comet's tail points away from the Sun, and is tens of millions of kilometers in length. The head or coma of NEOWISE is larger than the planet Jupiter, while all of the gas and dust forming the head and tail was released from the nucleus that is less than 5 km in size.

Dr. David Schleicher

Several comets were the focus of observations in 2020 by Dr. David Schleicher and former Lowell post-doc Dr. Matthew Knight (U. S. Naval Academy). They used two techniques, CCD imaging to study gas and dust jet morphology of each comet's coma, and classical photoelectric photometry to determine the rate of outgassing and the chemical composition for each comet. What was expected to be the brightest comet of 2020, ATLAS (C/2019 Y4) suffered a major fragmentation event in April. Though characterized in the press as having disappeared, they obtained additional photometry and imaging of the remnants through mid-May; the images showed that fragmentation was continuing to take place with the location and brightness of features changing from night-to-night. A gas coma was observed nightly, suggesting that at least one fragment remained active, though significant gas was also being released by material in the debris tail.

Discovered in March, it was quickly determined that Comet NEOWISE (C/2020 F3) might become bright by mid-summer. Its orbit is very elongated, going from 10 times the distance of Pluto to inside the orbit of Mercury, with its last appearance 4800 years ago. Indeed, as it escaped the Sun's glare in July, it became the brightest comet visible from the northern hemisphere in over a decade, and conveniently for everyone it was an evening object – dominated by its extensive dust tail, though close to the horizon. Photometry confirmed its composition was similar to the majority of comets, and imaging focused on studying the detailed structure of the inner coma. The left-hand panel of the figure below shows an enhanced dust image, revealing the inner-most portion of the dust tail. In the right-hand panel, several arc-like features are visible in the enhanced cyanogen gas image. In the limited time NEOWISE was available each night, these features moved outward from the center with a counter-clockwise spiral rotation, somewhat changing shape from night-to-night, and indicating the nucleus is rotating every seven-to-eight hours.

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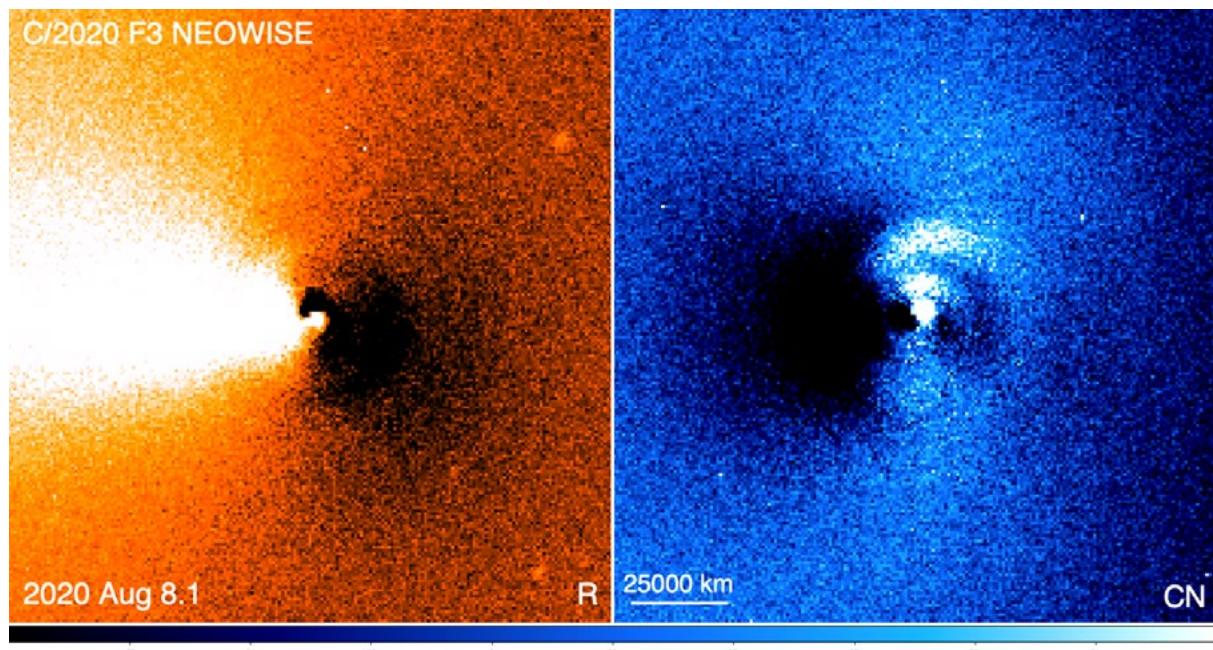
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The final significant comet, 88P/Howell, is a short orbital period object observed beginning in May and continuing through the end of 2020. Schleicher determined that its water production varied far more steeply with distance from the Sun than is usual, suggesting a dominant, isolated source region rapidly “moved” from winter to summer as the sub-solar latitude drastically changed, and back to winter following its closest approach. Its measured gas jet morphology will be modeled in the future to test this hypothesis.

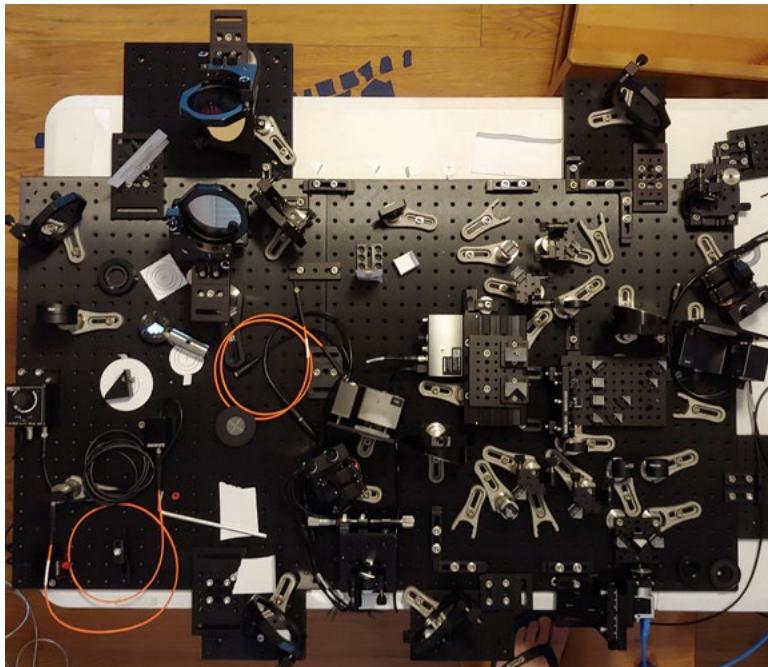
Away from the telescope, the primary efforts for Schleicher and Knight were analyses of the extensive 46P/Wirtanen data obtained between 2018 September and 2019 March, working with another former Lowell post-doc, Dr. Tony Farnham (University of Maryland). Imaging revealed two gas jets whose shapes varied greatly during the apparition due to the rapidly changing viewing geometry, especially near closest approach in December 2018. Motion during each night and from night-to-night yielded the first unambiguous determination of its rotation period of ~ 9.0 hr. The resulting pair of publications contain complete results from the imaging studies and associated jet modeling, including changes in the rotation period due to torques from the jets, and a nucleus model with a precise pole orientation and jet source locations on the surface. Derived gas and dust production rates were another major component.

Schleicher and Research Associate Allison Bair added the most recent batch of five years of comet photometry obtained from the John S. Hall 42-inch telescope to their database, now encompassing over 220 objects observed since 1976 – the largest in the world. A taxonomic classification of the chemical composition of these comets reveals six groupings, several of which are clearly tied to a comet’s origin. A variety of analyses are continuing. ■



A dust (left) and cyanogen gas (right) pair of images of Comet NEOWISE obtained on August 8th with the Lowell 42-inch John S. Hall telescope located on Anderson Mesa, about 15 miles southeast of Flagstaff. Each image has been processed to remove the bulk brightness radial fall-off from the center, and then had false colors applied, revealing structure in the inner coma. By this date the comet had moved such that the Sun was towards the west (in the direction of the arrow on the dust image) and the tail dominates the frame towards the left. The processed cyanogen image exhibits several arc or shell-like structures, created by two or more source regions on the surface of the nucleus releasing gas. These jets form spirals due to the rotation of the nucleus. Images obtained by Brian Skiff (Lowell Observatory) and processed by Matthew Knight (U. S. Naval Academy).

ASTRONOMER HIGHLIGHTS



Tabletop lab prototype of an optical beam combiner for the Optimast project, a joint Lowell / Made In Space.

Dr. Gerard van Belle

The year of 2020 was a very busy and productive one for Dr. van Belle and his team, in spite of the unusual nature of the year.

The Quad-camera Wavefront-sensing Six-channel Speckle Interferometer (QWSSI) instrument completed construction in the spring, and saw first light on the LDT on July 30, 2020. It has since entered regular use at the LDT, and replaces the previous speckle camera, the Differential Speckle Survey Instrument (DSSI) from Lowell adjunct Dr. Elliott Horch (Southern Connecticut State Univ.) Van Belle was assisted in QWSSI efforts with his speckle team, including graduate students in residence at Lowell, Catherine Clark (Northern Ariz. Univ.) and Zachary Hartman (Georgia State Univ.), as well as Horch and Lowell adjunct Dr. Kaspar von Braun. A preliminary instrument paper was presented at the 2020 virtual SPIE Telescopes & Instrumentation meeting by Clark. QWSSI is the only instrument currently able to obtain diffraction-limited images from the LDT, with a resolution limit of 30 millarcseconds.

Robotic operations commenced at the 20-inch Titan Monitor (TiMo) telescope on June 10, 2020, and TiMo has been operating every clear night since that time (Figure TiMo). TiMo has been generously supported by a grant from the Mount Cuba Foundation, as well as Bob Ayres. TiMo is currently outfitted with a CCD imager and 20-position filter wheel, allowing it to make absolute, precise measurements of object brightnesses at discrete wavelengths across the visible. These brightnesses can then be used in unison to establish the overall flux emitted by these objects - such measures of 'spectral energy distribution' can be complemented with angular size measurements from NPOI to directly measure temperatures of stars.

Van Belle has also been working with industry partner Redwire / Made In Space on development of a space interferometer flight concept, 'Optimast'. This effort transitioned from general design studies to a lab experiment in 2020. The original intent was to assemble a prototype optical payload for the spacecraft concept on Mars Hill, but COVID-19 derailed those plans. Not to be thwarted, van Belle assembled the prototype at home on a plastic picnic table in his kids' playroom (Figure opEDU), and first fringes were detected with the Optimast Optical Engineering Development Unit (opEDU) on September 18, 2020. Not a instrument shop cleanroom by far, but the circumstances actually proved out the ability of the opEDU to deal with vibrationally 'dirty' environment as expected on board a flight mission. The opEDU has since shipped to Redwire labs in Jacksonville, FL, for integration with a representative spacecraft bus. A paper describing the Optimast mission concept was presented by van

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ASTRONOMER HIGHLIGHTS

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Belle at the December SPIE meeting.

As a general backdrop to all of these projects, work has also progressed at the Navy Precision Optical Interferometer (NPOI). In particular, development has continued on the 1-meter upgrade project, 'PALANTIR', for the facility. Two prototype adaptive optics systems have been built and are being lab tested, and efforts continue to route the light into the NPOI interferometric beam lines. In advance of interferometric use, the robo-operations system from TiMo (above) were propagated (in part due to a generous grant from the Slipher Society for the ACP robot software) to the first 1-meter in December 2020, and its currently available on-sky time will be made available to Lowell faculty in 2021. Thanks to the tireless advocacy efforts of Lowell Trustee W. Lowell Putnam, the facility has been awarded a congressional \$5M 'Plus-Up' grant for repairs, rejuvenation, redirecting from the first two decades of its life towards readying for the next two decades of cutting-edge research. In support of the Plus-Up work, David Noble has been hired as project manager for advance planning, and engineer and technician hires will proceed in 2021 to rapidly spool this project up.

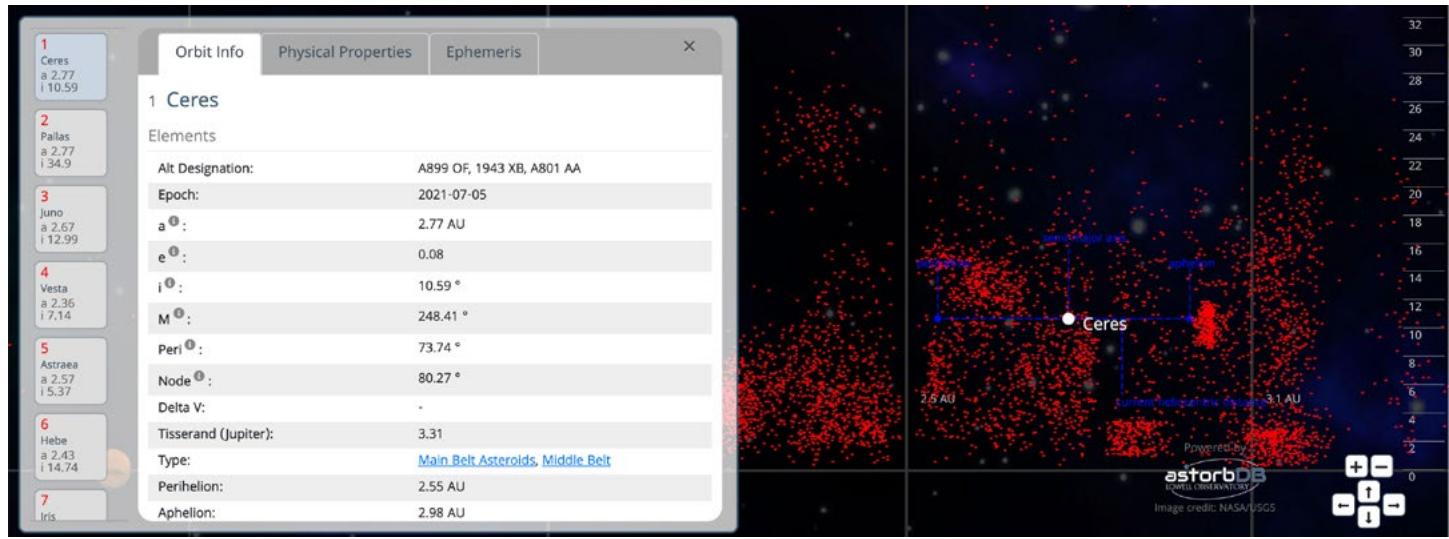
Together with von Braun, in 2020 van Belle finished a research project using Hubble Space Telescope's Fine Guidance Sensors (HST-FGS), directly measuring the parallactic distance to 5 eclipsing binary M-dwarf systems. HST-FGS has seen extensive use previously by Lowell emeritus astronomer Dr. Otto Franz.

Finally, in his copious spare time, van Belle delighted in joining various virtual outreach activities, including Cosmic Coffee and Meet an Astronomer. Along with the rest of the Lowell staff, he's been happy to reach out that way, but is looking forward to rejoining in-person activities soon! ▀



TiMo: The 20-inch Titan Monitor telescope on Mars Hill.

ASTRONOMER HIGHLIGHTS



An example of asteroid orbit info from the ASTORB website.

Dr. Larry Wasserman

Dr. Wasserman, who is partially retired and working at about 1/3 full time, had a relatively quiet year. He continued observing Kuiper belt objects (KBOs) with the Lowell Discovery Telescope in order to keep the errors in their ephemeris positions small for as many objects as possible. The problem here is that most KBOs have relatively short observational arcs (five, ten to 20 years) while their full orbital periods are in the many hundreds of years (400-600). As a result, we only know a short piece of their orbit and thus when we extrapolate their positions into the future, these positions can have substantial errors, making it difficult to find these very faint objects in telescope images. He also continued updating orbits for the Lowell asteroid database. These updated orbits appear in the Lowell ASTORB website at asteroid.lowell.edu. ■

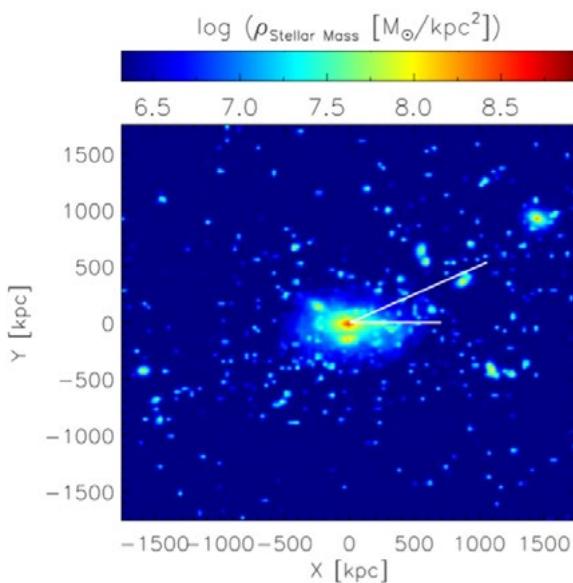
ASTRONOMER HIGHLIGHTS

Dr. Michael West

Dr. Michael West divided his time between research, public outreach and leadership duties as Deputy Director for Science. His research activities included:

Galaxy alignments

One of the most striking features of the distribution of matter in the universe is its filamentary appearance, with long, luminous strands of galaxies woven together into a vast cosmic web. Michael co-authored a paper led by Roberto De Propris (University of Turku, Finland) and an international team of collaborators which suggests that the biggest galaxies in the universe formed from mergers within filaments, aligning their orientations with the cosmic web. A second paper, led by Cinthia Ragone-Figueroa (Universidad Nacional de Córdoba, Argentina), used state-of-the-art hydrodynamical computer simulations to study this alignment effect and predict its evolution with time.



Left: A computer simulation of the birth of a cluster of galaxies. The long line shows the orientation of the cluster, while the short line shows the orientation of its largest member galaxy. From Ragone-Figueroa et al. (2020).

Beckoning black holes

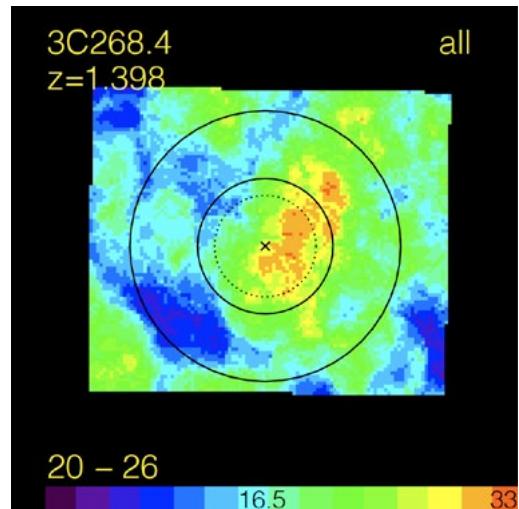
Gravity shepherds galaxies together into communities of tens, hundreds, and even thousands of members. But when did the first of these galaxy clusters form? Michael is part of an international team searching for clusters of galaxies in the early universe. The project, led by Ph.D. student Zohreh Ghaffari (Ruhr-Universität Bochum, Germany), uses quasars and radio galaxies – rare objects powered by supermassive black holes – as markers of faraway galaxy clusters.

Using data collected by the Hubble Space

Telescope, the team found that most of quasars and radio galaxies inhabit regions rich in galaxies. A paper was recently submitted and is currently being reviewed. Work continues using observations made with the Lowell Discovery Telescope.

Right: A map showing the distribution of galaxies around the quasar 3C 268.4 (indicated by the 'x'). Red indicates regions of high galaxy density, while blue shows underdense regions. 3C 268.4 resides in the outskirts of a galaxy cluster seen nearly 10 billion years in the past. From Ghaffari et al. (2021).

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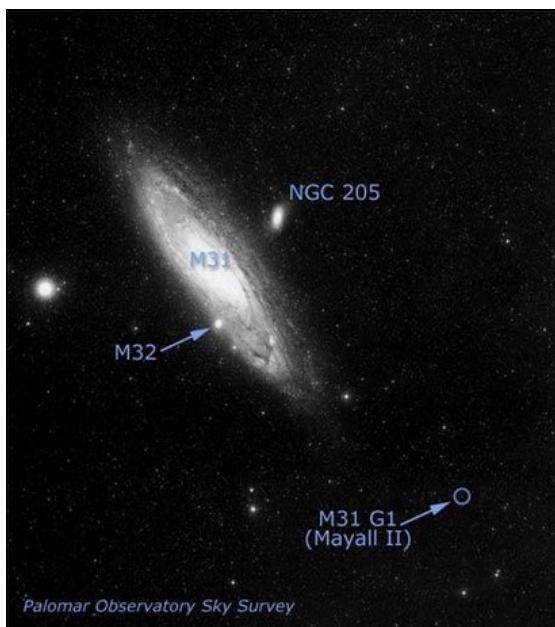


ASTRONOMER HIGHLIGHTS

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The strange case of G1

Things aren't always as they appear. G1 is the largest globular cluster in the Andromeda Galaxy – or is it? Using observations made with the Keck II telescope in Hawaii, Michael and a team of collaborators led by Michael Gregg (University of California, Davis) discovered stars being plucked from G1. This suggests that G1 was once larger and is most likely the surviving core of a small galaxy that has been slowly cannibalized over time by Andromeda's gravitational pull. A paper was recently published in MNRAS.



Left: The Andromeda Galaxy and the location of G1.

Right: Hubble Space Telescope image of G1. Published in Gregg, West, Lemaux, and Küpper (2021).

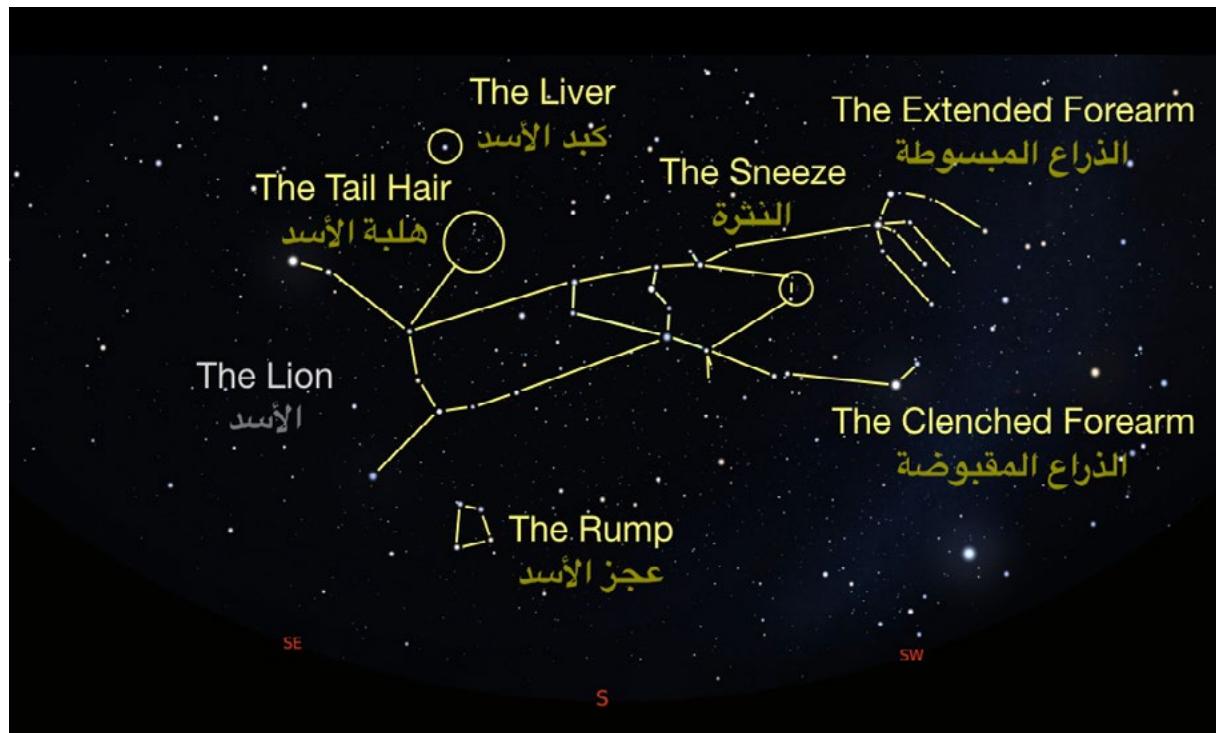
On the public outreach front:

West was selected as a U.S. Fulbright scholar for 2020-2021, however this was deferred for a year because of the ongoing pandemic. He plans to spend two months in Finland in late 2021 and again in 2022 to teach a course on Communicating Science with the Public and also to research Finnish methods of science communication. The knowledge gained will benefit Lowell's science and outreach missions.

West continued to serve on the Content Working Group that is developing exhibits for Lowell's new Astronomy Discovery Center. Additionally, he researched and wrote all the biographies for the ADC's Diverse Universe Wall, which will profile 70 amazing astronomers from around the world and their inspiring stories. He also continued to write his regular columns for the observatory's monthly *What's Up at Lowell* newsletter and the quarterly *Lowell Observer*, as well as his popular *AstroAlerts*, which go out to more than 3,500 subscribers.

West was scheduled to step down as Deputy Director for Science in August 2020, however he continued for an additional year to help the observatory through the current pandemic. A new DDS will take over in late 2021. ■

RESEARCHER HIGHLIGHTS



Pictured here is the indigenous Arabian constellation of al-asad, The Lion. It was an enormous constellation that stretched across 3/4 of the night sky, from modern Gemini and Canis Minor in the west through Cancer, Leo, and Coma Berenices to Bootes and Virgo in the east, a staggering 135 angular degrees of the night sky.

By Dr. Danielle Adams
Deputy Director for
Marketing &
Communications

Besides serving as Lowell Observatory's Deputy Director for Marketing and Communications, Dr. Danielle Adams is a cultural astronomer whose focus is the development of indigenous astronomy in Arabia before the influence of Greek astronomy. Her research addresses the origins of many of the Arabic-derived star names that astronomers use today, and so she serves on the Working Group for Star Names (WGSN) of the International Astronomical Union (IAU).

Adams began 2020 at the winter meeting for the American Astronomical Society (AAS 235), where, in addition to promoting Lowell Observatory at its booth, she gave an iPoster talk about integrating cultural astronomy that goes beyond traditional Greek mythology into public astronomy outreach programs. She used some examples from Arabian astronomy to tell cultural stories that interface with modern concepts in astronomy like precession of the equinoxes and proper motion.

Throughout the year, Adams presented her research in several live streams for the general public. In April, she spoke about Arabian traditions surrounding the Pleiades (known in Arabia as ath-Thurayyā, an Arabic proper name having to do with abundance and possibly moisture) during a live stream on the April 3 conjunction of Venus with Pleiades. Adams also presented virtual tours of Arabian skies for the Grand Canyon Star Party, the Amateur Observers' Society of New York, Dr. Amanda Bosh's introductory astronomy class at MIT, and a third-grade class at FUSD as part of the Flagstaff Festival of Science.

On June 9, Adams presented an overview of her research for the observatory's virtual "Meet an Astronomer" series on YouTube (<https://youtu.be/wpKz80cy9iE>). During the program, one of the viewers posted a tweet that exemplified a benefit of researching indigenous Arabian astronomy: "[Danielle Adams] is quoting Imrul Qais in Arabic while speaking about Arabian astronomy and my mind is blown. Literally, it's like she's helping us see the world through the eyes of Muslim and Arab stargazers. Thanks for this @LowellObs!"

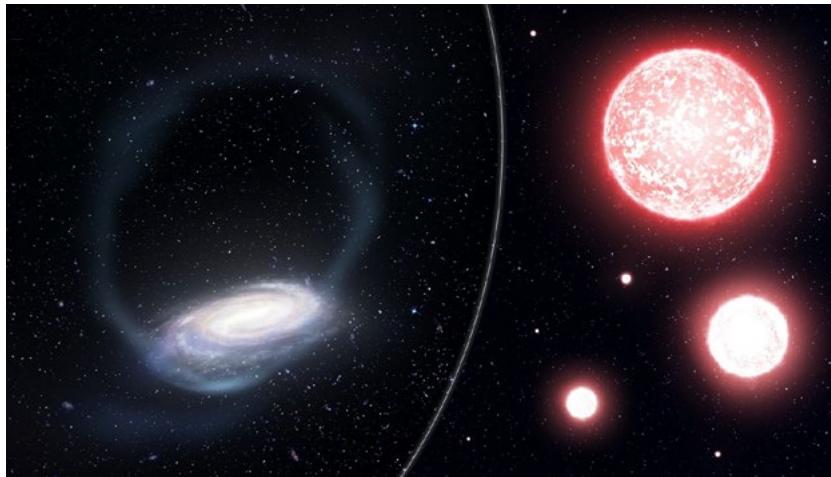
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RESEARCHER HIGHLIGHTS

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In November 2020, Adams published her first invited peer-reviewed book chapter, "Early Islamic Encounters with the Rains Stars of pre-Islamic Arabian Astronomy," which was published in edited volume, *Intersections of Religion and Astronomy* (Routledge). In this publication, she surveyed the encounter between early Muslims and the cultural milieu of pre-Islamic Arabian astronomy, in particular the agency-laden Arabian complex of the rain stars (*al-anwā'*). The ascription of divine agency to the rain stars for bringing the seasonal rains drew the condemnation of the Qur'an and the special ire of Muhammad, and so the system of rain stars was redefined by Islamic scholars as an Islamic lunar zodiac of 28 lunar stations (*manāzil al-qamar*) that were devoid of divine agency. This Islamic repositioning of the pre-Islamic rain stars exemplifies the notion that astronomy can shape—and be shaped by—religious beliefs and traditions, a core finding of cultural astronomy. ■

RESEARCHER HIGHLIGHTS

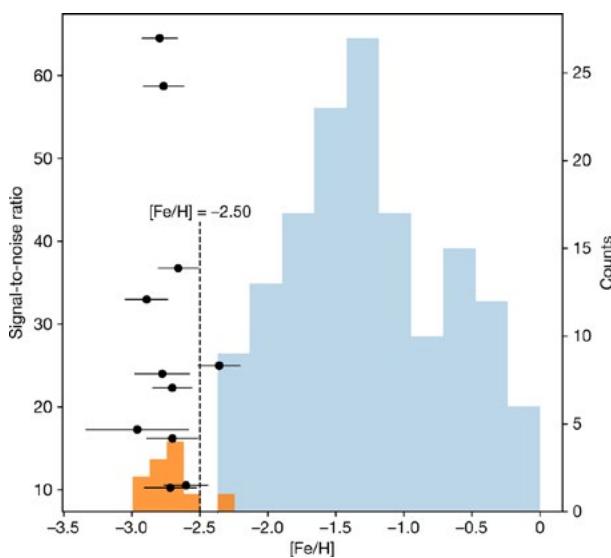


Artist's impression of the thin stream of stars torn from the Phoenix globular cluster, wrapping around the Milky Way (left). Astronomers targeted bright red giant stars (artist's impression, right) to measure the chemical composition of the disrupted Phoenix globular cluster. Credit: James Josephides, Swinburne Astronomy.

Dr. Kyler Kuehn

During 2020, Dr. Kuehn continued his collaboration with the Dark Energy Survey – which has completed its primary observations with the Dark Energy Camera and continues analysis of its six years of data with the goal of providing a deeper understanding of dark energy (see the front-page story in the Lowell Observer #122 for more details). Kuehn also continued his work with the Southern Stellar Stream Spectroscopic Survey (S5), observing with both the Anglo-Australian Telescope and the Lowell Discovery Telescope to identify and investigate the properties of stellar streams – the remnants of small galaxies or globular clusters pulled apart by the gravitational force of the Milky Way.

In the middle of 2020, the S5 collaboration received significant publicity for its discovery of the remnants of a globular cluster that had much lower abundances of certain chemical elements (such as iron) than any previously-observed cluster. Up until that point, astronomers had thought that globular clusters would all have at least a minimum fraction of these elements, but the discovery by Kuehn and his colleagues has upended that previous understanding. See <https://www.sydney.edu.au/news-opinion/news/2020/07/30/stars-that-time-forgot-phoenix-stream-globular-cluster-metallicity.html> for more details.



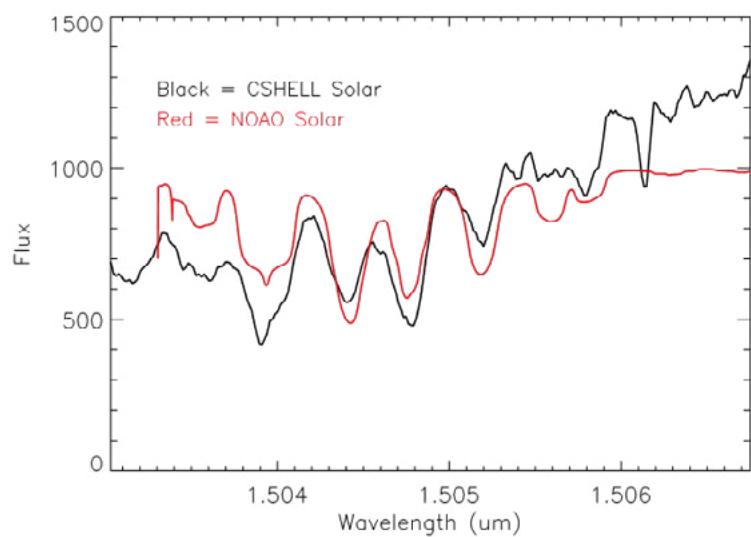
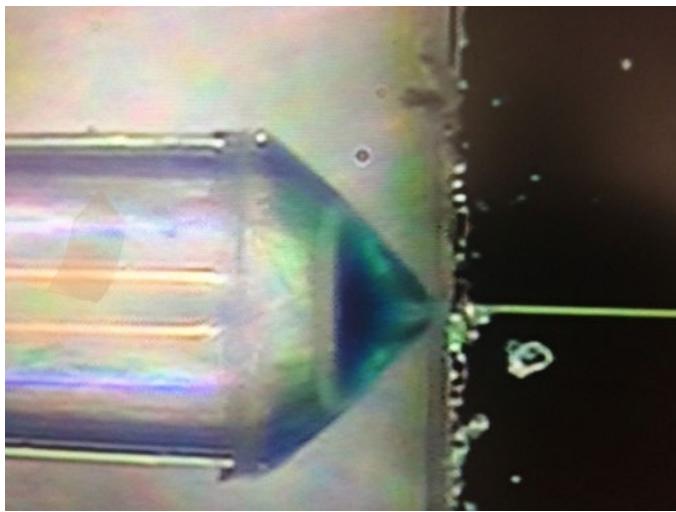
Left: A histogram of the metallicities – the logarithm of the ratio of iron to hydrogen, $[Fe/H]$ – of Phoenix member stars with signal-to-noise ratios greater than 10 is presented in orange (right axis); the metallicity distribution for individual globular clusters in the Milky Way is shown in blue (right axis). The signal-to-noise ratios of individual Phoenix members are also shown as black points (left axis) with error bars (1σ). The dashed line indicates the empirical ‘metallicity floor’ at $[Fe/H] = -2.5$, above which are all globular clusters in the Milky Way, the Local Group and other nearby galaxies.

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RESEARCHER HIGHLIGHTS

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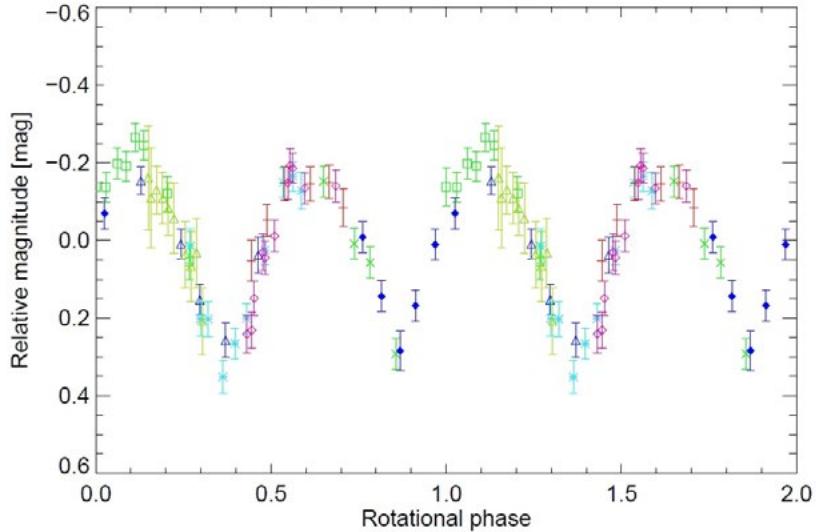
Additionally, Kuehn continued his research into the application of photonic technologies to new astronomical instrumentation. With support from Lowell Observatory's Slipher Society, he and his research assistant performed laboratory and on-sky tests of microscopic ring resonators, a cutting-edge technology that will reduce unwanted interference caused by emission from OH molecules in the upper atmosphere (see <https://doi.org/10.1364/AO.421383> for further details). They not only successfully fiber-coupled the ring resonators to the CSHELL spectrograph, they also made multiple observations of the night sky, including identifying the troublesome infrared OH emission at several different wavelengths. The next step for Kuehn will be upgrading the capabilities of his laboratory, to confirm suppression of the OH emission by the ring resonators. ■



Left: A highly-magnified view of an 8um-core fiber nearly aligned with a waveguide on a silicon device. This device contains the ring resonators used for OH suppression (not pictured), and is coupled to another fiber on the other edge of the device that leads to the CSHELL spectrograph.

Right: A narrow-band spectrum taken by CSHELL with its input fiber pointed directly at the sky, showing the natural solar spectral features (black line) as compared to an NOAO references spectrum (red line).

RESEARCHER HIGHLIGHTS



Rotational lightcurve of a trans-Neptunian contact binary recently discovered. Different colors/symbols correspond to different nights of observations. The rotational period is $\sim 21\text{h}$.

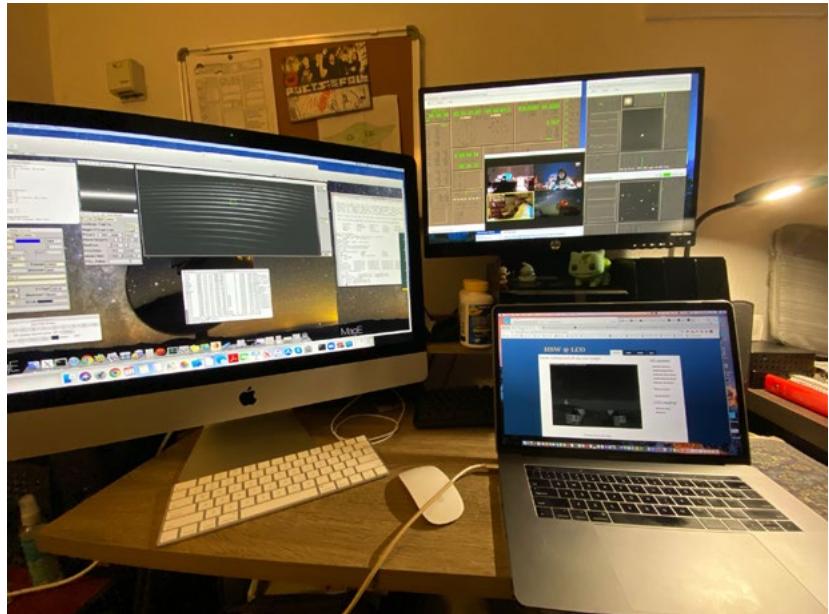
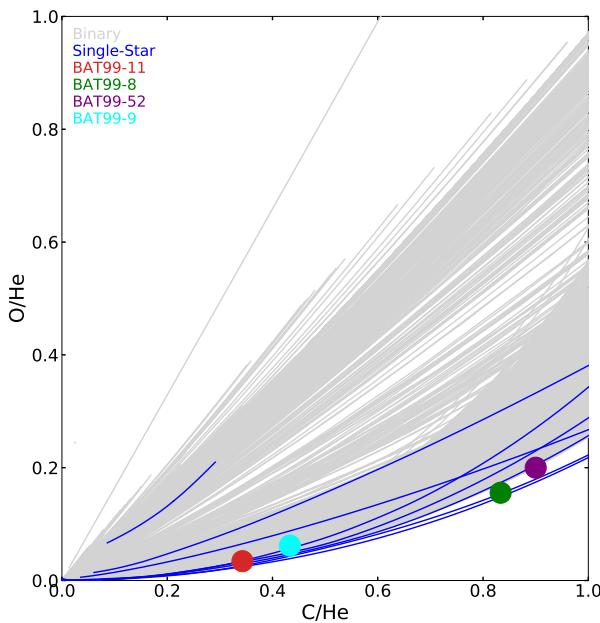
Dr. Audrey Thirouin

Dr. Thirouin's research focuses on the small body population beyond Neptune's orbit known as the trans-Neptunian objects (TNOs).

A couple of years ago, Thirouin and colleague started a search for contact binaries in the trans-Neptunian belt using the Lowell Discovery and Magellan telescopes. A contact binary can be an object with a bilobed shape (like Arrokoth visited by NASA's New Horizon spacecraft or the comet 67P visited by ESA's Rosetta mission) or a system with 2 objects very close to/touching each other. After focusing mostly on the dynamically Cold Classical TNOs (objects at low inclination and low eccentricity between the 3:2 and 2:1 mean motion resonances with Neptune), they have extended their search to objects trapped in Neptune's mean motion resonances. To find a contact binary, the team studies the morphology of the object's lightcurve which is the periodic variation of an object's brightness as a function of time resulting from its rotation. The lightcurve of a contact binary has a large amplitude and has a V-/inverted U-shape at the minimum/maximum of brightness (see Figure). In 2020, 3 new contact binaries trapped in mean motion resonances with Neptune were found, increasing the total to 15 contact binaries discovered by the team with the lightcurve technique. After finding an excess of contact binaries in the 3:2 Neptune's mean motion resonance with a fraction of 40-50%, a deficit is reported for the 2:1 mean motion resonance with only 8-10%. Results from this work have been presented at the virtual Division for Planetary Science (DPS) meeting in October 2020.

Thirouin was involved in community service works by reviewing several manuscripts for diverse journals, and she also reviewed telescopes proposals. She was invited by the National Academy of Science to work on the Planetary Science and Astrobiology Decadal Survey 2023-2032. She serves in the Small Solar System Bodies panel, one of six panels which task is to review the status of planetary science and provide recommendations for the upcoming decade to promote discoveries. These prioritized recommendations range from medium and large class space missions, ground-based facilities to infrastructures and will shape the planetary science field for years. ■

PHD STUDENT HIGHLIGHTS



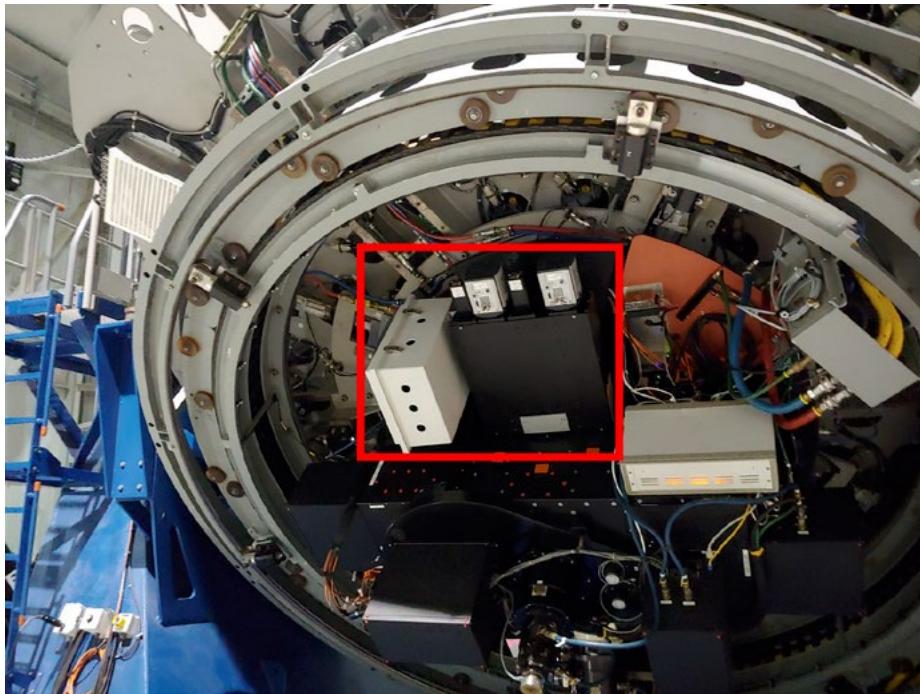
Left: Four WC-type stars (BAT99-8, BAT99-9, BAT99-11, and BAT99-52) compared to the evolutionary models for single star evolution (blue) and binary evolution (gray) in terms of their chemical abundances. All four stars lie on the single-star evolutionary models indicating that a close companion is not required for the stripping process.

Right: Observing from home requires all of the computers and monitors in the house.

Erin Aadland

Erin Aadland is finishing her third year in the Astronomy and Planetary Science graduate program at Northern Arizona University, working with Dr. Phil Massey at Lowell Observatory. Her thesis project is determining the evolution of massive stars, in particular Wolf-Rayet stars. These massive stars evolve from O-type stars and have He-burning cores. Their outer layers have been mostly stripped away either solely by their own stellar winds or with the assistance of a close companion star. Whether Wolf-Rayet stars can evolve by themselves or require a companion star is still a mystery. Wolf-Rayet stars have two subtypes based on their optical spectrum: the WN-type, which have strong nitrogen and helium lines, and the WC-type, which have strong carbon lines. A possible third subtype or a subcategory of the WC-type is the WO-type, whose stars have a similar spectrum to the WC-type stars but with stronger oxygen lines. The strength of these lines could either be due to the star having more oxygen or the temperature of the star being higher than the WC-type stars. Erin is currently evaluating which answer is responsible for the oxygen lines' strength by modeling the spectra of WC-type stars and WO-type stars. The models allow us to determine what the physical properties (temperatures and oxygen abundances) of the stars are, which can then be compared between the types. Erin has finished modeling 4 WC-type stars' spectra and compared them to evolutionary models that predict the physical properties throughout a stars' evolution for both single-star and binary evolution. The comparison showed that a close companion star is not necessary for the stars' evolution. While modeling these stars, Erin and her collaborators found nitrogen in one of the WC-type stars. This is unheard of, as in a WC-type star all of the nitrogen has been completely stripped away. The presence of nitrogen suggests that this star could be a transition star between the WC and WN subtypes. This past year, Erin compared the star's physical properties with the evolutionary models to determine if a transitional star like this could be observed for either single-star or binary evolution. They found that this star could exist in either type of evolution and evolutionary models even predict 10% of a star's WC-type phase would have trace amounts of nitrogen. The paper on this topic has been submitted to MNRAS. Aadland and Massey were also scheduled to observe on the Baade Magellan Telescope at Las Campanas Observatory in Las Serena, Chile. However, due to COVID-19, the observing run became remote. They hope to be back to observing in person soon. ■

PHD STUDENT HIGHLIGHTS



QWSSI was commissioned on the 4.3m LDT in July 2020. Since then, researchers from multiple institutions have utilized QWSSI for their high-resolution imaging needs.

Catherine Clark

Catherine Clark began 2020 with an internship at the American Museum of Natural History (AMNH) in New York City. Clark received a travel grant to work with her committee member, Dr. Rebecca Oppenheimer, to learn more about astronomical instrumentation. Unfortunately, her time in New York was cut short due to the pandemic, but she did deliver a seminar to the Department of Astrophysics at AMNH in April 2020.

Clark has also continued her work with Dr. Gerard van Belle on projects related to her dissertation. This work has resulted in the Pervasive Overview of Kompanions of Every M-dwarf in Our Neighborhood (POKEMON) speckle survey of nearby M-dwarfs. This survey has inspected, at diffraction-limited resolution, every M-dwarf out to 15 pc, with additional brighter targets to 25 pc. The primary purpose of this survey is to detect low-mass companions to these M-dwarfs for refinement of the M-dwarf multiplicity rate, and to determine the M-dwarf multiplicity rate by subtype for the first time. This survey has resulted in over 30 new companions to these M-dwarf primaries. These results have implications not only for stellar astrophysicists, but also for the exoplanet scientists searching for worlds orbiting our low-mass neighbors. Clark presented on this work at the American Astronomical Meeting in Honolulu. She also presented on Lowell computer Elizabeth Williams, and this talk was written about on space.com. Additionally, Clark's help in observing binary star systems with speckle imaging resulted in co-authorship on a paper by Lowell adjunct faculty member Dr. Elliott Horch (Horch et al. 2020).

In order to complete the observations for the POKEMON survey, Clark observed two nights at the 4.3m Lowell Discovery Telescope (LDT) in February 2020 using the Differential Speckle Survey Instrument. Clark also observed two nights at the LDT in October 2020 using the Quad-camera Wavefront-sensing Six-channel Speckle Interferometer (QWSSI). QWSSI was built by Clark, van Belle, and Zach Hartman, and was commissioned on the LDT in July 2020. Clark gave a talk and published a conference paper (Clark et al. 2020) on the design, commissioning, and operations of QWSSI at the SPIE meeting in December 2020. Since then, researchers from multiple institutions have utilized QWSSI for their high-resolution imaging needs.

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PHD STUDENT HIGHLIGHTS

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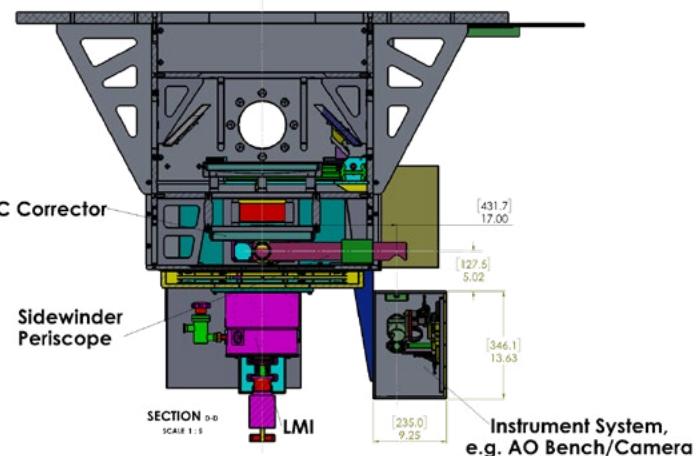
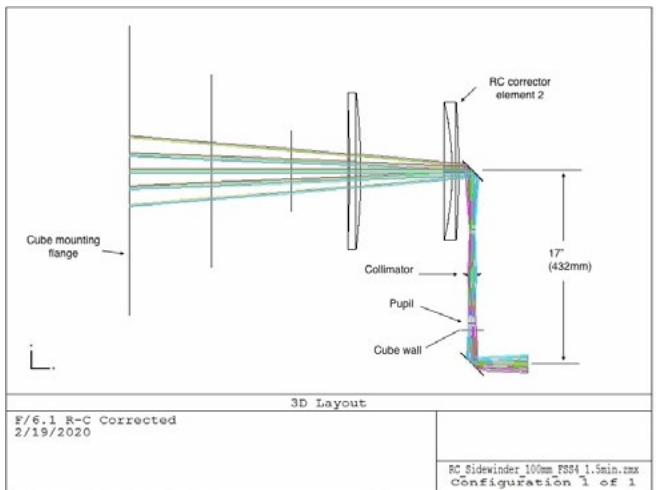
During the October observing run with QWSSI, Clark continued her work with TESS Objects of Interest (TOIs), which are the most promising exoplanet host candidates discovered by the Transiting Exoplanet Survey Satellite (TESS), and are therefore high-priority targets for high-resolution imaging follow-up. Clark has now observed 85 TOIs with five different speckle imagers around the world. These observations will help in the search for and validation of exoplanets orbiting M-dwarfs.

In addition to her work as a graduate research assistant, Clark was elected Student Representative to the Faculty by her peers in August 2020. Clark was also selected to be an Astrobites author in December 2020. Clark continues to work on her Graduate Certificate in Science Communication, which she hopes to complete in Fall 2021, and she plans to defend her dissertation in Spring 2022. ▀



Clark delivered her first conference talk at the American Astronomical Meeting in Honolulu in 2020. Here she discussed Elizabeth Williams, a computer for Lowell Observatory who helped with the calculations that ultimately led to the discovery of Pluto. She also gave a talk on the first results from the POKEMON survey.

TECHNICAL SUPPORT HIGHLIGHTS



A CAD rendering of the Sidewinder periscope on the LDT instrument cube (left), and a display of the optical path from the instrument cube through the Sidewinder periscope (right).

By Dr. Kyler Kuehn
Deputy Director for
Technology

The Technology Group was incredibly busy in 2020. One of our most important accomplishments was changing the operational models of our telescopes to deal with the pandemic. This primarily included improved sanitation, personal protective equipment, and (most difficult of all) distancing among staff to prevent the spread of the Covid-19 virus. This was particularly challenging for the team at the Lowell Discovery Telescope, where many engineering and night operations tasks had been performed by multiple people working together. The solution included moving all observing to remote facilities, and having a Safety Technician stationed at the Giovale-Millis Lodge. This provided an isolated working environment for the Telescope Operators, while still ensuring that other personnel were nearby in the event of an emergency.

Despite the challenges presented to our operations, we nevertheless managed to make significant progress on the instrumentation front. The Instrument Group designed the "Sidewinder" instrument interface, which will allow for instruments to be mounted at the auxiliary port of the LDT Instrument Cube, increasing the simultaneous instrument capacity of the telescope. They also fully rebuilt the cryogenic cooling system for the NASA42 camera, which is now back in operation at the 42-inch Hall Telescope on Anderson Mesa.

Meanwhile, at NPOI, the staff worked hard to recover from a series of hardware failures that led to extended down-time for that facility. But with repairs completed, we are now back in regular 3-way interferometric operation. Beyond that, significant upgrades to the entire NPOI array were begun, thanks to supplemental funding from the Department of Defense. Additionally, the new 1-meter PlaneWave telescopes advanced toward regular operation, and we expect at least one of them to be on-sky every night in the second half of 2021.

Finally, the IT Group performed numerous important upgrades to a variety of systems, from migrating all telephone landlines to VOIP, to improving the wireless internet range at all of our sites, to introducing improved data storage facilities at Anderson Mesa.

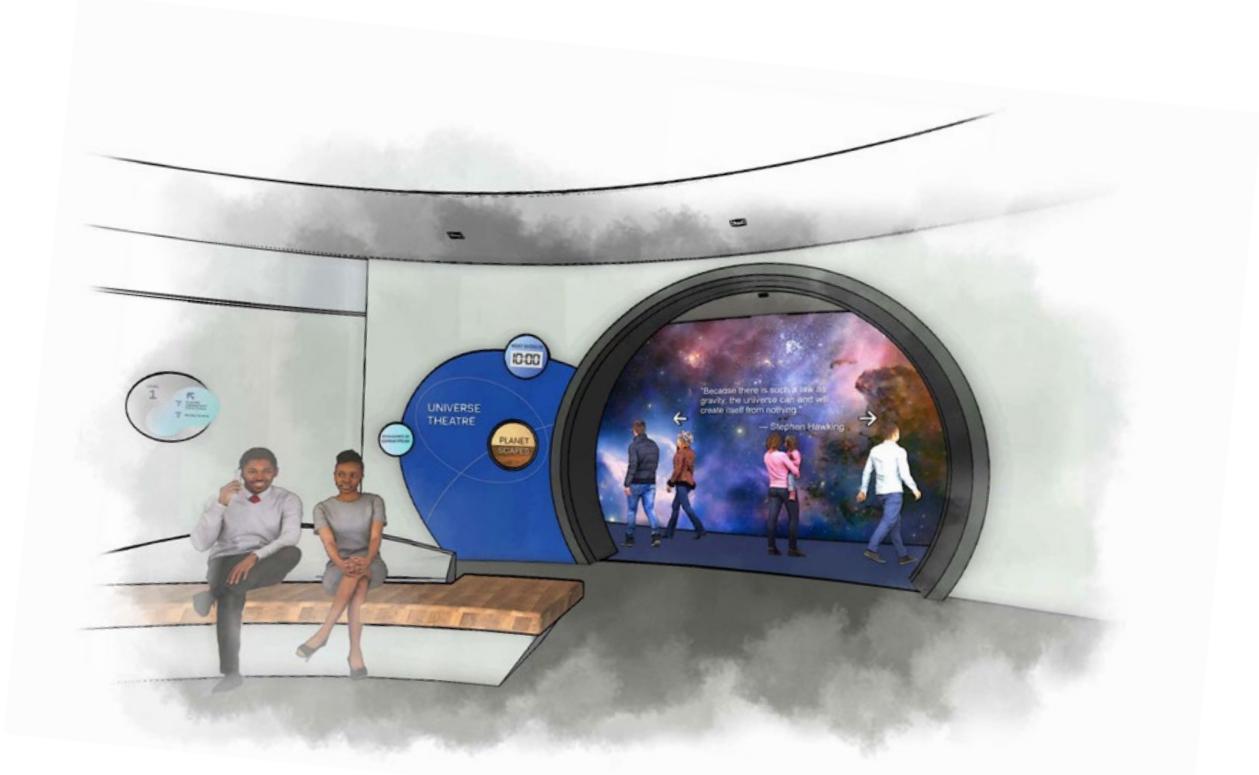
TECHNICAL SUPPORT HIGHLIGHTS

All of these feats were accomplished by the 30 or so staff of the Technology Group, many of whom were brand new to the observatory in 2020. The operations manager position vacated by Teznie Pugh in early 2020 was quite capably filled by Amanda Bosh. The newly-created Support astronomer position was taken up by Timothy Ellsworth-Bowers, and the NPOI Project Manager position was filled by Dave Noble. Ben Reed joined the LDT engineering staff, while Lowell Discovery Telescope Operators Thomas Kelley and Sydney Perez, and NPOI Operator Technician Solvay Blomquist joined the Night Operations staff. Meanwhile, Safety Technicians Hannah Caldwell-Meurer, Claire Gibson, Max Levine, Kathryn Turrentine, and Victoria Girgis began their duties at the LDT (special thanks to Lowell's Public Programs group for sharing their staff with us when we needed them). With all of our new and veteran staff, the Technology Group is ready to take on the challenges that 2021 will bring. ■



The NASA42 camera being tested after function was restored to its cryogenic system.

DEVELOPMENT HIGHLIGHTS



The ADC Universe Theater gateway.

By Stephen Riggs
Development Manager

By any standard, the year 2020 changed the definition of normal for fundraising across the country. Lowell Observatory's Development Department would heartily agree. The Covid crisis and observatory closure completely upended the way fundraising has been practiced for years and required the creation of a new paradigm, one in which personal visits with supporters were no longer the mainstay. Instead, virtual meetings, telephone calls, and email correspondence came to the fore, and Lowell supporters responded in record numbers. In all, loyal supporters contributed \$11,342,341.00 to the observatory in 2020.

Much of the 2020 total was directed to the Kemper and Ethel Marley Foundation Astronomy Discovery Center (ADC) with ten gifts for \$100,000 or more along with scores of smaller, but still significant, gifts. These gifts elevated the amount of ADC funding to the magic 80% raised, the amount needed to begin construction.

Endowments also received a healthy increase in 2020. More than \$2 million was added to the Lowell Observatory Foundation (LOF) bringing the total of LOF endowments up to \$8.5 million. Significant gifts were received for the Native American Astronomy Outreach Program and from the estate of Don Trantow.

Science funding had gains as well. The new Slipher Society was created to support new science endeavors at the Observatory. Ten supporters joined the Society during its first year and contributed more than \$60,000 to support astronomy research.

The only dark spot in 2020 was that the lack of visitors drove new memberships down. Existing members still renewed at a high rate, though. And, an exceptional performance by the Annual Fund program made up some of the difference with many members giving several times during the year to support important Lowell programs and activities.

We cannot thank supporters enough for staying with us during a most challenging year and for giving so much to see the observatory through a difficult time...and for helping to turn the new Astronomy Discovery Center into reality. ▀

PUBLIC PROGRAM HIGHLIGHTS



The GODO was opened for Premium Access in August as a way to cautiously welcome guests back to Mars Hill.

Credit: Abe Snider

By Sarah Burcher
Public Program Manager

As a department whose basis is welcoming thousands of visitors from around the world, the Public Programs ad to adapt constantly to the drastic changes wrought by the coronavirus. To ensure guest and staff safety, the Lowell Observatory Public Programs closed its doors on March 13th. This left the education staff adrift without the public to educate, but assurances from the management and directors promised that though the program was shuttered for the time being, Lowell would find meaningful work for all of its staff.

So began the hunt for ways to keep the education staff engaged in their field without allowing direct interaction with the public. The Public Program supervisors created virtual seminars on some of the finer points of informal education that are not part of regular training, and educators were provided with resources such as videos and articles to further their own knowledge on astronomy, and encouraged to delve into topics they had never had the opportunity to learn.

Other departments at Lowell reached out to offer their assistance in giving our educators opportunities for work. Some educators were able to assist science staff with their research, and others served as Safety Technicians at the Lowell Discovery Telescope. The astronomers graciously agreed to hold virtual presentations about their work for our educators to learn more about the current research at the observatory. These talks quickly evolved into public livestreams hosted on our YouTube channel.

In collaboration with the Marketing and Communications Department, educators have provided content for our expanding digital presence. These programs include recurring livestreams such as Interactive Stargazing, the Mars Hill Almanac, and Sagas in the sky, as well as programs for special celestial occasions such as the Planetary Oppositions, Lunar Eclipses, and conjunctions.

Beginning in August, we began to welcome guests back to the hill for "Premium Access Programs" at the Giovale Open Deck Observatory. The Public Program Supervisor team developed a creative program that allowed for a solely outdoor experience to minimize risk of transmission. They devised a clever solution to address the issue of eyepiece sanitization without damaging the optics; rather ironically, the solution was to attach petri dishes to the top of the eyepiece. These optically-clear plastic coverings were sanitized regularly with an alcohol spray.

These Premium Access Programs were extremely well received by guests. The privacy of a single group at a telescope facility allowed the educators to tailor each experience to the guests' astronomy background and areas of interest.

In September, the Public Program welcomed its newest telescope: the Dyer Telescope, a 24-inch

PUBLIC PROGRAM HIGHLIGHTS

Planewave mounted inside a newly refurbished dome. This telescope has been a boon during Lowell's cautious reopening; it gives the Public Program another venue to hold intimate and personalized Premium Access programs.

In December, the planets Jupiter and Saturn drifted closer together in the sky than they have been in centuries, and the whole world turned its eyes on the Great Conjunction. In addition to the largest livestream to date, the Public Program developed special programming to allow dozens of guests to view the Great Conjunction from our GODO and Dyer telescopes. ■

Imaged from 4.3m Lowell Discovery Telescope (Dec 20)



Enjoying this? Become a member: lowell.edu/membership

Screenshot from *The Great Conjunction* live stream which has amassed more than 2,000,000 views on YouTube.

PUBLIC PROGRAM HIGHLIGHTS



Sixth-grade teacher training workshop, discussion about Book Club.

By Dr. Deidre Hunter

Native American Astronomy Outreach Program

As one can imagine, 2020 was a very trying year for students and teachers. Because of the pandemic, most of the 2019-20 school year participants lost out on their spring field trips to Lowell Observatory and the last two months of classroom visits as the school went from in-person to online. It is likely that the entire 2020-21 school year will be online. The Navajo Nation has been particularly hard hit by the pandemic. In terms of cases and deaths per population, it exceeded anywhere else in the United States. Teaching students online has been complicated even further than it would be by the fact that some households do not have electricity and those that do often have no or poor internet connection. We have found that a fraction of the students are not even in online class, and those who are turn their video off in order to keep demands on their internet down.

The 2020 6th and 7th grade summer camps were also held online. We met four hours per day for five days in each camp, and did demonstrations or hands-on activities with the materials that we mailed the participants in advance.

The 2020-21 school year is the last of the three-year collaboration with the Kayenta Unified School District on the Navajo Nation. This school year NAAOP is working with KUSD teachers who are new to our program: four 4th grade teachers, three 5th grade teachers, and the one 8th grade teacher. Our veteran teachers from the past two years of the collaboration are acting as mentors to these new teachers. We are also working with the 6th grade science teacher at the White Mountain Apache Theodore Roosevelt School.

In August we determined how to carry out the new curriculum units online and assembled and mailed to the schools a packet of materials to be given to each student, a total of 494 packets to KUSD and 50 to the Apache school. The packets included pictures that would have been viewed as a class, academic articles for reading, a composition notebook, pencil, eraser, pencil sharpener, highlighter and note tabs, and supplies for hands-on activities to be done as a group online. The packets also included the book for Book Club. Bins of classroom supplies were mailed directly to the new teachers.

Teacher training workshops were held in October and November for 4th, 5th, and 6th grade teachers. After that, NAAOP team members began working with their partner teachers and making classroom visits by joining the teacher's Zoom sessions. ■

PUTNAM COLLECTION CENTER HIGHLIGHTS



The new Zeutschel Zeta book scanner.

By Lauren Amundson
Librarian/Archivist

Despite the challenges a global pandemic presented in 2020, the Lowell Observatory Library and Archives continued its mission of collecting, preserving, and providing access to current research and historical resources.

In January, Abbey Buckham joined the team as Plate Scanning Intern, paid for by a grant from the Arizona Historical Records Advisory Board. Working with Archivist/Librarian Lauren Amundson and astronomer Dr. Stephen Levine, Buckham was going to spend her internship digitizing a small subset of the observatory's collection of glass plate negatives. She began by cataloging and organizing part of the collection, and the plan was to begin digitization in March or April. Then COVID-19 struck, and the entire staff began working remotely on March 23. The project was put on hold until June, at which point the team decided it wouldn't be feasible to begin the scanning. Instead, Buckham created a large-scale inventory of the 40,000+ plates. With the remaining hours of her internship, she re-housed 3,600 plates in archival envelopes and boxes.

Adriana Duenas joined the team in January as an exhibits intern. She worked with Archives and Museum Specialist Stacey Christen to create a small exhibit in the Putnam Collection Center lobby called *I Heart Pluto*, designed to coincide with the observatory's *I Heart Pluto Festival* in February. When the shutdown began, Duenas shifted to remote work and spent the remainder of her internship designing a digital exhibit centered around Lowell's historic buildings and telescopes. The exhibit went live in May at <https://collectionslowellobservatory.omeka.net/exhibits/show/historic-buildings>.

In late March, at the beginning of the shutdown, Public Program Manager Sarah Burcher and Visitor Experience Manager Miriam Robbins asked Amundson if she could provide any project hours to educators and retail staff. Amundson began training educator Joyce Binnie and retail associate Béatrice Loulergue on creating a digital exhibit about brothers and Lowell astronomers E.C. and V.M. Slipher. Working entirely remotely, Binnie and Loulergue conducted research, selected items for digitization, and built the online exhibit. It went live in June at <https://collectionslowellobservatory.omeka.net/exhibits/show/slipherbrothers>.

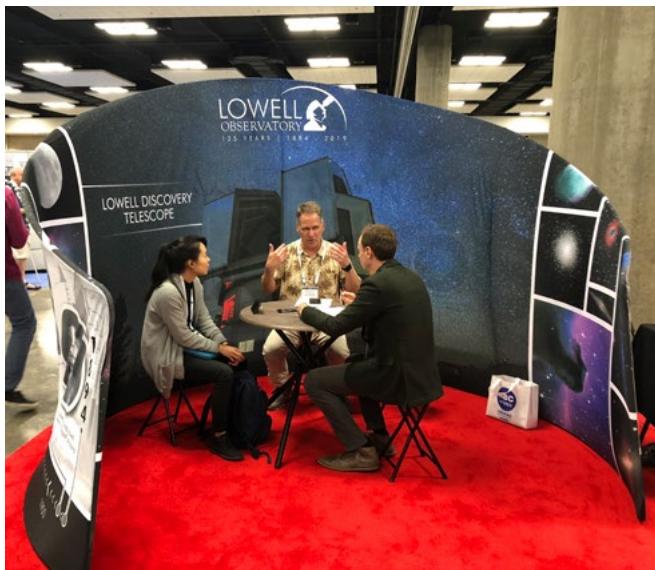
PUTNAM COLLECTION CENTER HIGHLIGHTS

The May issue of *The Southwestern Archivist* featured an article by Amundson about the collection of letters between Percival Lowell and A.E. Douglass that comprise the "Flagstaff It Is - The Founding of Lowell Observatory" collection on the Arizona Memory Project (<https://societyofsouthwestarchivists.wildapricot.org/resources/Documents/Newsletters/SWA2020v43no2-May.pdf>). The American Astronomical Society's HAD (History of Astronomy Division) Newsletter published an article by Amundson and Lowell Historian Kevin Schindler highlighting V.M. Slipher's correspondence with Edwin Hubble: <https://had.aas.org/sites/had.aas.org/files/HADN95.pdf>.

The archives had a successful fundraising year. In July, the Arizona Historical Records Advisory Board awarded a \$1,300 grant to digitize drawings made by retired Director of Technical Services Ralph Nye during his 40-year career at Lowell. The Fall Appeal led by Rachel Edelstein was a huge success, raising more than \$20,000 to purchase a Zeutschel Zeta Book Scanner from the Crowley Company. The generosity of private donors and a matching \$10,000 gift from an Advisory Board member funded the purchase of equipment, accessories, and software. Staff and volunteers will use the scanner to digitize fragile items such as Carl Lampland's observation logbooks, Percival Lowell's handwritten manuscripts, photographs, and bound materials such as diaries and scrapbooks.

The pandemic allowed Amundson and Christen to attend several conferences virtually, including the Society of American Archivists, Special Libraries Association, and Digital Directions 2020. Amundson served on a disaster preparedness panel for the American Association for State and Local History conference. ■

MARKETING & COMMUNICATIONS HIGHLIGHTS



Right: Astronomer Gerard van Belle (center) at the winter AAS meeting.

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

It's an understatement to say that 2020 didn't turn out the way anyone had expected, but like everyone else, Lowell Observatory's Marketing and Communications team learned how to adapt. In the previous 2019 Annual Report is this statement: "On November 12, the observatory hosted its first ever YouTube live stream for the transit of Mercury. ...this broadcast unexpectedly generated more than 30,000 views during the 4-hour event, plus another 15,000 views afterwards." Little did the M&C team know at the end of 2019 that they would finish 2020 with more than 3 million views on YouTube as a devastating pandemic pushed informal science education online. The results they achieved in 2020 were had through the collaborative efforts of the observatory's faculty, educators, visitor experience team and marketing staff—involving more than half of the observatory's personnel. This short report cannot include the names of all who helped, but all of them are remembered for what they did.

The M&C team began 2020 at the winter meeting for the American Astronomical Society (AAS), where Historian and PIO Kevin Schindler and Deputy Director for Marketing and Communications Danielle Adams represented Lowell Observatory in a brand new booth that Senior Creative Specialist Sarah Gilbert had designed. The circular booth highlighted current research on the inside, and on the outside it featured a timeline of the observatory's past 125 years. Following this appearance at AAS, Adams led the finalization of a new cooperative marketing agreement with Discovery that also formally renamed the Discovery Channel Telescope (DCT) as the Lowell Discovery Telescope (LDT).

In February, the observatory held its first "I Heart Pluto Festival," intended to set off a 10-year marketing campaign that will culminate in the 2030 centennial celebration of Pluto's discovery in 1930. Kevin Schindler orchestrated the two-day festival, which featured special tours and activities on Mars Hill and an evening of events at NAU's Cline Library Auditorium on February 15, as well as a celebration at the Orpheum Theater on February 18, the actual 90th anniversary of Pluto's discovery by Clyde Tombaugh. Sarah Gilbert built a new website (iheartpluto.org) for the festival and designed the festival logo and supporting materials.

Two events at the beginning of March would be the last ones the M&C team attended for the remainder of 2020. Four team members attended Social Media Marketing World on March 1-3 for training in the latest tactics and strategies for social media, video marketing and analytics. Next was the annual Viola Awards, where Kevin Schindler had been nominated for the Community Impact Award for an individual and where the Lunar Legacy celebration that Schindler had birthed won the Community Impact Award for an organization. Lowell Observatory also won the first-ever Viola Award for Placemaking for the Giovale Open Deck Observatory (GODO), which had just opened on October 5, 2019. During the five months following the GODO's opening, general admission visitation to the observatory increased by 20%. The marketing campaign for the GODO, "Stargazing Reimagined", won the marketing award from the Museum Store Association in August, and the observatory also won Discover Flagstaff's Eco-Tourism Award in October.

MARKETING & COMMUNICATIONS HIGHLIGHTS

The observatory's decision to shutter its public program on March 13 (ironically, Percival Lowell's birthday) to prevent Mars Hill from becoming a vector for the spread of COVID-19 had immediate and profound impacts across the organization. Some of the teams hardest hit were public program and visitor experience—without on-site guests on Mars Hill, they were without a *raison d'être*—but the observatory did not let any employees go, and some temporarily adopted new roles to help out in other departments across campus.

In the Starry Skies Shop, Visitor Experience Manager Miriam Robbins had put the team on track for record revenue in January and February before COVID-19 closed on-site purchases. Focus quickly shifted to the online portal for the gift shop, and in the meantime Visitor Experience Supervisor Kim Denune led the reconfiguration of the on-site gift shop to accommodate social distancing and established sanitization procedures to prepare for reopening. Visitor Experience Lead Rob Hall and Robbins were instrumental in setting up a new online ticketing system from ACME, which made the phased reopening far more manageable and for the first time provided ticketing analytics.

Ahead of the observatory's reopening, the M&C team worked with Public Program staff to determined a phased approach to reopening that aligned with CDC protocols, and Sarah Gilbert designed a series of visuals to illustrate this reopening plan and its procedures. Danielle Adams contracted part-time with JB DeWitt to fill in the gap as the team developed a new marketing campaign for the phased reopening; the Director's Opportunity Network (DON) funded much of this. The observatory opened with very limited Premium Access programs in August and did not get to Phase 2 until 2021.



Cosmic Coffee, Meet an Astronomer, and Interactive Stargazing were all popular weekly series developed during the closure of the onsite Public Program.

Upon the closure of the public program in March, the observatory immediately pivoted to digital programming and started building a library of streaming programs on YouTube, greatly aided by Public Program Manager Sarah Burcher and her team. Just six days after the closure, the M&C team broadcast its first live program about COVID-19, and that evening they broadcast a program about the March equinox from the Astrolab at the GODO (in a snowstorm). These initial programs set off a wave of live streaming that included numerous weekly series—Cosmic Coffee, Meet an Astronomer, and Interactive Stargazing—and one-off streams for special celestial events like planetary conjunctions and oppositions, meteor showers, and lunar eclipses. Behind the scenes, Director Jeff Hall, Heather Craig, Visitor Experience Associate Richard Montano, and Danielle Adams learned how to run the broadcasting software and manage the streams on YouTube, and DON purchased a fast streaming laptop for us.

Supplied with help from visitor experience associates and educators, the observatory also produced edited videos that included regular programs like Science Challenges, Mars Hill Almanac, and Sagas in the Sky. DON funding provided a 24-core video editing computer that was used throughout the year to build explainer videos ahead of major celestial events, promotional videos, and other programs. In December, Educator Ariel Daniel and marketing consultant JB DeWitt started up a Lowell Observatory TikTok channel, which rapidly grew to a couple thousand followers before the year ended.

MARKETING & COMMUNICATIONS HIGHLIGHTS

The observatory capped off the year with the once-in-400 years Great Conjunction of Jupiter and Saturn. Educators developed for December special daytime programs with telescopic views of Jupiter and Saturn—the Great Conjunction Experience—that completely sold out within two weeks of starting. On December 21, the observatory broadcast live for 2.5 hours from the GODO and from a telescope set up near the LDT, which garnered more than 1.6 million views from around the globe while it was live.

From March 13 to December 31, the M&C and Educator teams had created 194 videos, including 110 livestreams and 84 edited videos that totaled close to 100 hours of new content. On YouTube, these videos had earned over 3 million views from some 2.5 million people. YouTube subscribers had increased from less than 500 to almost 25,000, and all of the observatory's social media channels had grown, especially Instagram, which more than doubled. Many of the programs for major celestial events were also promoted or embedded on the websites of media outlets like CNN, NPR, Discovery, National Geographic, Space.com, and Forbes.

Even though 2020 saw far fewer on-site guests on Mars Hill, the quick adjustment that the M&C team made to virtual programming greatly expanded the awareness of Lowell Observatory to 25 times more people online than would have visited Mars Hill in person. ■

VOLUNTEER HIGHLIGHTS



Left: Archivist Lauren Amundson and volunteer Bob Nastan discuss a plan for archiving drawings.

Above: Sister/brother team Julianna and Brandon Ersepke staffed the Lowell information booth at NAU's Cline Library Assembly Hall during the first I Heart Pluto Festival, one of several events commemorating the 90th anniversary of Pluto's discovery. Many other volunteers assisted Lowell staff during the multi-day celebration of Pluto's discovery.

By Catie Blazek
Volunteer Coordinator
and
Lauren Amundson
Librarian/Archivist

Like many other activities in 2020, the volunteer program at Lowell was in hibernation for most of the year. The year started off strong with volunteers working in all areas of the observatory, operating telescopes, engaging with visitors in the telescope lines or in the various open houses, lending a hand in the archives, and many other opportunities. Then came March and the program was almost entirely put on hold.

In recognition of their dedication to Lowell, four volunteers whose tenure with Lowell surpassed 5 years had asteroids named for them. These volunteers were presented with citations approved by the International Astronomical Union (IAU) showing their asteroid's orbit, the IAU citation as published, and specifics about their asteroid including an estimate of its size.

Mary Demuth who has run the volunteer program for many years, retired at the end of 2020. Catie Blazek will now be leading the volunteer program. DeMuth will still be around, volunteering in the archives.

In 2020, Jon Ford, Senior Public Program Educator stepped in as a Volunteer Liaison for the volunteers in the Public Program. The Liaison is the point person for volunteers, facilitating volunteer orientation and training, and helps the volunteers identify their strengths and areas of interest in the public programs.

Longtime volunteers Gene and Glenda Hill left the Lowell team in September to begin a new adventure in North Carolina. Gene began volunteering at Lowell in 2009 and for many years demonstrated his passions for teaching and astronomy while giving daytime tours of the Observatory's historic campus and operating the solar telescopes. Glenda began volunteering in the archives in 2010. She cataloged the correspondence of V.M. Slipher, Percival Lowell, and Wrexie Louise Leonard. Many of the letters are located in copy books on fragile onion skin paper, and Glenda became adept at deciphering poor and faded handwriting.

We said goodbye to another husband and wife volunteer team, Bob and Sherry Nastan, in June. Sherry helped the Development department with monthly mailings, served as a greeter for the Rotunda open house, organized and digitized Lowell Discovery Telescope documents, and assisted with the Native American Astronomy Outreach Program. Bob volunteered in the archives, where he humidified and flattened historic blueprints and created a catalog system for filing them. His engineering background and attention to detail brought some much-needed efficiency upgrades to the process. The Nastans are now enjoying their retirement in Colorado. ■

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STATEMENT OF FINANCIAL POSITION

Combined Statements of Financial Position for the Year Ended December 31, 2020
 (with comparative totals for the year ended December 31, 2019)

ASSETS	2020	2019
Current Assets		
Cash and cash equivalents	\$ 474,939	\$ 156,179
Restricted cash and cash equivalents	796,970	790,973
Restricted certificates of deposit	4,808,558	403,582
Investments	2,172,476	849
Research grants receivable	572,103	319,429
Promises to give, current portion	3,151,810	2,788,205
Other current assets	596,347	341,900
Total Current Assets	12,573,203	4,801,117
Property and equipment, net	47,612,883	48,356,606
Promises to give, net of current portion	11,421,025	10,389,449
Collection item	400,000	400,000
Investments with donor restrictions	22,220,045	22,787,049
Total Noncurrent Assets	81,653,953	81,933,104
Total Assets	\$ 94,227,156	\$ 86,734,221
LIABILITIES AND NET ASSETS		
Current Liabilities		
Accounts payable	\$ 241,901	\$ 375,473
Accrued expenses and other current liabilities	110,455	52,661
Total Current Liabilities	352,356	428,134
Note payable, bank	2,200,971	2,595,000
Long-term debt	150,000	-
Deferred research grant revenue	45,908	44,576
Deferred access fee revenue	7,409,621	7,470,403
Total Liabilities	\$ 10,158,856	\$ 10,538,113
Net Assets		
Without donor restrictions	\$ 27,977,666	\$ 28,884,020
With donor restrictions	56,090,634	47,312,088
Total Net Assets	84,068,300	76,196,108
Total Liabilities and Net Assets	\$ 94,227,156	\$ 86,734,221

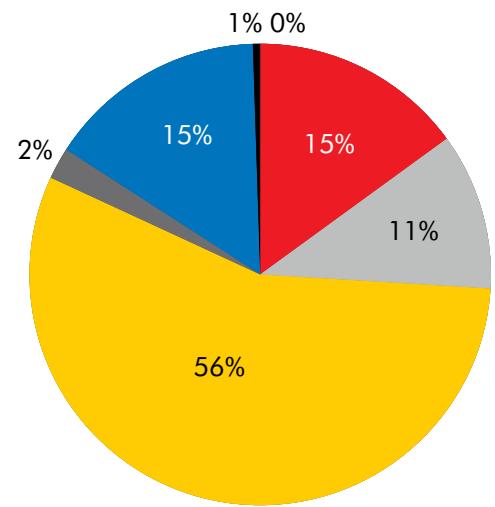
STATEMENT OF FINANCIAL ACTIVITIES

Combined Statements of Financial Activities for the year ended December 31, 2020

(with comparative totals for the year ended December 31, 2019) (before depreciation)

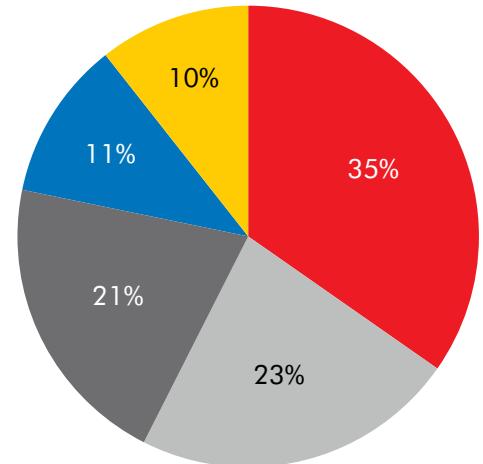
REVENUE & SUPPORT

	2020			2019		
Grant and contract revenue	\$ 3,195,523	15%	\$ 3,276,144	11%		
Telescope access fees	2,350,197	11%	2,376,660	8%		
Contributions	11,980,863	56%	19,501,430	62%		
Public program revenue	455,745	2%	1,434,428	5%		
Investment income net	3,284,206	15%	4,013,478	13%		
Other income	114,301	1%	194,861	1%		
Gain on sale of assets	1,642	0%	56,500	0%		
Total Revenue and Support	\$ 21,382,477		\$ 30,853,501			



EXPENDITURES

	2020			2019		
Program services:						
Research	\$ 3,948,721	35%	\$ 4,172,506	36%		
Technology	2,599,068	23%	2,617,092	25%		
Public program	2,396,691	21%	2,445,484	18%		
	8,944,480		9,235,082			
Support services:						
Management and general	1,247,337	11%	1,292,400	11%		
Fundraising	1,209,096	10%	1,183,757	10%		
	2,456,433		2,476,157			
Total Expenditures	\$ 11,400,913		\$ 11,711,239			
Gain on interest rate swap	-		-			
Change in net assets	\$ 9,981,564		\$ 19,142,262			



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 2020 and 2019 was \$2,109,000 and \$1,954,000.

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, 2020. Copies of the audited financial statements are available at lowell.edu/about/governance_and_financials/

2020

LOWELL
OBSERVATORY
125 YEARS | 1894 - 2019

ANNUAL REPORT



Front Cover: Comet NEOWISE and the Pluto Telescope Dome | Credit: Michael West
Back Cover: The 24" Dyer Telescope | Credit: Danielle Adams

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