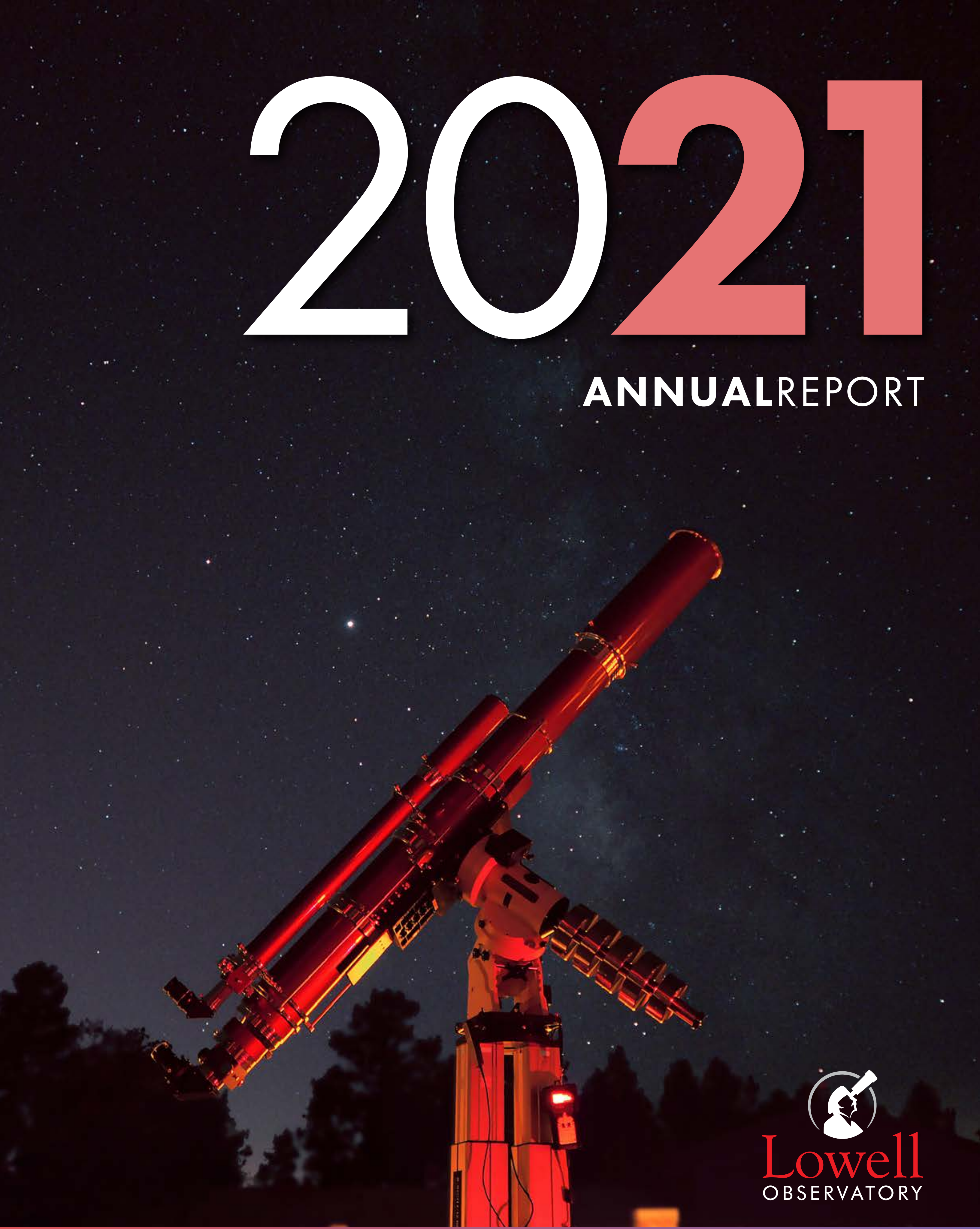
2021

ANNUAL REPORT



Lowell
OBSERVATORY

2021

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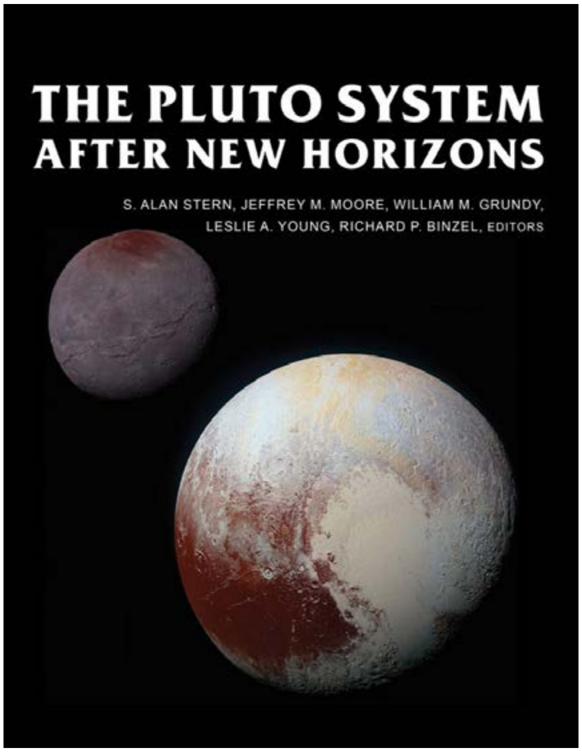
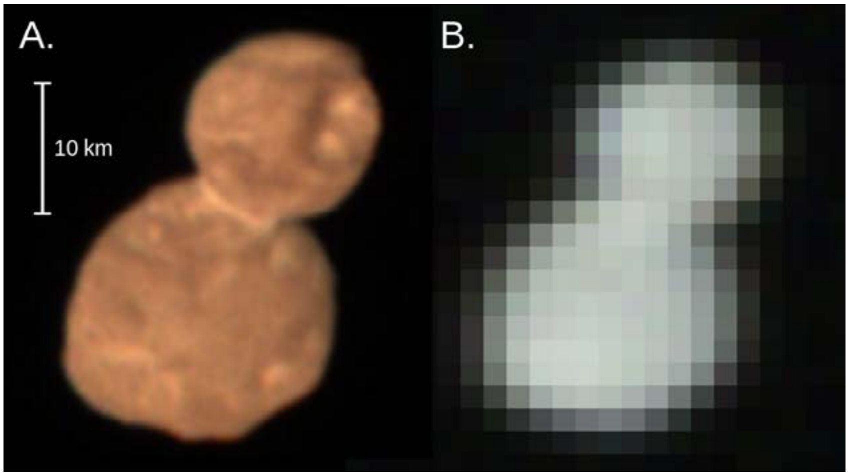




(Above): Arrokoth as seen by New Horizons at visible wavelengths (A.) and at infrared wavelengths (B.). The reddish visible wavelength color is due to the presence of complex organic macromolecular material called tholin. The infrared data indicates a relatively uniform composition across Arrokoth's surface. Methanol ice (CH3OH) 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 2021. Grundy was an author on 28 peer-reviewed scientific articles and book chapters published during the year, and an editor of *The Pluto System After New Horizons*, a major new textbook published in 2021 in the University of Arizona Press's Space Science series.

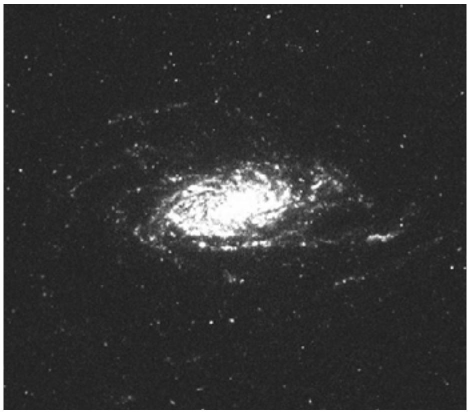
Grundy is a co-investigator on two NASA space missions. New Horizons explored the Pluto system in 2015 and, a billion miles beyond Pluto, the small Kuiper belt object (486958) Arrokoth in 2019. Grundy leads the surface composition science theme team for New Horizons. Lucy is enroute to explore Jupiter's co-orbiting Trojan asteroids after a successful launch from NASA Kennedy Space Center in October 2021. Grundy is the instrument scientist for Lucy's infrared imaging spectrometer system.

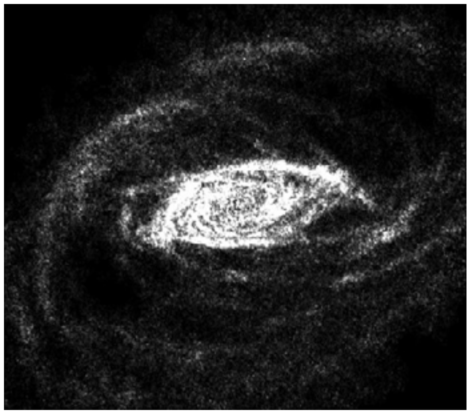
During 2021, Grundy was involved in observational projects using ground- and space-based telescopes including Hubble, Keck, LDT, and IRTF. These projects ranged from spectroscopic and photometric observations to high spatial resolution imaging to discover satellites of Kuiper belt objects and determine their orbits.

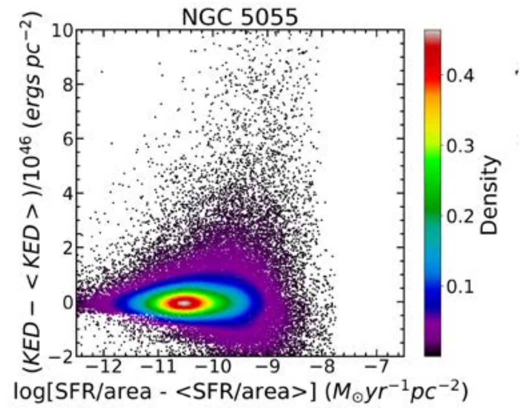
Grundy investigates low temperature materials in the Astrophysical Materials Laboratory at Northern Arizona University, in collaboration with Lowell's Dr. Jennifer Hanley and several NAU faculty members. This project involves numerous undergraduate and graduate students in researching the complexities of the low temperature materials that enable the spectacular geology of Pluto, Triton, Titan, and other small, icy planets and moons across the outer solar system.

Grundy served on the DPS Committee, the leadership body for the largest professional society of American planetary scientists, and as an editor for Icarus, the leading international scientific journal in planetary sciences. Grundy reviewed manuscripts during 2021 for many other scientific journals as well, including *Nature Communications, Monthly Notices of the Royal Astronomical Society, Earth & Space Chemistry, Journal of Molecular Structure*, and *Planetary Science Journal*. He reviewed funding proposals for three NASA Research & Analysis funding programs and reviewed observing proposals for the Hubble Space Telescope. •

ASTRONOMERHIGHLIGHTS







(Left): Image of far ultraviolet emission, related to star formation, of spiral galaxy NGC 5055 (data from the GALEX UV satellite).

(Middle): Image of atomic hydrogen gas in spiral galaxy NGC 5055 (data from Walter et al. 2008, "Astronomical Journal", 136, 2563).

(Right): Kinetic energy density of atomic hydrogen gas plotted against star formation rate per unit area, pixel-by-pixel, for spiral galaxy NGC 5055 (from Elmegreen, Martinez, and Hunter, 2022, "Astrophysical Journal", 928, 143).

Dr. Deidre Hunter

In summer of 2021 undergraduate Zorayda Martinez worked with Dr. Deidre Hunter as part of the Research Experiences for Undergraduates program run by the Department of Astronomy and Planetary Science at NAU. Their project was to look for a potential relationship between star formation and turbulence in the gas of a sample of spiral galaxies. Young massive stars live “fast and furious” lives, stirring up their surroundings with strong winds and finally shock waves when they explode as supernovae. One would expect that this energy from stellar feedback would drive turbulence in the surrounding gas and perhaps over large distances within galaxies.

Previously, Hunter with research assistant Haylee Archer and collaborators Bruce Elmegreen (IBM T. J. Watson Research Center), Caroline Simpson (Florida International University), and Phil Cigan (George Mason University) had looked for a correlation between turbulence and star formation in the LITTLE THINGS dwarf irregular galaxies. They constructed maps of kinetic energy density (KED) caused by excess motions of atomic hydrogen in the galaxies and compared them pixel-by-pixel to maps of star formation. Unexpectedly they found that star formation and KED maps were poorly correlated.

Elmegreen suggested that the group look at a sample of spiral galaxies for comparison, and that is what Hunter and Martinez did, again plotting values of KED against star formation for each pixel in the galaxy images. They found that there is at most a very weak correlation of star formation with KED, suggesting, just as with the dwarf irregulars, that stellar feedback does not drive turbulence beyond disrupting the region in which the stars formed. The large-scale driver for turbulence in dwarf and spiral galaxies, therefore, must come from some other process. •

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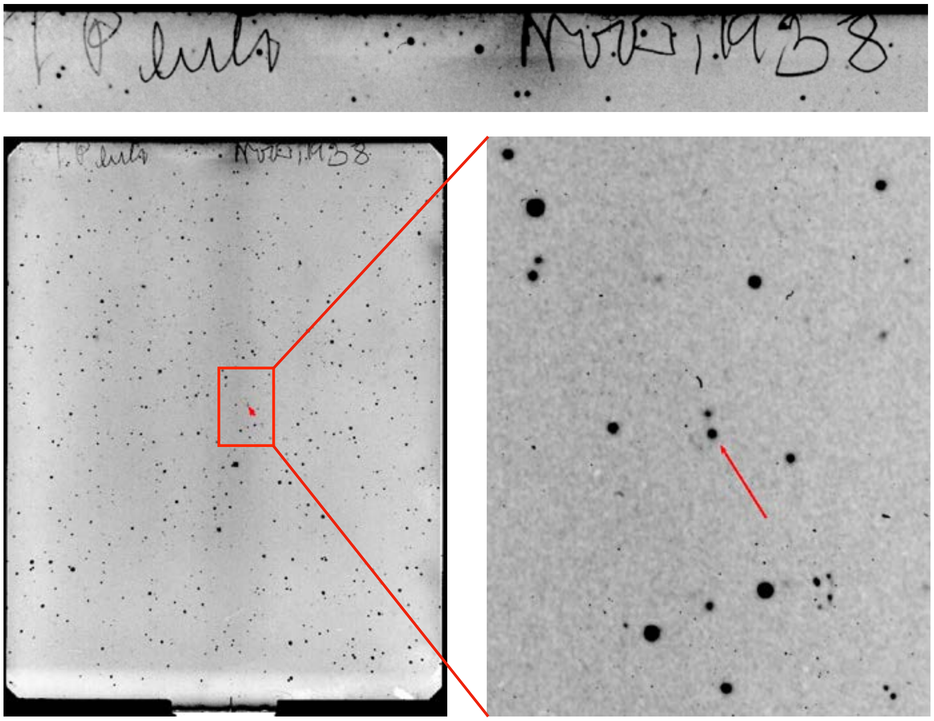

A scan of plate number 1561, featuring Pluto. On the left is an image of the whole plate. The banner is an enlargement of the observer's handwritten note on the plate emulsion identifying the field as that containing Pluto, and the local date Nov 5, 1938. The red box outlines the expanded view on the right. The arrow points to the position of Pluto.

Dr. Stephen Levine

Dr. Stephen Levine's research interests include large astrometric surveys and numerical simulation of the dynamics of astrophysical disk systems, with an emphasis on understanding the structure and evolution of lopsided disk and irregular galaxies. He is also interested in understanding the importance of passing stellar systems on the evolution of the outermost reaches of our own solar system. He maintains an active interest in stellar occultation studies of outer solar system objects, focusing on trans-Neptunian objects (TNO), Centaurs and comets. During 2021, he had the pleasure of observing an occultation by the TNO 2002 MS4 at LDT with a class of astronomy students from the University of Toledo.

Levine is working with Archivist Lauren Amundson on a project to digitize the Lowell collection of astronomical photographic images and spectra. The long-term goal is to preserve these data and make them available to the broader community in digital form over the internet. Levine was successful in landing a two-year grant from the NASA Planetary Data Archiving, Restoration and Tools program to support development of the tools needed to efficiently digitize the more than 50,000 plates and films in the observatory's collection. The plates in the Lowell collection range from 40 to more than 100 years old and are quite fragile. The data on these plates can extend our record of the sky by 60 to almost 100 years back before the widespread introduction of digital imaging to astronomy.

During 2021, Levine continued to serve as the Lowell Discovery Telescope (LDT) Scientist, working with the LDT observing, instrumentation, operations, and engineering communities to get the best out of the facility. As part of looking ahead to improving the image quality at the LDT, Levine began putting together a lab for developing adaptive optics capabilities with the goal of including corrective systems in current and future LDT instrumentation. •

ASTRONOMERHIGHLIGHTS

The Lowell Observatory solar telescope continues to observe the Sun with EXPRES in an effort to help astronomers better understand the manifestation of stellar activity in extreme precision radial velocities to try and detect the presence of an earth-mass planet.

Dr. Joe Llama

Dr. Llama works on detecting and characterizing exoplanets using high-resolution spectroscopy. In 2021 he continued overseeing the operation of the Lowell Observatory Solar Telescope (LOST). LOST is Lowell's smallest telescope; however, what it lacks in size it more than makes up for in data rates! Since commissioning, LOST has acquired 30,000 high-resolution spectra of the Sun with the EXtreme PREcision Spectrograph (EXPRES). Coupling LOST and EXPRES, Llama and his team are curating the most precise and extensive dataset of Sun-as-a-star observations.

Llama and his colleagues are using this dataset to better characterize stellar activity, which is the primary obstacle hindering our ability to measure the mass of an Earth-sized exoplanet. An exoplanet like earth, orbiting a star like our Sun, located in the habitable zone exerts a minuscule 10 cm/s radial velocity amplitude. This signal is an order of magnitude lower than the signal from stellar activity (star spots, place, faculae), meaning the signal of a potential exoplanet can be completely drowned out by the star itself. The Sun offers an amazing opportunity to develop techniques to mitigate these activity signals since spacecraft such as NASA's Solar Dynamics Observatory (SDO) provide incredible spatially resolved images of the Sun in multiple wavelengths.

In addition to the data Llama is acquiring with LOST/EXPRES during the day, he is also a part of the science team for the 100 Earth's survey, which is the primary science program for EXPRES. He and astronomers from Yale and San Francisco State University are searching for earth analog exoplanets around bright, solar-type stars. In 2021 the team have continued to collect data with LDT/EXPRES on a number of promising candidates and hope to publish exciting results in 2022! To help with this effort, Llama hired Postdoctoral Researcher Dr. Vedad Kunovac to join him at Lowell. Kunovac did his PhD work on the Rossiter McLaughlin effect, a phenomenon that enables us to characterize the spin-orbit alignment between an exoplanet and its host star. Kunovac will continue this work while at Lowell and to join the effort to search for earth analog exoplanets.

In collaboration with Dr. Evgenya Shkolnik (ASU) and Dr. Tyler Richey-Yowell (ASU PhD candidate, joining Lowell as the first Prize Postdoc in 2022), Llama enjoyed using the Keck Telescope to search for auroral emission from exoplanets. By using the near-infrared instrument, NiRSPEC, Llama, Shkolnik, and Richey-Yowell are conducting a survey of close-in exoplanets around low-mass stars where the contrast ratio between the star and planet is most favorable to detect this key signature of an exoplanetary magnetic field. They were awarded four half-nights on Keck to conduct this survey and the data is currently being analyzed. •

ASTRONOMERHIGHLIGHTS

Massey & Neugent's searches for Wolf-Rayet stars were carried out with data from the Kitt Peak 4-meter and the 6.5-meter MMT in southern Arizona, and the Swope 1-meter and Baade 6.5-meter telescopes on Las Campanas in northern Chile. Pictured here is the Swope 1-meter, with the Large Magellanic Cloud ("cloud" near upper left) and southern Milky Way (bright band of stars). Image by Kathryn Neugent.

Dr. Phil Massey

Despite the many successes that modern massive star evolutionary theory has enjoyed, one of the most vexing (apparent) failures has been its inability to correctly predict the relative number of red supergiants (RSGs) and Wolf-Rayet (WR) stars. Both red supergiants and Wolf-Rayet are evolved massive stars, burning helium in their cores, having exhausted their supplies of hydrogen. In 1980, the evolutionary theorist Andre Maeder (Geneva University) led a study showing that the relative number of these stars changed drastically as one went from the inner to outer parts of the Milky Way. Maeder attributed this to the effect of mass-loss on the evolution of massive stars. Stars in the inner regions of the Galaxy would lose more mass during their lifetimes because their heavy element content (the "metallicity") was greater, extending the lifetime of the Wolf-Rayet phase relative to that of the red supergiant phase.

Phil Massey was an impressionable graduate student at the time, about to obtain his PhD from the University of Colorado in Boulder. He recalls sitting in the JILA reading room pouring over this paper. The idea that one could use population studies as a test of evolution theory seemed really cool to him, and this paper set him on a path that led him to study the massive star populations in nearby galaxies for the next 40+ years. During the ensuing decades, he and his collaborators conducted many similar tests. Their work helped establish the validity of current evolutionary models while at the same time identifying places where the model predictions did not work so well. For instance, studies with (then) undergraduate Maria Drout showed that evolutionary models did a poor job of reproducing the number of yellow supergiants as a function of luminosity. Their theorist collaborators and colleagues (including Maeder) then made the physics a little more rigorous, and work with Drout and Kathryn Neugent showed that the problem was solved. Later studies, with Neugent, showed that the relative number of WN- and WC-type Wolf-Rayet stars were correctly predicted by modern models. (Drout is now a professor at the University of Toronto, while Lowell Research Associate Neugent will be begin her Hubble Postdoctoral Fellowship at the Center for Astrophysics at Harvard this coming year.)

However, a nagging concern has always been that the models have never agreed with Maeder's observations. Indeed, in a 2004 Annual Reviews paper, Massey had used the best data available at the time and showed that while the observations showed a steep decrease in the number of red supergiants (relative to Wolf-Rayet stars) with increasing metallicity, the models actually predicted a relatively flat distribution in this ratio.

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The following decade resulted in a number of better surveys, however. Neugent and Massey obtained a complete census for Wolf-Rayet stars in the Magellanic Clouds, M31, and M33, and subsequently developed a technique for identifying red supergiants in these galaxies. (The trick in this is to be able to distinguish red supergiants from foreground red stars, and from the insidious asymtotic giant branch stars.) The goal of these studies was not to address the RSG/WR ratio problem (although that was always in the back of their minds) but as part of their overall work to better characterize the massive stars in the local neighborhood.

Given the success of all of these recent surveys for red supergiants and Wolf-Rayet stars, Massey and Neugent decided to revisit the issue this year, comparing their observations to the predictions of the latest evolutionary models. Despite all the improvements incorporated into theory, the models still predicted a relatively flat distribution of the relative number of red supergiants and Wolf-Rayet stars as a function of metallicity. And low and behold, this is now exactly what the observations show as well! Furthermore, the absolute numbers agree well between the observations and the numbers. The issue for the past 40 years has turned out not to be deficiencies in theory but rather incompleteness in the observations, a problem which they had solved with their many surveys. Their work was done in collaboration with Trevor Dorn-Wallenstein and Emily Levesque (both at the University of Washington), theorists Jan Eldridge (University of Auckland) and Elizabeth Stanway (University of Warwick) and published in the December 2021 issue of the *Astrophysical Journal*. •

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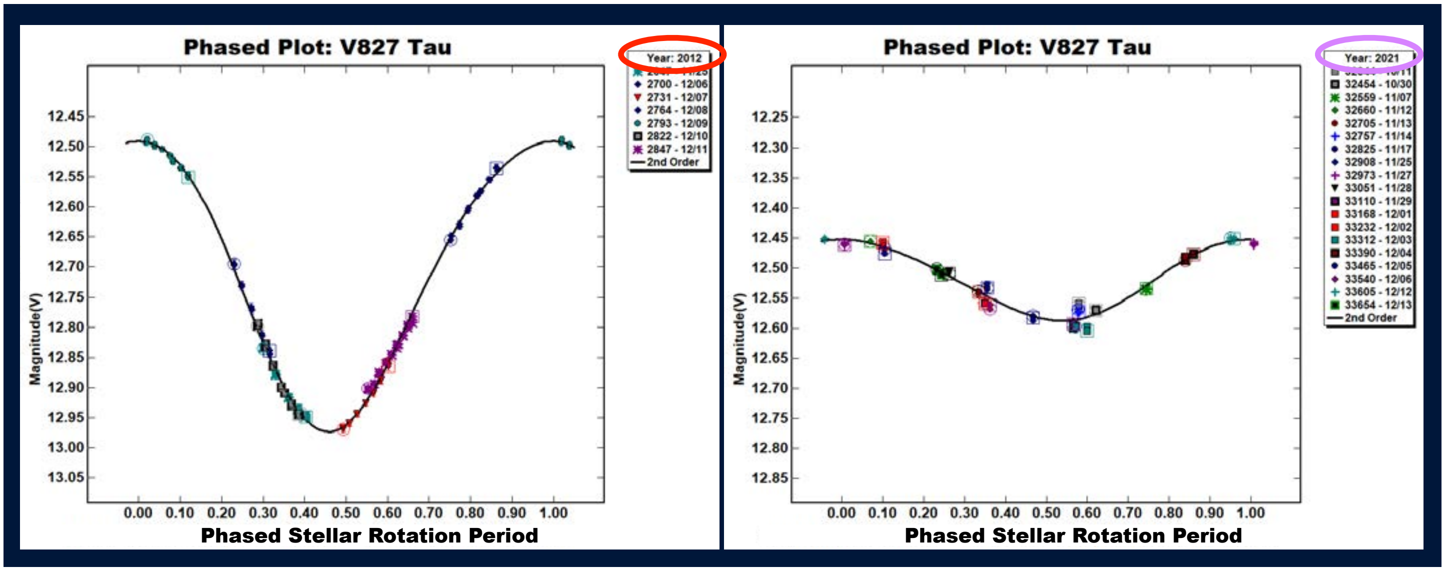

Brightness fluctuations of the young star V827 Tau in 2012 (left) and 2021 (right) showing how the magnitude of the variability decreased by a factor of three over the 11-year period. These brightness changes are plotted phased to the 3.8-day rotation period of the star and occur as the result of giant star spots on the stellar surface. The evolution of the spotted fraction over time is evident from the change in depth of the variations.

Dr. Lisa Prato

Team DEFT (Disks and Exoplanets Flagstaff Team) and Dr. Lisa Prato had another great year of science even as the pandemic lingered on, and the majority of our activities took place via zoom. Participation at conferences, workshops, committee meetings, and on panels and reviews and observing at telescopes continued to be remote but that didn't slow down team members' accomplishments. Graduate students Lauren Biddle and Shih-Yun Tang both published papers and attended meetings online, giving talks and participating in discussions remotely. Lauren chaired the opening session of the (Virtual) Stars & Planets in the UV symposium in 2021 May and presented her work at the (Virtual) 20.5th Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun in a poster; her paper on accretion hot-spot induced variability in the young star CI Tau was published in the Astrophysical Journal (Biddle et al. 2021). In September, Biddle and Prato gave (Virtual) tandem FLASH talks at NOIRLab on Biddle's young star accretion work and Prato's project to understand the potential for planet formation around young binaries. Biddle also applied for several postdocs and obtained a position at UT Austin! Tang completed and published, also in the Astrophysical Journal, his 2nd year NAU project on brown dwarfs and free-floating planets (Tang et al. 2021) and together with Prato and colleagues at Rice University, completed and published in the Journal of Open Source Software and in the Astronomical Journal version 1 of the publicly available Python software package IGRINS RV for precision radial velocity measurements with the IGRINS spectrograph, which was deployed at the LDT part time from 2016-2019 (Tang et al. 2021; Stahl et al. 2021). Tang also designed and taught an online Python class for NAU and Lowell students and faculty in collaboration with Christian Tai Udovicic, successfully completed his PhD written prospectus, and presented a talk on his 2nd year project work at the (Virtual) Emerging Researchers in Exoplanet Science symposium.

Post-baccalaureate interns Hannah Zigo, Cody Huls, and Sean Graham made progress on analysis and compiling of critically important observed and synthetic standard star libraries (Zigo and Huls), contributed to a draft paper on the young binary V562 Ori (Huls), and carried out data analysis of the unusual young binary system UY Aur (Graham); Graham departed DEFT for Phoenix and is currently pursuing opportunities in Data Science. Team guru Brian Skiff has continued to monitor the brightness variability of the young star sample DEFT members are studying; Skiff's figures of the young V827 Tau system show how its variability changed dramatically from 2012 to 2021! NAU undergraduate Hunter Brooks joined the team in September and worked with Tang on identifying low-mass stars and brown dwarfs in the open cluster Blanco 1.

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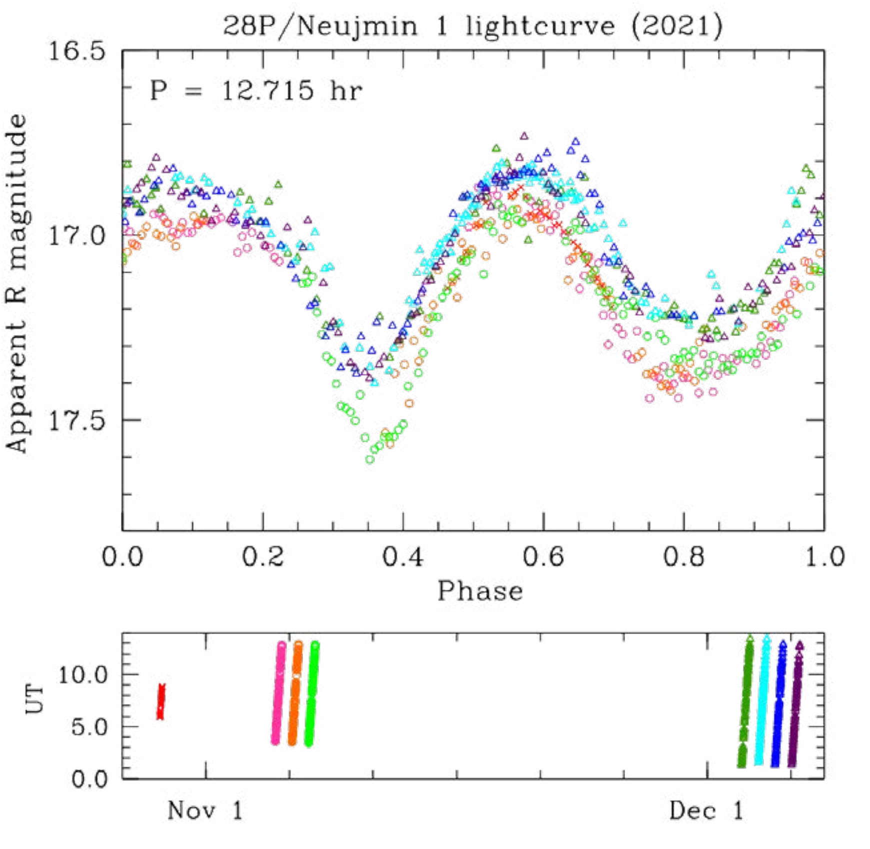
Prato continued as co-Chair of the AAS Publications Committee, helping to usher in the new era of Open Access publishing for the Society and participating in the AAS Strategic Assembly. In March 2021, Prato guest taught a 3-week unit in the NAU graduate Applications in Spectroscopy course in the Department of Astronomy & Planetary Science. Prato chaired the Scientific Organizing Committee for the Sagan Summer Workshop (July 2021) and served on NASA and NSF panels and reviews. In addition to 3 existing NASA and NSF grants, in August 2021, Prato was awarded an NSF grant for the study of young binary stars (~$0.5M) and in November, a sub-contract award (~$0.26M) from Rice University for a joint NASA program involving Prato and Joe Llama in the study of direct detections of young exoplanet atmospheres. Prato was granted 36 nights of observing time in 2021 on the Keck (10m), Blanco (4m), McDonald (2.7m), and Steward (90") telescopes and published a total of eight refereed papers, including the four noted above, with colleagues, primarily at Rice University and UT Austin. Prato co-authored a paper (Benedict et al. 2021, Astronomical Journal) with Lowell colleagues Otto Franz, Larry Wasserman, and Brian Skiff on the intriguing quadruple system vA 351, a hierarchical system comprised of three low-mass M stars and a white dwarf star that Otto Franz has been studying for decades. Prato also participated in outreach activities at the national and international level, from a speaking presentation to the Star Academy high school students in Puerto Rice (in Spanish) to outreach events at the Atlanta Aquarium and the San Diego Fleet Science Center with the American Chemical Society, and in the Diversity, Equity, and Inclusion committee at Lowell. •



The phased light curve of Comet 28P/Neujmin 1, based on our best determined rotational period of 12.715 hr. Note that the amplitude and shape of the light curve is nearly constant throughout this interval. The variations in the overall brightness of the nucleus from month to month are due to a combination of changing distance from both the Sun and Earth, along with a decrease in the phase angle thereby altering the bulk reflectivity.

Dr. David Schleicher

Dr. David Schleicher continued his long-standing program of photoelectric photometry of comets throughout 2021. More than a dozen objects were measured with narrowband filters, allowing the emission from five molecular species to be used to determine both the rate of outgassing and the chemical composition for each comet. Several, including 4P/Faye, 6P/d'Arrest, and 67P/Churyumov-Gerasimenko, had been observed multiple times since the 1980's, and the new observations were intended to look for evidence of secular changes – a few indeed showed decreased activity since previous apparitions while the others were unchanged. Several additional comets were newly arrived from the Oort Cloud, so their characteristics were completely unknown. Of these, the most notable was Comet PanSTARRS (2017 K2), discovered four years earlier and not reaching its closest approach to the Sun until late in 2022. Schleicher successfully first detected cyanogen gas (CN) when the comet was still beyond Jupiter's orbit, and he will continue to determine at what distance each gas species becomes detectable as the comet heats up during its approach.

Schleicher, along with Research Associate Allison Bair, have examined trends in water production among comets based on orbital dynamical class. Their database includes over 190 objects having OH measurements obtained since the OH filter was first introduced in 1980. The OH values have now been converted to yield the production rates and vaporization rates of water from each comet's nucleus. These show a clear downward trend as comets age, with comets that have approached the Sun more often having lower amounts of outgassing. This result is reinforced when taking into account the sizes of the nuclei involved. Of the more than 50 comets with nucleus size measurements, Bair and Schleicher could compute the fraction of the surface area with exposed ice vaporizing from solar heating, and again there was a clear trend towards smaller active fractions with increasing age.

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A comet having the 2nd smallest active fraction (less than 0.1% of its surface is still active) is Comet 28P/Neujmin 1. With an unusually long orbital period of 18.3 years, Neujmin 1 has only been investigated a few times in the modern age of digital cameras. Because of its very low activity level, the nucleus is easy to directly detect, especially as its size is quite large – double that of Halley's comet! Schleicher, Research Associate Brian Skiff, and former Lowell post-doc Dr. Matthew Knight (U. S. Naval Academy) began collecting brightness measurements in November to remeasure its rotational period (approximately 12.7 hr); as an elongated body, its brightness regularly varies as the cross-section changes as viewed from the Earth. The amplitude of the variations directly relates to the degree of elongation, and the details of the measured light curve as seen from differing viewing angles (as the comet moves along its orbit) can be used to infer both the 3-dimensional shape of its nucleus as well as the orientation of its polar axis. By the end of 2021, the amplitude was larger than in 1984 or 2002, implying that the body was now being seen more equator-on, rather than from closer to pole-on. Observations will continue through early 2022 as the body recedes from the Sun.

Finally, Schleicher completed analyses of the outgassing and composition of Comet 21P/Giacobini-Zinner. This study confirmed that G-Z is nearly unchanged since it was first investigated in detail in 1985; at that time it was determined to have strong depletions of certain molecules, including diatomic (C2) and triatomic (C3) carbon, with respect to both hydroxyl (OH, a direct byproduct of water) and cyanogen. Note that the pure carbon species, thought to be the byproducts of acetylene and ethane, have more recently been discovered to be depleted in about 15% of all comets within the Lowell comet photometry database. Nearly all of these depleted objects are believed to have arrived from the Kuiper Belt and are thought to reflect the colder conditions present at the time of their formation in the very early Solar System. Comet G-Z was the first of these depleted comets to be measured and is considered the prototype of this compositional class. •

ASTRONOMERHIGHLIGHTS

The new JPL rollaway enclosure (left), next to the 20-inch Titan Monitor telescope (center) and the 21-inch telescope on Mars Hill (right).

Dr. Gerard van Belle

The 2021 Research Year was another busy one for Dr. Gerard van Belle and his research group. A full year of pandemic meant no travel, and a focus on local research and development.

Completing a major research effort that lasted well over a decade, van Belle published a survey of the sizes of giant stars, "Direct Measurements of Giant Star Effective Temperatures and Linear Radii: Calibration against Spectral Types and V - K Color". This journal article used archival angular diameters for 191 giant stars from the Palomar Testbed Interferometer, a facility he worked on while at JPL and Caltech. This effort had been funded by grants from both the National Science Foundation and NASA Astrophysics, and the resulting 310-page preprint has been noted for both its content and behemoth size. (Like Mark Twain, van Belle was obviously paid by the word.) PhD students Dr. Zach Hartman and Catherine Clark contributed to this effort, as well as Lowell adjunct Dr. Kaspar von Braun. This project also benefited from contributions by William Bucklew and Gary Cole, originally begun under the Lowell Amateur Research Initiative (LARI) project, who were also named as co-authors on journal article. This work is intended to be the definitive reference resource for temperatures and radii of these stars, which are the evolved counterparts to our Sun.

Additional work with Clark include continuing speckle observing & instrument development, using the Quad-camera Wavefront Sensing Speckle Interferometer (QWSSI) instrument on the Lowell Discovery Telescope (LDT). Clark published her first first-author paper at the end of 2021, "A Dearth of Close-in Stellar Companions to M-dwarf TESS Objects of Interest", with additional papers in support of her dissertation expected in 2022. This first paper showed that stars indicated by the NASA TESS satellite to be likely planet hosts were less likely to have a secondary stellar companion, which is consistent with expectations such stellar companions would inhibit the presence of planetary systems around the primary star. Improvements to QWSSI include elimination of a light leak problem that has allowed the instrument to achieve its design goals for sensitivity.

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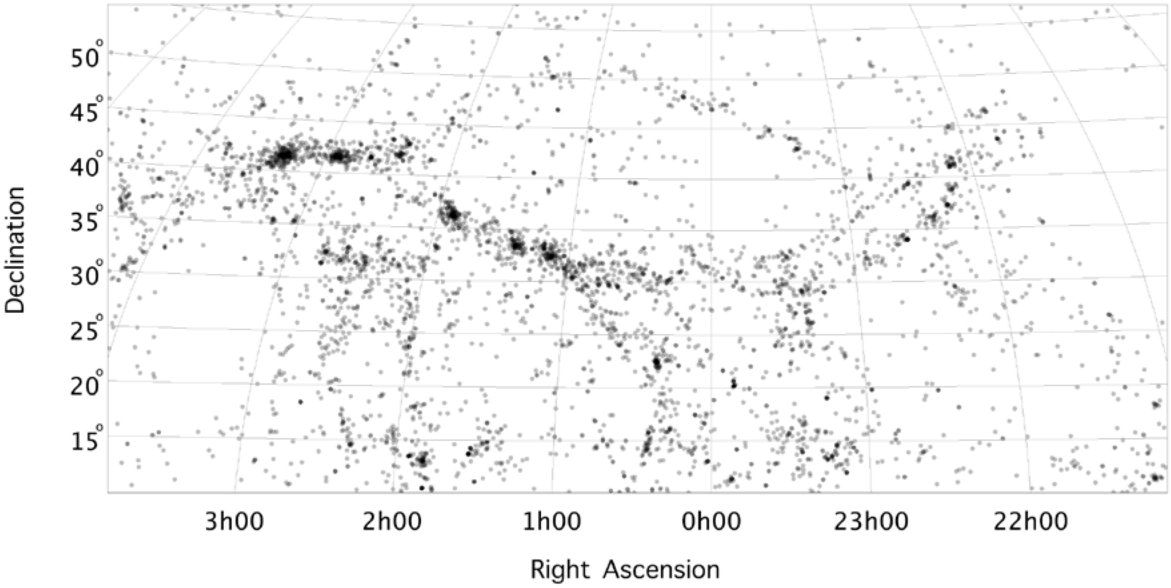
In partnership with colleagues Drs. Mike Shao and Navtej Saini at NASA Jet Propulsion Laboratory in Pasadena, van Belle installed a new rollaway observatory shed on Mars Hill to house a JPL Synthetic Tracking Telescope. This telescope is sited next to the 20-inch Titan Monitor Telescope on Mars Hill next to the ADC construction site, and both are conducting robotic operations on clear nights. The JPL telescope has four co-mounted 11-inch Celestron RASA imagers, and analyzes 240 megapixels from the four imagers at a one-minute cadence with 16 teraFLOPS of GPU processing power in real time, looking for near-earth asteroids.

Additional instrumentation work has proceeded with the Navy Precision Optical Interferometer 'Plus-Up' work. A full engineering team has now been staffed up by van Belle and project manager David Noble, and includes Thomas Coleman (software), Ben Hardesty (mechanical engineering), and Khristian Jones (electrical engineering). Along with site staff Jeff Gehring, Heidi Larson, and Beau Wigman, a collection of over 200 punch list items are being addressed at the site, for repairs and rejuvenation of the facility. Two of the 1-meter PlaneWave telescopes are in regular use as individual telescopes as we develop the beam routine to integrate them into the array. 'Lessons learned' on these operations are being incorporated into the observatory's plans for the Peggy and Eric Johnson 1-meter telescope.

From van Belle's group, PhD student Dr. Zach Hartman successfully defended his dissertation in June of 2021 at Georgia State University, and Catherine Clark was preparing to do the same in April of 2022 at Northern Arizona University. TUndergraduate student interns also transitioned, with NPOI engineering interns Adam Schilperoort, Peter Kurtz, and Nicholas Green all graduating and landing jobs; NPOI interns Wyatt Clark and Bradley Kingsley are slated for the same in 2022. •

Two of the 1-meter telescopes on-sky for the night for single-aperture robotic telescope use. Inset: an image of the moon on a notecard, in the beam train of the 1-m fast tip-tilt system.



The galaxy distribution in the region of the Perseus-Pisces Supercluster. Each dot represents a galaxy. Prominent filamentary features spanning many millions of light-years can be seen.

Dr. Michael West

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

West's main research activities were:

- *Quasars as tracers of the large-scale structure in the early universe.* One of the most striking features of the distribution of galaxies is its filamentary appearance, with long, luminous strands of galaxies woven together into a vast cosmic web. Nowhere is this more evident than the nearby Perseus-Pisces Supercluster (below), a colossal chain of galaxies that snakes across millions of light-years. But how and when did such enormous structures form? Finding filaments when the universe was younger can provide insights into the cosmic web's evolution. Unfortunately, galaxies become increasingly faint and sparse tracers of filaments as we look further into space. However, there's another way.

  Quasars are the bright hearts of distant galaxies. They're powered by supermassive black holes and shine so brightly that they can be seen across enormous distances. This makes quasars ideal tracers of the large-scale matter distribution in the early universe. Michael has developed an innovative statistical method to identify filaments in the distribution of more than a million known quasars. This research is ongoing.

- *Galaxy cluster alignments at early epochs.* Galaxies often cluster together into systems of hundreds or even thousands of members bound together in a gravitational dance. Numerous studies have shown that neighboring galaxy clusters tend to "point" toward each other. These alignments are imprinted by the large-scale filaments in which clusters are born. However, studies to date have looked only at clusters in the nearby (present-day) universe. Michael is leading a project to study the evolution of cluster alignments, looking back across billions of years of cosmic time. This is an ongoing collaboration with astronomers in Finland and Estonia.

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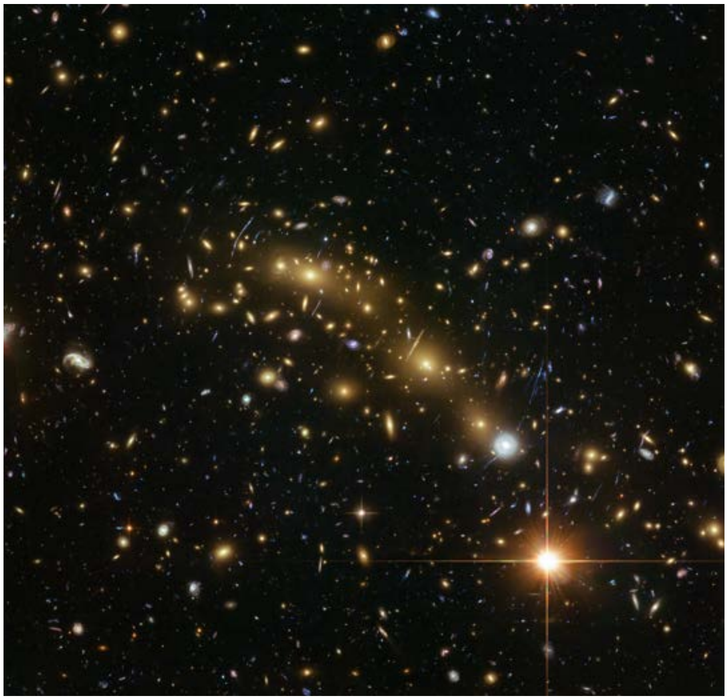
On the public outreach and community fronts:

- Michael continued to have a leading role in developing exhibits and writing text for Lowell's new Astronomy Discovery Center. 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*. He reached a milestone this year of having written 100 columns for Lowell newsletters since his arrival in 2015.
- At the invitation of the Office of Astronomy for Development, Michael served on its project review panel. The OAD's mission is "to use astronomy to make the world a better place" through socio-economic development. With support from the International Astronomical Union, the OAD has funded more than 200 projects on five continents since 2013 (including an award to Lowell's Native American Astronomy Outreach Program in 2020). A total of more than 100,000 EUR was awarded to projects around the world in 2021.
- Michael was selected as a U.S. Fulbright Scholar for 2020-2021. However, this was deferred for a year because of the pandemic. He will spend two months in Finland in 2022 and again in 2023 to teach a course on *Communicating Science with the Public*. While there, he'll also research Finnish ways of communicating science and the role that culture plays. The knowledge gained will benefit Lowell's science and outreach missions.

West will step down as Deputy Director for Science in January 2022 but will remain at Lowell as a tenured astronomer. Dr. Christoph Keller will take over as the newly named Director of Science. •



Galaxy clusters like this, MACS J0416.1–2403, are often highly elongated and aligned with neighboring clusters. We see this cluster as it looked four billion years ago. Credit: ESA/ Hubble, NASA.

Dr. Danielle Adams

Dr. Danielle Adams is a cultural astronomer who studies indigenous Arabian astronomy and its heritage in the star names we continue to use today. In 2021, she continued her service on the Working Group for Star Names (WGSN) of the International Astronomical Union (IAU). Later in the year, she was invited to join the IAU's Working Group on Astronomy in Culture (WGAC) and participate on the working group's Culturally Sensitive Sites committee.

When her duties as the observatory's Deputy Director for Marketing and Communications permitted, Adams conducted original research in a collection of Arabic rhymed prose and started drafting her first post-dissertation monograph. Arabs used pieces of rhymed prose long ago to codify the floral, faunal, and societal impacts of seasonal changes throughout the year. Because these rhymes were as easy to memorize as modern-day nursery rhymes, they formed an informal calendar that people supplemented with new rhymed phrases as years passed. Adams' work marks the first time that this collection of Arabic rhymed prose has been translated into English.

An example of the above is the following piece of rhymed prose for the Two Grumbling Dogs (al-harrārān in Arabic), a pair of bright stars that rose together and are known today as Vega and Antares.

- Arabic text (transliterated): "Idhā ṭalaʿa l-harrārān, hazalati s-simān, wa shtadda z-zamān, wa waḥwaḥa l-wildān."
- English translation: "When the Two Grumbling Dogs rise, emaciated become the fat animals, the winter season intensifies, and children exhale into their hands."

The Two Grumbling Dogs rose out of the eastern horizon during the morning twilight at the end of November, so the weather was cold, and food was scarce, causing previously fat animals to lose weight. In the last phrase, the Arabic word waḥwaḥa reflects the "haa" sound made when people exhaled hot air onto their hands on a cold day. Thus, this simple piece of rhymed prose reveals much cultural information about Arab practices during the onset of winter.

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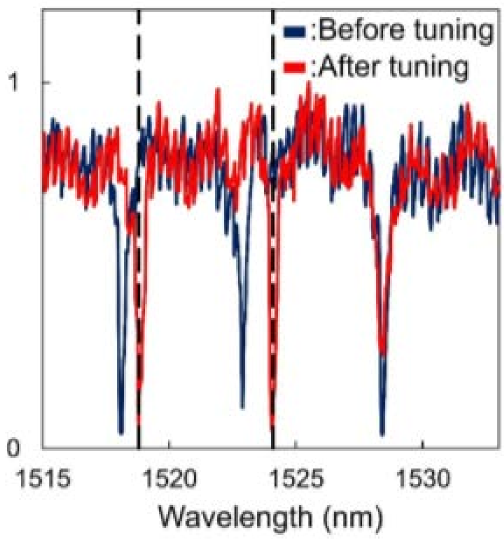
As many events were again virtual during much of 2021, Adams continued her public outreach through virtual meetings and live streams. Among them, she was invited to give a virtual talk on May 14 for Native Sky watchers as part of the NASA-funded Two-Eyed Seeing project (https://www.nativeskywatchers.com/two-eyed-arabian&stardust.html). Drawing from Arabic sources of poetry and rhymed prose, she presented ancient methods for using rising and setting stars to forecast seasonal changes. In October, Adams gave another invited talk about indigenous Arabian astronomy as part of NASA's Universe of Learning (https://www.universe-of-learning.org/science-briefings/2021/10/07/multicultural-perspectives-on-astronomy). Adams also presented virtual tours of Arabian skies to a 2nd grade class and a 4th grade class as part of the Flagstaff Festival of Science, and to a public audience as part of the Flagstaff Star Party. •



The dashed lines show the wavelengths corresponding to the atmospheric OH emission lines, the blue curve shows the suppressive effect of the ring resonators as initially fabricated, and the red curve shows suppression after the rings have been "tuned" properly.

Dr. Kyler Kuehn

Dr. Kyler Kuehn is one of the founding members of the Southern Stellar Stream Spectroscopic Survey (S5). In 2021 his research group released the results of five separate studies of stellar streams (see https://s5collab.github.io/#publications for details). These streams used to be dwarf galaxies or globular clusters in the halo of our Milky Way galaxy, but they have been pulled apart by its gravitational forces, and can now be observed as long, thin streams of stars all moving in similar orbits around the Galaxy. Kuehn participated in the original discoveries of these streams by the Dark Energy Survey, as well as follow-up studies by the S5 team using the Anglo-Australian Telescope to distinguish the members of these streams from other nearby stars. The chemical composition of the stars is also used to confirm stream membership and provide insight into the formation and evolutionary history of the stream. For this reason, Kuehn has added high-resolution spectroscopic observations with LDT's EXPRES instrument to S5's capabilities. A publication with exquisite details on several stars from these streams will be forthcoming from Kuehn and the S5 group in the next year.

In addition to his observational astronomy research, Kuehn directs the Optics and Photonics Applications Laboratory (OPAL) at Lowell Observatory. This is a new effort within the Technology Group, focusing on two areas:

1) laboratory development of adaptive optics (AO), with the ultimate goal of installing an AO module on the 4.3m Lowell Discovery Telescope (as well as the observatory's smaller telescopes) to improve their light-gathering capabilities, and

2) micron-scale technologies such as photonic ring resonators to suppress the infrared emission from OH molecules in the Earth's upper atmosphere that would otherwise overwhelm the observed signal from astronomical sources.

The ring resonator technology in particular was described in previous Annual Reports, and Kuehn and his collaborators continue to advance the state-of-the-art in this field. For example, they developed several methods to "tune" ring resonators that were fabricated slightly outside of the required specifications (namely, filtering out light at wavelengths exactly corresponding to the OH emission lines). A nanolithography facility will be contracted to fabricate several of these photonic devices in mid-2022.

In addition to founding OPAL in 2021, Kuehn secured initial funding to outfit the AO test laboratory from a variety of Lowell sources, including the Director's Opportunity Network and the Technology Development Fund. •

RESEARCHERHIGHLIGHTS

Cover pages of the mission design reviews for CORAL and Calypso as reported in the Decadal Survey.

Dr. Audrey Thirouin

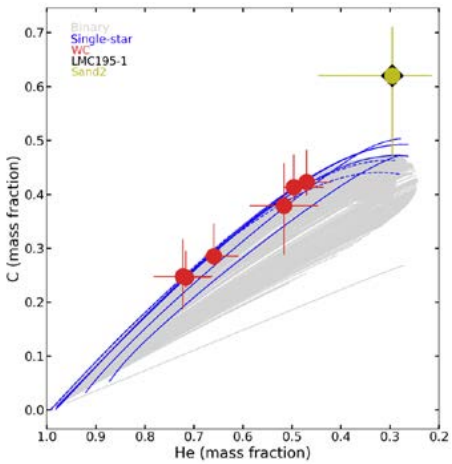
Dr. Audrey Thirouin's research focuses on the small body populations from the highly evolved minor bodies in the inner Solar System to the primordial bodies at the edge of our solar system.

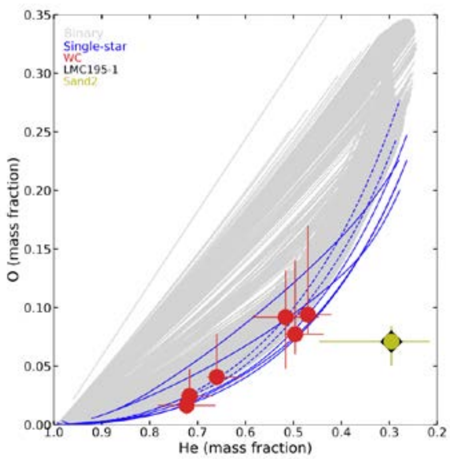
From September 2020 to April 2022, most of Thirouin's time was dedicated to the Planetary Science and Astrobiology Decadal Survey 2023-2032, which is organized by the National Academy of Science. The main goal of the Decadal is to provide recommendations for the upcoming decade to promote discoveries, improve the field of planetary and astrobiology sciences, and recommend the next generation of space missions. She was a member of the Small Solar System Bodies panel and worked on several chapters identifying the key scientific questions to answer over the next decade. She also participated in the concept and design of two space missions to the outer solar system: CORAL and Calypso. The Centaur ORbiter And Lander (CORAL) aims to characterize and obtain landed in-situ compositional measurements of a Centaur (small body on unstable orbits between those of Jupiter and Neptune) whereas Calypso's goal is to search and characterize ocean worlds in the Uranian system and the trans-Neptunian belt (see Figure). The CORAL mission has been recommended by the Decadal Survey for NASA's New Frontiers 6 program.

Thirouin was also involved in additional service to the community, from reviewing publications for several journals to evaluating Hubble Space Telescope Cycle 29 proposals. In 2021, she co-authored two refereed papers. One of these papers by graduate student Ben Sharkey (Lunar and Planetary Laboratory, LPL) described the rotational and compositional properties of the Earth's quasi-satellite named Kamoʻoalewa as well as its possible origin. This work received a lot of attention from the public thanks to a press release organized by the University of Arizona/LPL and was even highlighted in The New York Times.

In September 2021, Thirouin and Dr. Scott Sheppard (Carnegie Institution for Science) obtained a National Science Foundation (NSF) grant to pursue their work on the discovery and characterization of contact binaries in the outer solar system using the Lowell Discovery Telescope and the Magellan Telescope. In June 2021, Thirouin submitted a proposal to NASA's Solar System Observations program to model and detect mutual events in trans-Neptunian binary systems. This proposal, with Thirouin as Principal Investigator, Dr. William M. Grundy (Lowell Observatory), Dr. Scott S. Sheppard, and Dr. Keith S. Noll (NASA-Goddard Space Flight Center) as co-investigators, was awarded in January 2022. Thirouin's line of investigation is fully funded by external grants for the upcoming years. •

PHD**STUDENT**HIGHLIGHTS





(Left): The carbon and helium abundances of the WC-type stars (in red) and the WO-type stars (LMC195-1 and Sand 2, the overlapping yellow dot and black diamond) compared to the single-star and binary evolutionary models. The WC-type stars are in agreement with both types of evolution, while the WO-type stars have more carbon than predicted.

(Righ): The oxygen and helium abundances of the WC-type stars (in red) and the WO-type stars (LMC195-1 and Sand 2, the overlapping yellow dot and black diamond) compared to the single-star and binary evolutionary models. The WC-type stars are in agreement with both types of evolution, while the WO-type stars have less oxygen than predicted.

Erin Aadland

Erin Aadland is finishing her fourth and final year as a graduate student in the Astronomy and Planetary Science program at Northern Arizona University, working with Dr. Philip Massey on the evolution of massive stars at Lowell Observatory. This past year, she has finished the research for her dissertation on Wolf-Rayet stars. These stars are the massive descendants of O-type stars and have had their outer layers stripped away revealing their He-burning cores. This stripping process can either occur via the star's own stellar winds or with the aid of a close companion star stripping material off. Aadland's dissertation looks into two longstanding questions: 1) how the Wolf-Rayet star last two subtypes relate; 2) whether Wolf-Rayet stars evolve with a companion star or by themselves.

These Wolf-Rayet stars have three subtypes, two of which are incredibly similar. The subtypes are classified by the emission lines in their optical spectrum. The first is the nitrogen sequence, WN-type, which have nitrogen and helium lines. The carbon sequence, WC-type, and oxygen sequence, WO-type, both have carbon, helium, and oxygen lines. The WC-type and WO-type have an almost identical spectrum, except that the WO-type stars have one high-excitation oxygen line that is much stronger (five times as strong). This oxygen line could be due to further chemical evolution, where the WO-type stars simply have more oxygen than the WC-type stars. However, the strength of this line could also be due to a higher temperature, meaning the WO-type stars are not actually more evolved than the WC-type stars as previously thought.

Aadland and her collaborators compared WC-type and WO-type Wolf-Rayet stars to see whether the WO-type Wolf-Rayet stars have a higher oxygen abundance or a higher temperature than the WC-type stars. They accomplished this by modeling the spectrum of six WC-type and two WO-type stars. By modeling the spectrum, one can determine the physical parameters (temperature, chemical abundances, etc.) of the star. During the comparison, they found that the WO-type stars were indeed further evolved. The stars had more carbon and less helium than the WC-type stars, indicating further He-burning had taken place. However, the WO-type stars did not have more oxygen than the WC-type stars but did have a higher temperature. They concluded that the WO-type Wolf-Rayet stars are indeed further evolved, but that the strength of the high-excitation oxygen line was due to a higher temperature abundance.

Another aspect of this study was evaluating which stripping mechanism was responsible for the evolution of Wolf-Rayet stars. This comes down to whether a close companion star is necessary for their evolution. To evaluate this, Erin compared the physical parameters of the WC- and WO-type stars to theoretical evolutionary models that predict the physical parameters for each timestep of a star's life. There are evolutionary models for both single-star evolution and binary evolution. As shown in the figures, the WC-type stars are in agreement with both types of models. However, the WO-type stars are not in agreement with either. This disagreement is due to the reaction rate that is producing oxygen, producing too much oxygen. If this rate is reduced by a factor of 3, both sets of evolutionary models can actually predict the chemical abundances observed in the WO-type stars. This has huge implications for other astronomical processes, in particular black holes.

By reducing the oxygen reaction rate, higher mass black holes could form which would solve a long-standing issue. Theory could not support the formation of high mass black holes as they would succumb to instability and blow apart, but LIGO has observed gravitational waves from these high mass black holes. This discrepancy is solved by reducing the oxygen reaction rate, as it allows theory to explain the higher mass black holes that have been observed. •

PHD**STUDENT**HIGHLIGHTS

False-color image of WLM created by combining U, B, and V-band images taken with the Lowell Observatory 1.1-meter Hall Telescope.

Haylee Archer

Small, but not to be forgotten, dwarf irregular galaxies represent an important laboratory for studying star formation in environments different from those we see in the Milky Way. More similar to the early universe, these galaxies have lower gas densities and metals typically needed to form stars. It is surprising, then, that there is active star formation occurring in them.

Stars form in clouds of dense gas primarily consisting of molecular hydrogen. It's an unpleasant fact of galactic astronomy, however, that molecular hydrogen in nearby galaxies is mostly undetectable. Instead, astronomers look for the next most abundant molecule in these clouds which is carbon monoxide (CO). These clouds are smaller and more difficult to detect in dwarf irregular galaxies, so when Dr. Deidre Hunter and her collaborators detected tiny CO clouds in WLM — a dwarf irregular in our local neighborhood — Archer, Dr. Hunter, and their collaborators took the opportunity to study the environments in which the CO clouds formed.

They looked for relationships between different properties of regions surrounding and encompassing the CO clouds including age, pressure, stellar mass surface density, atomic hydrogen (HI) gas surface density, CO mass, CO surface density, and inferred molecular hydrogen gas. They also compared the properties in these regions to other star forming regions without detected CO clouds. They found no difference between regions with and without CO for any of the properties compared. They found that regions with higher CO cloud masses also have higher HI gas surface densities, but that higher HI gas surface densities don't necessarily result in higher CO cloud masses. They also found no relationship between the region age and the CO cloud mass, suggesting that the tiny clouds are all that can be formed in galaxies with these low gas densities and metallicities. They submitted a follow-up proposal to use the Hubble Space Telescope to get a more comprehensive look at the regions. •

PHD**STUDENT**HIGHLIGHTS

Clark presented her poster at the Cool Stars 20.5 conference virtually using a meetup platform called Gather.

Catherine Clark

In 2022, Catherine Clark continued her work as both a PhD candidate in the Department of Astronomy and Planetary Science at Northern Arizona University (NAU), where she also began working as a Graduate Teaching Assistant for AST 201 (Introduction to Indigenous Astronomy) and AST 401 (Observational Astronomy). She also continued her work as a Graduate Research Assistant at Lowell Observatory, working with Dr. Gerard van Belle.

As a Graduate Research Assistant, Clark has been studying the multiplicity of our smallest, coldest, and faintest stellar neighbors: the M dwarfs. The M dwarfs have become favorable targets for finding exoplanets, but understanding their multiplicity is imperative to eliminate false positives for planet detection and to properly characterize these worlds. In order to study their multiplicity, Clark has been using a technique called speckle imaging. Clark and van Belle commissioned a new speckle camera called the Quad-camera Wavefront-sensing Six-channel Speckle Interferometer (QWSSI) at the 4.3-meter Lowell Discovery Telescope in July 2020 and have carried out multiple observing runs in 2021 to study M-dwarf multiplicity and other exciting science prospects. Clark also gave a talk on QWSSI at the American Astronomical Society meeting in January 2021.

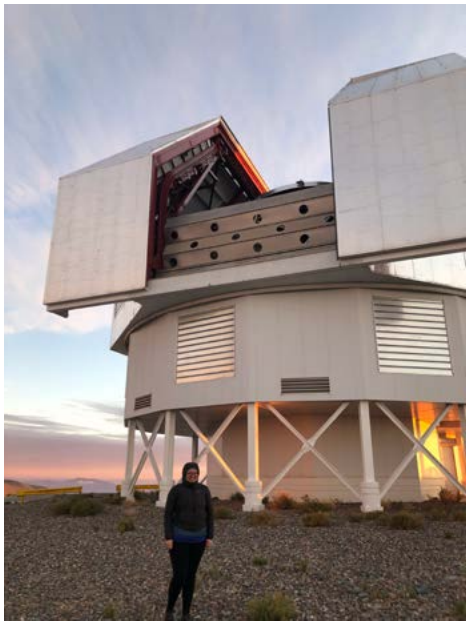
Clark also presented a poster at Cool Stars 20.5. There she discussed the first results from the POKEMON speckle survey. The POKEMON survey consists of multiplicity measurements for 1070 nearby M dwarfs and has revealed 26 new companions to these objects. These new discoveries increase the number of M dwarfs in the POKEMON sample with a known companion by 7.6%.

Clark also presented a poster at TESS Science Conference II, and gave a contributed talk at TESS Science Meeting #26. There she discussed her study of M-dwarf TESS Objects of Interest, which she has been following up with high-resolution imaging. This study revealed that the stellar companions to M-dwarf TESS Objects of Interest have longer periods than the stellar companions to non-planet-hosting M dwarfs. These observations also revealed a serendipitous discovery of a new stellar companion to an F1V stars, which Clark published in RNAAS (Clark et al. 2021).

Clark's other science highlights from 2021 include giving eight colloquia at various institutions, serving as executive secretary on a NASA review panel, two nights of CHARA time as PI, 0.5 nights of LBT time as PI, two co-authored papers (Horch et al. 2021; van Belle et al. 2021), and an article in the Arizona Daily Sun.

Clark also continued volunteering with the Skype a Scientist program, as well as writing for Astrobites. During the Spring 2021 semester, she took "Ethics and Strategies in Science Communication" as well as "Writing Scientific Papers" at NAU. During the Fall 2021 semester, she completed the final project for her Graduate Certificate in Science Communication, which resulted in a narrative photo essay documenting the work of a telescope operator.

She will defend her dissertation in April 2022. •



Observing candidate red supergiant binary systems on the 6.5-m Magellan telescopes at Las Campanas, Chile both before COVID and in person, and during-COVID and remotely.

Kathryn Neugent

Massive stars are the cosmic engines of the universe. The majority of the oxygen we breathe, the silver and gold we prize, and the carbon that allows for life as we know it, is created during the explosive death of a massive star. Such massive stars begin their lives turning hydrogen into helium. But once they've exhausted their hydrogen supply, their surface temperatures decrease and visually their colors become redder as they cool off. Such stars are called red supergiants, and if you placed one at the center of our solar system, it would extend past the orbit of Mars – red supergiants are huge! While many of these stars are like the Sun and exist by themselves, some of them have companion stars that orbit around them forming a binary system. Such binary companions can heavily influence how the red supergiants end their lives, and potentially even change the types of elements created during their explosive deaths. Kathryn Neugent spent the last four years studying these red supergiants and their companions for her dissertation at the University of Washington, while continuing as a research associate at Lowell Observatory with long-time collaborator, Phil Massey.

Until she began her dissertation, the number of red supergiants with companions was not well understood. In fact, out of the thousands of red supergiants known in the Universe, there were only a dozen with confirmed companions. However, theoretical models suggested there should be many more. Was this discrepancy due to a lack of effort put into searching for such red supergiant binary systems, or did they simply not exist?

She began her investigation by determining what type of star would most likely be in a binary system with a red supergiant. She found that, due to the relatively short lifetimes of red supergiants, their companion stars will also be short-lived stars of slightly smaller mass. Such smaller mass and young stars are very hot and thus have very blue colors. Knowing this, she was able to devise a method of searching for red supergiants with blue companions. Using archival images of three galaxies located close to our own Milky Way Galaxy, she and Lowell collaborator Phil Massey first identified the total number of red supergiants in each of these galaxies. Next, Kathryn determined which of these stars had an abnormal amount of blue light that might indicate the presence of a blue companion.

She then observed these candidate red supergiant binaries with some of the largest telescopes in the world in Arizona, Hawaii, and Chile. By examining the observed spectral data and searching for tell-tale features that indicated the presence of a red supergiant as well as a hot blue companion, she was able to confirm new red supergiant binary systems. As part of this work, she discovered over 250 new red supergiant binaries, therefore increasing the number of known systems by a factor of 20! It turns out these systems do exist, but they just hadn't been discovered yet.

Understanding the binary fraction of red supergiants is vital towards deciphering many open questions in astronomy. For example, red supergiant binaries are the progenitor systems to the gravitational wave events being detected at the Laser Interferometer Gravitational-Wave Observatory (LIGO) in eastern Washington. Kathryn's research found that many more such systems exist than we previously expected and hopefully with time and further characterization, we can better understand how these massive red supergiants enrich our universe with heavy elements. •

TECHNICALSUPPORTHIGHLIGHTS

Re-installing the rails on the Dyer Telescope dome.

The new and improved tires on which the Clark Telescope dome rotates.

Dr. Kyler Kuehn
Deputy Director for Technology

The Technology Group was very busy in 2021, especially in our core functions of maintaining and operating our research and public outreach telescopes at Happy Jack, Anderson Mesa, and Mars Hill. Our flagship Lowell Discovery Telescope entered its "surly teenager" years, with a variety of components requiring repair and maintenance by our top-notch engineering and instrumentation teams. In addition, the numerous wildfires over the summer caused a temporary shutdown of operations and required careful coordination between our Observatory Operations Manager and the US Forest Service (along with other local and state authorities on occasion). Though the fires were devastating for some in the surrounding community, our own facilities were fortunately spared any direct damage.

Meanwhile, our Technical Facilities team participated in development of the new Technology Center. This building represents a significant improvement in the instrumentation, laboratory R&D, and related capabilities of the Observatory. Once it is built, it will also allow us to remove the current instrumentation shop, located on what will be the primary access routes for the Astronomy Discovery Center. The Technical Facilities group also replaced the dome rails on the Dyer Telescope, and all 24 tires on which the historic Clark Telescope dome rotates. This included a fresh coat of paint on the wheels and even some adjustment to the lights.

Our team made major strides in completing deferred maintenance and other upgrades to the Navy Precision Optical Interferometer, culminating in successful six-way beam combining for the first time in about a decade! Below are pictures of our NPOI Operator/Technician, Solvay Blomquist, and a close-up of the control screen showing signals from six separate telescopes being combined. The NPOI engineering group also made significant progress in the installation and integration of three 1 m telescopes that will be part of the larger-aperture operating mode of the interferometer. Finally, the team provided critical infrastructure and operational support to Amon Hen, a visiting project sponsored by the Naval Research Laboratory.

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TECHNICAL SUPPORT HIGHLIGHTS

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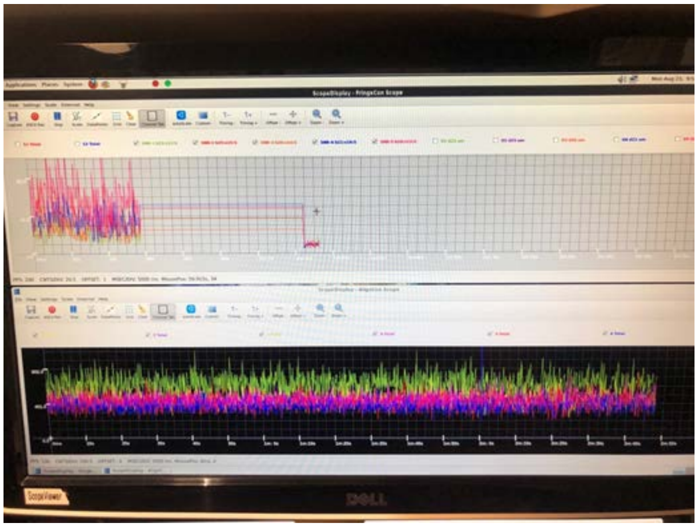
Lowell's IT group also improved important infrastructure across the Observatory, including greatly expanding wireless access on Mars Hill and upgrading the entire network at NPOI. They also upgraded the performance of the Observatory's firewall, and initiated Endpoint Protection capabilities on the computer systems of nearly all our network users, significantly reducing cybersecurity risks to the organization.

Next, several new projects were initiated within the Technology Group as a whole. The Optics and Photonics Applications Laboratory (OPAL) was founded this year, bringing together research & development projects in adaptive optics and new photonic technologies. Successfully translating these advances from the laboratory to the telescopes has the potential to significantly improve the performance of many of our observational facilities. Additionally, the group made significant progress on the Peggy and Eric Johnson 1-meter telescope, a brand-new addition to our Observatory that is expected to be commissioned in late 2022, with regular operations commencing in 2023.

Finally, the Tech Group experienced some significant staffing changes over the last year. We expanded our NPOI Plus-Up team with three new staff: Software/Systems Engineer Thomas Coleman, Electrical Engineer Khristian Jones, and Optomechanical Engineer Ben Hardesty. We added Erin Maier as NPOI Observer/Technician and Beau Wigman as NPOI Site Steward, while Cecilia Siqueiros and Ben Shafransky joined us as LDT Telescope Operators. And near the end of 2021, Dr. Ryan Hamilton was promoted from Instrument Scientist to Head of Instrumentation, while our Observatory Operations Manager, Dr. Amanda Bosh, was promoted to Lowell's Chief Operating Officer. With several new hires planned for 2022, the expanded Technology Group will be more than ready to advance the Observatory's science and technology vision for the future. •



(Left): Operator/Technician Solvay Blomquist showing off 6-way beam combining at NPOI.

(Right): Signals from six separate telescopes being combined at NPOI.

PUBLICPROGRAMHIGHLIGHTS

(Left): From left, Jos Schindler, Sarah Burcher, Ariel Daniel, and Claire Gibson celebrate the completion of Lowell Observatory's first live-streamed Messier Marathon.

(Right): An image of M27 (the Dumbbell Nebula) captured by Curtis Dankof using the QSI camera attached to the 17" Planewave at Lowell's Giovale Open Deck Observatory.

Samantha Gorney
Deputy Director for Education

Lowell Observatory's suite of educational programs grew significantly over the last decade. In response to this growth, the outreach team recently split into three sub teams: Public Programs, Education, and Community Outreach and Events. Each area has a manager and a group of employees. The managers overseeing these areas are Sarah Burcher, Todd Gonzales, and Jelena Lane. Sarah, Todd, and Jelena ensured that Lowell delivered high-quality outreach programs in 2021, despite all the challenges posed by the coronavirus pandemic.

Public Programs

Lowell Observatory developed a phased reopening plan based on CDC guidelines in response to the COVID-19 pandemic. Public Programs moved seamlessly through all three phases of this plan in 2021, transitioning from Phase 1 to Phase 2 in April and from Phase 2 to Phase 3 in November. Phase 2 came with a new suite of limited-capacity tours, including a 1.5-hour "Mars Hill Tour" (daytime), a 1-hour "Dark Sky Tour" (evening), and a 2-hour "Expanding Universe Tour" (evening). These tours, which often reached capacity, were well-received by guests. Limited-capacity Dyer Telescope programs were also very successful. New talks introduced during Phase 3 included "The Search for Life on Mars," "The Secret Lives of Stars," "The Dark Universe," and a family-friendly program replete with science demos titled "Colors of the Cosmos!".

Working in collaboration with the Marketing and Communications Department, the outreach team continued to offer educational programs virtually. Regular programming included "Cosmic Coffee," "Interactive Stargazing," "Sagas in the Sky," and "Mars Hill Almanac," as well as a monthly series celebrating the 125th anniversary of the 24-inch Clark Refractor. Special online programming in 2021 included a week-long virtual edition of the second annual I Heart Pluto Festival, Lowell's first-ever Messier Marathon, and livestreams highlighting lunar eclipses, meteor showers, National Astronomy Day, and Earth Day.

Lowell's outreach programs are supported by people from every department at the observatory. The effort put in by the technology team in 2021 was particularly significant. Members of this team installed a new set of tires in the Clark Telescope dome, an air quality monitor at the Giovale Open Deck Observatory (GODO) and assisted with the installation of a new Mallincam (model Ds26cTEC) and other imaging instruments at the GODO. They also trained public program employees on the use of astrophotography equipment and software, which enabled the launch of an astrophotography program for the public.

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Education

Lowell Observatory Camps for Kids (LOCKs) onsite programs, which resumed in the summer after an extended hiatus, served more than 200 children in 2021. Nine additional preschool classes were added to the LOCKs - Expansion project, six from Cave Creek, Arizona, and three from Flagstaff.

The Native American Astronomy Outreach Program (NAAOP) team conducted classroom visits virtually throughout the school year and hosted virtual summer and winter camps for students. See below for full report.

Community Outreach & Events

Lowell educators returned to the Flagstaff Family Food Center (FFFC) to lead science activities for the children that FFFC serves. These visits occurred every other week from January through December. The observatory also participated in several local outreach events, including the Flagstaff Star Party and Science in the Park. Private events and facility rentals also resumed in 2021, and the events team pulled off several successful events both on- and off-campus. •

Middle school campers use the Whale Watch element within the Jill Allen Challenge Course to explore physics concepts

Todd Gonzales
Education Manager

Native American Astronomy Outreach Program

After 25 years of dedication to teachers and students in many indigenous communities, Dr. Deidre Hunter passes the torch of leadership to Alethia Little and Todd Gonzales.

Undoubtedly, 2020 was an extremely tough year for schools on the reservation and NAAOP. This program relies heavily on bringing the excitement and opportunities of science to schools that would otherwise not often have such opportunities or engagement from institutions like Lowell Observatory. The 2021 academic year began on the same cautious track of strictly connecting with classrooms virtually.

The multi-year project with Kayenta Unified School District concluded in low light without seeing the partnerships on campus presenting their posters. NAAOP received good feedback regarding the curriculum and the need for more cultural connections in the lessons. NAAOP will combine a bit of what it did in the past with its smaller, impactful activities and combine it with a modern cultural project. An example of this is the new 2022 summer robotics summer camp. While students will be learning about what Mars is like through building and programming rovers, the students will also be tackling ideas of using the technology of yesterday and today to fight drought at home.

In 2021 the summer and winter camps were virtual, seeing participation from 23 and 4-5 students, respectively. The virtual learning environment is not very practical for communities that do not have stable internet access at their disposal.

To help bolster the cultural connections the program can make in the future, Alethia Little has officially started a Cultural Advisory Board made up of representatives from the Dine, Hopi, and Apache communities. The board's task will identify cultural teachings that can be paired with the lessons that NAAOP uses. The Cultural Advisory Board will be meeting for the first time this summer.

Misha Pipe has begun expanding on the NAAOP partnerships with the first-ever addition of preschools on the reservation. NAAOP now covers early learning, elementary, and middle school in its partnerships.

With all the changes, NAAOP's goal is still very much the same; show the students and teachers that science is fun and exciting and being a scientist is for everyone. •

PUTNAMCOLLECTION**CENTER**HIGHLIGHTS

Pluto discovery plates and envelopes.

Lauren Amundson
Librarian & Archivist

In 2021, the Lowell Observatory Library and Archives continued its mission of collecting, preserving, and providing access to current research and historical resources. The department received a $2500 grant from the Arizona Historical Records Advisory Board to purchase disaster recovery supplies for the collections. Archivist/Librarian Lauren Amundson assembled the supplies into four caches and distributed them to libraries in northern Arizona.

The Fall Appeal led by Rachel Edelstein raised more than $30,000 to purchase new archives management software called ArchivEra. It offers a customizable public portal, intuitive searching capabilities, hosted cloud storage, and a suite of backend administrative tools to manage and make accessible our collections of correspondence, historic photographs, observation logbooks, manuscripts, audiovisual files, and blueprints.

The Putnam Collection Center (PCC) lent artifacts to two museums for exhibits. The Centre de Cultura Contemporánia de Barcelona borrowed an original Percival Lowell globe, hand-drawn map, color drawing, and observation logbook for its "Mars: The Red Mirror" exhibit. The Arizona Historical Society borrowed duplicates of the Pluto discovery plates, a lunar map and globe, and airbrush for its "Ready to Launch: Arizona's Place in Space" exhibit.

In addition to lending objects, the PCC received a very exciting return from the Smithsonian National Air & Space Museum (NASM). One of the original Pluto discovery plates, lent to NASM in 1977, was reunited with its companion plate in July. Both are now housed in the PCC in a box and folders specially made by the preservation supply company Gaylord.

Amundson and Archives and Museum Specialist Stacey Christen attended several conferences virtually throughout the year, including the Arizona Archives Summit, Society of American Archivists, Special Libraries Association, and Library and Information Services in Astronomy.

In June, several volunteers returned to the archives after more than a year away due to the pandemic. Lindsey Cillis, Mary DeMuth, Karen Kitt, Jeff Pickens, Barbara Robinson, John and Linda Spahn, and Gary Tallman assisted with collections processing, digitization, cataloging, and book repair.

A new virtual exhibit called "Traversing the Arizona Territory: A.E. Douglass' 1894 Expedition to Establish Lowell Observatory" made its debut in July. The exhibit features primary source material including letters, photographs, maps, and drawings that tell the story of Lowell Observatory's founding.

In August, Melissa Valenzuela began her internship as a NAU/NASA Space Grant recipient. Her project, the creation of a virtual exhibit called "The Story of Pluto," focuses on the search for Planet X, Pluto's discovery, public reaction, its place in popular culture, and current science. The exhibit uses digital publishing software called Omeka.

The archives received approximately sixty requests for materials from authors, editors, publishers, filmmakers, students, and artists. •

VOLUNTEERHIGHLIGHTS

(Left): Karen Kitt uses the Zeta scanner to digitize a logbook.

(Right): Barbara Robinson demonstrates the book repair process.

Catie Blazek
Volunteer Coordinator

After more than a year away, volunteers were welcomed back in mid-2021.

In the Archives department, John and Linda Spahn, Jeff Pickens, Karen Kitt, Gary Tallman, Mary DeMuth, and Barbara Robinson assisted with collections processing, digitization, and book repair. It was nice to have the team back together again!

In the Public Programs, we welcomed back returning volunteers and some new volunteers to assist in areas such as public telescope viewing, open houses, crowd control, boxing up and shipping out the classroom subscription boxes, and more. We even had a mother/son team join as new volunteers as part of the son's homeschool coursework. •

Linda and John Spahn pose with archival boxes that will be used to house planetary photographs.

DEVELOPMENTHIGHLIGHTS

Grounding breaking for the new Kemper and Ethel Marley Astronomy Discovery Center took place this year.

Stephen Riggs
Development Manager

2021 was another stellar year for fundraising at Lowell Observatory. Generous donors contributed $17,605,100, making 2021 the second best fundraising year in the observatory's history. It also marked the third consecutive year that fundraising totals have surpassed $10 million. These gifts helped fund the Marley Foundation Astronomy Discovery Center (ADC), astronomical research, the Lampland dome restoration, the Steele Learning Center, the Native American Astronomy Outreach Program, the Percival Lowell Trust, endowment Funds in the Lowell Observatory Foundation, and general operations...as well as many other projects and programs vital to the Observatory.

Notable was the large number of donors to the Annual Fund, whose gifts broke previous records. Membership, too, exceeded goals despite Covid closures for part of the year. All these gifts have allowed us to begin construction on the ADC, acquire a new one-meter research telescope for our Anderson Mesa facility, and offset income gaps cause by the lengthy closure.

Notable, too, were two very generous bequests. One of which was used, in part, to fund a permanent endowment to provide visits from area K through 12 students as a way of enhancing their interest and education in science.

Thank you to all who supported in 2021 for your outstanding generosity and support of the observatory's mission. •

MARKETING&COMMUNICATIONSHIGHLIGHTS

Dr. Danielle Adams
Deputy Director for Marketing & Communications

2021 was a year of many transitions. We began the year in Phase 1 of our COVID-19 phased reopening plan, offering just private stargazing experiences. In April, we entered Phase 2, adding daytime and evening tours with mixed groups of people, and we finally resumed general admission in mid-November, although we closed again in early January 2022, due to the omicron variant. Through all of these transitions, the Marketing and Communications team (which itself transitioned to "Marketing and Revenue" at the top of 2022) ensured our guests had the most up-to-date information and excellent experiences once they arrived on Mars Hill.

Our Visitor Experience team, lead by Miriam Robbins, experienced a lot of transition in 2021 as we hired new Visitor Experience Associates in several waves to replace VEAs who were graduating or otherwise moving on. In March, we promoted Richard Montano to Visitor Experience Lead, and in October, we adjusted the VE structure to better empower our leaders, and so we promoted both Richard and Rob Hall to Visitor Experience Supervisor to work alongside Kim Denune, who had been the team's only Supervisor up to that point.

In the Starry Skies Shop, Rob and Miriam led the transition to Shopify for gift shop purchases, both on-site and online, a transition that was completed in early April. This change made analytics and inventory much easier, as the same system is used for both on-site and online purchases. With more guests coming to the observatory with our move to Phase 2 in early April, Miriam and Richard navigated the new waters of the international supply chain disruption. Despite this, we were able to stock new merchandise featuring the Clark 125th anniversary logo and new observatory branding, both of which were developed by Sarah Gilbert.

Throughout the year, the excellent management of personnel and inventory by Miriam, Kim, Rob, and Richard kept the Starry Skies Shop well ahead of expectations, generating $326,033 in revenue, nearly half the pre-COVID amount from 2019, despite only a quarter of the number of guests in 2019 coming to the observatory in 2021. As a measure of the guest experience, guests on average spent more in the gift shop, increasing the 2019 average of $6.73 per guest to $11.15 per guest in April–December 2021.

We continued 2020's rigorous schedule of livestreams in 2021, but as we progressed through the reopening phases, some of these programs, such as Cosmic Coffee, ended as focus shifted to bringing people back to Mars Hill. Heather Craig increasingly took on the mantle of running the broadcasting software for most of these streams from Danielle Adams as the year progressed, with Alex Elbert and Madi Mooney interacting with viewers via YouTube chat. In February, our second I Heart Pluto Festival was fully virtual due to COVID-19, and 4800 people from around the world participated. In March, we broadcast our first-ever Messier Marathon, during which our Educators used the 14" PlaneWave CDK telescope to find all 110 Messier objects in a single night, from sunset to sunrise. In April, Kevin Schindler began to host a monthly livestream series that celebrated the 125th anniversary of the Clark Refractor. In the spring, the joint effort of our Marketing & Communications and Education teams to

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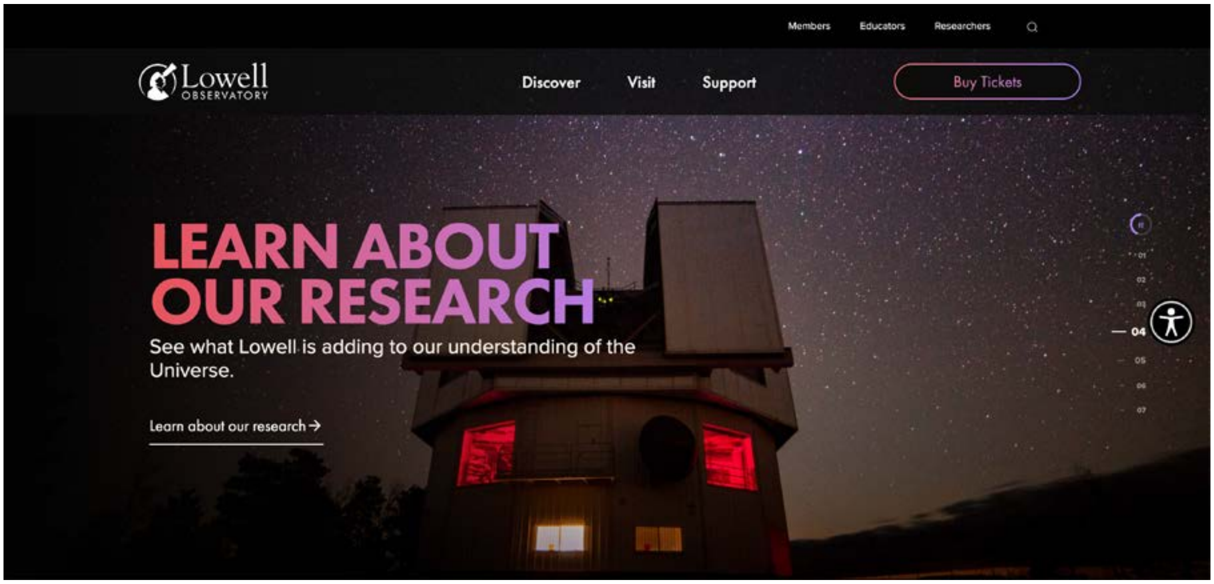
stream educational content throughout the pandemic was chosen as a finalist for the Viola Awards for Excellence in STEAM; although we did not win the award, it was a great honor to have our live-streaming efforts recognized in this manner. We continued running livestreams for major celestial events through the end of the year, including two early morning lunar eclipses in May and November. Through the efforts of Kevin Schindler to develop media relationships, several of these livestreams were promoted or carried by local or national media outlets.

We experimented with other methods of creating video content as well. On the heels of December 2020's Great Conjunction of Jupiter and Saturn, our brand new TikTok channel grew rapidly under the direction of our marketing consultant, JB DeWitt, and with the talent of Ariel Daniel, one of the observatory's wonderful educators. We also started a Twitch channel that featured educators Hannah Zigo and Jakob Irish, although we paused this effort as more guests returned to Mars Hill in Phase 2.

At the end of June, we unveiled a new logo and visual branding for Lowell Observatory that replaced the 125th anniversary logo that Sarah Gilbert had developed in early 2019. Once again, Sarah created a clean logo that looks to the future and honors our history at the same time; Sarah and Alex Elbert together cascaded this new branding across our various online platforms and physical signage around campus, including a beautiful new entry sign.

Running concurrently with the branding update, we soft-launched a brand-new public-facing website with an embedded microsite for researchers. This project had been managed over many months by Miriam Robbins, and the updated content was written by Kevin Schindler, Madi Mooney, and Danielle Adams, with support for the new pages coming from Sarah Gilbert and Rob Hall. This new website was made possible by a generous annuity gift from the observatory's departed friend, Don Trantow.

In September, we hired a Marketing Manager, Cody Half-Moon, who has been leading our Marcom (marketing communications) team ever since. After a short time, Cody set to creating the observatory's first podcast program, called "Star Stuff: A Space Poddity," which will launch in the first week of January 2022. •



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STATEMENTOFFINANCIALPOSITION

Combined Statements of Financial Position for the Year Ended December 31, 2021

(with comparative totals for the year ended December 31, 2020)

ASSETS	2021	2020
Current Assets		
Cash and cash equivalents	$ 839,737	$ 474,939
Restricted cash and cash equivalents	3,038,607	796,970
Restricted certificates of deposit	6,760,301	4,808,558
Investments	2,321,618	2,172,476
Research grants receivable	375,713	572,103
Promises to give, current portion	2,517,396	3,151,810
Estates and bequests receivable	3,900,000	-
Other current assets	1,171,332	596,347
Total Current Assets	**20,924,704**	**12,573,203**
Property and equipment, net	49,803,548	47,612,883
Promises to give, net of current portion	10,776,404	11,421,025
Collection item	400,000	400,000
Investments with donor restrictions	28,935,069	22,220,045
Total Noncurrent Assets	**89,915,021**	**81,653,953**
Total Assets	**$ 110,839,725**	**$ 94,227,156**

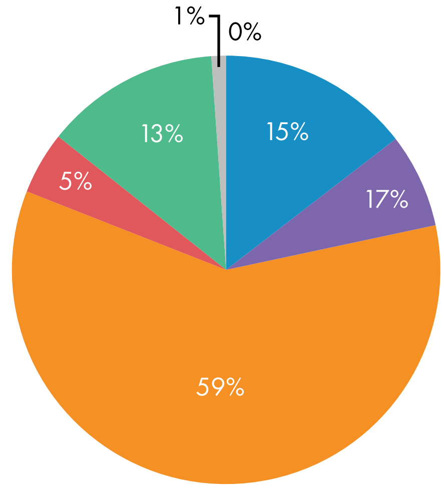
LIABILITIES AND NET ASSETS	2021	2020
Current Liabilities		
Accounts payable	$ 687,451	$ 241,901
Accrued expenses and other current liabilities	93,789	110,455
Current portion of deferred access fee revenue	1,433,332	2,033,332
Total Current Liabilities	**2,214,572**	**2,385,688**
Note payable, bank	5,525,971	2,200,971
Long-term debt	500,000	150,000
Deferred research grant revenue	48,420	45,908
Deferred access fee revenue, net of current portion	5,167,424	5,376,289
Total Liabilities	**$ 13,456,387**	**$ 10,158,856**
Net Assets		
Without donor restrictions	$ 32,279,606	$ 27,977,666
With donor restrictions	65,103,732	56,090,634
Total Net Assets	**97,383,338**	**84,068,300**
Total Liabilities and Net Assets	**$ 110,839,725**	**$ 94,227,156**

STATEMENTOFFINANCIALACTIVITIES

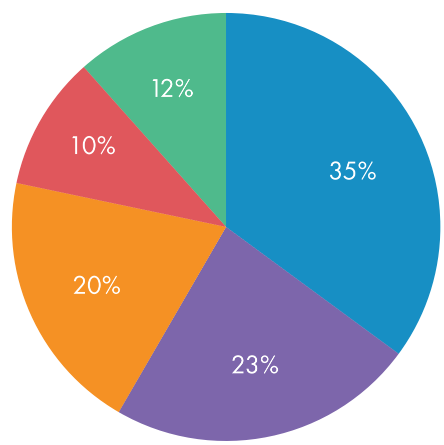
Combined Statements of Financial Activities for the year ended December 31, 2021

(with comparative totals for the year ended December 31, 2020) (before depreciation)

REVENUE & SUPPORT	2021		2020	
Grant and contract revenue	$ 4,231,559	15%	$ 3,195,523	15%
Telescope access fees	2,071,708	7%	2,350,197	11%
Contributions	17,268,006	59%	11,980,863	56%
Public program revenue	1,372,759	5%	455,745	2%
Investment income net	3,846,661	13%	3,284,206	15%
Other income	320,597	1%	114,301	1%
Gain on sale of assets	-	0%	1,642	0%
Total Revenue and Support	**$ 29,111,290**		**$ 21,382,477**	



EXPENDITURES	2021		2020	
Program services:				
Research	$ 4,790,909	35%	$ 3,948,721	35%
Technology	3,175,059	23%	2,599,068	23%
Public program	2,721,371	20%	2,396,691	21%
	10,687,339		8,944,480	
Support services:				
Management and general	1,383,937	10%	1,247,337	11%
Fundraising	1,578,963	12%	1,209,096	10%
	2,962,900		2,456,433	
Total Expenditures	**$ 13,650,239**		**$ 11,400,913**	
Change in net assets	$ 15,461,051		$ 9,981,564	



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 2021 and 2020 was $2,146,000 and $2,109,000.

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, 2021. Copies of the audited financial statements are available at https://lowell.edu/about/governance_and_financials/

2021 ANNUALREPORT

Lowell OBSERVATORY

Front Cover: The Moonraker Telescope | Credit: Alex Elbert
Back Cover: The Saturn Gate | Credit: Harun Mehmedinovic/Skyglow Project

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