2018

LOWELL OBSERVATORY

ANNUAL REPORT

2018

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TRUSTEE'S UPDATE

By W. Lowell Putnam

While this report is about 2018, it is published in 2019 on the 125th anniversary of the observatory, so a certain amount of reflection is expected. As you will see is looking through this document, Lowell Observatory is continuing to follow the mission established by our founder, and the current staff are doing an excellent job scientifically and in public outreach. Supporting those individuals are other hard working groups in technology, operations and development. All of them contribute to making this institution the success it is today, and all that success is built on the hard work and efforts of those in prior years all the way back to 1894.

We are also looking forward to what 2019 has to offer. If you come to our main campus on Mars Hill you will see major changes. With over 105,000 visitors last year we have gone well beyond the capacity of our current facilities. Thanks to great support from our donors we will be opening the Giovale Open Deck Observatory as well as adding increased parking, more storage, and improved traffic flow… with more to come in the next few years.

In looking back through our archives for this milestone year we came across the original seal that Percival used in publications about research work done at Lowell. There will be a full story about that later, but the Latin motto Percival chose for the seal translates as "Worlds Revealed". As you look through the science articles noted in the following pages, you will see that works continues to this day, and the increasing success of our public programs allows us to help reveal that work to new guests and generations.

Thank you for supporting all this great work! ▪

DIRECTOR'S UPDATE

By Jeffrey Hall

Perchance, I am writing this note for our annual report on the morning of May 28, 2019—125 years to the day after Percival Lowell stepped off a train in the frontier hamlet of Flagstaff and made his way up Mars Hill to found the observatory that bears his name.

Looking out my office window on this clear and sunny morning, I can see the Clark Telescope dome not far up the hill, where Percival spent many nights making meticulous maps of Mars.

A few decades later, Clyde Tombaugh walked into the very office where I am now sitting and said to then-Director V. M. Slipher, with what must have been quivering excitement, "I have found your Planet X."

Quite a few decades after that, Trustee William Lowell Putnam, III and Director Bob Millis committed the observatory to remain a vital institution of research, starting us down a 20-year, $53 million road that would lead to the construction and commissioning of the 4.3-meter Discovery Channel Telescope.

A few weeks ago, the observatory's management team and I met to discuss project and cost management of our next massive undertaking, the $35 million Astronomy Discovery Center.

One hundred and twenty five years is a long time, and a lot has changed on Mars Hill. But as we begin our second 125 years, I see not just change but an opportunity that begins anew a cycle of discovery and inspiration. The fin de siècle era when that train arrived in Flagstaff was one when a number of private-sector visionaries and philanthropists like Percival Lowell, Charles Yerkes, James Lick, and Andrew Carnegie devoted their energy and their fortunes to the advancement of science. Their vision led to the creation of several great observatories that pushed forward the national frontier of astronomy and inspired generations to come. Today, as Federal support for science and basic R&D seems increasingly deprioritized, private-sector support again comes to the fore. The Discovery Channel Telescope and its instrument cube were built entirely with private funds. The Astronomy Discovery Center will be substantially or entirely privately-funded as well. With these facilities, we strive to learn more about the Universe of which we are a part, and we return our supporters' investment by communicating the wonder, the power, and the fun of science to all.

Lowell, Yerkes, Lick, and Carnegie no doubt understood that this is much more than doing well by doing good. It is a national and ethical imperative, for we are retreating today into almost medieval superstition. Climate change is a hoax. Vaccines cause autism. Cell tower emissions will kill you. Planes spray chemtrails. Evolution is "just a theory." There are canals of intelligent construction on Mars. No, no, no; no, no, and no. All of those statements face overwhelming evidence indicating they are false. But increasingly, evidence and data no longer matter; perception and Internet trolling are the order of the day.

Everything you'll read in these pages is part of our commitment to performing and communicating real science, both in our research as well as our outreach. Here at Percival Lowell's observatory, we would be failing our founder to do any less. Percival was wrong about Mars, and that's OK: he inspired generations of scientists to learn more about the true nature of our neighbor planet, and that's how science works. As we begin our second 125 years, we'll use the Discovery Channel Telescope and, soon, the Astronomy Discovery Center to continue to explore our weird and wondrous Universe, and to promote to the greatest extent we can the rational, data-driven thinking and decision-making our technical society must have. ▪

America's observatory enters a new age

In the January 2019 issue of *Astronomy* magazine, editor (and Lowell Observatory Advisory Board member) Dave Eicher wrote an outstanding article about "America's Observatory", as he calls Lowell. With Dave's permission we've reproduced that article here.

Within the dome protecting the 24-inch Clark refractor at Lowell, many historic observations were made, including Percival Lowell's viewings of Mars. INSET: LOWELL OBSERVATORY

Powered by plans laid long ago, Lowell Observatory is moving ahead with dramatic ideas for expansion and scientific greatness. **text and images by David J. Eicher**

Lowell Observatory. Mention the name to any astronomy enthusiast, and immediately visions of Pluto arise, and memories of stories about the observatory's founder, Percival Lowell, and his observations of Mars. Situated in northern Arizona at an elevation of 7,250 feet (2,210 meters), the observatory stands atop Mars Hill, which overlooks the charming town of Flagstaff below.

I like to call Lowell "America's observatory" because of its unique combination of astronomical history and famous discoveries. It's a place like no other on Earth, within or outside of science. Lowell Observatory is an independent, non-profit organization governed by a sole trustee. This gives the observatory, as well as the astronomers who work there, incredible freedom to plan and execute their own research programs.

But these days, there's a lot more going on than usual. The institution is entering a new age, one that will transform it into something well beyond what its founder might have imagined. A multimillion-dollar effort to modernize the observatory is being led by the institution's current trustee, Lowell Putnam, Percival Lowell's great-grandnephew.

A unique history

Lowell Observatory's story begins with Percival Lowell (1855–1916), part of the famous Lowell family of Boston. Percival graduated from Harvard University and MIT, and he spent his younger days running the family business based in Lowell and Lawrence, Massachusetts. Keenly interested in science from his youth, however, he was especially attracted to the mystery of Mars. In 1894, he set about establishing his childhood dream: building an observatory dedicated to studying Mars and other phenomena.

Lowell chose what would be called Mars Hill in Flagstaff after a series of site tests, and he oversaw the construction of the 24-inch Clark refractor as the observatory's primary instrument. Lowell made many observations of the Red Planet, producing drawings and famously believing that the linear features he observed — the same ones noted by Italian astronomer Giovanni Schiaparelli — could be irrigation canals built by a martian civilization. Lowell also initiated a widespread and systematic search for "Planet X," a hypothetical ninth planet believed to lie beyond the orbit of Neptune.

Starting in 1910 at Lowell, astronomer V.M. Slipher used a special spectrograph to find that many "spiral nebulae" were receding at high velocities, thus discovering the expansion of the universe. This huge cosmological find provided the initial data sets used by Edwin Hubble more than a decade later. Slipher used the same spectrograph to discover gas lurking in the Pleiades star cluster and elsewhere, thus discovering what came to be known as the interstellar medium — the stuff between the stars.

Then in 1930, a young astronomer who traveled from Kansas to work at Lowell Observatory, Clyde Tombaugh, discovered Pluto. As he compared two photographic plates made with the observatory's 13-inch telescope, he saw Pluto's image move relative to the fixed stars. Though Lowell's death preceded the discovery by 14 years, the detection of the dwarf planet permanently fixed Lowell Observatory into the American consciousness.

During the 1940s and '50s, Henry Giclas conducted a large proper motion survey that serves as a record of many years — one that is still valuable today. Indeed, the New Horizons mission used Lowell Observatory astronomer Carl Lampland's plates from 1921 to refine the course of that spacecraft. Among other discoveries made at Lowell are the co-discovery of the rings of Uranus, the detection of Pluto's atmosphere, accurate orbits for Pluto's moons Nix and Hydra, oxygen in the spectrum of Jupiter's moon Ganymede, and periodic variation in the activity of Comet Halley, just to name a few.

Members of the Lowell, Putnam, Tombaugh, Sykes, Slipher, and Christy families stand in front of the rededicated Pluto Telescope on Mars Hill during a historic gathering last June.

UNDER THE HOOD OF THE DISCOVERY CHANNEL TELESCOPE

The Discovery Channel Telescope (DCT), which saw first light in 2015, stands on a mountaintop near Happy Jack, Arizona, some 40 miles (64 kilometers) southeast of Flagstaff at an elevation of 7,740 feet (2,359 meters). Several specialized instruments are key to the current research being conducted with the scope.

One of them is the Immersion Grating Infrared Spectrometer. Developed by the University of Texas and KASI, this instrument has broad spectral reach and high spectral resolution to help astronomers study the interstellar medium, how stars form, and the early evolution of star systems.

The Extreme Precision Spectrograph is a product of Debra Fischer from Yale University. This powerful instrument has been installed at the DCT and will be used to attempt to detect Earth-like worlds around Sun-like stars.

Another specialized DCT instrument is the Rapid Infrared Imager Spectrograph, from the University of Maryland. This device will combine imaging and spectrographic capabilities so astronomers can make follow-up observations of gamma-ray bursts, as well as peer deep into star-forming regions, plus much more. — *D.J.E.*

Eyes on the stars

But at Lowell, the past is prologue, as Shakespeare said. The current expansion plans are spectacular, and they promise a very different institution a few years from now. The change is already beginning to happen, in fact. Last fall, the observatory broke ground on a new project, the Giovale Open Deck Observatory (GODO).

Named in honor of Lowell supporters Ginger and John Giovale, the complex will be built atop Mars Hill, not far from the Pluto Telescope, and it will consist of a circular observing platform and a massive building with a roll-off roof. The elevated plaza will measure almost 5,000 square feet (465 square meters) and will host multiple telescopes for public viewing, including a 32-inch Dobsonian that will be the largest telescope on the hill. The GODO will be unique in the world of public observing. It is planned to open for visitors this spring.

Thanks to a steadily growing base of more than 100,000 visitors each year, Lowell is undertaking an ambitious fundraising effort to help achieve a whole set of new goals that will bring the observatory into a new era. Among many other upgrades, the plans include a huge new building called the Astronomy Discovery Center. It will house numerous displays and exhibits, contain a theater that can host astronomical lectures and state-of-the-art shows, and feature the Dark Sky Planetarium, where crowds can gaze up at the night sky while presenters point out visible features and constellations.

The 4-meter telescope

Where did this incredible expansion and sense of drive come from? A generation ago, Lowell's astronomers and trustee had big ideas. Though the institution is deeply steeped in history, they realized they needed a modern large telescope. In 2003, former Discovery CEO and founder John Hendricks proposed what would become a $16 million gift to commence the 4.3-meter Discovery Channel Telescope (DCT), the largest and most sophisticated telescope in northern Arizona.

The DCT completely reworked Lowell and sent the organization into a more modern, more complex era of operations, one that depends on a committed staff of around 120 employees and many hard-working volunteers. The DCT saw first light in 2015 and has been a workhorse ever since.

The DCT is by no means all of Lowell's science activities. Some 12 miles (19 kilometers) southwest of Flagstaff stands Anderson Mesa, a shelf that has supported multiple telescopes from both Lowell Observatory and the U.S. Naval Observatory since the 1950s.

But the big news at Anderson Mesa in recent times has come from a different angle. Construction began in 1992 on a telescope that is so modern, it challenges technology and data interpretation. The Navy Precision Optical Interferometer (NPOI) is a joint effort of Lowell, the U.S. Naval Observatory, and the Naval Research Laboratory.

This specialized telescope can take measurements of the universe in high-precision ways. NPOI uses an array of up to six mirrors laid out in a Y-shaped configuration, bringing the beams of light together to create ultra-high-resolution images. Because of the technique, NPOI can produce images of close binary stars that only appear as a single point of light in even the largest conventional telescopes, measure the diameter of supergiant stars, and record the positions of stars in the sky so accurately that the Naval Observatory uses it as a standard for timekeeping.

With such great history and an amazing array of instruments, Lowell has become an extremely active center of

MEET THE RESEARCHERS AT LOWELL

Deputy Director for Science **Michael West** is a longtime galaxy expert whose research interests include star clusters, galaxy formation and evolution, clusters of galaxies, and the large-scale structure of the cosmos. He is also very active in astronomy education and outreach, as well as promotion of dark skies.

Astronomer **George Jacoby**, former deputy director for technology, is an expert on planetary nebulae who spent most of his career at the National Optical Astronomy Observatory in Tucson. Jacoby, who retired last fall, also conducted a great deal of research at Kitt Peak National Observatory, where he served as director of WIYN Observatory.

Ted Dunham, who also retired last fall, was responsible for astronomical instrumentation developed at Lowell Observatory. His research centered on stellar occultations by planets in the solar system, using observations made aboard the airborne observatory SOFIA.

Focusing on icy outer solar system objects, **Will Grundy** uses a variety of techniques to discover and determine the orbits and masses of binary Kuiper Belt objects. He is the surface composition team lead for the New Horizons mission to Pluto and beyond, and an editor of the planetary science journal *Icarus*.

Jennifer Hanley is interested in the stability of liquids throughout the solar system, with particular focus on Mars, Titan, and Europa. By studying the properties of liquids at low temperatures and pressures, Hanley hopes her work sheds light on the worlds of Pluto and Titan. She also researches the stability of water and associated chlorine salts on Mars and Europa.

A longtime expert on galaxies, **Deidre Hunter** focuses on star-forming properties of dwarf galaxies, and all aspects of tiny, irregular galaxies, the most plentiful type in the universe. Hunter is an award-winning leader of Lowell's innovative program to teach science and astronomy to Navajo and Hopi classrooms around Flagstaff.

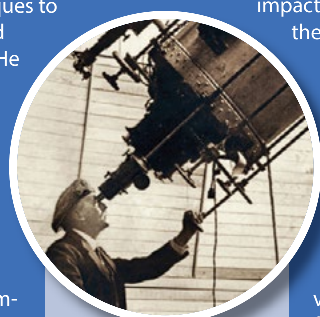
As Discovery Channel Telescope scientist, **Stephen Levine** was vital in bringing Lowell's modern instrument from concept to full-time science operations during its commissioning phase. Levine's primary research interests include large astrometric surveys and numerical simulations of astrophysical disk systems, with a particular focus on the evolution of lopsided disks and irregular galaxies.

Joe Llama focuses on solar systems throughout the Milky Way Galaxy, investigating their potential for habitable planets. He is also actively involved in searching for exoplanetary magnetic fields and understanding how they may shield a planet from overpowering radiation.

Phil Massey is the principal investigator for the Large Monolithic Imager, the primary optical camera on the Discovery Channel Telescope. He is interested in studying massive stars, binary stars, young star clusters, and the young stars in nearby galaxies to understand how the most luminous stars evolve.

Focusing on the solar system, **Michael Mommert** is chiefly absorbed with studying the physical properties of asteroids and comets. He observes these objects in wavelengths ranging from optical to near-infrared to help unravel their compositions, masses, reflectivities, rotational properties, and overall shapes.

Also highly interested in small solar system objects is **Nick Moskovitz**, who studies asteroids using observations and modeling. His work focuses on collecting data to understand the link between asteroids and meteorites, the origins of asteroid impactors, and the geologic processes in the early history of the solar system.



Percival Lowell observes with the Clark refractor at Lowell Observatory in 1914. LOWELL OBSERVATORY

Lisa Prato is a stellar and planetary astronomer who focuses on three specialized areas: measuring accurate mass ratios in binary star systems within young star-forming regions, studying the properties of stars and their planet-forming disks in binary systems, and surveying radial velocities for the youngest planets forming around low-mass stars.

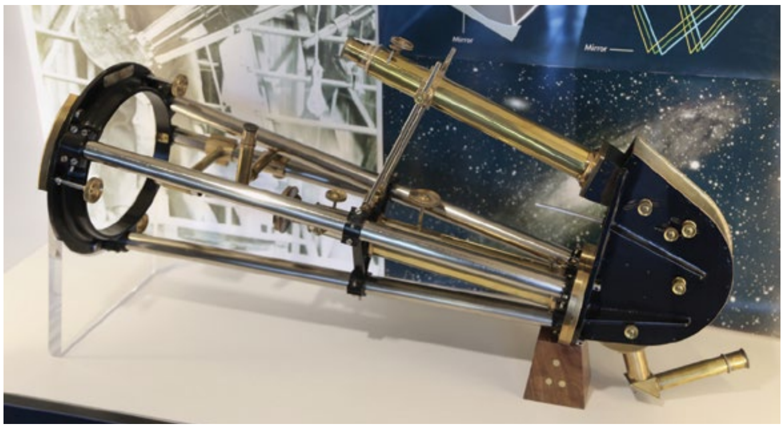
A veteran of Lowell's staff, **Dave Schleicher** is an expert on comets — specifically their physical properties, chemical compositions, and evolutionary behaviors. A co-discoverer of periodic variability of Comet Halley, Schleicher uses both observation and theoretical modeling to push forward our understanding of these icy bodies.

Gerard van Belle, director of the Navy Precision Optical Interferometer, is an expert on the fundamental properties of stars — their masses, sizes, and temperatures. He is interested in understanding the internal structures and evolution of stars so that astronomers can understand the numerous planets being discovered orbiting nearby stars.

Larry Wasserman, also a veteran of Lowell's staff, studies solar system bodies using occultations. His predictions, observations, and resulting data from these events have produced a huge amount of knowledge of the properties of solar system bodies. — *D.J.E.*

RIGHT: The refurbished and rededicated Pluto Telescope gleams in its dome in June 2018.

RIGHT: Clyde Tombaugh's son and daughter, Alden and Annette Tombaugh, stand next to the Pluto Telescope, with which their father discovered Pluto in 1930.



BELOW: In Lowell's Collection Center, you can see the Slipher Spectrograph, with which V.M. Slipher discovered the expansion of the universe and the existence of the interstellar medium.

ABOVE: Atop Mars Hill, Jim Christy poses with fellow astronomers and his wife, Charlene, commemorating the 40th anniversary of his discovery of Charon, Pluto's largest moon. Pictured from left are Paul Shankland, director of the U.S. Naval Observatory; Jim Christy; Jeff Hall, director of Lowell Observatory; Lowell Observatory trustee Lowell Putnam; and Charlene Christy, for whom Charon was named.

LEFT: Percival Lowell's first telescope, which was given to him when he was a boy.

astronomical research. The coordinated effort at Lowell begins with the facility's energetic, expert, and affable director, Jeff Hall. The director since 2010, Hall is an astronomer and dark-sky activist with considerable expertise in solar and stellar science. He and several colleagues run a program monitoring solar and stellar activity cycles aimed at better understanding the full range of variations that Sun-like stars exhibit, lending a more complete view to the possible influence of the Sun on Earth's climate.

The future starts now

In June, I was privileged to be at Lowell once again, attending the annual meeting of the observatory's board of advisers, asked to join this group by Lowell Putnam. Having been to just two of these meetings, I can't tell you how exciting the future looks for Lowell. Discussing the huge plans for expansion and science outreach with Putnam, Jeff Hall, Michael West, and others, really crystallizes a vision for the place.

The Lowell gathering was magical, as we celebrated the rededication of the Pluto Telescope with members of astronomy's royal families attached to the observatory: Lowells, Putnams, Sykes, Tombaughs, Sliphers, and Christys were there for the ceremony. (In 1978, across town at the U.S. Naval Observatory, Jim Christy discovered Pluto's moon Charon, named for his wife Charlene; both Jim and Charlene were on hand 40 years after the discovery, to help with the celebration.) Thanks to the graciousness of the observatory staff, I was able to stay in the apartment in which Clyde Tombaugh lived when he discovered Pluto in 1930. The sense of history there was palpable: I could almost hear Clyde delivering his many rapid-fire puns once again.

The future of Lowell began this past fall with the groundbreaking of the GODO. An ambitious program — with an expanded visitor center, museum spaces, logistics for handling larger crowds on Mars Hill, dark-sky planetarium, and much more — will follow. It strains the imagination that Percival Lowell could have imagined the explosive growth and science leadership that seems destined for this institution. America's observatory is about to take on an entirely new role, and it will be an exciting ride to watch unfold.

David J. Eicher *is the editor of* Astronomy *and a member of the Board of Advisors of Lowell Observatory.*

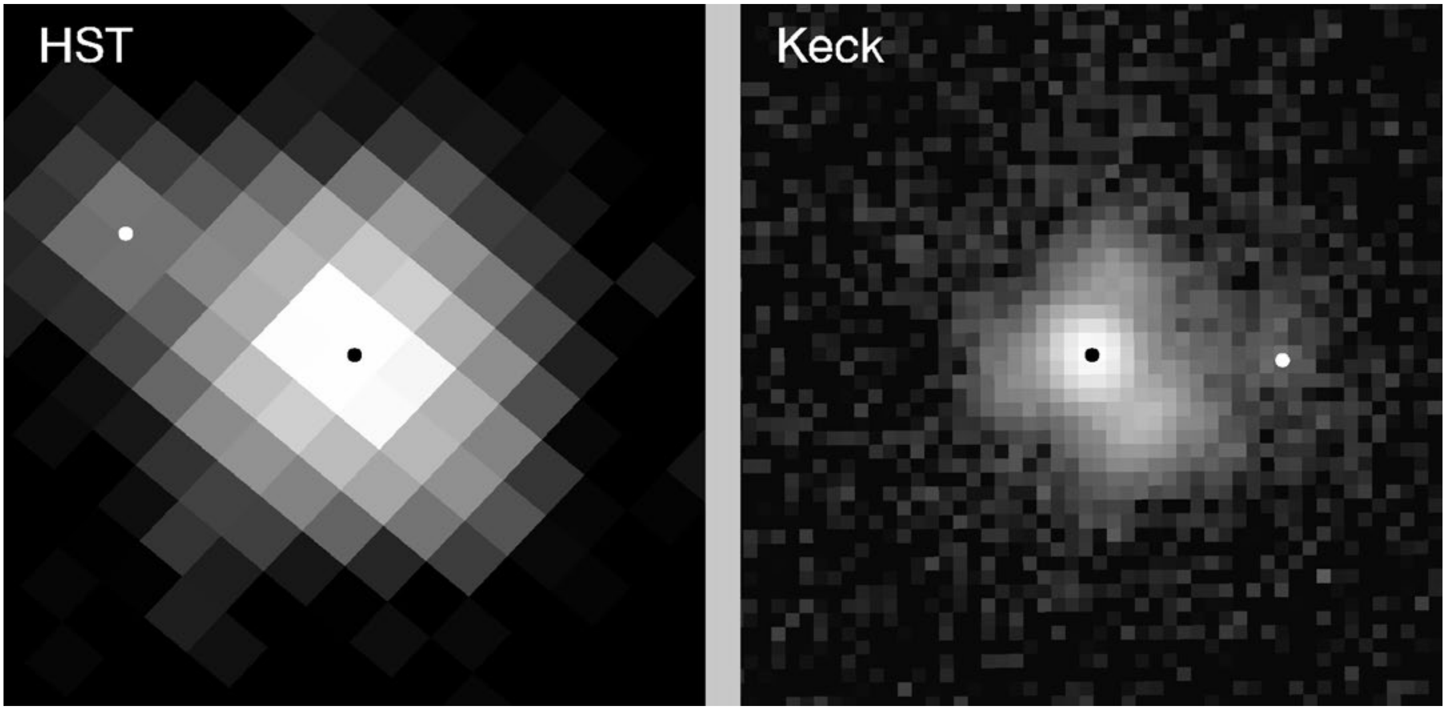
Check out an extended version of this story at www.astronomy.com/magazine/news/2018/10/lowell-observatory. For more information on Lowell, visit www.lowell.edu.

Dr. Ted Dunham

The most important parts of any technical activity are the people who make it work. The instrument group was very fortunate this year to be able to hire Mike Collins as our Electronics Specialist. Mike came from NXP in Phoenix and, in the Lowell tradition, now wears many hats.

Dr. Dunham's primary efforts in 2018 were related to his upcoming retirement in June of 2019. These included passing on his corporate knowledge of instrumentation at Lowell and preparing Anderson Mesa for the divestment of the 72-inch Perkins Telescope. As part of the divestment preparation we had to take on the task of clearing out about 60 years worth of accumulated equipment (and just plain junk). Dunham and Ralph Nye, with help from Jeff Gehring, Mike Collins, and Tom Bida brought all of this material back to Mars Hill to sort out the wheat from the chaff, as it were. With help from Molly Baker and Lauren Amundsen, we organized a video interview session with Nat White, Wes Lockwood, Bob Millis, and Otto Franz to keep a record of the instruments that we won't be able to keep. Our hope is that the history of these instruments won't be lost as long as we keep the pictures and videos we made before salvaging useful items from them and scrapping the rest. We are retaining sample equipment relating to important technologies of the past either for preservation in the historic collections or for possible use in future exhibits. Sample plate holders, Planetary Patrol equipment, image tubes, photomultipliers, image intensifiers, and CCDs are all being kept. One or two instruments will be kept in their entirety. We are in possession of a great number of astronomical mirrors, flat or otherwise, that we will retain in the new warehouse. Some items are useful as they are and have been kept in the lab.

Looking forward, Dunham participated in the hiring process for our new Deputy Director for Technology, Kyler Kuehn, helped with a NASA proposal to test laser communication with interplanetary spacecraft, helped initiate a partnership with UC Santa Cruz on a spectrograph for the Thirty-Meter Telescope project, began a project to replace the LOIS software used at Anderson Mesa and DCT, and helped with the ongoing project to port Larry Wasserman's MOVE telescope control program from old DOS computers to new hardware and the Linux operating system. Finally, Dunham worked with Jeff Gehring to develop requirements for a new technical center since the existing lab, machine shop, maintenance shop, and garage will all be demolished at some point to make room for the new public program facility. This planning work will cast a long shadow into the future as our ability to develop, operate, and maintain instrumentation will be dependent on these new technical facilities. ■



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 2018. Grundy was an author on 17 peer-reviewed scientific papers and book chapters published during the year, plus a book co-authored with Lowell's historian Kevin Schindler.

During 2018, Grundy was involved in observational projects using ground- and space-based telescopes including Hubble, Keck, DCT, ALMA, Kepler, 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 (see Figure 1).

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

Grundy is a co-investigator on two NASA space missions. The first, New Horizons, explored the Pluto system in 2015. He heads that mission's surface composition science theme team. Analysis of Pluto system data continued during 2018, even as preparation for the encounter with small Kuiper belt object 486958 2014 MU69 "Ultima Thule" ramped up toward the end-of-year encounter that

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Figure 1: Hubble Space Telescope and Keck adaptive optics images of the 400-mile-diameter Kuiper belt object G!kúnǁ'hòmdímà and its satellite G!ò'é !Hú. Each panel is ½ arcsec wide, about 10,000 miles at Kuiper belt distances. Small dots show the actual locations of the two objects. The names (originally proposed by Grundy et al.) are from the rich folklore of Southern Africa's Juǀ'hoan culture. G!kúnǁ'hòmdímà is a beautiful and plump aardvark maiden, who sometimes appears as a python or as an elephant, always defending her people and punishing wrongdoers. In one story she spears her husband to avenge his murder of her mother. In another she leads people to kill her elephant husband for selfishly failing to share water. Brothers of her dead husband attempt to forcibly "marry" her, but she flattens them with a magical oryx horn, g!ò'é !hú. When pursued by enemies, she casts ɡǁámíɡǁàmì spines to slash their feet and summons a hailstorm to erase her tracks and shred her foes' garments.

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revealed this primitive planetesimal. The second, Lucy, will be launched in 2021 to explore Jupiter's co-orbiting Trojan asteroids between 2027 and 2033. Grundy is the Instrument Scientist for Lucy's infrared imaging spectrometer system.

Grundy was elected in 2018 to serve 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 premier journal of planetary science, and on the advisory council of NASA's Planetary Data System Small Bodies Node. Grundy reviewed manuscripts in 2018 for scientific journals including Science, Monthly Notices of the Royal Astronomical Society, Journal of Geophysical Research Planets, and Planetary & Space Science. He reviewed proposals for four different NASA Research & Analysis funding programs and chaired the combined review meeting for two others. He also reviewed telescope time proposals for two different Hubble Space Telescope time allocations competitions, including the Cycle 26 review which pioneered a new approach, masking proposer identities. That test paves the way to fairer peer-review based allocation of resources. ▪

Figure 1: Global color mosaic of Triton, taken in 1989 by Voyager 2 during its flyby of the Neptune system.

Credit: NASA/JPL/USGS.

Dr. Jennifer Hanley

Dr. Jennifer Hanley's main research topic focuses on understanding liquid stability across the Solar System. One way to affect stability of water on Mars and Europa is by adding salt. Chlorine salts in particular (chlorides, perchlorates and chlorates) can lower the freezing point of pure liquid water from 273 K (0°C) down to 204 K (-68°C). In 2016 she was awarded a NASA Mars Data Analysis grant from NASA to determine the distribution of these salts on the surface of Mars. This past year Hanley worked with an undergraduate student from Purdue University to study the spectral characteristics of the chlorine salts and to identify them in Columbus Crater. This resulted in new parameters that can be used by themselves and other research groups to distinguish between different hydrated salts, a particularly challenging problem. In addition, Hanley was PI of an observing campaign to investigate whether these chlorine salts are found on the surface of Jupiter's moon Europa, and if so, what the distribution is. She used IGRINS, a high-resolution near-infrared spectrometer that was visiting Lowell's Discovery Channel Telescope, to obtain spectra of Europa across various longitudes to determine spatial variations.

Another focus of Hanley's research is the mechanical and spectral properties of cryogenic liquids and ices on outer Solar System bodies. Hanley was PI of an observing campaign to use IGRINS on Gemini South to detect this mixture on Neptune's largest moon, Triton. Laboratory experiments performed at NAU's Astrophysical Ice Laboratory on the spectral characteristics of mixtures of nitrogen and carbon monoxide showed a new absorption feature that could aid in their detection, as well as tell if they are physically mixed together. This is the first time these ices have been shown to be mixed together on the surface of Triton.

Other laboratory work performed by Hanley on the stability of nitrogen, methane, and ethane liquids under Titan conditions revealed some interesting results. In Titan's lakes and seas, which are composed of methane and ethane and are hundreds of meters deep, the liquid separates into two stable phases in equilibrium with a vapor phase. With any change in temperature, pressure, or composition, the two liquids' stability will change. This could cause ice or particulates to float or sink, bubbles to rise, and may even explain the "magic islands" seen by Cassini. Hanley was awarded a NASA Solar System Workings grant in 2017 and over the summer worked with an undergraduate student from Western Washington University, as well as hiring post-baccalaureate researcher Anna Engle to further explore this strange phenomenon.

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In 2018, Hanley was invited to talk about her research at The American Physical Society's Four Corners Section meeting in Salt Lake City, UT, at the Experimental Analysis of the Outer Solar System Workshop held in Fayetteville, AR, the Coconino Astronomical Society, the University of Arizona's Lunar and Planetary Laboratory, and at Embry-Riddle Aeronautical University, in addition to presenting her work at other conferences and workshops. ▪

Fig. 1

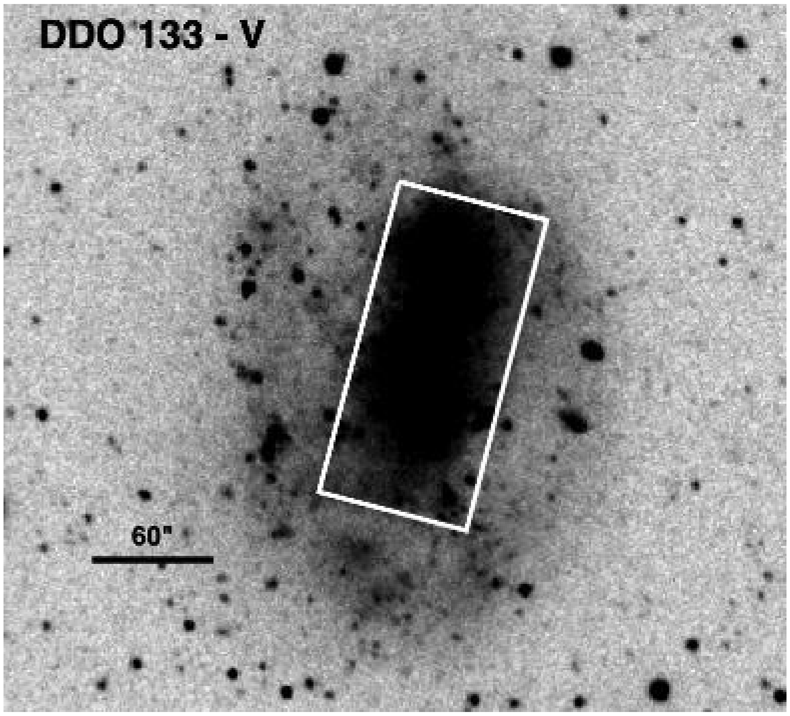
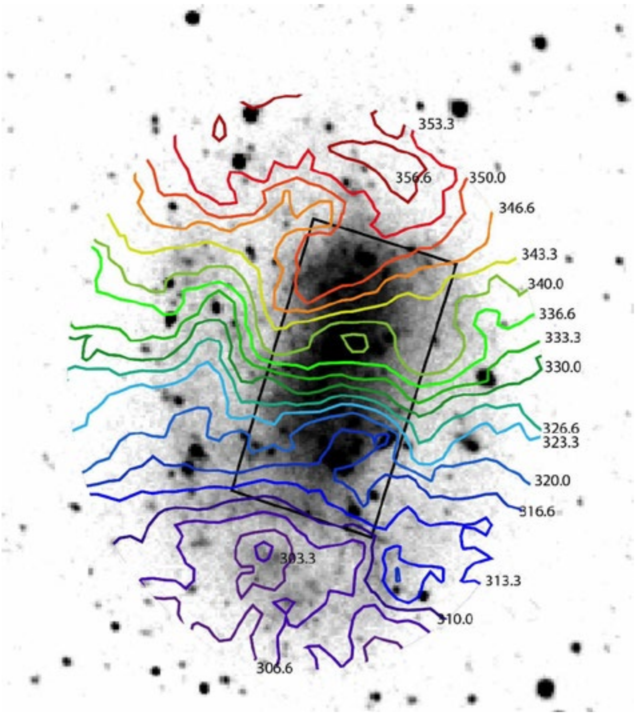


Fig. 2



Dr. Deidre Hunter

Galaxies usually contain stars, gas, and dust that are held together by gravity. Galaxies rotate about their centers, and it takes the Sun approximately 220 million years to travel the circle that takes it once around the Milky Way. However, in some galaxies there can be gas engaged in motions about the center of the galaxy that are not part of the well-behaved rotation of the galaxy. Dr. Hunter studies dwarf irregular galaxies, the tiniest but most common galaxy in the universe. She is seeking to understand how these galaxies bring gas together into clouds that then form new stars. It is possible that gas in peculiar orbits around the galaxy could collide with other gas and form clouds. More exotic is the possibility that gas flowing along the dark matter filaments of the "cosmic web" that formed from the Big Bang could still be falling onto galaxies, pulled by the galaxy's gravitational attraction. This process of cosmic accretion is predicted by simulations but has never been observed.

One of Hunter's collaborators, Se-Heon Oh, developed a computer code that uses her LITTLE THINGS team's atomic hydrogen data cubes (images of the galaxy at different velocities) to de-convolve gas engaged in ordered rotation from the gas that is not. He produced images of the gas in peculiar motions. So Hunter asked REU student Lauren Laufman last summer to look at the maps of gas in peculiar motions in their dwarf galaxies to see if there was anything interesting going on. Although two galaxies have large filaments of gas in their outer parts, Laufman did not find any evidence for cosmic accretion. However, she did find evidence in one galaxy, DDO 133, for streaming motions around a central stellar bar. The bar is evident as a rectangular structure in Figure 1, and the telltale "crinkle" pattern is visible in the velocity field along the edge of the bar in Figure 2. Furthermore, the streaming motions of the gas around the bar have caused gas to pile up at one end and stars are now forming from that cloud of gas. However, other than that case, there was no other evidence for gas engaged in peculiar motions to be associated with star formation in the galaxies. ▪

Figure 1: Inverted gray-scale image of DDO 133 taken through a green filter. The white box outlines the stellar bar in the galaxy.

Figure 2: Gray-scale image of DDO 133 with a black rectangle around the stellar bar. The colored lines trace the velocities in the atomic hydrogen gas. The numbers at the end of each line represent the velocity traced by that line in kilometers per second. The crinkle pattern due to the streaming motions of the gas along the bar is best seen to the left of the long side of the bar. They appear as bumps in the curve.

Fig. 1

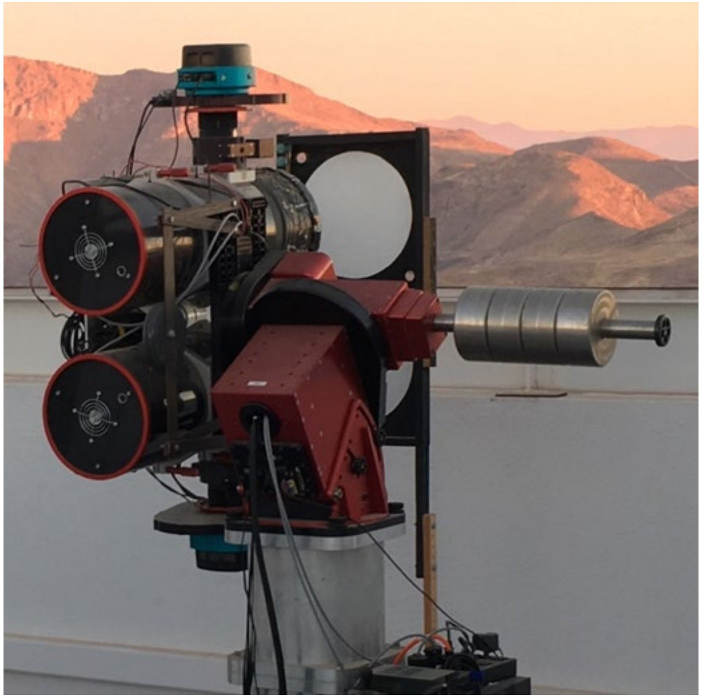
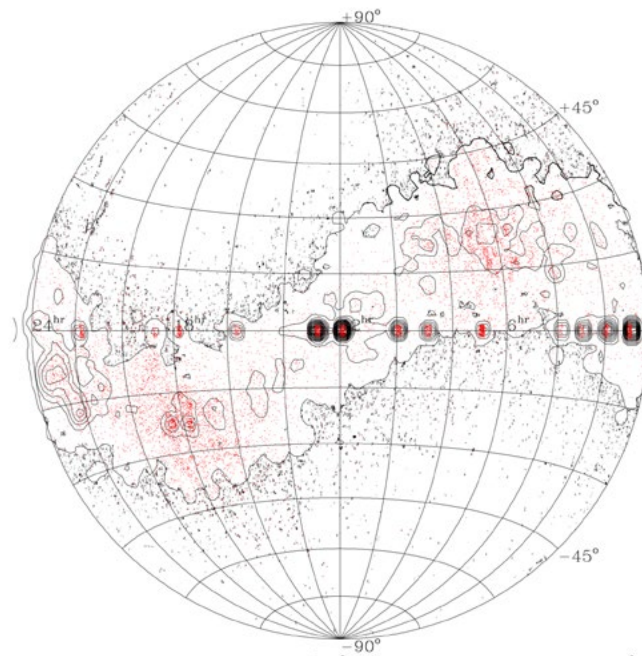


Fig. 2



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. He worked with Dr. Massey on modeling the orbital history of a high velocity halo star, showing that it was probably ejected by the black hole at the center of the Milky Way.

Levine continues collaborating with Dr. A. Henden (AAVSO), Dr. D. Welch (McMaster), Dr. D. Terrill (SwRI) and Dr. B. Kloppenborg (Pratum Labs) on the construction of the AAVSO Photometric All-Sky Survey (APASS). This will greatly simplify photometric calibration over the entire sky in the under-served magnitude range from 10 to 17. During 2018, the team continued their complete re-reduction of all the data taken between 2009 and 2016 and published Datac Release 10 in the fall. This survey covers the entire sky in five colors, and provides an empirical link between the earlier Johnson B and V, and the Sloan Digital Sky Survey g', r' and i' passbands. Levine also began a project to find and characterize all the known Solar System objects observed as part of the APASS survey. Initial results look promising with over 300,000 detections of over 32,000 distinct objects.

During 2018, Levine continued to serve as the DCT Scientist, working with the DCT observing, instrumentation and engineering communities to get the best out of the facility. Levine worked on rejuvenating a two CCD imaging camera for use in Chile; he was able to bring the instrument to a level where it was successfully used for three science programs. He also helped evaluate CSHELL (an infrared spectrograph) for transfer to Lowell, and dealt with long delayed maintenance on the APASS telescopes at CTIO. ▪

Figures 1: The APASS South installation at CTIO consists of two 8-inch astrographs on a common mount (the red mount in the foreground). Each telescope images a 2.9 x 2.9 degree region of the sky. The CCD cameras are the blue boxes mounted above and below the black telescope tubes. We appreciate the MEarth project's willingness to host the APASS South installation in their building at Cerro Tololo Inter-American Observatory.

Figure 2: The distribution of the Solar System objects detected in the APASS survey images. The bulk of the detections are along the ecliptic. The calibration fields along the equator show an overabundance of detections because they were imaged much more frequently. Red points are matches that were confused with stars.

Dr. Joe Llama

Dr. Joe Llama's main research topic is to characterize exoplanets, including their atmospheres and interactions with their host stars. Of particular interest to Llama are hot Jupiters, these are planets the size of Jupiter but orbit their parent star closer than Mercury does to the Sun. At such close separations, these planets have equilibrium temperatures anywhere between 1000 - 4000K.

This year, Dr. Llama enjoyed using the Immersion Grating Infrared Spectrograph, IGRINS, while it was visiting DCT to continue his survey to characterize the atmospheres of hot Jupiters. The unprecedented wavelength coverage and efficiency of IGRINS makes it the perfect instrument for this task. Working with MIT summer student Tomas Cabrera, Llama has been carrying out a survey of multiple hot Jupiters using data taken with IGRINS on the DCT to search for carbon monoxide, which acts as a diagnostic of whether these planets formed in place (incredibly close to their star), or formed further out in the disk and migrated inwards.

Working with previous Lowell Master's student Laura Flagg (now at Rice University), and collaborators Dr. Chris Johns-Krull (Rice University), Dr. Lisa Prato, and Lowell Predoc Larissa Nofi, the team used IGRINS to characterize the atmosphere of one of the youngest exoplanets, a two-million-year old planet that is approximately 11 times heavier than Jupiter. The team detected carbon monoxide in the atmosphere of the planet and they were able to constrain the likely formation mechanism for this fascinating planet.

In collaboration with Dr. Jayne Birkby (University of the Netherlands), Llama was awarded five nights on NASA's Infrared Telescope Facility to search for molecules in the atmosphere of another

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Figure 1: In November 2018, Llama took a trip to Tromsø in Norway to search for the Northern Lights. The weather was favorable and the solar wind co-operated and he had three nights of amazing aurora!

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young exoplanet, V830 Tau b. The weather cooperated and he was able to observe the system for all five nights. Data reduction and analysis is underway so stay tuned! Llama was also the Lowell science lead on a team led by former Lowell Astronomer Dr. Evgenya Shkolnik at Arizona State University to develop and launch a CubeSat to study the ultraviolet emission of low-mass stars. The Star Planet Activity Research Cubesat (SPARCS), will be a spacecraft the size of a Cheerios box tasked with monitoring the flares and star spots of small stars with the goal of assessing how habitable the space environment is for planets orbiting them. The year 2018 was a big one for SPARCS as the final spacecraft design was approved and plans were set in motion to finalize the launch date (currently slated for late 2022).

In Summer 2018, Llama presented an invited talk at the 20th Cambridge Workshops of "Cool Stars, Stellar Systems and the Sun", where he showed how understanding the host star is crucial to detecting exoplanets. He showcased results from the DCT, including the young planet radial survey and also how the next generation of planet-finding spectrographs such as EXPRES will lead to the discovery of true Earth-analog planets. ▪

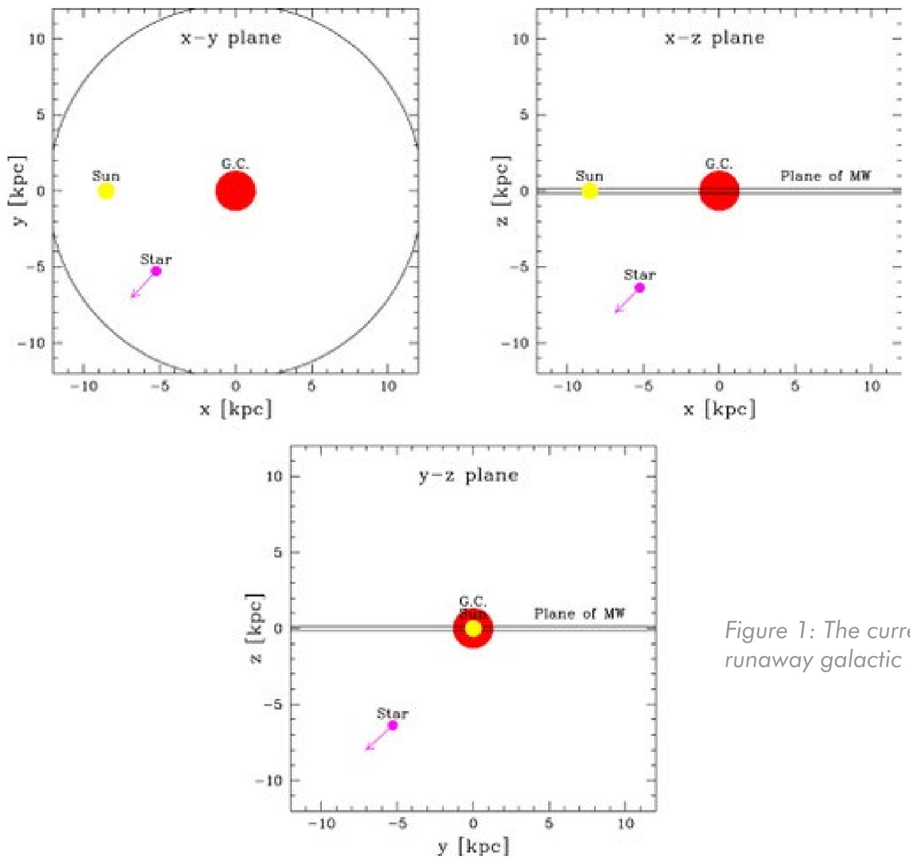

Figure 1: The current motion of the runaway galactic halo star is shown.

Dr. Phil Massey

One of the great privileges of being a scientist is that “eureka moment,” when you and your colleagues suddenly make sense of a previously enigmatic phenomenon. For a short time, there’s something about the Universe that only you know. Dr. Philip Massey felt this way thanks to research that he, Stephen Levine (Lowell), Kathryn Neugent (University of Washington and Lowell), Emily Levesque (University of Washington), Nidia Morrell (Carnegie Observatory), and Brian Skiff (Lowell) carried out in trying to understand a “runaway,” a star with an anomalously large space velocity. Back in 2013, in her first research project with Massey, Neugent discovered a yellow supergiant in the Small Magellanic Cloud (SMC) that was moving away from us at a much higher rate of speed than other SMC stars. Was the star simply a spectroscopic binary caught on an off day? Neugent urged our good friend and colleague Morrell to obtain additional spectra of the star, which showed that no, it wasn’t a binary. Runaway massive stars are not uncommon; these are usually unevolved OB stars that have been flung away from their birth place when a companion star suddenly loses mass in a supernova explosion. No yellow supergiant runaways had ever been found, but they are expected since these stars evolve from OB stars. Neugent, Massey, Morrell and Skiff wrote a paper about the star in 2017, but then along came new information: the Gaia satellite showed that the star was actually much closer than the SMC, and was a member of the Milky Way’s own halo. That meant that the star was not a yellow supergiant at all (surprise!) but rather a red giant. In their earlier paper they had considered this possibility but rejected it as halo stars are “metal poor,” lacking in heavier element, while their spectra of this star showed the opposite. So, how did this star get into the halo, and why was it moving at such a high velocity? Levine’s expertise in interpreting kinematic and orbital data proved essential in answering this; his careful analysis of the Gaia and ground-based velocities showed that the star was moving in a straight line away from the very center of the Milky Way. The most reasonable explanation was that it had experienced a close gravitational encounter with the

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supermassive black hole known to lurk at the center of the Milky Way. The presence of other high-velocity stars in the halo of the Milky Way have been attributed to the central black hole, but this is the first case where it has been possible to backtrack the orbit to show that such an encounter very likely occurred. Their results were published in the November 2018 issue of the Astronomical Journal.

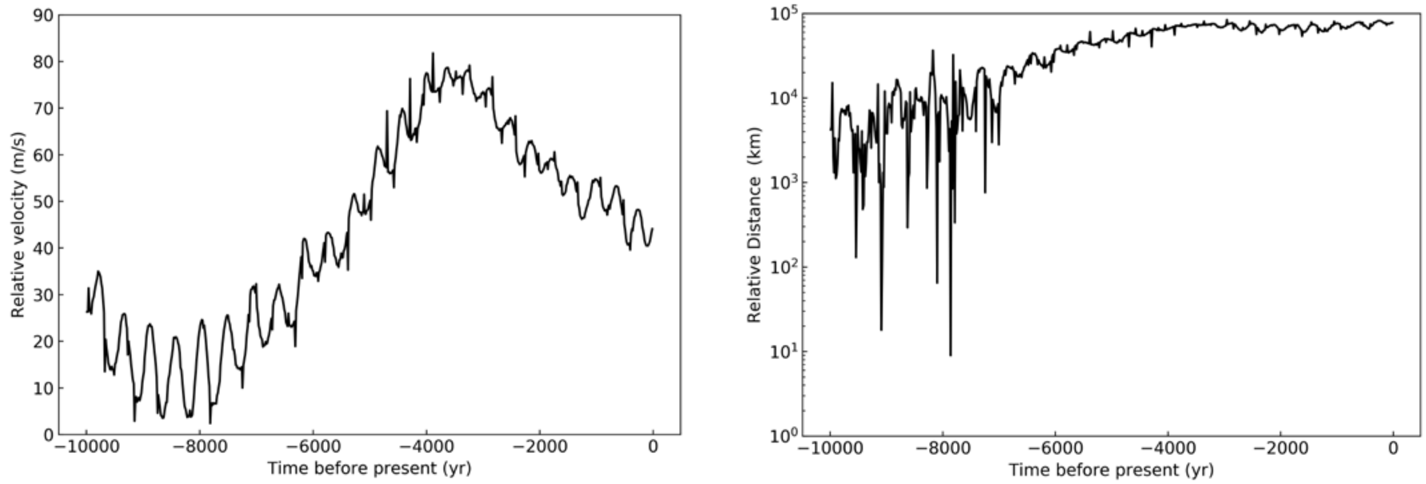
In other work, Massey's, Neugent's, and Morrell's four-year-long survey for Wolf-Rayet (WR) stars in the Magellanic Clouds came to completion. In all, they discovered 15 new WR stars in the Large Magellanic Cloud (LMC), along with a variety of other rare emission-line stars. Neugent took the lead on this work, and the summary paper was published in the August 2018 issue of the Astrophysical Journal. The paper includes the "Fifth Catalog of LMC Wolf-Rayet Stars," which includes new spectral classifications for all 154 known LMC WRs.

Massey was also co-author on Neugent's first two papers as part of the PhD thesis at the University of Washington under the direction of Dr. Emily Levesque. For her thesis Neugent is investigating the binary frequency of red supergiant stars. In Paper I she developed a technique for identifying such stars from their colors; in Paper II (to be published in 2019) she demonstrated that the method worked by obtaining spectra of stars she had identified as likely binaries. Prior to this work, only about a dozen RSG binaries were known; now 87 new RSG+B star binaries have been discovered.

Finally, Massey helped organize "Massive Stars and Supernovae," a meeting to celebrate the 65th birthday of his good friend and colleague Nidia Morrell. Morrell is a staff astronomer at Las Campanas Observatory, known for her expertise both on massive stars and supernovae. The meeting was held in San Carlos de Bariloche in November 2018, with about 150 participants from around the world. Both Massey and Neugent gave invited talks. A highlight of the meeting was the announcement that—thanks to Lowell's Larry Wasserman—an asteroid had been named in honor of Morrell. The journey to Bariloche included a 3-day drive across the Andes from Temuco, Chile with Morrell and other colleagues. ▪

Figure 2: Phil Massey presents Nidia Morrell with a plaque showing the orbit of the asteroid named in her honor.

Fig. 1



Dr. Nicholas Moskovitz

Dr. Nicholas Moskovitz continued a number of projects focused on the study of asteroids, comets, and meteors. This work was carried out with collaborators around the world, but perhaps one of the more interesting collaborations that began in 2018 was a project initiated through contacts with amateur astronomers, and eventually led to identification of a rare type of near-Earth asteroid (NEA).

Back in 2008 a class of asteroids referred to as "asteroid pairs" was discovered in the Main Belt between Mars and Jupiter. These asteroid pairs are different from binary systems (a primary body with an orbiting satellite) in that they are not gravitationally bound to one another, but instead trace out very similar yet independent orbits around the Sun. To date several hundred Main Belt asteroid pairs have been identified. However, there are many open questions regarding the process(es) of formation and separation age of these systems. Answers to these questions can provide important insights into planetary dynamics and evolutionary processes that modify the physical properties of minor planets throughout the Solar System.

In October 2018 Moskovitz noticed several postings on the Minor Planet Mailing List (an email forum for professional and amateur astronomers) that called out the newly discovered near-Earth asteroids 2017 SN16 and 2018 RY7. These objects were identified by amateurs as having incredibly similar orbits around the Sun (at a difference of <1% in their Keplerian orbital elements). Moskovitz reached out to one of these amateurs, which helped to identify some of the first ever asteroid pair candidates in the NEA population. This is noteworthy because NEAs experience close encounters with the Earth and the other terrestrial planets, which leads to chaotic scattering of their orbits on timescales as short as a few thousand years. Finding NEA pairs suggests that separation of these objects had to have been a recent event, otherwise their orbits would not remain close. Moskovitz and his collaborators set out to determine whether the members of such NEA pairs could in fact be related, and if so to address questions of how and when they formed.

Focusing on 2017 SN16 and 2018 RY7, the team obtained spectroscopic observations that revealed these two objects likely have the same composition, akin to a rare class of meteorites here on Earth. The chance of two random NEAs both having this rare composition is very low, thus suggesting that these two objects are in fact related and must share a common origin.

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Figure 1: Simulations of the velocity (a) and distance (b) between near-Earth asteroids 2017 SN16 and 2018 RY7 in time before the present. These evolutionary tracks show that these objects experienced convergence events (separations <10 km) with low relative velocity (<1 m/s) around 8,000 years ago. Such distances and velocities are so small on planetary scales that they are consistent with these two asteroids originating from a common progenitor.

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Motivated by this finding, the team performed numerical simulations to look at how the orbits of these two objects evolved in the past. DCT observations (conducted in December 2018 when 2018 RY7 had a V-band magnitude of 24.5) helped refine the object's orbits to increase fidelity in the simulations. To their surprise, they found that 2017 SN16 and 2018 RY7 may have separated as recently as 8,000 years ago (see Figure 1), making this pair one of the youngest multiple asteroid systems known in the Solar System. Unraveling further details of this separation event will be the focus of future observations and simulations. Ultimately Moskovitz and his collaborators aim to understand the specific pathway of formation for the pair 2017 SN16 and 2018 RY7. In doing so, this will help to identify other asteroid pairs in the NEA population. ▪

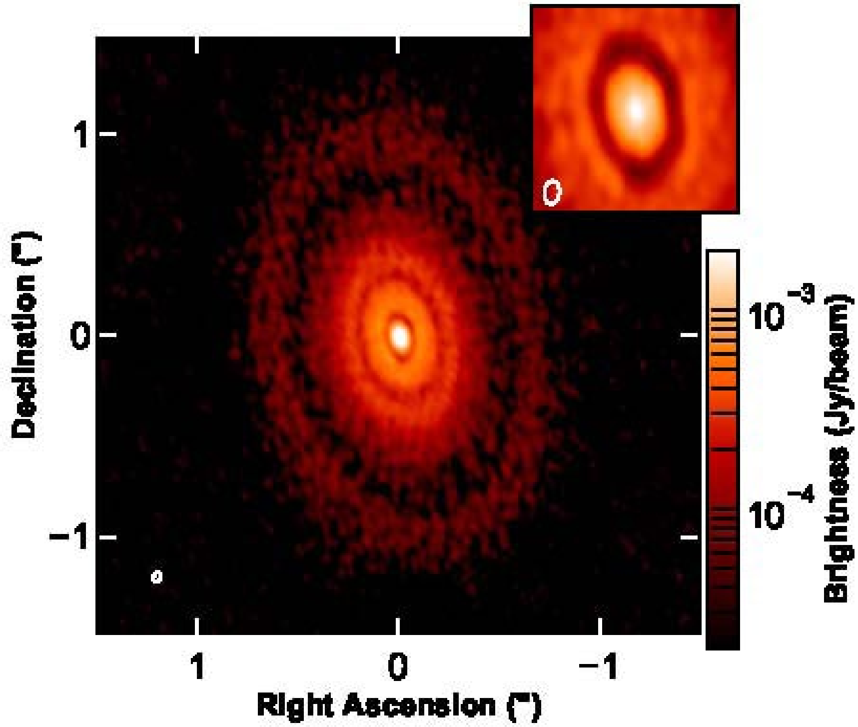

Figure 1: Warm dust in the primordial circumstellar disk around the young star CI Tau, imaged with the ALMA telescope array at millimeter wavelengths. The dark areas are gaps carved by newborn, massive planets. The inset shows a zoom in of the central region around the star.

Dr. Lisa Prato

Dr. Lisa Prato's group, DEFT, or Disks and Exoplanets Flagstaff Team, enjoyed a busy and productive year in 2018 focusing on young exoplanet and binary star research. NAU graduate student Lauren Biddle published a paper demonstrating a signal induced by the very young exoplanet, CI Tau b, discovered in 2016 by our team with collaborator Dr. Christopher Johns-Krull of Rice University, in the circumstellar disk around the parent star. Prato also collaborated with colleague Dr. Cathie Clarke of Cambridge University in a study of the structure of the CI Tau disk, published in October. The accompanying figure shows the Atacama Large Millimeter Array image of warm dust in this disk; the gaps apparent in the disk are likely cleared out by a family of large, newly-formed planets! The inset shows a zoomed region around the young star. The giant planet identified by our team is too close to the star to be detected in this image but the discovery of a system of accompanying Jupiter-mass objects also forming in this disk is an exciting development in the field of planet formation. In other exoplanet news, Lowell pre-doctoral scholar and University of Hawaii graduate student Larissa Nofi completed the observations for her survey for new young planets around stars in the Taurus region in January, 2018 and last autumn began her final series of intensive observations to confirm candidate exoplanets she has identified around the young star V1075 Tau and others. Nofi used the DCT with the high-resolution, infrared IGRINS spectrograph, which arrived for its final visit to Flagstaff in August. Look for more exciting results on CI Tau and V1075 Tau in the 2019 annual report!

Interns Sean Graham (NAU), Kyle Lindstrom (NAU), Kendall Sullivan (UMass), Tomas Cabrera (MIT Winter Field Camp), and David Kelly (NAU) worked with Prato throughout the year. Kyle won first prize in NAU's College of the Environment, Forestry, and Natural Sciences Undergraduate Research Symposium in April, 2018. Sullivan was accepted to the highly competitive University of Texas at Austin graduate program in astronomy and astrophysics. Tomas returned for the summer of 2018 as an REU student to work with Dr. Joe Llama. All five interns made significant contributions to the team's science and several papers based on their work have been submitted or are in preparation.

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Prato first-authored or contributed to 11 refereed publications and conference papers in 2018, ranging from determining masses and other properties of very young stars to further our understanding of star formation and evolution, to imaging extensive jets of gas generated by embedded young stars in the Aquila Galactic molecular clouds. Also in 2018 Prato was awarded close to $0.5 million in NASA and NSF grant funding, observed at the DCT, the Keck-II 10-meter telescope, the McDonald Observatory 2.7-meter, and the 3-meter IRTF. She taught a professional development course for graduate students at NAU, traveled to National Central University in Taiwan as a visiting scholar (see Figure 2), and was invited to give a talk at the invitation-only Lorentz Center workshop on triple star systems in Leiden. Prato served on time allocation committees both for Arizona telescopes and the IRTF, helped lead scientific organizing committees for two national conferences and a local STEM poster session and workshop, hosted three visiting scientists from Rice University and Keck Observatory, launched a local Journal Club seminar series with NAU graduate student Annika Gustafsson (working on her PhD with Nick Moskovitz) and continued to serve on the American Astronomical Society's Publications Committee. ▪

Figure 2: Dr. Prato with the research team of her host, Dr. Wen-Ping Chen (4th from left) at Taiwan's National Central University. Masters student Shih-Yun Tang, 5th from left, was accepted to the PhD program at Northern Arizona University and will begin his thesis work there and at Lowell with Dr. Prato in 2020.

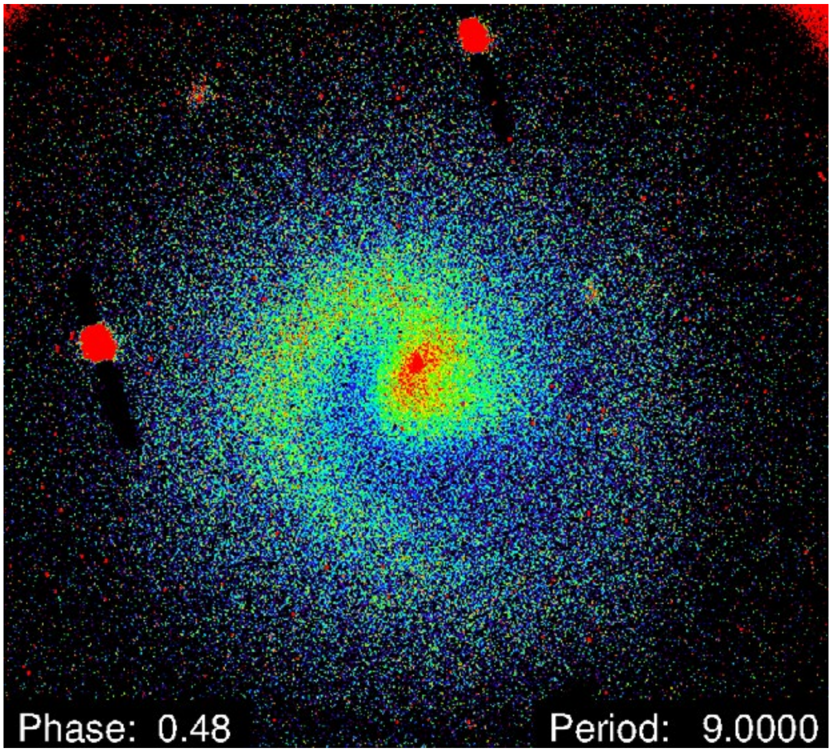

Figure 1: A representative image of two overlapping gas jets detected in Comet Wirtanen taken on Nov 11, a month before closest approach. A narrowband filter isolating light from cyanogen molecules (CN) was used with the CCD camera at the John S. Hall 42-inch telescope. This image was enhanced by first averaging a series of images throughout one rotation sequence, and then removing the average from individual frames, followed by adding false colors (red is brightest, then yellow, green, and blue). Note that the bright red dots are stars, while the dark streaks that the bright stars are embedded within are artifacts of the image enhancement. The frame has a field of view of 60,000 km.

Dr. David Schleicher

Drs. Schleicher and Matthew Knight (University of Maryland), in coordination with Drs. Tony Farnham and Lori Feaga (University of Maryland), performed extensive observing campaigns for two comets in 2018. The first, Comet 21P/Giacobini-Zinner, made a comparable passage by Earth as in Schleicher's initial studies in 1985, during which he discovered that G-Z, as it is known, has a very unusual chemical composition. In addition to obtaining similar data in 2018, confirming and extending the earlier results, the team obtained images using the DCT, the John S. Hall 42-inch, and the robotic 31-inch telescopes with narrowband comet filters that revealed gas jets having an unexpected radial morphology that evolved from month-to-month and still need to be interpreted. The second object, arriving shortly following G-Z, was Comet 46P/Wirtanen, the original planned target for the European Rosetta spacecraft mission. Due to a postponement in the launch, that mission went to another comet but Wirtanen remains of interest, and it came very close to Earth (0.08 AU), permitting rapidly changing and a wide range of viewing geometries. Gas images were again obtained using the same telescopes, which revealed two overlapping cyanogen (CN) gas jets (see Figure 1) with partial spiral morphology. Based on the motion of these jets both during each night and from multiple nights, the team was able to determine that Wirtanen's rotation period was approximately 9.0 hours, substantially different from prior estimates. Observations continued into 2019 and will be used to constrain the tilt of the rotation axis and determine seasonal changes. Finally, the results from similar studies of Comet Lulin (2007 N3) during its 2009 apparition were completed and published by Research Associate Allison Bair and Schleicher. Again, two CN jets were detected but in this case each appears as a side-on corkscrew, i.e. a tight spiral seen from the side rather than face-on, with each near its respective pole in opposite hemispheres.

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Modeling 32 nights of observations (see Figure 2) tightly constrained the orientation of the rotation axis and yielded a rotational axis tilt of about 97°. Lulin thus experienced extreme seasonal variations with first one pole pointing almost exactly towards the Sun and then, only five months later, the other pole having the Sun high in the sky. ▪

Figure 2: A representative enhanced image obtained on 2009 February 25 of CN jets detected in Comet Lulin (left) and a simulated image from Bair and Schleicher's preferred model solution (right). Because the coma of a comet is much brighter at the center and falls off in all directions, a radial profile was first removed, and false colors added (red is brightest, then yellow, green, and blue) to reveal the more subtle jets. One jet, color-coded yellow in the model, is emitted from a source region located at a latitude of -80°, while the second, color-coded blue, has its source at a latitude of +77°. Each frame has a field of view of 120,000 km, nearly 10 times the diameter of Earth.

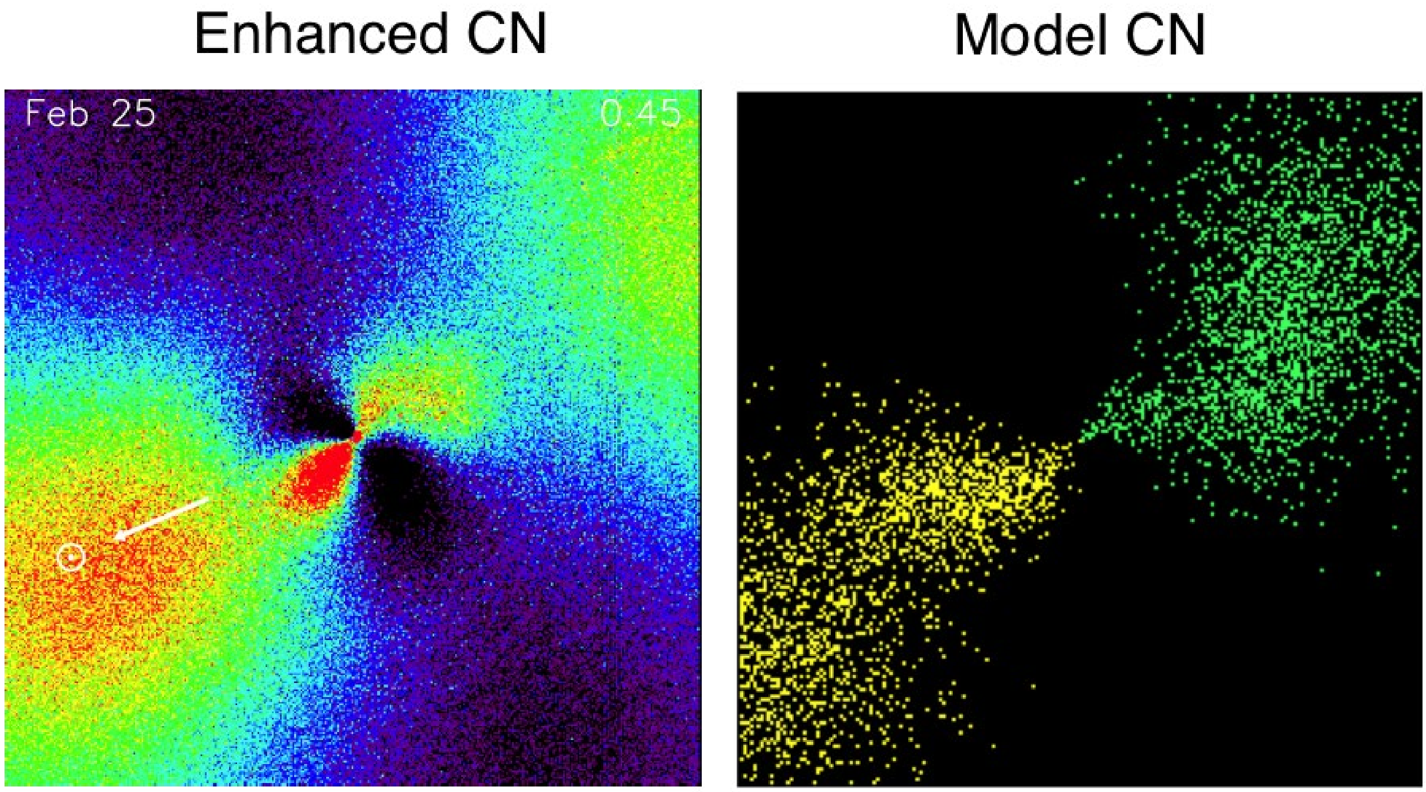

Fig. 1

Dr. Gerard van Belle

Substantial progress on the $3.26 million PALANTIR (Precision Array of Large-Aperture New Telescopes for Image Reconstruction) upgrade project for the Navy Precision Optical Interferometer (NPOI) was seen in 2018. All three PlaneWave PW1000 1-meter telescopes were on site, as well as two of the three AstroHaven 16Dash1 trailer-mounted domes; the first PW1000 was operational on-sky in its dome. Lowell adjunct Dr. Kaspar von Braun collaborates with van Belle on this project, and has been the Los Angeles local point-of-contact for PlaneWave.

Completing a one-year tenure as NPOI Director, van Belle rotated off that assignment and is now serving as NPOI's Chief Scientist, effective June 11, 2018; Dr. Jim Clark of NRL took over the NPOI Directorship at that time.

At the DCT, van Belle neared completion of the POKÉMON (Pervasive Overview of Kompanions of Every M-dwarf in Our Neighborhood) survey. This large survey of every low-mass star down to the hydrogen fusion limit covers 1,263 targets out to 15 parsecs; van Belle has been joined by NAU grad student Catherine Clark in carrying out this work. They were successful in supplementing the POKÉMON survey with additional time from the WIYN telescope on Kitt Peak via NASA's NN-EXPLORE program. This work was enabled by the visiting Differential Speckle Survey Instrument (DSSI) speckle, in partnership with Lowell adjunct Dr. Elliott Horch. The three researchers are extending DSSI's capability at DCT with the construction of the Quad-channel Wavefront-sensing Speckle Survey Instrument (QWSSI) upgrade to DSSI.

Dr. van Belle also completed a NASA-funded Small Business Innovation Research (SBIR) Phase I research project with industry partner Made In Space, which explored the possibility of flying a space-based optical interferometer based upon MIS's in-space manufacturing techniques. The resulting Optimast-SCI concept (Photo 2), which would 3D print two 10-meter booms in orbit for a 20-meter optical interferometer, was presented by van Belle at the January 2019 Winter AAS meeting in Seattle.

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Figure 1: Assembly and initial alignment of the QWSSI upgrade for DSSI, taking place at the Lowell instrument ship.

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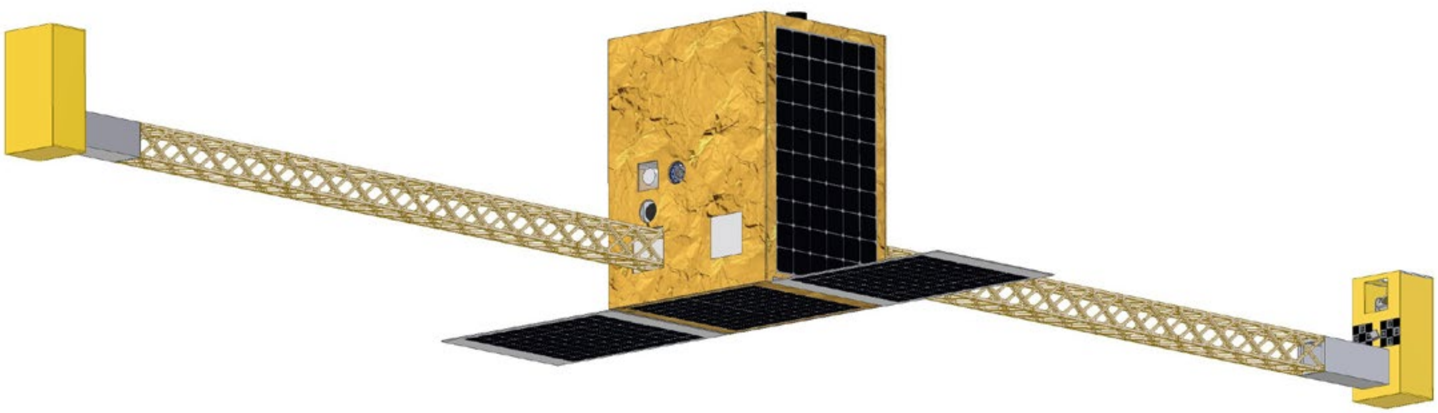
Science partnerships of van Belle resulted in multiple journal articles, including "Observations of Binary Stars with the Differential Speckle Survey Instrument. VIII. Measures of Metal-poor and Triple Stars from 2015 to 2018" with Dr. Horch et al. (*Astronomical Journal* 2019 157 56), "The Planet Formation Imager" with Dr. John Monnier et al. (*Experimental Astronomy* 2018 46 517), and "Fundamental Parameters of 87 Stars from the NPOI" with Dr. Ellyn Baines et al. (*Astronomical Journal* 2018 155 30). ▪

Figure 2: A render of the Optimast-SCI mission concept being developed by van Belle and Made In Space. Two 10-meter booms would hold outboard optics which relay light to a central beam combiner spacecraft. The in-space manufacturing of long, lightweight booms enables the entire launched spacecraft package to fit as a small secondary payload on a launch vehicle.



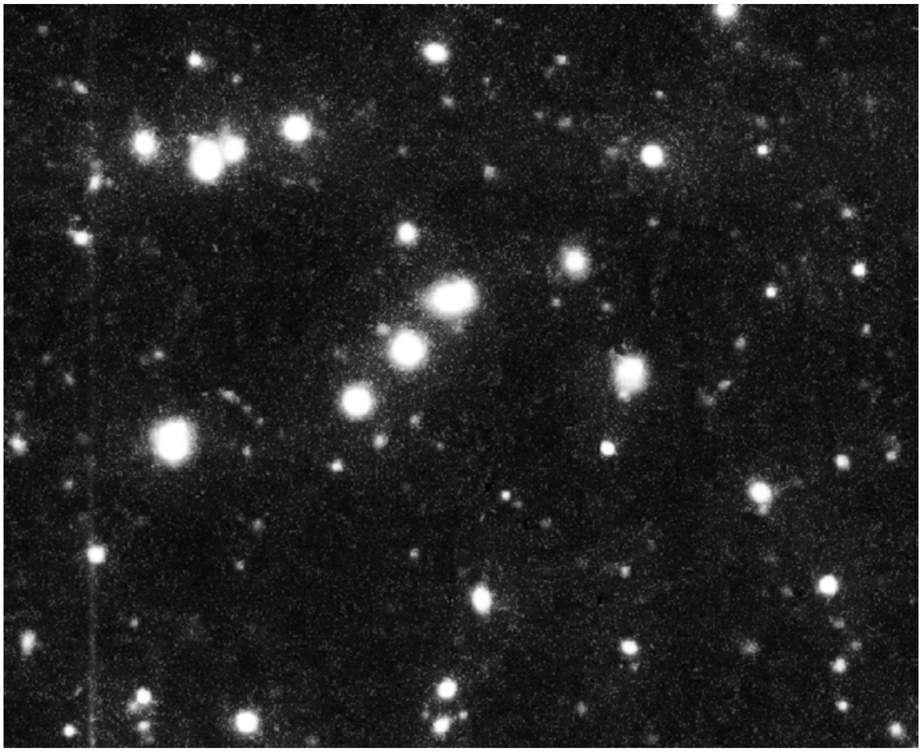


Figure 1: An image of the distant galaxy cluster 3C 322 captured by Lowell's Discovery Channel Telescope. These galaxies are seen as they appeared 10 billion years ago, a glimpse into the cosmic past.

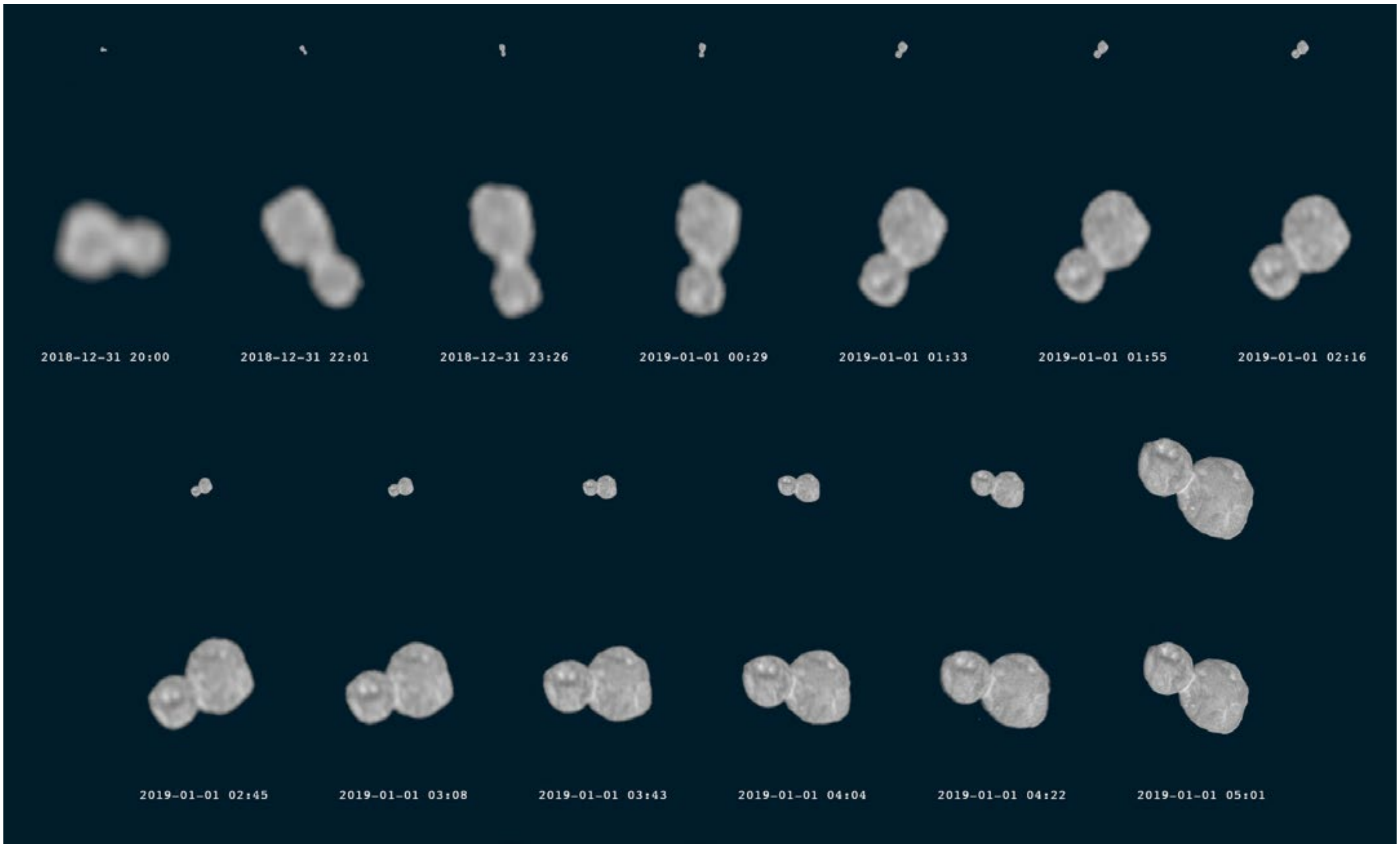
Dr. Michael West

Dr. Michael West used Lowell Observatory's DCT to search for distant clusters of galaxies, the urban centers of the cosmos. Like archaeologists looking for the earliest human settlements, West and his collaborators at the Harvard-Smithsonian Center for Astrophysics, Ruhr-Universität Bochum in Germany, and the University of Turku in Finland are using the DCT as a time machine to search for ancient cosmic villages where galaxies first gathered billions of years ago. These clusters are identified by intense radio emission coming from their largest galaxies, which is created by supermassive black holes similar to the one recently imaged in M87, a galaxy much closer to Earth. An example shown here, a cluster known as 3C 322, is seen looking back across 10 billion years of cosmic time.

David Kelly, a MSc student at NAU working under West's supervision, successfully defended his thesis in May 2018, which was titled *Mapping the Extent of the Magellanic Clouds using Gaia Data*. West also co-supervised Suei Hei Hon's MSc thesis at the University of Turku in Finland. Hon's thesis was titled *The Starving Ellipticals of Fossil Groups*. He is now enrolled in the astronomy PhD program at the Swinburne University in Australia.

In addition to his research, West continued to devote substantial time and energy to public outreach. He was elected to the International Astronomical Union's commission on Communicating Astronomy with the Public. The IAU is the largest organization of professional astronomers in the world, with 13,533 members in 107 countries. The commission's raison d'être is to explore and facilitate new ways of communicating astronomy with the public, guided by the belief that, "It is the responsibility of every astronomer to play a role in explaining the interest and value of science to our fellow citizens."

West continued to write regular columns for the observatory's monthly *What's Up at Lowell* newsletter and quarterly *The Lowell Observer*, as well as his popular *AstroAlerts*, which go out to nearly 2,500 subscribers. He also continued work on two books that he is writing. ▪



Dr. Audrey Thirouin

Dr. Audrey Thirouin's research focuses on the small icy trans-Neptunian Objects (TNOs) at the edge of our Solar System, with a special interest for binary systems. Since August 2017 and thanks to an NSF grant, Dr. Audrey Thirouin is working with Dr. Scott S. Sheppard (Carnegie Institution for Science) to study the rotational properties of the TNOs and understand the formation and evolution of binary systems with Lowell's 4.3-meter Discovery Channel Telescope and the 6.5-meter Magellan Baade telescope in Chile.

With the successful flyby of the dynamically Cold Classical TNO known as 2014 MU69 by NASA's New Horizons spacecraft, we now have for the first time a very detailed picture of a small TNO. Unfortunately, the spacecraft only visited one object out of the ~2,000 known TNOs. And so, the main question is: should we consider that 2014 MU69 is a typical TNO which can be considered the archetype of the trans-Neptunian population or did we just happen to visit a strange TNO? To answer this question, Thirouin and Sheppard observed a large number of dynamically Cold Classical TNOs to derive their rotation, their shape, their binarity rate among other parameters. Thanks to this survey, they predicted that 2014 MU69 would likely be a slow rotator with a deformed shape, and both predictions were confirmed by the flyby (see Figure 1). The team is also searching for TNOs with a similar shape as 2014 MU69, classified as a contact binary. So far, they have discovered 15 of the 16 known contact binaries in the trans-Neptunian belt (excluding 2014 MU69). Their results have been published in one referred paper, presented at the Division for Planetary Science meeting, and at the TNO meeting in Coimbra in 2018.

Dr. Thirouin was also involved in community service works, including the review of funding proposals and telescopes proposals. She was also invited to be a co-author of two chapters for the book entitled "Transneptunian Solar System". ▪

Figure 1: Raw images of 2014 MU69 obtained by the NASA New Horizons spacecraft. Credit: New Horizons team.

Fig. 1

Fig. 2

Erin Aadland

In June 2018, Erin Aadland started the first year of her PhD program at Northern Arizona University working with Dr. Philip Massey on massive stars. Her thesis project is evaluating the physical parameters of Wolf-Rayet stars in order to better understand their evolution. The outer layers of these stars have been stripped away by an unknown source. The two leading theories is that the stripping could be due to a close companion star or by stellar winds. One way to determine which is to model the star's spectra. This modeling process allows the star's chemical composition and other physical parameters to be determined. The parameters can then be compared to evolutionary models, which will help identify what the unknown stripping source is.

Wolf-Rayet stars have three subtypes: WNs, WCs, and WOs. The subtype is determined by what spectral lines are observed, indicating different chemical compositions. However, some debate exists over whether the subtypes WC and WO actually have different chemical compositions or if they have different luminosities and temperatures causing the various spectral line strengths. This is a question of whether the WC and WO subtypes are the same age or if WOs evolve from WCs. By modeling these stars, the two subtypes' physical parameters can be compared. Aadland is in the middle of working on this project, which will also be part of her thesis.

In November, Aadland went to Las Campanas Observatory in Chile to observe the remaining stars for her thesis. They are located in the Large Magellanic Cloud, one of the closest galaxies and only visible from the southern hemisphere. She observed on the 6.5-meter Magellan Baade Telescope.

In addition to working on her thesis, Aadland also published her first first-author paper working on the isolation of luminous blue variables. Luminous blue variables are thought to be an intermediate step between O-type stars (massive, blue stars) and Wolf-Rayet stars. A recent study proposed that these luminous blue variables were actually in binaries which would change the evolution sequence. To investigate this, Aadland and her team looked into the isolation of luminous blue variables (more isolation means binary evolution, less isolation means single star evolution). They found that the isolation of luminous blue variables does not support the new idea of binary star evolution. ▪

Figure 1: The 6.5-meter Magellan Baade Telescope dome at the Las Campanas Observatory in Chile, with the Moon rising above the mountains.

Figure 2: Erin Aadland in front of the 6.5-meter Magellan Baade Telescope.

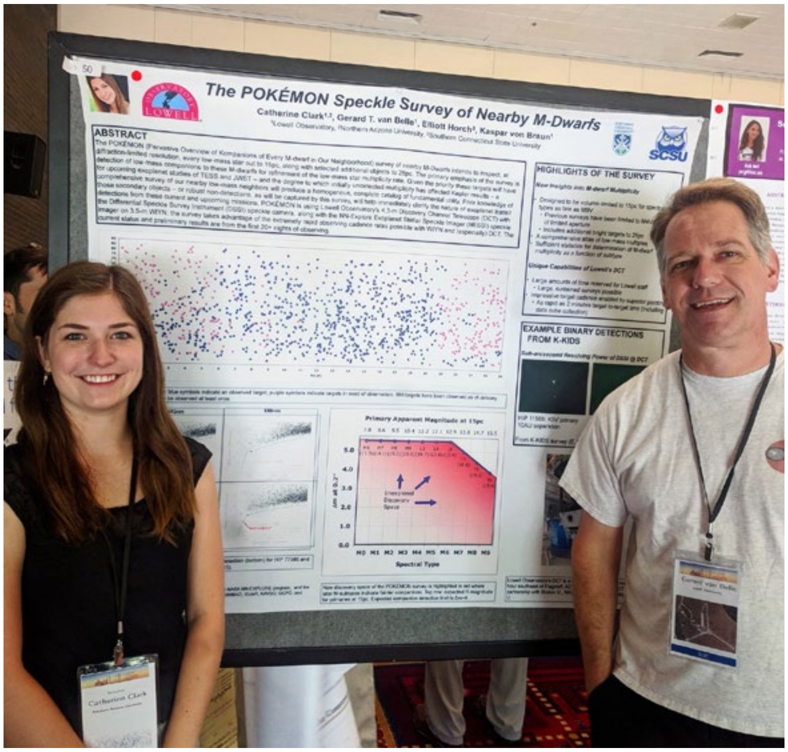


Figure 1: Catherine Clark and Dr. van Belle pose with the poster for the POKEMON survey at the Cool Stars Conference in Boston.

Catherine Clark

In 2018 Catherine Clark continued her PhD research working with Dr. Gerard van Belle. The main focus of her research thus far has been the Pervasive Overview of Kompanions of Every M-dwarf in Our Neighborhood (POKEMON) speckle survey. This survey intends to inspect, at diffraction-limited resolution, every low-mass star out to 15 pc, with selected additional objects to 25pc. The primary emphasis of the survey is detection of low-mass companions to these M-dwarfs for refinement of the low-mass star multiplicity rate. This survey has implications not only for stellar astrophysics, but for exoplanet studies as well. To complete this survey, Clark observed five nights at the Discovery Channel Telescope in 2018: one in October, two in January, and two in August. Additionally, Clark submitted an NOAO proposal for time with the NN-Explore Exoplanet Stellar Speckle Imager (NESSI) on the 3.5-meter WIYN telescope. This proposal was submitted with Dr. van Belle, Dr. Kaspar von Braun, and Dr. Elliott Horch of Southern Connecticut State University as co-investigators. Clark was awarded four nights of queue observing, as well as NASA funding to cover travel, research expenses, and publication costs. With these observations, the survey is nearly complete, and the project is intended to be published by late 2019.

In addition to the POKEMON survey, Clark and van Belle are in the process of building an upgrade to the Differential Speckle Survey Instrument (DSSI) called the Quad-camera Wavefront-sensing Speckle Survey Instrument (QWSSI). While DSSI observed in two channels, QWSSI will observe in six channels simultaneously, while also providing wavefront sensor data. The optical design was completed and parts were ordered in late 2018, and QWSSI is intended to be on-sky by mid-2019.

In order to supplement her knowledge of astronomical instrumentation, in July 2018, Clark received a travel grant to attend the Dunlap Institute Summer School. This summer school consisted of lectures and labs led by astronomers from around the world who specialize in the development of astronomical instruments, and provided a comprehensive understanding of the kind of planning and research that goes into the development of an astronomical instrument.

Also in July 2018, Clark traveled to Boston University to attend the Cool Stars Conference on low-mass stars, solar physics, and exoplanets. There she presented a poster on the POKEMON survey, and represented Lowell Observatory with Drs. van Belle, Dr. Jeff Hall, and Dr. Joe Llama.

In addition to her work as a graduate research assistant, Clark continued to take classes at Northern Arizona University, both in the Physics and Astronomy Department, as well as for her Graduate Certificate in Science Communication. ▪

TECHNICAL SUPPORT HIGHLIGHTS

Fig. 1

Fig. 2

Fig. 3

Figure 1: Routine washing of the DCT primary mirror. Washing of the primary occurs on a roughly six-month basis.

Figure 2: Former DCT Mechanical Engineer Ben Hardesty.

Figure 3: Former Telescope Facilities Manager Bill DeGroff.

By Dr. Teznie Pugh

2018 marked a year of substantial change to the structure of technical staffing at Lowell Observatory. Ben Hardesty (DCT Mechanical Engineer) left the observatory and Bill DeGroff (Telescope Facilities Manager and Former DCT Site Engineer) retired in October. There were several internal promotions following the retirement of DeGroff: Dr. Teznie Pugh to Operations Manager, Frank Cornelius to Engineering Manager, and Jason Sanborn to Night Operations Manager. There were also several additions to the team, Michael Collins (Electronics Specialist), Jake Tiegs (DCT Mechanical Technician) and Andrew Henrici (DCT Telescope Operator). In addition, two other senior staff, Dr. George Jacoby (Deputy Director for Technology) and Dr. Ted Dunham (Instrument Manager), both announced retirements for 2019. Late in the year, Dr. Kyler Keuhn of the Australian Astronomical Observatory accepted the position of Deputy Director of Technology starting in early 2019.

DCT

The DCT has now been in full science operations for four years. In 2018, part or all of 334 nights were scheduled for science. Total actual science time was 311 nights, with 18 nights lost due to weather, power outages and smoke, and five nights lost due to technical issues. Night operations support was provided by the telescope operations team, including: Lead Telescope Operator Dr. Teznie Pugh and Telescope Operators Jason Sanborn, Heidi Larson, Andrew Hayslip and Andrew Henrici.

During 2018, site engineering support at the DCT was provided by Bill DeGroff, Frank Cornelius, Ben Hardesty, Dr. Georgi Mandushev, Mike Sweaton, and Jake Tiegs. This group provided routine maintenance and upgrades of the telescope, dome, and facility, including:

- The water catchment system at DCT was made operational; by catching water off of the roof of the auxiliary building, filtering and treating it, regular water deliveries are no longer needed
- Upgrade of the dome tracking system to lessen wear and tear on the supporting structures

TECHNICALSUPPORTHIGHLIGHTS

Instrument support was provided by Dr. Ted Dunham, Tom Bida, Len Bright, Dyer Lytle, Dr. Ryan Hamilton, Jeff Gehring, and Dr. Stephen Levine. In addition, specific support for NIHTS and EXPRES was provided by Dr. Nick Moskovitz and David Sawyer, respectively.

- EXPRES completed instrument commissioning and met wavelength precision specifications for the wavelength reference spectrum
- Work began on upgrading and documenting the entire instrumental control software suite for DCT; this will be ongoing for several years

In addition to these tasks several members of the group participated in a NASA proposal to use the DCT as a laser communications receiver for the SETH space laser communications test project. Selection takes place in July 2019.

NPOI

Lowell Observatory maintains and operates the Navy Precision Optical Interferometer (NPOI) under contract to the US Naval Observatory (USNO) and in partnership with the Naval Research Laboratory (NRL). Daytime support for maintaining the facilities and infrastructure at the site were led by Jim Gorney with assistance from the larger Technology Team as required. In addition, daytime support was used to assist with NRL opto-mechanical efforts and in set-up of infrastructure related to the PLANATIR (Precision Array of Large-Aperture New Telescopes for Image Reconstruction) upgrade that was funded in 2017. Further efforts related to PLANATIR are being led by Lowell Astronomer Dr. Gerard van Belle.

In addition to daytime support Lowell provides skilled observers to operate the instruments and collect science data. In 2018 this team comprised of Dr. Teznie Pugh, Jason Sanborn, Ishara Nisley and Casey Kyte. Observations were conducted on a half-time basis in accordance with the funding level provided by USNO.

By the end of 2018 all three 1-meter Plane Wave telescopes had been delivered to NPOI. One of these telescopes was set-up in its trailer riding dome during 2018 and achieved first light with an attached camera. Integration into the NPOI array will occur in 2019 with first fringes expected in the fall. All mechanical and civil plans for the project were completed in 2018, with only minor tweaks and construction cost estimates remaining into 2019. With the completion of the drawing package, US Forest Service approval was pending by the close of 2018.

Figure 4: Delivery of the first Astrohaven dome to NPOI.

Figure 5: 72-inch Perkins mirror at the DCT coating facility awaiting its new aluminum coating.

Mars Hill

With the ongoing Master Plan work and planning taking place, several members of the Technology Group wer directly involved in helping to set requirements for the Technology facilities. Input was also given on GODO design. Facilities and maintenance needs of the Mars Hill telescopes (the Clark and Pluto telescopes) and domes were provided by Ralph Nye and Jeff Gehring. Michael Collins assisted astronomer Gerard van Belle on his work with the 20-inch Plane Wave telescope for variable star monitoring. ▪

Figure 6: The dome-trailer enclosure system after construction.

DEVELOPMENTHIGHLIGHTS

Fig. 1

Fig. 2

By Lisa Actor and the Development Team

Giovale Open Deck Observatory (GODO) funding took off in 2018, with gifts committed for the six telescopes, educational exhibits, eight benches, and 80 plaques inscribed with astronomy-related quotes and equations. Lowell celebrated the groundbreaking for the $3.7 million project in late September. A generous gift for the GODO, received in late December, gave the project construction a full green light. The development team then shifted its focus toward building the GODO Endowment Fund created by the Lowell Observatory Foundation. Payments from the GODO Endowment Fund will provide for this new observing facility's maintenance in perpetuity.

Lowell Observatory received a generous gift in the third quarter of 2018 to fund the schematic drawings and detailed engineering plans for the Astronomy Discovery Center (ADC). Once these plans were completed, BEC Southwest conducted a thorough cost analysis to determine the cost to construct the 31,000-square-foot new visitor facility. These activities set the stage for ADC fundraising in 2019.

Planned Giving

2018 saw a new initiative to identify and help Lowell supporters who are considering providing a lasting legacy to astronomy research and education at the observatory. Last summer, the development team contracted with Legacy Leaders, a Toronto-based company specializing in helping non-profit organizations with planned giving. The company identified 605 Lowell members who, based on giving history, age, and a number of other factors, were statistically likely to make a lasting, ultimate gift through their estate. After reaching 293 of them, the team learned that more than 45 percent had either already made arrangements for Lowell in their wills, retirement or insurance plans, or other forms of planned gift vehicles, or would consider doing so in the future. The Development Team is following up with these supporters to offer assistance and to gain more knowledge about their intention to give in such a way.

Figure 1: Ginger and John Giovale address the crowd during the GODO groundbreaking event.

Figure 2: Dignitaries turn the first spadeful of earth to ceremonially break ground for GODO.

DEVELOPMENTHIGHLIGHTS

Lowell is honored that so many members have or are considering supporting the observatory through their life estates. Many have chosen to direct their ultimate gifts to endowment funds in the Lowell Observatory Foundation. Gifts to endowment funds support the observatory in perpetuity. Currently, four percent of the endowment fund earnings directly support the observatory's activities and any earnings above four percent are reinvested to grow the original gift.

In support of this new initiative, all members of the Lowell Observatory Advisory Board's Executive Committee have included the Observatory in their estate plans and many other Advisory Board members have followed suit.

Native American Astronomy Outreach Program

The Native American Astronomy Outreach Program (formerly the Navajo-Hopi Astronomy Outreach Program) is growing and with it, the program budget. In 2018 the development team worked closely with the program staff to raise funds for this effort that partners Lowell staff with teachers on the nearby reservations to impact students' lives with STEM education. More than 80 individual donors contributed to support exciting changes in the program. The remainder of the funds came from seven private foundations and an NSF grant.

Annual Campaign Giving Three–year Comparisons

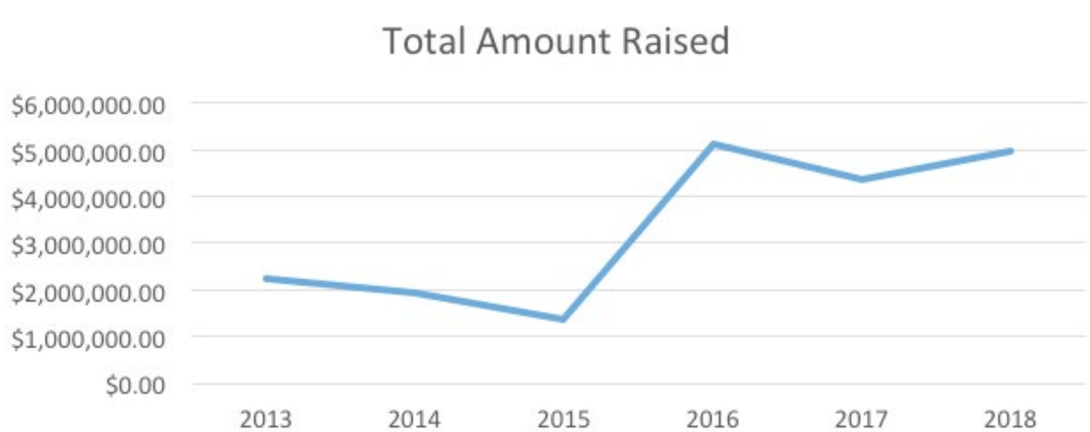
Annual Campaign giving (gifts in addition and separate from membership gifts) supports the general operation of the observatory as well as special project fundraising endeavors such as the Native American Astronomy Outreach program, Lowell Observatory Camps for Kids (LOCKs), and archival preservation of historic documents and artifacts. In 2018 Annual Campaign efforts brought in $144,124 for general operating and special project needs. This compares to $126,245 in 2016 and $157,710 in 2017.

Membership Renewals

One thing that sets Lowell Observatory apart from other non-profit and science organizations is the fierce loyalty of its members. Observatory members have recognized the valuable contributions that Lowell has given to the astronomical community throughout the years and support the current research and educational activities that it provides now. Membership renewals regularly top 40 percent each year, something almost unheard of with other membership-based non-profit organizations. Lowell is grateful for the on-going funding from members who support science and science education at the observatory.

Total amount raised in 2018: $4,949,317 ▪

Six-year Fundraising Trend:



Amount Raised

2013	$2,234,127
2014	$1,913,328
2015	$1,343,906
2016	$5,116,915
2017	$4,355,253
2018	$4,949,317

PUBLICPROGRAMHIGHLIGHTS

Fig. 1

Fig. 2

By Megan Stanley

Last year was historic for the Public Program as 104,344 people visited the observatory, marking the first time annual attendance has surpassed the 100,000 mark. This is a significant growth over the past several years, and a few individual months saw all-time high attendance as well. In January, for instance, 5,757 visitors came to Mars Hill—almost 2,000 more than the previous record—and in March the number reached 12,428—30% more than in 2017. To accommodate this increase in attendance, Public Program staff initiated several changes. The most significant was moving the gift shop into the space previously used as the exhibit hall. The new area is much larger and allows for not only a less cramped visitor experience, but room for much more stock to be displayed, as well as a sitting area where guests may enjoy packaged food.

The Lawrence Lowell (Pluto Discovery) Telescope restoration was completed in December 2017 and the Public Program held a Grand Re-Opening event on March 10, 2018. This was attended by donors, advisory board members, Lowell staff, Flagstaff's mayor, and members of the public. This event celebrated the hard work by Lowell's technical team in restoring the telescope and dome, the 90th year since the telescope was built, and the continued interest and engagement in science in Flagstaff.

On July 20, Lowell joined other organizations around town in launching Flagstaff's Lunar Legacy, an 18-month-long celebration of northern Arizona scientific role in the Apollo Moon missions that centers around the 50th anniversary of the first Apollo moon landing (July 20, 2019). At Lowell, Public Program staff added a new daytime tour detailing the Moon mapping and astronaut training that took place at the observatory, and also enjoyed showing guests the new Lunar Legacy exhibit in the Putnam Collection Center.

Lowell Observatory Camps for Kids (LOCKs) included 24 opportunities for children to actively engage in Lowell's education efforts. Under the leadership of Kelly Ferguson, on-site attendance totaled 174 Pre-K kids, 132 elementary-aged students, and 32 middle-school students. Off-site LOCKs program attendance in Cave Creek, Arizona doubled in 2018 growing from about 25 to 50 students. This was largely due to the integration of the LOCKs Preschool curriculum into a kindergarten class at Annunciation Catholic School in Cave Creek, as well as the support from Kiwanis and the work of Tom Ensign and Bruce Kosaveach. Other off-site efforts saw participation by 350+ students at the Flagstaff Family Food Center and other areas across Flagstaff.

Figure 1: Ribbon cutting to officially reopen the Lawrence Lowell (Pluto Discovery) Telescope dome (left to right): Frank Edmondson, Margaret Edmondson Olson, Flagstaff Mayor Coral Evans, Lowell Director Jeff Hall, Sam Storch.

Figure 2: Visitors viewing the refurbished Pluto Discovery Telescope during the rededication ceremony.

PUBLICPROGRAMHIGHLIGHTS

School visitation to Lowell benefited from the generosity of Advisory Board member Bob Ayers. His gift made it possible for all of Flagstaff Unified School District's fifth graders to visit Lowell during the 2018-2019 school year. The more than 500 students who visited the observatory as part of this program participated in tours and hands-on Moon-themed activities.

Todd Gonzales led a collaboration with the United States Geological Survey and Northern Arizona University to develop an astronaut training curriculum called PLANETS. Lowell Observatory is serving as a test site for the curriculum, which began with Lowell's desire to engage schools with hands-on labs instead of lectures.

Updates to the Master Plan began to solidify throughout various meetings with external consultants and representatives of the Lowell Observatory staff. Several of the proposed new facilities will greatly benefit the Public Program staff's ability to enhance the visitor experience, including the Giovale Open Deck Observatory (GODO), a suite of six state-of-the-art telescopes housed under a roll-off roof and named for donors John and Ginger Giovale.

Fig. 1

Fig. 2

Fig. 3

By Dr. Deidre Hunter

Native American Astronomy Outreach Program

The 2018-19 schoolyear is the first year of our three-year collaboration with the Kayenta Unified School District. The collaboration centers around partnerships with seven fifth-to-seventh-grade teachers to test astronomy-focused curriculum units in the classrooms. These units were developed during the summer by Todd Gonzales, Lowell's Master Teacher, and use Project Based Learning so that the students can better see themselves as scientists. In addition, our Navajo collaborator Verna Tallsalt added cultural connections so that the students can see science as relevant to their lives. Our teacher-astronomer partners carried out the curriculum, with additional activities as desired, and we are now in the process of reviewing each unit and making revisions for next year. The product of the

Figure 1: Fourth-grade students visit Mystery Valley to study erosion and sand dunes on the Navajo Nation.

Figure 2: Seventh-grade terrariums give hands-on experience with growing food as one might in space.

Figure 3: 2018 seventh-grade summer camp: a Mars habitation.

work that the students do at each grade level is a poster that demonstrates what they learned. These posters were shared with the parents at the spring star party and with Lowell staff on the class field trips to Flagstaff.

The fourth-grade unit is on erosion and in particular sand dunes. The students can see that sand dunes are overtaking Navajo Nation grazing land and they made a trip to Mystery Valley to study erosion in person (Figure 1). They created sand dunes in the classroom and watched as a gentle wind changed the shape and location of the dunes with time. They then applied what they had learned to interpreting a picture of sand dunes on Mars.

The fifth-grade unit is on characteristics of the planets. The students learned about Mars and Venus in contrast to Earth and constructed small environments of each in bottles. They observed how well yeast does in each of these environments. Their posters, in the form of travel posters, explained their thoughts on what they would need to live on Mars or Venus.

The sixth-grade unit is on the energy cycle that for us initiates with sunlight. Students learned about glucose and played a game in which runners provide the interface between the producers and primary and secondary consumers. They also learned where the choke points occur and what happens if sunlight is interrupted. For their posters, they applied the energy cycle to life on Europa or Titan.

The seventh-grade unit is on ecosystems in space. They created an ecosystem in a sealed terrarium (Figure 2) and then considered how they would take a human-friendly ecosystem into space.

Last summer, Lowell also held two week-long residential summer camps, one for rising sixth graders and one for rising seventh graders. These camps build off of the classroom curriculum units (Figure 3), and also immerse the students in astronomy at a real observatory. ▪

PUTNAMCOLLECTIONCENTERHIGHLIGHTS

Fig. 1

Fig. 2

By Lauren Amundson

In 2018, Putnam Collection Center (PCC) staff continued their mission of acquiring, preserving, making available, exhibiting, and interpreting collections. Archivist and Librarian Lauren Amundson oversaw all aspects of the daily activities and larger projects in the PCC. The department added a second staff member, Stacey Christen, as Collections Assistant.

Amundson welcomed five individuals who visited the archives to conduct research.

Dr. Craig Bowers traveled from Australia to research the relationship and collaboration between Lowell and Perth Observatories. Historian Emily Simpson looked into Percival Lowell's impact on science and the public. Tetsuro Irie, a doctoral student at the University of Tokyo and visiting scholar at New York University, spent a week in the archives conducting research on the life and intellectual career of Percival Lowell. Dr. Gary Wihl from Washington University in St. Louis visited to look at some of Percival Lowell's papers. Author David Baron spent four days in the archives researching Percival Lowell and his contributions to the science and culture of Mars. Amundson received roughly two dozen requests from authors, publishers, filmmakers, educators, and historians for the reproduction and use of archival materials.

Volunteers continued to move documents, drawings, photographs, and books from the Slipher Building basement to the PCC's walk-in freezer and repository. Amundson managed twelve volunteers and their projects, which included collections processing, cataloging, and digitization; humidifying and flattening drawings; and preparing materials for transfer to the PCC.

In March, Amundson and Christen designed and installed an exhibit for Women's History Month called Women in Astronomy. The exhibit, with both physical and online components, focused on the careers of former Lowell staff members Wrexie Leonard and Elizabeth Williams and University of Arizona astronomer Dr. Elizabeth Roemer.

In May, Amundson and Christen, assisted by Historian Kevin Schindler and Archival Restoration Specialist Peter Rosenthal, designed and installed an exhibit called Lowell's Lunar Legacy in the PCC lobby. The exhibit highlights Lowell Observatory's contribution to the Apollo program, focusing on lunar mapping and astronaut training in northern Arizona. Amundson created an online exhibit to complement the physical display.

Figure 1: Archives Month poster.

Figure 2: Lunar Legacy exhibit.

Amundson and Emeritus Astronomer Dr. Wes Lockwood continued their oral history project by interviewing Dr. Ted Dunham, Antoinette Beiser, and Brian Skiff.

The archives partnered with the Arizona Memory Project and Arizona Archives Online to make its digital collections and finding aids available to the public, and Amundson and Christen maintained a blog and Twitter account. In October, for American Archives Month, Amundson and Christen created a poster and special exhibit around the theme “Science Fiction in the Archives.” Various locations around Flagstaff, including the Public Library, Cline Library, Pulliam Airport, and Flagstaff Visitor Center, displayed the poster throughout October. Lowell educators and docents hosted daily public open houses in the PCC lobby. ▪

COMMUNICATIONHIGHLIGHTS

Fig. 1

By Dr. Danielle Adams

The singular goal of marketing is to create new customers, by making more people aware that Lowell Observatory exists and by communicating how the observatory can meet their needs. To that end, the communications team in 2018, led by Molly Baker, deepened relationships with key stakeholders, increased the observatory's presence on social media channels, added new team members, and instigated the city-wide Flagstaff's Lunar Legacy campaign. Through these efforts, guest attendance increased by 6% over 2017, passing the 100,000 mark for the first time with a total of 104,344 guests visiting Mars Hill in 2018.

In March, the team met with consultants from Kei Space Design to discuss the graphical identity of Lowell Observatory, the continuation of a 2017 branding discussion. The explorations that emerged through this workshop were the precursor to the temporary logo that Sarah Gilbert designed for use in our 125th anniversary year (2019).

Both offline and online media were used to increase the awareness and reach of the observatory among the general public. Online social followers grew collectively by 12%, with the addition of more than 3000 followers across all channels. C-SPAN filmed at Lowell for several days in the summer as part of their "2018 Cities Tour," beginning with a live event hosted at Lowell, during which Flagstaff Mayor Coral Evans and other community leaders spoke. In the fall, "CBS This Morning: Saturday" filmed at Lowell in an Apollo-themed segment that will be aired in 2019.

Locally, community relationships improved as well, with the observatory creating new partnerships with local hotels and expanding the Lowell Observatory Kids Zone to NAU home football games for the first time. Findlay Toyota donated a new Toyota RAV4 with a beautiful graphic wrap that showcases the Clark Dome. Relations with the Flagstaff Convention and Visitors' Bureau reached new heights as Kevin Schindler originated the Flagstaff's Lunar Legacy campaign, an 18-month-long, city-wide celebration of northern Arizona's scientific role in the Apollo Moon missions.

Figure 1: Anne LaBruzzo and Molly Baker accept keys for Toyota Rav4 from Findlay Toyota officials.

COMMUNICATIONHIGHLIGHTS

In March, the reopening of the restored Lawrence Lowell (Pluto Discovery) Telescope was accompanied with a book signing of Pluto and Lowell Observatory, written by Kevin Schindler and Dr. Will Grundy. Over the course of the year, Schindler gave a total of 39 public programs and 27 tours, and he wrote 56 articles for a variety of publications.

Several new team members were added in 2018. NAU graduate Heather Craig (2018, Marketing) came on board just ahead of the summer to increase the observatory's presence on social media. In the summer, Senior Creative Specialist Sarah Gilbert had a Lowell baby, Skyler, born on June 29. Miriam Robbins arrived in June, bringing experience in marketing, member acquisition and gift shop management from her previous role at the Grand Canyon Association. Lastly, Dr. Danielle Adams joined in December as the team's first Deputy Director, bringing expertise in strategic marketing and customer experience. To house these new team members, generously donated DON funds were used to remodel the historic White House (the former residence of Lowell astronomer Dr. Nat White) into the Marketing and Communication offices at the end of 2018.

DON funds were also used in the summer of 2018 to nearly double the size of our gift shop. This larger footprint has enabled Lowell to better curate products, resulting in gross sales of $595,646 for 2018, nearly $70,000 above expectations. Under the leadership of Miriam Robbins, the retail staff (now called Visitor Experience Associates) are now responsible for admission, gift shop sales and on-site membership recruitment. ▪

Figure 2: Lowell's Marketing and Communications Team, enjoying a meal together in the restored White House (left to right): Kevin Schindler, Heather Craig, Sarah Gilbert (with Skyler), Molly Baker, Miriam Robbins and Danielle Adams.

VOLUNTEERHIGHLIGHTS

By Mary DeMuth

Lowell Observatory has enjoyed the support of volunteers for many years. They are dedicated individuals who share a commitment to their community and pride in their association with the observatory. In 2018, volunteers could be found almost any day in one or more areas of the Mars Hill campus hosting open houses in the Rotunda Museum and Pluto and Clark telescope domes; creating and delivering presentations in the evening public programs; helping maintain and organize the observatory's historic collections; ensuring growth in Lowell membership by assisting with Development Department mailings; lending a hand in the business office to help keep things running smoothly; helping DCT staff scanning and organizing documents; working with the groundskeeping crew to install signs identifying campus flowers, trees and shrubs; assisting in planning volunteer appreciation events; and helping the Development Department organize and host fundraising events in Sedona and Seattle. In the summer, volunteer counselors-in-training assisted Lowell summer camp counselors in creating an exciting and educational camp experience for young astronomy lovers. On the horizon, volunteers will continue to play an important role in the observatory's success as Lowell looks forward to the fall opening of the Giovale Open Deck Observatory, carrying out additional outreach expansion plans, and continued growth in all aspects of the observatory's operations.

Members of Lowell staff worked with volunteers to help them identify how to best tap into their unique abilities and individual interests through rewarding and worthwhile assignments, and continue to support volunteers throughout their tenure with the observatory. Lauren Amundson, Catie Blazek, Sarah Burcher, John Compton, Curtis Dankof, Rachel Edelstein, Kelly Ferguson, Todd Gonzales, Robin Melena, Teznie Pugh and Kevin White are among staff that have helped guide new and veteran volunteers to success in their roles.

Fourteen new volunteers joined Lowell in 2018, and a total of 60 individuals clocked just over 4,700 hours of volunteer time. Among active volunteers, Lowell is proud that nine have celebrated five years or more on the volunteer team, and six have reached or surpassed the ten-year milestone in their volunteer service. Lowell is indebted to these volunteers for their years of dedicated service:

FIVE YEARS: Pat Benson, Tina Freeman, Helen Horstman, Karen Kitt, Lori Lombardi, Jonna Peterson, Linda Spahn, John Spahn, and Gary Tallman

TEN YEARS: Klaus Brasch, Rich Comnick, Gene Hill, Glenda Hill, Kris Naylor, Andy Odell ▪

Figure 1: Husband and wife volunteer team Gene and Glenda Hill prepare a box of archival materials for the Putnam Collection Center freezer.

Figure 2: Linda Spahn works with grounds keeping assistant Juan Alaniz installing signs identifying campus flowers and shrubs.

PEER-REVIEWEDPUBLICATIONS

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STATEMENT OF FINANCIAL POSITION

COMBINED BALANCE SHEET | DECEMBER 31, 2018 (with comparative totals as of December 31, 2017)

ASSETS	2018	2017
Current Assets		
Cash and cash equivalents	$ 265,651	$ 614,670
Restricted cash	206,178	199,778
Investments without donor restrictions	8,893	1,119,757
Research grants receivable	360,146	281,584
Contributions receivable, current portion	1,265,726	547,385
Inventory and other assets	338,767	458,895
Total Current Assets	**2,445,361**	**3,222,069**
Property, plant and equipment, net	45,626,539	43,452,560
Contributions receivable, net of current portion	364,302	924,921
Collection item	400,000	400,000
Investments with donor restrictions	25,990,107	32,975,170
Total Assets	**$74,826,309**	**$80,974,720**

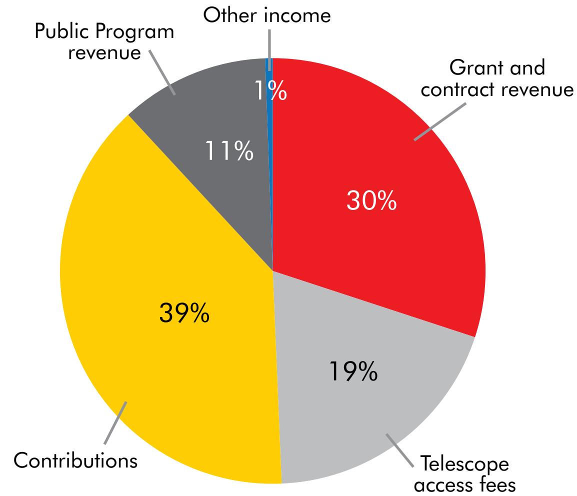
LIABILITIES AND NET ASSETS	2018	2017
Current Liabilities		
Accounts payable	$ 427,401	$ 309,969
Accrued expenses and other current liabilities	90,636	90,491
Total Current Liabilities	**518,037**	**400,460**
Note payable, bank	7,453,421	10,200,000
Deferred research grant revenue	85,454	598,953
Deferred access fee revenue	7,761,824	8,310,268
Total Liabilites	**$15,818,736**	**$19,509,681**
Net Assets		
Unrestricted	$ 28,770,277	$ 24,476,856
With donor restrictions	30,237,296	36,988,183
Total Net Assets	**59,007,573**	**61,465,039**
Total Liabilities and Net Assets	**$74,826,309**	**$80,974,720**

STATEMENT OF FINANCIAL ACTIVITIES

DECEMBER 31, 2018 (with comparative totals as of December 31, 2017)
(before depreciation)

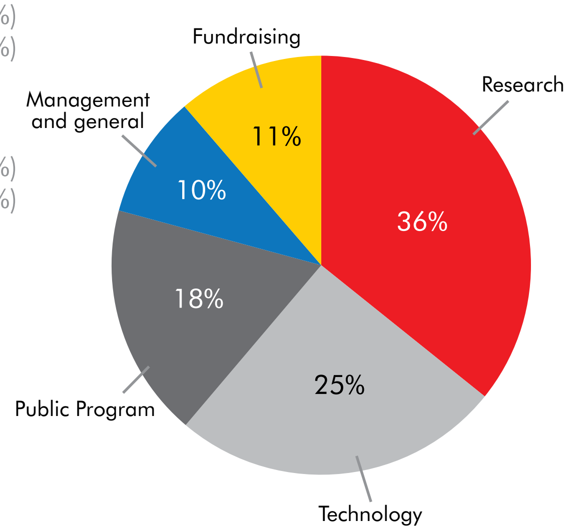
REVENUE	2018		2017	
Grant and contract revenue	$ 3,649,780	(30%)	$ 4,061,731	(36%)
Telescope access fees	2,343,970	(19%)	1,538,425	(14%)
Contributions	4,711,035	(39%)	4,329,074	(38%)
Public program revenue	1,374,743	(11%)	1,205,816	(11%)
Other income	69,684	(1%)	147,752	(1%)
Revenue before investment income (loss) net	12,149,212		11,282,798	
Investment income (loss) net	(1,930,770)	(-19%)	4,263,752	(27%)
Total Support and Revenue	**$10,218,442**		**$15,546,550**	

2018 REVENUE



EXPENDITURES	2018		2017	
Program services:				
Research	$ 3,842,835	(36%)	$ 3,420,837	(35%)
Technology	2,731,196	(25%)	2,579,866	(26%)
Public program	1,935,954	(18%)	1,581,820	(16%)
	8,509,985		7,582,523	
Support services:				
Management and general	1,018,522	(10%)	964,353	(10%)
Fundraising	1,215,339	(11%)	1,239,189	(13%)
	2,233,861		2,203,542	
Total Expenditures	**$10,743,846**		**$ 9,786,065**	
Gain on interest rate swap	-		248,960	
Change in net assets	$ (525,404)		$ 6,009,445	

2018 EXPENSES



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 2018 and 2017 was $1,932,000 and $1,966,000.

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, 2018. Copies of the audited financial statements are available at https://lowell.edu/about/governance_and_financials/

LOWELL OBSERVATORY ANNUAL REPORT

2018

Image (Front Cover): The grand reopening of the refurbished Pluto Discovery Telescope

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