2017

LOWELL OBSERVATORY

ANNUAL REPORT

2017

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TRUSTEE'S UPDATE

By W. Lowell Putnam

About a decade ago the phrase, "The transformational effect of the DCT", started being used around the Observatory. We were just beginning to understand that a 4 meter class telescope was going to be more impactful than our original, and naïve, concept of "2x the Perkins". Little did we know then, and we are still learning just how transforming the DCT has been.

As you read Jeff's report and look through the rest of this report you can begin to see the results in terms of scientific capability and productivity. The greater awareness of Lowell on the regional and national level has also lead to the increases in the public program, and the natural progression to building a better visitor program and campus infrastructure on Mars Hill. The visitors who come to the Hill find the combination of engagement with our volunteers and researchers to be a unique, enriching and transformative as well. We are committed to building on that in all that we are doing going forward.

We are not the only growing entity in the Flagstaff area. There has seen substantial growth at NAU, at our other partner institutions and in the number of high technology, for-profit business in the region. This collective growth is now creating opportunities for collaboration and partnerships that did not exist a decade ago. We have the potential to do things that we would not have considered even a few years ago. The challenge will be doing them in ways that keep the Observatory the collegial and collaborative haven that it has always been. Thanks to the incredible staff, volunteers and members of our Advisory and Foundation boards, I am confident this is one we can meet. ▪

DIRECTOR'S UPDATE

By Jeffrey Hall

What a great time it is to be at Lowell Observatory!

Check out the science "highlights" in this annual report—a solid 29 pages of wide-ranging research and results that only scratch the surface of the progress and discoveries throughout the year.

On the technical and instrumentation front, we see DCT running at full capacity and with its characteristic efficiency and quality, and we have major infrastructure is under construction to enhance the capabilities of the Navy Precision Optical Interferometer.

The team has rarely been in finer form than it was for the Great American Eclipse on August 21, 2017, welcoming some 7,000 guests at two venues - on campus in Flagstaff and 1,100 miles away in Madras, Oregon.

And then there are The Plans: the major expansion of our outreach infrastructure via a new public observing facility and a much larger new Visitor Center. The first component, the Giovale Open Deck Observatory, is proceeding full steam ahead with a Q2 2019 target for opening, while we have set our sights on spring 2022 to open the new visitor center. Detailed planning for all the components is underway, and the Development team is working hard to raise the funds needed to make our lofty aspirations a reality.

Our astronomers and technical staff, our outstanding education staff and fundraising team, the communication and marketing staff, our business office, building and grounds crew, and volunteers all play critical roles in making all this happen, and all the good things in the pages that follow are a testament to heir hard work and ability. And on behalf of everyone, I thank our Board members and our many supporters around the US and the world who help us do all that we do. ▪

Ted Dunham

Dr. Ted Dunham, together with Tom Bida and Georgi Mandushev, and in collaboration with Mike Person and Amanda Bosh, took HIPO for its last flight aboard SOFIA in late September and early October for an occultation of a bright star by Neptune's satellite Triton. SOFIA observed the event with HIPO, FLITECAM, and the facility focal plane imager from a location well out in the Atlantic, operating from the Daytona Beach airport. The flight featured a prediction update shortly before takeoff that was sufficiently accurate for us to see the central flash. It also featured clouds at high altitude thanks to the tail end of the very active hurricane season and a nail-biting failure of the SOFIA computer system only 20 minutes before the occultation. Fortunately they were able to observe the event through clear skies, but just a few minutes later we were flying under clouds at 40000 feet!

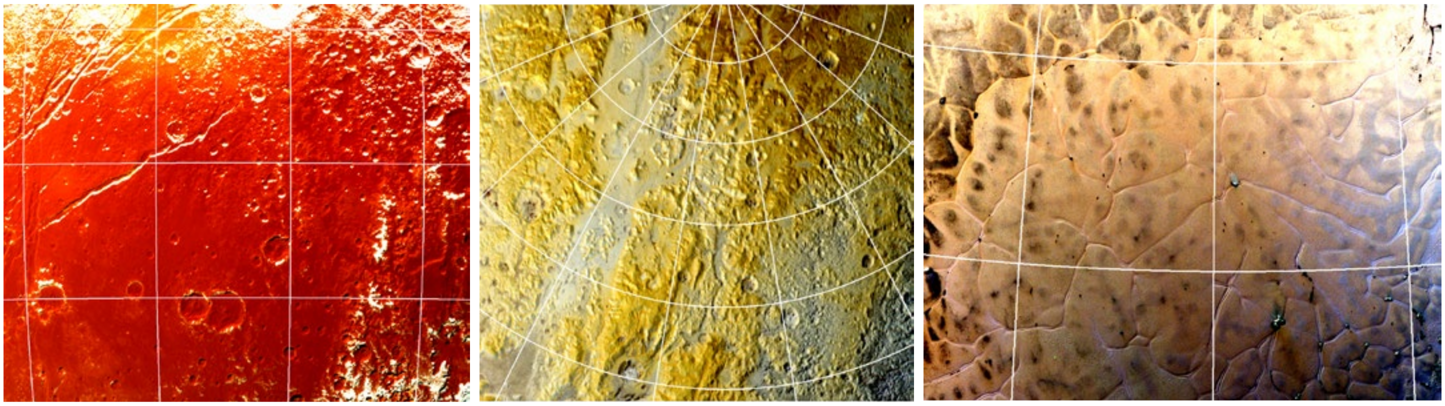
Dunham announced early in the year that he would terminate his, and HIPO's, association SOFIA following the Triton occultation. In turn, SOFIA has decommissioned both HIPO and FLITECAM for SOFIA operations.

Dunham announced his phased retirement plan toward the end of 2017. He will be ramping down his efforts in the next two years with the intention of retiring fully by the end of 2019. ▪

Image (Above): Tom Bida, Ted Dunham, and Georgi Mandushev on the tarmac in front of SOFIA.

Image (Left): Dunham and Mandushev with the magic "witch doctor" bone, seen hanging from the left monitor, and the FLIPO mascot peeking out between the two monitors.

ASTRONOMER **SCIENCE**HIGHLIGHTS



Will Grundy

Dr. Will Grundy's research involves small, icy outer Solar System planets, satellites, and Kuiper belt objects, studied using a combination of laboratory, theoretical, and observational techniques, as well as direct exploration using robotic space probes.

In 2017, Grundy was involved with a variety of outer Solar System observational projects using a number of large ground- and space-based telescope including Hubble, Keck, K2, and IRTF. These projects range from discovering binaries and determining their mutual orbits and masses, to studying binary mutual events, to spectroscopic and thermal infrared observations.

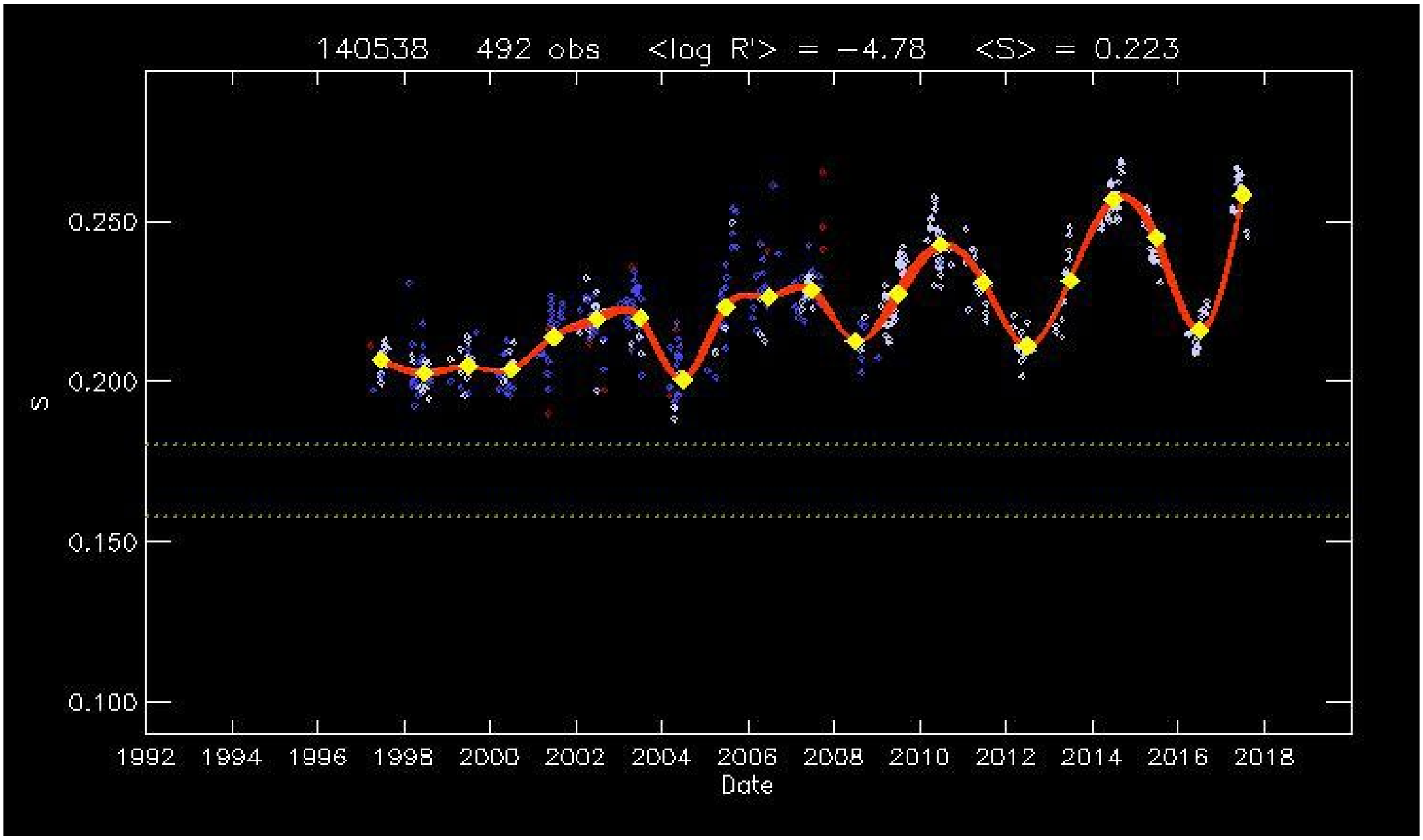
To complement this observational work, Grundy did laboratory studies of volatile ices and ice mixtures at Northern Arizona University (NAU) where numerous students seeking hands-on laboratory experience readily contribute to the research. Collaborators on this work include Jennifer Hanley at Lowell, as well as a number of NAU faculty members in both Physics & Astronomy and Chemistry departments. The rich thermodynamic complexity of volatile ice mixtures is emerging as a major theme in need of deeper investigation, since these materials enable the spectacular geological activity seen on Pluto, as well as on other small, icy planets and satellites across the outer solar system.

Grundy was a co-investigator on two funded NASA missions. The first, New Horizons, explored the Pluto system in 2015. Grundy heads the mission's surface composition science theme team. Analysis of New Horizons Pluto system data continued during 2017, even as planning for the upcoming encounter with small Kuiper belt object 2014 MU 69 "Ultima Thule" ramped up. That encounter is to take place at the end of 2018. The other mission, Lucy, is to be launched in 2021 to explore several of Jupiter's co-orbiting Trojan asteroids during the years from 2027 through 2033. Grundy's role in the Lucy mission is Instrument Scientist for the infrared imaging spectrometer system.

Grundy's research was fully funded during 2017 by grants. He was an author on 14 peer-reviewed scientific papers published during the year.

Grundy was involved in a wide variety of community service and public outreach work during 2017, including serving on the Scientific Organizing Committee for the annual meeting of the AAS Division for Planetary Sciences and serving as an editor for Icarus, the leading journal of planetary science. He also served on the advisory council of NASA's Planetary Data System Small Bodies Node (PDS SBN). Grundy reviewed manuscripts for a number of journals including *Nature Astronomy*, *Astrophysical Journal*, *Spectrochimica Acta*, *Monthly Notices of the Royal Astronomical Society*, and *Planetary & Space Science*. He also reviewed book chapters for Cambridge University Press and for the University of Arizona Press's Space Science Series, as well as a number of funding proposals and telescope proposals for various NASA programs. Grundy mentored a summer student through the National Science Foundation's Research Experience for Undergraduates (REU) program, and served on the thesis committees of two graduate students at the University of Northern Arizona. He gave numerous public presentations and media interviews. ▪

Image: The diversity of Pluto's colors and landscapes are illustrated by these stretched-color images of three regions, from a study of the influence of Pluto's atmospheric haze particles settling onto regions affected by distinct geological processes. From left to right, Cthulhu Macula, Lowell Regio, and Sputnik Planitia. Pluto feature names used by New Horizons team include a mix of official and informal names.



Jeff Hall

Dr. Jeff Hall, Dr. Wes Lockwood, Brian Skiff, and Len Bright continued the long-running Solar-Stellar Spectrograph (SSS) project, which in September 2017 reached its 25-year anniversary of observations. This project complements the similar program begun in 1966 at the Mount Wilson Observatory (MWO) near Los Angeles, which ended in 2003.

The SSS is a dedicated facility at the 1.1-meter telescope at Anderson Mesa. The SSS is fed by dual optical fibers that allow sunlight and starlight to be fed to the spectrograph optics, and the objective of the program is to improve our understanding of the types of variability exhibited by a sample of about 90 stars similar to the Sun. Such observations provide a fuller context for understanding the familiar 11-year sunspot cycle and 22-year magnetic cycle of the Sun. This is a topic of particular interest nowadays, because the apparent cessation of the sunspot cycle, during the Maunder Minimum of 1645-1715, is correlated with a time of significant multi-decadal climate change in Europe. Were our star to behave similarly strangely in upcoming decades, what might be the effects? We don't know, and we must remember that correlation is not the same as causation. But maybe the stars can provide some clues.

Hall, Dr. Ricky Egeland of the High Altitude Observatory, and BASIS Flagstaff Charter School senior Logan Bayer completed the reductions and time series analysis of all SSS data through December 31, 2017 – a data set comprising some 35,000 individual observations. Egeland succeeded in performing a definitive calibration of all the extant solar data sets, including the SSS solar data to the so-called "S-index" from MWO, no mean feat and an important step in understanding the Sun's activity relative to that of its closest stellar siblings. Hall and Bayer have reduced the entire stellar data set and have discovered several stars that display behavior either not seen in the MWO data, or (for stars that overlap with the earlier program) that show changed behavior relative to 20-30 years ago.
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Image: Activity record of psi Serpentis from 1996-2017.

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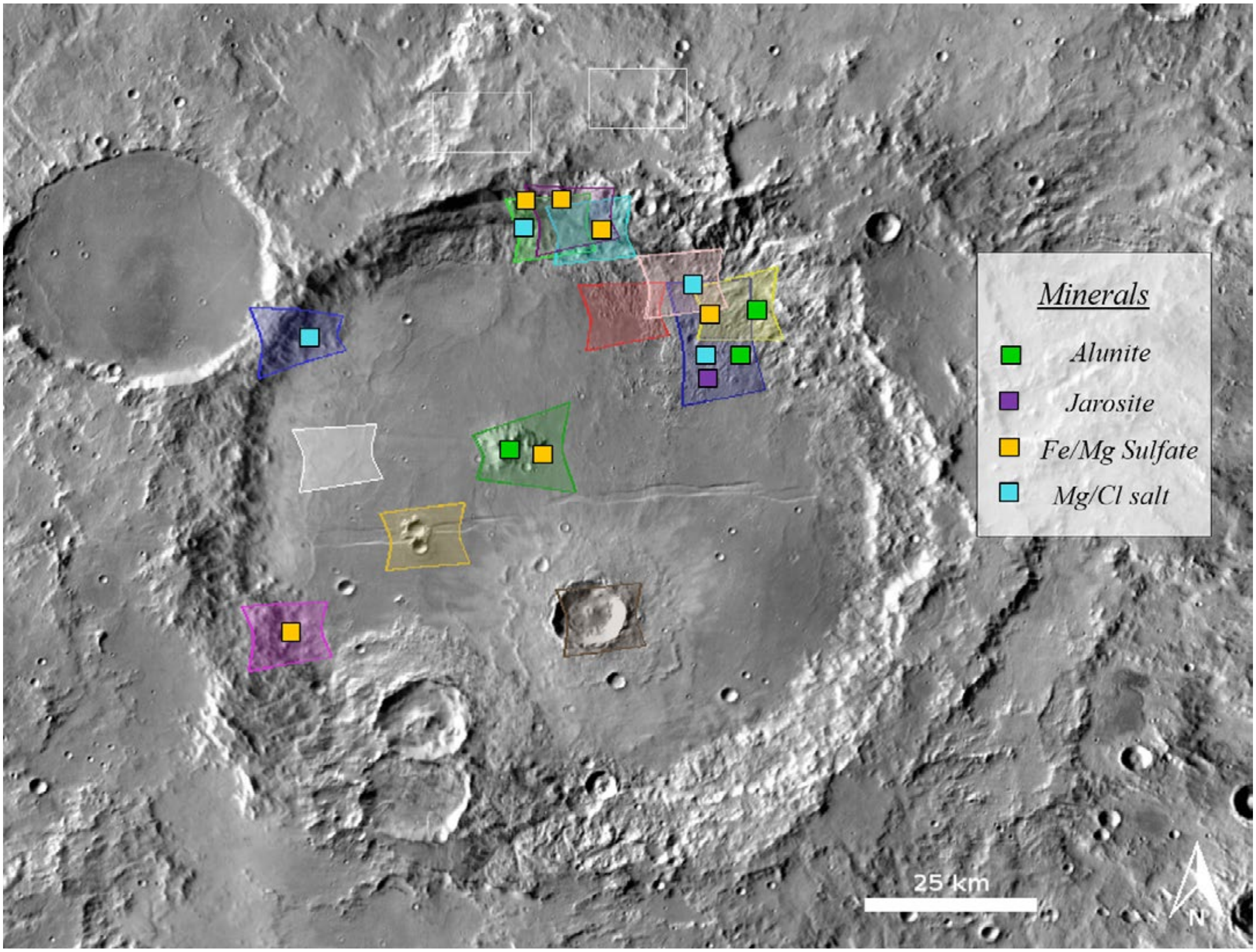
One such star is psi Serpentis, and its activity record from 1996-2017 is shown in the adjoining image. The more active the star, the higher the individual data points lie on the time series. After a four-year dormant period from 1996-2000, it shifts into a period of vigorous four-year cycles of increasing amplitude. This is much like the Sun's emergence from the Maunder Minimum (except the Sun's cycle is 11 years, not four), and that makes psi Serpentis a bit of a stellar Rosetta stone. Here we see behavior the Sun has not exhibited for 400 years, so stars like this one let us look through a glass darkly into the possible nature of the Sun's past.

Egeland and Hall are now working on a complete combination of all the SSS data with the earlier MWO data for stars covered by both programs. For many of these, we now have more than 50 years of continuous observations, and the variety of cycle behaviors on display will form a rich foundation for analysis by scientists trying to model the physical processes at work in the interiors of cool stars. Hall is presently compiling the full set of SSS results into a paper for publication in 2018 in The Astrophysical Journal, and Egeland will likewise publish an analysis of the combined SSS+MWO data sets. The full time series from both programs will also be made available online in a database for the astronomical community and the public. ▪



Jennifer Hanley

Dr. Hanley's main research topic is understanding liquid stability across the Solar System. One way to affect stability of water on Mars and Europa is by adding salt. Chlorine salts in particular (chlorides, perchlorates and chlorates) can lower the freezing point of pure liquid water from 273 K (0°C) down to 204 K (-68°C). 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 two undergraduate students—one from Northern Arizona University (NAU), the other from Purdue University—to understand the spectral characteristics of the chlorine salts and to identify them in Columbus Crater (see the Figure 1). She was also invited to participate in a Keck Institute of Space Science workshop entitled "Unlocking the Climate Record Stored within Mars' Polar Layered Deposits" which was the first step in proposing a mission to Mars' polar regions.

Another focus of Hanley's research is the mechanical and spectral properties of the hydrocarbon lakes of Titan, as well as cryogenic ices on Pluto and other icy satellites. Laboratory experiments performed at NAU's Astrophysical Ice Laboratory 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 (continued on next page)

Image (Figure 1): Salts in Columbus Crater, Mars. Colored hexagons are footprints of spectral images from the Mars Reconnaissance Orbiter. Colored squares depict where different salts were detected. Mg/Fe sulfates with patches of Mg/Cl salts are a widespread unit, while K-bearing sulfates are rare and occur in isolated areas.

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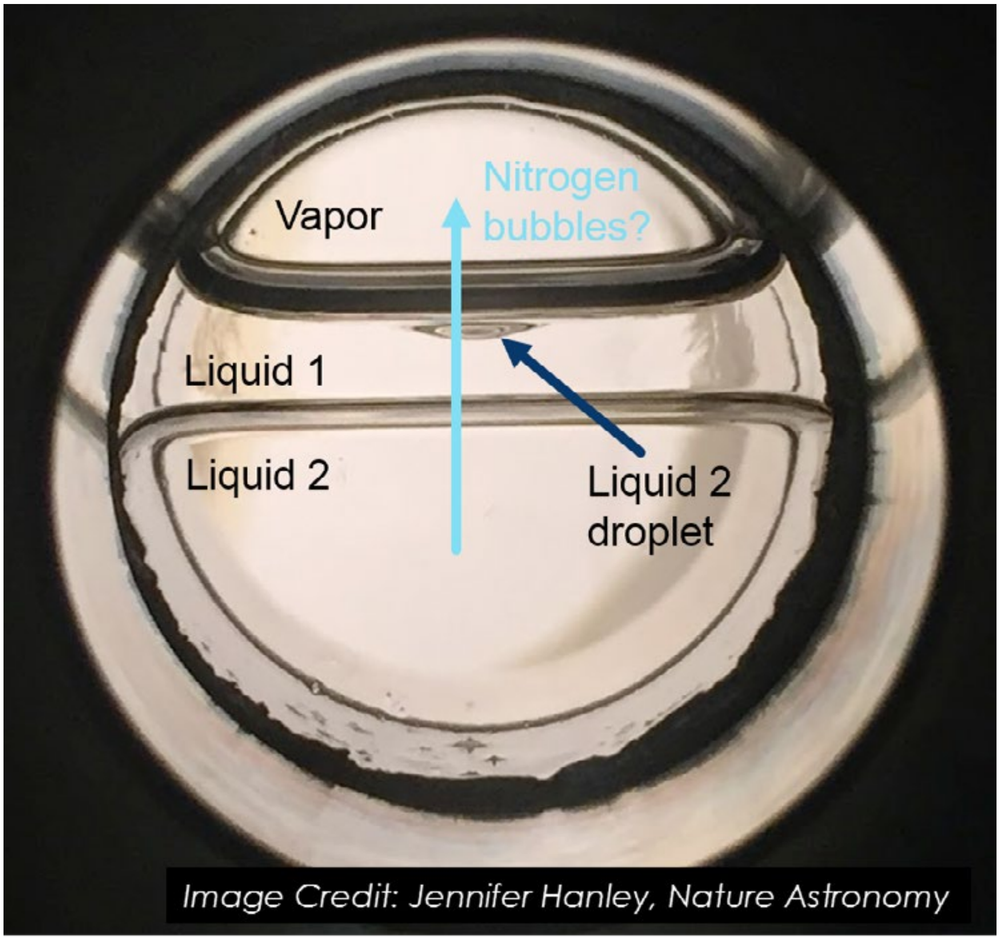
liquid separates into two stable phases in equilibrium with a vapor phase (see Figure 2). With any change in temperature, pressure, or composition, the two liquids' stability will change. This could cause ice or particulates to float or sink, bubbles to rise, and may even explain the "magic islands" seen by Cassini. This result was publicized in a *Nature Astronomy News and Views* article written by Hanley. She was awarded a NASA Solar System Workings grant, along with an Early Career Fellowship, to further explore this strange phenomenon. She was also part of a recently successful Solar System Exploration Research Virtual Institute that will study the mechanical and spectral properties of asteroids for human exploration over the next five years. ▪

Image (Figure 2): Laboratory simulations of the seas on Titan. The cell contains a mixture of nitrogen, methane, and ethane, at 95 K. The pressure is 2.5 bar, equivalent to hundreds of meters below the surface of one of Titan's seas. Although at the surface of Titan the liquid is well-mixed, at this temperature and pressure, liquid separates into two stable phases in equilibrium with a vapor phase.



Deidre Hunter

Dr. Deidre Hunter and her collaborators started the LITTLE THINGS study of nearby dwarf irregular galaxies 10 years ago with the goal of understanding how these little galaxies form new stars. The sample was chosen to be fairly isolated, or at least not obviously interacting gravitationally with a nearby galaxy. The reason for this selection was that they wanted to examine internal processes, and interactions between galaxies are known to spur star formation activity. The group has multi-wavelength images of the stars in the 40 galaxies, as well as wide-field images of the gas in the galaxies, and only one galaxy was later shown to have a gas tail that could indicate an interaction or merger with another dwarf.

Then in 2012 another group published an image of a dwarf that Hunter knew was messed up by an interaction but whose companion had not been previously found. The deep image, obtained by an amateur astronomer, revealed the companion dwarf. It had not been found in images of the gas because the little dwarf had already been stripped of its gas by the somewhat larger, splashier irregular galaxy, and the stars left in the little dwarf had been missed by images Hunter and others took because their fields of view weren't large enough to capture both the larger dwarf and the smaller one. Hunter realized that her wide field of view gas maps weren't going to be sufficient to rule out interactions for the LITTLE THINGS galaxies, so it would be important to search the regions around the LITTLE THINGS dwarfs in the optical to look for little dwarfs with just stars.
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Image: Most LARI images were taken through a single filter, but Steve Leshin observed this galaxy through several filters and put them together to form a color image. The galaxy is DDO 187 and it is the blue object near the center. The other galactic objects in the image are far in the background of DDO 187.

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A few months later, Hunter was at a conference of research by amateur astronomers to launch the Lowell Amateur Research Initiative (LARI). LARI was designed to bring amateur and professional astronomers together in collaborative research projects. Hunter realized that this was an excellent opportunity to obtain the needed images of the galactic environments of LITTLE THINGS, and so this became one of the LARI projects.

Over the next five years, 10 dedicated amateur astronomers from across the United States, Canada, Israel, and Tasmania obtained deep, wide-field images of 36 of the 40 LITTLE THINGS galaxies. Typical exposure times were of order 40 hours per image. The contributors included Stephen Leshin, Alson Wong, Maurice Clark, Jerald Kamienski, Netzer Moriya, Burley Packwood, Bob Birket, William Edwards, Mervyn Millward, and Ian Wheelband. In addition Casey Melton, a 2017 MIT Field Camp student, did a lot of the work of organizing and rectifying the images and examining them for objects.

John Menke, Bruce Koehn, Michael Beckage, Klaus Brasch, and Sue Durling were responsible for starting LARI, setting up the web site, and vetting applications, and Mattie Harrington, Klaus Brasch, Michael West, and Michael Beckage subsequently vetted applications and advertised the program. Hunter is grateful to all of these people for the effort they put into the project and into LARI which made this project possible.

In the end, Hunter and her group of LARI collaborators did not find any unknown companion galaxies around the LITTLE THINGS galaxies. This was not a splashy result, but it was a relief to Hunter and the LITTLE THINGS project to know that there was nothing lurking beyond the limits of their original images influencing the star formation in their galaxies. ▪

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.

During 2017, Levine upgraded the control systems for three portable occultation cameras and began work rejuvenating a CCD imaging camera for use in Chile. He was also involved in observations of several Kuiper belt objects, including two by 2014 MU69, the next target for the New Horizons space probe, and ground-based observations in concert with SOFIA observations of a Triton occultation.

Levine continued collaborating with Dr. Arne Henden (AAVSO), Dr. Doug Welch (McMaster) and Dr. Dirk Terrill (SwRI) on the construction of the AAVSO Photometric All-Sky Survey (APASS), which will greatly simplify photometric calibration over the entire sky in the under-served magnitude range from 10 to 17. During 2017, the team continued their complete re-reduction of all the data taken between 2009 and 2016 in preparation for data release 10. 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' colors.

Levine continued to serve as the Discovery Channel Telescope (DCT) Scientist, working with the DCT observing, instrumentation, and engineering communities to get the best out of the facility. ▪

Image: The APASS South installation 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. Each camera has a multi-slot filter wheel. The computer to control the mount and cameras is at the base of the pier. We appreciate the MEarth project's willingness to host the APASS South installation in their building at Cerro Tololo Inter-American Observatory.

Joe Llama

One of the most exciting highlights of the year for Dr. Joe Llama was representing Lowell at an event organized by the Phoenix-based NPR station, KJZZ in Garden Valley, Idaho. The eclipse was particularly exciting for Llama because one of his primary research interests is understanding the space weather environments of exoplanets. Jupiter-sized planets with orbital periods of just a few days represent a class of planet we do not have in our own Solar System and are interesting laboratories for extreme planetary physics. These planets are so close to their parent star that they are orbiting within the stellar corona. Having the chance to directly view the corona of our own Sun was a truly amazing experience that he will remember for a long time!

This past winter, Llama used the Immersion Grating Infrared Spectrograph, IGRINS, while it was visiting DCT this last winter to characterize the atmospheres of a number of exoplanets that orbit incredibly close to their parent star. Amongst the systems studied by Llama this winter was the recently announced planet, KELT-9b, which is the hottest gas giant exoplanet currently known. This planet has a dayside temperature of 4,500 K, making it hotter than many low-mass stars. IGRINS on DCT represents the highest sensitivity and broadest wavelength coverage of any infrared spectrograph and telescope combination in the world, making it the perfect instrument to characterize exoplanet atmospheres. Exploiting the wavelength coverage and resolution provided by IGRINS, Llama uses a technique to resolve the high-resolution lines into a unique spectral fingerprint to determine whether the molecule is present in the atmosphere of the planet. The analysis of this system is still underway, and Llama is looking forward to using IGRINS during its third visit to DCT this winter to characterize the atmospheres of more recently announced exoplanets. (continued on next page)

Image: The view of NASA's twin Keck telescopes from the summit of Mauna Kea. This image was taken while Llama was observing at NASA's IRTF telescope searching for exoplanet aurorae.

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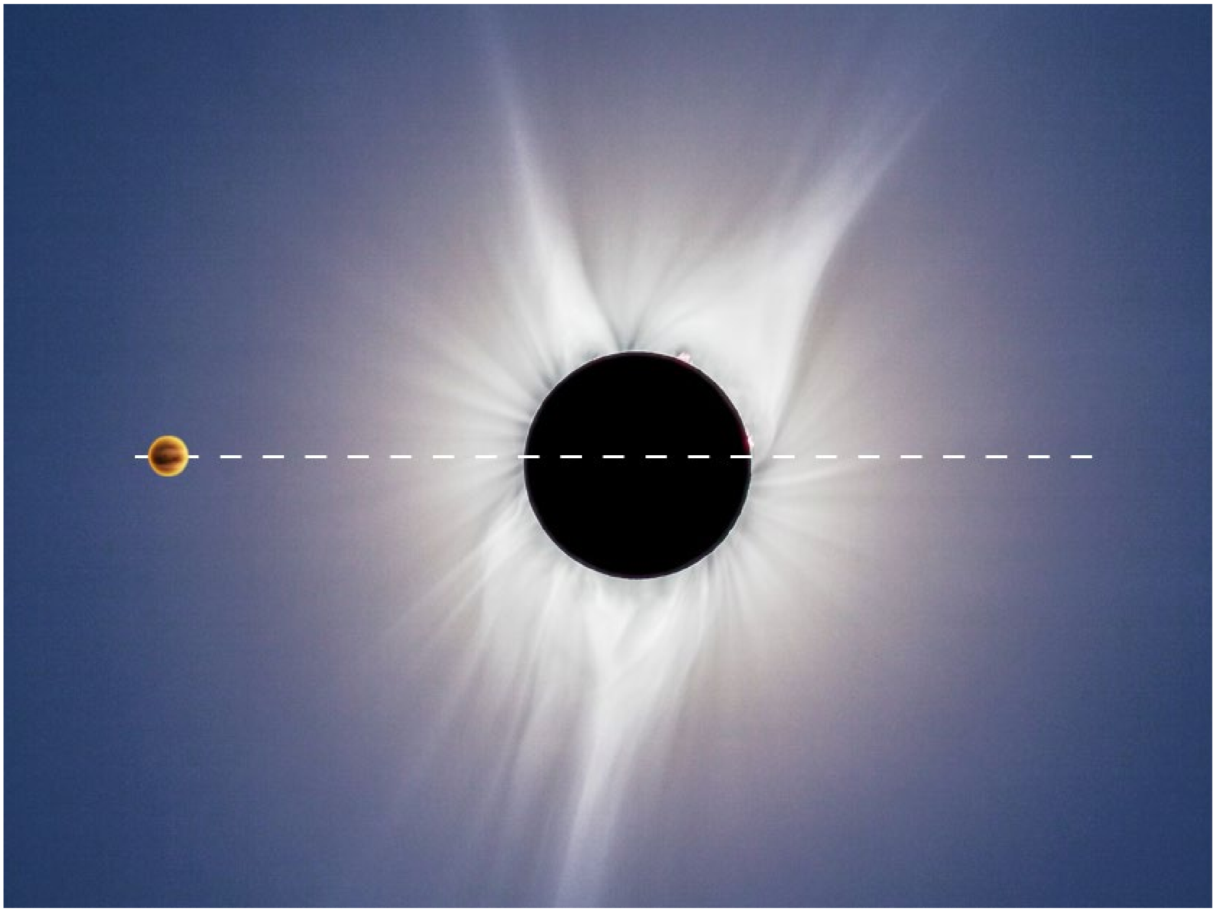
Another highlight for Llama this year was an observing run at NASA's Infrared Telescope Facility (IRTF) on the summit of Mauna Kea in Hawaii. Together with former Lowell astronomer Dr. Evgenya Shkolnik, he observed a number of exoplanet systems to search for auroral emission that is caused by the interaction of the stellar wind with the planets' magnetosphere. They have submitted a proposal to continue this survey to help answer the question, "Do exoplanet's host magnetic fields similar to the planets in our own Solar System?"

With collaborator Professor Moira Jardine in St Andrews, Llama has completed a project to simulate the signature of radio emission from low-mass stars. This work was recently published in the *Astrophysical Journal* and will help guide the search for radio emission from exoplanets, which is a crucial factor in characterizing the internal compositions of these planets.

Finally, Llama is the Lowell science lead on a team lead by 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 starspots of small stars with the goal of assessing how habitable the space environment is for planets orbiting them. Stay tuned for more updates on SPARCS as the launch date gets closer! ▪

Image: Llama's photograph of the 2017 Eclipse taken in Garden Valley, Idaho. Over plotted to scale is the typical orbit of a close-in Jupiter sized exoplanet.



Phil Massey

On a clear moonless December night on a high mountain top in northern Chile, the sky is ablaze with wonders we cannot see from Flagstaff. Looking south, brilliant Alpha and Beta Centauri will be close to the horizon; Alpha Cen is the nearest star to our sun. The Milky Way runs up the Southern Cross (Crux), with an evident dark patch—the Coal Sack nebula. The most amazing features though are two extended fuzzy patches: the Large and Small Magellanic Clouds.

The Large and Small Magellanic Clouds are the nearest galaxies to our own Milky Way, 10 to 15 times closer to us than the well-known Andromeda Galaxy in the north. The Magellanic Clouds are rich in massive stars, and close by: a mere 50,000 parsecs (165,000 light years) and 60,000 parsecs (200,000 light years), respectively. Furthermore, the newly formed stars in the Magellanic Clouds have a smaller fraction of heavy elements (so-called "metals," anything heavier than helium). These trace constituents have a huge effect on the evolution of massive stars. This makes the Magellanic Clouds ideal laboratories for studying massive stars.

This year Dr. Phil Massey continued several projects involving massive stars in the Magellanic Clouds. Working with University of Washington summer student Locke Patton, Massey has been investigating the stellar content of two very populous OB associations, Lucke-Hodge 41 in the LMC and NGC 346 in the SMC. Using photometry from the Hubble Space Telescope and optical spectra obtained in Chile at the Las Campanas Observatory, they have identified dozens of new O-type stars, the hottest and most massive type of "main sequence" (hydrogen-burning) stars. The work will be completed in 2018 with help from the help of Hannah Umansky, a summer student from the University of Virginia. (continued on next page)

Image: The Large Magellanic Cloud is visible at upper left, above the two 6.5-meter Magellan telescopes. Photograph by Kathryn Neugent.

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Lowell research assistant Kate Evans (who is now a PhD student at Montana) spent the summer working with Massey on the red supergiant content of the Small and Large Magellanic Clouds. They are using data obtained with the Anglo-Australian telescope and multi-object fiber positioner. Evans had done the difficult task of reducing these data during the summer of 2016, and spent this summer analyzing the data. She has a paper almost ready to submit.

Lowell research associate Kathryn Neugent (who is now a PhD student at the University of Washington), Las Campanas staff astronomer Dr, Nidia Morrell, and Massey were also busy taking spectra with Magellan of a new type of Wolf-Rayet star that they found in the Large Magellanic Cloud several years ago. It's still a bit of a mystery what these new stars are. They might be the products of binary evolution, where one star's gravity strips the hydrogen-rich material off the other star, leaving behind a bare stellar core. Or they might be a normal "missing link" in the evolution of massive stars. One test is to see if they show periodic radial velocity variations, and the team has been hard at work obtaining multiple spectra of this new type of star. In addition, the team has been taking spectra of normal Wolf-Rayet stars in the Magellanic Clouds as part of a NASA-supported effort to determine the fundamental properties of these enigmatic stars. The data will be analyzed by Erin Aadland as part of her PhD thesis at Northern Arizona University.

Elsewhere in this report, Neugent describes another exciting discovery that the team has made in the Small Magellanic Cloud, a runaway yellow supergiant.

The trip to Chile is an arduous one, requiring about 30 hours door-to-door, but it is well worth it for the opportunity to study the Magellanic Clouds! ▪

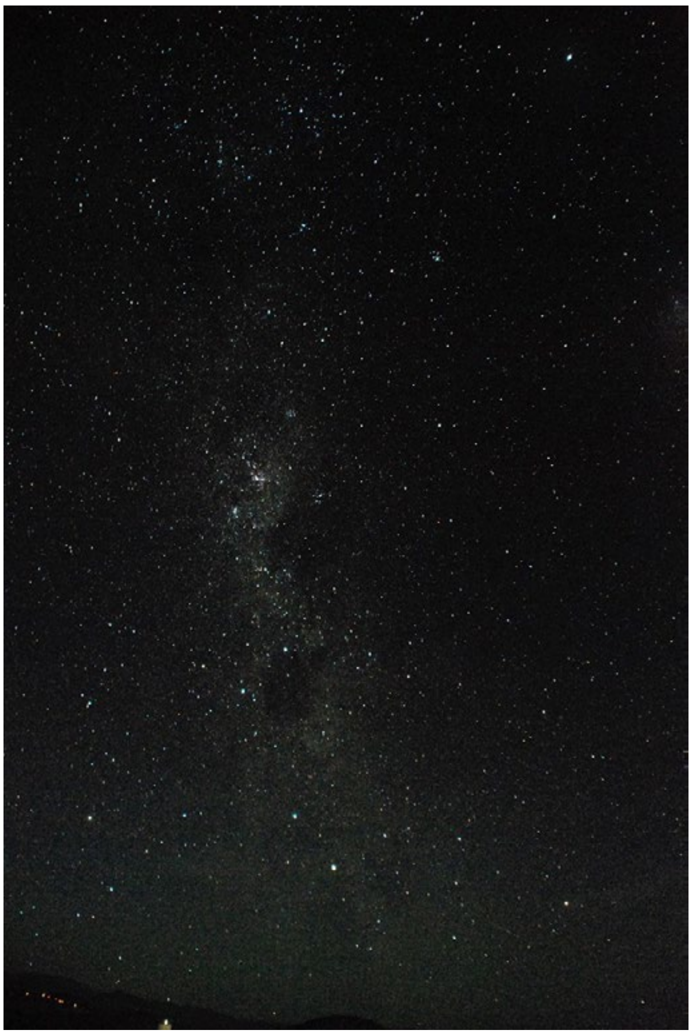
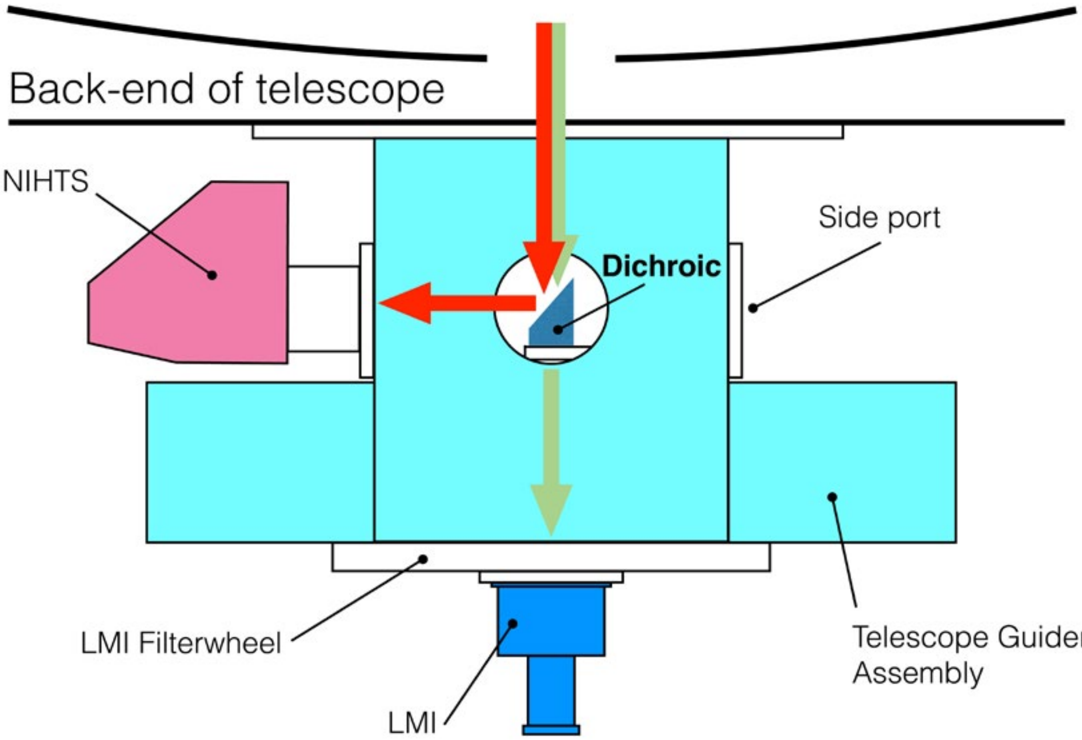


Image: Alpha and Beta Cen are the two bright stars at the bottom of this picture; the Coal Sack is the dark feature slightly below and to the left of center. The Southern Cross (Crux) consists of the four stars directly to the left of the Coal Sack. Photograph by Kathryn Neugent.



Nick Moskovitz

In 2017 Dr. Nick Moskovitz continued to work on investigations of small planetary bodies including asteroids, comets, and meteors. One of the big objectives in the study of these minor planets is to understand how their compositions inform formational and evolutionary process in the Solar System. In support of this goal Nick and Northern Arizona University Ph.D. graduate student Annika Gustafsson have been leading efforts to commission the Near-Infrared High Throughput Spectrograph (NIHTS, pronounced "nights") at Lowell's Discovery Channel Telescope (DCT). NIHTS operates at near-infrared wavelengths (0.8-2.4 microns) and is the third and final of the first generation facility instruments to be deployed at the DCT. NIHTS was built in-house by the Lowell instrument group and was partially funded by NASA. As the name suggests, NIHTS is optimized for high throughput (achieved with a compact design and no moving parts) meaning it can access and obtain spectra of faint objects outside the reach of other facilities.

After an initial brief run at DCT in 2016, NIHTS was permanently installed on the telescope in early October 2017. Gustafsson and Moskovitz led the commissioning observations to test the performance of the instrument and the development of software for the observer interface. The capabilities of NIHTS were further enhanced in December when a dichroic mirror was installed in the instrument cube to enable simultaneous operation of NIHTS and the facility imager LMI. This upgrade enables a capability that is almost unique in the world — for every science target we can now simultaneously collect visible images with LMI and near-infrared spectra with NIHTS.

NIHTS produces relatively low resolution spectra across a wide wavelength range which is ideally suited to measuring the compositions of planetary surfaces. In fact, NIHTS was originally conceived as an instrument specifically for measuring ices on minor planets in the outer Solar System. Determining the diversity and relative abundances of ices amongst these distant objects is important for understanding the variety of possible outcomes from the planet formation process. NIHTS is equally well suited to measuring rocky compositions in the inner Solar System, which overlaps nicely with

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Image: Schematic of the DCT instrument cube. Light from the telescope enters the cube from the top of the diagram. Near-infrared wavelengths are redirected to the NIHTS side port while visible is passed through the LMI.

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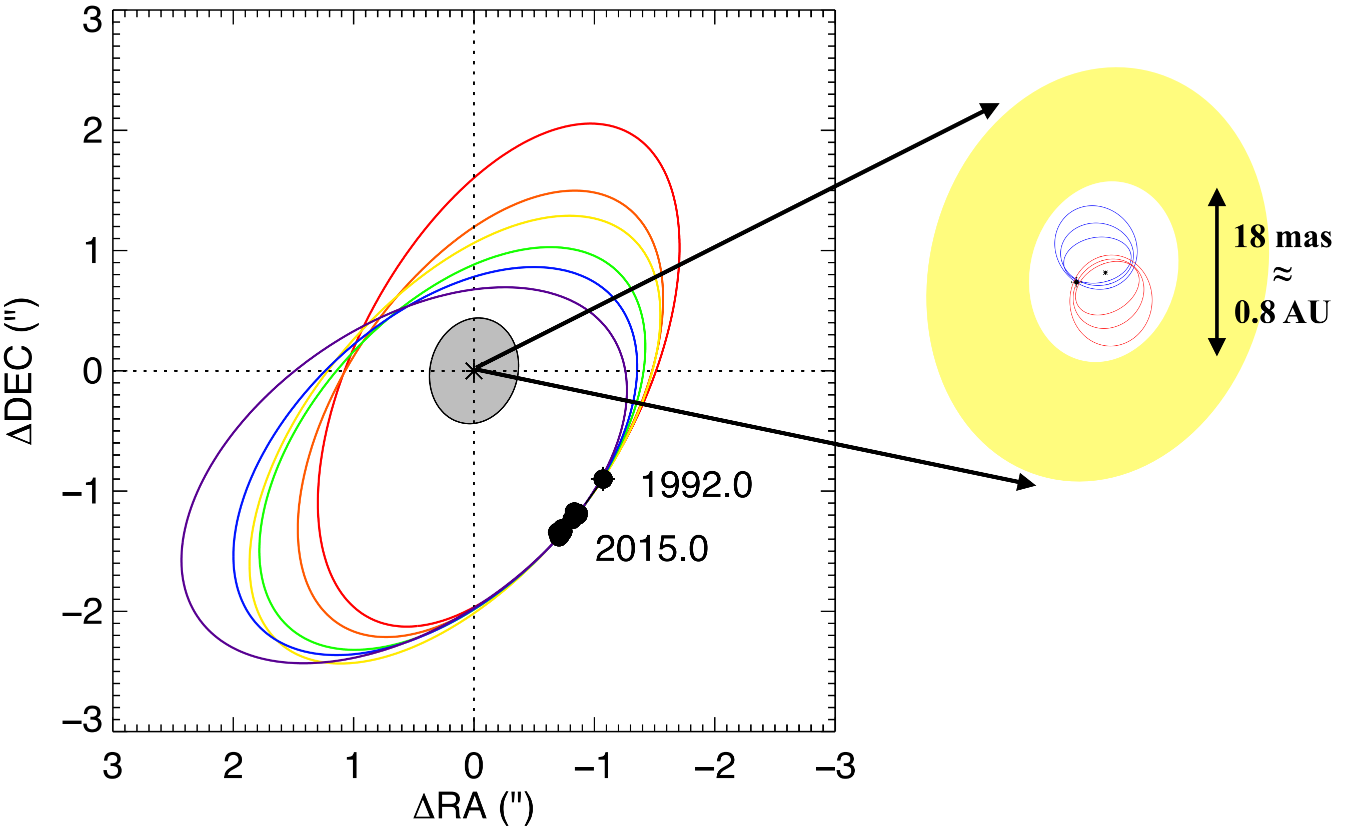
Moskovitz's ongoing work related to near-Earth asteroids. The ability to efficiently obtain simultaneous LMI images and NIHTS spectra is particularly important for these objects as they fly past the Earth with observing windows that can be as short as a few hours.

A great example of the efficiency of the DCT for minor planet observations took place in December. Moskovitz and collaborators at the University of Maryland (including former Lowell researcher Matthew Knight) organized a DCT campaign to focus on the near-Earth flyby of the asteroid Phaethon. This particular object is of interest as the future target of the Japanese space agency's DESTINY+ mission. Scientifically Phaethon is interesting because it is classified as an asteroid yet shows low levels of cometary activity. Furthermore, Phaethon is thought to be the parent body of the Geminid meteor shower, which is a puzzle because Phaethon's activity is far too low to explain the flux of meteors we see during the this shower. The DCT campaign to study Phaethon leveraged all three facility instruments (NIHTS, LMI, the visible-wavelength DeVeny spectrograph) and exemplified the power of DCT as a highly efficient facility for collecting diverse data products in a single observing session. These data will ultimately provide new insights into the physical properties of this interesting object.

As NIHTS continues to get used at the DCT a variety of new science cases are being developed, including studies of low mass stars and transiting exoplanets. Moskovitz is looking forward to working with astronomers and students at Lowell and DCT partner institutes to continue coming up with creative uses for NIHTS at the DCT. ▪



Lisa Prato

It was another great year for Dr. Lisa Prato's team in 2017! They published and submitted a total of 10 papers in refereed journals including five first-authored papers, three by current or former students, one by former postdoc Tom Allen, and one by Prato. One of the student papers, led by former NAU undergraduate and Lowell researcher Kendra Kellogg, was a study of the unusual triple star system TWA 3. The team determined the orbital, stellar, and circumstellar characteristics of this hierarchical group of young stars. An inner pair of low-mass stars, cooler and redder than our Sun, orbits each other every 34 days. Surrounding this binary is a substantial disk-shaped structure of hydrogen gas and dust grains; some of the gas in this disk funnels onto the surface of the stars through magnetic fields connecting the star and the disk; energetic emission from the shock of the hot gas hitting the stars provides some of the evidence for the presence of the disk. The excess infrared emission from the warm dust grains in the disk also signals its presence. Outside of this disk, another low-mass star is gravitationally locked to the very close pair; however, this orbital period lasts for hundreds of years! This tertiary star surprisingly has no disk of gas and dust around it, possibly the result of dynamical interactions between it and the close pair and their disk. A cartoon schematic of the system is shown in the accompanying figure. Studying these systems is important because most stars are located in binary and multiple configurations like this one and if astronomers are going to fully understand planet formation, which takes place in these disks, we must understand disk formation and evolution in complex multi-star systems. (continued on next page)

Image: A diagram of the position on the sky for the young triple star system TWA 3. The grey oval on the left shows the location of a planet-forming disk of gas and dust surrounding a very close binary star; an expanded view of the inner disk (yellow annulus) is illustrated at the right. The gap in the center has a diameter of about 0.8 AU, 80% of the Earth—Sun separation. Dynamically stable orbits for the inner stars, indicated with black crosses, are shown in blue and red. Also on the left side of the figure, rainbow ovals delineate potentially stable long period orbits, of several hundred years, for the third star in the system, plotted in large black circles for different years of observation. One of the most fascinating things about this system is that the plane of the inner binary orbit, of the disk, and of the outer triple orbit are all misaligned!

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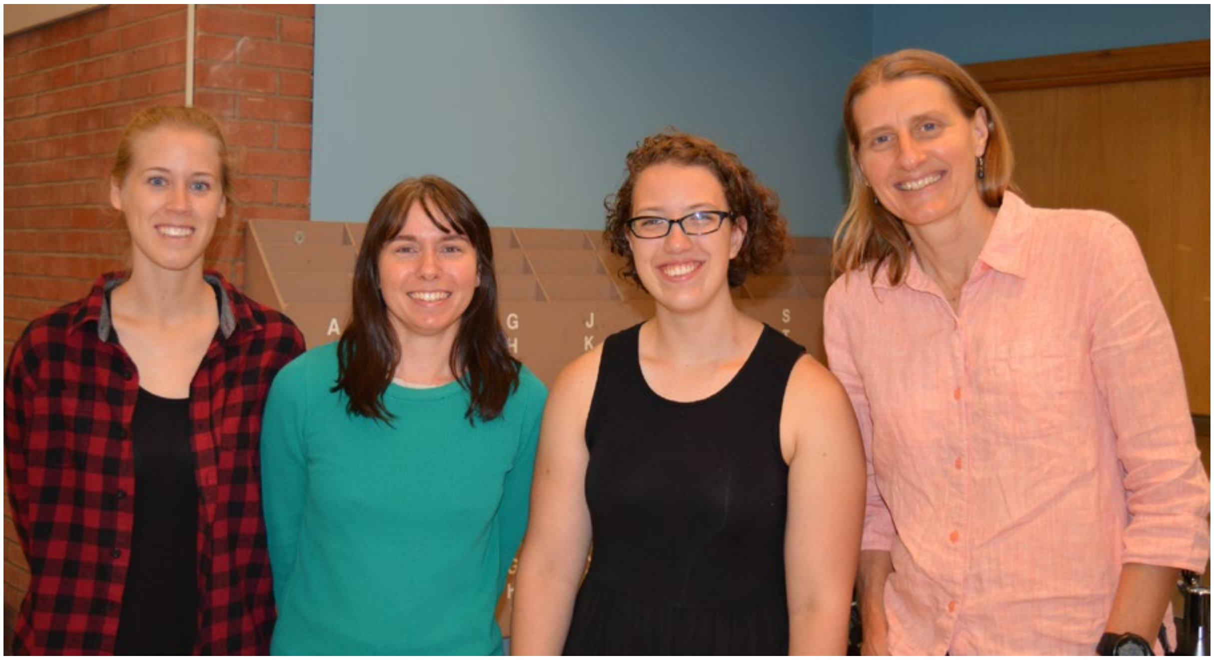
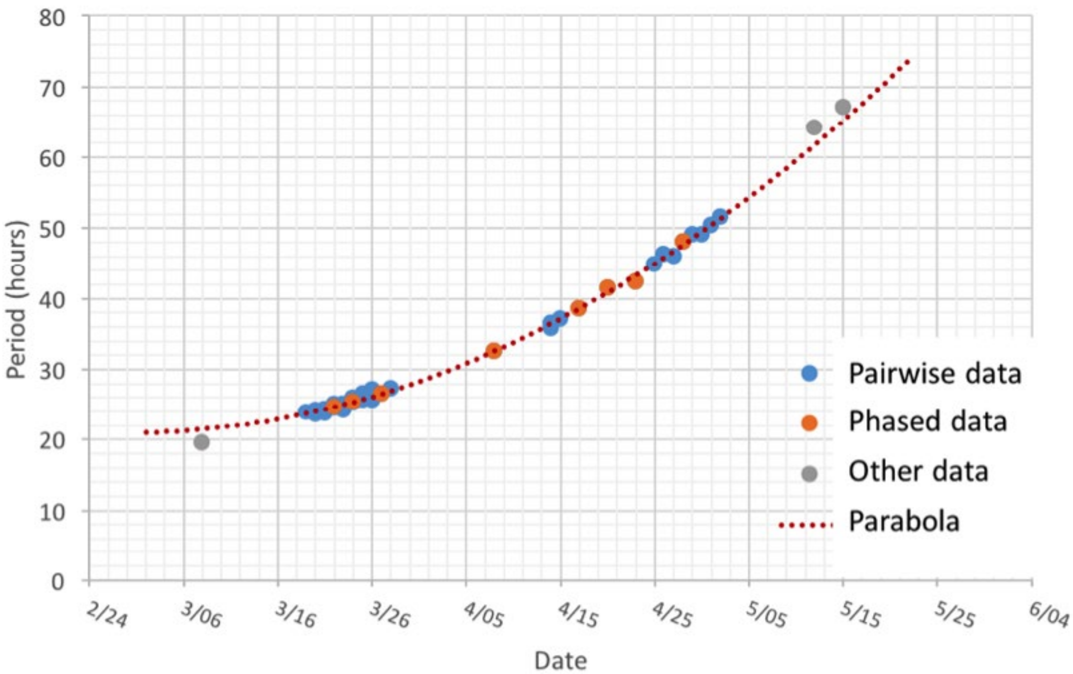
Intern Ian Avilez departed for graduate school at the University of Virginia and summer student Kendall Sullivan joined the team through the REU program. Two NAU undergraduates, Kyle Lindstrom and Sean Graham, also began doing research with the team. In collaboration with Lowell's Joe Llama and Brian Skiff, and new NAU faculty Ty Robinson, the team coined an acronym for its extended group—DEFT: Disks and Exoplanets Flagstaff Team. Lauren Biddle was accepted into the PhD program at NAU and is working on her thesis with the DEFT group. Predoctoral graduate student Larissa Nofi, from the University of Hawaii, has made big strides in her PhD dissertation work and may be announcing an important science result in the coming year.

In other news, IGRINS, the Immersion GRating INfrared Spectrograph, arrived in late August ready for its second DCT observing season. The autumn weather was extremely cooperative for the team and they completed the survey phase of their young exoplanet search and will next move on to intensive follow up observations. In addition to postdocs and faculty, more than a dozen graduate students, from Boston University, the University of Texas, Lowell Observatory, the University of Toledo, and the University of Maryland, have used IGRINS to obtain data for their PhD theses. IGRINS is scheduled for the next visit beginning in September, 2018. ▪

Image: Lauren Biddle, Larissa Nofi, Kendall Sullivan, and Lisa Prato.





Dave Schleicher

Drs. Schleicher and Matthew Knight (Univ. Maryland), assisted by post-doc Audrey Thirouin (Lowell Obs.) and undergraduate student Nora Eisner (Univ. of Sheffield) obtained observations, performed analyses, and presented results of Comet 41P/Tuttle-Giacobini-Kresak (T-G-K) in 2017. Making its closest approach to Earth since its initial discovery in 1858, the comet remained within 20 million kilometers for over two months in early 2017. Narrowband filter imaging obtained with DCT, the John S. Hall 42-inch, and the robotic 31-inch telescopes, revealed two cyanogen gas jets (see image below) whose motion during each night and from night-to-night enabled the team to measure T-G-K's rotation period. Most surprisingly, the period changed extremely rapidly from about 24 hr to over 48 hr in only 6 weeks, a rate of change more than a factor of 10 greater than observed in any previous comet. With the gas jets acted like rockets, producing the torque necessary for slowing the rotation of the nucleus, such a large change implies a small, highly elongated body with the source regions located near the ends, somewhat similar to an old fashioned lawn sprinkler. Extrapolating backwards in time, the nucleus would have been rotating close to the break-up velocity, possibly explaining the major outburst observed during the comet's 2001 apparition, when it unexpectedly brightened by a factor of a thousand. Key results were presented at the annual Division of Planetary Sciences meeting in Provo, Utah, and at an associated press conference. ▪

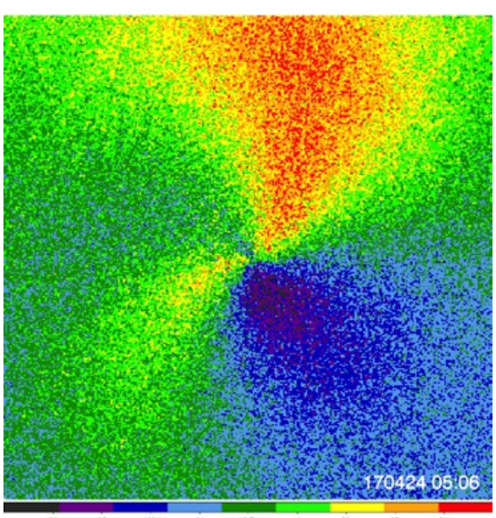
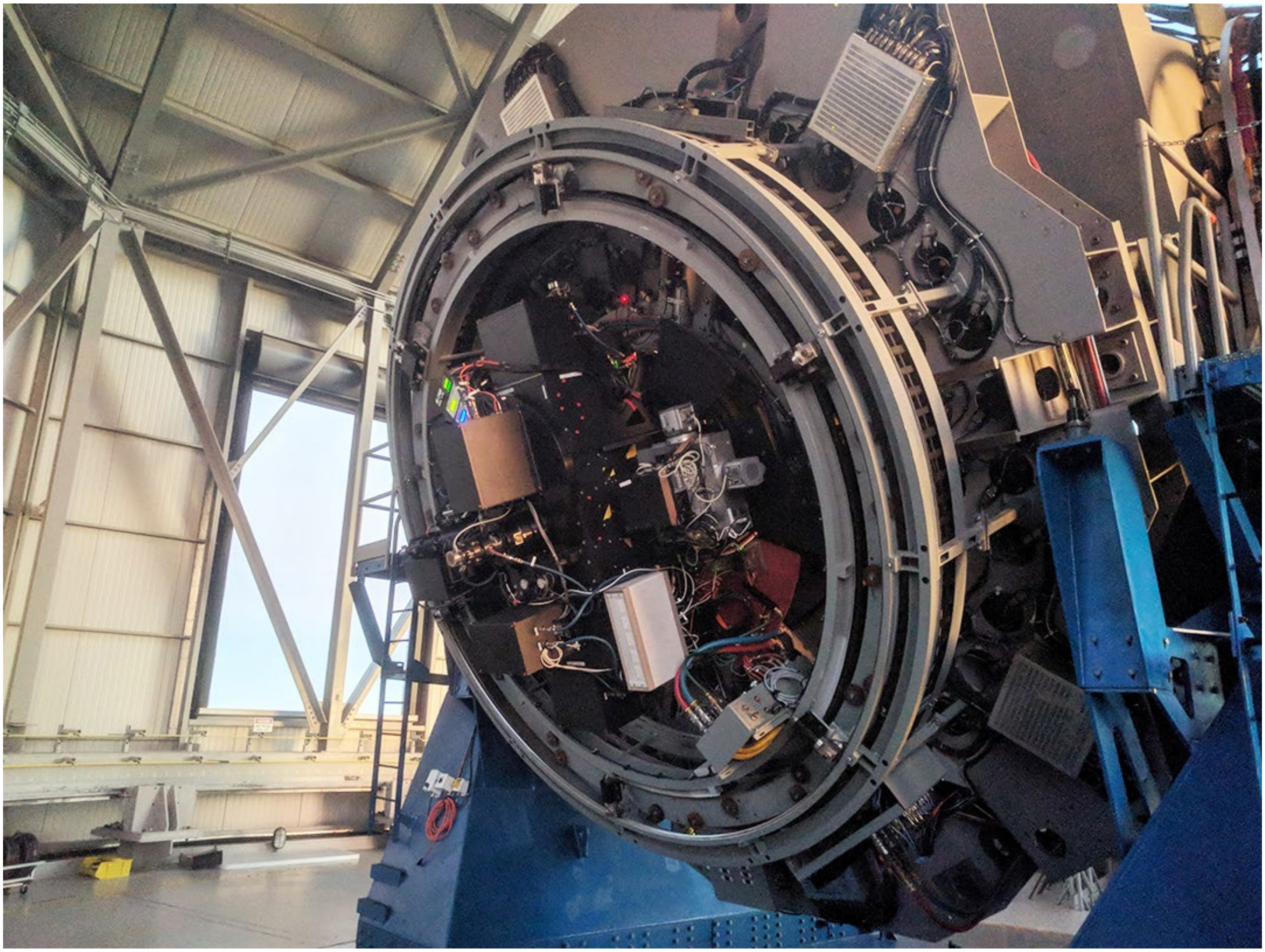


Image (Above): Comet Tuttle-Giacobini-Kresak's rotation period increased smoothly at an ever increasing rate from March 18 (24 hr) to April 28 (48 hr). Images obtained later in the apparition will require modeling of the jets to determine if the period continued to increase or leveled off with the comet's decreased activity as it moved away from the Sun.

Image (Left): A representative image of gas jets detected in Comet Tuttle-Giacobini-Kresak. A narrowband filter isolating light from cyanogen molecules (CN) was used with the CCD camera at the John S. Hall 42" telescope. Because the coma of a comet is much brighter at the center and falls off in all directions, a radial profile is first removed, and false colors added (red is brightest) to reveal the more subtle jets. The frame has a field of view of 30,000 km.



Gerard van Belle

January 2017 saw the formal funding of the $3.26M PALANTIR (Precision Array of Large-Aperture New Telescopes for Image Reconstruction) upgrade project for the Navy Precision Optical Interferometer (NPOI). Dr. Gerard van Belle moved rapidly to secure contracts with PlaneWave Instruments for three 1-meter telescopes for NPOI, along with three 'enclosure-transporter' (ET) mobile domes from AstroHaven Enterprises. Factory acceptance of the first 1-m telescope (PWI serial number #003) was anticipated for January 2018. With delivery of the first ET expected in the spring of 2018, single 1-meter testing and operations will begin at Anderson Mesa. Lowell adjunct Dr. Kaspar von Braun has been collaborating with van Belle on this project, and has been the Los Angeles local point-of-contact for PlaneWave.

Another major development for van Belle with NPOI was his appointment as Director of the array, effective May 1, 2017. He took the reins from Dr. Don Hutter of the USNO-Flagstaff Station, who had helmed the array for more than a decade. (continued on next page)

Image: The DSSI speckle camera on the DCT, at the 3 o'clock position of the instrument cube. DSSI takes advantage of DCT's superior pointing and tracking to enact observing programs based on rapid cadence observing. During the April 2017 run, nightly observing was averaging roughly five minutes open-shutter to open-shutter, for 10 hour stretches –a pace certain to keep any observer on their toes!

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Van Belle's portfolio of extreme angular resolution astronomy included the commencement of a major survey of nearby low-mass M-dwarf stars, using the visiting Differential Speckle Survey Instrument (DSSI) speckle camera on the DCT. This survey, in partnership with Lowell adjunct Dr. Elliott Horch, aims to investigate every low-mass star out to 15 parsecs for possible companionship. Observing in 2017 covered nearly 2/3 of the 1,250 possible targets. Possible permanent residence of DSSI at DCT will be expanded with the continued development of the Quad-channel Wavefront-sensing Speckle Survey Instrument (QWSSI) upgrade.

Science partnerships of van Belle have resulted in multiple journal articles, including "A Catalog of Calibrator Stars for Next-generation Optical Interferometers" in the *Astronomical Journal* with Mr. Sam Swihart, "The Kepler Follow-up Observation Program. I. A Catalog of Companions to Kepler Stars from High-Resolution Imaging" with Dr. Elise Furlan et al. in the *Astronomical Journal*, and "Single-Photon Intensity Interferometry (SPIIFy): utilizing available telescopes" with Mr. Genady Pilyavsky et al. in *Monthly Notices of the RAS*. ▪

Larry Wasserman

Dr. Larry Wasserman continued his NASA funded project of obtaining astrometric measurements of the positions of Kuiper Belt Objects (KBOs) using the Discovery Channel Telescope. The problem with these objects is that all of them were discovered recently (within the last 25 years) and, since they all orbit beyond Neptune, they all have orbital periods which are many hundreds of years. That is, their observational arc is much shorter than their orbital period. As a result, their positions in the sky are always extrapolated. This leads to errors in their sky-plane positions. Furthermore, the sky plane error grows with time, making these faint objects difficult to find, especially in large telescopes with small fields of view. The rate of growth of the sky plane error is a function of the object's orbital speed and observational arc. After an astrometric observation is made, the error drops to near zero and then rises again with time, but more slowly because the object now has a longer observational arc.

Wasserman also continued observing occultations of objects in the Solar System. Occultations are useful in that they offer the only way to accurately measure the sizes of small objects and also to probe the atmospheres of distant objects in the Solar System.

The New Horizons spacecraft is going to fly by the KBO 2014 MU69 on Jan 1, 2019. NASA needed to measure the size of this object (which was estimated to be about 20-30 kilometers across and at a distance of 6.3 billion kilometers from Earth) because, while we knew how bright it was as seen from Earth, we didn't know its intrinsic brightness (i.e., its albedo)—it could be a small very bright object or a big dark object). NASA needed to know its albedo in order to decide what exposure times to use for the spacecraft flyby. To determine the albedo, one needed to know its size, and that, in turn, could only be determined via an occultation. Three occultations were predicted for this object in the summer of 2017. Two were in locations accessible to ground-based telescopes. The first was visible from Argentina and South Africa; the second only from Argentina. These were especially difficult occultations to observe—one must place observers in the shadow of the object which is cast by the occulted star. The shadow is only as wide as the occulting body—in this case only 20-30 kilometers wide. In order to observe these events, NASA provided 25 (continued on next page)

Image: Wasserman (far right) and his occultation team in Georgia. The event was shortly after sunset and here they are looking for a first star to become visible in order to set up the telescope pointing. The same telescopes were used in Argentina/South Africa.

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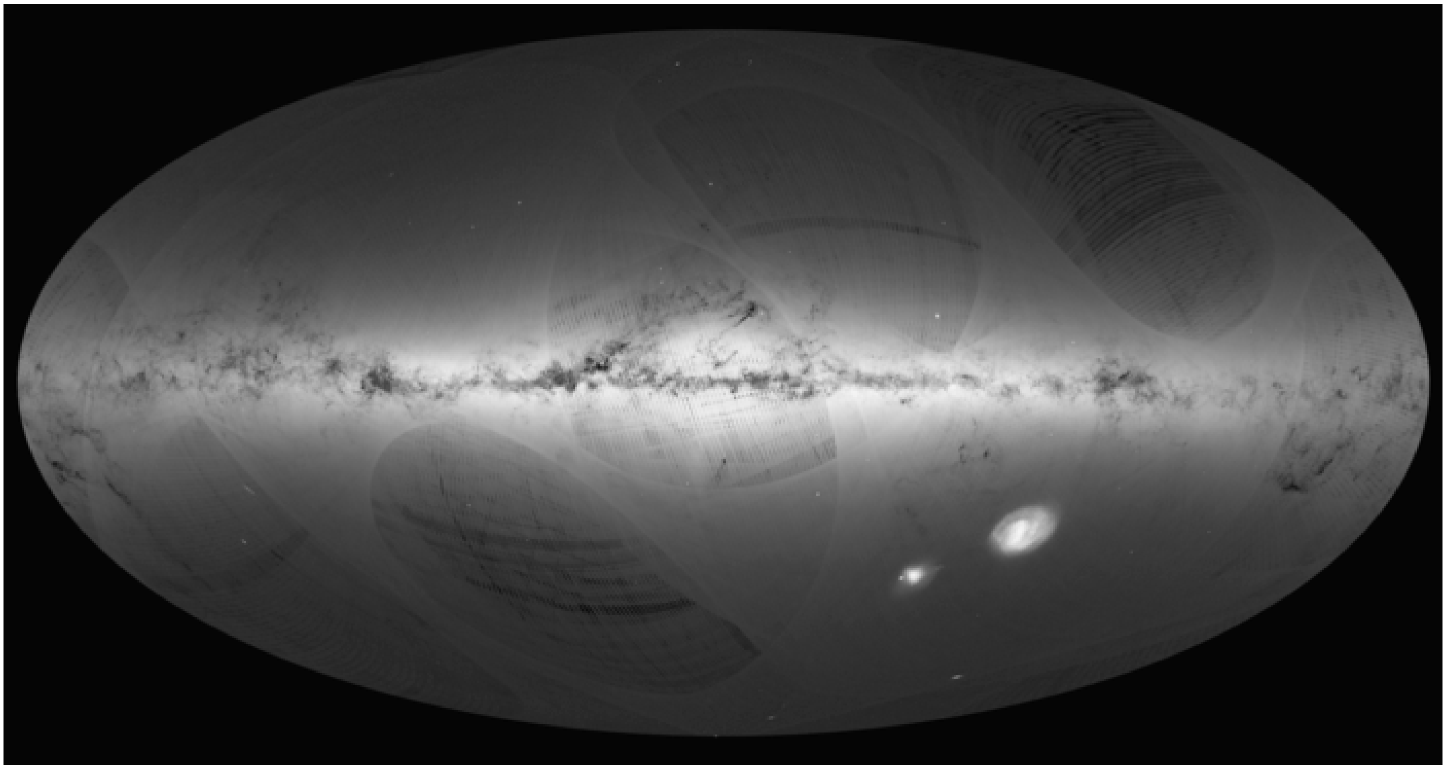
16-inch telescopes and cameras. For the first event, half were sent to Argentina, half to South Africa. For the second, all the telescopes were in Argentina.

The idea of having so many telescopes is to set up a wide "picket fence" with the hope that at least some of the telescopes will be in the shadow. Unfortunately, for the first event, the shadow missed the fence. But, for the second event, five of the 25 telescopes saw the event. The resulting data indicates that 2014 MU69 may actually be a binary object with each object being about 10 kilometers in diameter. There is another occultation of this object in summer 2018 which crosses Columbia in South America and Senegal in Africa. Wasserman is hoping to participate in this event.

Wasserman also participated in observing an occultation of the large moon of Neptune, Triton, which has a thin atmosphere. This event, which was observed from the state of Georgia, will provide data on the temperature/pressure structure of the atmosphere of the object. ▪



Michael West

"The universe is made of stories, not of atoms," wrote poet Muriel Rukeyser. Every galaxy has a unique story, and telling those stories is the goal of Dr. Michael West's research.

Using observations made with the Hubble Space Telescope, West and collaborators discovered that the orientations of the biggest galaxies in the universe have been aligned with their surroundings since the dawn of time. Their paper, titled "Ten Billion Years of Brightest Cluster Galaxy Alignments," was published in the journal *Nature Astronomy* in June 2017. These results provide important clues about how environment influences the birth and properties of galaxies.

David Kelly, a graduate student at Northern Arizona University, continued his MSc thesis research under West's supervision. Kelly's project uses observations made with the Gaia satellite to map the Large Magellanic Cloud and Small Magellanic Cloud, two small galaxies that are satellites of the Milky Way. West also continued to co-supervise MSc student Suei-Hei Hon's thesis at the University of Turku, in Finland. Hon's thesis aims to learn more about giant cannibal galaxies that have devoured their neighbors. Hon traveled to Flagstaff in June 2017 to observe with West at the Discovery Channel Telescope, where they collected data for his thesis.

West began a new scientific collaboration with an international team of astronomers from the Ruhr-Universitat Bochum in Germany, the Harvard-Smithsonian Center for Astrophysics in the U.S., and the University of Turku in Finland. Like archaeologists looking for the earliest human settlements, they are searching for ancient cosmic villages where galaxies first gathered billions of years ago. The team is using powerful radio galaxies and quasars, whose tremendous energy output is fueled by supermassive black holes, as beacons to identify the most distant galaxy clusters in the universe. The goal is to quantify the cluster environments surrounding these objects by combining data from Lowell's Discovery Channel Telescope, the Spitzer Space Telescope, Hubble Space Telescope, and other observatories. (continued on next page)

Image: An all-sky view of more than a billion stars in the Milky Way and beyond, as seen by the Gaia satellite. The Large and Small Magellanic Clouds, two small companion galaxies that orbit the Milky Way, are clearly visible in the lower right region. Credit: European Space Agency.

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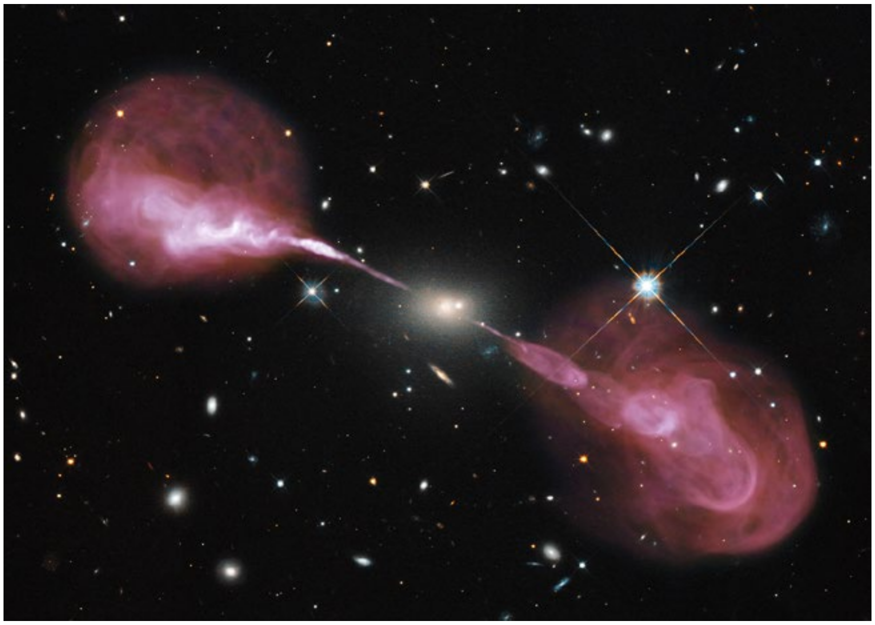
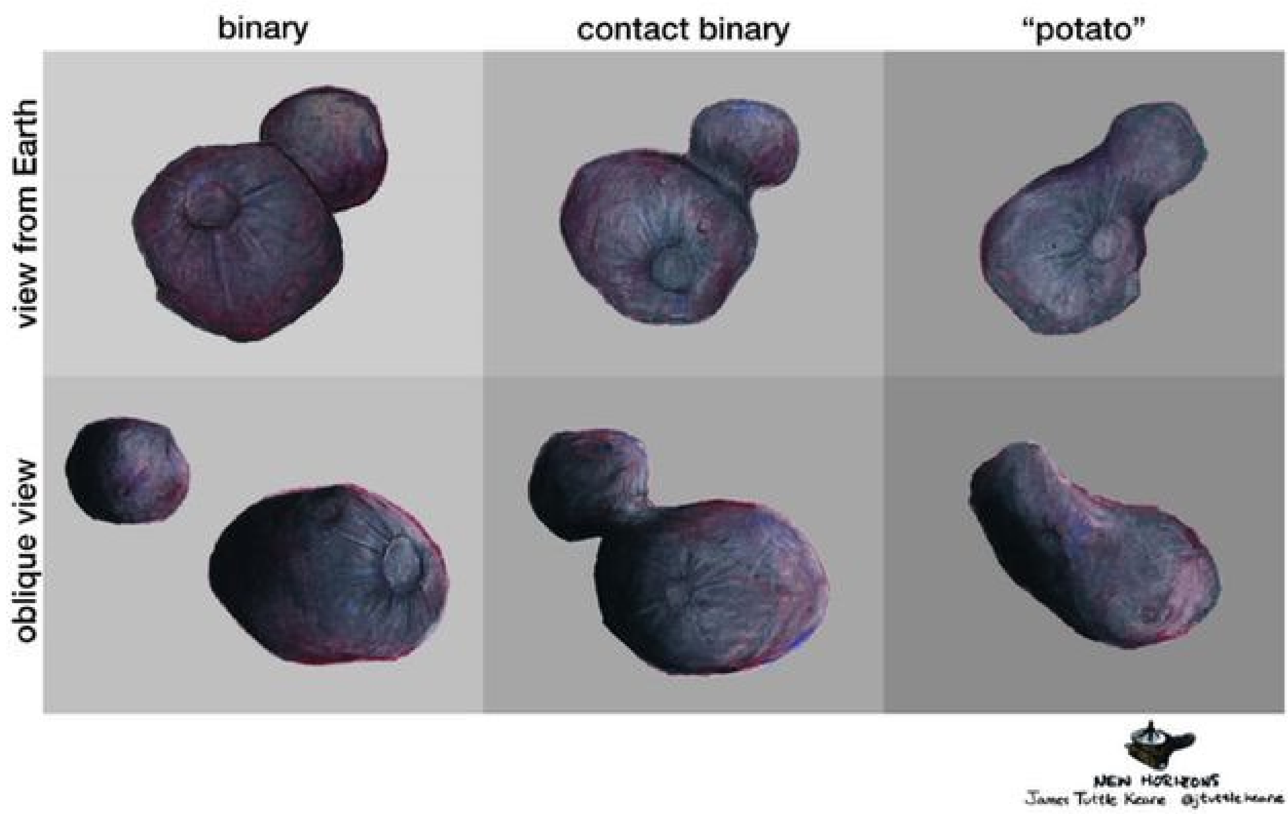
In addition to his research, West continued to devote substantial time to communicating astronomy with the public. These efforts included writing regular columns for Lowell Observatory's monthly *Members Update* and quarterly *The Observer*, as well as his popular *AstroAlerts*, which now have nearly 1,000 subscribers. Additionally, *Discover* magazine reprinted his article "When Galaxies Become Cannibals" in its October 2017 issue (first published in *Astronomy* magazine in 2016). He also continued work on two books that he is writing. ▪

Image (Left): Hubble Space Telescope image of the galaxy cluster Abell 370. Credit: ESA/Hubble, NASA and the HST Frontier Fields.

Image (Right): Hercules A, also known as 3C 348, is a powerful radio galaxy that harbors a supermassive black hole at its center. West and an international team of collaborators are using rare objects like this as beacons for finding groups and clusters of galaxies in the early universe. Credit: NASA, ESA, and the Hubble Heritage Team.





Audrey Thirouin

After a successful flyby of the Pluto-Charon system, the NASA's New Horizons spacecraft is now on its way to a new Trans-Neptunian Object (TNO): 2014 MU69. This object, nicknamed Ultima Thule, is thought to be one of the foundation stones responsible for the building of our Solar System, and thus its study will help us to uncover a couple of secrets concerning our early Solar System,

Until last summer, the basic characteristics of 2014 MU69 were a mystery, but thanks to a successful stellar occultation, scientists have been able to obtain some information about its shape, albedo, size and binarity. One of the most striking results is the shape of 2014 MU69 (see accompanying image). So far, three potential shapes can interpret the stellar occultation data: Ultima Thule can be a close binary, a contact binary, or a single object with a "potato" shape.

Despite an expected high fraction of close/contact binaries in the Trans-Neptunian belt, finding them is a daunting task with only one detected so far (excluding 2014 MU69). Therefore, even before knowing that 2014 MU69 was a potential close/contact binary, Dr. Audrey Thirouin decided to team up with Dr. Scott S. Sheppard (Carnegie Institution for Science-Department of Terrestrial Magnetism) to find and characterize this elusive population. In August 2017, they received an NSF grant to carry out this investigation with the Lowell's Discovery Channel Telescope (DCT) and the 6.5-meter Magellan twin telescopes. Their work will give context to the second flyby of the NASA's New Horizons mission as well as improve our understanding about the formation and evolution of the TNOs.

So far, the team has discovered eight of the nine known contact binaries in the Trans-Neptunian belt (excluding 2014 MU69), and six of them with the Lowell's DCT. The results were published in two referred papers, presented at the Division for Planetary Science meeting. ▪

Image: Artistic representation of the potential shapes of 2014 MU69. Credit: James Tuttle Keane.

Kathryn Neugent

Kathryn Neugent and Dr. Phil Massey have discovered a rare "runaway" star that is speeding across its galaxy at a speed of 300,000 miles per hour (at that speed it would take about half a minute to travel from Los Angeles to New York). The runaway star (designated J01020100-7122208) is located in the Small Magellanic Cloud, a close neighbor of the Milky Way Galaxy, and is believed to have once been a member of a binary star system. When the companion star exploded as a supernova, the tremendous release of energy flung J01020100-7122208 into space at its high speed. The star is the first runaway yellow supergiant star ever discovered, and only the second evolved runaway star to be found in another galaxy.

After ten million years of traveling through space, the star evolved into a yellow supergiant, the object that we see today. Its journey took it 1.6 degrees across the sky, about three times the diameter of the full moon. The star will continue speeding through space until it too blows up as a supernova, likely in another three million years or so. When that happens, heavier elements will be created, and the resulting supernova remnant may form new stars or even planets on the outer edge of the Small Magellanic Cloud (SMC). The supernova will also leave behind a neutron star. Since the star's velocity is greater than the escape velocity of the SMC, the remaining neutron star will eventually escape the galaxy and zoom off into outer space. (continued on next page)

Image: The 6.5-meter Magellan telescope at Las Campanas Observatory. Photo by Kathryn Neugent.

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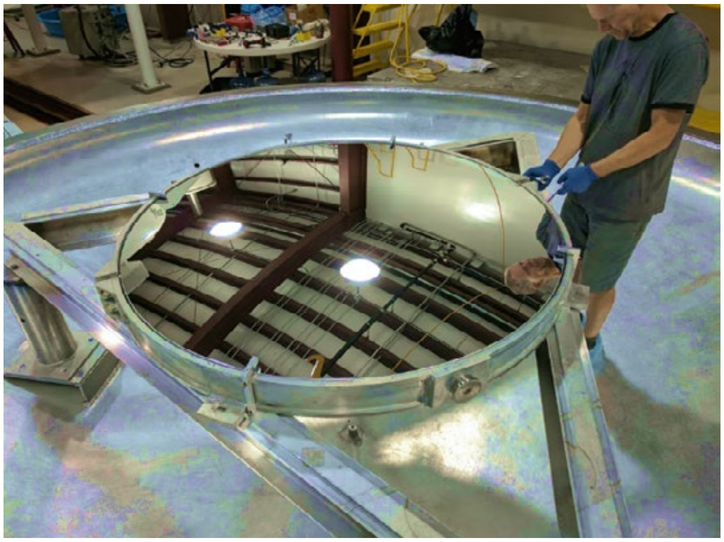
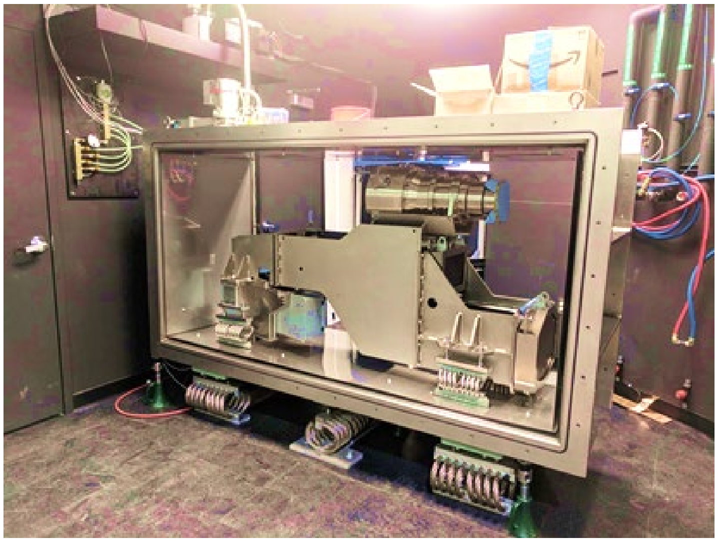
Spectroscopic observations of this star were taken using the 6.5-meter Magellan telescope at Las Campanas Observatory (shown in the accompanying image). The Large Magellanic Cloud (companion galaxy to the Small Magellanic Cloud, not shown) is visible right above the telescope enclosure. The bright band of light from lower left to upper right is the southern Milky Way.

Although yellow supergiants are extremely rare, a few are household names such as the north pole star, Polaris, is a yellow supergiant, as is Canopus, one of the brightest stars visible from the southern hemisphere. Yellow supergiants are very rare objects because the yellow supergiant phase is so short. A massive star may live for as much as ten million years but the yellow supergiant phase itself lasts only ten to a hundred thousand years, an eye-blink in the life of a star. After this short time, yellow supergiants expand into giant red supergiants, like Betelgeuse, with sizes as large as the orbits of Mars or Jupiter. These stars eventually die in spectacular supernova explosions.

Neugent and Massey anticipate publishing these results alongside collaborators Dr. Nidia Morrell (Las Campanas Observatory, Chile), Lowell's Brian Skiff, and Cyril Georgy (Geneva University, Switzerland) in 2018 before hopefully continuing their search for even more runaway stars. ▪

TECHNICALSUPPORTHIGHLIGHTS





By George Jacoby

DCT

The Discovery Channel Telescope (DCT) has now been in full science operations for three years.

In 2017, part or all of 282 nights were scheduled for science. Total actual science time was 194 nights, where 80 nights were lost due to weather, power outages, and smoke, and 8 nights were lost to technical or staffing issues.

DCT site engineering support was provided by Frank Cornelius, Ben Hardesty, Georgi Mandushev, and Mike Sweaton. Instrument support was provided by Tom Bida, Ted Dunham, Len Bright, Jeff Gehring, Dyer Lytle, and Ryan Hamilton. These groups provided routine maintenance of the telescope, dome, and facility systems. In addition, they enhanced science operations through upgrades, including:

- Installed a new Xenon calibration lamp and restarted software development of NIHTS to bring it to full science readiness
- Re-aluminized the 1.4-m secondary mirror during the summer shutdown in the DCT chamber, now using much more cost effective aluminum filaments
- Improved the safety and operations of the instrument cube, adding positional homing switches, superior fold mirror mounts, and installing an internal camera and microphone to monitor fold mirror motions. These upgrades greatly reduce the likelihood of a fold mirror collision like that in 2016.
- Purchased and installed a dichroic mirror in a fold mirror slots in the instrument cube. This allows simultaneous operation of LMI and NIHTS, doubling the efficiency of the DCT for some projects. A second dichroic mirror will be installed when RIMAS is delivered in 2019 to allow similar double-instrument observing.
- LMI's first corrector element was replaced, as the original was scratched in the 2016 fold mirror collision.
- IGRINS was installed at the DCT for its second of three 6-month visits from the Univ. of Texas. IGRINS at the DCT has now contributed to 8 refereed journal papers and 15 student PhD theses across 5 DCT partner institutions.
- The EXPRES spectrograph room was installed after assisting Yale with delivery and installation of the instrument in the new spectrograph room. (continued on next page)

Image (Left): The recently re-aluminized secondary mirror from the DCT.

Image (Right): The Yale University EXPRES spectrograph, designed to find Earth-like planets around Sun-like stars. It is on the ground floor, fed from the telescope by fiber optics.

TECHNICALSUPPORTHIGHLIGHTS

(continued from previous page)

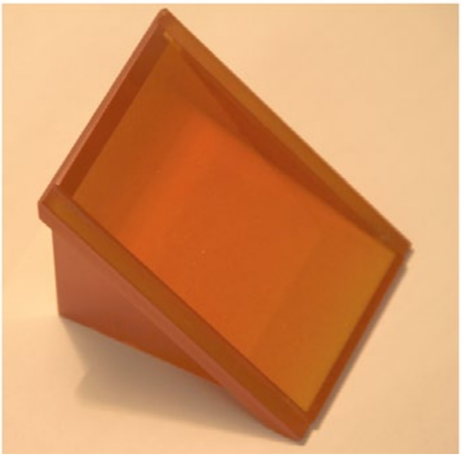
- Safety at the DCT was reviewed and improvements made, including: redesigning the ladders on the telescope for more secure foot and hand holds, adding a covered back door entrance for use during icy conditions, and implementing a strict 2-person rule at the site.

Night operations support was provided by the telescope operations team, including lead telescope operator Dr. Teznie Pugh and operators Heidi Larson, Jason Sanborn, and Andrew Hayslip. They ensured the telescope was ready for operations each night, and expertly operated the telescope in support of scheduled science and engineering programs.

Alexander Kutyrev at the University of Maryland has made good progress with the development of the RIMAS (Rapid Infrared Imaging Spectrometer) instrument. This instrument is designed for quickly moving to and setting up on targets of opportunity, such as gamma ray bursts. It had been delayed waiting for two unique near infrared grisms. One of these has now been fabricated at the Lawrence Livermore National Laboratory and the other is underway. RIMAS is expected to arrive at the DCT in

Image: The Perkins 72-inch Telescope enclosure at Anderson Mesa. In the foreground, the microwave mast and antenna which provides high-speed data communications with Mars Hill.

Image (Below): A unique grism (grating plus prism) needed by the infrared spectrograph RIMAS. It can only be fabricated at Lawrence Livermore National Laboratory. A second grism will be delivered in 2018 for the second channel of RIMAS.



Anderson Mesa

Anderson Mesa telescopes continued to support science operations with 253 science nights scheduled for the 72-inch Perkins Telescope, 191 nights for the 42-inch Hall Telescope, and 365 nights for the 31-inch telescope. Technical support for the telescopes was provided by Ralph Nye, Len Bright, Ted Dunham, Ryan Hamilton, and Larry Wasserman; Jim Gorney and Jon Depinet provided grounds and facility maintenance.

Work to reactivate the LONEOS telescope is complete. This project, partially funded by a NASA/NSF grant to Northern Arizona University, includes a camera on the telescope for follow-up observations of near-Earth object discoveries from the Catalina Sky Survey. The facility was also modified for robotic operations.

The 31-inch telescope was improved to use the guider during robotic operation. Interest in robotic operation has grown at Lowell, leading to a study to enable robotic operation at the 42-inch telescope.

All three Anderson Mesa telescopes use a computer control software package that runs on an ancient computer system (MSDOS). We are converting the software to operate on modern computers running Linux, and that conversion should be complete in 2018. ▪

NPOI

Lowell Observatory maintains and operates the Navy Precision Optical Interferometer (NPOI) on Anderson Mesa under contract to the US Naval Observatory – Flagstaff Station (NOFS) and in partnership with the Naval Research Lab. In addition to maintaining the infrastructure a the site, the observatory provides skilled observers to operate the instrument and gather science data at a steady rate of half-time on-sky operations in accord with the funding level provided by the Navy.

Observers in 2017 comprised Teznie Pugh, Jason Sanborn, and Susan Strosahl. In November 2017, observers Casey Kyte and Ishara Nisley were hired and began their formal training process. We expect the new observers to be fully trained by end of 1st quarter, 2018.

Daytime support was provided by Jim Gorney and Jon Depinet. Their efforts ensured that all of the facility systems needed for instrument operation were operational, such as heating and air conditioning, chillers, dehumidifiers, and gaseous nitrogen purge systems.

The $3.26M PALANTIR (Precision Array of Large-Aperture New Telescopes for Image Reconstruction) upgrade was funded in Jan 2017 and has been progressing rapidly. PlaneWave Instruments was contracted to provide three new one meter CDK1000 telescopes to improve NPOI's limiting sensitivity by 3-4 magnitudes. AstroHaven Enterprises is providing three "enclosure transporters"—mobile domes that allow us to move the telescopes around the NPOI site, thereby changing the "zoom" of the system. Designs for incorporating the new telescopes into the existing vacuum beam transport system were completed. Those designs will be folded into civil plans and a US Forest Service permit amendment. First fringes with the new telescopes are anticipated by March 2019. ▪

Image: Assembly begins at AstroHaven for one of the 16-ft domes needed for the 1-meter PlaneWave telescope upgrade at NPOI.

TECHNICALSUPPORTHIGHLIGHTS

Mars Hill

During 2017, the restoration of the Lawrence Lowell (Pluto Discovery) Telescope was a central project being carried out by Ralph Nye, Peter Rosenthal, Ted Dunham, Glenn Hill, Jeff Gehring, and Dave Shuck.

The instrument shop purchased a 3D printer to greatly accelerate prototyping of parts and to fabricate items that cannot be machined easily. ▪

Information Technology

In addition to providing daily IT support to all of Lowell Observatory, Scott Do and Charles von Buchwald-Wright completed a number of key activities to ensure a safe and effective computing and communication environment. Here are a few:

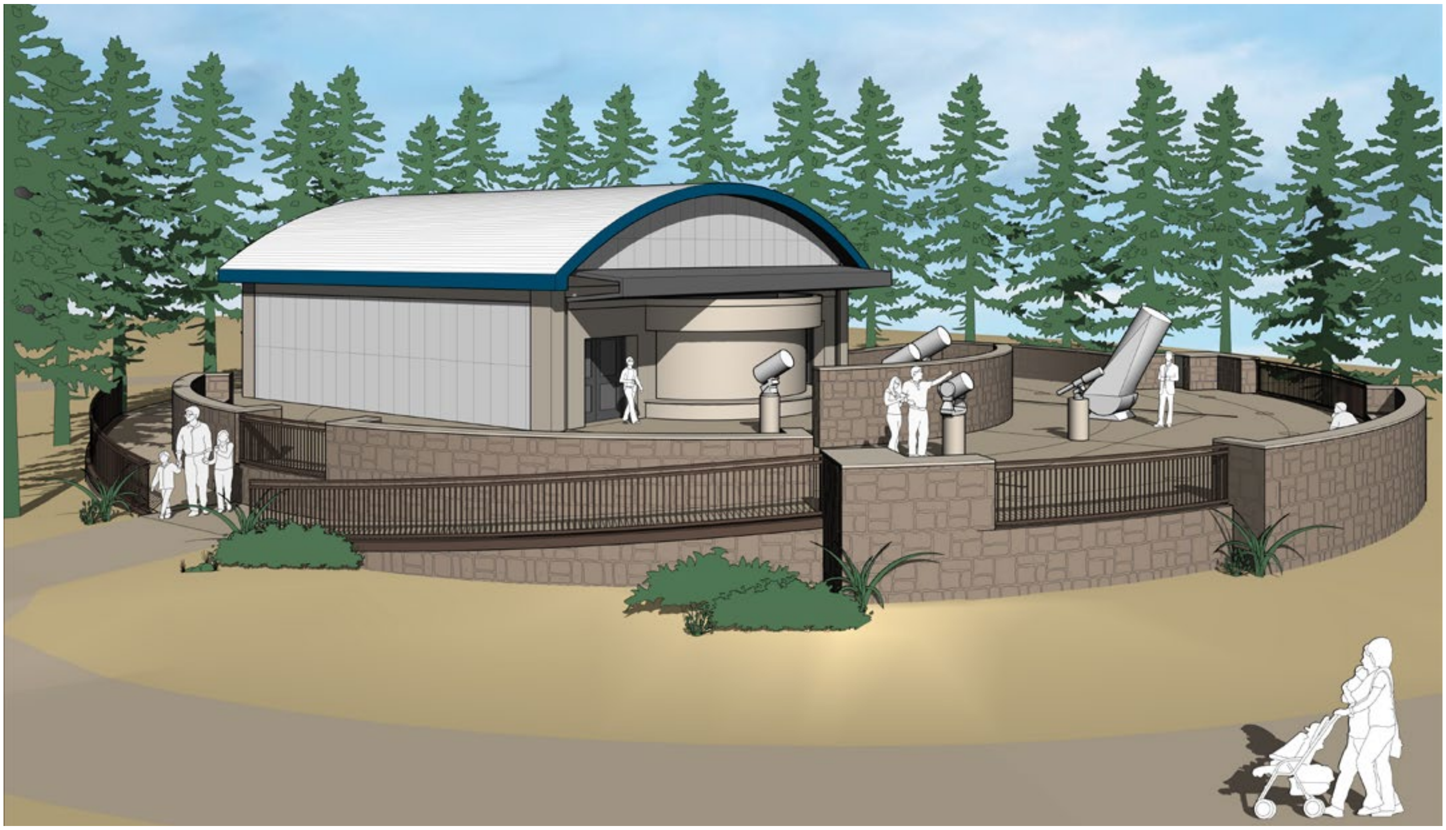
- Installed anti-virus protection server
- Enhanced and spared the virtual environment servers that support basic functions across all of Lowell Observatory
- Implemented the Eduroam facility, giving Lowell staff transparent access to Wifi at educational institutions around the world, and vice versa
- Installed the Webex video conferencing and Webinar software for a greatly improved meeting experience for off-site attendees
- Installed a much improved projection system in the HCPS conference room for improved clarity, brightness, and audio in support of colloquia and meetings
- Upgraded the Mars Hill internet bandwidth speed from 30 to 50 Mbps
- Developed a computer based vehicle checkout logging system to replace the old paper and pen system ▪

Personnel

A number of changes took place in 2017. Joining us are Jon Depinet, Ryan Hamilton Andrew, Hayslip, Casey Kyte, Dyer Lytle, and Ishara Nisley. Unfortunately, 2017 marked the unexpected death of Peter Collins, and the departures of Saied Zoonemat Kermani, Susan Strosahl, and Mike Sakosky. ▪

Image: The refurbished Lawrence Lowell (Pluto Discovery) Telescope is being lowered into the dome by a crane, while Jeff Gehring and Peter Rosenthal guide it into position on the telescope mount. Ralph Nye communicates with the crane operator during the delicate operation.

DEVELOPMENTHIGHLIGHTS



By Lisa Actor

Giovale Open Deck Observatory

Like most good ideas, the Giovale Open Deck Observatory began as a practical solution to a problem.

"The public program staff spends precious time hauling telescopes out of storage every night," said Michael Beckage, chair of Lowell Observatory's Executive Committee. "If the telescopes were permanently mounted under a roll-off roof, the staff could spend more time with Lowell's nighttime guests."

The idea of a roll-off telescope facility had been around for years. As we began planning new facilities to address the popularity of our public programs, an open deck observatory became an integral part of the plan. In March 2017, Mike Beckage made the case for putting this facility first. An open deck observatory would alleviate crowding around the Slipher Building and Clark Telescope Dome on busy nights. It would create buzz and build excitement for the other new visitor amenities.

Last June, Mike and his wife, Bridget Spanier-Beckage, came to the annual Advisory Board meeting with the first gift to the open deck observatory. Their gift inspired Pam and Charlie Ross to make an equivalent donation for the project. The Orr Family Foundation committed an additional gift. By the end of August, we had 15% of the needed funds.

Inspired by others, John and Ginger Giovale offered a gift that made it clear this dream would become a reality. Since January, we have received commitments for five new telescopes for the facility. A year after Mike proposed we put the roll-off facility first, we have 84% of funds raised. The Giovale Open Deck Observatory will open in Spring 2019. Our thanks to everyone who is making the GODO a reality. ▪

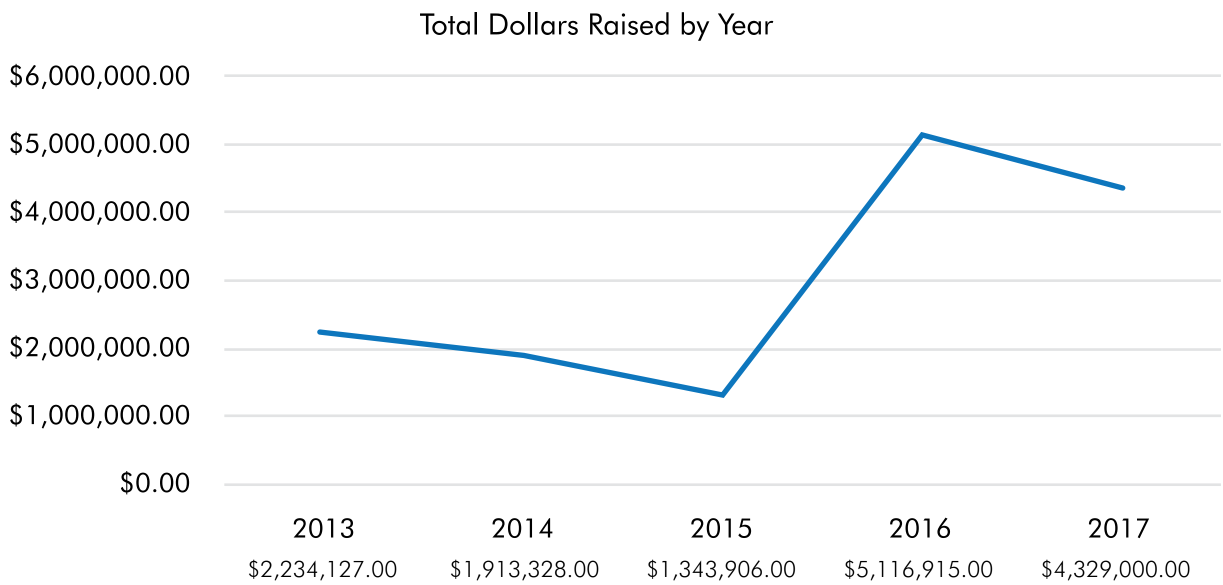
Image: The Giovale Open Deck Observatory (GODO).

DEVELOPMENTHIGHLIGHTS

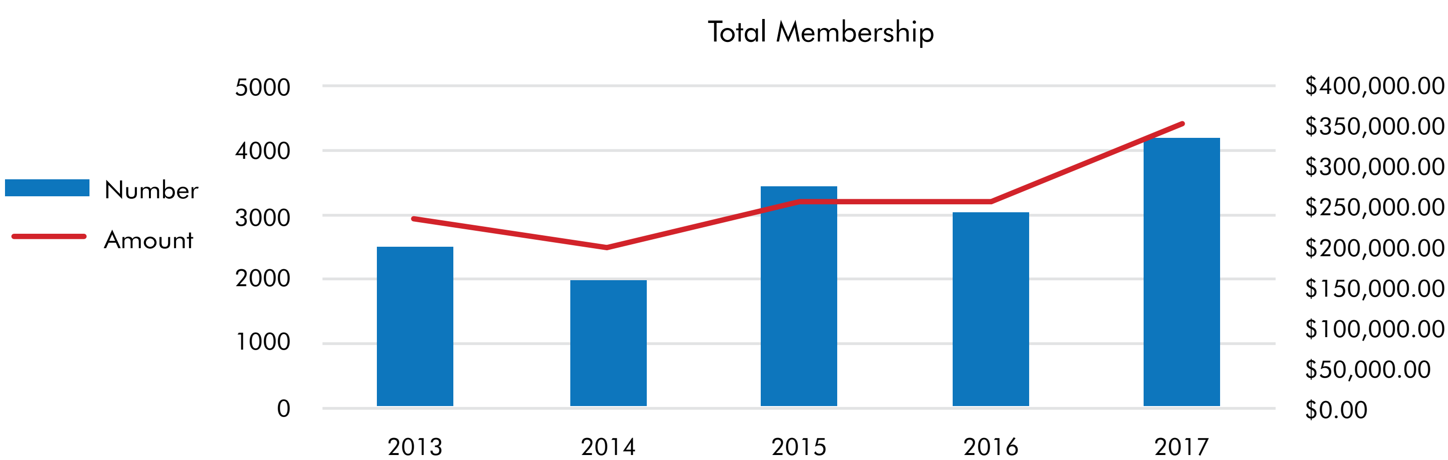
By Stephen Riggs

Fundraising and Membership

Fundraising at Lowell Observatory was particularly strong in 2017. Lowell received more than $4,355,000 in gifts from individuals and organizations. While this was driven in part by capital improvement projects such as the Giovale Open Deck Observatory, it was also due to much effort spent in improving the efficiency and effectiveness of the Development Department's activities.



Lowell Observatory memberships reached an all-time high in 2017 with 4,210 active members. An increase in Observatory visitation was partially responsible for the increase, but dedicated members who renew year after year are an even larger factor. These memberships provide an important percentage of Lowell's operating funds which help pay for educational and research activities.



Year	Number	Dollars
2013	2489	$235,637.64
2014	2004	$200,546.45
2015	3444	$256,547.38
2016	3054	$257,367.36
2017	4210	$353,162.52

DEVELOPMENTHIGHLIGHTS

The Great American Eclipse

Lowell hosted an eclipse event in Madras, Oregon. More than 3,500 visitors converged for two days to celebrate with a star party, astronomy talks, and fun science learning activities. It all culminated on the Madras High School football field where dozens of telescopes were set up allowing everyone to have a close-up look at the eclipsing sun. Guests from 11 different countries joined Lowell members, local residents, and visitors to view the spectacular celestial occurrence. In partnership with the Science Channel, Director Jeff Hall and Astronomer Gerard van Belle broadcast live on-air and online to 70 million homes, giving minute-by-minute descriptions of what was taking place. One hundred Lowell volunteers and 23 staff members were on hand to help make this a truly memorable event. ▪

Image: Visitors set up camp on the Madras High School football field in anticipation of the Great American Eclipse.

PUBLICPROGRAMHIGHLIGHTS

By Samantha Gorney

Public Program

Approximately 99,000 guests visited Lowell Observatory in 2017. The Steele Visitor Center was open to the public Mondays through Saturdays from 10 a.m. to 10 p.m. and Sundays from 10 a.m. to 5 p.m. Daytime tours of the campus, solar viewing and Putnam Collection Center lobby open houses were offered daily. Telescope viewing and astronomy-based presentations were offered Monday through Saturday evenings.

New solar viewing equipment including a Shelyak Lhires Lite Spectroscope and a Lunt LS100THa Solar Telescope provided guests with an enhanced solar viewing experience. The Shelyak Spectroscope allowed visitors to observe the solar spectrum in high resolution and to gain insight into the study of stellar composition. The Lunt Solar Telescope further augmented the solar viewing program by providing guests with exceptionally detailed views of photospheric and chromospheric features.

January 12, 2017 marked the beginning of the Pluto Discovery Telescope restoration project. Over the course of the year, members of Lowell's technical team spent many hours refurbishing various parts of the telescope and repairing the telescope's dome. The beautifully restored telescope was reinstalled in the dome in December at which point Pluto Telescope tours resumed.

A new discussion-based program, titled Lowell42, launched on April 22. The program addresses the big questions that relate to our place in the universe and brings to light the connections that exist between science and the humanities. Discussions in 2017 featured questions like, "What roles do science and religion play in shaping our view of the universe?" and "Do science and politics influence each other in subtle ways that we might not expect?"

The marquee event for outreach in 2017 was the August 21 solar eclipse. More than 1,200 visitors including 150 elementary school students came to Lowell Observatory to take in the partial eclipse visible from Flagstaff. Guests viewed the eclipse through solar glasses, binoculars, telescopes, and pinholes projectors and participated in sun-themed talks and activities.

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Image: Visitors on the Mars Hill campus waiting to watch the Great American Eclipse.

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Lowell Observatory Camps for Kids (LOCKs) programs continued to be offered both on- and off-site. Enrollment in on-site programs reached record levels for all age groups. Preschool camps, which had previously been offered on 12 Saturdays a year, were offered on 24 Saturdays in 2017. A partnership between Lowell Observatory and the College of Education at Northern Arizona University made it possible for a group of NAU education majors to earn course credit while serving as LOCKs camp counselors. Off-site, Lowell educators led LOCKs activities for children at the Flagstaff Family Food Center twice a month throughout the year. And the preschool teacher at Horseshoe Trails Elementary in Cave Creek, Arizona integrated LOCKs: Preschool lessons into her curriculum.

Master planning efforts related to outreach ramped up during 2017. A preliminary version of a master plan for outreach was released on May 19. The report, which was informed by numerous internal workshops and external consultations with community stakeholders, identifies a set of new attractions that would significantly enhance the visitor experience. Those attractions include a roll-off roof observatory, a new visitor center, an immersive theater and an open-sky planetarium. ▪

Image: LOCKs campers learned about STEM through hands-on activities.

PUBLICPROGRAMHIGHLIGHTS

By Deidre Hunter

Navajo-Hopi Astronomy Outreach Program

The Navajo-Hopi Astronomy Outreach Program finished the second half of the 2016-17 school year, the program's 21st year, with eight astronomer-teacher partnerships. At the start of the 2017-18 school year the program was inundated with 23 applications from teachers, but it could only afford eight partnerships. However, it did start the year fully funded for the first time in 22 years.

In three of the 2016-17 partnerships the outreach program tested a new curriculum unit on Characteristics of the Planets for 5th grade developed by Todd Gonzales and our Navajo collaborator Verna Tallsalt. This curriculum is characterized by a Project Based Learning approach, cultural connections woven throughout, attention to Navajo, Arizona, Common Core, and Next Generation Science standards, and inclusion of reading, writing, and math. The goal is to better enable students to see themselves as scientists and to see science as relevant to them. At the review of the curriculum in May, the consensus was that the 5th grade unit was great and that the Program should continue with developing units for 4th-7th grades. In the 2017-18 school year three of the teachers are 5th grade teachers who all elected to use the new curriculum unit. The Program held a training day for these teachers and their astronomers in October, and the teachers and astronomers have been carrying out the unit since then. The program also added a technology component consisting of a simple Sphero robot programmed with a tablet by the students to explore a planetary surface of their making. The program also is implementing this unit, originally designed to include Navajo cultural connections, in a Hopi classroom this school year.

Alethia Little designed summer camps for Navajo 6th and 7th graders that will be initiated in the summer of 2018. These camps are designed to extend the classroom curriculum and include strong cultural connections and traditional astronomy.

In July 2017 the program was invited for the second time to present at the Second Navajo Nation Annual Youth & Elder Summit. Alethia Little and several others from Lowell held a star party and led the Navajo Constellation Bingo game that she designed. ▪

Image: Pictures from Todd Gonzales' work with Verna Tallsalt's 5th grade class, implementing the new Characteristics of the Planets unit that the two of them had designed.

PUTNAM COLLECTION CENTER HIGHLIGHTS

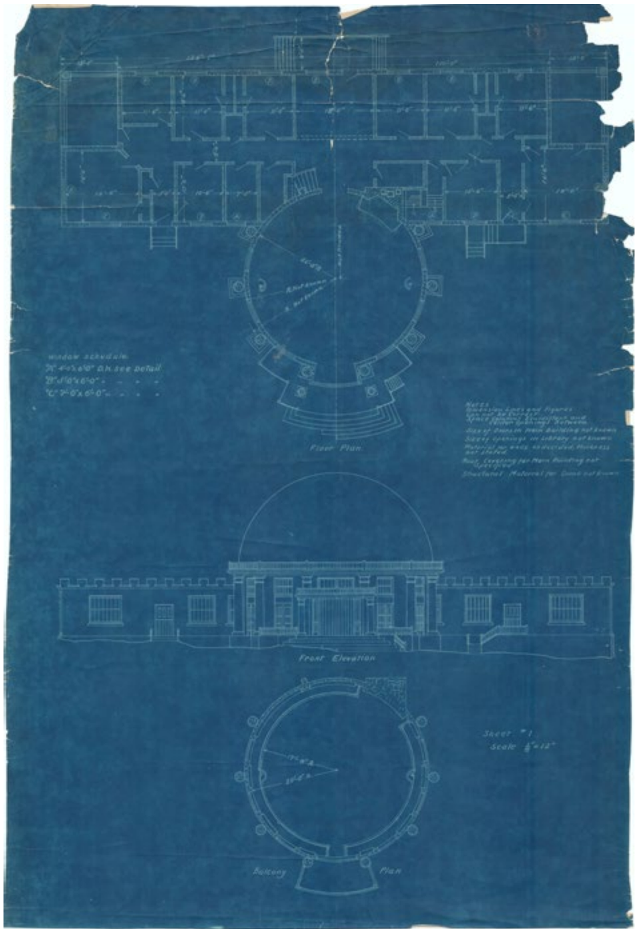


Image (Left): A blueprint of the Slipher Building.

Image (Right): Elizabeth Roemer Archive Intern Stacey Christen.

By Lauren Amundson

In 2017, the Putnam Collection Center (PCC) continued its mission of acquiring, preserving, making available, exhibiting, and interpreting collections. Archivist/Librarian Lauren Amundson oversaw all aspects of the daily activities and larger projects in the PCC.

Amundson attended the annual Arizona Archives Summit in Tempe in January. In June, she served as co-moderator of a roundtable group for the Physics, Astronomy and Math division of the Special Libraries Association at its conference in Phoenix.

Natalee Martino and Tim Yamamura of Northern Arizona University visited the archives several times to conduct research on Percival Lowell's writings, particularly his poems. Amundson received roughly two dozen requests from authors, publishers, filmmakers, educators, and historians for the reproduction and use of archival materials.

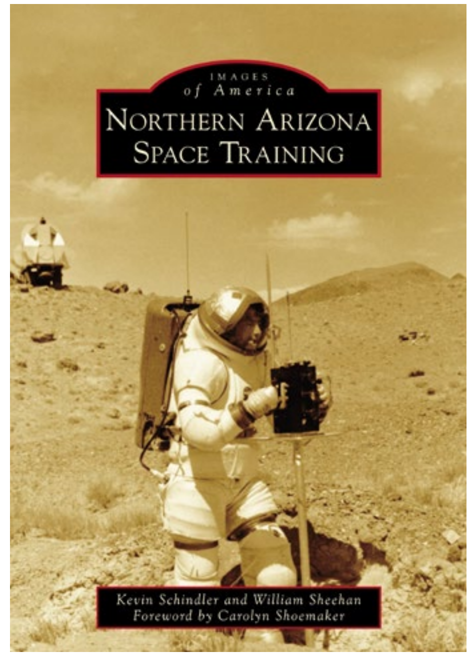
Paid staff and volunteers continued to move manuscript materials, photographs, and books from the Slipher Building basement to the PCC's walk-in freezer and repository. Amundson managed twelve volunteers and their projects, which included collections processing, cataloging, digitization, and preparation for moving materials to the PCC.

In May, Stacey Christen was hired as the Elizabeth Roemer Archives Intern. Dr. Elizabeth Roemer was a prominent astronomer whose primary studies included comets and asteroids. She left her papers and glass plate negatives to Lowell upon her passing in 2016, and Stacey processed the collection throughout 2017. When she has completed the project, historians and researchers will have full access to Dr. Roemer's correspondence, photographs, and research notes.

Amundson had a local printing company digitize roughly 200 blueprints and drawings of various Lowell telescopes and buildings. A volunteer flattened the prints using humidity, which makes them easier to store and digitize.

The archives continued to partner with the Arizona Memory Project and Arizona Archives Online to make its digital collections and finding aids available to the public. Lowell educators and docents hosted daily open houses in the PCC lobby, where various artifacts are on display. ▪

COMMUNICATIONHIGHLIGHTS



By Molly Baker

Last year was a year of growth for the Communication Department. Not only did our team physically grow with new members to the team, but also the scope of our projects with the goal of national exposure with the Great American Eclipse.

Towards the end of the year, we gained two "new-to-us" members of team. Both Alma Ruiz-Velasco and Jelena Lane have worked in the Lowell Public Program for years, but new position openings brought them our way and we greeted the extra hands with open arms.

Alma Ruiz-Velasco filled a position funded by long-time donor and supporter, Bob Ayers. As astronomy liaison, Alma gets to share Lowell research and discoveries with the public. This includes everything from writing and distributing press releases to the media, attending star parties with amateur astronomer groups, and participating in Deidre Hunter's Navajo-Hopi outreach program to bring STEM education to the reservation.

The goal with the astronomy liaison position is to fulfill the latter half of Lowell Observatory's mission, "to maintain quality public education and outreach programs to bring the results of astronomical research to the general public." It may sound like an overstatement, but there are interesting things that happen at the Observatory everyday. Alma is helping to show the public just that.

Jelena Lane took the position of event coordinator and organizes special events up at Mars Hill, and our presence at off-site events, including star parties, and various expos. Her work has specifically been helpful in attracting more locals up to Lowell, as well as getting us more active in community partnerships.

Our goal is to make Lowell a visible supporter of the Flagstaff community and in return, foster support for the Observatory from our locals. We've seen this support growing as we partner with other entities like the Convention and Visitors Bureau and Northern Arizona University. When people think Flagstaff, we want them to think Lowell Observatory, a destination for locals and tourists alike.
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Image (Left): Sébastien Vaugnet of Agence France Presse sets up his camera in front of the media tent in anticipation of live streaming the Great American Eclipse from Lowell's event in Madras, OR. The tent was set up by the Communication team to include press kits, access to electrical outlets, and wifi hot spots for media personnel.

Image (Right): Kevin Schindler's book, Northern Arizona Space Training.

COMMUNICATIONHIGHLIGHTS

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For Lowell Observatory and much of the nation, 2017 was the year of the Great American Eclipse. The Communication Department was tasked with advertising an event of proportions unlike the Observatory had ever taken on before.

One of the many goals of the Lowell Observatory Solar Eclipse Experience 2017 was getting Lowell Observatory national exposure. We racked up a total of 64 registered media personnel, some from as close as our hometown NPR station and others as far as BBC radio in London and Cosmos magazine out of Australia with a few ABC news channels scattered across the nation. Not to mention being our partnered stream with Science Channel being viewed by over 1.7 million people.

Our website views and social media follows reflected the effects of successful advertising with an all-time record 6,436 website view on August 21, 2017 and 471 new followers on Facebook.

An estimated total of 7,000 people experienced the Great American Eclipse with Lowell Observatory at the event in Madras and on Mars Hill in Flagstaff.

For the year, Kevin Schindler gave 26 presentations and wrote 56 articles and columns for a variety of publications, as well as a book, *Northern Arizona Space Training*, with astronomy historian Dr. Bill Sheehan. ▪

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STATEMENTOFFINANCIALPOSITION
COMBINED BALANCE SHEET

ASSETS	2017	2016
Current Assets		
Cash and cash equivalents	$ 614,670	$ 1,390,759
Restricted cash	199,778	747,782
Investments, unrestricted	1,119,757	863,573
Research grants receivable	281,584	291,790
Contributions receivable, current portion	547,385	484,266
Inventory and other assests	458,895	338,081
Total Current Assets	**3,222,069**	**4,116,251**
Property, plant and equipment, net	43,452,560	43,242,180
Contributions receivable, net of current portion	924,921	1,010,845
Collection item	400,000	400,000
Investments, temporarily restricted	27,856,353	-
Investments, permanently restricted	5,118,817	39,413,921
Total Assets	**$ 80,974,720**	**$ 88,183,197**

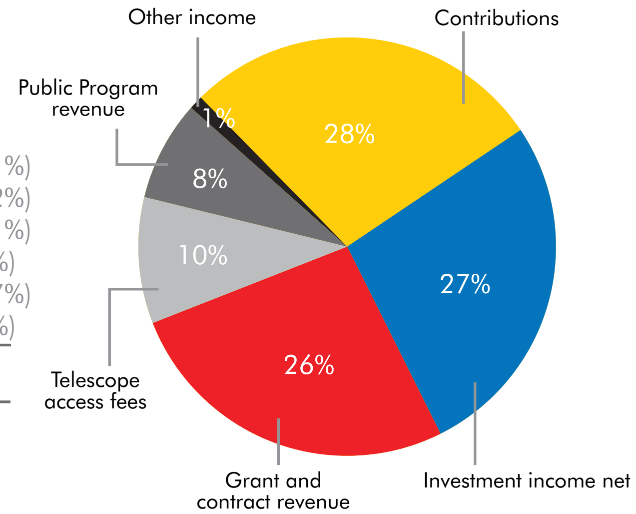
LIABILITIES AND NET ASSETS	2017	2016
Current Liabilities		
Note payable, bank	$ -	$ 20,400,000
Accounts payable	309,969	245,042
Accrued expenses and other current liabilities	90,491	387,962
Total Current Liabilites	**400,460**	**21,033,004**
Note payable, bank	10,200,000	-
Deferred research grant revenue	598,953	1,271,349
Deferred access fee revenue	8,310,268	8,207,916
Obligation under interest rate swap	-	248,960
Total Liabilites	**$ 19,509,681**	**$ 30,761,229**
Net Assets		
Unrestricted	$ 23,850,068	$ 15,030,945
Temporarily restricted	32,701,067	2,620,850
Permanently restricted	4,913,904	39,770,173
Total Net Assets	**61,465,039**	**57,421,968**
Total Liabilities and Net Assets	**$ 80,974,720**	**$ 88,183,197**

STATEMENT OF FINANCIAL ACTIVITIES

DECEMBER 31, 2017 (with comparative totals as of December 31, 2016)
(before depreciation)

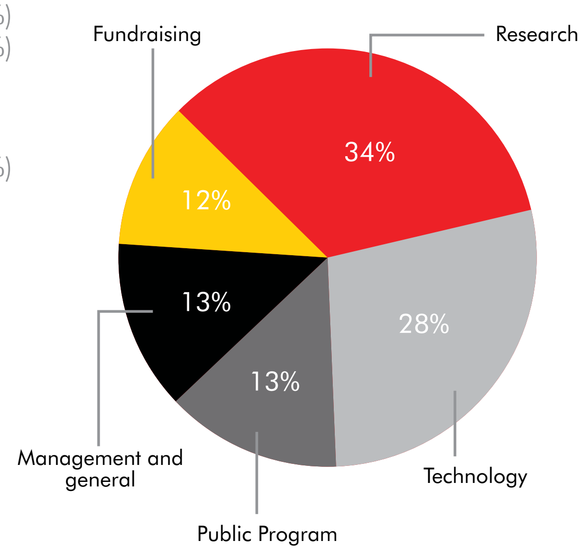
REVENUE	2017		2016	
Grant and contract revenue	$ 4,061,731	(26%)	$ 2,674,069	(21%)
Telescope access fees	1,538,425	(10%)	1,508,029	(12%)
Contributions	4,329,073	(28%)	4,985,558	(41%)
Public Program revenue	1,205,815	(8%)	1,056,878	(8%)
Investment income (loss) net	4,263,753	(27%)	2,085,518	(17%)
Other income	147,752	(1%)	132,224	(1%)
Total Support and Revenue	**$ 15,546,549**		**$ 12,442,276**	

2017 REVENUE



EXPENDITURES	2017		2016	
Program services:				
Research	$ 3,317,034	(34%)	$ 3,482,086	(34%)
Technology	2,732,224	(28%)	2,991,020	(30%)
Public program	1,307,766	(13%)	1,290,173	(13%)
	7,357,024		7,763,279	
Support services:				
Management and general	1,291,967	(13%)	1,373,347	(14%)
Fundraising	1,137,066	(12%)	910,313	(9%)
	2,429,033		2,283,660	
Total Expenditures	**$ 9,786,057**		**$ 10,046,939**	
Gain on interest rate swap	248,960		241,246	
Change in net assets	$ 6,009,452		$ 2,636,583	

2017 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 2017 and 2016 was $1,966,000 and $1,941,000.

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, 2017. Copies of the audited financial statements are available at https://lowell.edu/about/governance_and_financials/

LOWELL OBSERVATORY ANNUAL REPORT

2017

Image (Front Cover): The Great American Eclipse photographed from Terrebonne, OR. Credit: Len Bright

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