



2016

LOWELL
OBSERVATORY
ANNUAL REPORT



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TRUSTEE'S UPDATE

By W. Lowell Putnam



I recently had the opportunity to buy some "Pluto...explored" stamps at my local post office, and I will use them on my increasingly infrequent envelopes sent through the mail. But it felt good to purchase them as a visible acknowledgment of the accomplishments that the Observatory, with the culture and vision given to us by Percival Lowell, has produced over the past 120 years.

As you will read and see in this report, 2016 was a very successful year on all fronts: scientifically, in outreach, and financially. Our scientists continue to do great work, which is clearly well-regarded by their peers and the organizations that support research. With more than 98,000 visitors and incredible reviews on social media, our public program staff are creating great experiences that educate and are enjoyed. Our technology, operations, and administrative staff do great "behind the scenes" work that keeps everything moving smoothly. And, thanks to the friends and supporters, our development team had a record year. All of this is very heartwarming, but it is also indicative of the level of commitment we need to sustain in the years to come.

We have both the opportunity and

requirement to grow the Observatory.

Astronomy is a great vehicle to promote discussions around science and discovery, and the public clearly enjoys the approach we have taken. As we work to expand our efforts in this area we will need to address a number of physical limitations on Mars Hill as well as the resources we need to improve our presence in the virtual world of the Web.

One of Percival Lowell's greatest commitments was to academic freedom coupled with sustained access to the instrumentation and facilities needed to do great research. We live in a time where the level of technology creates incredible opportunities for new discoveries and understanding. Because of the investments we have made at Happy Jack and on Anderson Mesa, we are well-positioned to participate in this era. But it will require more support to give our staff the independence needed at a time when Federal funding for research is in decline.

Opportunities and challenges are a matter of perspective. At the observatory, with your support, we see them as a way to do even more. ■

DIRECTOR'S UPDATE

By Jeffrey Hall



I happily concur with Trustee Lowell Putnam's comments: 2016 was indeed a good year. I was pleased to be able to give our Advisory Board this assessment as well at its annual meeting, which wrapped up the weekend before I wrote these remarks.

Our Discovery Channel Telescope continues to be a major success. In 2016, we brought a new instrument to DCT for a six-month visit: the Immersion Grating Infrared Spectrograph (IGRINS), built by the University of Texas and the Korea Astronomy and Space Science Institute. IGRINS on DCT was the most powerful high-resolution infrared spectrograph in the world, thanks to the combination of the IGRINS' innovative technology and DCT's aperture and operational efficiency. Additionally, in the summer, our technical team successfully applied a fresh coat of aluminum to the 4.3-meter primary mirror, a procedure that took several weeks and that involved removing the entire 13-ton back end of the telescope and moving it to the on-site recoating building. In all of its scientific and technical activities, DCT continued to be one of the best-performing 4-meter telescopes in the world.

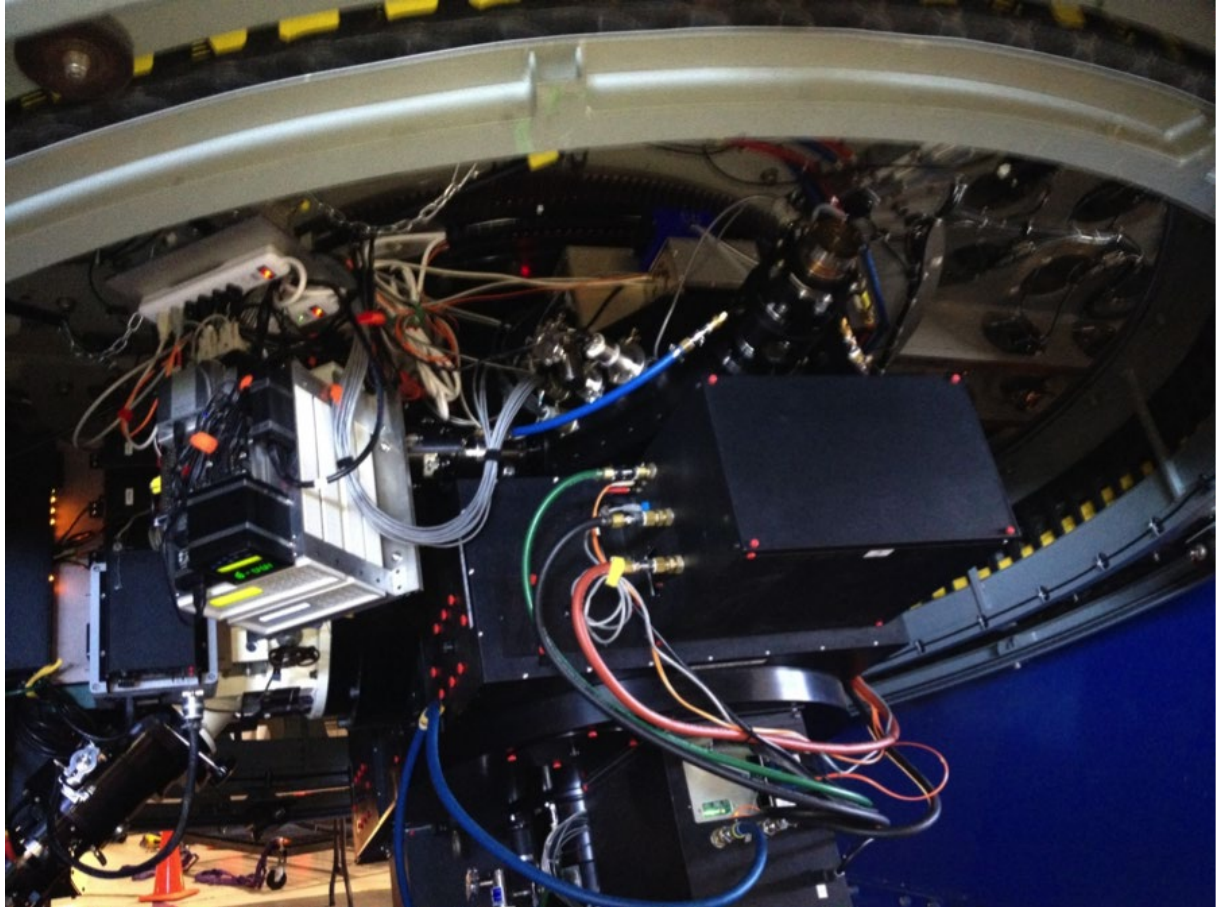
Now, as I told our Advisory Board, success begets success. More highly innovative instruments will arrive at DCT in 2017, and the exciting science we can do with DCT has received major support, including a \$1.12M gift in support of DCT research in December 2016 from the Kemper

and Ethel Marley Foundation. For several reasons, our outreach program attendance has jumped, in 2015 and 2016, from about 80,000 visitors per year to almost 100,000.

These successes demand that we look forward. We have established funds in our new Foundation to support the scientific and technical work being done at DCT and at our other facilities. We are developing plans for the future of Mars Hill, including accommodating the greatly increased interest and attendance in our outreach programs as well as the facility needs for what we anticipate will be a steadily expanding scientific and technical staff. These plans are ambitious, and you will be hearing about them as we get them more fully developed in 2017.

One thing is clear. The outstanding performance of DCT puts us in a very strong competitive position to do outstanding science and to tackle observational projects few other places in the world could. The breadth and repute of our outreach programs gives us a singularly strong platform to advocate widely for science in our community, our state, and the nation; it would be to our shame if we failed to take advantage of it.

Our plans are intended to ensure we do indeed take maximum advantage of our unique scientific and educational position. We look forward to sharing the fruits of these efforts with all of you in the annual reports to come. ■



Ted Dunham

Dr. Ted Dunham's work in 2016 began with completion of the NIHTS instrument for the DCT, which was handed over to Henry Roe in February. After that his activities were dominated by operational support and work supporting partner instruments. Operational work was focused on the DCT primary mirror recoating and instrument maintenance downtime. This included procurement and assembly of a very nice vacuum pump station for the DCT made possible by a generous donation from Dr. Bob and Julie Millis, and outfitting of the DCT clean room area as part of the preparations for IGRINS' arrival. Partner support work focused on integrating IGRINS with the DCT with support from the Technology Committee of the Advisory Board and upgrading and converting the LONEOS telescope to serve the NAU FRoST project. There were no HIPO flights on SOFIA because no good occultations occurred in 2016. ■

Image: NIHTS mounted to the DCT in late 2015. Covers for the electronics were missing at this time but were completed in early 2016.



Will Grundy

Dr. Will Grundy's research involves small, icy outer Solar System planets, satellites, and Kuiper belt objects, and was fully funded during 2016 by research grants. He was an author on 16 peer-reviewed scientific papers published this year, including first-author papers in both *Science* and *Nature*.

Grundy is a co-investigator on NASA's *New Horizons* mission that explored the Pluto system in 2015. He heads the mission's surface composition science theme team. The encounter was a spectacular scientific success, yielding a rich trove of data that will be analyzed for years to come. It was also a high profile event, setting a new high-water mark for public engagement in a NASA mission, and garnering numerous awards and accolades including a set of postage stamps. Even during 2016, the year after the flyby, Grundy fielded well over 40 follow-up media interviews.

One of Grundy's numerous scientific contributions to analysis of Pluto system data was the development and publication of a hypothesis to explain Charon's unique dark red polar caps, as a result of synthesis of organic molecules from chemical feedstock supplied by Pluto's escaping atmosphere.

In 2016, NASA selected for funding the *New Horizons* team's extended mission proposal to fly past a small Kuiper belt object. That encounter will happen at the beginning of 2019.

Grundy is a co-investigator on another newly-selected NASA mission, called *Lucy*, after the *Australopithecus* discovery that revolutionized our understanding of human evolution. The *Lucy* mission will be launched in 2021 and explore a series of Jovian 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. (continued on next page)

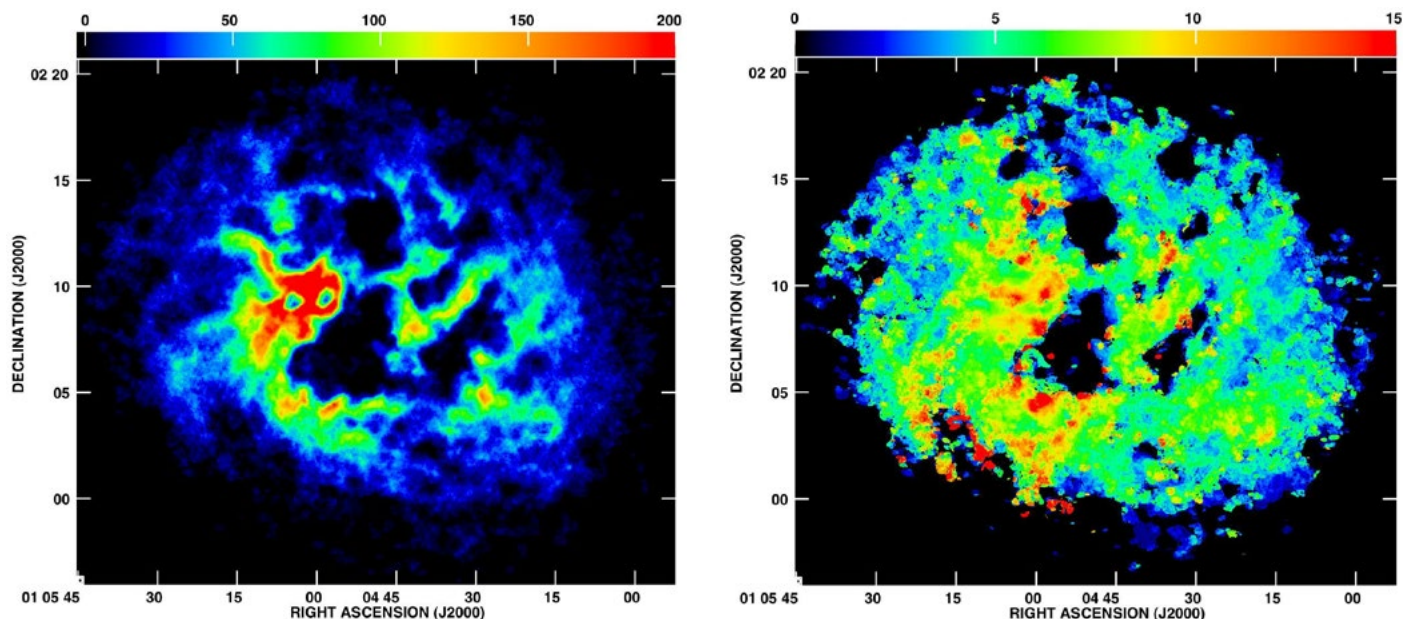
Image (Left): Postage stamps issued by the United States Postal Service in 2016 to honor the exploration of the Pluto system by *New Horizons*.

Image (Right): Pluto's largest moon Charon, showing its distinctive, reddish northern polar cap. (NASA/SwRI/JHUAPL)

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Grundy is involved with numerous other scientific projects. These include discovering Kuiper belt binaries and determining their mutual orbits and masses, using Hubble Space Telescope, as well as ground-based laser guide star adaptive optics techniques. Another major area of research is spectroscopic and thermal observations of outer solar system bodies. Grundy participated in observations from a number of large ground- and space-based telescopes during 2016 including Hubble, Keck, and IRTF.

To complement this observational work, Grundy does laboratory studies of cryogenic ices and ice mixtures at Northern Arizona University where numerous students seeking hands-on laboratory experience can readily contribute to the research. The recent hiring of Jennifer Hanley and addition of a Raman spectrometer system are greatly advancing that work. The rich thermodynamic complexity of cryogenic ice mixtures is emerging as a major theme in need of deeper investigation. These are the materials that enable the spectacular geological activity seen on Pluto by *New Horizons*, as well as on other small, icy planets and satellites across the outer solar system. ■



Deidre Hunter

In galaxies gas is turned into stars, which evolve and die, and new stars are born. Models that explain how galaxies make the clouds of gas that then form stars may work in giant spiral galaxies. However, dwarf irregular galaxies, the tiniest but most numerous galaxies in the universe, form new stars under conditions where the models say no star formation should take place. So how are those clouds of gas made in dwarfs? Random motions in the atomic hydrogen gas can sporadically produce regions with high enough density for gravity to take over and pull the gas into a dense cloud of molecular hydrogen that forms stars. This could be key in facilitating star formation in dwarfs where the gas density is too low to form clouds by other processes, but we don't know how important this process is; in fact, we know very little about turbulence in dwarfs. Therefore, Dr. Deidre Hunter and her collaborators—Dr. Bruce Elmegreen (IBM), REU students Erin Maier (2015) and Gigja Hollyday (2014), Dr. Lisa Chien (NAU), Dr. Caroline Simpson (FIU)—undertook a first look at turbulence in the interstellar gas of the nearby LITTLE THINGS¹ dwarf irregulars. They also analyzed the THINGS sample of nearby spirals for comparison.

The analysis involved looking, not directly at turbulence, but at the consequences of the turbulence: the number of pixels at different densities in a map of the atomic hydrogen in the galaxy. They calculated the third (skewness) and fourth (kurtosis) statistical moments of these density distributions. Skewness is a measure of the symmetry of the distribution, and kurtosis is a measure of the sharpness of the peak and extent of the tails of the distribution to high gas densities. These statistics were then compared to the group's models to infer the Mach number of the motion of the gas.

Hunter and her colleagues found that the kurtosis values in the LITTLE THINGS dwarfs measured over the whole galaxy are higher in galaxies with higher integrated star formation, and this would imply that higher turbulence enables more star formation. The kurtosis and skewness values of a typical dwarf are consistent with the groups' models in which the gas has subsonic to weakly supersonic motions. A similar analysis by another group of the Small Magellanic Cloud, a dwarf companion to the Milky Way, showed that the gas in that galaxy is also mainly transonic. Transonic regions are less likely to produce structures in the gas than supersonic regions. The group also found that the further out one goes from the center of these galaxies, the lower the maximum density of the atomic hydrogen, as would be expected if the atomic hydrogen was turning into molecular hydrogen above these densities.

The next step to explore turbulence in the LITTLE THINGS dwarfs will be to cross-correlate, on a pixel-by-pixel basis, a convolution of gas density and velocity dispersion with far ultraviolet emission, a proxy for star formation. The group will use an existing code put together by a THINGS team member for this analysis. ■

¹The acronym stands for Local Irregulars That Trace Luminosity Extremes (LITTLE), and is a complement to The HI Nearby Galaxy Survey (THINGS), which studied spirals.

Images: IC 1613, a typical LITTLE THINGS dwarf irregular galaxy. (Left) Map of integrated atomic hydrogen gas. Red regions are higher density; dark blue are lower density. (Right) Map of the dispersion in the velocities of the gas at each point in the galaxy, with red being dispersions in the velocity of up to 15 km/s and blue being less than 5 km/s. Velocity dispersion is related to turbulence in the gas.

K: $14 < V < 16$

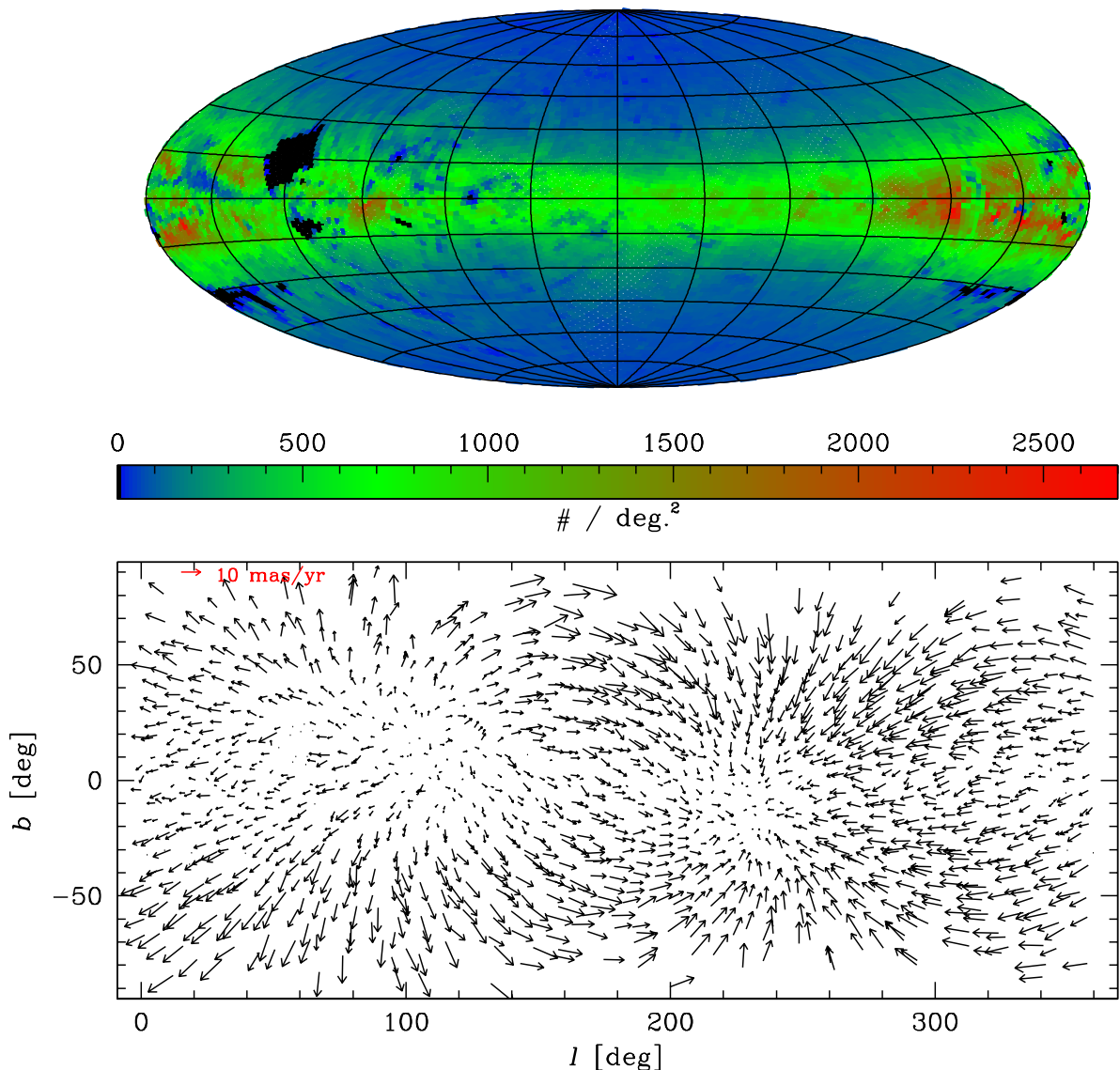


Fig. 1

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 also maintains an active interest in stellar occultation studies of outer solar system objects, and in understanding the importance of passing stellar systems on the evolution of the outermost reaches of our own solar system.

He continues 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 2016, the team undertook a complete re-reduction of all the data taken between 2009 and 2016. It 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. (continued on next page)

Fig. 1: The upper panel shows the distribution of moderately faint K stars. The red and green band is the plane of our Milky Way galaxy. In this projection, the direction towards the Galactic center is at the left and right edges. The lower panel shows the apparent flow of these stars as seen from the Sun. The regions where the flow arrows disappear correspond to the directions directly ahead of and behind the Sun; they show the direction of solar motion with respect to this group of stars. By looking at groupings like this, we are better able to understand the kinematic evolution of ensembles of stars over the age of our Galaxy.

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By combining the colors from APASS with proper motions from catalogues like UCAC, or in the next year, GAIA, the team was also able to look at the motions of specific types of stars in the local neighborhood of the Milky Way (see Fig. 1). As a by-product, Levine is working on a five-color catalog of solar system objects that were imaged during the course of the survey.

Levine continues to be actively involved with the DCT as the telescope scientist. Among his current projects is an assessment of the delivered image quality of the full system, and looking at how that compares with the original site survey data and the telescope requirements. During 2015, the average image quality on the DCT exceeded the specifications in the telescope requirements document. A critical component in the success of the DCT in meeting the project goals has been the model for how the telescope optics behave as a function of pointing elevation and temperature. Without it, the image quality would be significantly worse (1.13 instead of 0.93 arcseconds median - see Fig. 2). ■

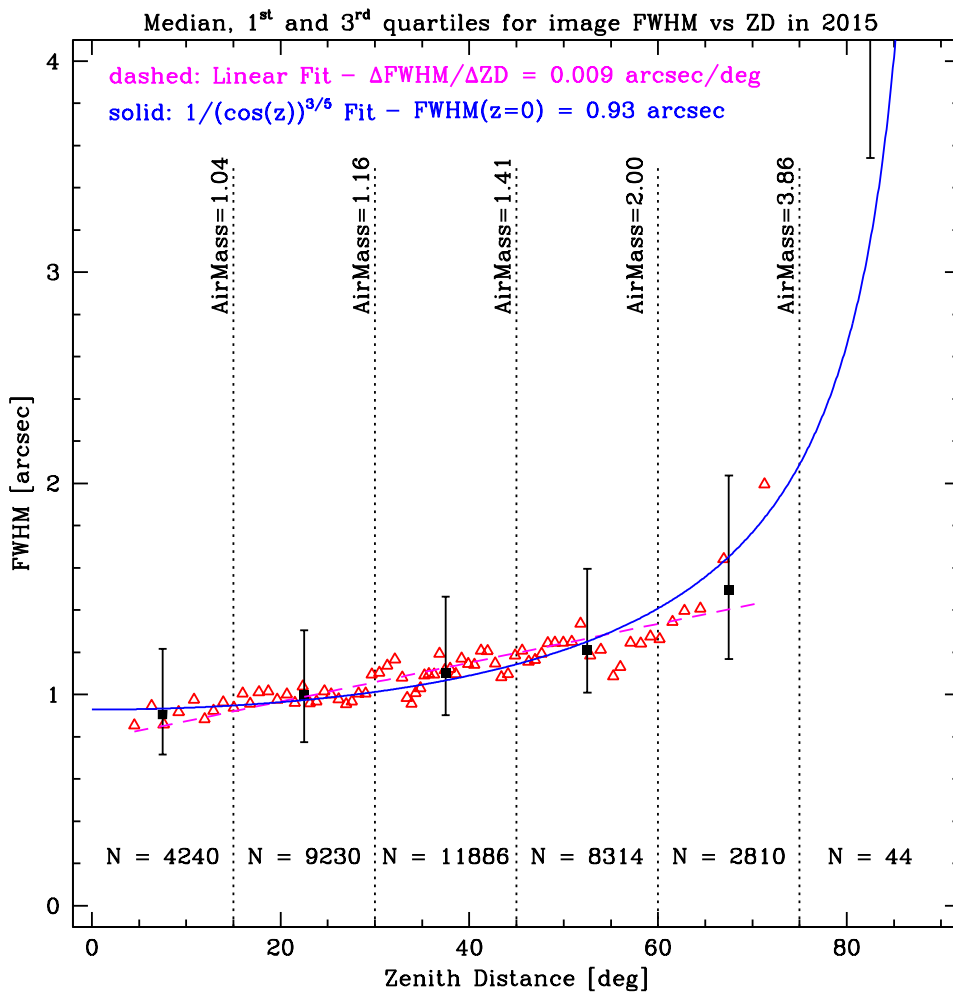
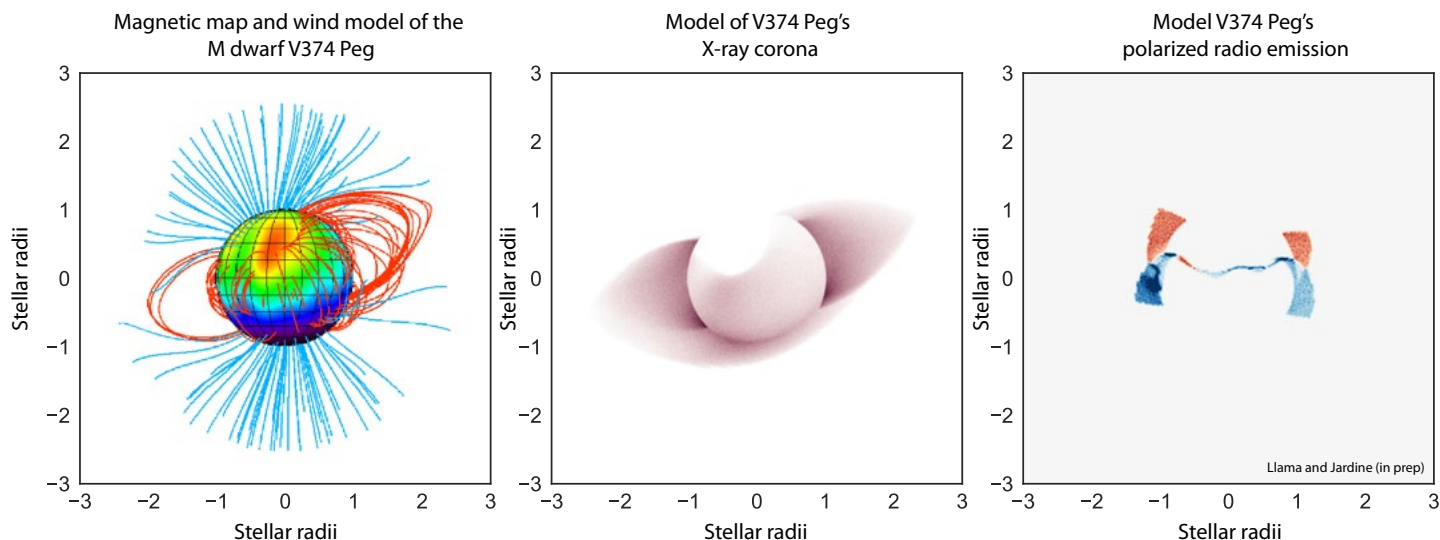


Fig. 2: The ensemble of image median full width at half maximum (FWHM) measurements sorted in zenith distance (90 degrees minus the pointing elevation); the smaller the FWHM, the better the image quality. The median and 1st and 3rd quartiles were computed for the set of measurements within each 15-degree-wide bin. The black points are the median values within each bin, and the red points are the medians for sets of 500 images. The dashed magenta line is the best fit line to the red points. The blue curve is a fit for a Kolmogorov turbulence model of the degradation of the seeing as a result of moving to lower elevation. The median seeing overhead is roughly 0.93 arcseconds, and it degrades at about 0.009 arcseconds/degree of zenith distance. Without the optics model, the data would be shifted to larger FWHM by roughly 0.2 arcseconds (based on data taken before the model was put into service). The smaller FWHM means that DCT is better able to resolve objects that are very close together on the sky. It also means that the telescope can reach a given detection threshold more quickly; the system puts more of the real signal into the instrument, and less background light, improving observing efficiency.



Joe Llama

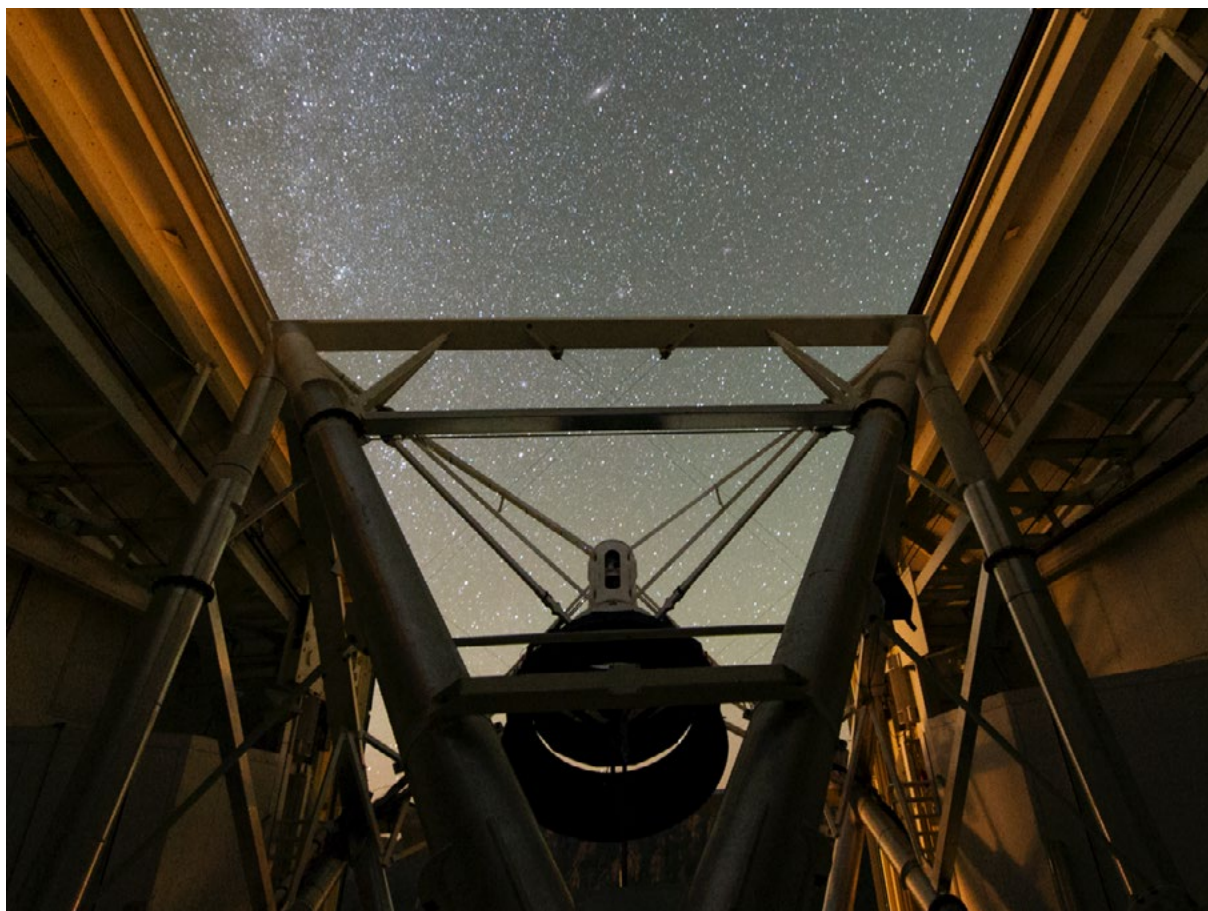
Since moving to Lowell in August 2016 as a tenure-track astronomer, Dr. Joe Llama has continued researching the impact of stellar activity on exoplanets. His research is focused on understanding how host stars impact the environments of close-in planets and searching for the signatures of star-planet interactions.

With his collaborator Evgenya Shkolnik at Arizona State University, he is carrying out an extensive archival search of high-resolution spectra of planet-host stars to search for activity indicators that are the signature of star-planet interactions. These magnetic interactions appear as enhanced stellar activity modulated by the planet as it orbits the star rather than by stellar rotation. By searching for star-planet interactions, Llama is studying the magnetic fields of exoplanets and also their atmospheric evolution. Together with Shkolnik, they have recently published a chapter in an Exoplanet Handbook published by Springer on star-planet interactions.

With collaborator Moira Jardine in St. Andrews, Llama is pursuing a project to simulate radio emission from low-mass stars that host exoplanets in an effort to understand the expected radio signatures from these planets.

Llama also enjoyed using IGRINS on DCT to search for the signatures of auroral emission from exoplanets and low-mass stars. This emission manifests in both the H and K bands, which are covered by IGRINS. By observing Jupiter, which shows the same auroral emission, he was able to characterize the signal in IGRINS data. The unprecedented spectral resolution and wavelength coverage of IGRINS makes it an ideal instrument to search for this emission. Detecting auroral emission on an exoplanet will help constrain the magnetic field properties of these worlds and is an important step in characterizing their internal compositions. ■

Images: (Left) Magnetic map and wind extrapolation of the rapidly-rotating M dwarf V374 Pegasi. (Middle) Llama's model for the X-ray corona. (Right) Llama's model for the polarized radio emission that would be observable from Earth.



Philip Massey

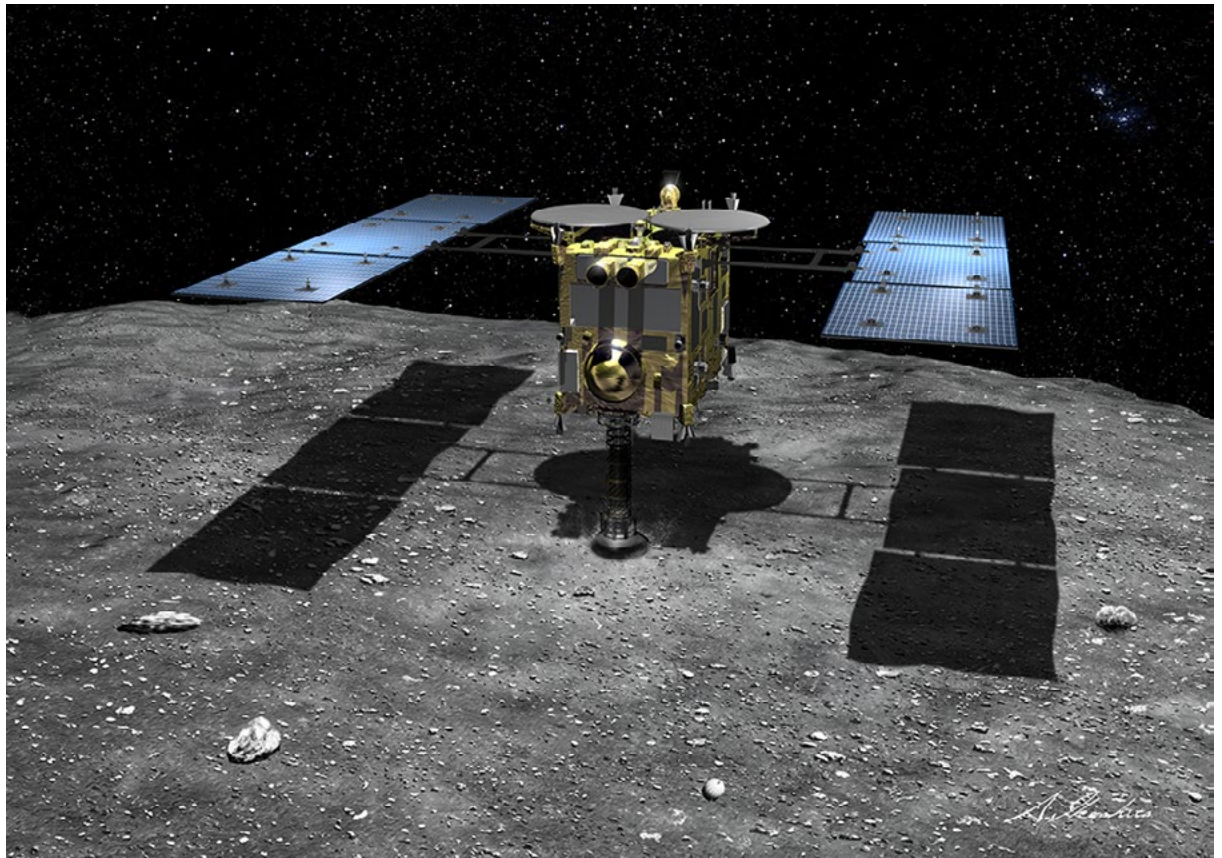
All but a few galaxies are so far away that we can't resolve individual stars even with the most powerful telescopes; instead, the light from billions of stars blur together into a fuzzy patch in the sky. The exceptions are the galaxies in our immediate neighborhood, such as the Andromeda Galaxy (M31) and the Triangulum Galaxy (M33), the two nearest spirals to our own Milky Way. These galaxies are so nearby (a mere 2.5 million light-years) that we can make out many of the individual brightest stars. The resolved stellar content of these galaxies provide a snapshot in time of stars at various evolutionary stages, providing an observational test of modern theories of stellar evolution.

Lowell astronomer Dr. Phil Massey, research associate Kathryn Neugent, and summer student Bri Smart completed a spectroscopic survey of the massive star content of M31 and M33. The data were collected over several years with the Hectospec multi-object spectrometer on the 6.5-meter MMT telescope in southern Arizona. Their paper, published in the November 2016 issue of the *Astronomical Journal*, reported new spectroscopy of 1,895 stars in these galaxies! The vast majority of spectral information available on stars in these galaxies comes from this study. For instance, of the 64 O-type stars known in M31, 53 (83%) were identified in this paper. Similarly, 62 (87%) of the 71 A-type supergiants known in M33 were discovered as part of this survey.

Nevertheless, the scant number of O-type stars is in itself quite a surprise. A few years ago, Neugent and Massey completed a survey of Wolf-Rayet stars in M31, identifying 154 of them, a value they argued was complete to 95%. Wolf-Rayet stars are a type of evolved massive stars, a short-lived phase near the end of the life of a very massive star. There should be about 15 times more O-type stars than Wolf-Rayet stars. In other words, there should be about 2,300 O-type stars in M31. But, only 64 are known. Where are the missing ones? A similar problem is found with the O star content of M33.

To answer that, Massey and Neugent submitted a proposal to use the Hubble Space Telescope (HST) to image selected regions of M31 and M33 in the ultraviolet. Combined with other HST and ground-based images, these should help identify where the missing O-type stars are. The proposal was successful, and the investigators are awaiting these new data. Stay tuned! ■

Image: The 6.5-meter telescope observing the Andromeda Galaxy, visible as a faint smudge. Photograph by Kathryn Neugent.



Nick Moskovitz

Dr. Nick Moskovitz carried out a variety of projects in 2016 related to the study of asteroids, with a particular focus on those asteroids whose orbits bring them close to Earth. These are known as near-Earth asteroids (NEAs) and are of interest for a number of reasons: they originate from a variety of locations throughout the solar system and thus allow us to probe distant small body populations, they inform understanding of hazards associated with Earth-impact events, and they are readily accessible by spacecraft. As such, a number of space agencies around the world are carrying out or are planning spacecraft missions to specific NEAs. One such mission led by the Japanese space agency, JAXA, is called Hayabusa2 (H2) and is on its way to a kilometer-sized NEA named Ryugu. Moskovitz was selected in 2016 to join H2 as a NASA-supported participating scientist.

H2 will rendezvous with Ryugu in the summer of 2018. The spacecraft will spend a year and a half at the asteroid conducting a multitude of experiments, including the deployment of four different rovers to the surface, the firing of a projectile to produce an artificial crater, and the collection of material from the surface which will then be returned to Earth in 2020.

Moskovitz's specific role in support of this mission is to use ground-based telescopes to help address certain unknowns about Ryugu before the spacecraft arrives. For example, we currently do not have a clear understanding of the composition of the asteroid, there are debates about whether the surface of the asteroid is compositionally and texturally uniform or heterogeneous, and there remain uncertainties about the spin state of the asteroid. Moskovitz has been using Lowell's DCT to measure rotational lightcurves of Ryugu to constrain the spin rate, spin axis orientation, and shape of the asteroid. These are all critical parameters for planning the spacecraft rendezvous, but have proven elusive in previous studies due to the intrinsic faintness of Ryugu, a rotational period near eight hours, and a near spherical shape which translates to muted rotational brightness variations. These DCT observations have resulted in the best available lightcurve to date of Ryugu, (continued on next page)

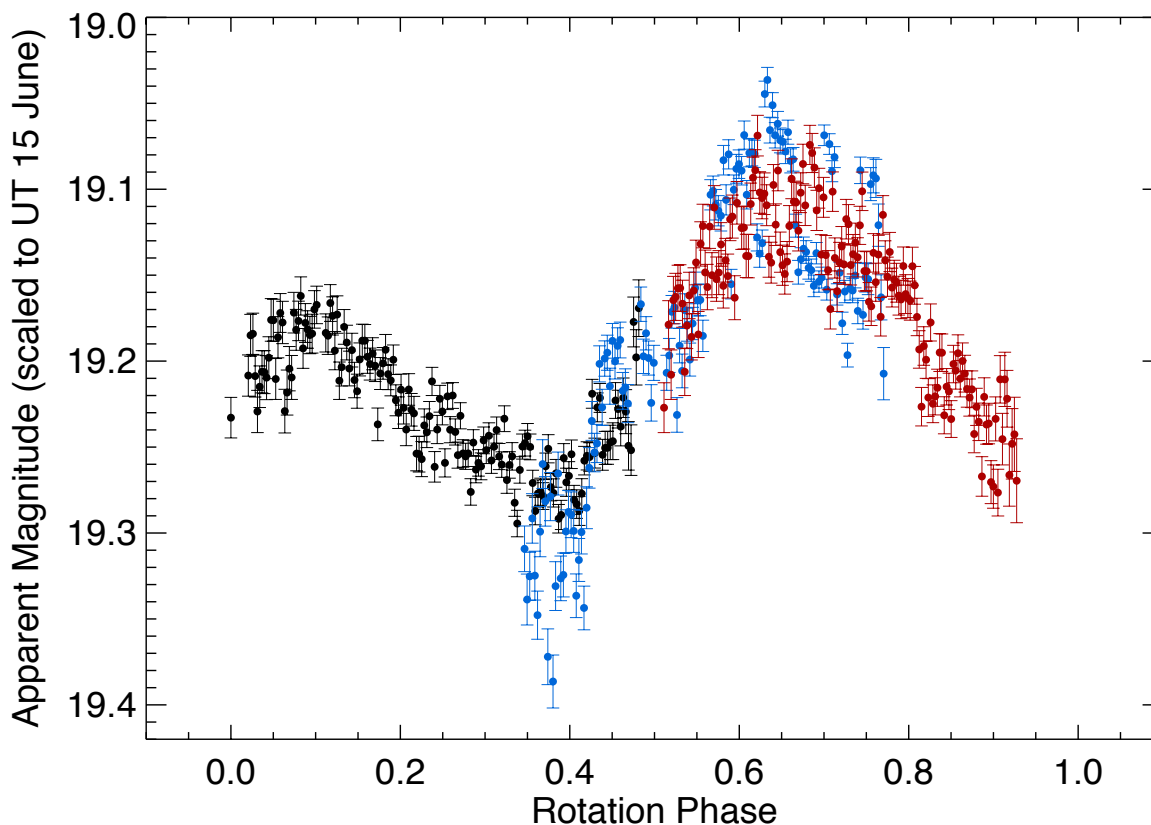
Image: Artist conception of the Hayabusa2 spacecraft touching down and sampling material from the surface of Ryugu. The spacecraft is about two meters across. Note the small, golf ball-like homing beacon in the foreground. It will be deployed prior to sampling and will help guide the spacecraft to the surface. Image courtesy of JAXA.

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showing that the asteroid is not in a tumbling rotation state but instead is spinning like a top about its primary axis, which is good news for mission operation planning. This observational campaign at DCT could only have been performed at a few facilities in the world, where sustained access to a large-aperture telescope was an absolute necessity.

Due to the orbital geometry of Earth and Ryugu, these data represent the last opportunity to telescopically study the asteroid ahead of spacecraft arrival. Ultimately, these telescopic data will be directly compared to *in situ* observations obtained by the spacecraft, thereby providing an important test of ground-based techniques for determining the spin state and shape of asteroids. It will be an exciting couple of years as the point source of light observed by DCT in 2016 is eventually resolved as a miniature world that will provide clues about the origin and evolution of our solar system. ■

Image: Rotational lightcurve of Ryugu measured at DCT on three nights in June 2016. As the asteroid rotates, it reflects variable amounts of sunlight and thus appears to fluctuate in brightness or apparent magnitude. The amplitude of these variations provides clues about the shape of the asteroid. The periodicity of these fluctuations constrains the rotation period, in this case about 7.6 hours.





Lisa Prato

2016 was a watershed year for Dr. Lisa Prato's young exoplanet survey. The publication of the discovery of a young, giant planet in the process of formation from a circumstellar disk of gas and dust around a new-born star validated more than a decade of intensive observations. The young planet, with a mass 11 times that of Jupiter, orbits the star CI Tau in the Taurus star-forming region every nine days, making it a member of the hot Jupiter class of planets. This exciting result prefaced several publications of two other groups of researchers reporting on newly discovered young planets; however, only for the CI Tau system was the young planet caught "red-handed": young star, disk of raw planet-forming material, and the young planet! These results were published in the *Astrophysical Journal*. Former Lowell predoctoral Ph.D. student Christopher Crockett, former Lowell undergraduate interns Jacob McLane and Gregory Mace, and Lowell researcher Brian Skiff were all involved in the program. In September a new predoctoral Ph.D. student, Larissa Nofi, from the Institute for Astronomy at the University of Hawaii, joined Prato's exoplanet research team at Lowell to carry out her thesis work on the exoplanet survey.

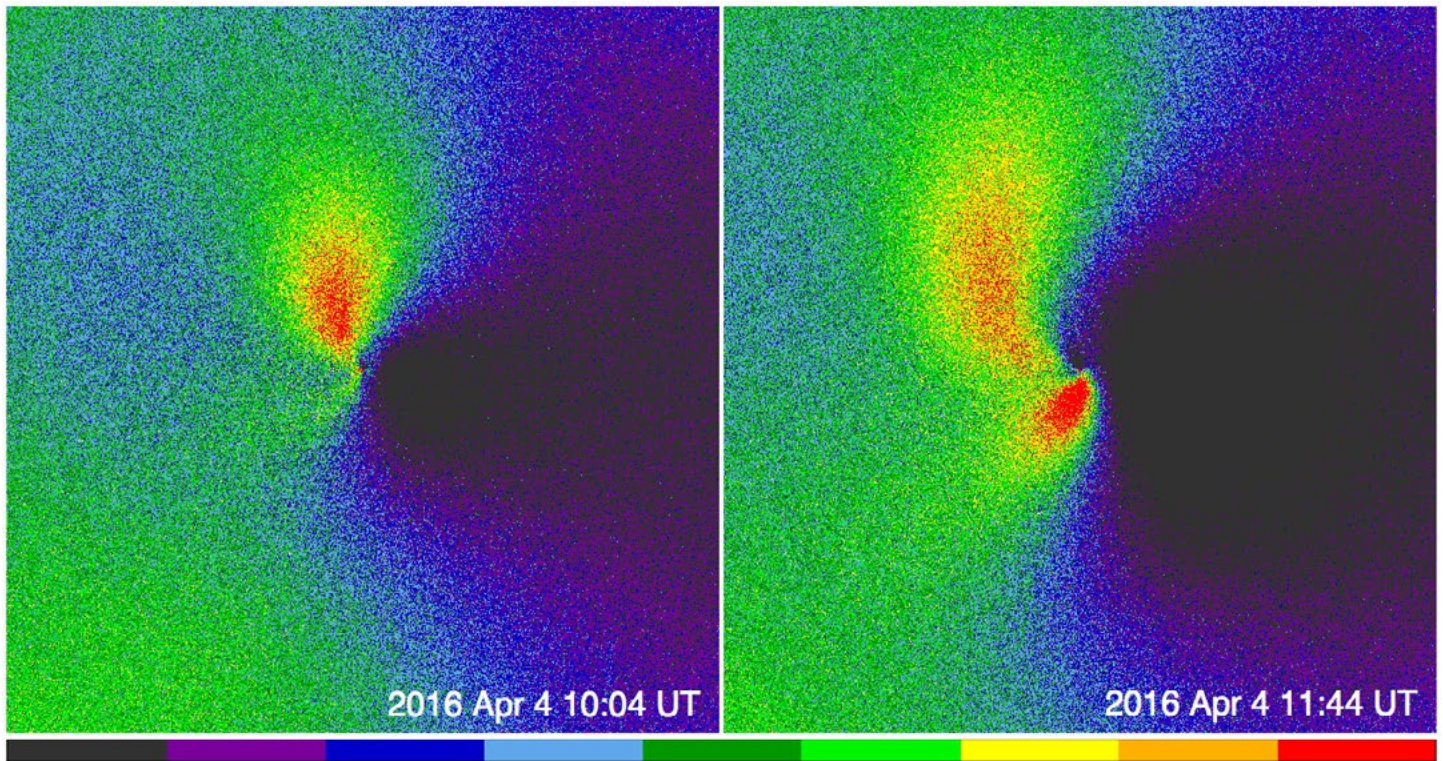
In related news, the premier high-resolution infrared spectrograph in the world, the Immersion GRating Infrared Spectrograph, IGRINS, was successfully commissioned on the DCT in September for the first of three six-month visits between 2016 and 2019. IGRINS on the DCT yields the highest sensitivity, the broadest wavelength coverage, and the best stability of any infrared spectrograph currently in use on any telescope in the world. For example, it is more sensitive by a factor of three than the NIRSPEC spectrograph on the 10-meter Keck II Telescope! The combination of IGRINS on the DCT is a tremendous asset to not only Lowell astronomers but also to faculty and students at our partner institutions; almost a dozen Ph.D. students are using IGRINS+DCT data as a key component of their dissertations. This spectacular instrument is the key factor in Prato's team's ability to complete their young exoplanet survey in Taurus and to lay the foundations for a robust planet formation theory anchored in direct observations.

Undergraduate research intern Ian Avilez, who won the Outstanding Graduating Senior award at Northern Arizona University (NAU) in December, collaborated with former Research Experience for Undergraduates (REU) student Ryan Muzzio, postdoc Thomas Allen, and summer 2016 REU student, Matthew Wittal on studies of young visual binary stars, measuring the stellar (continued on next page)

Image: Lisa Prato, Frank Cornelius, and Ben Hardesty prepare to lift the IGRINS cryostat and cart up through the hatch onto the observing floor of the DCT. Credit George Jacoby.

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properties and investigating the characteristics of the planet-forming disks in close binary systems in which the companion star has the potential to disrupt the nascent solar system of the other star. Several journal articles involving these students and begun in 2016 are slated for 2017 publication. Former NAU student and Lowell intern Nuria Wright-Garba worked on reduction of spectroscopic binary data taken with IGRINS at its other home at the McDonald Observatory. In June 2016 Wright-Garba received several exceptional long-term job offers and left Lowell to work as a telescope operator and technical assistant for the National Solar Observatory in New Mexico and Hawaii. NAU masters student Lauren Biddle moved into the final months of her thesis research involving the study of massive star spots on young stars and the modeling of how these features impact our observations of the systems. ■



David Schleicher

Drs. Dave Schleicher and Matthew Knight (U. Maryland) completed their analyses of Comet 209P/LINEAR, an extremely “anemic” comet, presumably near the end of its life. In addition to having the smallest “active area” ever successfully measured in a comet, it also has the smallest ratio of active area to total surface area of a nucleus. These and other results were published in the *Astronomical Journal*. In contrast, they measured another close approaching object, Comet 252P/LINEAR, in early 2016 only to discover that it was much more active than 209P, and displayed two CN gas jets in the shape of tilted spirals sometimes seen nearly edge-on (see image). These jets rotated slowly each night, and repeated every ~ 22 hours, implying a period of ~ 22 hours or a sub-multiple. There was also a repetition of features after ~ 95.5 hours, indicating that the actual period is 7.35 ± 0.05 hours. With the constantly changing viewing geometry from week to week, a 3-D model can ultimately be computed, revealing the orientation of the rotation axis and the location of the source regions on the nucleus that produces the gas jet.

Schleicher, together with Research Assistant Allison Bair, made major progress on a project involving photometric narrowband measurements of gas and dust production rates and the composition of comets. In addition to adding the most recent five years of observations obtained with the 42-inch Hall Telescope to the database started in 1976, they systematically reanalyzed the entire database, now totaling 190 comets – the largest compositional database in the world. A taxonomic study revealed a total of six compositional groups, some of which are directly tied to their site of origin, the Kuiper belt and/or the Oort Cloud. Key results were presented at the Division of Planetary Sciences meeting in Pasadena. ■

Images: Two representative images of gas jets detected in Comet 252P/LINEAR. A narrowband filter isolating light from cyanogen molecules (CN) was used with the CCD camera at the DCT. Each frame has a field of view of 20,000 km across at the comet, and is centered on the nucleus (which cannot be seen because it is much too small and obscured by the coma). Because the coma of a comet is much brighter at the center and falls off in all directions, a radial profile is first removed to reveal the more subtle jets, and then false-colors are applied, with black being the darkest areas and red the brightest (see color bar at the bottom). Note the change in the jets’ appearance due to the counter-clockwise rotation of the nucleus. In particular, the bottom jet (barely evident in the first image) “turns on” in the 100 minutes before the second image because its source region on the surface of the nucleus has just rotated into sunlight, i.e. local dawn, while the top jet has stretched out and begun to fade as its source’s location is losing sunlight late in the day.



Image: Dr. van Belle (left) and Lowell adjunct Dr. Kaspar von Braun next to the prototype Plane Wave Instruments CDK1000 1.0-meter (40-inch) telescope, at PWI in Compton, CA.

Gerard van Belle

Dr. van Belle's research work continued to emphasize characterization of stars at the highest levels of observational precision. At Lowell, he has emphasized use of both the DCT as well as the Navy Precision Optical Interferometer (NPOI) to make high-angular-resolution stellar observations.

With DCT, van Belle has been collaborating with Dr. Elliott Horch, a Lowell adjunct astronomer, to bring Horch's well-traveled Differential Speckle Survey Instrument (DSSI) camera to Happy Jack to conduct observations at the full diffraction limit of the DCT. A volume-limited star survey using DSSI on the DCT to observe all of the nearby 'M-dwarf stars'—objects like our Sun but roughly half the mass—was selected for funding by the NSF. These stars are of particular interest for in-depth studies, since it is expected yet-to-be-discovered exoplanets orbiting these stars will be most amenable for follow-up studies of habitability. Working with Ted Dunham, van Belle began designing an upgrade of DSSI, the Quad-channel Wavefront-sensing Speckle Survey Instrument (QWSSI), is being designed for permanent use at DCT.

At NPOI, van Belle is principal investigator for a \$3.27 million facility upgrade selected for funding in October of 2016 by the Naval Research Laboratory (NRL), which will add three 1.0-meter Plane Wave Instruments telescopes to the array. This upgrade will substantially increase the light-gathering power of the individual telescopes of the array, by a factor of roughly 70 times, greatly increasing the faint-object sensitivity of NPOI. These telescopes are slated for delivery to Anderson Mesa by December of 2017.

Also at NPOI, the VISION ("Visible Imaging System for Interferometric Observations at NPOI") instrument was selected in 2016 for DURIP (Defense University Research Instrumentation Program) funding for two new EMCCD camera heads, which will improve its sensitivity. The detailed instrument paper for VISION was published in the PASP in May of 2016, with van Belle's former graduate student, Dr. Victor Garcia, as the lead author. Science topics that will be emphasized by VISION include direct mapping of the spotted stellar surfaces of evolved stars and latitude-dependent brightness variations of rapidly rotating stars. (continued on next page)

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van Belle additionally published an article on “Bolometric Flux Estimation for Cool Evolved Stars”, with Lowell postdoc Dr. Alma Ruiz-Velasco and long-time New Mexico Tech collaborator Dr. Michelle Creech-Eakman. This paper presents a newly developed tool for determination of stellar brightness (‘bolometric flux’), which when joined with stellar angular sizes from long-baseline interferometers such as NPOI, allow for direct determination of stellar effective temperatures. Determination of such brightnesses has always been problematic, particularly for very cool stars, a situation this study addresses. Incidentally, this paper extensively re-reduced data originally found in a 1974 paper co-authored by Dr. Wes Lockwood. ■



Michael West

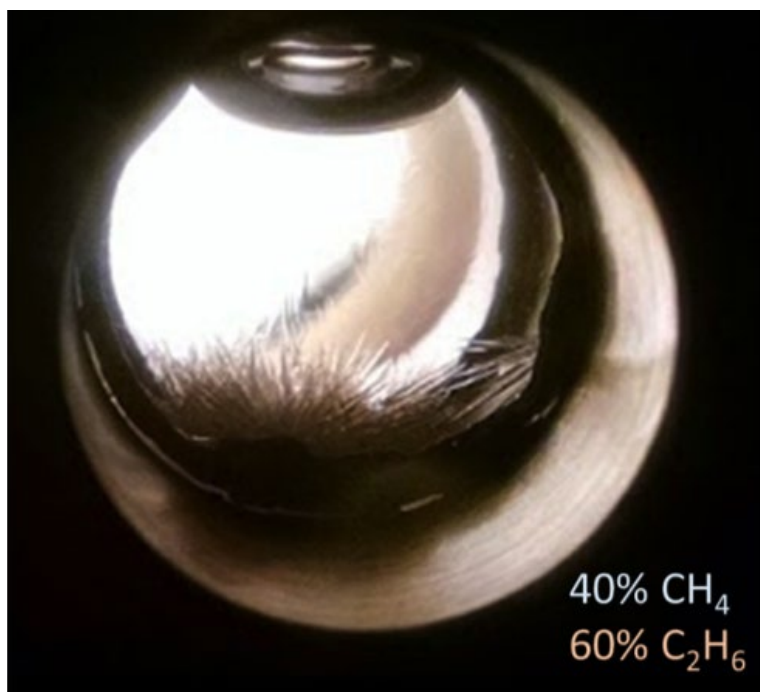
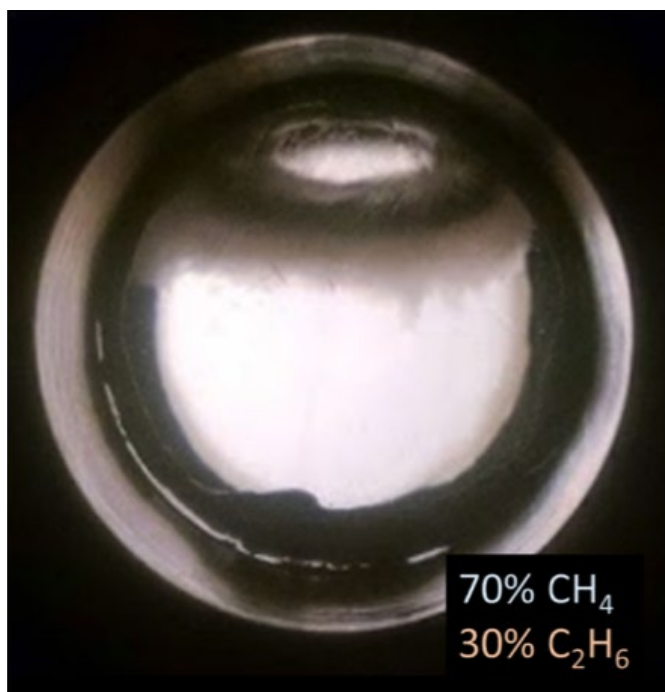
"The universe is made of stories, not of atoms," wrote poet Muriel Rukeyser. Every galaxy has a unique story, and telling those stories is the goal of Dr. Michael West's research.

West spent October 2016 in Finland as a guest of Tuorla Observatory, supported by an award from the Finnish Centre for Astronomy. Using data from the Hubble Space Telescope, he and his collaborator, Dr. Roberto De Propriis, showed for the first time that the most massive galaxies in the universe have been aligned with their surroundings for at least 10 billion years. Their paper, "Ten Billion Years of Brightest Cluster Galaxy Alignments," will be published in the journal *Nature Astronomy*.

West and an international team of collaborators continued their study of galaxy cannibalism using data from Lowell Observatory's DCT, the Hubble Space Telescope, and Keck Observatory. Like forensic scientists investigating the scene of a crime, the team searches for clues that reveal the violent histories of cannibal galaxies and their victims. In 2016 their work focused on the most extreme cannibals in the universe, known as fossil groups, which appear to have completely devoured their neighbors in a galactic feeding frenzy. West wrote a feature story about galaxy cannibalism titled "When Galaxies Eat Each Other," which was published in the December 2016 issue of *Astronomy* magazine, the world's best-selling magazine for stargazers.

In addition to his research, West devoted substantial time to communicating astronomy with the public, writing regular columns for Lowell Observatory's monthly *Members Update* and quarterly *The Observer*, as well as his popular *AstroAlerts*. He also continued work on two books that he is writing. ■

Image: Hubble Space Telescope image of the galaxy cluster MACS J0416.1-2403.



Jennifer Hanley

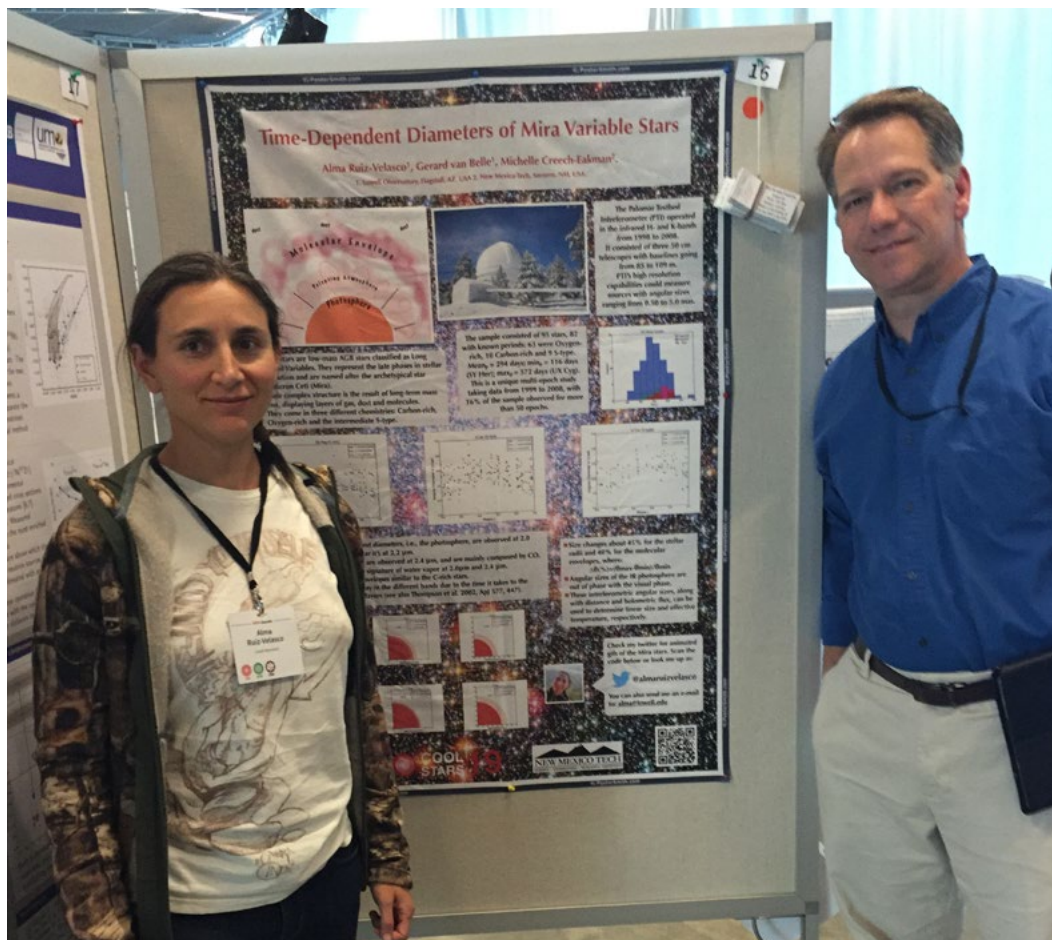
Dr. Jennifer Hanley's main research topics include working in the Northern Arizona University Ices Laboratory to understand the mechanical and spectral properties of the hydrocarbon lakes of Titan, as well as cryogenic ices on Pluto and other icy satellites.

Laboratory experiments on the stability of methane and ethane liquids under Titan conditions revealed some interesting results. Although the surface of Titan is $\sim 89\text{--}95\text{ K}$, and the freezing points of both methane and ethane are each $\sim 91\text{ K}$, when mixed together their freezing points become depressed to a minimum $\sim 72\text{ K}$. This means that any mixture of these two species will remain at least partially liquid under current Titan surface conditions.

Additionally, when mixing these together, the properties of the ice that forms are different from when the pure species freeze (pictured): methane will form shapeless ice on the top of the liquid, while ethane will form spiky, needlelike ice crystals on the bottom. This tells us something about the ice properties, namely their relative densities in relation to the liquid, as well as some of the thermodynamic properties of these species.

Hanley's other research interests include the stability of water on Mars and Europa in the presence of chlorine salts (chlorides, perchlorates and chlorates). In 2016 she was awarded a Mars Data Analysis grant from NASA to determine the distribution of these salts on the surface of Mars. She was invited to give a talk in Iceland for a conference on Martian Polar Science, allowing her to participate in field work related to analogue remote sensing of the Martian surface. This work utilizes laboratory spectra Hanley acquired that had never before been measured, allowing detection of perchlorate salts on another planet by remote sensing for the first time. ■

Images: Ice forming in different methane-ethane liquids. (Left) Methane ice forming in a methane-rich liquid. (Right) Ethane ice forming in an ethane-rich liquid.



Alma Ruiz-Velasco

In 2016 Dr. Alma Ruiz-Velasco continued her work on Mira variable stars, which are the main dust factories of the Universe, and hence, are responsible for the chemical enrichment of the interstellar medium. These old, low-mass stars are going through an unstable and short-lived phase before turning into a planetary nebula.

The most important result of 2016 was without a doubt the direct measurement of the diameters of 88 Mira stars as well as their change with respect to the epoch of observation. In this project, Ruiz-Velasco also studied the behavior of stellar atmospheres and their dependence with the phase. This was only possible due to the great amount of epochs observed in these variable stars, for which periods range from 100 to 500 days.

She used archival data from the Palomar Testbed Interferometer (PTI). The PTI survey consists of almost a hundred variable stars observed between 1999 and 2008, when the facility was decommissioned. Some of the stars in the survey had up to 80 epochs of observations and the sample included oxygen-rich, carbon-rich and S-type Mira stars.

The PTI consisted of three 40-cm telescopes and had baselines ranging from 85 to 109 meters. The data were divided into narrow bands across the K-band (infrared) of 2.0, 2.2 and 2.4 microns, allowing to directly measure the changes in size for both the star and its atmosphere and determine how these changes relate to the phase. Angular sizes obtained with the PTI range from 6.08 to 0.64 milli-arcseconds, with errors as low as 0.01 milli-arcseconds, providing one of the most accurate surveys available for these type of Stars. (continued on next page)

Image: Alma Ruiz-Velasco (left) and Gerard van Belle (right) presenting a poster during the Cool Stars 19 conference in Uppsala, Sweden.

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The high-resolution capabilities of the PTI together with the use of several epochs showed that these stars experience a change of 40% in their sizes, where the smaller diameter will correspond to the time where the star has the maximum brightness and the larger diameter will be during the time the star has its minimum brightness.

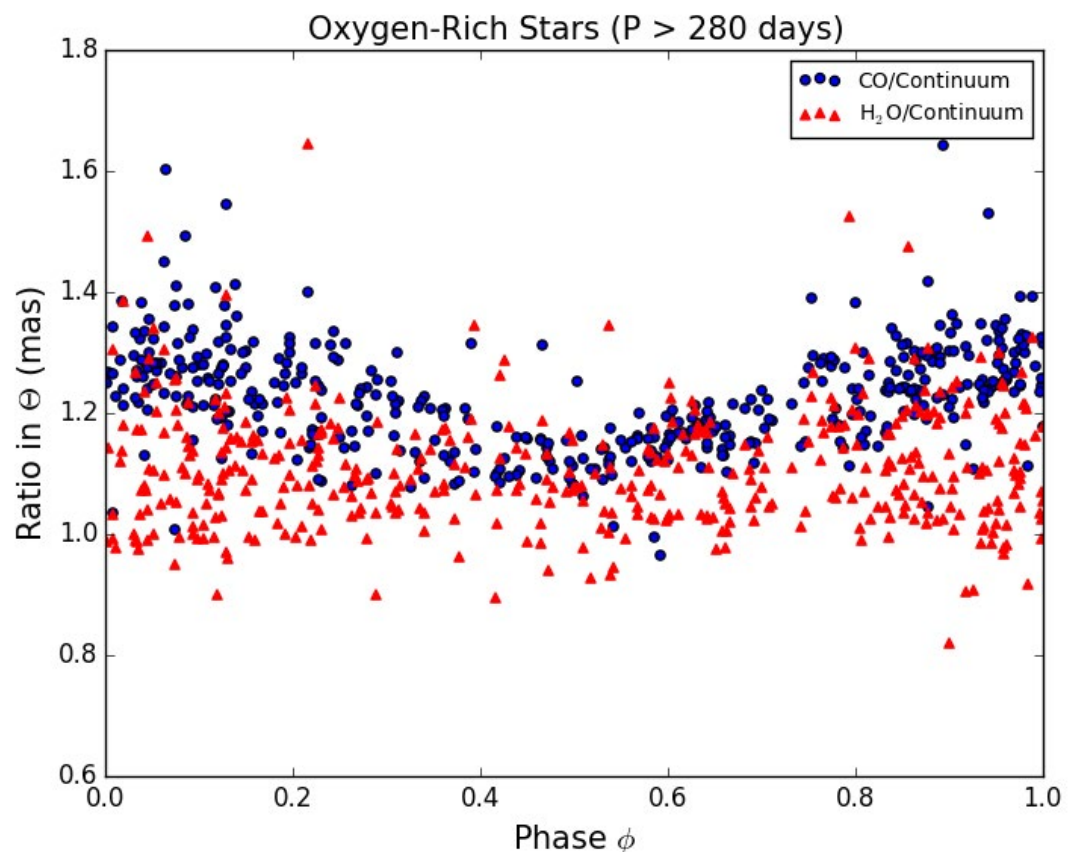
The data from the oxygen-rich stars is divided into two groups according to the period length. For stars with periods longer than 280 days, the water vapor layers seem to disengage from the pulsation as the star shrinks.

The figure shows the ratio between the continuum (the photosphere) and the atmosphere of the stars with respect to the phase. According to this, in stars with longer periods the atmosphere has started to detach, compared to what we see in stars with shorter periods. This detachment, produced by the pulsation process, is what allows the gas to set free from the gravity of the star and depart to the interstellar medium, eventually forming a planetary nebula.

Longer periods would then mean older stars, stretching the pulsations until they give out their last breath, leaving only a naked stellar core in the form of a white dwarf.

The stellar radius is a fundamental parameter used in the development of evolutionary models of low-mass stars and Ruiz-Velasco's results contribute to the understanding of the evolution of stars similar to our Sun. ■

Image: Ratios between the continuum (the photosphere) and the atmosphere of oxygen-rich stars with respect to the phase.





Audrey Thirouin

Dr. Audrey Thirouin is part of the Mission Accessible Near-Earth Object Survey (MANOS, PI: Nick Moskovitz) whose main purpose is to provide information on the orbital, rotational, and compositional properties of near-Earth objects (NEOs) that are accessible to spacecraft for robotic and/or human exploration. MANOS already derived rotational properties for 220 sub-km NEOs, and discovered two new ultra-rapid rotators with rotational periods below 20 seconds. The first photometric results were published in the *Astronomical Journal*.

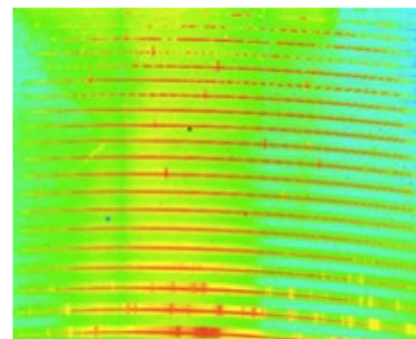
Thirouin started a new project dedicated to the contact binary systems in the trans-Neptunian belt. The extended definition of a contact binary is an object consisting of two lobes in contact (bi-lobed object with a peanut/bone shape), and system of two separated objects almost in contact. This kind of peculiar system is found across all the small body populations in our solar system, from the near-Earth objects population to the trans-Neptunian belt. The expected fraction of contact binaries is high in all the small body populations with estimates up to 20%. The trans-Neptunian belt is not different. Several studies suggest that between 10% and 30% of the trans-Neptunian objects could be contact binaries.

Contact binaries are not resolvable with the Hubble Space Telescope because of the small separation between the system's components. Only light curves with a characteristic V-shape/U-shape at the minimum/maximum of brightness and a large amplitude can identify these objects. Despite an expected high fraction of contact binaries, 2001 QG298 is the only confirmed contact binary in the trans-Neptunian belt. If the contact binaries are so common, where are they?

Using Lowell's Discovery Channel Telescope, Thirouin has begun searching for these elusive objects. ■

Image: Artistic view of a contact binary.

TECHNICAL SUPPORT HIGHLIGHTS



By George Jacoby

DCT

Throughout the year, the Discovery Channel Telescope (DCT) reliably supported scientific research. In 2016, part or all of 286 nights were scheduled for science operations. Total actual science time was 247 nights, and approximately 63 hours were lost due to technical issues, mostly due to utility power outages.

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, Peter Collins, Saeid Zoonemat Kermani, Len Bright, Jeff Gehring, and Peter Rosenthal. In addition to routine maintenance of the telescope, dome, and facility systems, the crew performed numerous upgrades to improve the scientific operation of the DCT. During 2016, these included:

- Completed NIHTS and installed it on the instrument cube, turning it over to its PI, Henry Roe, for commissioning.
- Re-aluminized the 4.3-m primary mirror. [see: The Lowell Observatory Youtube Channel]
- Outfitted the DCT clean room, including new vacuum pump and leak detection systems.
- Cleaned and made various modifications and improvements to the instrument cube, and serviced the instruments during the mirror aluminization downtime.
- Installed a helium compressor in preparation for the arrival of IGRINS from the University of Texas, along with helium cooling lines to the instrument cube.
- Managed the transfer and supported the installation of IGRINS at DCT, enabling studies of new areas of science at Lowell facilities. IGRINS was scheduled for nightly use approximately 60% of the time in quarter 4 (Oct-Dec 2016).
- Remodeled the observing control room and started construction of the EXPRES spectrograph room, in preparation for the arrival of the Yale instrument in mid-2017.
- Completed the DeVeney remote control upgrade, allowing full operation of the spectrograph from the control room, and acquisition of an additional 5 gratings to double the grating complement and open new wavelength / resolution regimes. (continued on next page)

Image (Left): The Discovery Channel Telescope's 4.3-m primary mirror after being recoated.

Image (Top Right): The IGRINS instrument (gold rectangle) mounted on the DCT instrument cube.

Image (Bottom Right): The first-light K-band spectrum from IGRINS, Sept 8, of Wolf 1130.

TECHNICAL SUPPORT HIGHLIGHTS (continued)

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Night operations support was provided by the telescope operations team, including lead telescope operator Dr. Teznie Pugh and operators Heidi Larson, Jason Sanborn, and Amy Guth. They ensured the telescope was ready for operations each night, and expertly operated the telescope in support of scheduled science and engineering programs. Progress in DCT instrumentation became very visible in 2016 with the installation and commissioning of the DeVeney spectrograph. In late November, the NIHTS spectrograph was installed and achieved first light. Commissioning of NIHTS will continue into early 2017.

As the year progressed, activities in support of partner instruments began to ramp up. Coordination meetings were held with University of Texas and the Korea Astronomy and Space Science Institute (KASI) for the IGRINS instrument, and with Yale University for the EXPRES fiber-fed spectrograph. Both of these instruments required substantial engineering support from the DCT engineering group and the Lowell instrument development group as the instruments approach finalized design and installation. In addition, the University of Maryland's RIMAS instrument is progressed. One outcome of the planning for these instruments was the decision to re-aluminize the DCT primary mirror. This activity occurred during the monsoon period in 2016. ■

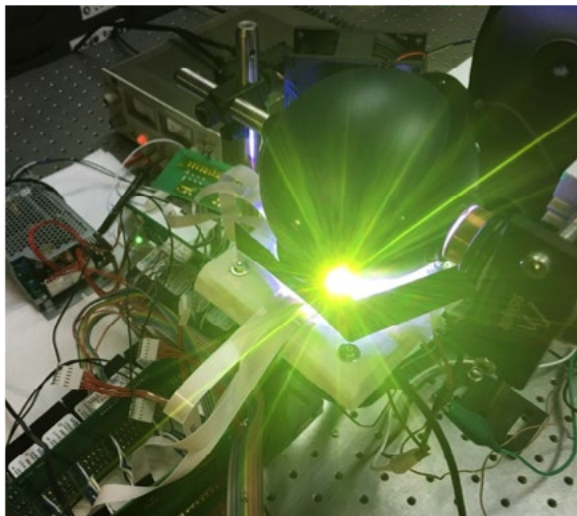
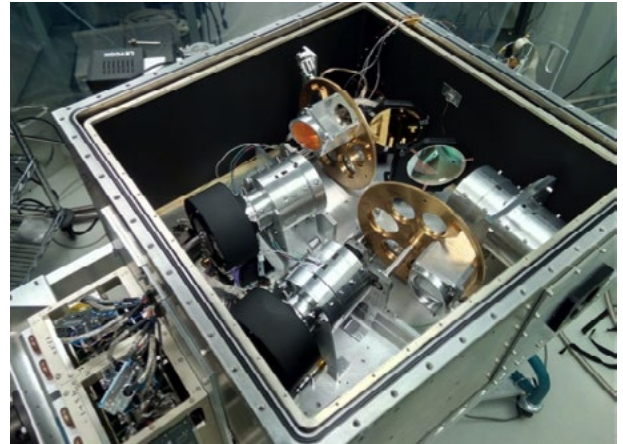
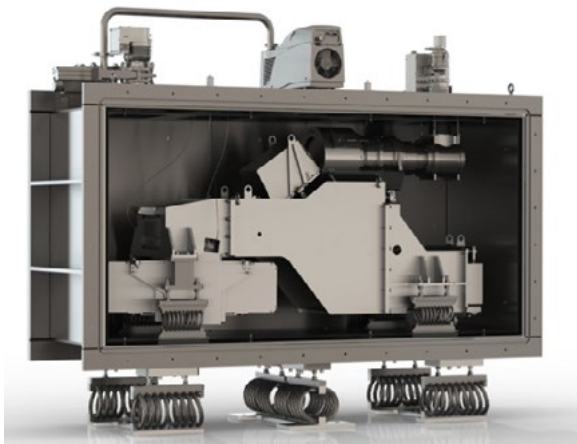


Image (Top Left): A computer rendering of the Yale EXPRES spectrograph in its vacuum enclosure. The enclosure is scheduled to be installed at the DCT in mid-2017, and the spectrograph in the fall of 2017.

Image (Top Right): The RIMAS spectrograph, partly assembled, as of December. The two detector housings and filter/grating wheels are easily seen.

Image (Bottom Left): The Yale EXPRES LED-based flat-field lamp

TECHNICAL SUPPORT HIGHLIGHTS (continued)



Anderson Mesa

Anderson Mesa telescopes continued to support science operations with 288 science nights scheduled for the 72-inch Perkins Telescope, 277 nights for the 42-inch Hall Telescope, and 366 nights for the 31-inch telescope. Technical support for the telescopes was provided by Ralph Nye, Frank Paschal, Len Bright, Ted Dunham, and Larry Wasserman; grounds and facility maintenance was provided by Jim Gorney and Steve Winchester.

Activity began this year in support of reactivation of the LONEOS telescope. This project, partially funded by Northern Arizona University, includes a camera on the telescope to permit follow-up observations of findings from the Catalina Sky Survey. This required installation of a new camera and modification of the facility to permit unattended operation (i.e., a robotic facility). By November, Ralph Nye, Ted Dunham, and Larry Wasserman had nearly completed the engineering work, with completion scheduled for mid-2017. ■

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 NOFS and the Naval Research Lab. In addition to maintaining the infrastructure at the site, the observatory provides skilled observers to operate the instrument and gather science data on all nights excluding observatory holidays.

In 2016 the operations crew, led by Teznie Pugh, observed for 131 nights out of 191 nights scheduled through mid-July when the fast delay lines went offline.” Observers in 2016 included Amy Guth, Mike Sakosky, Susan Strosahl, and Stephen Zawicki, with support from the day crew, Steve Winchester and Jim Gorney. Their efforts were instrumental in ensuring 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. A major effort in 2016 was signing the agreement for a scientifically exciting upgrade that will add three 1-m telescopes (from Planewave) to the array, dramatically improving the sensitivity of the facility. Upgrade work will begin in late 2017. ■

Image (Left): 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 (Right): A 1-m Planewave telescope.

TECHNICAL SUPPORT HIGHLIGHTS (continued)



Mars Hill

During 2016, the restoration of the Pluto Telescope was begun. Completion is expected in 2018. This effort will require a complete disassembly, rework and repair, and re-assembly of the telescope and mount, with significant repairs and improvements performed to the dome as well. We are also reverse engineering the triplet objective lens so we understand how it works, and the drive electronics are being replaced with maintainable modern equipment. Key personnel in this effort include Ted Dunham, Ralph Nye, Peter Rosenthal, Glenn Hill, Jeff Gehring, and Dave Shuck. ■

Image (Left): Jeff Gehring, Ralph Nye, Dave Shuck, and Peter Rosenthal strap the Pluto Telescope's tube down in preparation to move it to the machine shop to be worked on.

Image (Right): The lab setup used by Ted Dunham to measure the properties of the glass lens in the Pluto telescope.

DEVELOPMENT HIGHLIGHTS



By Hannah Graves

Lowell Observatory Foundation

In the Lowell Observatory Foundation's first full year, the corpus grew by \$2.1 million. The Foundation's primary goal is to build an endowment that will help sustain Lowell Observatory by providing a source of predictable income. In 2016 loyal supporters contributed planned gifts and endowments that doubles the Foundation's assets.

A six-figure contribution from Dr. Joseph Marcus created the Marcus Cometary Research Endowment. This new fund will support Lowell astronomers and research staff engaged in cometary research. One of several generous estate gifts in 2016 created another new fund to the Foundation: the Instrumentation Fund, which supports the acquisition, development, maintenance of, and access to technologies, instruments, and telescopes. The fund was established from a gift from Dr. Elizabeth Roemer, who passed away in April 2016. ■

The Space Guard Academy Exhibit

Lowell Observatory raised \$250,000 to develop the Space Guard Academy Exhibit. It premiered on May 21 to members in Lowell's Steele Visitor Center and more than 60,000 visitors have enjoyed the high-tech, asteroid education experience. ■

Pluto Discovery Telescope Restoration Campaign

In 2016 Lowell launched a Kickstarter crowdfunding campaign to restore the Pluto discovery telescope. The goal was to raise the funds needed for restoring the instrument itself. The restoration team will also preserve the dome in which it is housed.

A total of \$32,172 was raised from 577 Kickstarter backers, nearly \$10,000 more than the initial goal. Donors from fourteen countries around the world supported the campaign and most were new supporters of Lowell.

Another 151 donors contributed \$197,215 for the restoration project. These included a generous gift of \$75,000 from the Veritas Foundation. ■

Image: Curatorial Intern Gerald Lamb explains Space Guard Academy during the members-only opening reception.

DEVELOPMENT HIGHLIGHTS (continued)



Campaign to Bring IGRINS to the DCT

Lowell raised more than \$500,000 to bring what is perhaps the world's most sophisticated spectrometer to Lowell. IGRINS, the Immersion Grating Infrared Spectrometer, will support numerous research projects including determining the properties of young stars which impact the planet-forming potential of stellar systems, detecting the presence and characteristics of planets around other stars, and measuring the temperatures and compositions of planetary atmospheres in our own solar system.

Thanks to a generous donor who contributed \$100,000 outright and another \$200,000 matching gift, Lowell raised the funds needed to successfully install IGRINS on DCT. Lowell astronomers began collecting data with IGRINS in September 2016. ■

Gala

On June 4, 263 people attended "The Science of Space", Lowell Observatory's fifth annual fundraising gala, at the High Country Conference Center. Highlighted by a science expo and presentation by space exploration pioneer Dr. Stamatios Krimigis, the event generated nearly \$80,000. Guests mingled with Lowell astronomers and heard about recent discoveries in their research. The proceeds supported new research and outreach initiatives and the preservation of the Pluto discovery telescope. ■

2016 Membership and Annual Fund

Lowell's membership program received 1,142 renewals in 2016, 112 more than the previous year. There were also 176 membership upgrades, a 44% increase over 2015. Support raised through membership in 2016 totaled \$257,251.

The 2016 Annual Campaign raised \$187,029 thanks to 335 supporters. Lowell Observatory's Annual Fund supports astronomical exploration as well as public astronomy programs. ■

Image: Keynote speaker Dr. Stamatios Krimigis speaks to the crowd at the Science of Space Gala.

PUBLICPROGRAMHIGHLIGHTS



By Samantha Gorney

In 2016, 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 open houses in the Putnam Collection Center lobby were offered daily. Telescope viewing and astronomy-based presentations were offered Monday through Saturday evenings.

A significant upgrade was made to the Public Program's video-based observing system, which enabled educators to use it on a more regular basis. Using this system, it is possible to display live images of astronomical objects on a large screen that several people are able to see at the same time. Lowell astronomers made use of this system during "Meet an Astronomer" events, which were held on Friday and Saturday nights throughout the summer. Live constellation tours were added to the suite of evening programs in 2016. On these tours, educators use green laser pointers to trace out constellations for guests. They also teach visitors about the mythology associated with the constellations and about the characteristics of the stars and astronomical objects found within them.

Space Guard Academy, a Lowell Observatory exhibit featuring cutting-edge asteroid research and science, opened on May 22, 2016. This interactive exhibit teaches guests about photometry and how it can be used to determine the movement of asteroids. Visitors are also able to learn about the different classifications for near-Earth objects and how astronomers are able to spot asteroids in a sky full of stars.

Lowell Observatory experienced another record year in terms of visitation in 2016. Approximately 98,000 guests visited the Observatory over the course of the year and attendance in March reached an all-time high of 11,400. More than 4,000 school children visited Lowell on field trips throughout the year.

Lowell Observatory Camps for Kids (LOCKS) programs were offered onsite for children ages 3-15. Students who participated in these LOCKS programs learned about topics in astronomy and physics through hands-on exercises and explorations. These onsite programs served more than 200 children and a number of local teachers. Enrollment in the LOCKS: Elementary School and LOCKS: Middle School programs numbered 144 and 28, respectively.

Off-site LOCKS programs continued to be offered at the Flagstaff Family Food Center (FFFC) and at Horseshoe Trails Elementary School in Cave Creek, Arizona. Lowell educators led LOCKS activities at the FFFC twice a month throughout the year and LOCKS activities were also included in the FFFC's summer camps. The preschool teacher at Horseshoe Trail Elementary led LOCKS: Preschool lessons for her students throughout the school year. ■

Image (Left): Visitors are guided by several different Space Guard Academy characters as they navigate the exhibit.

Image (Right): A LOCKS camper using paint and marbles during an activity.

PUBLICPROGRAMHIGHLIGHTS (continued)



Navajo-Hopi

In the 2016-17 school year, our 21st, we had eight partnerships, involving nine teachers and about 170 students. Last summer we developed a Project Based Learning curriculum unit for 5th grade on characteristics of the planets. This unit helps teachers address all of the standards, includes traditional astronomy and perspectives, and helps students see themselves as scientists through self-directed investigation. We tested the unit in three of our partnerships, which will culminate in a poster session at Lowell in which students present their work to the astronomers. In November we also hosted our teacher workshop that included seven classroom activities and discussions on the nature of science, Project Based Learning, and *New Horizons* and Pluto. This brought together 19 teachers, including one Northern Cheyenne college professor who plans to hold his own K-12 workshop in Montana. ■

Image (Left): Students at Newcomb Elementary School in New Mexico prepare scale models of the planets made out of Playdoh.

Image (Right): Public star party at Shonto Preparatory School in northeastern Arizona.

PUTNAM COLLECTION CENTER HIGHLIGHTS



By Lauren Amundson

In 2016, the Putnam Collection Center (PCC) continued its mission of acquiring, preserving, making available, exhibiting, and interpreting collections. Archivist/Librarian Lauren Amundson and Curator Samantha Thompson oversaw all aspects of the daily activities and larger projects in the PCC.

They welcomed six scholars who conducted archival research on topics such as Percival Lowell's travels in Korea and Japan, observatory staff's 1907 expedition to the Andes, Percival Lowell's last year, astrophotography, and women who worked at Lowell Observatory. In addition to the visiting scholars, the archives received roughly two dozen requests for historic photographs and moving images from authors, publishers, researchers, and producers.

The Archives acquired two large manuscript collections in 2016. Staff moved the papers of retired Lowell Observatory astronomer Dr. Ted Bowell into the PCC and began processing them with funding from a private donor. In April, Dr. Elizabeth Roemer of the University of Arizona's Lunar and Planetary Laboratory passed away and left her papers and glass plate negatives to the Lowell Archives, as well as funding to process the collection in 2017.

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. She also supervised a summer intern who processed two manuscript collections.

In March, Amundson visited the conservation lab at the State Archives in Phoenix to learn how to flatten rolled blueprints using humidity. Lowell's Facilities Assistant Glenn Hill built a humidifier, and volunteers began flattening and cataloging the observatory's extensive collection of historic blueprints and drawings.

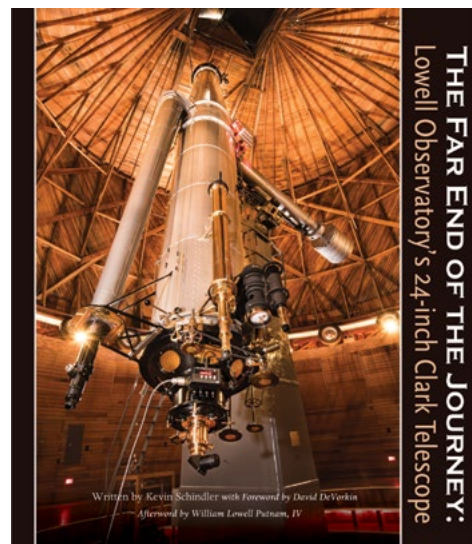
Amundson received a \$3,000 grant from the Arizona State Historical Records Advisory Board to digitize Lowell's media collection, which includes motion picture film, open reel audio tapes, audio cassettes, and other magnetic media. The collection includes audio of conferences and meetings from the 1950s-1980s, the dedication of the Planetary Research Center in 1965, the ceremony granting Historic Landmark status for Lowell Observatory in 1966, and video footage from the 2003 announcement of Discovery Channel's partnership with Lowell to build the DCT.

In October, the observatory recognized the centennial of Percival Lowell's death by hosting an evening program which included talks from five speakers on various aspects of Lowell's life and legacy. Thompson created a special exhibit in the PCC lobby with items from the collections that highlight Percival's research, travels, and personal life. ■

Image (Left): Humidifier used to flatten historic maps and blueprints.

Image (Right): PCC walk-in freezer, used for pest eradication in archival material prior to storage in the repository.

COMMUNICATION HIGHLIGHTS



By Molly Baker

In 2016 the communications team set the goal of increasing Lowell Observatory's online presence through social media, video content, and interactive press releases.

Focusing on Facebook to grow this presence, the team made strategic monthly plans for posts, videos, and event promotion. Our "Likes" increased from 9,482 on January 1, 2016 to 11,680 on December 31, 2016, with an online rating of 4.8/5 stars.

We had an especially good reaction to sharing our stories via video and received 86.3 thousand video views over the year.

Hosted by Lowell Observatory Historian Kevin Schindler, *From the Archives* highlights items from the Putnam Collection Center that aren't always on public display. The bi-weekly show quickly gained a fan base racking up 15.2 thousand video views during its premier year.

In an effort to highlight the science demonstrations of the public program, as well as introduce people to the basis of Lowell Observatory Camps for Kids, we created *Kelly's Space*. Education Coordinator Kelly Ferguson hosts the bi-weekly show and guides viewers in a science experiment that can easily be done at home with household items. *Kelly's Space* received 14 thousand views, requests from teachers for in-class presentations, and an inquiry from a professional production company looking for onscreen science talent.

The communications team also worked to foster a relationship with the Science Channel to grow our international reach.

In addition to these online efforts, Creative Specialist Sarah Gibert designed exhibits, flyers, posters, invitations, postcards, and other visual material. Schindler contributed written content for magazine and newspaper articles, flyers, and two books highlighting Lowell history: *Images of America: Lowell Observatory* and *The Far End of the Journey: Lowell Observatory's 24" Clark Telescope* (with a foreword by Sole Trustee W. Lowell Putnam and chapter contribution by Archival Restoration Specialist Peter Rosenthal). ■

Image (Left): Education Coordinator Kelly Ferguson shows kids how to perform at-home experiments during an episode of Kelly's Space.

Image (Right): The cover of Historian Kevin Schindler's coffee table book The Far End of the Journey: Lowell Observatory's 24" Clark Telescope.

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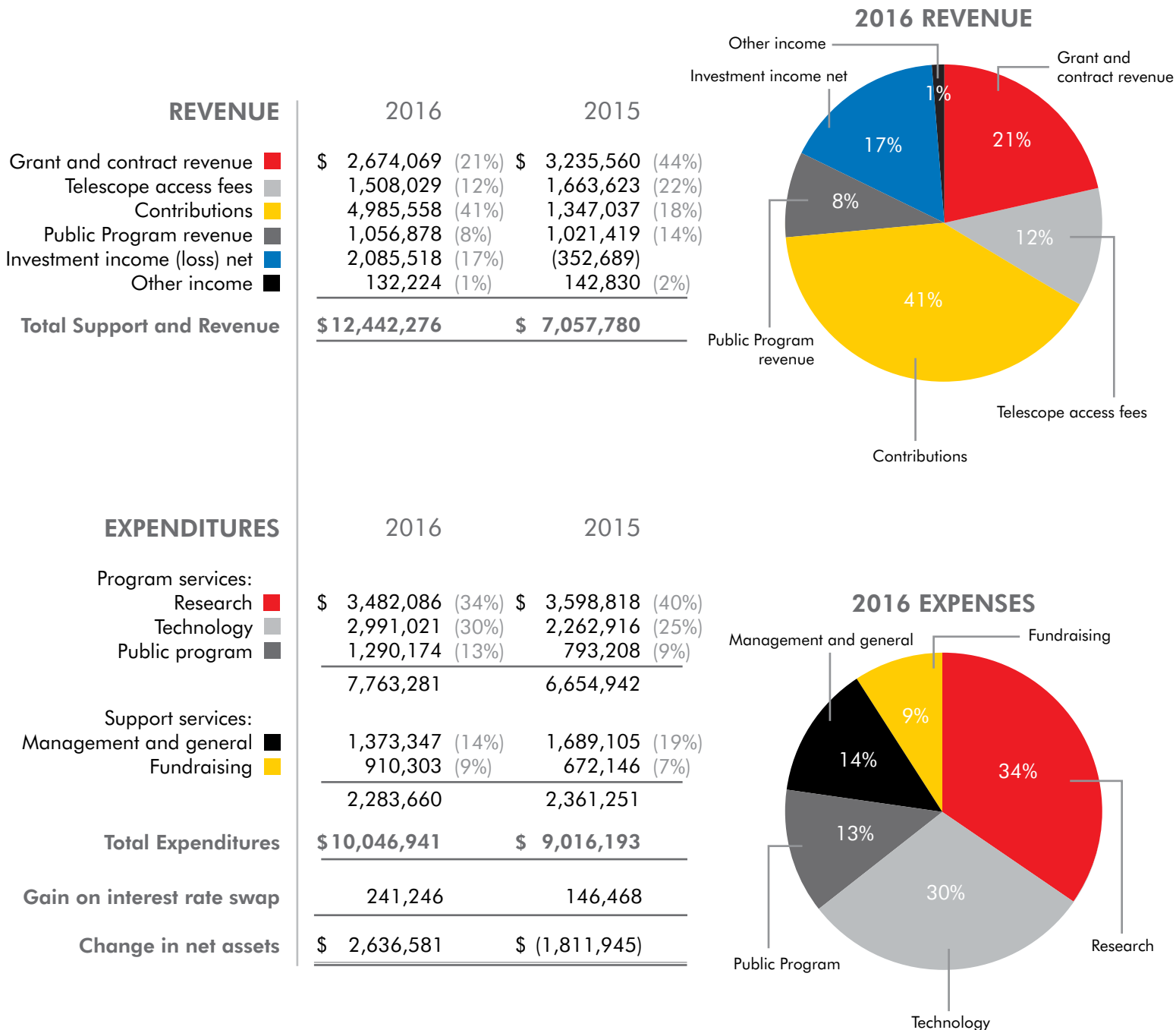
STATEMENT OF FINANCIAL POSITION

COMBINED BALANCE SHEET

ASSETS	2016	2015
Current Assets		
Cash and cash equivalents	\$ 1,390,759	\$ 98,558
Restricted cash	747,782	887,715
Investments	863,573	1,645,941
Research grants receivable	291,790	331,296
Contributions receivable, current portion	484,266	366,202
Inventory and other assests	338,081	306,928
Total Current Assets	4,116,251	3,636,640
Property, plant and equipment, net	43,242,180	44,483,157
Contributions receivable, current portion	1,010,845	375,000
Collection item	400,000	400,000
Investments, permanently restricted	39,413,921	37,221,789
Total Assets	\$88,183,197	\$86,116,586
LIABILITIES AND NET ASSETS		
Current Liabilities		
Note payable, bank	\$ 20,400,000	\$ -
Accounts payable	245,042	263,167
Accrued expenses and other current liabilities	387,962	359,620
Total Current Liabilities	21,033,004	622,787
Note payable, bank	-	20,400,000
Deferred research grant revenue	1,271,349	119,405
Deferred access fee revenue	8,207,916	7,757,977
Obligation under interest rate swap	248,960	490,206
Total Liabilities	\$30,761,229	\$29,390,375
Net Assets		
Unrestricted	\$ 15,030,945	\$ 18,223,610
Temporarily restricted	2,620,850	1,073,173
Permanently restricted	39,770,173	37,429,428
Total Net Assets	57,421,968	56,726,211
Total Liabilities and Net Assets	\$88,183,197	\$86,116,586

STATEMENT OF FINANCIAL ACTIVITIES

DECEMBER 31, 2016 (with comparative totals as of December 31, 2015)
(before depreciation)



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 2016 and 2015 was \$1,941,000 and \$2,071,000.

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, 2016. Copies of the audited financial statements are available at https://lowell.edu/about/governance_and_financials/

LOWELL OBSERVATORY ANNUAL REPORT



2016

Image (Front Cover): The DCT's primary mirror after re-aluminization.

Image (Back Cover): The DCT on its perch in Happy Jack, AZ. (Credit: Michael West)

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