2015

LOWELL OBSERVATORY ANNUAL REPORT

2015

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DIRECTOR'S UPDATE

By Jeffrey Hall

In the column below this one, Trustee Lowell Putnam makes note of some essential successes Lowell Observatory achieved in 2015.

We define "full science operations" for the Discovery Channel Telescope (DCT) as 300 science nights per year (leaving the other 65 for maintenance and engineering); in fact, we delivered 297. With agreements completed or proceeding toward completion with Yale and with the University of Texas and the Korea Astronomy and Space Science Institute (UT/KASI), we have a full complement of scientific partners at DCT and exciting instrumental capabilities on the way.

Aided in part by the *New Horizons* flyby, our public programs enjoyed not only our highest yearly attendance ever, but our largest single-day crowd (about 1,600 on July 14, the flyby day) and weekly attendance (7,000 during flyby week).

Contrast this with ten years ago. Construction work at the DCT site had just begun, and much of the telescope was still in early design phases. *New Horizons*, now zooming toward a New Years' Day 2019 rendezvous with a Kuiper Belt object, was still on its way to Jupiter. Our annual operating budget, now about $10 million, was just shy of $5 million.

As 2015 drew to a close, the radical transformation of 2005-2015 was forcing us to ask: What will DCT, our public program, and our infrastructure look like in 2025? What science will we be doing, and how will we be engaging with our guests to present that science in compelling and credible ways? Whatever the financial requirements of those goals turn out to be, we are presently short of meeting them, so how will we build the necessary revenue to support our aspirations?

And perhaps encompassing all of those questions is: What kind of place will we be in 2025? As corporations and projects grow, they have to become increasingly mindful of all the proverbial p's and q's that dictate how they must operate. It's easy, under the stress of such growth, for an organization to become an uncaring corporate machine, grinding along toward its finish line at the expense of its people.

Lowell is at risk of drifting into that territory. Despite addressing some especially pressing staff needs during 2014 and 2015, we are still running lean and mean. Our books, grants, and policies and procedures are under increasingly regular Federal scrutiny, with serious consequences for missteps. Under such stress, it becomes very easy to examine only what's needed, rather than what's right or what simply makes sense. The trick, of course, is to do both.

Lowell Putnam's and my commitment to the institution is to cross the finish line in several years with the deep-rooted culture in place since V. M. Slipher's time still intact, so among our other deliberations in 2015, we've asked ourselves and the staff what that really means. There are lots of details in that discussion, but above all, it means we achieve our goals having done well by our people. That philosophy helped carry Lowell through its lean times in the mid-20th century, and it's the foundation that will carry us through the explosively changing times now. We'll stick with it as we move toward the goals of the next several years. ▪

TRUSTEE'S UPDATE

By W. Lowell Putnam

The day Kevin Schindler gave me this writing assignment for this report I was eating at my favorite local Chinese restaurant. My fortune that day was "Mystery and knowledge come from the same source." Certainly for Lowell Observatory that is very true. Even as we learn more, we keep finding that there is much more to learn.

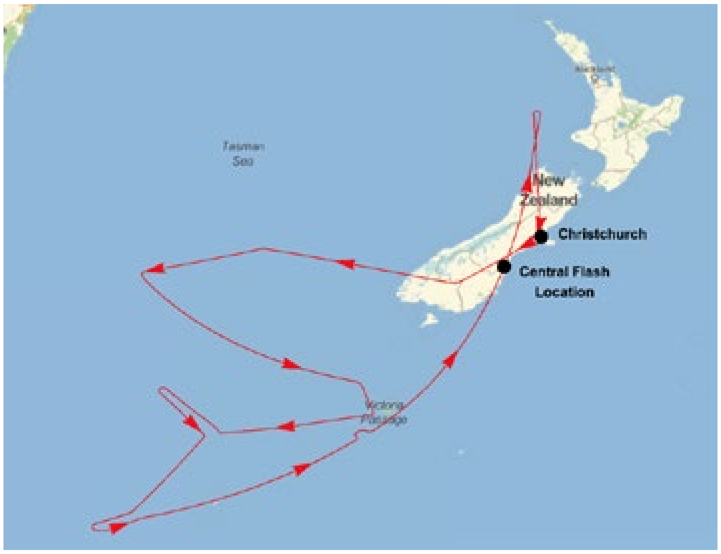
The *New Horizons* images and data that are coming back show us a much more active body than any prior predictions. We now have a much better understanding of Pluto, but a growing number of questions to answer to explain how it has gotten this way. This theme of knowledge and mysteries continues across all the work being done by our researchers, and underscores the reason Percival was so intrigued by the study of astronomy.

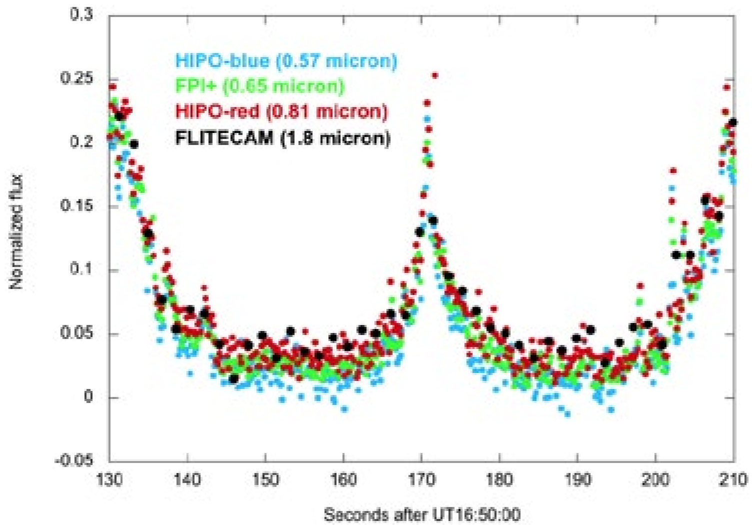
Over the past few years, the organization has been going through a transition and a "repositioning". Most attribute this to the Discovery Channel Telescope (DCT) achieving full science operations as it did this past year. While adding the operational capability (and cost) of the DCT certainly has had a major impact on Lowell, there are also a number of other efforts that are affecting the observatory in fundamental ways.

On the science side, the DCT has brought more attention and consideration of Lowell and Northern Arizona as a great place to do ground-based astronomy. Our commitment to providing sustained access has attracted other researchers to join us, from the University of Texas, Korea Astronomy and Space Science Institute (KASI), and Yale. Over the next three-to-five years, we can expect to see new instruments provide our astronomers with capabilities that are among the best in the world. At the same time, and on the same timeframe, the Navy (through the Naval Research Laboratory and U.S. Naval Observatory) is investing in improvements to the Navy Precision Optical Interferometer (NPOI) that will enhance its capabilities to see fainter objects, thus increasing the science capacity of that facility to which we have access, making it among the best in the world as well. The challenge to the institution is to find the best way to support our researchers so they can take advantage of all this to do great research.

The public program has also experienced tremendous growth and opportunities. While we expected the *New Horizons* flyby to increase the number of guests who came to visit last July, we were not sure if this was going to be a "blip" or a sustained increase. As you will read elsewhere in this report, and thanks to great work by our staff, it is definitely a sustained increase that shows no signs of slowing down. Percival would be proud and excited at the public interest and engagement. As we look ahead we can see the need for increased infrastructure to support this and provide these larger numbers of visitors with the quality of experience and education that they would expect.

Just as mystery and knowledge have the same source, so it would appear that success and challenge come from the same place. We have a great institution and the current generation of staff are doing excellent work. I look forward to working with them and our friends to build upon all that is being done for the future. Who knows what more we will learn! ▪





Ted Dunham

Late last year the SOFIA project decided to support a multi-wavelength observation of an occultation of a bright star by Pluto that occurred just two weeks before the *New Horizons* flyby. The observation would use Dr. Ted Dunham's HIPO instrument, FLITECAM (developed at UCLA by Ian McLean's group) and the SOFIA Focal Plane Imager. That decision paid off handsomely this year thanks to major efforts by many people in the project, on the observing teams, and particularly due to the astrometric tour de force accomplished by the MIT prediction team led by Amanda Bosh.

The goal was to target the SOFIA flight plan to view the central flash in the occultation, a bright spot in the center of the occultation shadow not more than 70 kilometers in radius, using a prediction update received in flight. This was successful in every respect. The prediction update was about 300 kilometers offset from what it had been all of the previous week, but Drs. Dunham and Person (MIT) decided to follow the update rather than discount it as a fluke. It became clear later that the sudden shift was due to a bright area on Pluto rotating out of view in the day prior to the occultation. Thanks to the prediction update and the skill (and practice!) of the flight crew, SOFIA passed only 23 kilometers from the center of the occultation shadow—not bad for an object 4.75 billion kilometers away! (continued on next page)

Image (Top Left): SOFIA takes off from Christchurch for the occultation test flight. (Credit: Greg Perryman, USRA)

Image (Top Right): Ted Dunham and Mike Person (MIT) in flight during the occultation. (Credit: Heinz Hammes, DLR)

Image (Bottom Left): The actual occultation flight track, factoring in the in-flight prediction update. (Credit: Mike Person, MIT)

Image (Bottom Right): Central part of the four SOFIA occultation light curves showing the central flash and the minimum brightness levels increasing with wavelength. (Credit: Amanda Bosh, MIT & Lowell)

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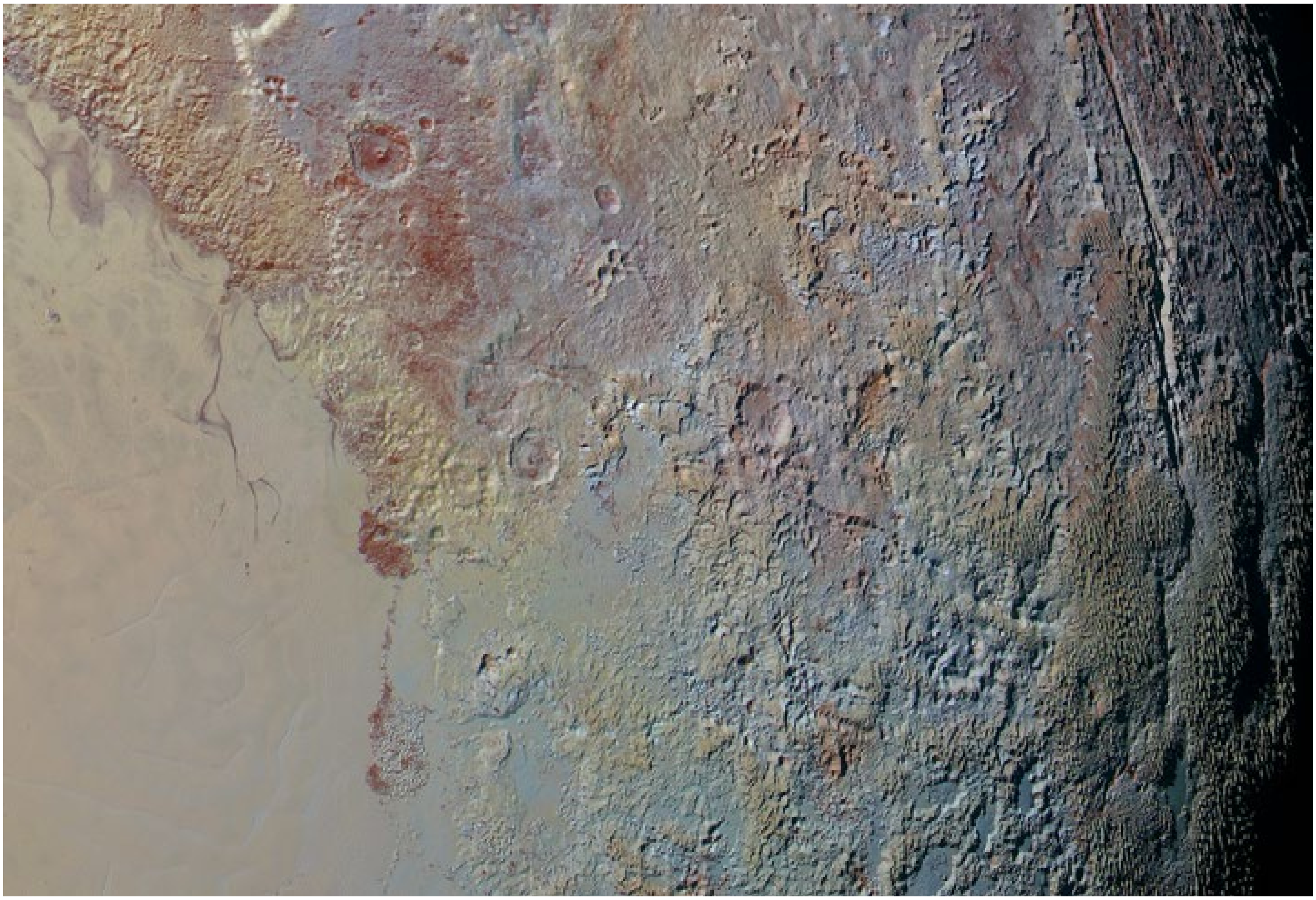
Pluto's haze is more transparent at longer wavelengths just as smoke from a forest fire is. This measurement was exactly why the combined HIPO and FLITECAM configuration was developed beginning in 1997.

On the airplane everything worked well and the flight plan changes were easy thanks to a block clearance from Air Traffic Control. The observing teams recorded four excellent light curves at different wavelengths that clearly showed the effects of the haze in Pluto's atmosphere including an indication of the size of the haze particles.

Earth-based stellar occultations probe the region between spacecraft radio occultations and UV solar occultations (REX and ALICE projects, respectively, for *New Horizons*). The coincidence of this excellent event with the *New Horizons* flyby provided a thorough look at the vertical structure of Pluto's atmosphere and also placed occultation data—present, past, and future—in the context of the rest of the *New Horizons* results. It is likely that continued presence of atmospheric haze is the result of ongoing geological activity, and the variable shapes of occultation light curves seen over the years likely reflect this too.

After the occultation effort waned later in the summer Dr. Dunham focused on completing the NIHTS instrument for the DCT. It achieved first light in November, had a second engineering run in December, and will be commissioned in 2016. ▪



Will Grundy

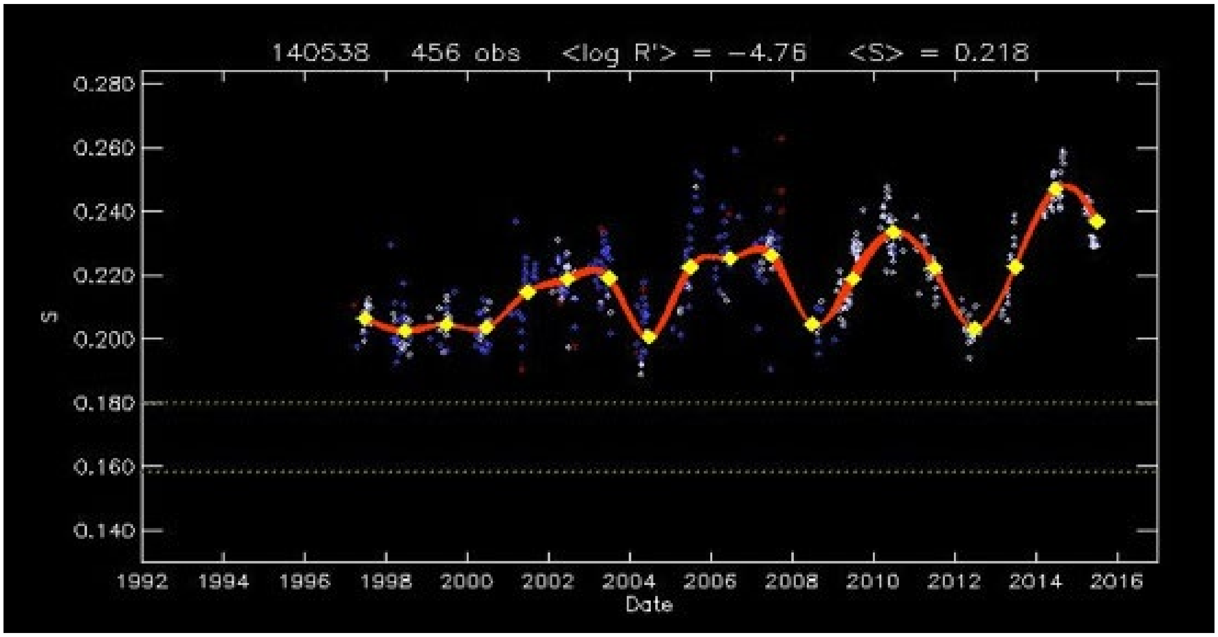
Dr. Will Grundy's research involves icy outer solar system planets, satellites, and Kuiper belt objects, and was fully funded during this period by research grants. He was an author on seven peer-reviewed scientific papers published during this period plus another five in press or undergoing review. Grundy was involved with numerous observational projects using large ground-and space-based telescopes including Hubble, Spitzer, Keck, SALT, IRTF, and DCT.

A highlight of this year was exploring the Pluto system. *New Horizons* flew through the system in July, after many years of planning and design work, followed by nearly a decade en route at more than 30,000 miles per hour.

Grundy is a co-investigator on the *New Horizons* team and heads the mission's surface composition science theme team. The encounter was a spectacular scientific success, and is re-shaping how people think about Pluto and other objects in the Kuiper belt. The rich trove of data will be analyzed for years to come. It was also highly visible, attracting huge media attention and driving unprecedented traffic to NASA's web sites and other outreach channels. The Pluto encounter brought a huge surge of visitors to Lowell Observatory, too. The first-ever up close look at a previously unexplored planet is not something the world gets to experience very often, and about half of the world's population was too young to remember the previous such first exploration, by *Voyager II* at Neptune in 1989.

Grundy also 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 Pluto encounter underscored the complexity of the geology that cryogenic ices can produce and the importance of laboratory studies of these materials. That work is essential for understanding the materials' unique properties and interactions and is essential for enabling scientists to make sense of Pluto's alien landforms. ▪

Image: Diverse landforms on Pluto result from the sublimation, condensation, and glacial flow of volatile ices N2, CO, and CH4, and their action on the H2O ice "bedrock".



Jeffrey Hall

Dr. Jeff Hall works with Dr. Wes Lockwood, Brian Skiff, and Len Bright on the Solar-Stellar Spectrograph (SSS) project, also described in Dr. Lockwood's research summary. The SSS team has monitored the activity levels of bright Sun-like stars for more than 20 years to characterize the morphology of their activity cycles and to better understand the Sun's place among its closest stellar siblings.

In 2015, Hall worked with Ricky Egeland, a graduate student at the High Altitude Observatory in Boulder, Colorado, and his mentor Dr. Philip Judge to combine the SSS data with the long-term data series from the Mount Wilson Observatory HK Project, the predecessor program to SSS. In a number of cases, the combined Mount Wilson and Lowell data sets span 30 to as many as 50 years, allowing unprecedented examination of the long-term behavior of stars like the Sun. A number of phenomena also seen in the Sun, such as periods of extended quiescence and apparent lack of active features, as well as multiple cycles operating on different timescales, are apparent. Egeland and Hall are collaborating to place the Lowell and Mount Wilson data in a comprehensive database accessible to the astronomical community and the public. ▪

Image: The solar analog star psi Serpentis shows a period of relative inactivity from 1997-2000 followed by a transition to four-year activity cycles of steadily increasing amplitude. The Sun exhibited a similar transition in behavior in the 1600s and 1700s, with well-demonstrated impacts on terrestrial climate. Observations of stars such as psi Serpentis help shed light on the range of variations our own star may exhibit.

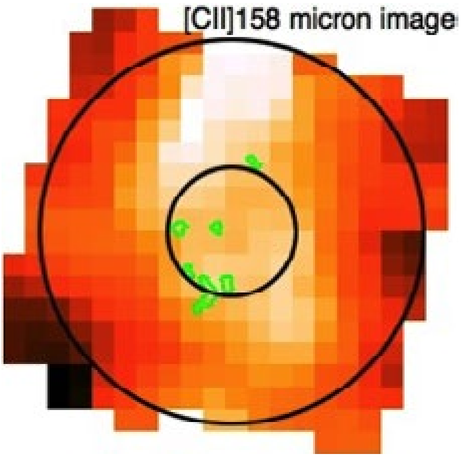


Image: Tiny CO clouds in the dwarf irregular galaxy WLM are outlined in green. The orange image is of the [CII] emission line at 158 microns that shows the protective "skin" of the molecular cloud (white are peaks). The CO cores are nestled in the central valley. The inner black circle outlines the original detection of CO in WLM using the single-dish radio telescope APEX. The outer black circle outlines the region mapped in CO with ALMA. From Rubio et al. (2015).

Deidre Hunter

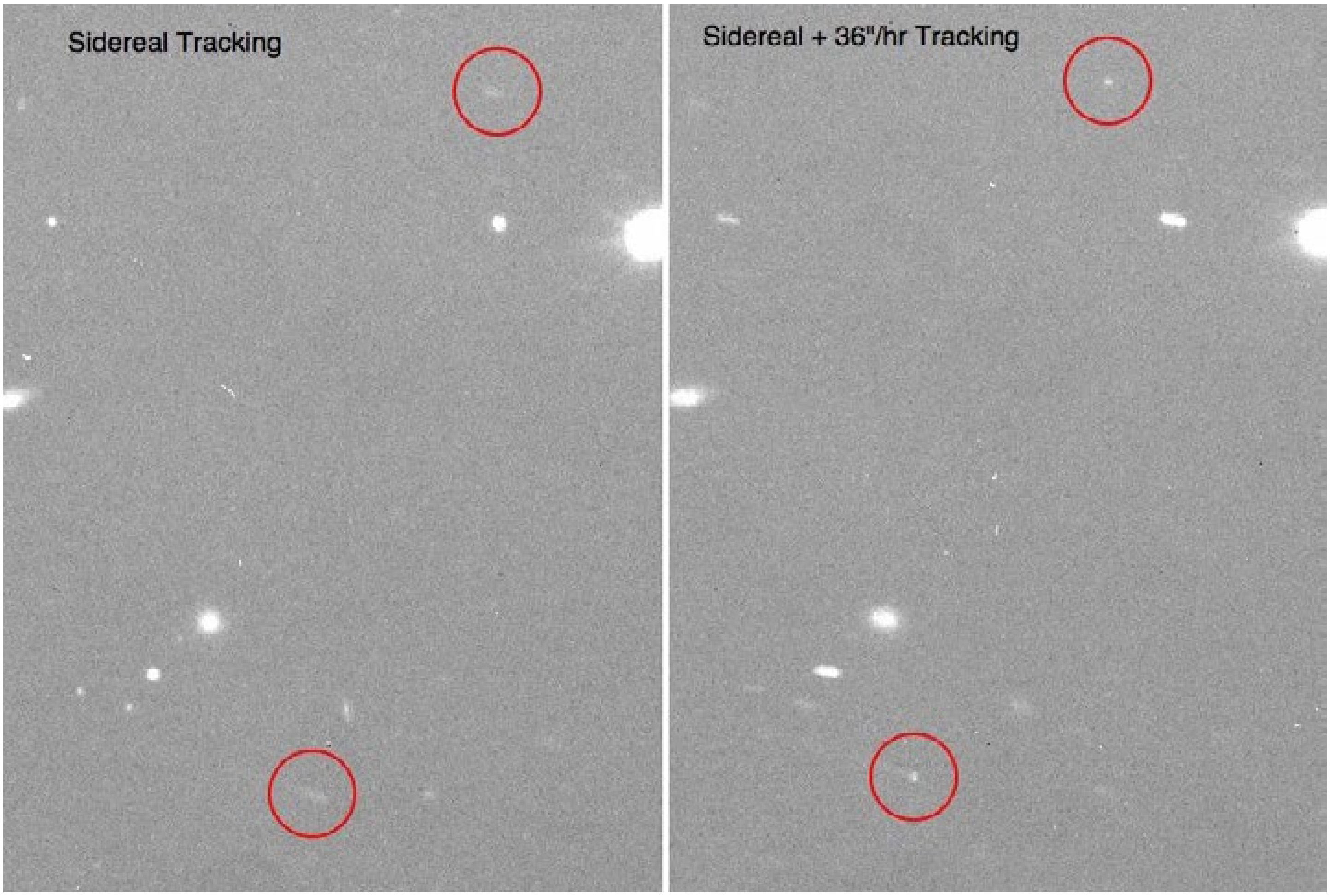
New stars in the Milky Way are seen to be forming in clouds that are primarily molecular hydrogen. The hydrogen molecule is easily disrupted by ultraviolet radiation from stars in the rest of the galaxy, so the outer rim of the molecular cloud acts as a skin that absorbs the ultraviolet light.

This protects the molecules in the interior of the cloud where stars are forming. Because the Milky Way is rich with dust and atoms heavier than helium that are efficient at absorbing the ultraviolet photons, the skins of the molecular clouds are thin. However, in the early universe there was no dust or atoms heavier than helium, so what did molecular clouds look like then?

Theory predicts that as the abundances go down, the skin of the molecular clouds will become thicker and thicker and the cores of the clouds will shrink, perhaps even shrinking away to nothing in environments with extremely low abundances. We can't observe those early clouds directly, but with a new radio interferometer called ALMA rising in the Atacama Desert of Chile, we can for the first time map molecular clouds in nearby dwarf irregular galaxies that have very low abundances of heavy atoms.

Dr. Deidre Hunter and her collaborators used ALMA to map CO in a star-forming region in the dwarf irregular galaxy called WLM. (CO is commonly used as a tracer of molecular clouds because the hydrogen molecule is not detectable in such clouds.) The ALMA map revealed six tiny dense CO clouds with an average radius of only six light-years. The team also had observations of the skin of clouds in the region using a European far-infrared space telescope called Herschel. Those images showed that the CO cores are all surrounded by a very thick skin that is five times larger than the CO cores. This was, more or less, what was predicted except that the dense cores are much smaller than expected at the abundance levels of WLM.

In spite of the unusual environment in which these clouds formed compared to the Milky Way, they fit a standard "law" determined for Milky Way clouds in which the range of velocities in the cloud gas correlates with the size of the clouds. This work was published in *Nature* (Rubio et al. 2015). The team has ALMA and Herschel observations of three more dwarf galaxies, now under analysis, that have even lower amounts of dust and heavy atoms and so the molecular clouds should be even more extreme. With this information, they will then address the question of what effect these extreme molecular clouds have on the formation of new stars in the galaxies. ▪



Stephen Levine

Dr. Stephen Levine's institutional responsibilities (which occupied the bulk of his time this past year) included helping with science operations of the DCT (scheduling science time, working with observers, and evaluating the overall performance of the telescope and instruments), and general oversight of Lowell's observing facilities. As noted in the Technical Highlights section, formal, full time science operations on DCT began on January 1, 2015 with science observations scheduled on 293 nights (out of a planned 300).

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 investigating uses of observations of gravitational microlensing for disentangling astrophysical disk structures. He continues collaborating with Arne Henden (AAVSO) 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 16.

Levine also maintains an active interest in stellar occultation studies of outer solar system objects. In June 2015, our group observed a bright Pluto occultation just two weeks before the *New Horizons* flyby of Pluto. This was observed from SOFIA (the Stratospheric Observatory for Infrared Astronomy—see T. Dunham's highlights) and from several ground stations in New Zealand. The observations provide a solid link between the *New Horizons* flyby results and past and future ground based observations of Pluto and Charon. ▪

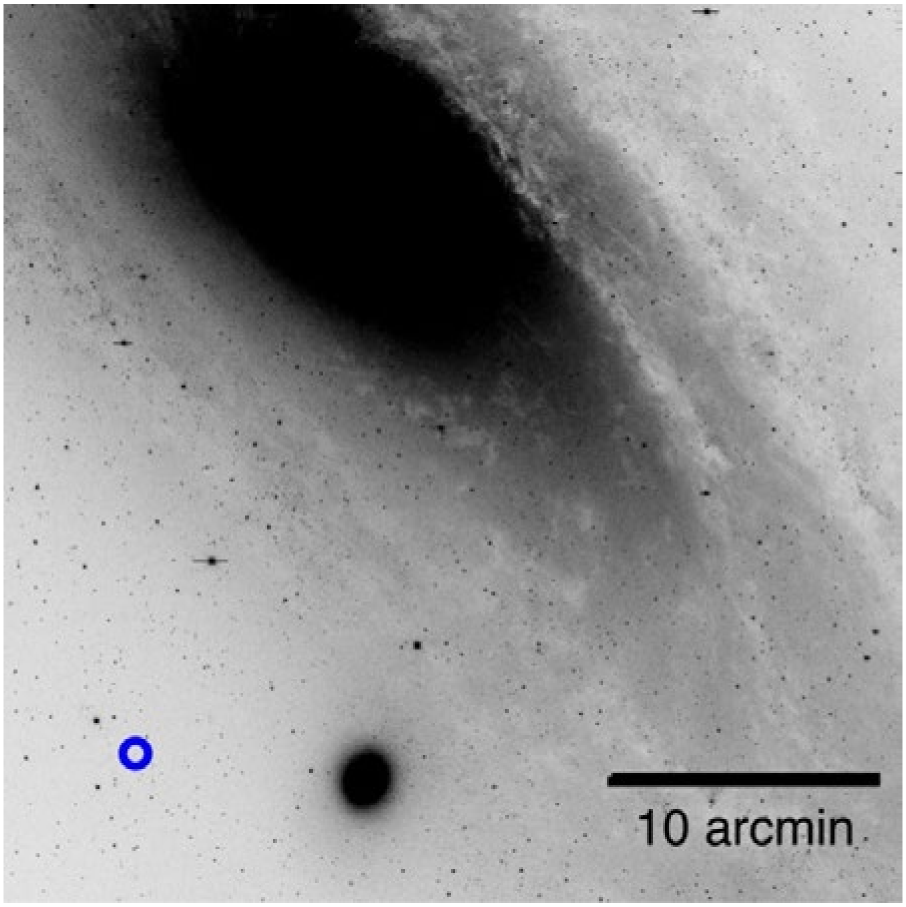
Images: Side-by-side comparison of different tracking rates with the DCT, which can be used to help improve images of objects that move relative to the stars. Left: Image of a star field with two main belt asteroids (circled). The telescope was tracking at the rate the stars move, resulting in point like stars, and streaked asteroids. Right: The same field, but this time tracking the motion of the asteroids. The asteroids are now captured as points, while the stars are streaked.

Wes Lockwood

Semi-retired astronomer Dr. Wes Lockwood continued two long-running research projects. As a follow-up to photometric studies carried out until 2000 with Brian Skiff, Lockwood, in collaboration with Gregory W. Henry at Tennessee State University, analyzed precision photometry of hundreds of Sun-like stars obtained by robotic telescopes in southern Arizona. The goal here is to better understand the Sun's variability on solar cycle (approximately 11 years) timescales. These measurements, when combined with data from Lowell's solar-stellar spectrograph project, give an improved picture of just how the Sun fits in among its peers of similar mass and age. The (minor) role of solar activity in climate change adds some spice to this work and has led to Drs. Jeff Hall and Lockwood being regular attendees at conferences organized by the operators of the SORCE (Solar Radiation and Climate Experiment) satellite.

Hall and Lockwood both presented papers at the most recent SORCE conference in November 2015. Lockwood's other research, still sponsored by NASA, involved continuing measurements of the brightness of the planets Uranus and Neptune. This work, conducted at the 21-inch reflecting telescope on Mars Hill since 1972 without interruption, has the goal of learning how the atmospheric properties (disk integrated albedos) of these planets vary over decades in response to changing insolation and viewing angle as seen from Earth. ▪

Image: For decades, the 21-inch telescope has been a staple of long-range studies of planetary atmospheres and Sun-like stars.



Philip Massey

Dr. Phil Massey and summer student Kate Evans (Caltech) identified the first "runaway" red supergiant star. The star is located in the Andromeda Galaxy (M31), which also makes this the first extra-galactic runaway massive star ever found.

Massive stars are born in giant molecular clouds, creating associations of OB stars. OB stars that are close to one of these associations, but with discrepant velocities, were first discovered by Adriaan Blaauw in 1961, who termed these "runaways". These have likely been ejected from their birth places by close encounters with other members of the group, and flung out by these gravitational interactions. About 30% of all OB stars are considered runaways, with velocities discrepant by 30 kilometers per second or more from their fellows.

Despite this high percentage of runaway OB stars, few evolved massive runaways are known. A few red supergiants, including Betelgeuse, are known to have bow shocks, which may be evidence that the star is a runaway. The problem is that since evolved stars are much older than OB stars, they have long since drifted far from their birth places, and there is nothing to which one can compare their velocities.

Massey and Evans conducted a radial velocity survey of red stars seen towards M31 in order to distinguish foreground red dwarfs in our own Milky Way from bona fide red supergiants in M31. In doing so, they noticed that one of the stars in their sample had a highly discrepant velocity from what is expected from M31's rotation curve: it was moving 300 kilometers per second faster towards us than its neighbors! Furthermore, the star was located 4.6 kiloparsecs from the plane of M31's disk; if its transverse motion is similar to its radial velocity motion, that's just about the distance a star would travel during 10 million years, the approximate age of the star.

Evans enthusiastically drafted the paper, and it was published a few months later in the *Astronomical Journal*. They have now completed a second paper together describing the full sample of stars, and have plans to work in 2016 on a project involving the red supergiant content of the Magellanic Clouds. ▪

Image: The location of the M31 runaway red supergiant is well away from the disk of M31, where all of the other red supergiant stars are found.

Nick Moskovitz

Dr. Nick Moskovitz continued to carry out a number of programs related to the study of small bodies in the solar system. In 2015, he worked on projects that involved Hubble Space Telescope observations of recently disrupted asteroids, observations at the Discovery Channel Telescope (DCT) in support of an upcoming joint mission between NASA and ESA called AIDA (the Asteroid Impact and Deflection Assessment mission), development and expansion of a database of asteroid properties called astorb that has been curated at Lowell for many years, and the continuation of a large ground-based telescopic study of near-Earth asteroids called MANOS (the Mission Accessible Near-Earth Object Survey).

Moskovitz also began a new project in 2015 that focuses on observing meteors, i.e. small particles from comets and asteroids that vaporize when they impact Earth's atmosphere at speeds in excess of 20,000 mph. The Lowell Observatory Cameras for All-sky Meteor Surveillance (LO-CAMS) is a system of off-the-shelf security cameras that autonomously capture video of the night sky to detect moving objects. LO-CAMS consists of two stations, one located on Mars Hill and one at DCT, each of which has 16 cameras looking in different directions to create a high resolution video of nearly the entire night sky. Triangulation of meteors imaged by the two stations enables retrieval of their 3D trajectories including altitude, speed, and impact angle. This provides a measure of the pre-impact orbit of the particles, and fall location on the ground for meteors that are large enough to survive passage through the atmosphere, otherwise known as meteorites.

LO-CAMS is based on an analogous network of cameras called CAMS that is deployed in California. The overall goals of these meteor camera networks are to discover new meteor showers, monitor the variability of known meteor showers, and to enable recovery expeditions in rare instances of large meteorite fall events.

On an average night, a single LO-CAMS station can detect several hundred meteors. These are typically particles no bigger than an inch across but do produce meteors that get bright enough (~ 6th magnitude) to be visible to the naked eye. With all of these detections, LO-CAMS is rapidly building a large data set of meteor detections that will ultimately provide new insights into Earth's meteor environment and the origin of these small impacting particles.

Based on a system of simple hardware, the LO-CAMS design can readily be scaled to augment the network with new stations. And the large flow of data is ripe for crowd sourcing efforts to engage the public in the data analysis process. As LO-CAMS works to collect new data every night, the future for meteor science at Lowell is bright. ▪

Image (Left): LO-CAMS station on the roof of the Slipher Building on Mars Hill. Five of the 16 cameras are visible through the window on the lid of the aluminum enclosure. Each camera captures about a 20 square degree field of view, creating a mosaic video of the night sky from zenith down to 30 degrees above the horizon.

Image (Right): Bright meteor captured by the DCT LO-CAMS station. The top of the DCT dome is visible to the lower right. The meteor is passing in front of the constellation Leo. Jupiter is the bright source on the left side of the image.

Lisa Prato

In 2015, Dr. Lisa Prato's team investigated a range of problems, from planet formation to individual young binaries stars, to brown dwarfs, objects intermediate in mass between low-mass stars and giant planets. Postdoc Dr. Tom Allen, interns Nuria Wright-Garba and Lauren Biddle (currently a masters thesis student at Northern Arizona University (NAU) working on her thesis with Prato), summer REU undergraduate student Ryan Muzzio, and NAU undergrads Jacob McLane (now in the Ph.D. program at the University of Texas at Austin) and Ian Avilez have all been collaborating with Prato on observing, processing, and analyzing rich sets of spectroscopic and photometric data taken with telescopes in Chile, Hawaii, and Lowell's DCT.

With former summer students Sara Bruhns and Frankie Encalada, and with collaborator Dr. Gail Schaefer, Prato exhibited four posters at the American Astronomical Society meeting in Seattle, Washington in January, 2015. Team members Prato, Allen, Biddle, McLane, and Wright-Garba all attended the Star and Planet Formation in the Southwest topical conference at the Biosphere in Oracle, Arizona in March 2015, presenting work in posters and leading focused discussion sessions as part of the main conference program.

Allen and Prato presented work at the Gordon Research Conference in Holyoke, Massachusetts. Participation in these meetings focused on the team's work on young visual binaries, based on unique data which resolves the two stellar components, providing their characteristics in unprecedented detail. In July, Prato gave an invited talk at the Extreme Precision Radial Velocities conference at Yale University about her pioneering program to identify the youngest exoplanets.

Prato completed and published results from a search for close binary companions in brown dwarf systems. By searching for small, regular motions in the target objects, it is possible to surmise the presence of a companion because both objects orbit around a mutual central point. This provides a strategic approach to looking for very low-mass companions because such objects are generally too faint to detect directly. Identifying this wobble in the brighter object is a smoking gun for the presence of a bound secondary. Interestingly, no low-mass companions were found around the already low-mass brown dwarfs. This is important because it provides astronomers with clear clues to the nature of how brown dwarfs formed. (continued on next page)

Image: From left to right – Jacob McLane, Lisa Prato, Lauren Biddle, Tom Allen, Ryan Muzzio, and Nuria Wright-Garba (Ian Avilez not shown).

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The same technique, searching for a regularly timed wobble in the radial velocity of a young star, is the approach Prato's team and colleagues use for identifying newly-formed giant planets close-in to the parent star, work that is now coming to fruition because for the first time the team is exploring the infancy of young planets, key to illuminating how they form. Furthermore, the team's studies of very close young binary stars, with mutual orbital periods of a few weeks down to as short as a day or two, also exploits this method. If the two stars are both bright enough to be detected and have their motions measured, it becomes possible to calculate their mass ratio and ultimately their absolute masses, a rosetta stone for our understanding of star and planet formation.

In September, Prato was awarded a three-year grant from the National Science Foundation to continue the team's research on these young double stars. ▪

Henry Roe

Coordinating with the *New Horizons* flyby of Pluto, Dr. Henry Roe continued his long-term W.M. Keck 10-meter telescope observations of methane in Pluto's atmosphere and expanded the program to include the IGRINS high-resolution spectrometer at McDonald Observatory's 2.7-meter telescope. IGRINS is planned to come to Lowell Observatory's 4.3-m DCT later in 2016. The combination of IGRINS and DCT will be excellent for continuing this work going forward. Roe also supported the *New Horizons* flyby with additional near-infrared observations of Pluto and Charon from the Keck telescopes during the weeks around flyby, including several nights when Roe and collaborators had both Keck telescopes focused on Pluto simultaneously.

In the fall of 2015 Roe and colleagues achieved first light with the Near-Infrared High-Throughput Spectrometer (NIHTS, pronounced 'nights'), first in the lab and then on-sky in late November. This is a low-resolution, wide-bandwidth spectrometer designed for observing faint targets, such as smaller Kuiper Belt Objects (KBO), with DCT. The instrument was funded by NASA for a large spectral survey of KBOs and will also be useful for work ranging from rapid classification of brown dwarfs to studying Titan's weather to monitoring cloud variability on brown dwarfs. Commissioning of the instrument will be completed in 2016 and NIHTS will be available to users across the DCT partnership later in 2016.

In 2015 Roe and Dr. William Grundy hired Dr. Jennifer Hanley to work with them as a Postdoctoral Researcher on studies of cryogenics ices and fluids relevant to the surface of Titan and other bodies in the outer solar system. This work is made possible by a generous gift from the John and Maureen Hendricks Charitable Foundation. Related to this laboratory work, Roe started a significant upgrade to the 0.5-meter Titan Monitor (TiMo) telescope, which is located on Mars Hill. This upgrade, funded by a generous gift from Bob Ayers, will significantly increase the sensitivity and reliability of the facility, as well as enable a low-resolution spectral capability. ▪

Image: Henry Roe used the Titan Monitor (TiMo) to observe dynamic weather events on Titan.

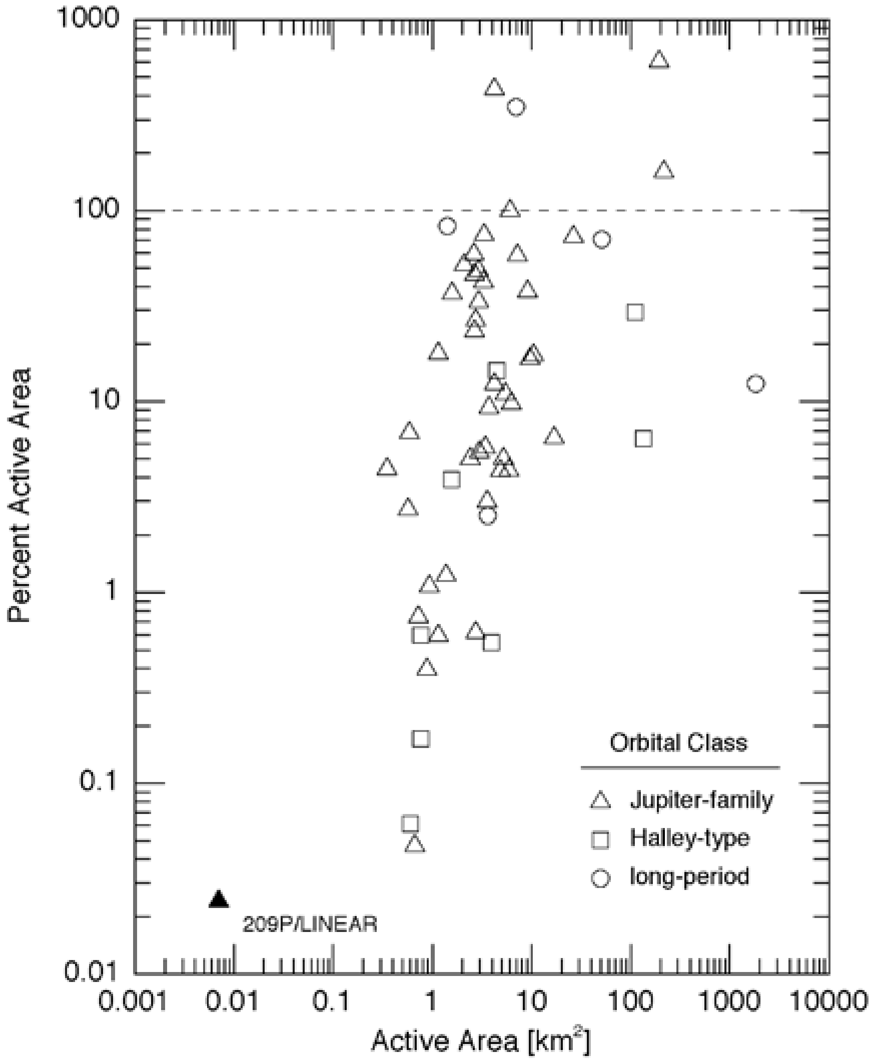


Image: The fractional active area of the nucleus plotted as a function of the effective active area on a logarithmic plot. The active area is calculated based on how much ice must be vaporizing to produce the observed amount of water, given the available sunlight at the distance of the comet from the Sun. As can be seen, the active area determined for Comet 209P/LINEAR is only about 2% of the next-smallest comet. For comets that have had the size of their nucleus determined (either from radar or using HST), the fraction of the surface area that is active can also be computed (the left axis) and LINEAR is again the most extreme, with a value of only 0.024%. A few comets at the top of the plot have active fractions exceeding 100%, and are thought to have some or most of their outgassing from icy grains rather than directly from their surfaces. Symbols are based on the type of orbit, with objects "controlled" by Jupiter having orbital periods of less than 10 years, comets similar to Halley having periods between 10 and 200 years, and long-period comets (few of which have a measured nucleus size).

David Schleicher

Dr. David Schleicher, together with Research Assistant Allison Bair, completed analyses of brightness variations measured in Halley's Comet during 1985/86. In addition to findings presented in last year's annual report regarding Halley's complex rotational state where the nucleus precesses more rapidly than it rotates, Schleicher and Bair have tightly constrained the rotation period to one of two values—about 6.95 days or 7.85 days, depending on the direction of the roll—rather than the previously assumed 7.4 days. Which case is correct will be determined from future modeling. They also discovered an unexpected correlation of the timing of brightness minima with plasma tail activity.

Schleicher and Dr. Matthew Knight obtained new observations of Comet 6P/d'Arrest, an object long-suspected of also being in a complex rotational state. Prior measurements strongly suggest that it has a rotation or precession period of less than three hours—shorter than that of any other comet and implying a higher limit on a comet's structural strength than has been assumed. Observations will continue with DCT into early 2016.

Analyses of extremely anemic comet 209P/LINEAR continued by Schleicher and Knight. 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, as shown in the image, strongly suggestive that this object is well on its way to becoming an inert body and thus being misclassified as a near-Earth asteroid (NEA). Note that numerous NEAs have comet-like orbits and might have a cometary origin. Such objects presumably have icy interiors—only the surface layer is either de-volatilized or crusted over—and could be a useful resource for future astronauts.

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 been emphasizing use of both Lowell's DCT as well as the Navy Precision Optical Interferometer (NPOI) to make high-angular-resolution stellar observations.

With DCT, Dr. 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. DSSI@DCT observations have recently been published covering observations of more than 1,000 stars with a precision of two milliarcseconds in separation. A proposed 3,000-star survey using DSSI@DCT to observe all of the nearby M-dwarf stars—objects like our Sun but roughly half the mass—is being considered 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.

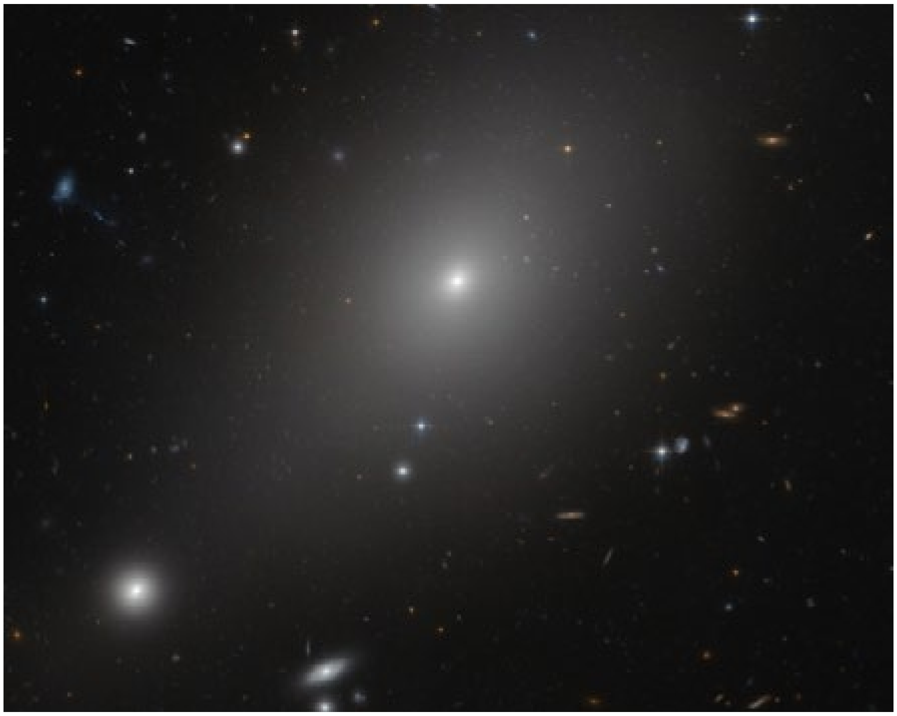
With NPOI, the new VISION (Visible Imaging System for Interferometric Observations at NPOI) camera recently completed commissioning work as part of (now-) Dr. Victor Garcia's dissertation work, which he carried out in collaboration with van Belle. This new instrument expands NPOI's capability to join up to six telescopes at a time, and will be beginning production science operations in May of 2016. 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.

Outside of DCT and NPOI, van Belle continued to work with archival data from the Palomar Testbed Interferometer (PTI), providing NPOI-like data on stellar angular diameters at the milliarcsecond level. A publication of his with Lowell post-doc Alma Ruiz-Velasco documents how to estimate brightness levels of time-variable cool evolved stars, which in conjunction with PTI data can provide a direct measure of stellar effective temperature. (Interestingly, this publication recycled, in a modern computational context, data first published by Lowell's Dr. Wes Lockwood back in 1974.) Constraining phenomena such as stellar mass loss for these 'retirement home' analogs of our Sun is challenging without a solid empirical basis for the physical parameters of the source stars, which this investigation helps solve. (continued on next page)

Image: Dr. van Belle (left) and Lowell adjunct Dr. Kaspar von Braun mounting the DSSI instrument (silver box in center) to the DCT instrument cube.

(continued from previous page)

Van Belle also contributed to the discovery of a Jupiter-mass planetary candidate around the young star PTFO 8-8695, a study led by Caltech's Dr. David Ciardi and joined by Lowell's Dr. Lisa Prato and adjunct Dr. Kaspar von Braun. This oddball object, if confirmed, is a close-in planet that passes in front of its host star during the course of its orbit, causing an apparent transit dip in brightness of the star. This time-dependent stellar brightness, modulated by the passage of the planet, varies in a way that reflects a subtle richness of the system: the planet's orbit is rapidly precessing, meaning its passage in front of the host star varies on ~monthly time scales; additionally, the host star is a rapidly rotating object, meaning its poles are brightened due to the phenomenon of gravity darkening. (Notably, the stellar surface appearance of rapidly rotating stars was observed first directly by van Belle, along with the phenomenon of gravity darkening.) The youth of the host star, estimated at only 3 million years, is of significant importance: when confirmed, this system will place strong constraints on how quickly a Jupiter-mass object must be able to form around a 'baby' star. Unraveling the mysteries of planet formation is a key observational and theoretical challenge in modern astrophysics, and this system is helping to guide the constraints on understanding the relevant physical processes. ▪



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 and an international team of collaborators continued their study of galaxy cannibalism using data from Lowell Observatory's Discovery Channel Telescope, 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 2015, 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 and Dr. Michael Gregg (UC Davis) found evidence that the Andromeda Galaxy's largest star cluster, G1, isn't a star cluster at all. It's actually the surviving nucleus of a small galaxy whose outer layers were slowly flayed by Andromeda's gravitational pull until all that remains today is its exposed heart. West & Gregg were able to detect stars still being plucked from this unfortunate galaxy.

Arp 105 is one of the most spectacular galaxy collisions in the universe today, a train wreck between two galaxies that's strewing stars and star clusters into space. Using observations made with the Hubble Space Telescope, West and Gregg completed a census of star clusters that were ejected during this collision. These star clusters no longer belong to any galaxy. Instead, they wander freely through space, accumulating over time to form a sea of orphaned star clusters.

Galaxy clusters are the urban centers of the cosmos. Here hundreds of galaxies are crammed into a region no larger than the distance between the Milky Way and the neighboring Andromeda Galaxy. Finding the most distant galaxy clusters is important because they let astronomers see how such structures formed in the early universe. But distant clusters are faint, which makes them difficult to find. To remedy this, West is using quasars as beacons to search for distant galaxy clusters. Quasars are extremely bright and distant objects that look like stars but are really galaxies powered by enormous black holes at their centers. Quasars are also very rare. This suggests that the presence of two or more quasars in the same region of space might indicate an exceptionally galaxy-rich environment. (continued on next page)

Image (Left): Hubble Space Telescope captured this image of ESO 306-17, a giant cannibal galaxy that grew to its bloated size by devouring most of its neighbors. (Credit: NASA, ESA and Michael West)

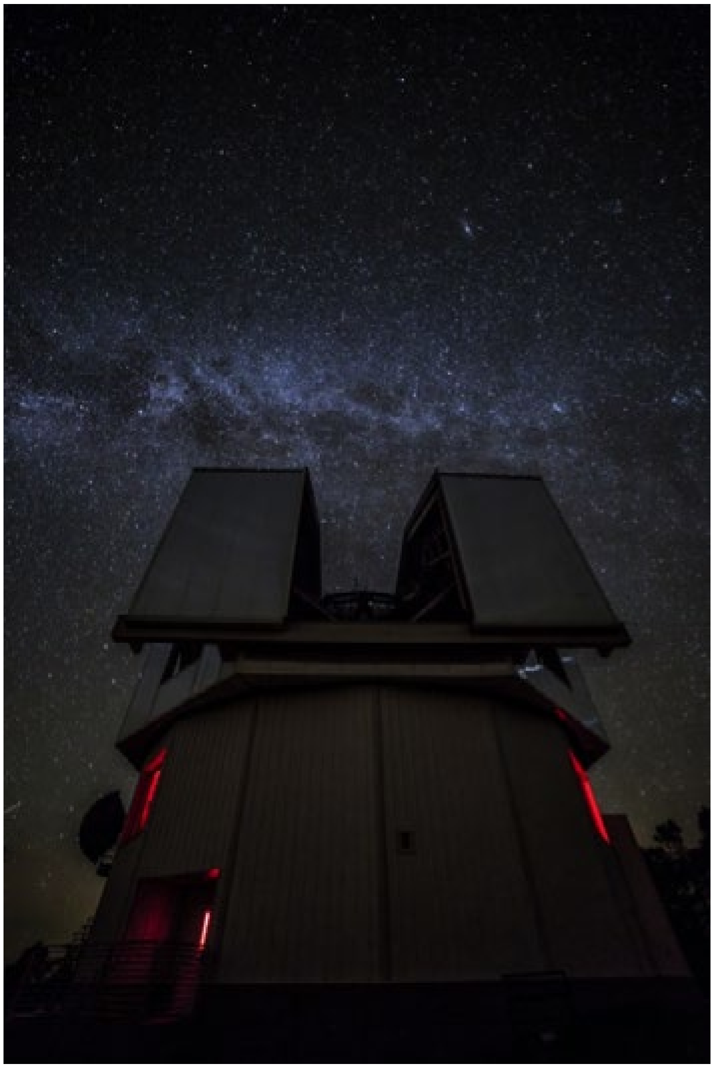
Image (Right): Once thought to be the largest globular cluster in the Andromeda Galaxy, G1 turns out to be the surviving nucleus of a small galaxy whose outer layers were picked clean by Andromeda's gravitational pull. (Credit: NASA and Michael Rich (UCLA))

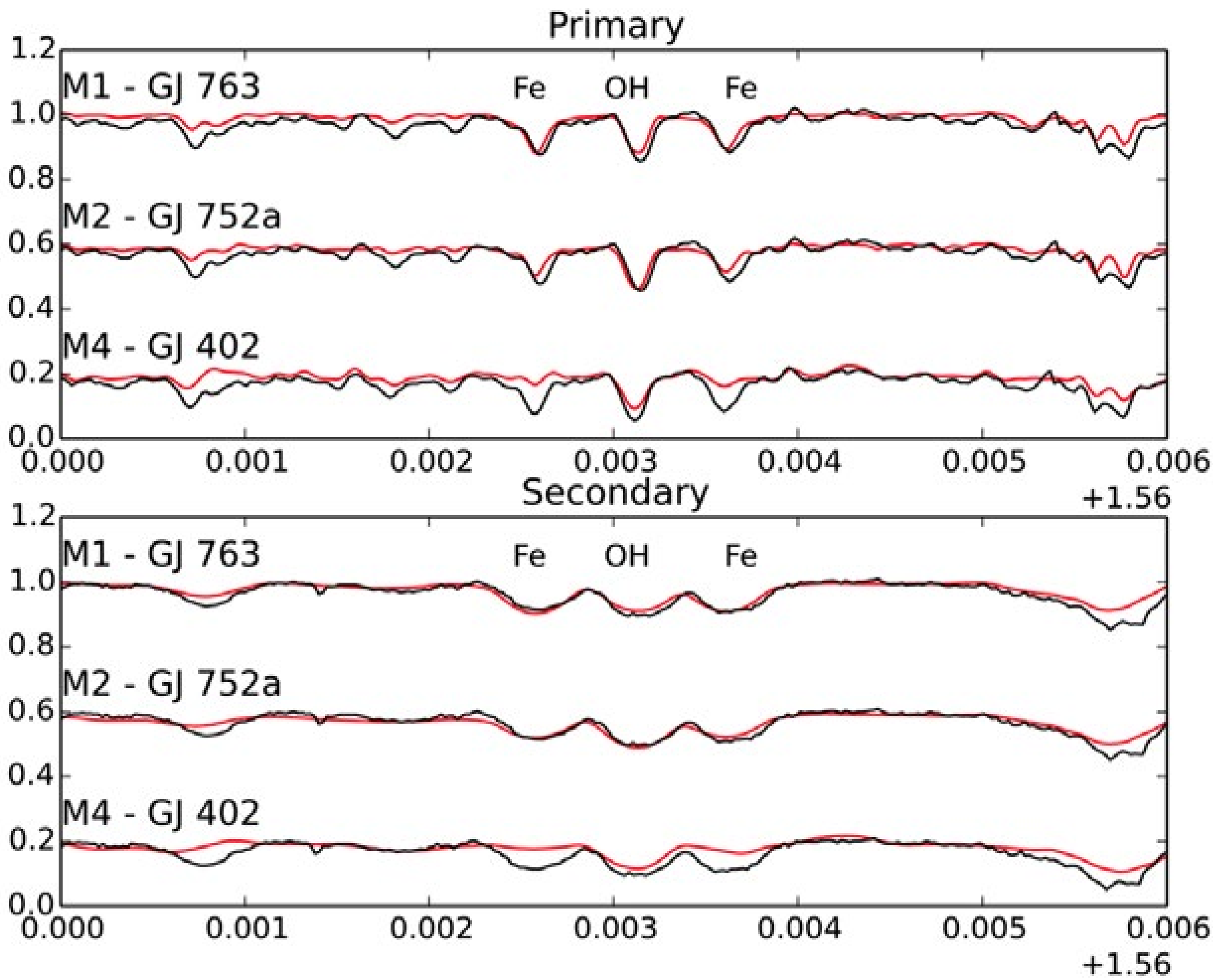
(continued from previous page)

Using Lowell Observatory's Discovery Channel Telescope, West has begun a project to quantify the number and distribution of galaxies around pairs and triplets of quasars, with the goal of determining whether they might indeed be reliable markers of faraway galaxy clusters.

West's new book, *A Sky Wonderful with Stars: 50 Years of Modern Astronomy on Maunakea*, was published in 2015 by University of Hawaii Press. ▪

Images: The DCT at night.





Tom Allen

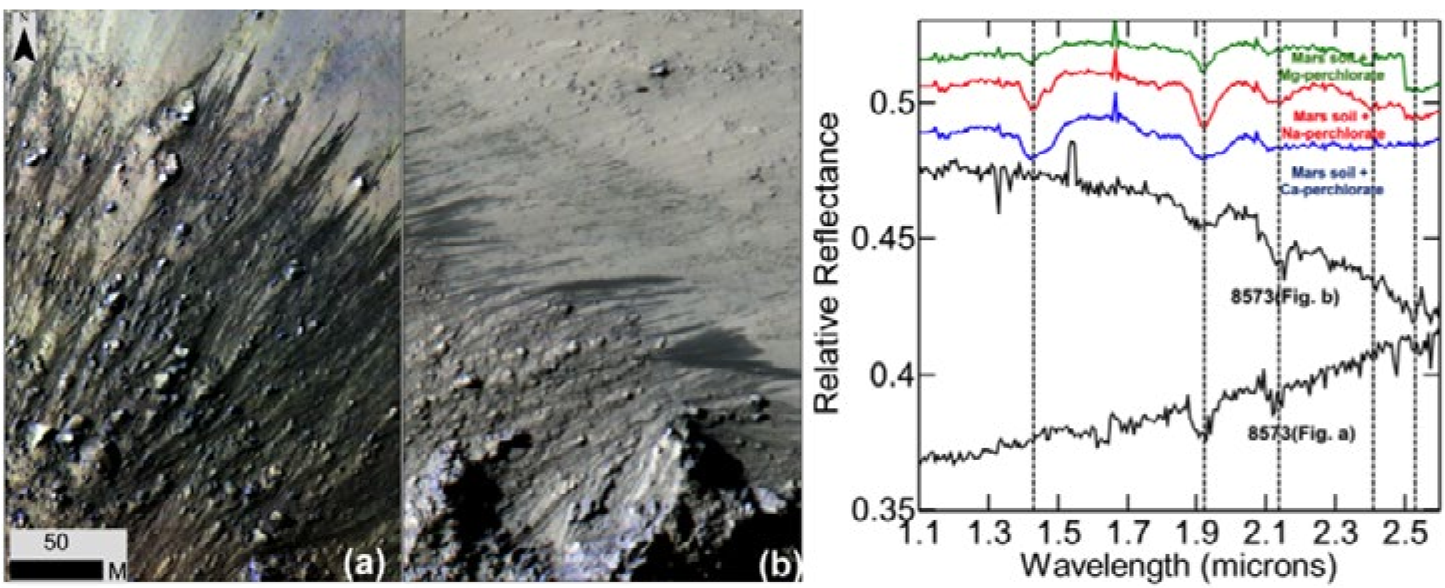
Dr. Tom Allen, postdoc at Lowell since August 2014, has spent his time observing and analyzing young stars. He is particularly interested in determining the properties of young stars with a focus on binary star systems with Dr. Lisa Prato's research group. Currently, Allen is finishing a paper on a particularity interesting young binary system called DF Tau that provides an example of how protoplanetary disks can regulate the rotation rates of stars. This work has utilized data from a number of space and ground-based telescopes, including the 31-inch and the DCT at Lowell Observatory. Allen presented results of his research as conferences, including the Gordon Research Conference in Holyoke, Massachusetts.

In addition to research, Allen helped mentor students in Prato's research group and participated in the Navajo-Hopi Astronomy Outreach Program. ▪

Image: Spectra showing the primary component (top) and secondary component (bottom) of DF Tau, in black, compared against M1, M2 and M4 spectral standard stars in red. The middle plot in each pane shows the best fitting template. The standards have been artificially veiled and rotationally broadened to match the observed spectra. The wide absorption lines in the secondary result from fast rotation, whereas the primary has narrow absorption lines from slow rotation. The primary rotates slower because of the presence of a protoplanetary disk.

Image (Left): NASA's IRTF telescope on top of Hawaii's Mauna Kea at sunset. The dome is open and the telescope is pointing at Europa ready to collect data.

Image (Below): HiRISE images of RSL activity in the central peaks of Horowitz Crater on Mars (a and b) and associated CRISM spectra (right). Black spectra are of the surface of Mars from the RSL in a and b. Colored spectra are results from spectral mixing between the Martian soil and a variety of laboratory salts. From Ojha et al. (2015) and Hanley et al. (2015).

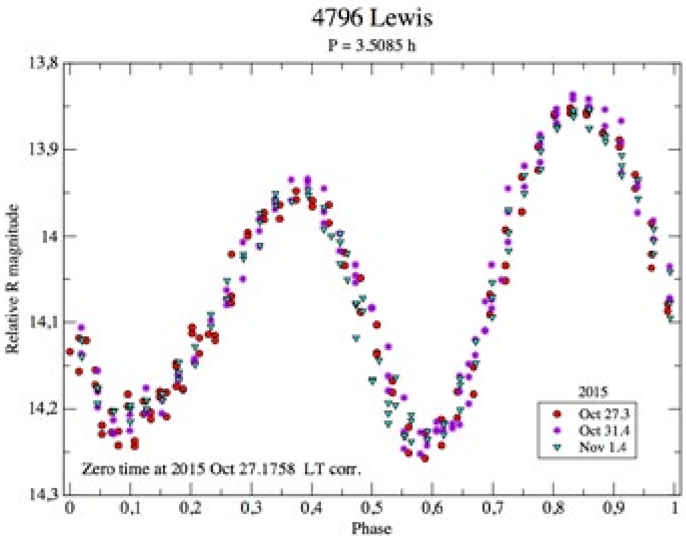


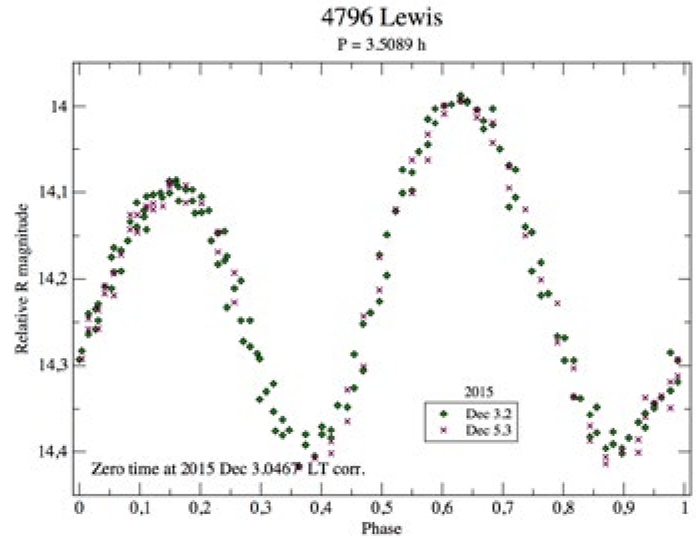
Jennifer Hanley

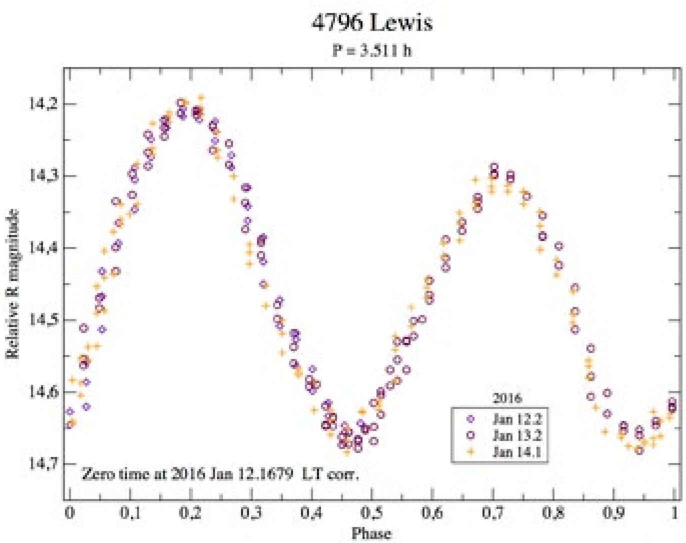
Dr. Jennifer Hanley joined Lowell in September, 2015 as a Postdoctoral Researcher. Her main research topics include working in the Northern Arizona University Ices Laboratory to understand the mechanical and spectral properties of cryogenic ices on Pluto and Triton, among other icy satellites, as well as the hydrocarbon lakes of Titan. She also studies the stability of water in the presence of salts on Mars and Europa.

In 2015, Hanley was awarded time on NASA's IRTF telescope to observe Europa and search for perchlorate salts to determine if they were present on Europa's surface. This could indicate whether the salty ocean beneath Europa's crust is indeed in contact with the surface, and how cold that water is.

A highlight of the last year was Dr. Hanley's co-authorship on a *Nature Geosciences* paper that identified hydrated salts in Recurring Slope Lineae (RSL) on Mars, indicating that they were formed by flowing liquid water. This work utilized 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: Light curves of asteroid (4796) Lewis observed at three different epochs at Lowell Observatory 42- and 72-inch telescopes. Opposition date: 2015/11/07. Asteroid synodic rotational period increases as the asteroid moves away from opposition suggesting that the object is more likely to be prograde rotating rather than retrograde. Prograde V-type rotators in the inner main asteroid belt are likely to originate from other body than asteroid (4) Vesta. Asteroid (4796) Lewis may therefore be a fragment of other differentiated parent body, however more data and modeling is necessary to confirm its origin.

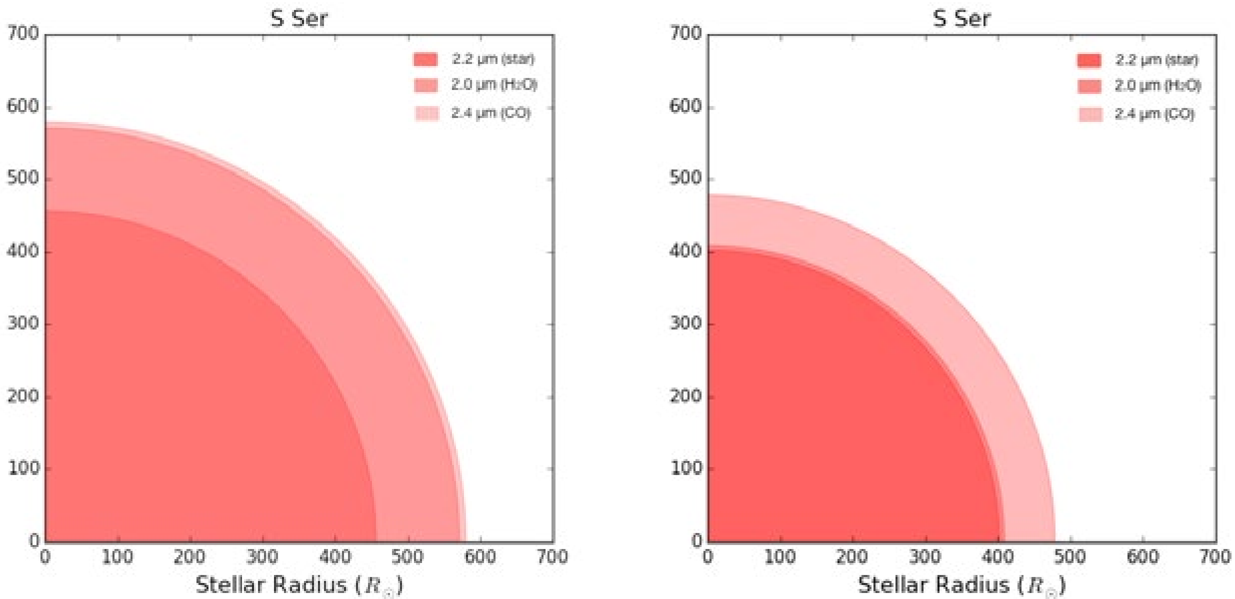
Dagmara Oszkiewicz

Dr. Dagmara Oszkiewicz joined the Lowell team in October 2015 to work with Dr. Will Grundy on properties of trans-Neptunian objects including the Pluto and Charon system. Her other work is related to deriving asteroid phase curves and physical properties from Pan-Starrs and OGLE surveys. Part of her work since joining Lowell has focused on searching for traces of planetary differentiation in the inner asteroid main belt (2.06 AU - 2.5 AU). Differentiation is a process in which planetary bodies of the size of 200 kilometers in diameter or larger separate different constituents and develop distinct geological layers such as an iron core and silicate mantle and crust. According to planet formation models and meteoritic evidence this process occurred early in the solar system formation.

The first bodies that formed in the solar system were so-called planetesimals. They were heated to high temperatures by the decay of radio-active elements, such as 26Al that led to the separation of the different constituents. The heavier, denser elements sank to their centers, creating an iron core. The less-dense elements rose to the surface, creating mantle and crust. Abundant iron and basaltic meteoritic evidence shows presence of the 50-100 such differentiated in layers bodies in the Solar System. However the observational evidence of those objects or their collisional remains is missing.

In her research, Oszkiewicz focuses on tracing collisional remains of the differentiated parent bodies. In particular, she tries to identify basaltic composition (so called V-type asteroids) fragments of mantles and crusts of the differentiated parent bodies. Most V-types known up to date are thought to be parts of asteroid Vesta, the only known intact and fully differentiated asteroid in the asteroid belt. To identify fragments of crusts and mantles of other differentiated parent bodies, Oszkiewicz determines rotational properties of V-type asteroids from photometric observations obtained at the 42- and 72-inch telescopes at Lowell Observatory. The rotational and thermal properties of those objects are then a crucial element into determining their migration paths in the asteroid belt and provides important insights into planet formation models and evolution of planetary systems. ▪

POSTDOC **SCIENCE**HIGHLIGHTS



Alma Ruiz-Velasco

Dr. Alma Ruiz-Velasco came to Lowell in December, 2014 to study Mira stars. These are old stars that die slowly, expanding and contracting until they cannot burn hydrogen anymore and end up as colorful planetary nebulae.

Mira stars produce a lot of dust in a recurrent process that veil their photosphere for some part of their cycles. To observe these changes we need a few things. First, multiple infrared telescopes are used to measure the stellar diameters. Using a technique called interferometry, where the light of two or more telescopes is combined together, astronomers can obtain very high resolution measurements of a few milli-arcseconds. Then, astronomers make long-term observations since these stars can have periods ranging from 100 to 600 days.

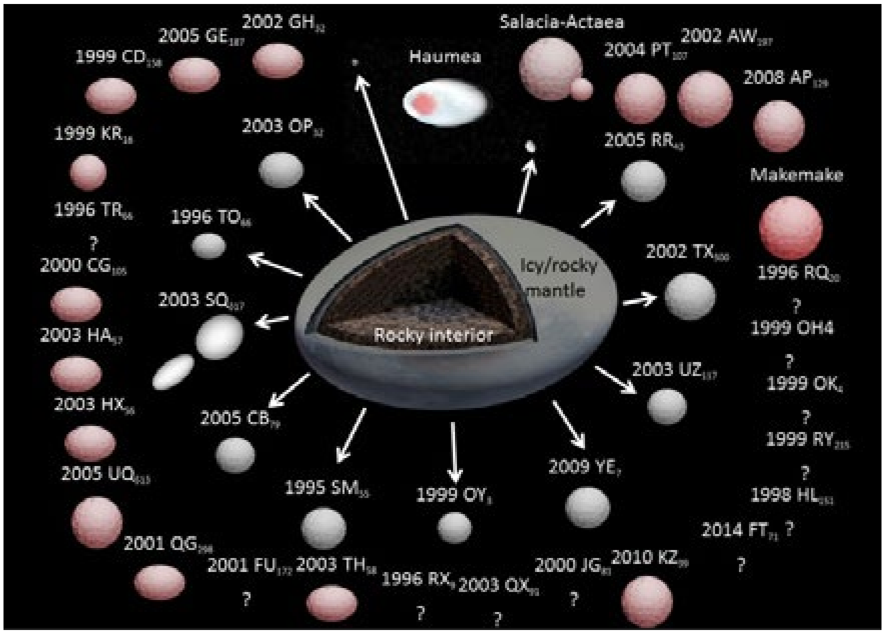
Ruiz-Velasco dug into the archives of the Palomar Testbed Interferometer to work on a sample of 96 Mira stars observed from 1999 to 2008. This data was acquired during a monitoring program of Mira variables in which Lowell's Dr. Gerard van Belle participated.

Ruiz-Velasco divided the observations in narrow-band data at 2.0, 2.2 and 2.4 micrometers so she could distinguish the photosphere from the atmosphere of the star, where the latter is usually enriched with molecules like water, carbon monoxide and silicates. For example, S Serpentis is an oxygen-rich star, which means it will have water vapor and carbon monoxide layers in its atmosphere. The photosphere of S Serpentis, observed at 2.2 micrometers, shows a star with a diameter that varies from 3.9 to 4.6 milliarcseconds. The molecular envelope observed at 2.4 micrometers, on the other hand, varies from 4.6 to 5.8 milliarcseconds.

S Serpentis is located at 0.93 kiloparsecs, or 3033 light years. Knowing the distance is very important because astronomers can use it to convert angular sizes to linear sizes, and hence, put it in terms of the size of the Sun. Hence, S Serpentis measures 390 solar radii at its minimum and 450 solar radii at its maximum (where one solar radius is 432,450 miles). Its molecular envelope extends from 460 to 580 solar radii. If we could put S Serpentis in the center of our solar system, it would easily fit beyond the orbit of Mars.

S Serpentis has a period of 372 days and was observed during 13 different epochs over five years. Other stars in the sample were observed for as much as a hundred epochs, and their sizes range from 200 to 600 solar radii. ▪

Images: The Star S Serpentis during its maximum (left) and minimum expansions.



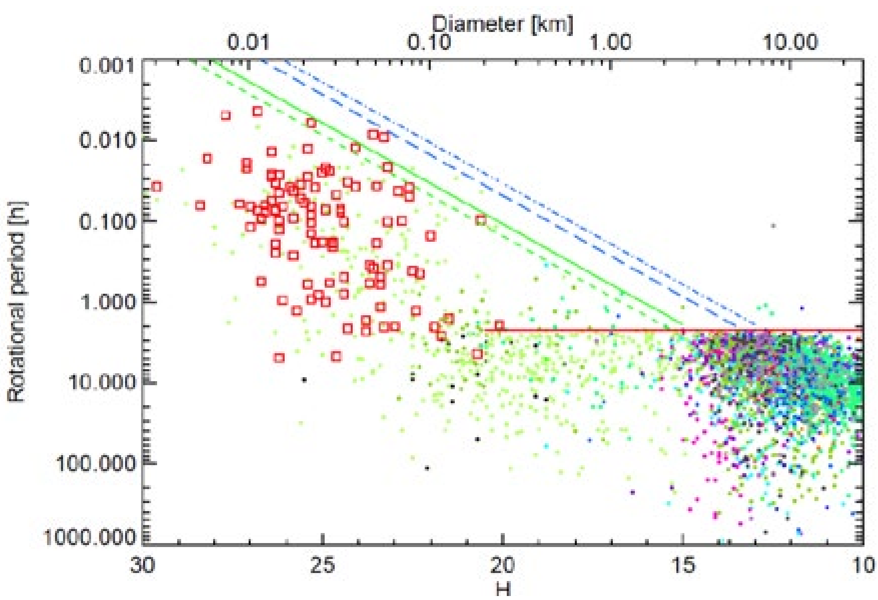


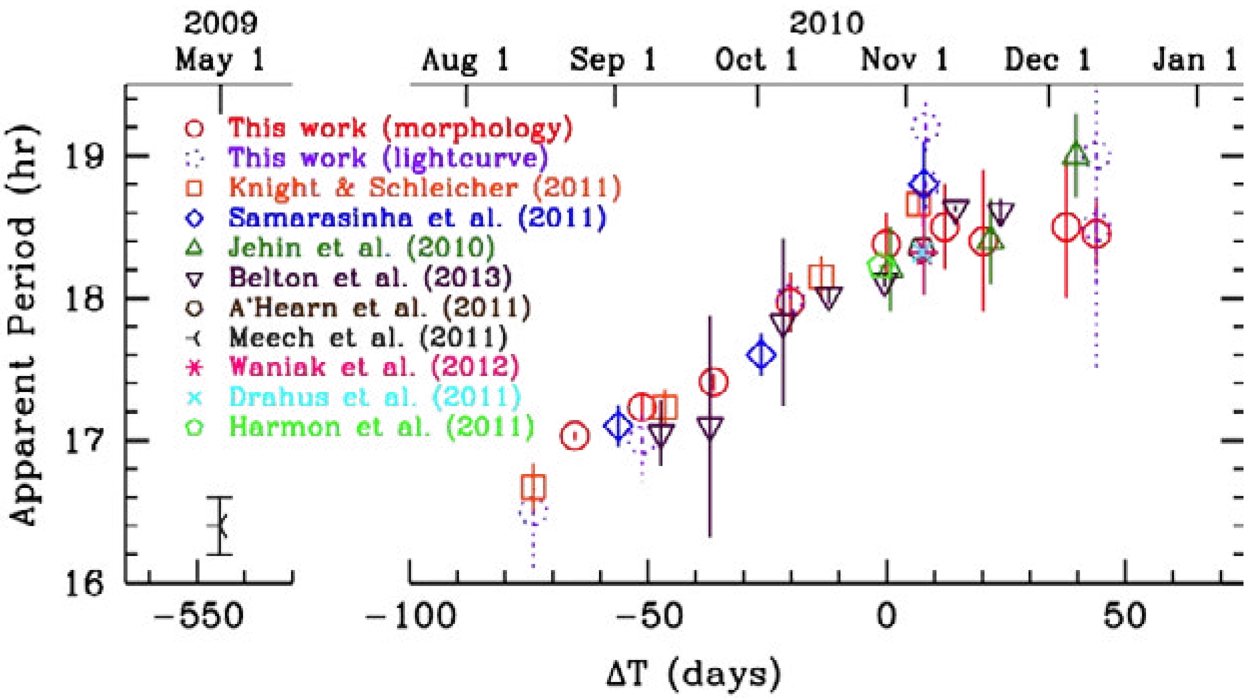
Image (Top): Scientists think that the proto-Haumea (large object in the center of the figure) was a differentiated/partly-differentiated object with a rocky interior and an icy/rocky mantle. Probably after a collision, most of the icy/rocky mantle has been removed and the fragments ejected created the Haumea family members (grey objects). The leftover of the proto-Haumea is the current Haumea. Several objects are classified as candidates to the family (red objects). They are not official members of the family because their composition is unknown or because they have no ice on their surface as the other members of the family. Shape of these objects is approximate and has been derived from their light curves. In some cases, objects have never been observed for light curves and so we do not have a good constraint about their shape. These objects are indicated with a question mark.

Image (Bottom): All asteroids with a known rotational period are plotted. Different colors correspond to different asteroid families (circles). MANOS data are indicated with red squares.

Audrey Thirouin

Since moving to Lowell in September 2014, Dr. Audrey Thirouin has investigated the rotational properties of the small bodies in our solar system. Her main topic was to understand the formation of a specific group of objects called the Haumea family. Members of this family have a similar surface composition of pure water ice and they are clustered in a specific area of the Kuiper belt. Thanks to several observing nights at Lowell Observatory's DCT, Thirouin and her team observed all the members, as well as some potential members of this family. They derived information about the shape, the density, and the rotational period of these objects in order to constrain the formation of this family.

Thirouin also participated in the Mission Accessible Near-Earth Object Survey (MANOS) project, 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 or human exploration. MANOS observes between 5 to 10 newly discovered NEOs per month, with a special focus on the smallest objects (sub-kilometer size objects). MANOS uses a large variety of telescopes around the world, and especially Lowell's DCT, for photometric and spectroscopic studies. Thirouin is working on the NEO rotational properties which can provide useful information about physical properties, like shape, surface heterogeneity/homogeneity, density, internal structure, and internal cohesion. MANOS already derived rotational properties for 104 objects, and discovered the two fastest rotators known to date with rotational period of 15.8s and 17.6s. ▪



Matthew Knight

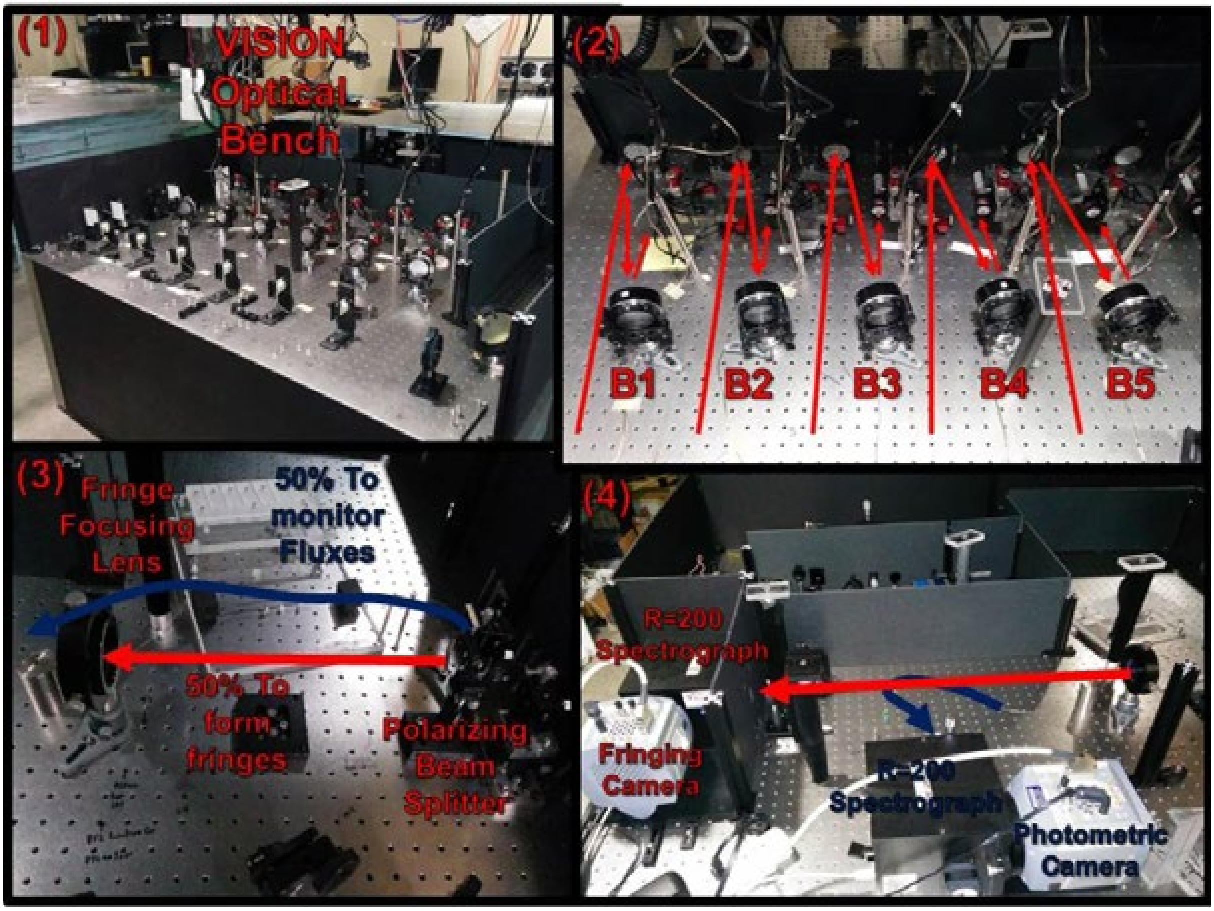
In 2015, Dr. Matthew Knight completed a study of the rotation state of Comet 103P/Hartley 2, the target of NASA's EPOXI mission in 2010. This project combined data that Knight and David Schleicher acquired at Lowell with data collected at Kitt Peak National Observatory by colleagues at the Planetary Science Institute in Tucson, and with data obtained by the EPOXI spacecraft. Knight and colleagues used this combined dataset to place important new constraints on Hartley 2's changing rotation period.

Knight began working on the European Space Agency's Rosetta mission in 2015. Rosetta has been studying comet 67P/Churyumov-Gerasimenko since arriving at the comet in 2014; Knight joined the Alice UV spectrometer team and helps study gas and dust in the coma. In addition to his Rosetta duties, he observed 67P extensively with a variety of telescopes on Earth, highlighted by ongoing optical and IR observations with the world-class Gemini telescopes in Chile and Hawaii.

Knight also continued his studies of comet C/2012 S1 ISON, publishing a paper with Schleicher on their 2013 observations and co-authoring two other papers about this unique comet. He co-authored papers on several other topics, notably including a white paper on potential cometary science with the James Webb Space Telescope and another on the likely comet detection capabilities of the upcoming Solar Orbiter mission.

Finally, Knight was awarded a prestigious Early Career Fellowship by NASA's Planetary Science Division based on his "scientific record, merit of current research, and future promise as a member of the planetary science community. ▪

Image: The changing apparent rotation period of comet 103P/Hartley 2 as a function of time (ΔT) relative to its closest approach to the Sun (which occurred at ΔT=0). Hartley 2 was observed intensively from about -50 days until +20 days and exhibited an unprecedented lengthening of its rotation period by nearly 2 hours during that interval. The work by Knight and colleagues produced nine new measurements of the rotation period, most either earlier than -50 days or later than +20 when there were few, if any, constraints from other observers. They showed that the change in the rotation period likely slowed or stopped after about +20 days. The ultimate rotation period at the end of the 2010-2011 apparition is currently unknown, but Knight and Schleicher have observations planned with the DCT in summer 2016 to measure it again before activity begins on Hartley 2's next approach to the Sun. Hartley 2 is one of just three comets definitively known to be in "complex" rotation (e.g., tumbling), so gaining a better understanding of its rotation is critical for helping to understand ongoing processes in the Solar System.



Victor Garcia

Pre-doctoral Fellow Victor Garcia completed his dissertation in December, 2015 and will receive his PhD in Physics in 2016 from Vanderbilt University in Nashville, Tennessee. For his dissertation work, he led a team of astronomers to commission the Visible Imaging System for Interferometric Observations at NPOI (VISION) for the Navy Precision Optical Interferometer.

Visible-light long baseline interferometry holds the promise of advancing a number of important applications in fundamental astronomy, including the direct measurement of the angular diameters and oblateness of stars, and the orbits of binary and multiple star systems. VISION advances the field by being the first six-telescope visible-light beam combiner in the world. VISION will see, at optical wavelengths, for the first time, the surfaces of stars that are trillions of miles away. Observing stars in such close detail will allow astronomers to advance stellar astrophysics via direct comparisons of stars with complex 3-dimensional models. ▪

Image: VISION incorporates a system of single-mode fibers to combine light from up to six telescopes simultaneously.

Kathryn Neugent

Wolf-Rayet (WR) stars are evolved, massive stars in the last stages of life before exploding into supernovae. Kathryn Neugent has been collaborating with Phil Massey for the past six years studying these stars in the Local Group Galaxies. After searching for WRs in M31 and M33 a few years ago, Neugent and Massey recently turned their focus to the Magellanic Clouds. As part of an ongoing search for new WRs, Neugent, Massey and their collaborators have discovered 16 new WRs, including four in 2015. These discoveries involved a ten-night run on the Swope Telescope at Las Campanas, Chile, to image the Magellanic Clouds using interference filters sensitive to the WR's strong emission lines. After the run, an image subtraction technique was used to help identify possible WR candidates. Finally, spectroscopic follow-up was done using the 6.5-meter Magellan telescopes to confirm the new WRs. However, the most exciting outcome of their survey was not the number of new WRs, but their unique characteristics.

Ten of the discoveries appear to belong to an entirely new class of WRs. WR star spectra is dominated by strong emission lines. However, these stars additionally have absorption lines. One might naively think these absorption lines point to a companion star in a binary system, but the observations don't support this interpretation. We've designated these new WRs as WN3/O3s since the emission lines point to a WN3 designation (nitrogen rich WN star) and the absorption lines point to an O3 star. Both WN3 and O3 stars are fairly bright. However, our WN3/O3s are faint. If you take two bright objects and put them together, the resulting system won't be fainter. Thus, we believe these stars are single as opposed to binary. (continued on next page)

Image: Observing the Magellanic Clouds with the Swope Telescope at Las Campanas, Chile.

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Neugent spent the majority of 2015 modeling the spectra of these stars and found she could fit the spectra using a single set of physical parameters which again points to these stars being single stars. The resulting parameters are similar to those of other early-type, Nitrogen-rich WRs, but the temperatures are slightly higher and the mass-loss rates are slightly lower.

In June, Neugent presented her results at the International Workshop on Wolf-Rayet stars conference held in Potsdam, Germany. Her presentation was well-received by the Wolf-Rayet community and has led to further discussion in the field about these new stars. She was additionally chosen by the Scientific Organizing Committee to participate in the panel discussion on, "The future of massive star research" held on the last day.

Future WR research includes modeling the remaining WN3/O3s as well as investigating their formation and role in massive star evolution. ▪

TECHNICALSUPPORTHIGHLIGHTS

By Bill DeGroff

DCT

Throughout the year, the Discovery Channel Telescope (DCT) reliably supported scientific research. In 2015, part or all of 293 nights were scheduled for science operations. Total actual science time was 274.5 nights (some nights were half-nights), and approximately 47 hours were lost due to technical issues.

DCT site engineering support was provided by Frank Cornelius, Ben Hardesty, Georgi Mandushev, and Mike Sweaton. In addition to routine maintenance of the telescope, dome, and facility systems, the crew carried out engineering improvements aimed at improving the productivity, and reliability of DCT. During 2015, these improvements included:

- Replacing the primary mirror sacrificial definer pins with an improved design with greatly improved life.
- Installing a facility air compressor to augment the existing instrument air compressor.
- Implementing a horizon-pointing mirror wash procedure, simplifying the mirror cleaning procedure, and achieving a significant labor savings.
- Installing a new system for archiving engineering data (active optics, dome motion, weather data, etc.). This resolved a data congestion issue that has been a problem with the original database system since its inception.
- Designing and installing a new, improved grease guard for the mount elevation bearings. The new design prevents grease from dripping onto the elevation axis encoder tapes.
- Reconfiguring the dome slip ring system to prevent nuisance trips of the emergency stop system, eliminating a fault that had interrupted night operations on several occasions.
- Re-designing the optical fiber system for the telescope, improving the fiber runs and the reliability of the data connections.
- Adding UPS outlets for the instrument chiller system remote controls, ensuring the ability to control the chiller during power outages.

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

Image (Left): The Discovery Channel Telescope.

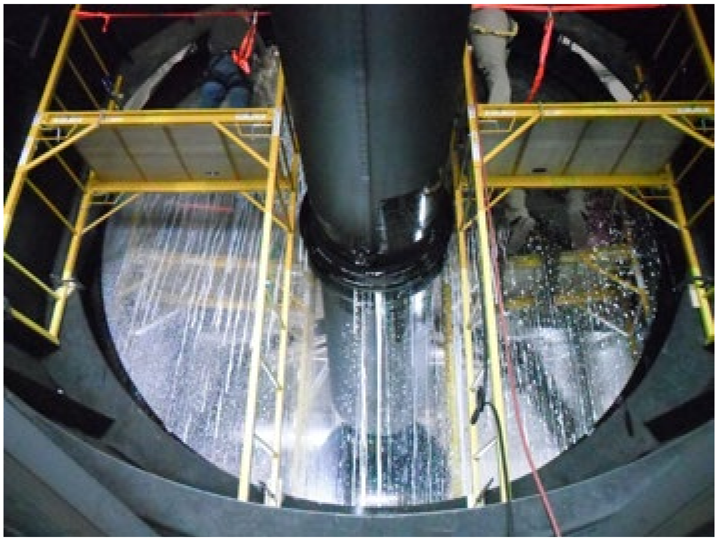
Image (Right): The new DCT facility air compressor system.

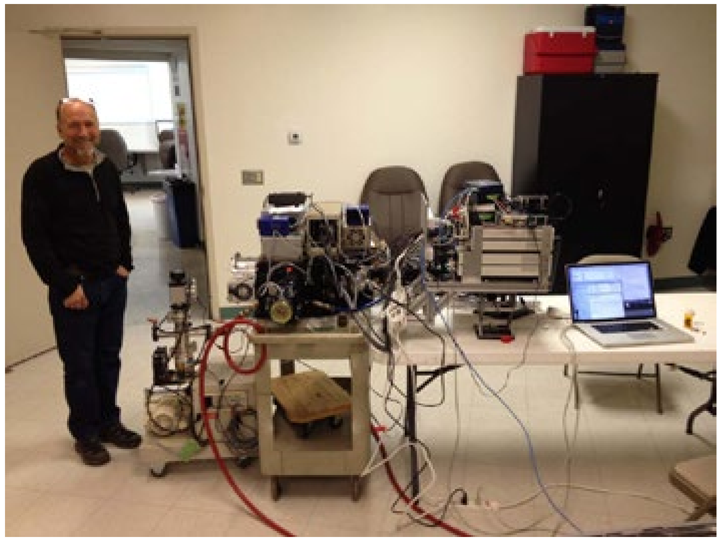
TECHNICALSUPPORTHIGHLIGHTS (continued)

(continued from previous page)

Progress in DCT instrumentation became very visible in 2015 with the installation and commissioning of the DeVeny spectrograph. In late November, the NIHTS spectrograph was installed and achieved first light. Commissioning of NIHTS will continue into early 2016.

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 will require substantial engineering support from the DCT engineering group and the Lowell instrument development group in 2016 as the instruments approach finalized design and installation. In addition, the University of Maryland's RIMAS instrument is progressing and expected to arrive at DCT as early as late 2016. One outcome of the planning for these instruments was the decision to re-aluminize the DCT primary mirror. This activity is expected to occur during the monsoon period in 2016. ▪





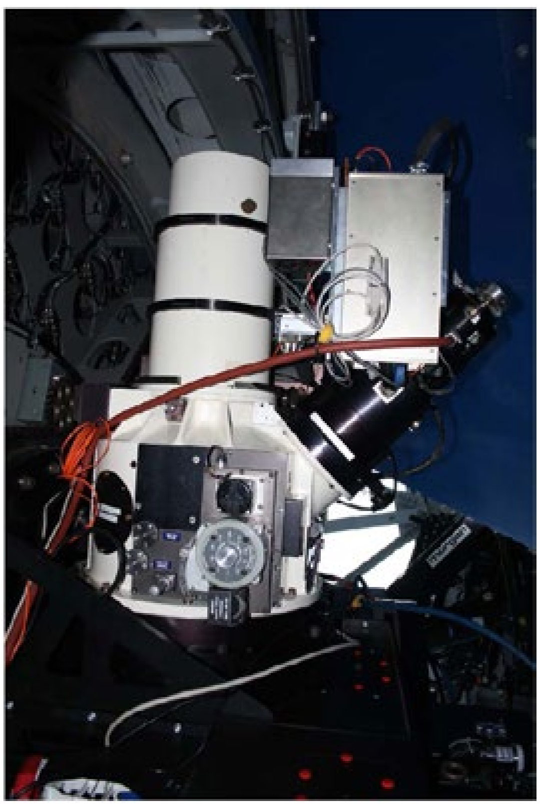


Image (Top Left): The DCT primary mirror undergoing an aqueous wash in May, 2015.

Image (Top Right): The NIHTS spectrograph in the Lowell instrument lab. Tom Bida (shown) and Ted Dunham perform final tests of the instrument the day before it was installed on DCT for the first time.

Image (Bottom Left): The DeVeny Spectrograph, installed on the DCT instrument cube

Image (Bottom Right): The Yale EXPRES fiber-fed spectrograph. Left, the Back-end Module (BEM) which will reside in DCT's instrument room. Right, the Front-end Module, which mounts to the instrument cube. (Credit: Colby Jurgenson and the EXPRES team at Yale University)

Anderson Mesa

Anderson Mesa telescopes continued to support science operations with 304 science nights scheduled for the 72-inch Perkins Telescope, 253 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, 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, will install a modified camera on the telescope to permit follow-up observations of findings from the Catalina Sky Survey. This will require modification of the facility to permit unattended operation. In November, Ralph Nye and Frank Paschal began the engineering effort needed for these modifications. ▪

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 2015 the operations crew, led by Teznie Pugh, produced a remarkable operations record of 351 nights out of 355 nights scheduled. Observers responsible for this solid achievement included Jacob Gannon, Amy Guth, Mike Sakosky, Susan Strosahl, and Stephen Zawicki. The observers were supported in expert fashion by the day crew, including 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. The day crew also performed routine facilities maintenance and support instrument-related upgrade and maintenance tasks at the request of NOFS or NRL. ▪

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): The N07 imaging station at NPOI. Assembly of these imaging stations was supported by the Lowell site crew.

Mars Hill

During 2014 the highly anticipated restoration of the Clark Telescope was begun, and subsequently completed in 2015. This effort comprised 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. Key personnel in this effort included Ralph Nye, Peter Rosenthal, Rich Oliver, Steve Winchester, Glenn Hill, Jeff Gehring, Dave Shuck, and Wyatt Jordan. ▪

Image: The refurbished Clark Telescope.

DEVELOPMENTHIGHLIGHTS

By Hannah Graves

Development Staff

On March 31, Lisa Actor joined the staff as Deputy Director for Development. For the past 18 years Lisa served in a variety of fundraising roles at Westminster College in Salt Lake City, including Associate Vice President of Advancement. For the rest of 2015, Lisa led the team responsible for Lowell's fundraising and membership efforts including: Antoinette Beiser (Leadership Gifts Officer), Mica Gratton (Annual Gifts Officer), Hannah Graves (Grant Writer), and Shannon Gonzales (Development Assistant). ▪

Membership and Annual Fund

The membership program was hugely successful in 2015 with an 87% growth. We received 470 new members in July alone reflecting the public's interest in NASA's *New Horizons* mission that flew by Pluto on July 14. To further engage members with the Home of Pluto, we created the Lunar Membership level with the benefit of an invitation to a quarterly webinar with a Lowell astronomer. Membership income in 2015 totaled $256,680.

A major highlight of the year was our Pluto Flyby Reception on July 14th. Members at the Pluto Circle level and above were invited. Guests mingled with staff and waited patiently to hear the "beep" from *New Horizons* as it flew by Pluto. They also enjoyed a special tour of the Pluto Discovery Telescope.

Lowell Observatory supporters contributed $155,299 to the 2015 Annual Campaign. Funds raised supported Lowell's dual mission of exploration and outreach. Revenue from membership and the annual fund is crucial to the continued development of dynamic programs for the public. ▪

Lowell Observatory Foundation

The newly created Lowell Observatory Foundation board held their first meeting on June 13. The board of seven Foundation trustees elected David Connell as Chair and Bruce Kosaveach as Vice Chair. In the latter half of 2015 they developed the policies that will guide the Foundation as it receives, manages, and invests gifts to benefit Lowell Observatory's mission in perpetuity. The Mars Hill Fund, the Millennium Fund, the Edith Waddell Fund and the Exploration Fund (formerly the Science Research Fund) are now managed by the Foundation for a total of $2.1 million in endowments. ▪

Image (Left): On July 14, members of the Pluto Circle and above were invited to a Pluto Flyby Reception at the Trustee's residence.

Image (Right): The Lowell Observatory Foundation board.

DEVELOPMENTHIGHLIGHTS (continued)

Annual Gala

Lowell's Fourth Annual Gala reflected the excitement of the year with the theme "Pluto and Beyond." A total of 374 guests attended the event which was held at the High Country Conference Center and presented by APS. The spotlight was on three of our own: Kevin Schindler spoke about Pluto's legacy at Lowell; Dr. Gerard van Belle told us how our favorite world captivated him both personally and professionally; and Dr. Henry Roe shared hints as to what we might expect to learn about Pluto from *New Horizons*. We surpassed our goal of $50,000 for the evening with the help of live and silent auctions, which raised more than $10,000. ▪

Percival Lowell Society

At the end of 2015, the Percival Lowell Society (PLS) included 54 members. The Society was created in 2002 to recognize individuals who plan to leave a legacy gift to the observatory. These bequests, trusts, annuities, and other estate gifts help ensure Lowell astronomers continue making discoveries that change the way we see our Universe.

The 2015 Annual PLS Brunch was held in Lowell's Rotunda Museum and included talks from Outreach Manager Samantha Gorney and Ralph Nye, Lowell's Director of Technical Services. Ralph gave the group a presentation on the recently completed restoration of the 24-inch Clark Refractor. ▪

DON

In 2015 Jeff Hall created the Director's Opportunity Network (DON). This inner circle of investors in Lowell Observatory provide $10,000 or more annually for Director Jeff Hall to invest in exploration, education, and outreach at Lowell. DON investors enjoy an annual dinner and the chance to travel with Lowell astronomers for behind-the-scenes tours at foreign observatories. The first trip will occur in the fall of 2016, when DON members will travel with Dr. Hall and Dr. Michael West to tour the Gemini Southern Observatory and Cerro Paranal Observatory in the Atacama Desert of Chile.

By the end of the year, DON included 14 members. Dr. Hall expects to use the funds for a wide range of opportunities in support of Lowell's dual mission of discovery and outreach. He has already used DON dollars in support of a graduate intern for Dr. Lisa Prato's studies of very young binary stars. The research experience offered a promising NAU astronomy graduate the opportunity to expand her academic portfolio for graduate school admission. ▪

Image (Left): Dr. Henry Roe speaks to the crowd at the Pluto and Beyond Gala.

Image (Right): Historian Kevin Schindler spoke about Pluto's legacy at the Gala.

PUBLICPROGRAMHIGHLIGHTS

By Samantha Gorney

Lowell Observatory welcomed a record number of visitors in 2015. The attendance total for the year was 97,591. This marked a 21% increase over the previous high water mark of 80,950, reached in 2008. Many factors including simplified visitor center hours, NASA's *New Horizons* mission, and the Clark reopening contributed to this increase in attendance.

We decided to eliminate seasonal fluctuation of visitor center hours in 2015. At the start of the year we simplified our hours to 10 a.m. to 10 p.m. (Monday through Saturday) and 10 a.m. to 5 p.m. (Sunday), year-round. The new schedule was easier for guests to understand and afforded them more opportunities to visit.

NASA's *New Horizons* mission piqued people's interest in Pluto in 2015. As the "Home of Pluto" we felt a responsibility to provide the public with special Pluto-themed programming. The emphasis we placed on Pluto throughout the year led us to dub 2015 the Year of Pluto. A special exhibit titled Pluto at 85: From Discovery to *New Horizons* was an integral component of the Year of Pluto. The exhibit features a variety of artifacts highlighting Lowell's long association with Pluto, including Clyde Tombaugh's discovery of Pluto at Lowell in 1930.

Our various Year of Pluto events were very well attended. A special week-long Pluto Palooza event, held in conjunction with *New Horizons* flyby of Pluto, attracted some 7,000 visitors. Numerous Pluto-themed events in July brought in more than 15,000 guests that month alone. The "Pluto effect" was clearly one of the driving forces behind the record attendance numbers in 2015.

Our Clark Telescope reopened for tours in September after undergoing a 20-month-long refurbishment. Viewing through the Clark resumed in October. The stunning views offered through the refurbished Clark dazzled guests and staff alike. Improved viewing through the McAllister telescope—the other workhorse of the public program—resulted from a thorough cleaning of the primary mirror and a new coat of aluminum on the secondary mirror.

Special School's Out Kids are Free events held on five separate occasions in 2015 attracted large numbers of local visitors. The observatory's programs designed for visiting school groups continued to be popular as well. More than 4,500 school children visited Lowell on field trips throughout the course of the year.

Lowell Observatory Camps for Kids (LOCKs) programs on Mars Hill served more than 155 students and a number of local teachers. Children in the LOCKs programs learned about topics in astronomy and physics through hands-on exercises and explorations. The expansion of the LOCKs program beyond Mars Hill was an exciting development in 2015. A satellite LOCKs: Preschool program launched in Cave Creek, Arizona in partnership with the Cave Creek Unified School District. A partnership with the Flagstaff Family Food Center brought LOCKs activities to children enrolled in the center's summer camp.

It is the exceptional members of the public program team that enabled us to have such a successful year in 2015. I want to thank them for their passion and dedication to outreach. ▪

Image (Left): Public Program staff display the "Pluto Salute" during Pluto Palooza.

Image (Right): Lowell Observatory Camps for Kids (LOCKs).

Navajo-Hopi

The Lowell Observatory Navajo-Hopi Astronomy Outreach Program continued strong in 2015. This is a science enrichment and outreach program for 5th-8th grade Navajo and Hopi students and their teachers. The program pairs astronomers with teachers for one year. The astronomer visits the classroom throughout the year, leading astronomy discussions and hands-on activities in collaboration with the teacher. The astronomer also holds star parties at the school and involves tribal educators in presenting traditional astronomical knowledge. The year-long partnership culminates in a field trip to Lowell Observatory in which the students visit the observatory's Steele Visitor Center during the day and observe on two of our research telescopes at night.

Two components of this outreach program make it unique: 1) The astronomers take the time to drive long distances to get to remote schools, not just once, but in a sustained effort throughout the school year; 2) The program provides all of the materials for classroom activities, allowing some classes the opportunity for hands-on activities that they would not otherwise be able to afford.

In 2015 the Navajo-Hopi Outreach program finished the 2014-15 school year with six partnerships and began the 2015-16 school year with eight partnerships that involves 260 students, nine teachers, and one student teacher. Participants included faculty, post-doc, and pre-doc astronomers and educators at Lowell Observatory and Northern Arizona University.

Schools ranged from Tuba City Boarding School, a 1.25 hour drive from Flagstaff, to Cove Day School, a 5.5-hour drive from Flagstaff. Over the course of the 2014-15 school year a total of 29 classroom visits were made. Classroom activities have included the modeling the solar system in which the sun is an 8-inch-diameter ball, modeling moon phases, modeling a comet nucleus, exploring the how one would recognize microbial life on another planet, Navajo Constellation Bingo, designing your own constellation, simulating mapping a planet surface with radar, optics and how telescopes work, modeling impact craters, modeling shield volcanoes, designing a space capsule for an egg (and dropping it from a second story to see if the egg survives), building an edible spacecraft and an edible rover, and more.

The Navajo-Hopi Outreach program was generously funded in 2015 by the O. P. and W. E. Edwards Foundation, the Stone Soup Foundation, NAU Space Grant, the Richard F. Caris Foundation, the John F. Long Foundation, the Arizona Public Service Foundation, a NSAS E/PO grant, and nine private individuals. ▪

Image (Left): Dr. Nick Moskovitz and students point to an asteroid during a visit to the control room of the 72-inch telescope.

Image (Right): Dr. Will Grundy demonstrates properties of liquid nitrogen to students.

PUTNAMCOLLECTION**CENTER**HIGHLIGHTS

By Lauren Amundson

The Putnam Collection Center (PCC) was a busy place in 2015. Librarian and Archivist Lauren Amundson and Curator Samantha Thompson oversaw the ongoing move of collections into the building. This included five manuscript collections, sets of the *Annals of the Lowell Observatory*, several textiles, and Percival Lowell's personal library.

The staff welcomed five scholars who conducted archival research on the 1918 solar eclipse, Pluto, the International Planetary Patrol, astrophotography, and the 24-inch Clark Telescope. The archives also received dozens of requests for Pluto-related material in conjunction with the 85th anniversary of its discovery and the *New Horizons* flyby. The digital collections on the Arizona Memory Project received 11,760 hits, including over 4,000 in July alone.

Staff offered a daily open house of the PCC lobby for the public. The lobby houses Percival Lowell's 1911 Stevens-Duryea touring car and exhibits that highlight the observatory's research and history. Staff gave several private tours of the archives to individuals and groups, including the state librarian and the Arizona Library Association.

In May, Lowell received the Institutional Award of Excellence from the Museum Association of Arizona. Only three institutions in the state received this honor.

Amundson and Thompson attended and presented at several conferences and meetings, including the Arizona Archives Summit, the Society for the History of Technology annual meeting, and the History of Science Society annual meeting.

Amundson managed ten volunteers and their projects, which included collections processing, cataloging, digitization, and preparation for moving materials to the PCC's freezer and repository. Thompson worked with three different interns to create exhibits for the Steele Visitor Center and Clark Telescope dome. Amundson and retired astronomer Wes Lockwood continued to conduct oral history interviews with former Lowell employees. ▪

Image (Left): A small section of the PCC's many collections.

Image (Right): Librarian Lauren Amundson (left) and Curator Samantha Thompson with Lowell's Award of Excellence from the Museum Association of Arizona.

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STATEMENTOFFINANCIALPOSITION

COMBINED BALANCE SHEET

DECEMBER 31, 2015 (with comparative totals as of December 31, 2014)

ASSETS	2015	2014
Current Assets		
Cash and cash equivalents	$ 98,558	$ 3,235,560
Restricted cash	887,715	261,760
Investments	1,645,941	1,332,537
Research grants receivable	331,296	266,765
Contributions receivable, current portion	366,202	800,141
Inventory and other assests	306,928	185,755
Total Current Assets	**3,636,640**	**6,082,518**
Property, plant and equipment, net	44,035,840	45,517,194
Contributions receivable, current portion	375,000	500,000
Collection item	400,000	400,000
Investments, permanently restricted	37,221,789	35,587,552
Total Assets	**$85,669,269**	**$88,087,264**

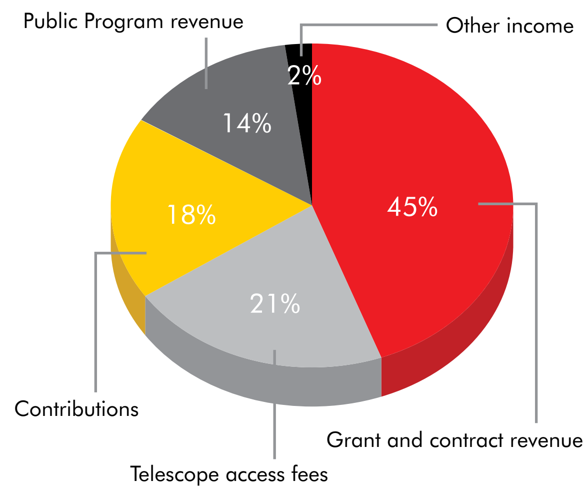
LIABILITIES AND NET ASSETS	2015	2014
Current Liabilities		
Accounts payable	$ 132,697	$ 157,784
Accrued expenses and other current liabilities	490,090	334,845
Deferred research grant revenue	119,405	72,263
Deferred revenue - other	8,050,368	6,980,427
Total Current Liabilites	**8,792,560**	**7,545,319**
Long-term debt	20,400,000	20,400,000
Obligation under interest rate swap	490,206	636,674
Total Liabilites	**$29,682,766**	**$28,581,993**
Net Assets		
Unrestricted	$ 17,483,902	$ 23,192,086
Temporarily restricted	1,073,173	1,214,507
Permanently restricted	37,429,428	35,587,552
Total Net Assets	**55,986,503**	**59,994,145**
Total Liabilities and Net Assets	**$85,669,269**	**$88,576,138**

STATEMENT OF FINANCIAL ACTIVITIES

DECEMBER 31, 2015 (with comparative totals as of December 31, 2014)
(before depreciation)

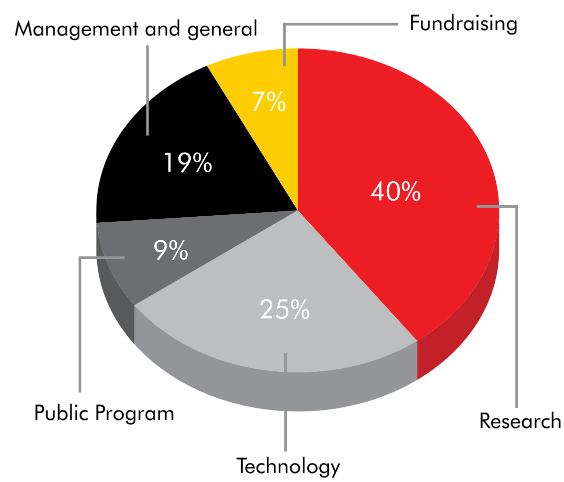
REVENUE	2015		2014	
Grant and contract revenue	$ 3,235,560	(45%)	$ 2,886,459	(30%)
Telescope access fees	1,539,293	(21%)	1,137,662	(12%)
Contributions	1,332,537	(18%)	2,169,117	(23%)
Public Program revenue	1,021,419	(14%)	1,074,509	(11%)
Investment income (loss) net	(352,689)		1,945,212	(21%)
Other income	157,330	(2%)	242,568	(3%)
Total Support and Revenue	**$ 6,933,450**		**$ 9,455,527**	

2015 REVENUE



EXPENDITURES	2015		2014	
Program services:				
Research	$ 3,598,818	(40%)	$ 3,623,368	(43%)
Technology	2,262,916	(25%)	2,181,051	(26%)
Public program	793,208	(9%)	586,561	(7%)
	6,654,942		6,391,250	
Support services:				
Management and general	1,689,105	(19%)	1,514,532	(18%)
Fundraising	672,146	(7%)	520,941	(6%)
	2,361,252		2,035,472	
Total Expenditures	**$ 9,016,193**		**$ 8,426,723**	
Gain on interest rate swap	146,468		131,734	
Change in net assets	$ (1,936,275)		$ 1,160,538	

2015 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 2015 and 2014 was $2,071,000 and $2,278,000.

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, 2015. Copies of the audited financial statements are available at https://lowell.edu/about/governance_and_financials/

LOWELL OBSERVATORY

ANNUALREPORT

2015

Image (Front Cover): Lowell staff in front of the Pluto Discovery Telescope with one of the first New Horizons Pluto images. Image (Back Cover): Pluto taken by the New Horizons spacecraft (Credit: NASA/JHUAPL/SwRI)