Lowell Observatory

Flagstaff, Arizona 86001

This report covers the interval 1 July 2002 through 30 June 2003.

1. PERSONNEL

William Lowell Putnam, grandnephew of Percival Lowell, continued as Trustee of the Observatory.

The scientific staff included A. S. Bosh, E. L. G. Bowell, M. W. Buie, E. W. Dunham, J. L. Elliot, O. G. Franz, W. M. Grundy, J. C. Hall, D. A. Hunter, K. L. Jessup, N. L. King, B. W. Koehn, G. W. Lockwood, G. Mandushev, P. L. Massey, R. L. Millis (Director), M. S. Oey, D. G. Schleicher, C. S. Shoemaker, J. R. Spencer, L. H. Wasserman, N. M. White, and L. M. Woodney. H. L. Giclas, though officially retired, has been involved in Observatory activities. Amanda S. Bosh was Boston University staff resident at Lowell.

Scientific support staff included T. A. Bida, S. B. Holmes, J. D. Levinthal, M. C. Lierz, B. A. Skiff, S. Strosahl, B. W. Taylor, and M. E. Van Ness.

Technical and administrative staff included J. J. Bailey, A. S. Beiser (Librarian), J. L. Darwin, M. E. DeMuth, M. L. Evans, H. S. Horstman, P. J. Houlahan (Information Technology Manager), M. M. Inge, M. Linzey, G. R. McGlothlin, R. M. Melena (Secretary–Treasurer), C. J. Millette, Jr., K. S. Morefield, R. A. Nye, C. J. Ochser (Director of Development), R. C. Oliver, K. A. Phillips (Manager, Media Relations and Public Affairs), S. Strosahl, and C. R. White.

Directly involved with the operation of the NPOI were L. P. Bright, E. K. Isbrecht, S. L. Nichols, B. O'Neill, J. A. Shannon, W. Wack, and N. M. White.

Working in the Observatory's educational program were R. C. Burgoon, J. P. DeDecker, R. W. Evans, J. C. Hall (Associate Director for Education and Special Programs), L. J. Gonzales, E. Hillyer, M. Hooker, E. Kuefler, H. M. Landau, K. Moore, T. A. Rodriquez, K. S. Schindler, P. R. Stiers, and R. P. Tweed.

Volunteers made a considerable contribution to the Observatory. Martin Hecht served as archival assistant. Reba Miller, Ava Stone, and Ed Nettell assisted in the library; Claudia Martin and Julia Millis in the business and development offices. Henry Holt assisted Shoemaker. Volunteering for the Public Program were J. Adams, S. Bogan, D. Chalke, B. Cole, J. Crisman, C. Dechambre, T. Fisk, J. Gordon, R. Helm, A. J. Inman, C. Kirkpatrick, E. Kuefler, H. Lacey, K. Lamson, J. McFarland, G. Mishkin, C. Moore, Y. Nemoto, S. Nichols, A. Odell, D. S. F. Portree, C. Sapio, M. Schimmelpenninck, A. Sherwood, A. Smith, C. Smith-Dowling, D. Smith, B. Sommers, and R. Taylor.

Instrument Scientist Edward Dunham was named 2002 Employee of the Year in recognition of his research accomplishments and his direction of the design and construction of complex instrumentation for the Observatory.

Approximately 26 visiting astronomers, in addition to several from Boston U., were awarded time on Lowell telescopes. Included in this number are several from the National Undergraduate Research Observatory consortium (NURO). A total of about 30 students accompanied the NURO observers at the telescope.

2. FACILITIES

2.1 Anderson Mesa Telescopes

The Lowell Observatory–Boston University partnership for shared use and development of the Perkins Telescope continued during the reporting period and has been extended for an additional five years. The partnership agreement provides for the two institutions to share time on the telescope equally and to work together on new instrumentation and other improvements to the facility.

No significant additional work was done this year to improve the seeing at the 72-in Perkins Telescope. Wavefront curvature measurements made by Massey indicate the telescope is seeing-limited, even though it does have measurable aberrations due to an incorrect secondary conic constant and mirror support problems. Oliver completed a set of new telescope interface electronics that will be put in service at the telescope. This upgrade is the first in a series to improve our ability to maintain and upgrade the telescope control software, improve reliability, and reduce our exposure to serious downtime due to failure of critical components.

New optics for the 42-in John S. Hall Telescope were completed. A new primary mirror cell and top end for the telescope have been built in the Lowell shop. It is expected the optics will be installed during the coming year.

The USNO IRCAM, the Lick/Loral 2K×2K CCD camera system continued in routine use at the 72-in Perkins Telescope during the report period.

Buie continues collaboration with D. Clemens (Boston U.) in the building of Mimir, a new 1–5 micron imager and spectrograph. Progress was substantial during this reporting period, with most of the work performed at Boston U. The dewar is complete, and successful cold tests have been carried out. The optics are being mounted. At Lowell, the Leach detector controller for Mimir has been cabled up and successful images from a bare Aladdin multiplexer have been obtained. The basic IR readout modes have been implemented, and the electronics have been shipped to Boston U. for integration with the rest of the system. We hope to bring Mimir on line at Lowell during the coming year.

PRISM, an imaging polarimeter for the Perkins Telescope designed by K. Janes of Boston U., has also made great strides this year. As with Mimir, most of the work is at Boston U. The optics have been mounted, and the CCD received. The mechanical parts are almost complete. It is hoped to bring PRISM on line at Lowell during the coming year.

Taylor continued work on the Lowell Observatory Instrument System (LOIS), an instrument control software system that will be used in the generation of Lowell instruments

now being developed. Efforts centered on improving its stability and reliability, incorporating Aladdin array control, and developments related to HIPO.

Dunham and Taylor have acquired much additional experience this year with the CCD control electronics from Astronomical Research Cameras (ARC), a small company in San Diego operated by Bob Leach. Leach controllers are used in almost all of our instruments, as well as in numerous instruments around the world. Taylor has assumed the task of moderating an email forum for users of these controllers.

2.2 Navy Prototype Optical Interferometer at Lowell Observatory

The Navy Prototype Optical Interferometer (NPOI) is a collaboration among the Naval Research Laboratory, U. S. Naval Observatory, and Lowell Observatory. Lowell observers continued science and engineering observations for about nine months. Lowell staff played significant roles in site maintenance, instrument deployment, and electronics development. For about three months, all efforts were directed towards installation of new optical vacuum tanks that will divert the light down the long delay lines. No observations were possible during this period. In general, progress last year fell into the categories of construction and instrument refinement.

Much effort was directed towards adding the components that will allow the instrument to be used with baselines longer than the maximum of about 60 m currently being used. This included adding six vacuum tanks containing four remotely controllable mirrors that will redirect the six optical beams down 100-m vacuum tanks, each containing twelve remotely controlled mirrors. Installation continued of vacuum tanks that receive the star light from the siderostats and their alignment for the long baseline stations.

Instrument refinements dealt with improving the quality of the observations, automation, and calibrations of various parts of the instrument. A new laser metrology system was developed and successfully tested to measure effects of thermally induced changes to the various reflectors that transport the beam to the laboratory. That path length was expected to be constant during a night but was found to vary in practice. The system allows measurement of these changes down to the micron and correction of the ''constant'' term. This improvement is essential for successful all-sky astrometry at milli-arcsecond accuracy.

Other refinements were dispersive corrections for the approximately 5% of the light path in the air between the primary mirror and beam combination. Testing of the optical mechanical systems within the long delay proved the components able to meet the alignment and time requirements. Connecting the long delay lines into the full system is anticipated in late 2003.

First-ever observations with a co-phased, six-station optical long-baseline array (NPOI) were published. The object was a triple star system, Eta Virginis. Preliminary, astronomically determined orbits of the two components in the close pair by reference to the third star were derived. The mass ratio for the close pair is 1.27, with an orbital inclination of 31 degrees.

2.3 Mars Hill Telescopes

The 18-in astrograph was equipped for partially automated operation. It contributed to prediction of the P126 and P131.1 occultations by Pluto. The long observational baseline it produced was critical in correcting the residual wobble of the Pluto–Charon blended center of light location.

2.4 Next Generation Lowell Telescope

A semi-permanent site-testing facility has been set up by White and Bida at a site near Happy Jack, Arizona, our current baseline site. Under Bida's direction, differential image motion observations have been undertaken every clear night by observers Bright and DeDecker. Analysis has been carried out by Moore. Median seeing has been found to be consistently near 0.8 arcsec (FWHM). We are also taking lunar scintillation data with an eye toward constraining the vertical turbulence profile. Thomas Sebring, who previously managed the Hobby–Eberly and SOAR Telescope projects, joined the staff to manage the NGLT project. Edward Dunham was appointed as the NGLT project scientist. The science and technical requirements for the telescope have been firmed up, and procurement packages for the study contracts have been prepared. A contract was awarded for modification of an existing building to serve as offices for the NGLT Project Team. The project will be ramping up to full strength during the coming year as the technical studies progress, the new office space becomes available, and the project office staff grows.

2.5 Instrumentation

HIPO, a two-channel, high-speed CCD photometer is being developed at Lowell for use on SOFIA, the Stratospheric Observatory For Infrared Astronomy. It will be used for occultation observations and for initial testing of the integrated SOFIA observatory. FLITECAM, an instrument being built at UCLA, will sometimes be mounted together with HIPO on the SOFIA telescope, both for testing purposes and for occultation observing.

HIPO development is progressing well, given the large amount of effort involved in the FAA certification packages. FAA requirements have delayed completion of the instrument. Approval of the main mechanical data package was received in January, and mechanical fabrication is in full swing. The electrical data package has been submitted and cabling will begin soon. HIPO will be tested on the telescope in the fall and will be ready for use in the SOFIA test program in the coming year.

Much progress was made on the ground-based extrasolar planet search project, carried out under the auspices of the NASA Origins program. The Planet Search Survey Telescope (PSST) is in routine automated operation and has obtained large data volumes on fields located in Perseus, Auriga, Bootes, Cancer, and Hercules. Mandushev has taken over the data analysis for this project and has finished three seasons on the Auriga field and one season each of three other fields. At the same time, he explored the possibility of using DAOPHOT and an image subtraction scheme in place of T. Brown's STARE analysis code. Both had significant

technical problems, though the image subtraction scheme still has some chance of being a practical improvement. This year we provided a list of Auriga candidates to D. Latham (SAO) and D. Charbonneau (Caltech) for spectroscopic and photometric follow-up observations. All candidates turned out to be either hot stars, eclipsing binaries involving giants, or blends of eclipsing binaries with third stars.

Our work is done in close collaboration with Brown's STARE system (HAO, but located in the Canary Islands), and D. Charbonneau's system (Caltech, located at Palomar). We are also continuing our somewhat looser collaboration with W. Borucki's Vulcan project at NASA Ames.

2.6 Instrument Labs and Shop

The laboratories have been improved with the addition of air conditioning, a residual gas analyzer for vacuum leak detection and evaluation, interferometric calibration of our CNC milling machine's metrology, and a new computer system.

2.7 Library

During the report period, a total of 42 individuals accessed the Lowell Observatory Archives. Included were publishers, historians of astronomy, and amateur astronomers from the United States, Japan, Great Britain, Canada, Australia, and France.

Volunteer E. Nettle made improvements to the historical photographic database; M. Hecht and R. Miller sorted and indexed archival correspondence and manuscripts; A. Stone continued to edit historical photographic database and began preliminary work to preserve historical logbooks. Grants from the Southwestern Foundation for Education and Historical Preservation and the Raymond Educational Foundation helped to fund preservation of 80 historical observation logbooks and letter copybooks.

2.8 Computer Facility

A number of incremental improvements to the Observatory's computing infrastructure were accomplished, including completion of the transition from NASA to Qwest internet connectivity, implementation of a RAID backup system, and initial implementation of an email Spam filter.

3. RESEARCH

3.1 The Solar System

3.1.1 Planets, Satellites, and Their Atmospheres

Bosh observed three Saturn occultations (with C. Olkin) at the IRTF using SpeX and at Lowell using IRCAM. Analyses of these data are ongoing.

Lockwood continues to collaborate with H. Hammel (SSI) and K. Rages (NASA Ames) on multi-wavelength spacecraft and ground-based near-infrared adaptive optics imaging of Uranus and Neptune. Hammel and Lockwood obtained Keck AO images in the summer of 2002.

Lockwood continues a long-term program to monitor seasonal and secular variability of the albedos of Titan, Uranus, and Neptune using photoelectric photometry in the *b* and *y* Strömgren passbands. Neptune's brightness may vary seasonally with a 30-year lag, but this hypothesis conflicts strongly with historic photometry obtained at Lowell in the 1950s and 1960s. The Titan photometry now covers a full orbit around the Sun (29.5 years), and we are positioned to see if the light curve repeats precisely.

Spencer continued his work with *postdoc* Jessup and collaborators on the analysis of new HST/STIS spectroscopy of Io's atmosphere, which provided for the first time a long-slit limb-to-limb profile of UV SO_2 absorption lines across Io's disk and included the volcanic plume Prometheus. The data showed, among other things, that Io's atmosphere varies smoothly with latitude and/or time of day, rather than being concentrated over volcanoes. This implies that the atmosphere on the anti-Jupiter hemisphere is predominantly supported by frost sublimation, rather than volcanoes. Results have been submitted to *Icarus* for publication. Spencer and Jessup also obtained new HST images and spectroscopy of the Pele plume in February and March 2003–preliminary analysis shows rapid temporal variations in plume activity.

Spencer and Jessup, with collaborators, also continued ground-based investigation of Io's atmosphere at thermal infrared wavelengths, using data from the high-resolution mid-IR spectrograph TEXES at the IRTF. New observations in December showed a decrease in SO_2 gas absorption line strength compared to the previous year, and large variations in line strength with longitude. Modeling of these data, in collaboration with E. Lellouch (Obs. de Paris, Meudon) and M. Lopez-Valverde (Inst. de Astrofisica da Andalucia, Spain), is under way; preliminary results were presented at the 2002 DPS meeting.

Spencer continued to work with J. Rathbun (Redlands U.) on observations of Io's volcanoes using the IRTF and the 72-in Perkins Telescope. Several occultations of Io by Jupiter and other Galilean satellites were observed and showed that the volcano Loki was inactive through much of the 2002/2003 apparition. A brief, bright eruption in March 2003 was discovered.

Spencer and Rathbun also continued analysis of *Galileo* Photopolarimeter/Radiometer (PPR) observations of Io, including production of a map of thermal emission from Io's night side that showed 52 active volcanic hot spots, some previously unknown. Results have been submitted to *Icarus.*

3.1.2 Asteroids

Bowell and Koehn continued work to increase the known population of near-Earth asteroids and comets under the aegis of the LONEOS program. Observation and moving-object detection have been largely automated. Their approach favors the detection of near-Earth asteroids (NEOs) larger than 1 km in diameter, the size range considered to be potentially hazardous to civilization. Secondary and tertiary science goals comprise the discovery of non-Earth-approaching asteroids and a suite of non-solar system projects, respectively. During the reporting interval, the LONEOS system was operated on 121 nights, resulting in

580,000 asteroid detections, most of which were published in the MPCs. Thirty-five NEOs and three comets were discovered during the reporting interval.

Using improved image-detection software, REU student T. R. Grimstad (McMurry U.) re-reduced and analyzed archived LONEOS images. About 2.5 times more asteroid images were detected than had been with the original software. During the MIT astronomy field camp, student A. Wallace worked on optimizing parameters in the moving- object detection software. W. S. Kelly (Antioch U. undergraduate) continued work begun by Grimstad.

3.1.3 Kuiper Belt Objects

Millis, Buie, and Wasserman, with J. L. Elliot, S. D. Kern, K. Clancy (MIT); R. M. Wagner (LBT Obs.); E. I. Chiang and A. Jordan (UC Berkeley); D. E. Trilling (U. Pennsylvania); and K. J. Meech (U. Hawaii) continued their Deep Ecliptic Survey, a reconnaissance of the Kuiper Belt with the MOSAIC Cameras on the KPNO and CTIO 4-m telescopes. To date, 219 KBOs and Centaurs discovered in the Survey have received preliminary designations or permanent numbers. A description of the search methods and initial results, based on the first 69 objects discovered, has been published (Millis *et al.*, AJ 123, 2083, 2002). Among other findings, the team has reported the discovery of the first Neptune Trojan, 2001 QR 322, and discussed implications of the relative population of various mean-motion resonances (Chiang *et al., AJ* 2003, in press). Extensive data products from the survey are available on the Lowell website (www.lowell.edu/Research/DES/). The survey images themselves will soon be available in the NOAO archive.

3.1.4 Comets

Schleicher obtained narrowband photometric measurements of eleven comets with the 42-in Hall Telescope during the reporting interval. Targets of focused observing campaigns included Comet Ikeya–Zhang (2001 C1), which last appeared in the mid-17th century, and several long-period comets: LINEAR (2000 WM1), LINEAR–NEAT (2001 HT50), LINEAR (2001 RX14), Kudo–Fujikawa (2002 X5), and LINEAR (2002 O7). Woodney obtained broadband imaging of two comets with the potential to be bright next year, LINEAR (2002 T7) and LINEAR (2002 O7), as well as broadband images of several other comets available at the time of observations. In collaboration with Y. Fernandez (U. Hawaii), two other observing runs were successful in the search for candidate comets with no coma, to obtain infrared spectra of with the Subaru Telescope on Mauna Kea.

Woodney and Schleicher have nearly completed analysis of photometry and narrowband imaging of Comet LINEAR (2001 A2). Imaging in CN, C_2 and C_3 revealed arcs symmetrical about p.a. 250°. Three successive arcs separated by approximately 12,000 km were observed on each side; outward motion of the arcs was detected. These arcs were not observed in the dust continuum. Results from Monte Carlo modeling of the source locations indicate that the data is best fit with two jets and an ''equator-on''viewing geometry. The data are consistent with a 5.8- or a 2.9-hour period. The 5.8-hour period gives an outflow velocity of 0.6 km/s. OH production rates from June 28 and July 27 were log Q(OH) = 28.69 and 28.14, respectively, with equivalent log Q (water; vectorial)= 28.82 and 28.20. Over the entire observed apparition the r-dependence of water was much steeper than that for dust.

In collaboration with T. Farnham (U. Maryland), Schleicher has completed the re-reduction and analysis of all Lowell Observatory Wild 2 photometry obtained during the 1978 and 1984 apparitions. After combining with our 1997 data, obtained in support of the *Stardust* spacecraft mission, the resulting gas and dust production rates were supplied to *Stardust* mission team members R. Newburn and M. Hanner (JPL). Analyses of 10 nights of narrowband imaging obtained during 1997 are nearly complete. The images show evidence of two fan-shaped jets, one early in the apparition and another jet during the second half of the year, implying two source regions on the nucleus whose gas and dust production rates varied with season.

Schleicher and Farnham completed photometry reductions from the 1999/2000 apparition of comet P/Tempel 2 that studied compositional variations with season. Results confirmed the very strongly asymmetric production rates about perihelion observed at previous apparitions. These results will be combined with image analyses to examine the hypothesis that Tempel 2's abrupt increase of activity at $r <$ 1.7 AU is due to the arrival of ''Spring'' at the location of a major active region on the surface of the nucleus.

Following the postponement of the January launch of ESA's ROSETTA mission, ESA began a search for new target candidates, with Comet 67P/Churyumov–Gerasimenko (C–G) as a preferred option. To assist in the final target decision, Schleicher re-reduced and analyzed photometric observations from the 1982/83 and 1995/95 apparitions and provided a summary of results to the ROSETTA team. Subsequently, Comet C–G has been selected as the new ROSETTA target, with launch in 2004. Gas and dust measurements yield the following results: Water production, based on OH, has a steep (~–5) dependence post-perihelion, while minor species and dust are less steep (~ –2 to –3). All species exhibit larger production rates following perihelion, with water having a ~2 times pre/post-perihelion asymmetry, while minor species and dust have a larger asymmetry. The asymmetry implies a strong seasonal effect and probable high obliquity of the rotational axis, along with one or more isolated source regions coming into sunlight near perihelion. Peak water production (which occurred about one month after perihelion) was $\sim 1.0\times10^{28}$ mol s^{-1} and, when combined with a standard water vaporization model, implies an effective active area on the surface of the nucleus of ~2 km^2. Abundances of carbon-chain molecules yield a classification of slightly ''epleted'' in the A'Hearn *et al.* (*Icarus* 118, 223, 1995) database. The peak dust production [as measured by $A(\theta)f\rho$] was ~450 cm, while the color of the dust is slightly reddened. In comparison to original ROSETTA target Comet 46P/Wirtanen, Comet C–G has essentially the same peak water production and a peak dust production about three times greater than does Wirtanen (assuming that the properties of the dust grains are similar).

The radial profiles of Hale–Bopp gas images obtained

near perihelion in 1997 were previously extracted to accurately determine scalelengths of the observed daughter species and their respective parents. The resulting parent and daughter scalelengths were systematically greater (by 2–3 times) than canonical values, due to the much higher outflow velocities in Hale–Bopp as compared to smaller, less productive comets. Schleicher has now begun an investigation of aperture photometry obtained as Hale–Bopp approached the Sun, in order to determine how the scalelengths evolved over time. Improved scalelengths are required so that the entire photometric data set for Hale–Bopp can be reduced to accurate gas production rates.

Woodney has begun analysis of Echelle spectra of Comet Hyakutake taken at the KPNO 4-m on the night of the closest approach of the comet to Earth. Spectra were taken on nucleus and at three offset positions, giving a unique look at the coma at both high spatial and spectral resolutions. Thus far, slit-integrated, continuum-subtracted spectra have been obtained for each offset position from our collaborators at U. Maryland [M. A'Hearn, D. Wellnitz, and R. Meier (now at Swissray)]. Schleicher has resurrected and updated his models of OH fluorescence and collisional quenching. These models have been run and used to determine that the observed OH has a sunward velocity of approximately 1 km/sec and is 65% to 75% quenched. This is consistent with the outflow velocity determined by Combi *et al.* (*ApJ* 512, 961, 1999) from CN, C_2 , NH_2 and O(^{1}D) spectra. Woodney is currently working to modify the NH fluorescence models developed by Meier to determine the velocity of NH.

3.2 Stars

3.2.1 Solar–Stellar

Hall and Lockwood continue their Solar–Stellar Spectrograph program (SSS) with NSF support. The goal is to monitor long-term (cycle timescale) magnetic activity and to compare that with irradiance variations of the Sun and sun-like stars. Lockwood has recently completed a successful merger of Mount Wilson Ca II H and K data with Lowell SSS data, and Lowell photometry (1984–2000) with similar photometry obtained by automatic telescopes of the Fairborn Observatory (1993–2002), thereby attaining nearly two decades of continuous photometric coverage of several dozen solar analog stars. The goal is to see if the Sun is truly ''normal'' and to identify solar twins that match solar behavior in every respect. Hall continues development of a wavelet–based method for noise reduction in SSS spectra and multi-parameter proxies of solar and stellar activity.

3.2.2 Binaries

Franz and Wasserman continued the reduction, analysis, and interpretation of observations obtained with HST Fine Guidance Sensor #1 in the Transfer Function Scan (TRANS) mode, primarily in the course of two multi- institutional investigations of binary stars. Most advanced of these and nearing completion is a long-term program on nearby M-dwarf binary systems designed to calibrate the empirical mass–luminosity relationship near the end of the main sequence. Although this project will continue for two more HST cycles, most of the targets even now have orbits, based on the TRANS observations, of an accuracy sufficient to lead to masses with formal errors of 5% or less from the orbital elements alone. This work is carried out in collaboration with T. J. Henry (Georgia State U., P.I.) and G. F. Benedict and B. E. McArthur (U. Texas, Austin). The second major project, undertaken in collaboration with E. Horch (U. Massachusetts Dartmouth, P.I) and J. Heasley (U. Hawaii), is aimed at determining masses and luminosities of Population II stars by directly resolving the components of orbital spectroscopic binaries. Owing to their small angular separations at mostly large magnitude differences, these targets pose exceptional demands on FGS-TRANS observations and their analysis.

3.3 Extragalactic

Over the past year, Hunter has made progress on the *UBV* images that she obtained as part of her multi-wavelength survey of 139 normal, non-interacting irregular galaxies. She has determined the standard star calibration solution for each of the 23 observing runs at Lowell Observatory, as well as calibrations for images observed under cloudy conditions that were calibrated later, and for images obtained at other observatories. From the *V*-band images she has determined the galaxy center, position angle of the major axis, and ellipticity of the disk. With this information, she has measured fluxes within elliptical annuli to determine the surface photometry in *B* and *V*, and fit the *V*-band surface photometry to obtain disk scalelengths and central surface brightnesses.

In June, REU undergraduate E. Bowsher (Wellesley College) began work with Hunter to look at two-dimensional variations in color within the survey galaxies. The colors are an indication of the stellar population and the star-formation history. The traditional azimuthally averaged colors have shown that Im galaxies, unlike spirals, are the same color at all radii, implying that the star formation history has been the same throughout the galaxy. However, two galaxies that Hunter looked at show that the azimuthally averaged colors do not tell the whole story; there is peculiar structure in ratio images. Bowsher is examining the entire sample to see how often such peculiar structures occur and what they might mean.

Hunter, collaborator C. Walker (NOAO), and undergraduate M. Mortonson used the Arizona Radio Observatory 12-m, single-dish radio telescope to observe CO in irregular galaxies. The purpose was to characterize the star-forming clouds and their relationship to HI complexes and star-forming regions. They observed HI complexes in five galaxies for which they had obtained low signal-to-noise maps with the Nobeyama 45-m telescope. The bigger beam of the 12-m allowed them to observe the CO flux of an entire HI complex at once. They detected two complexes.

In a poster presented at the Lowell Fall Workshop, Hunter described the results of surface photometry to m_V of 28–29 mag/arcsec^2 from very deep imaging of two Im galaxies DDO 133 and IZw115. In both cases, no edge was found to the stellar disk. In DDO 133, the surface photometry profile exhibits a break in the slope, while IZw115 shows no deviation from an exponential disk. The break in DDO 133 is

similar to those seen in very deep surface photometry of low surface brightness galaxies presented at the workshop by M. Pohlen and collaborators. In addition, the $B-V$ color of DDO 133 is constant as far out in radius as B was measurable. This implies that the star formation history has been the same throughout the galaxy, including the outer edges, in spite of the fact that on-going star formation is not detected in the outer parts.

In 2000, Hunter and collaborators began a program to determine the stellar kinematics and from that infer the stellar structure of Im galaxies. They used stellar absorption features detected in long-slit spectra at several position angles to determine the rotation of the stars in NGC 4449 and NGC 1156. In both galaxies, the rotation speed of the stars was lower than that of the gas. One possibility is that more of the kinetic energy of the stars is in random motions than in ordered rotation, and this would have profound implications for the shape of the galaxies. However, the spectral resolution of the previous observations was too low for measurement of the velocity dispersion of the stars. In May, they used the Echelle spectrograph on the KPNO 4-m telescope to measure the velocity dispersion of the stars in NGC 4449. These data, combined with the rotation information, will allow them to determine V/σ, a diagnostic of how kinematically hot a system is, with implications for the galaxy's stellar structure.

Hunter and collaborator E. Wilcots (U. Wisconsin) used the Green Bank Telescope in late June to search for the edges to the gas associated with irregular galaxies. Theoretical arguments suggest that all galaxies should have sharp edges at the same column density due to the metagalactic UV background radiation. They used the extreme sensitivity of GBT to map the edges of the HI envelopes to a column density 100 times lower than they could with the VLA mapping program. Hunter, collaborator B. Elmegreen (IBM), and undergraduates T. Dupuy and M. Mortonson examined the properties of 939 star clusters in the Large and Small Magellanic Clouds. They used CCD images obtained by Massey in UBVR passbands to determine colors and magnitudes of the clusters and deduce ages and masses. The resulting mass distributions were searched for the effects of fading, evaporation, and size-of-sample bias. The data show a clear signature of cluster fading below the detection threshold. The initial cluster mass function was determined by fitting the mass and age distributions with cluster population models, and the models suggested a new method to determine the cluster mass function. They determined that the LMC and SMC have similar cluster mass functions. The oldest clusters correspond in age and mass to globular clusters in the Milky Way. These clusters do not fit the trends for lower-mass clusters but appear to be a separate population that either had a very high star formation rate and became depleted by evaporation or formed with only high masses.

Hunter and collaborators J. Brodie (Lick Obs.) and S. Larsen (KU, Denmark) used the Keck telescope in May with a high-resolution spectrograph to determine velocity dispersions in star clusters in the Im galaxy NGC 4449. In a previous study Hunter and student A. Gelatt identified clusters with luminosities consistent with their being very massive, comparable to Galactic globular clusters in mass but younger in age. However, integrated colors and luminosities are not very reliable, and only velocity dispersions of the clusters themselves can give a good mass estimate.

King and co-investigators C. Froning (CASA, U. Colorado) and P. Crowther (UCL, London) have been working with FUSE observations of massive hot stars in the LMCs. These luminous, massive evolved stars have complex spectra that are best understood by applying modern stellar atmosphere codes to multi-wavelength spectra. The FUSE data have been used to constrain the luminosities, effective temperatures, and atmospheric abundances of these stars.

Massey, P. A. Henning (U. New Mexico), and R. C. Kraan-Korteweg (U. Guanajuato, Mexico) discovered a very nearby (1.8 Mpc) dwarf irregular galaxy. Henning *et al.* (*ApJ* 119, 26l6, 2000) had described a search for nearby galaxies hidden behind the Milky Way using single-dish 21-cm surveys. One of the objects they detected (HIZSS$\sim$3) has characteristics typical of a dwarf irregular galaxy, and a redshift that suggested it might be very nearby. Its location less than 0.1 degrees from the plane of the Milky Way had made optical identification difficult.

Using the Hall Telescope, Massey identified an extended Hα source about 70 arcseconds from the radio position. The size and intensity of this would be consistent with its being a first-ranked HII region if it were located at 1.8 Mpc. A spectrum was obtained at KPNO with the 2.1-m telescope and GoldCam spectrometer, which demonstrated that its velocity is the same as the radio source, thus establishing it as an optical counterpart. This would be the nearest dwarf irregular discovered in the last 25 years. Its properties are very similar to those of GR8, a nearby dwarf irregular found nearly 50 years ago by G. Reaves. Further observations are planned for fall in order to characterize its stellar population, determine the chemical abundances, and obtain a more reliable distance estimate.

Massey and S. Holmes (now a graduate student at U. Texas) used data obtained with the KPNO 4-m telescope and Mosaic camera to investigate the Wolf-Rayet content of the Local Group galaxy IC10. Previously, Massey and Armandroff identified 16 Wolf-Rayet stars, a phenomenally large number, given the small size of this galaxy. Since Wolf-Rayet stars are the evolved descendents of the most massive stars, this suggested that IC10 was undergoing a considerable starburst. However, one peculiarity was that the relative numbers of the two types of Wolf-Rayet stars (WCs and WNs) were quite different for this galaxy compared to galaxies of similar metallicity. To resolve this issue, Massey and Holmes used deeper imaging through interference filters to see if they could find additional WNs, which are harder to detect. Their results were quite surprising: they found nearly 100 new candidate WRs. Two of these were subsequently confirmed spectroscopically using the 6.5-m MMT telescope. If the rest of the candidates turn out to be Wolf-Rayet stars, then the relative number of WCs and WNs is quite normal in IC10, but the Wolf-Rayet content is factors of many times greater than what was previously thought. Indeed, IC10 would be basically an OB association scaled to a 1 $\sim$ kpc scale.

Massey and K. Olsen (CTIO) studied the red supergiant (RSG) content of the Magellanic Clouds. Spectroscopy obtained with Hydra on the CTIO 4-m telescope allowed them to distinguish foreground red dwarfs and giants from *bona fide* Magellanic Cloud supergiants. Of their sample of 118 stars (SMC) and 167 stars (LMC), 89% and 95%, respectively, proved to be RSGs. They also obtained spectral types for most of these objects, finding that the distribution of types is skewed towards earlier types at lower metallicities: the average type is K5–7 $\sim$ I in the SMC, M1 $\sim$ I in the LMC, and M2 $\sim$ I in the Milky Way. They argue that the RSGs in the Magellanic Clouds are 100°K (LMC) and 300°K (SMC) cooler than Galactic stars of the same type. The distribution of RSGs in the H–R diagram does not match that predicted by stellar evolution models. The models do not produce RSGs as cool and luminous as those actually observed. This discrepancy is much greater than any uncertainty in the effective temperature scale. Massey and Olsen find an elegant sequence of decreasing effective temperature with increasing luminosity, providing an important challenge to stellar evolutionary theory.

Massey is leading a team of collaborators in an optical survey of Local Group galaxies currently forming stars. Images in *UBVRI* as well as Hα, [OIII], and [SII] are being obtained with the KPNO and CTIO 4-m telescopes, with essential calibration carried out at Anderson Mesa with the Hall 1.1-m telescope. The data and photometry will be made available to others for general use, as well as being used to answer directly a number of questions concerning massive star evolution. All of the images have now been taken, reduced, and placed in the fledgling NOAO Science Archive. Photometric calibration will be completed during summer and fall 2003, with the final release slated for January 2004.

Oey, King, and R. Walterbos (NMSU) are investigating the clustering properties of massive stars in the Magellanic Clouds. With E. Gerken (NMSU), the group is also examining mechanical and radiative feedback properties in the Magellanic Clouds to quantitatively constrain feedback processes.

Oey and G. Garcia–Segura (UNAM/Ensenada) are investigating the effect of ambient interstellar pressure on the evolution of superbubbles generated by OB associations. This effect may be responsible for the unexpectedly small sizes of the objects.

Oey is completing a study of the properties of HII regions in grand design spiral galaxies, with J. Parker (U. Colorado), V. Mikles (U. Florida), and X. Zhang (NRL). They propose a new method for determining the co-rotation radius using spatial isochrones and the locus of star formation. They also suggest that the form of the HII region size distribution is a power law, consistent with the luminosity function.

With C. Clarke (IoA, Cambridge), Oey completed a study exploring the escape fraction of ionizing photons from galaxies. They suggest the existence of a threshold star formation rate beyond which photons escape easily and below which the system is essentially optically thick. They apply this model to various phenomena ranging from giant molecular clouds to Lyman break galaxies.

Oey completed a study extending the Simple Inhomogeneous Model (SIM) of galactic chemical evolution introduced by Oey (2000). The SIM predicts the fraction of zero-metallicity stars in the Galactic Halo, and the value of the expected low-metallicity threshold. These are compared to current empirical constraints. Interstellar mixing and element dispersal are also examined analytically.

Through the REU program, Oey and K. Kern (U. Wisconsin) are examining the stellar content of a galactic star-forming region, in collaboration with A. Watson (UNAM/Morelia). This association is part of a series of hierarchical shells, apparently due to triggered star formation.

4. EDUCATIONAL PROGRAMS

The Steele Visitor Center was open daily throughout the year, and on a varying number of nights per week seasonally. Programs for on-site visitors consisted of a spoken multimedia program in the Giclas Lecture Hall, followed by either a tour of the campus (daytime) or telescope viewing (evenings, weather permitting). When not precluded by high wind, viewing is done through the 107-year-old Clark refractor. For the report period, 51,695 persons attended Lowell's regular daytime and evening programs. Concurrent with the daily programs, special programs for K–12 school groups are offered. These groups come to Flagstaff from across Arizona, including a large number from the nearby Navajo and Hopi Reservations. Teachers select from a variety of programs that include spoken lectures, telescope tours and viewings, and science demonstrations. For the report period, 10,320 students came to Mars Hill for these programs.

In addition to our regular, on-site pograms, K–12 special programs, and off-site *Starlab* presentations, two major new programs were launched.

In April, the URL for the Lowell Observatory Public Astronomical Research Center (LOPARC) was opened to the public. Users at Lowell and across the Intenet can now login to our server, access astronomical data, and examine them using server-side image processing software or download data to their own machines. Final debugging of the completed telescope software was underway as the reporting period ended.

The first annual Lowell Star Party was held June 5–8. Nearly 150 registrants from all over the United States and abroad attended. All-night observing, tours of local science facilities included Anderson Mesa, the U. S. Naval Observatory, the U. S. Geological Survey, and Meteor Crater. Several Lowell astronomers also gave presentations on the Lowell Campus. Star Party attendees returned very favorable impressions of the event in their post-event evaluations, and the second Lowell Star Party will be held next June. Flagstaff Cultural Partners provided launch funding for the Star Party.

The Observatory participated in the Flagstaff Festival of Science, held for ten days beginning September 27. The Festival is a collaborative effort of local government, private agencies, research institutions, and industry. Staff members presented talks, special programs were held at the Steele Visitor Center, and tours of the Naval Observatory Prototype Interferometer at the Anderson Mesa dark-sky site were available.

The Lowell Observatory Navajo and Hopi Astronomy Outreach Program continued. Initiated in 1996 by Bosh and Hunter, the purpose of this program is to help teachers excite students about science through astronomy-related classroom activities. The focus is 5th through 8th grades, to reach students in the transition period during which negative attitudes form towards science. In 2002–2003, five astronomers from Lowell Observatory participated in the program: Bosh, Grundy, Hunter, Oey, and Woodney, with assistance from Portree. These astronomers worked with teachers at four Navajo schools and one Hopi school.

At the beginning of the school year, two of the teachers attended the NOAO workshop for teacher/astronomer pairs in Tucson. The purpose of the workshop was to acquaint the participants with activities they can do in their classrooms and advise on how to partner. This trip also featured a tour of and activities at Kitt Peak National Observatory. During the school year, each astronomer visited their teacher's classroom multiple times and engaged in hands-on astronomy activities with the class. The astronomers provided materials for the activities, which were then left with the teacher. They also did 1–3 star parties at the school. In the spring the classes visited Lowell Observatory. They spent the afternoon in a special program and tour at the Steele Visitor Center and the night observing with the Lowell research telescopes at Anderson Mesa. Also at Anderson Mesa, a Navajo educator told the students about the Navajo constellations.

The annual MIT Astronomy Field Camp took place in January. Undergraduates Martha Buckley, Sam Coradetti, Nancy Hsia, Leah Hutchinson, and Heather McEwen, Michael Mortonson; teaching assistants Kelly Clancy and Susan Kern; and Lowell astronomer/MIT Professor James Elliot were in residence at Lowell for most of the month. Projects included modeling comets, creating temperature maps of the Saturnian satellites, re-analysis of archived KBO Search data, and study of massive clusters in the Small Magellanic Cloud, The students worked with Lowell astronomers Bowell, Hunter, Koehn, Massey, Millis, Schleicher, Spencer, Wasserman, and Woodney. At the end of their stay, research results were presented in a seminar before the Lowell community.

A new group of REU students arrived in early June to begin work with Bowell, Hunter, Koehn, Massey, Oey, Schleicher, and Woodney. Welcomed were Nicole Baugh (Augusta State U.), Emily Bowsher (Wellesley College), Chris Jackolski (Appalachian State U.), Katie Kern (U. Wisconsin), and Wayne Schlingman (U. New Mexico). Their visit will culminate with presentations of their work.

Schleicher supervised NASA Space Grant student Erika Roesler (Northern Arizona U.) during the 2002/2003 academic year in analyses of narrowband photometry of Comet P/Tempel 2.

Chemistry major Stephanie Hammond was the recipient of the 2002 Lowell Prize. Ms. Hammond received the $500 award for maintaining the highest average (4.0) of scholarship in science, math, or a closely related field during four years of residence at Northern Arizona University. Constance Lowell established the Lowell Prize in 1918 in memory of her husband, Percival Lowell.

5. OTHER ACTIVITIES

The Lowell Observatory Advisory Board met in Flagstaff on June 6–7. Presentations to the members addressed many aspects of the Observatory, but focused on the Next Generation Lowell Telescope (NGLT) and strategic and financial planning. Members of the Board are Michael F. A'Hearn, Drew Barringer, Jack Clifford, Nicholas B. Clinch, Robert Furlong, Henry L. Giclas, John P. Giovale, Patricia C. Hecht, John S. Hendricks, David C. Henley, James F. Henriot, Gerald E. Kron, Katherine G. Kron, Edward B. Lopez III, Frances B. McAllister, James P. McCarthy, Greg Mort, Patrick M. Nackard, Michael C. J. Putnam, Gibson Reaves, John J. Rhodes, Pamela A. Ross, Vera C. Rubin, Brad Ryan, Carolyn M. Shoemaker, William M. Sinton, Earl Slipher, Paul Sloan III, Arthur R. Szeglin, Donald F. Trantow, Edward E. Vaill, Marcus R. Van Baalen, and John M. Wolff.

Board members Clifford, Furlong, Giovale, Hendricks, Ross, and Ryan, along with Trustee Putnam, serve as the Executive Committee of the Board. The Committee meets quarterly to discuss a variety of current issues, including development.

The 2002 Lowell Workshop, *The Outer Edges of Dwarf Irregular Galaxies: Stars and Gas*, was held on October 10–11. Organized by Hunter and Oey, the workshop was attended by 62 astronomers from around the world.

Four issues of the Observatory's newsletter, *The Lowell Observer*, were published, Consultant Cynthia Webster–Kanner served as Editor.

The Lowell Colloquium Series has been chaired by Oey. The Flagstaff Astrophysics Discussion series established by Oey and S. Levine (USNOFS) continues, taking place regularly in association with astrophysics colloquia. Twenty-four speakers presented colloquia at Lowell during the reporting period. (A complete list is posted at www.lowell.edu/Research/Colloquium/archive/.)

Beiser attended the 4th Library and Information Services in Astronomy Conference in Prague in the Czech Republic.

Buie, with Grundy and collaborators at Southwest Research Institute were awarded Cycle 11 time on HST to use the new Advanced Camera for Surveys (ACS) to image the surface of Pluto and from which a new epoch of maps will be derived. The observations began in June and will continue through June 2003.

Buie continues to work with K. Meech (U. Hawaii) to provide ground-based observational support or the NASA Deep Impact mission to P/Tempel 2. Buie and Meech are also conducting a pilot study to evaluate the use of an automated telescope facility within high-school and undergraduate education.

Dunham served as Co-Investigator on the *Kepler* mission, a Discovery-class space mission selected in December 2001 to proceed to development and flight. The purpose of this mission is to detect extra-solar terrestrial planets by photometric observation of transits of the planets across the disks of their respective suns. The required differential photometric precision for these observations is approximately 1:100,000. *Kepler* development activities are now in full swing, mainly at Ball Aerospace. Dunham helped define the CCD specifications and statements of work early in this pe-

riod. The CCD contracts are in place, and Ball has received initial engineering test devices. In the optics area, a contract is now in place and detailed design and fabrication are proceeding. Dunham has been actively involved in defining the *Kepler* test program during this period.

Dunham continued his longstanding connection with the NASA Airborne Astronomy program. He serves on the SOFIA Science Steering Committee, which provides advice to E. Becklin, SOFIA's Chief Scientist. In addition, Dunham works closely with SOFIA development staff on several issues related to telescope pointing stability, telescope control, and testing of the complete observatory.

Dunham gave talks on SOFIA and *Kepler* in a variety of venues, including the Saguaro Astronomy Club (Phoenix), the First Annual Lowell Observatory Star Party, the Flagstaff Festival of Science, the UCLA colloquia series, and the 2002 SPIE meeting.

Grundy reviewed manuscripts for *Icarus*, *Astrobiology*, and the *Journal of Georphysical Research*; served on an NSF review panel, and presented an invited talk at the Southwest Research Institute (Boulder).

In July, Jessup participated in the *Magnetospheres of the Outer Planets Conference* held at Johns Hopkins U. and the *Io Volcano Workshop* at the U. S. Geological Survey in Flagstaff.

Lockwood continues to represent Lowell Observatory on matters related to light pollution and outdoor lighting.

Massey participated in the review of Cycle 12 HST proposals for NASA and served as referee on behalf of *Astronomy & Astrophysics*, the *Astrophysical Journal*, the *Astronomical Journal*, and *Publications of the Astronomical Society of the Pacific*. Massey wrote an invited article, ''The Brightest Stars in Galaxies,'' for the *2003 Annual Reviews of Astronomy & Astrophysics* and gave a colloquium at Arizona State U., an invited presentation to the special ''Surveys'' session at the Seattle AAS meeting, an invited review talk at the Space Telescope workshop on the Local Group as an Astrophysical Laboratory, and a short presentation on behalf of the Local Group Survey Project to the NOAO ''Survey meeting.''

Millis continued his service on the NASA Planetary Systems Science and IRTF/Keck MOWGs, and the SIRTF Science Center Oversight Committee. He served on the AURA Observatories Council, the NOAO Solar System TAC, and the Space Telescope Institute Visiting Committee. Millis also presented a seminar on the Kuiper Belt at NASA Headquarters, and popular-level talks on the same topic to the Sun City West [AZ] Astronomy Club and the Bainbridge Island [WA] Astronomy Club.

Oey was one of only six astronomers to receive the National Science Foundation's prestigious CAREER grant, a five-year award given every year to promising young scientists. Award recipients are selected based on creative research proposals and career development plans that effectively integrate research and education within the context of their particular home institution's mission.

Oey gave invited review talks at the 2003 Space Telescope Science Institute May Symposium, at The Local Group as an Astrophysical Laboratory held in May; at the 2002 Joint European and National Astronomical Meeting (JENAM) session on the Interstellar Medium, held in Porto, Portugal, in September; and at the conference Star Formation Through Time, held in Granada, Spain, September.

Schleicher served as sub-panel chairperson for NASA's Planetary Atmospheres Review panel and continued to serve on the NAU/NASA Space Grant Steering Committee.

Spencer continued his work as a Science Team Associate for the *Cassini* CIRS IR spectrometer, planning CIRS observations of the icy Saturnian satellites during the *Cassini* tour. With MIT student Nancy Hsia, he used his thermophysical models to generate maps of predicted temperatures on each of the major satellites as a function of latitude, local time, and season. They also developed software to show the temperature distributions seen from the spacecraft at any point in the *Cassini* tour, for use in observation planning.

Spencer gave invited academic talks at the Southwest Research Institute, U. Colorado, and Harvard U. He presented public talks on various subjects: for the Denver Museum of Science; the American Alpine Club in Golden, CO; and the Saguaro Astronomy Club in Phoenix.

Spencer also continued work as a science team member on the *New Horizons* mission to Pluto and the Kuiper Belt, and was named Deputy Imaging Node Leader. He worked on planning of instrument calibration, Pluto encounter observation sequence plans, and KBO targeting strategies, and continued to lead efforts to plan the search for one or more KBO flyby targets for the mission. Spencer and Buie, organized a workshop at the 2002 DPS meeting, where Spencer described the search issues at the TNO workshop in Antofagasta, Chile, in March, and gave a general talk on the *New Horizons* mission. Details have been submitted for publication in the conference proceedings.

Spencer joined the Science Definition Team for the proposed Jupiter Icy Moons Orbiter and was co-leader of the Remote Sensing subgroup at a meeting held at LPI in June.

Woodney gave colloquia at: California State University, Sacramento; City University of New York, Staten Island; University of Central Florida; and Agnes Scott College.

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