Lowell Observatory

Flagstaff, Arizona 86001

This report covers the interval from 1 July 2001 through 30 June 2002.

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, B. W. Koehn, G. W. Lockwood, G. Mandushev, P. L. Massey, R. L. Millis (Director), N. L. King, J. C. Noble, M. S. Oey, C. B. Olkin, J. A. Rathbun, 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, M. F. Bielecki, S. B. Holmes, J. D. Levinthal, L. Levy, M. C. Lierz, K. Morzinski, B. A. Skiff, B. W. Taylor, and M. E. Van Ness.

Technical and administrative staff included J. J. Bailey, A. S. Beiser (Librarian), J. L. Darwin, M. DeMuth, M. L. Evans, H. S. Horstman, M. M. Inge, M. Linzey, G. R. McGlothlin, R. M. Melena (Secretary–Treasurer, beginning mid-October), K. S. Morefield, R. A. Nye, C. J. Ochser (Director of Development), R. C. Oliver, K. A. Phillips (Manager, Media Relations and Public Affairs), R. Slayton–Martin, A. W. Smith, C. Webster–Kanner (Editor, *Lowell Observer*), C. R. White, and K. M. Wilson (Secretary–Treasurer, until mid-October).

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. White.

Working in the Observatory's educational program were R. C. Burgoon, J. P. DeDecker, M. T. Del Margo, R. W. Evans, J. C. Hall (Associate Director for Education and Special Programs), M. S. Hill, M. Hooker, P. E. Kelleher, H. M. Landau, B. MacArthur, D. S. F. Portree, 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, Mary DeMuth, Ava Stone, and Ed Nettell assisted in the library; Claudia Martin in the business and development offices. Henry Holt assisted Shoemaker. Volunteering for the Public Program were Casey Attebery, Nicky Geisler, and Charles Moon.

Astronomer John Spencer was named 2001 Employee of the Year in recognition of his research accomplishments and his many other activities on behalf of Lowell.

Secretary–Treasurer Karen Wilson left the employ of the Observatory in October to begin a similar position with NOAO in Tucson.

Approximately 22 visiting astronomers, in addition to those from Boston U., were awarded time on Lowell telescopes. Included in this number are several from the National Undergraduate Research Observatory consortium (NURO), many of whom were accompanied at the telescope by their students.

Sadly, the Observatory lost two good friends. Elizabeth D. Pickard died in December. A past member of the Lowell Advisory Board, Betty served as Chairman of the fund-raising campaign for the Steele Visitor Center. Eleanor Waddell Libby, long-time Lowell supporter and charter member of the Advisory Board, passed away in February. Among her many contributions to the Observatory, Mrs. Libby, through the Donald Ware Waddell Foundation, established the Waddell Summer Internship and funded renovation of the Clark Telescope and the Rotunda.

2 FACILITIES

2.1 Anderson Mesa Telescopes

The Lowell Observatory–Boston University partnership for shared use and development of the Perkins Telescope continues. The partnership agreement provides for the two institutions to share time on the telescope equally.

Work to improve the seeing at the Perkins Telescope continued. Temperature monitoring indicates that the insulation installed previously is performing well. Next will be an attempt to control the temperature of and airflow across the primary mirror.

The new mirror for the Hall Telescope was delivered to Rayleigh Optical, where it has been figured, tested with a null lens calibrated by a computer-generated hologram, and found to meet our specifications. The secondary mirror is now in fabrication. Bida oversees these improvements.

Nye and Darwin have produced most of a new top end and focus mechanism for the Hall Telescope, to be put into service once the new optics have been installed.

Oliver completed the design and fabrication of a new and very flexible printed-circuit interface between Move (telescope control software) and the telescope. Now in service at the 18-in astrograph, the interface will be used later this year to upgrade the 31-in telescope. It is expected that the new interface will solve control problems when the 31-in is used for robotic observing. Wasserman continues to update and improve the telescope control software to support the new telescope control electronics.

Lowell continued to make time available on the 31-in Telescope to the NURO consortium—a program sponsored jointly with Northern Arizona U. (NAU).

An autoguider for the 31-in telescope continues under development with NAU.

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. Under direction of NPOI staff, Lowell observers continued science and engineering observations through most of the year. Science pro-

grams included six-baseline observations of single stars, close binaries, and spectroscopic binaries. Engineering efforts were directed toward improving instrument calibrations, automation, and NPOI hardware and software.

A major milestone for NPOI was the coherent combination of six beams (15 baselines), the first for any long-baseline, optical interferometer. Images of Eta Virginis, a triple-star system, were recorded at nearly 1 millisecond-of-arc resolution over a period of several months, allowing the mass ratio and relative orbital inclination to be determined for the close pair.

New infrastructure completed this year included the complete conversion to fiber optic-based communication. Six, 100-m by 51-cm, long-delay-line (LDL) tanks were completed and, after much work, met the requirements for holding a vacuum. Installation and testing of the LDL optical alignment and control system were begun. Optical alignment and installation of the ''elevator cans,'' the interface between the siderostats and the vacuum optical path, are being installed along the outer reaches of the array. This and the LDL vacuum tanks are major installation efforts necessary to enable observations with longer optical baselines than currently in use.

2.3 Next Generation Lowell Telescope

Planning continued for a 4-m telescope designed to support wide-field imaging surveys as well as detailed physical studies of individual objects. Information about the telescope concept can be found at http://www.lowell.edu/Research/NGLT/. A search for a site for this telescope has been initiated. Initial testing of four possibilities was carried out by Morzinski and Bielecki under the direction of Bida. The most promising of the four is at an elevation of 7700 ft near a former logging camp at Happy Jack, AZ. A conditional use permit has been obtained from the U. S. Forest Service to establish a ''permanent'' test facility. Sustained testing will begin in the fall. Discussions with a number of possible partners in the NGLT project are continuing.

2.4 Instrumentation

Buie and Dunham continued progress on Mimir, a new 1–5 micron infrared imager and spectrograph. Mimir is a joint project with Boston U., where the instrument is being built. The instrument is expected to see first light late in 2002. At Boston U., the optics have been designed and much mechanical and cryogenic work has been completed. At Lowell, the Leach electronics have been received with sufficient analog channels to operate a single quadrant of the ALADIN Mark III 1024x1024 InSb array. Software is in place to read out a single quadrant, but has not yet been tested.

HIPO, a two-channel, high-speed CCD photometer, is being developed at Lowell for use on SOFIA (Stratospheric Observatory For Infrared Astronomy). Progress has been made in the mechanical and optical areas. All custom windows, mirrors, and beamsplitters are in fabrication. Nye and Dunham have nearly completed the solid models of all mechanical parts; remaining are modifications to the camera lens mounts to accommodate the as-built optics. The detector dewar design has been approved, and the dewars are in fabrication. The finite element model of the instrument carried out by E. Loverich (NAU) is complete, showing a lowest resonant frequency above 100 Hz.

Taylor made substantial progress during this reporting period 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, but with the addition of several new features. Leach controllers operated by LOIS are in regular service in a number of instruments, including the *Kepler* testbed camera at NASA Ames and the MAGIC camera now in service at *Magellan.* The DSP code has been upgraded to v1.7, and hardware triggering was instituted in the astrograph system. Configuration control and a new software release policy have been addressed in an effort to balance the need for ongoing development with stability for instruments in heavy use for routine observing.

Much progress was made on the ground-based extrasolar planet search project. The PSST (Planet Search Survey Telescope) was in routine automated operation; and Morzinski and Noble obtained large data volumes on fields located in Perseus, Auriga, Orion, and Bootes. Telescope reliability was greatly improved over the last year.

The optics for PRISM, an imaging polarimeter for the Perkins Telescope, have been made, and much of the mechanical structure has been completed at Boston U. Lowell will provide the CCD camera system for this instrument, which will be controlled by LOIS.

The USNO IRCAM has been in routine use on the Perkins Telescope during this period. Significant software development and test activity have substantially improved the camera's reliability and user interface.

Bida began mechanical design of the parts needed to mate the Loral dewar to the KPNO ''White'' Spectrograph. The dewar will become available when PRISM comes on-line and the CCD currently housed in the dewar is moved to the new camera for the 31-in telescope.

The Lick/Loral 2Kx2K CCD camera system was in routine use at the Perkins Telescope during the report period. Software development and test activity similar to that for the IRCAM improved significantly the reliability of the control system.

The control computer for the LONEOS camera was replaced with a PCI-based machine. The system was converted to the same PCI-based Leach system used on all other Leach/LOIS cameras, and the DSP code was upgraded to v1.7. The camera's reliability greatly improved.

2.5 Library

The Lowell Observatory Archives Image Database, which contains over 1600 images dating from 1855, is now accessible from the Library's homepage. During the inventory of the collection, each glass plate and film negative was reenveloped in acid-free enclosures. The images were scanned as thumbnails, low-resolution (72 dpi) for screen viewing, and high-resolution (300 dpi) archival copies. The database

is searchable by personal names, equipment, buildings, telescopes, and staff. This task was accomplished with the assistance of library volunteers Stone and Nettell.

Library intern Elizabeth Dunham and volunteer Hecht processed correspondence and papers of former staff members and created finding aids to these collections. Volunteers Miller and DeMuth helped sort correspondence and photographic files in the archives. Evans assisted Beiser with new book processing, Library Homepage maintenance, and the processing of sky survey films. Beiser continued to oversee daily operations in the library and archives.

2.6 Instrument Labs and Shop

Under the direction of Bida, a class 1000 clean room has been installed in the John M. Wolff Building. The room was outfitted with antistatic equipment for safe handling of detectors.

2.7 Computer Facility

The Observatory's computing resources continue to be upgraded and revised. This year new Cisco firewalls were installed at both the Anderson Mesa and Mars Hill sites. Migration to a Fast Ethernet network has almost been completed, and new routers have been acquired and configured in preparation for our switching to commercial T1 services.

3 RESEARCH

3.1 The Solar System

3.1.1 Planets, Satellites, and Their Atmospheres

Buie and Grundy continued synoptic ground-based photometry and IR spectroscopy of Pluto. This study will provide an important understanding of the evolution of Pluto's surface as it recedes from the Sun. The photometric monitoring is accomplished with the 31-in telescope at Anderson Mesa operating under robotic control as developed by Buie.

Buie, 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. The observations began in June and will continue until June 2003. A new epoch of maps will be derived.

Buie, Grundy, and Spencer continued observations and analyses of Triton and Pluto in the 3–4 micron region. The work resulted in discovery of a new 4-micron absorption feature in the spectra of both bodies.

Lockwood continued a long-term program using photoelectric photometry to monitor seasonal and ''weather'' activity on Titan, Uranus, and Neptune. With Neptune's southern summer solstice now just a few years away (2007), the planet continues, inexplicably, to brighten slightly from one year to the next. Lockwood and D. T. Thompson published 30 years of Neptune photometry in *Icarus*. Annual updates are available upon request to Lockwood.

Lockwood continues collaborations with H. Hammel (SSI) and K. Rages (NASA Ames) on multi-wavelength imaging and spectroscopy of Uranus and Neptune using *HST*, Keck, and the IRTF. Lockwood and Marley (NASA Ames) carried out near-IR spectroscopy of Uranus and Neptune with the IRTF in August 2001.

Morzinski and Elliot made successful observations of the occultation of Tr231 by Triton from SAAO with the Ames PCCD. Dunham, Taylor, and Bida obtained useful data of a Titan occultation in December with the USNO IRCAM at the Perkins Telescope. Preparations for the occultation of P126 by Pluto on July 19 are in full swing.

Spencer continued his research on Io. A synthesis of his decade of monitoring of Io's Loki volcano demonstrated remarkable periodic eruptive behavior. He and Rathbun continued monitoring of Io's volcanism using the IRTF and the Perkins Telescope with IRCAM, in support of the final *Galileo* flybys of Io and to continue investigations of Loki's periodicity.

Spencer concluded 15 years of work with the *Galileo* PPR instrument, planning and performing initial analysis of the data from the I31, I32, and I33 flybys. These resulted in the best nighttime temperature maps of Io yet available, and the first global daytime temperature map. These maps will be invaluable in studies of Io's volcanism and heat flow.

Spencer continued his investigations of Io's heat flow, refining his estimates of its magnitude using a combination of *Galileo* PPR, *Voyager*, and ground-based data. Some of the *Voyager* data analysis was done with the help of summer students at the Lisbon Observatory in Portugal.

Spencer expanded his studies of Io's atmosphere through his program to obtain long-slit UV spectra of the distribution of SO_2 and other species at the Prometheus plume and across Io's disk. Data were obtained in November and December; Jessup and MIT field camp student M. Vigil have been analyzing the data, which are of very high quality and provide the first spectrally and spatially resolved observations of Io over a contiguous region extending from 60 N to 70 S latitude. Also included are data from the Isum hot spot, Zamama plume site, Colchis Regio, and high-latitude SO_2 frost patches in both the northern and southern hemispheres.

Spencer and co-investigators opened a new window on Io's atmosphere in November, with the discovery of atmospheric SO_2 lines in the 19-micron region. The high-resolution, mid-IR spectrograph TEXES was used on the IRTF—the first ground-based infrared detection of the atmosphere. Large longitudinal variation in band strength was seen. Modeling by European collaborators E. Lellouch (Obs. de Paris, Meudon) and M. Lopez-Valverde (Inst. de Astrofisica da Andalucia, Spain) is under way.

Much progress was made on Dunham's ground-based extrasolar planet search project (Planet Search Survey). Morzinski and Noble obtained large data volumes on fields located in Perseus, Auriga, Orion, and Bootes. Mandushev, who joined the staff late in the report period, began work on data analysis. A new, very powerful computer was installed, allowing analysis to proceed almost 30 times faster than before.

3.1.2 Asteroids

Bowell and Koehn continued work to increase the known population of near-Earth asteroids and comets under the ae-

gis 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 survey 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 (see Millis *et al., AJ* 123, 2083, 2002). 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

Buie and K. Meech (U. Hawaii) continued to provide ground-based observational support for the NASA Deep Impact mission to P/Tempel 2.

Schleicher and Woodney obtained narrowband photometric measurements and CCD imaging of eight comets with the Lowell 42-in Hall Telescope during the reporting interval. Targets of focussed observing campaigns included Comet LINEAR (2001 A2), for which support observations were obtained for X-ray measurements in July; Comet P/Borrelly, imaged by the Deep Space 1 (DS1) spacecraft in September; Comet LINEAR (2000 WM1), a bright, long-period comet; and Comet Ikeya-Zhang (2001 C1), which last appeared in the mid-17th century. Photometry of Comet LINEAR (2000 WM1) was also obtained by collaborator P. V. Birch (Perth Obs.), using the Lowell 24-in Planetary Patrol Telescope at Perth Observatory. Supervised by Schleicher and Woodney, REU student K. Barkume (Reed College) worked on the analysis of cyanogen gas jets detected in Comet LINEAR (2002 A2).

Woodney and Schleicher engaged in an extensive observing campaign of periodic Comet Borrelly between July and March. With Millis, they have completed analyses and submitted a paper to *Icarus*. Results include water and dust production rates just prior to the DS1 encounter, and evidence for a significant population of large dust grains released at peak water production before perihelion. A steep drop-off in the water production rate seen in previous apparitions was confirmed, with this rate dropping by about 25x between 1.36 and 1.89 AU, nearly a factor of 10 greater decrease than would be expected from a simple water vaporization model.

Imaging of Borrelly revealed a strong radial jet in the near-sunward direction that turns off late in the apparition. For the jet to appear radial, it must originate at or very close to the nucleus' pole. Modeling the measured position angle of the jet as a function of time during the 1994 and 2001 apparitions yielded a pole orientation with an obliquity of 102.7 ± 0.5 deg and an orbital longitude of the pole of 146 ± 1 deg, corresponding to an RA of 214.1 deg and a Declination of -5.7 deg. Additional modeling of archival measurements of the sunward jet from 1911–1932 implied a relatively small (8 deg) precession over the course of a century. The solution for the orientation of the rotation axis and the jet's source location and size directly predicts a strong seasonal effect as the source region moves from summer to winter following perihelion, quantitatively reproducing the extremely steep r-dependence previously noted. A much smaller fall-off in apparent dust production after perihelion is explained by a population of old, very slowly moving large grains released near peak water production, and therefore not indicative of the actual on-going release of dust grains. Based on the measured water vaporization rate, the source region has an area of approximately 3.5 km^2 or 4% of the total surface area of the nucleus, and water ice having an effective depth of 3–6 m is released each apparition from this source region.

Analysis of Comet Hyakutake's rotating dust jets as a function of changing viewing geometry was completed by Schleicher and Woodney; results have been submitted to *Icarus* for publication. A primary and a much weaker secondary dust jet were successfully reproduced using a 3-D Monte Carlo jet model, resulting in the determination of the orientation of the nucleus' rotation axis and the size and location of each source region on the nucleus. Because of these locations, there was a strong seasonal variation in the water vaporization rate as the comet passed close to the Sun, consistent with published radio measurements. The first measurement of the acceleration of dust grains in the inner coma was obtained and clearly showed that the acceleration region extends several thousand kilometers from the nucleus, well beyond theoretical predictions. The tailward motions of several cometary fragments released during an outburst were measured; their motion implies that these micro-comets had sizes of about 10–50 m.

3.2 Stars

3.2.1 Solar-Stellar

Hall and Lockwood continue their Solar-Stellar Spectrograph program (SSS) with new NSF support. The goal is to monitor long-term (cycle timescale) magnetic activity and

to compare that with irradiance variations of the Sun and sunlike stars. At the Albuquerque meeting of the AAS in June, Lockwood reported on a successful effort to merge the Mount Wilson Ca II H and K data with Lowell SSS data, and Lowell photometry with photometry from the Fairborn Observatory automatic photometric telescopes. The goal of all this 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 multiparameter proxies of solar and stellar activity.

3.2.2 Binaries

Franz and Wasserman continued the reduction, analysis, and interpretation of observations obtained with the *HST* Fine Guidance Sensors in the Transfer Function scan (TRANS) mode in the course of multi-institutional investigations of binary stars. Most mature of these and approaching completion is a program on nearby M-dwarf systems carried out in close collaboration with T. J. Henry (Georgia State U., P.I.) and with G. F. Benedict and B. E. McArthur (U. Texas, Austin) in an effort to calibrate the mass-luminosity relation near the end of the main sequence. Another project, inaugurated during the report period with E. Horch (RIT, P.I.) and J. N. Heasley (U. Hawaii), is aimed at determining masses and luminosities of a sample of Population II stars.

Franz continued to collaborate with E. Horch and Z. Ninkow (RIT) in an ongoing program of CCD speckle observations of binary stars with the Lowell–Tololo Telescope at CTIO.

3.3 Extragalactic

Hunter and collaborators C. Simpson (Florida International U.) and P. Knezek (WIYN) have conducted a study of the irregular galaxy DDO 88. Their data consist of HI interferometric maps and optical UBVR and Hα images. DDO 88 particularly intrigued the trio because its HI is distributed in the shape of a large doughnut the size of the optical galaxy. Yet, the galaxy appears otherwise fairly normal. Most likely, a burst of star formation long ago in the center of the galaxy forced the gas outward into the shell that is seen today.

Hunter and collaborators A. Tomita (Wakayama U.), K. Sunada (Nobeyama Obs.), and B. Elmegreen (IBM) were given 90 hours on the Nobeyama Radio Observatory 45-m telescope for observing CO in irregular galaxies. The purpose is to characterize the star-forming clouds and their relationship to HI complexes and star-forming regions. The molecular clouds are the gas that directly produces the stars, but the HI complexes produce the molecular clouds. They mapped an HI complex in each of five galaxies. The five galaxies cover a range in galactic properties, including HI distribution, and the five positions within the galaxies cover a range in properties of HI complexes, particularly relationship to current star formation. These data are part of a larger project to determine the drivers for cloud and star formation in irregular galaxies. The team has applied for more telescope time to improve the signal-to-noise of the spectra.

Hunter and collaborators V. C. Rubin (DTM/CIW), R. A. Swaters (Johns Hopkins U.), L. S. Sparke (U. Wisconsin), and S. E. Levine (USNO) used long-slit spectra to determine the stellar and ionized-gas kinematics in two irregular galaxies (NGC 1156 and NGC 4449). They compared this to the optical morphology of the galaxies and HI kinematics. In the ionized gas, they see linear velocity gradients. In NGC 1156 they also detect a weak linear velocity gradient in the stars. The stars and gas are rotating about the same axis, and the uncertainties in the rotation speed of the stars are large enough to allow for the possibility that the stars and gas have nearly the same velocity gradient. The misalignment of the kinematic line of nodes and the morphological axis is the result of NGC 1156 being dominated by a stellar bar. In NGC 4449, on the other hand, they do not detect any organized rotation of the stars. They developed a model that reasonably reproduces the observed kinematics of the stars and gas. In this model the stellar component is in a rotating disk seen nearly face-on while the gas is in a tilted disk with orbits that precess around the gravitational potential. This model reproduces the apparent counter-rotation of the gas in the inner galaxy. The gas on these peculiar orbits is presumably material that was accreted in the past interaction whose signature is also seen in the large extended streamers of HI.

Hunter, REU student O. Billett (Yale U.) and collaborator Elmegreen searched 22 nearby irregular galaxies for compact star clusters using data from the *HST* archive. The purpose was to learn what conditions are necessary for the formation of massive populous and super-star clusters. Three galaxies were found to host both populous clusters and super-star clusters. Another two galaxies were known from other studies. They found that these extreme clusters are found only in galaxies with an M_V as bright as -16, although there are also many galaxies brighter than this that have not formed compact clusters. They argue the formation of super-star clusters in irregular galaxies requires extraordinary circumstances: a starburst, strong bar, or interaction, for example, but only to bring the star-formation rate up to a high level somewhere in the system. Once the star formation rate is locally high, the actual formation of a super-star cluster appears to be random. They note that super-star clusters are often surrounded by additional compact clusters of similar age, suggesting that the formation of the super-star cluster occurred in a large star-forming complex with smaller compact star clusters and OB associations as part of the debris of star formation.

Massey used the *HST* to obtain spectra and photometry of four high-mass binaries in the R136 cluster, one of which proved to be the most massive binary known. In collaboration with L. Penny (U. Charleston) and undergraduate J. Vukovich (Wichita State U.), Massey derived orbit solutions from the radial velocities of these four systems. Three turned out to be eclipsing systems, allowing accurate determinations of the orbital inclinations, and hence good estimates for the stellar masses. The mass of the primary of R136-038 is 57 solar masses, somewhat more than the 51 solar masses recently measured by others for Plaskett's star, the previous record holder. More importantly, however, their analysis showed that the masses of all four systems were consistent with the values that one would infer from stellar evolutionary

theory. This appears to put to rest the long-standing contention that stellar evolutionary tracks overestimate a star's mass by factors of 2 for the highest mass stars.

C. Slesnick and L. Hillenbrand (both Caltech), and Massey have completed a modern study of the h and Chi Per ''double cluster.'' Although the double cluster is a naked-eye object, there has remained controversy about its fundamental properties. Their study used state-of-the-art wide-field Mosaic imagers and multi-object spectroscopy. This work demonstrated that the two cluster nuclei are at identical distances (2.34 kpc) and have identical reddenings [E(B−V)=0.56] and ages (12.8 Myr). They find a slope of the initial mass function of −1.3, essentially Salpeter, and use this to derive total masses of 3700 M_{solar} (h) and 2800 M_{solar} (Chi) for the two clusters.

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 Kitt Peak and Cerro Tololo 4-m telescopes, with essential calibration being done at Anderson Mesa with the 1.1-m Hall Telescope. The data and photometry will be made available to others for general use, as well as being used to directly answer a number of questions concerning massive star evolution. These data were among the first released in the NOAO Archive. Undergraduate S. Holmes (U. Texas) assisted with the photometry.

Oey is completing a study that further develops the Simple Inhomogeneous Model (SIM) of galactic chemical evolution. It offers a standard reference model in the stochastic, low-metallicity regime where the homogeneous Simple Model breaks down. The SIM is applied to predict the fraction of zero-metallicity, Population III stars in the Galactic Halo, and the value of the expected low-metallicity threshold. These are compared to current empirical constraints. Since these parameters depend on the dilution of newly synthesized supernova products by interstellar mixing, the process of element dispersal also is examined analytically.

In collaboration with C. Clarke (Inst. of Astronomy, Cambridge, UK), Oey is completing a study to predict the fraction of ionizing photons that escape from galaxies. The model is based on the superbubble structure of the ISM and suggests the existence of a threshold star-formation rate below which the escape fraction is negligible and above which it is high.

Oey and REU student S. Stokes (U. Wyoming) are further developing the [Ne III]/Hβ emission-line ratio as a nebular diagnostic of stellar T_{eff}. This is applied to observations of HII regions in a sample of disk galaxies to test for the existence of radial gradients in T_{eff}.

4 EDUCATIONAL PROGRAMS

Lowell Observatory's education and outreach staff continued to provide three main types of programming.

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 106-year-old Clark refractor. For the report period, 69,099 persons attended Lowell's regular daytime and evening programs. Concurrently with the daily programs, we offer special programs for K–12 school groups. 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, 13,423 students came to Mars Hill for these programs. New display signs were added to the Pluto Walk, wherein one travels through the Solar System within the space of just 350 feet. Displays were also created for the dendrochronology exhibit featuring the ''George Washington Tree,'' a ponderosa pine determined (through coring) to have been ''born'' the same year as the Father of our Country. The onsite control room for the Lowell Observatory Public Astronomical Research Center (LOPARC) opened in November, allowing users to load and study real astronomical data, as well as print out the images to take home. Control of a 16-in telescope and access to the Internet at large is expected in the upcoming report period.

The Observatory participated in the Flagstaff Festival of Science, held for ten days beginning September 28. 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 our Anderson Mesa dark-sky site were available.

The Lowell Observatory Navajo and Hopi Astronomy Outreach Program continued through the efforts of Bosh, Grundy, Hunter, Oey, and Woodney. The purpose of this program is to help 5^{th}–8^{th} grade teachers incorporate astronomy in their classrooms and use astronomy to promote an enthusiasm for and understanding of science.

The annual MIT Astronomy Field Camp took place in January. Undergraduates Kelly Clancy, Joyance Meechai, Miquela Vigil, Aletta Wallace, Amy Jordan (from UC Berkeley); graduate students Susan Kern and Michael Person; and Lowell researcher/MIT Professor James Elliot, were in residence at Lowell for most of the month. Projects included using *HST* data to conduct atmospheric studies of Io, studies of Pluto's atmosphere, searching for near-earth asteroids, and an audit of the Deep Ecliptic Survey search for KBOs. The students worked with Lowell astronomers Bowell, Buie, Dunham, Elliot, Koehn, Millis, Spencer, and Wasserman. 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, Buie, Dunham, Hunter, Koehn, Oey, Schleicher, and Woodney. Welcomed were Kristina Barkume (Reed College), Shane Bussmann (U. California, Berkeley), Trent Dupuy (U. Texas, Austin), Eric Furst (Bucknell U.), Andrew Morrison (U. Puget Sound), Jennifer Palguta (U. Wisconsin), and Moire Prescott (U. Wisconsin). Their visit will culminate with presentations of their work.

Jacqueline Marlette, an environmental sciences major with an emphasis in environmental management, was the recipient of the 2002 Lowell Prize. Ms. Marlette 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 May 16–18. 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, Martin Hecht, John S. Hendricks, David C. Henley, James F. Henriot, Gerald E. Kron, Katherine G. Kron, W. Jay Lovelace, Frances B. McAllister, James P. McCarthy, Greg Mort, Patrick M. Nackard, Michael C. J. Putnam, Gibson Reaves, John J. Rhodes, Pamela A. Ross, Brad Ryan, 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.

In response to a challenge grant from Mrs. Frances McAllister, a long-time supporter and Advisory Board member, the Observatory raised $576,000. Combined with the 1:2 match by Mrs. McAllister, a new endowment in excess of $800,000 was created to support Observatory programs. This endowment, known as *The Millennium Fund*, is administered by the Executive Committee of the Advisory Board.

In May, Putnam, Millis, and Ochser led a tour of the Keck Telescopes and the NASA Infrared Telescope Facility (IRTF) for 25 Lowell donors. We are grateful to the W. M. Keck Observatory and the IRTF staff for giving our group an in-depth, behind-the-scenes look at these fine Mauna Kea installations.

Bowell continues to serve as President of Commission 20 of the International Astronomical Union. With J. Virtanen and K. Muinonen (U. Helsinki) and A. Boattini (CNR, Rome), Bowell wrote a review chapter for the U. Arizona Space Science Series book, *Asteroids III*. The chapter stresses the increased use of statistical techniques for computation of orbits and looks forward to very high-accuracy astrometry from spacecraft.

Buie and K. Meech (U. Hawaii) are conducting a pilot study to evaluate the use of an automated telescope facility within high school and undergraduate education.

Dunham continued to serve as Co-Investigator on the *Kepler* mission, a Discovery-class mission to detect extrasolar terrestrial planets by photometric observation of transits of the planets across the disks of their respective suns. Taylor provided support for recent tests related to the possible use of saturated, bloomed images of bright stars in the *Kepler* data stream.

Dunham continued his longstanding connection with the NASA Airborne Astronomy program. He serves on the SOFIA Science Steering Committee, which advises Chief Scientist E. Becklin. In addition, he is working closely with SOFIA development staff on several issues related to telescope pointing stability, telescope control, and testing of the complete observatory. Taylor worked with the SOFIA Mission Control System development staff on definition of the SOFIA Command Language and on testing of prototype software systems.

Grundy co-chaired the DPS Kuiper Belt Community Panel and served as a reviewer for *Icarus* manuscripts.

Hall served as an advisory board member for the Gale Publishing series, ''Science in Dispute,'' periodically reviewing science articles for content.

Hunter worked with REU undergraduate O. Billett (Yale U.), who spent June–August identifying compact star clusters in irregular galaxies.

Hunter gave an invited talk at the Ringberg Workshop (The Lowest Mass Galaxies and Constraints on Dark Matter) held in July, presented two posters at the Washington, D.C. AAS meeting and an invited talk at the January Symposium honoring Vera Rubin, and made a presentation to Arizona State U. astronomers. She also serves as a member of the NRAO Users' Committee and served on a review panel for *HST* Cycle 11.

Koehn and Bowell maintained 16 URLs concerning asteroid science: catalogs, observational aids, asteroid target selection, and a description of LONEOS and its discoveries. Bowell maintained an asteroid orbital database, with up-to-date osculating elements of about 190,000 asteroids. The database is updated automatically on a daily basis, as are a list of minimum orbital intersection distances (MOIDs) between planets and planet-approaching asteroids, and their version of the ''critical list'' of asteroids (numbered and unnumbered asteroids in need of astrometric measurement). Much of the database is in the public domain. Wasserman continued to provide software support.

Lockwood continues to represent the Observatory on matters related to light pollution and outdoor lighting. He served on an NSF review panel and an advisory panel for Ph.D. candidates at Duke U.

Massey gave an invited talk at IAU Symposium 212, A Massive Star Odyssey, from Main Sequence to Supernovae, held at Costa Teguise, Lanzarote, Canary Islands, in June and served on the Scientific Organizing Committee. In addition, he presented poster talks at the Washington, D.C. and Albuquerque AAS meetings (January and June, respectively).

Massey also gave demonstrations about comets to a third grade class at Flagstaff's DeMiguel Elementary School and assisted at several star parties connected with the Navajo–Hopi Outreach Program.

Millis served as chairman of the NASA Planetary Astronomy Program proposal review panel. He continued to chair the NASA IRTF/Keck Management Operations Working Group and served on the NASA Planetary Systems Science Management Operations Working Group. He was a member of the NOAO Observatories Council, the NOAO Solar System TAC, and the SIRTF Science Center Oversight

Committee. An invited colloquium about the Kuiper Belt and the Deep Ecliptic Survey was presented at CTIO. Millis also made a presentation about the Kuiper Belt and the Next-Generation Lowell Telescope to the Primitive Bodies Panel of the NASA Solar System Exploration Division Decadal Survey.

Oey was a member of the NASA Science Archives Working Group. She also served on the *HST* Review Panel and presented invited colloquia at New Mexico State U., Ohio U., Ohio State U., and the Institute of Astronomy (Cambridge U., UK). Oey also gave invited reviews at the meetings Seeing Through the Dust: The Detection of HI and the Exploration of the ISM in Galaxies held in Canada in November; and at IAU Symposium 212, A Massive Star Odyssey, held in Spain, where she served on the Scientific Organizing Committee. She also served as co-organizer of the topical session, ''Gaseous Galaxy Haloes and Disk Galaxy Edges'' at the AAS meeting in Albuquerque, and a special session, ''Recent Advances in Nebular Diagnostics of Hot Star Atmospheres'' at IAU Symposium 212.

Schleicher continued to serve on the NAU/NASA Space Grant Steering Committee.

Spencer has joined the Cassini Composite Infrared Spectrometer Team, which has the responsibility for planning *Cassini*'s thermal IR observations of the icy (non-Titan) Saturnian satellites during its four-year tour of the Saturn system. Also a member of the 2001 Planetary Astronomy Review Panel, Spencer began a three-year term on the NASA Keck Telescope Allocation Committee. Spencer participated in the Second Interdisciplinary Solar System Summer School at Lisbon Observatory, Portugal, in August. He taught three classes on the ''Satellites and Rings of the Giant Planets'' to Portuguese undergraduates, as well as presented public talks. He presented the results of the ''Future of Io Exploration'' study to the Large Satellites Panel of the Decadal Survey in November; two invited seminars at Caltech in March; and an invited talk at a Pluto workshop at SWRI–Boulder in May.

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

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

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