Lowell Observatory

Flagstaff, Arizona 86001

This report covers the interval from 1 July 1999 through 30 June 2000.

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. Grundy (Hubble Fellow), J. C. Hall, S. Hunsberger (Lowell Fellow), D. A. Hunter, B. W. Koehn, G. W. Lockwood, R. L. Millis (Director), B. Oetiker, C. B. Olkin, J. Rathbun, D. G. Schleicher, C. S. Shoemaker, J. R. Spencer, L. H. Wasserman, and N. M. White. H. L. Giclas, though officially retired, has been involved in Observatory activities. John Noble was Boston University staff resident at Lowell.

T. A. Bida (Keck Telescope) and Drs. Philip Massey (KPNO), Sally Oey (Space Telescope Science Institute), and Will Grundy (Hubble Fellow) have accepted appointments at Lowell Observatory. We look forward to their joining the staff in the near future.

Scientific support staff included W. Ferris, G. Kanner, B. A. Skiff, and B. Taylor.

Technical and administrative staff included A. Beiser (Librarian), J. L. Darwin, M. L. Evans, E. Farabaugh, A. L. Ferris (Director of Development), E. Gilmore, H. S. Horstman, M. M. Inge, M. Linzey, G. McGlothlin, R. Melena, R. A. Nye, R. C. Oliver, L. Salce, R. Slayton-Martin, C. Webster Kanner (Director of Communications and Marketing), C. M. White, and K. M. Wilson (Secretary-Treasurer).

Directly involved with the operation of the NPOI were C. Denison, K. Isbrecht, S. Jennings, B. O'Neil, C. Sachs, and J. Shannon, and White.

Those working in the Observatory's educational program were R. Burgoon, M. Del Margo, S. Fladness, J. C. Hall (Associate Director for Education and Special Programs), C. Hauser, C. Jones, P. Kelleher, B. MacArthur, S. Nichols, T. Rodriquez, K. Schindler, P. Stiers, R. Tweed and J. Winse.

Volunteers made a considerable contribution to the Observatory. Martin Hecht served as archivist; Lynn Salce and Reba Miller as development staff. Ava Stone and Ed Nettell assisted in the library; Connie Jensen and Claudia Martin with the business office; and Sarah Hamlin, and Jennifer Marshall with the Public Program. Henry Holt assisted Shoemaker. Volunteer Jennifer Winse not only worked for the Public Program, but assisted Bosh with analysis of photometric data.

In recognition of his many contributions to the Observatory's research program, Larry Wasserman was named Employee of the Year.

Approximately 25 astronomers, in addition to those from Boston University, 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.

With sadness, we report the death in July of Arthur Allen Hoag, director of Lowell Observatory from 1977–1986. With his passing, the Lowell community and astronomy at large lost a good friend and a valued role model. Art served as Lowell director during a time of considerable financial uncertainty. With his unflagging good humor and personal interest in every member of the staff, he kept our research program on track and maintained the institution's essential infrastructure. His own research included the study of open star clusters and quasars. At the time of his death, Art was a member of our Advisory Board.

2 FACILITIES

a. Anderson Mesa Telescopes

The partnership between Lowell Observatory and Boston University for the shared use and development of the Perkins Telescope continues. Terms of the partnership agreement provide that the two institutions equally share the time on the telescope.

The new support building for the 31-inch telescope, the planet search project, and a possible future telescope near the 31-inch has been completed and is in routine use. The new building contains two telescope control rooms, a computer room, a lounge, and a restroom.

Work on improving the image quality at the Perkins telescope has progressed this year. The wavefront curvature analysis program ''ef'' was purchased with Boston U. to allow routine examination of the optical figure of the telescope. Measurements made by Noble, Massey, and Dunham indicate that the optical figure, while not perfect, remains a smaller contributor to the overall image size than the periodic drive error and the seeing. A new focus drive system was developed and installed by Nye, Oliver, and Wasserman with some help from Dunham and Taylor, so focus resolution is no longer a limitation. Nye has designed a modified RA drive mechanism that will reduce the amplitude of the periodic RA error by a factor of four so it will no longer be detectable. The walls, piers, and floor of the Perkins dome have been insulated, and those surfaces are now much more closely in equilibrium with the air in the dome. Simultaneous seeing measurements obtained by Buie, Dunham, Millis, and Wasserman with the NGLT site testing systems on the Perkins dome floor and outside indicate that the dome itself is not a major contributor to the image-quality budget. The major elements that remain out of thermal equilibrium are the primary mirror, the structure at the lower end of the telescope tube, and the warm rooms.

The project to improve image quality of the Hall 1.1-m telescope is currently focused on fabrication of the new primary mirror at Torus Optics and its new cell at Lowell. The mirror is polished but not fully figured and awaits delivery of the cell. Nye designed the cell, and Dunham worked with G. Loverich (Northern Az. U.), who carried out a finite element analysis (FEA) of the mirror and its cell. The FEA showed that modification of the design would provide slight improvements in the mirror figure. The decision was made to fabricate the cell as originally designed. It is expected that improvement from design changes would be very small and would be unnecessary, given that the final figuring of the mirror will be carried out by Torus with the mirror mounted in its cell. We feel confident that the new cell will provide adequate support for the mirror to meet its image-quality specifications. Installation of the optics is expected in summer of 2001.

b. Navy Prototype Optical Interferometer at Lowell Observatory

NPOI stellar interferometric observations were suspended for most of this report period in order to improve the operational effectiveness and extend the baselines. Based on the operational experience of previous years, major improvements were made to various sub-elements of the instrument. These included installation of an improved detector dewar, improvements to the light transportation system, and improvements in the software. The vacuum optical path and electrical power were extended the full length of the three 250-meter arms. Installation of the six long delay lines was begun.

A major effort was put into the implementation of six-way beam combination and extending the length of the available baselines. A regular schedule of stellar observations began in June.

c. Next Generation Lowell Telescope

Dunham and Millis have been actively involved in NGLT concept development with astronomers from the US Naval Observatory and with EOS Technologies, an Australian telescope manufacturer whose US operation is located in Tucson. We have abandoned the Paul-Baker optical system originally considered for this telescope in favor of a prime focus/Ritchey Chretién approach. The latter is deemed superior because an atmospheric dispersion corrector can more readily be included, because it provides better color correction across a wide band and because an unvignetted Cassegrain alternate focus is possible.

Limited progress was made this year in exploring possible sites for NGLT. Two differential image motion systems were set up together at Anderson Mesa in the fall of 1999 and data obtained by Millis and Wasserman showed that the two systems produced identical results. This experiment was reproduced in the spring of 2000 with the same outcome. Following this check, one of the systems was taken by Millis and Buie to Hutch Mountain, southeast of Flagstaff, for two nights, the USNO Flagstaff Station site for one night, and Anderson Mesa again for two nights (with the mobile system mostly located in the Perkins dome on these two nights). On each night, Dunham and Wasserman operated the fixed station at Anderson Mesa to serve as an experimental control. We were pleased to see that the differential nature of the measurement made the results immune to common-mode image motion to a very high degree. The differences between sites that we see appear to be real and reproducible. The Hutch Mountain site had approximately 20% lower differential motion than at Anderson Mesa, while the USNO site was about the same as Anderson Mesa, in agreement with earlier site testing observations.

d. Instrumentation

Work on Mimir, an infrared imaging spectrograph for the Perkins Telescope, continued under Buie's supervision in collaboration with Boston University. The instrument is expected to be commissioned for regular use in 2002. Funding from both NASA and NSF was secured, allowing the project to enter full-fledged development. Design work is progressing at Boston U. Lowell's tasks for Mimir development include the electronics and software for operating the detector and mechanisms in the instrument, and this will begin toward the end of the summer. The detector will be controlled by Leach electronics, with the mechanisms controlled by hardware also used in the Move systems. If, as we expect, we are successful in operating the Aladdin detector array with Leach electronics, it will be the first time any group has done this.

HIPO is a 2-channel high-speed CCD photometer 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. The instruments will be tested separately and together on the Perkins telescope prior to their first use on SOFIA.

The pace of HIPO development quickened somewhat this year, due in part to the FAA certification process becoming better defined. Dunham worked on mechanical certification issues with Jason Andringa, an MIT mechanical engineering student, during the January field camp. FLITECAM development began in earnest this year, and Dunham served on its Preliminary Design Review panel, attending its Preliminary Airworthiness Design Review. He has kept in close contact with the FLITECAM team, and has drafted an Interface Control Document detailing the important interfaces between HIPO and FLITECAM when they are co-mounted on the SOFIA and Perkins telescopes. Dunham has begun the final optics optimization for HIPO, a prerequisite for carrying out the detailed mechanical design of the instrument. A great deal of progress was made on the LOIS instrument control system that will be directly applicable to HIPO. The Leach controllers for HIPO were also delivered during this reporting period.

The *Kepler* Technology Demonstration project, for which Dunham and Taylor provided the CCD system last year, was brought to a successful conclusion this year, and preliminary results were presented at the SPIE meeting in Munich. The test was very challenging, but in the end showed that the photometric precision required by Kepler is realizable in a realistic environment with realistic hardware and analysis software. A proposal to the Discovery program is being written taking into account the progress made in the Technology Demonstration as well as progress made elsewhere in a number of related areas (*e.g.*, large CCD focal planes and the discovery of the first transit by an extrasolar planet).

Dunham, Taylor, and Oetiker made much progress on the ground-based extrasolar planet search project being carried out under the auspices of the NASA Origins program. The semiautomated camera system has been installed in its new shelter at Anderson Mesa. Data were successfully obtained on about 10 nights in June. The quality of the data is as expected, indicating that the CCD quantum efficiency is very high and the optical performance of the lens is good. This system includes a Move-controlled telescope mount and a Loral 2Kx2K back-illuminated CCD operated by a Leach controller under LOIS. The hardware and control software are still not quite in their final form, but are close enough that the bulk of the effort is now shifting to data analysis.

Dunham and Taylor acquired much additional experience this year with the CCD control electronics (''Leach controllers'') from Astronomical Research Cameras. Leach controllers are now in regular service in the *Kepler* test system, the Lowell Observatory Near Earth Object Search (LONEOS) camera, the planet search system, and the Lick CCD system. They will also operate the strip-scanning CCD astrometry system on the 18-inch astrograph (the first use of hardware readout triggering), the White spectrograph, HIPO, Mimir (our first infrared application), and MAGIC, a joint MIT/SAO instrument for Magellan. Development problems with the Leach PCI interface card have been largely overcome, and two PCI-based systems are now in regular use.

The Lick/Loral 2Kx2K CCD Camera System has been completed and is in use on the Perkins telescope. The camera enjoys the flexibility of four binning factors and three readout rate speeds with low display and storage overhead time. The reliability of LOIS for this PCI-based system is still somewhat shaky, but is expected to improve steadily with experience and debugging.

The major improvement to the LONEOS system is the new Lowell-developed 4Kx4K camera. This camera is based on the Marconi (formerly EEV) 2Kx4K CCD42-80 detector and LOIS control software. The new LONEOS camera has lived up to its promise in every respect. The quantum efficiency is more than twice that of the older detector, the area covered in a frame is nearly twice that of the original camera, and the readout and storage overhead is dramatically reduced. These changes, taken together with new object identification software, have improved the performance of the LONEOS system tenfold. The new camera's cooling system is much more efficient, keeping the CCD much cooler while dissipating only 500 W compared to the 7000 W dissipated by the older system. The next activity to help reduce the dome seeing problem will be installation of air conditioning with the compressor located outside the dome and a fan to ventilate the region beneath the observing floor.

The Loral CCD destined for use with the White Spectrograph was delivered during this reporting period. (The White Spectograph, on loan from KPNO, is slated for major renovation and modernization, after which it will be used at the Perkins Telescope.)

PRISM is a proposed reimaging system for use with the Perkins telescope, under development by Ken Janes at Boston U. Following an unsuccessful proposal, the PRISM concept was revised to use Lowell's Lick/Loral 2K CCD with somewhat smaller optics. A proposal for the revised PRISM concept is pending.

Taylor made substantial progress 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. Main efforts centered on the large frames and high data rate of the LONEOS camera and the debugging of new hardware, firmware, and software associated with the new PCI interface card. Taylor's modifications to the PCI card's device driver and firmware were essential in achieving the level of stability that LOIS currently exhibits. LOIS is currently operating the older CCD camera systems (but not the SITe 2K CCD), and the *Kepler* test demonstration, LONEOS, planet search, and Loral cameras. Development for these instruments will help reduce the time and cost for development of the planned astrograph camera, HIPO, the White spectrograph, and Mimir.

e. Library

In June, Beiser attended the annual meeting of the Special Libraries Association in Philadelphia.

During the report period, a total of 29 individuals accessed the Lowell Observatory Archives. These included publishers, historians of astronomy, and amateur astronomers. The requests came from as far as England, Germany, Spain, and Italy.

Volunteers Ava Stone and Ed Nettle continued to scan historic photographs and to enter descriptive information on them so that they can eventually be accessed over the Web. Also, intern Bonnie Perry worked on the Web interface to these photographs, and intern Phil Floersh entered descriptive information into a separate database dealing with scientific plates.

Library volunteer Martin Hecht continued to process archival correspondence and to assist the librarian in responding to requests from the public.

f. Instrument Labs and Shop

A 2000-sq. ft. addition to the instrument shop was completed, occupied, and named the ''John M. Wolff Building,'' in recognition of major financial support received from the John M. Wolff Foundation. The 1900-sq. ft. area made available by the relocation of the shop is being retrofitted for use as laboratories and will house the electronics shop and instrument lab facilities previously located in the basement of the Slipher Building. The new lab area will be much larger and will incorporate an excellent facility for instrument test and characterization. It will be large enough to work on the large instruments that will be commonplace in a year or two: the White spectrograph, Mimir, HIPO, and FLITECAM. Also provided is a clean assembly area for large components, a well-equipped CAD area, and secure storage for FAA-certified materials and components for HIPO. We hope to move into the new labs later in the summer.

A numerically controlled (CNC) milling machine was purchased with funds generously provided by the John M.

Wolff Foundation. The machine has seen heavy use in fabrication of parts for the cell for the new Hall Telescope primary mirror.

3 RESEARCH

a. The Solar System

1. Planets, Satellites, and Their Atmospheres

During this period, Bosh observed three occultations: by Jupiter and Titan in October, and by Saturn in December. Volunteer Jennifer Winse worked with Bosh, doing photometry of occultation candidate stars. The Jupiter and Titan lightcurves are being analyzed by others; Bosh is leading the analysis of data from the coordinated worldwide observations of the Saturn event.

Buie continues to pursue occultation observations but this year concentrated primarily on the modernization of the data acquisition hardware and software along with continued efforts concerning system calibrations and characterizations.

Buie continued to work with A. Stern (SW Res. Institute) on high-resolution imaging and mapping of Pluto, Triton, and Ceres using instruments on the Hubble Space Telescope (*HST*). He continued a project to image the inner coma of Chiron in collaboration with K. Meech (U. Hawaii) which aims to confirm previous results and extend the work as part of the world-wide Chiron Perihelion Campaign. This investigation includes, but is not limited to, photometry, spectroscopic monitoring in addition to near nucleus imaging with the *HST*. Buie's work with Meech has now expanded to include ground-based observational support of the NASA Deep Impact mission to comet P/Tempel 2.

Buie continued to monitor Pluto with ground-based photometry and IR spectroscopy. This study will provide an important understanding of the evolution of Pluto's surface as it recedes from the Sun. Grundy, a Hubble Postdoctoral Fellow, has assisted in this research. To further aid in long-term photometric monitoring, Buie has begun developing tools and systems for eventual unattended robotic observations with either the Hall 42- or Lowell 31-inch telescopes at Anderson Mesa.

Elliot, M. Person (MIT), Olkin, Wasserman, Buie, Millis, Dunham, Nye, and colleagues at other institutions have completed their analysis of data for the occultation of a star by Triton in July 1997. Their results support previous findings that (i) the pressure in Triton's atmosphere has increased since the Voyager encounter in 1989, and (ii) Triton's atmospheric figure is distorted from a spherical shape, most likely due to very strong winds.

Lockwood continued a long-term program monitoring seasonal and ''weather'' activity on Titan, Uranus, and Neptune using photoelectric photometry. Lowell photometry is included in an analysis of Titan's seasonal variability by Lorenz *et al.*, published in *Icarus*. E. Karkoschka (LPL) attempted to establish whether physical variations occur in Uranus' atmosphere by comparing the observed Lowell light curves with those predicted by recent Hubble NICMOS imaging at wavelengths from 0.27 to 1.7 microns. Two conclusions emerged: (1) the two hemispheres of Uranus have distinctly different albedos, and (2) physical variations may have been minimal in the decade bracketing the 1986 solstice, but certainly occurred prior to about 1982. Whether such variations are asymmetric about the planet's solstice will be determined by further observations as Uranus' northern hemisphere becomes exposed to sunlight for the first time in decades. Neptune continues to brighten inexplicably year after year, continuing a linear trend unbroken since about 1980. Lockwood and Hammel are using *HST* images obtained since 1994 and 1989 Voyager images to model the variability. Since Neptune is now nearly at southern summer solstice, the variations cannot be merely an artifact of viewing angle.

Lockwood continued to collaborate on multi-wavelength spacecraft imaging of Uranus and Neptune in collaboration with Hammel (Space Science Institute) and Rages (NASA Ames) under of the auspices of two *HST* Cycle 9 grants. Observations are expected in the 2000 apparitions.

Rathbun, with collaborator S. Squyres (Cornell U.) made progress on modeling hydrothermal systems in Martian impact craters. The work was begun as part of Rathbun's graduate thesis, but new information has prompted continuing work. Results were presented at the Lunar and Planetary Sciences in Houston and a paper will soon be submitted to *Icarus*.

Rathbun began to catalog all PPR Io observations, with the assistance of summer REU student Lindsay Deremer (Wellesley). All data are being reduced and examined for usefulness to other projects.

Spencer continued intensive observations of Io's volcanos from the IRTF on Mauna Kea in support of the *Galileo* Mission. He was assisted in these runs by Stansberry (now Steward Observatory) and Rathbun. The resulting record of volcanic activity spanned the critical period of close-up observations of Io by *Galileo*; several major eruptions were discovered. Some, but not all, of the eruptions were also seen by *Galileo*.

Spencer participated in *HST* observations of Io as one of four sub-group leaders in the *HST/Galileo* Io campaign. He was largely responsible for proposing, planning, and reducing STIS observations of Io's Pele plume, which resulted in the discovery of S2 gas in the plume during the *Galileo* I24 flyby. This was only the third astrophysical context in which S2 had been seen and helped to explain the bright red deposits around Pele and other Io volcanos (also discovered by Spencer with *HST* observations in 1994). Results were published in *Science*.

Spencer's third set of Io observations in 1999 was with the *Galileo* spacecraft itself. He was responsible for the planning and analysis of *Galileo*'s high-resolution thermal mapping of Io with the PPR instrument. These observations included the first global map of nighttime temperatures on Io, which provided a new and independent estimate of Io's heat flow and thermal mapping of the Loki volcano, which showed massive resurfacing of the volcano's caldera floor between October and February. Results were published in *Science*.

During an IRTF run in August with NSFCAM, Spencer discovered the brightest cloud yet seen on the planet Uranus.

He provided the images to L. Sromovsky (U. Wisconsin), and a resulting paper is in press.

2. Asteroids

Bowell and Koehn are working to increase the known population of near-Earth asteroids and comets (collectively, near-Earth objects or NEOs) by undertaking an observational and theoretical effort using a CCD-mosaic camera mounted on the 59-cm Schmidt telescope at Anderson Mesa. Observation and moving-object detection have been largely automated. Their approach favors the detection of 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 (main-belt, the brightest members of the transneptunian population, etc.) and a suite of non-solar system projects, respectively. During the reporting interval, the LONEOS system was operated on 178 nights, resulting in 257,608 asteroid detections published in the *Minor Planet Circulars*, together with 46,499 unpublished single-night detections. The new CCD camera, discussed in section 2d, resulted in a ten-fold increase in discovery rate over a year earlier. Thirty-two near-Earth asteroids ($q < 1.30$ AU) and four comets were discovered during the reporting interval. REU student Lorenza Levy (Northern Az. U.) contributed to this project as an observer and also calculated star densities in standard LONEOS observing fields.

Koehn and Bowell are maintaining sixteen URLs concerning asteroid science. They comprise catalogs (asteroid orbits and stars), observational aids (asteroid ephemerides, finder charts, optimum observing strategy, survey coverage and the like), asteroid target selection, and a description of LONEOS and its discoveries. Bowell maintains an asteroid orbital database, currently comprising up-to-date osculating elements of about 80,000 asteroids.

Daily updates of the database have entailed the computation of about 10,000 asteroid orbits/month. Much of the database is in the public domain and can be found at (http://www.lowell.edu/users/elgb). It is updated automatically on a daily basis, as are a list of minimum orbital intersection distances (MOIDs) between planets and planet-approaching asteroids, and our version of the ‘‘critical list’’ of asteroids (numbered and unnumbered asteroids in need of astrometric measurement).

With K. Muinonen and J. Virtanen (U. Helsinki), Bowell has been working on a method of statistical ranging of asteroid orbits for cases when the orbital arc is too short for a general orbit solution. The method, still under development, provides sky-plane uncertainty domains, a probabilistic estimate that a moving-object detection is a planet-approacher, and a means of recovering lost asteroids.

Wasserman has begun a monthly search with the 42-inch Hall Telescope for inner solar system bodies. These are objects with orbits whose perihelion and aphelion lie totally inside the orbit of the Earth. Currently, no such objects are known; however, theoretical predictions indicate they should exist.

3. Kuiper Belt Objects

Millis, Buie, Wasserman, and Elliot collaborated with R. M. Wagner of the Large Binocular Telescope Observatory on a continued deep survey of the ecliptic using the MOSAIC Camera on the Mayall Telescope at Kitt Peak National Observatory. To date, their survey has yielded 68 new Kuiper Belt Objects and two new Centaurs. Additional astrometric observations of many of these objects have been secured during queue-scheduled time on the WIYN Telescope, with the Steward 90-inch Telescope on Kitt Peak, and at other telescopes around the world including the Perkins Telescope at Anderson Mesa.

4. Comets

Schleicher obtained narrowband photometric measurements of six comets with the 42-inch Hall and the 72-inch Perkins telescopes during a total of 20 nights of observations. Observing campaigns were conducted for LINEAR (1999 S4), an apparently dynamically new comet; Lee (1999 H1); and Tempel 2, an object for which M. A’Hearn (U. Maryland), Schleicher, Millis, and Campins (Research Corp.) previously determined several fundamental nucleus properties, including size, albedo, minimum elongation, and fractional active area. The new Tempel 2 campaign will investigate the comet’s activity with orbital position and the rapid turn-on of activity at $r < 1.7$ AU, possibly due to the arrival of ‘‘Spring’’ for an active region on the nucleus. The measured production rate for Tempel 2 will also be compared with measurements obtained on previous apparitions. Photometry of Comet Hale-Bopp was obtained by P. Birch (Perth Obs.) using the Lowell 24-inch Planetary Patrol telescope located at Perth Observatory, as the comet receded to beyond 10 AU from the sun.

Schleicher recorded monthly CCD images at the Hall telescope, primarily monitoring the same objects also measured photometrically. Images were obtained with the Hale-Bopp narrowband filters, as well as with wideband filters. These data will be used to study the morphology of the dust and gas species in the comae of the comets. Specifically, the Tempel 2 images will be used to search for jets or other structures in the coma connected with the seasonal variations in the production rates of this object, and an attempt will be made to constrain the position of the rotational pole.

T. Farnham (U. Texas) and Schleicher completed the calibrations for the new Hale-Bopp narrowband filter sets distributed to 35 observers around the world. The results were distributed previously to interested researchers and have been accepted for publication in *Icarus*. They also finalized revised calibration coefficients for filter sets used previously for comet photometry at Lowell, including the IHW standard set, in preparation for a re-reduction of all Lowell comet photometry obtained since 1976.

Schleicher and Farnham continued their analyses of images of Comet Hale-Bopp obtained with the Hall Telescope in 1997; REU student Wendy Williams (Vanderbilt U.) assisted in this work. A multi-jet Monte-Carlo model is being used to determine the orientation of the rotation axis and the location of the primary active regions on the nucleus. Image processing techniques were developed to enhance features so that the arc locations could be accurately measured and used to constrain the models. In support of this rotation analysis, sequences of images (both dust and gas) were assembled to create movies illustrating the arc motions as a function of time. Each of the gas species exhibit jet structures spiraling out from the nucleus, with a velocity roughly twice that of the dust. While complete spirals are observed for each of the gas species, the dust images require significant enhancement to make the jets visible on the anti-sunward side. The differences in jet structures will be used to investigate possible inhomogeneities in the composition between active regions on the surface of the nucleus. Spatial profiles of each gas species were extracted and fitted with a Haser model to determine appropriate gas scalelengths in this high production rate object. Resulting scalelengths were typically 2–3 times larger than in smaller, less productive comets.

A detailed analysis of the photometric behavior of Comet Hyakutake (1996 B2) in the interval of February–April 1996 was begun by Schleicher and D. Osip (MIT). Previously, Schleicher, Millis, Osip, and Lederer (U. Florida) determined a precise value of Hyakutake's rotation period, 6.23 ± 0.23 hr, from their photometric measurements of dust production combined with simultaneous images of the morphology of the dust coma. The new study includes investigation of the rotational lightcurves obtained in each gas species A strong outburst observed shortly before the comet's close approach to Earth and trends in the gas and dust production rates as a function of distance from the sun are also being explored.

b. Stars

1. Solar-Stellar

Hall and Lockwood continued their Solar Stellar Spectrograph program with NSF support. The goal is to monitor long- and short-term solar and stellar activity on solar cycle timescales and to compare that variability with irradiance variations measured by spacecraft for the sun, and by ground-based photoelectric photometry for a sunlike stars. Hall has devised a technique that exploits the broad coverage of the spectrograph's echelle output to greatly improve the S/N ratio by using an ensemble of activity-sensitive lines, thereby improving the sensitivity of the measurements over that obtained from the Ca II H and K lines alone. A paper describing this approach covering rising activity in the current solar cycle was accepted by the *Astrophysical Journal*.

Lockwood, assisted by Skiff, is concluding a 16-year time series measuring the brightness variations of about three dozen sun-like stars using the 21-inch telescope. Lockwood and G. Henry (Tennessee State U.) have demonstrated that the Lowell measurements can be merged precisely with a similar but more extensive time series of observations obtained over the past several years by automatic photoelectric telescopes. Observations to date still suggest that the sun's present level of irradiance variation is low compared with stars of similar age and average magnetic activity.

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 primarily of nearby M-dwarf systems. This work is carried out in collaboration with T. J. Henry (Johns Hopkins U.) and G. F. Benedict (U. Texas) as part of an effort to calibrate the mass-luminosity relation near the lower end of the main sequence.

Franz and E. Horch (Rochester Inst. Technology) used the RIT fast-readout unintensified CCD camera on the Lowell-Tololo 61-cm telescope at CTIO during 5-16 October for speckle observations of known and suspected binary stars. A total of 304 observations yielded 281 measures of 146 pairs, including 11 discovered by HIPPARCOS.

c. Extragalactic

Hunter worked on reducing VLA D-array data of the irregular galaxy Sextans A. She and collaborator E. Wilcots (U. Wisconsin) are studying the extended gas around irregular galaxies. Sextans A is the second in their study that uses mosaicking techniques to image HI over a degree of sky at 1-arcminute resolution. A peculiar ghost image problem was finally solved by Wilcots. The resulting map of Sextans A does not show extended HI emission, contrary to the findings of Huchtmeier *et al*.

As part of her participation in an ISO Key Project team, Hunter examined mid-infrared imaging and far-infrared spectroscopy of five irregular galaxies observed by ISO as part of the team's larger study of the interstellar medium of normal galaxies. The mid-infrared imaging was in a band centered at 6.75 μm that is dominated by polycyclic aromatic hydrocarbons (PAHs) and at 15 mm that is dominated by emission from small dust grains. The spectroscopy of three of the galaxies included a suite of emission-lines that are important coolants of photodissociation regions (PDRs). In the mid-infrared images they found that most of the emission is associated with the brightest HII regions in the galaxies. The integrated mid-infrared ratios are consistent with the irregulars being dominated more than spirals by star-forming regions, where PAHs have been suppressed and small dust grains have been heated, and with irregular galaxies having smaller dust column densities compared to spirals. The deduced physical properties of the PDRs are similar to those in spirals except that the far-ultraviolet stellar radiation field is stronger in two of the galaxies. In addition, the clouds are much more massive than typical giant molecular clouds in the Milky Way. These similarities imply that the conditions for the star-forming portions of clouds are similar in normal disk galaxies and that forming stars from a cloud of gas is a very local process.

Hunter and REU student E. Roye (Yale U.) used CCD Hα and V–band images to examine the distributions of star-forming regions in 34 irregular galaxies. They found that the HII regions are concentrated towards the inner halves of most of the optical galaxies, and most giant HII complexes are even more centrally located. Furthermore, most of the HII regions and complexes are located within the part of the galaxy that is rotating as a solid body.

Finally, the overall distribution of HII regions is symmetrical in most of the galaxies. Most of the galaxies without measurable rotation have lower star formation rates, while those with measurable rotation velocities extend to higher star formation rates. In addition, the degree of central concentration of HII regions is low in the galaxies with no measurable rotation, and the galaxies with the fastest rotation speed have among the highest central concentrations of HII regions.

Collaborator B. Elmegreen (IBM) and Hunter found that, unlike spiral galaxies, the pressures of giant HII regions in irregular galaxies are a factor of $\sim$10 larger than the average pressures of the surrounding galaxy disks. The anomalous pressures in star-forming regions are most likely the result of local peaks in the gravitational field that come from large gas concentrations. These peaks would also explain the anomalously low column density thresholds for star formation that they found earlier.

Hunter and collaborators examined star clusters in the irregular galaxy NGC 1569 from *HST* images. In addition to the two superstar clusters that are well known, they identified 45 other clusters that are compact but resolved. Integrated colors of the clusters suggest a range in ages, with a large number of the clusters having formed at the tail-end of the recent starburst. Four of the clusters examined in detail have the small half-light radii and core radii that are in the range observed for globular clusters in our Galaxy. They examined the resolved stars in the outer parts of the two superstar clusters, and found that cluster A contains many bright blue massive stars with a small population of red supergiants. Their color ratio map, however, is not consistent with the suggestion that the red supergiants belong solely to one of the two sub-clusters of A. The stars resolved around cluster B, on the other hand, contain a large population of red supergiants. The presence of red supergiants is verified in near-infrared spectra that show strong stellar CO absorption features. Cluster B appears to be of order 10–20 Myrs old, while cluster A is probably of order 7 Myrs old. The timescale to form the holes seen in Hα and HI around these clusters is comparable to the age of cluster B.

In January, Hunter and collaborator V. Rubin (Dept. Terrestrial Magnetism) obtained long-slit spectra of several irregular galaxies with the Kitt Peak 4-m telescope. They observed stellar absorption features along the galaxy in several position angles from which they will determine the stellar kinematics and infer the structure of the galaxies. These data will help to determine whether irregulars are disks or triaxial in shape, what contribution the stellar velocity dispersion makes to the instability of the gas, and what contribution the stellar velocity dispersion makes to the dynamical support of the galaxy as a whole. They will put limits on the amount and the distribution of dark matter in these galaxies and compare the stellar kinematics of the old stellar component to that of the gas which has a higher likelihood of having been perturbed by outside forces.

Hunter and Hunsberger built on discussions with summer student Roye and examined the possibility that some subset of normal irregular galaxies may have originated as tidal dwarfs. They examined the observational consequences of the two possible origins for irregular galaxies: formation from collapse of a primordial cloud of gas early in the age of the Universe, and formation from tidal tails in an interaction that could have occurred any time in the history of the Universe. Because the formation from tidal tails could have occurred a long time ago, proximity to larger galaxies is not sufficient to distinguish tidal dwarfs from traditional dwarfs. They considered the effects of little or no dark matter on rotation speeds and the Tully-Fisher relationship, the metallicity-luminosity relationship, structure, and stellar populations. They identified a small list of dwarf irregular galaxies that are candidates for having formed as tidal dwarfs.

4 EDUCATIONAL PROGRAMS

Public program personnel delivered daily and evening presentations, tours, and telescope viewing, reaching over 68,000 on-site visitors and K-12 schoolchildren.

An additional 8,000 schoolchildren across Arizona experienced the traveling *Starlab* planetarium programs. Special activities, including the Cosmic Cart (which features a variety of science demonstrations), solar telescope viewing, and the theatrical series *Voices From the Past*, continued to be popular with our visitors.

Work began on a major addition to Lowell's educational offerings, the Lowell Observatory Public Astronomical Research Center (LOPARC), which will be a fully functional, research-grade observatory available to the public. The 16-inch telescope of the John Vickers McAllister Public Observatory will be automated and made available for control via Web browsers. Users both on site and off site will be able to submit observing requests and make observations. Once data are acquired, users will have access to a set of software tools employing many of the same routines and techniques used by professional astronomers in their research. The purpose of the facility is to give the public a glimpse into how science is done and to foster improved understanding of how scientific data are used to obtain results. The on-site version of LOPARC is expected to come on line in mid-2001, with full access off site by the end of 2001.

Lowell outreach programs are supported by several generous corporate and private sponsors. Corporate sponsors include APS (*Starlab*, LOPARC), US West (LOPARC), Norwest/Wells Fargo (Cosmic Cart), and Bank One (*Voices from the Past*). Generous individual donations for LOPARC were received from Donald Trantow and Marshal Merriam. Additional support for LOPARC has been granted by the City of Flagstaff upon recommendation by the Arts and Sciences Commission.

The Observatory participated in the Flagstaff Festival of Science, with staff members presenting talks and special programs held at the Steele Visitor Center. Held for ten days beginning mid-September, the Festival is a collaborative effort of local government, private agencies, and industry and features free tours, public programs, workshops, lectures, exploratory hikes, and in-school programs and demonstrations.

The annual MIT Field Camp took place in January. Students Jason Andringa, April Deef, and Brendan Miller, along with Lowell researcher/MIT Professor James Elliot and graduate students Michael Person and Bryan Hilbert were in residence at Lowell for most of January. During that time, the students worked with Lowell astronomers Bowell, Dunham, Elliot, Koehn, and Spencer. At the end of their stay, research results were presented in a seminar before the Lowell community.

In February, the Observatory marked the 70th anniversary of the discovery of Pluto with a public lecture by Buie. The lecture described the history and current knowledge of the planet and its moon Charon.

Hunter continued her participation in Science-By-Mail, an outreach program run by the Boston Museum of Science that is aimed at encouraging young people in science. The program connects scientists with students who work on specific science activity packets.

Hunter, Bosh, and Hunsberger continued the Navajo-Hopi Outreach Program, whose purpose is to use astronomy to get kids excited about science and education in general. They are targeting grades 5–8 in Navajo and Hopi Reservation schools. Hunter, Hunsberger, and one of the outreach teachers attended the ASP's ASTRO workshop in Tucson in the fall.

Several students took up summer internships at Lowell: Chris Henry (U. Oklahoma), Susan Kern (U. Arizona), Lori Levy (Northern Arizona U.), Emily Lin (Harvard U.), Jen Owens (MIT), Kameron Rausch (Western Washington U.), Erin Roye (Yale U.), and Wendy Williams (Vanderbilt U.) Most of these students were supported by a grant to NAU's Department of Physics and Astronomy under the NSF Research Experiences for Undergraduates Program. They worked with Bosh, Buie, Dunham, Elliot, Farnham, Hunter, Koehn, Schleicher, and Spencer.

Jennifer Erin Baker, a chemistry major with a 3.97 GPA, was the recipient of the 2000 Lowell Prize. Ms. Baker received the $500 award for maintaining the highest average of scholarship in science, math, or a closely related field during four years of residence at Northern Arizona University. The Lowell Prize was established by Constance Lowell in 1918 in memory of her husband, Percival Lowell.

5 OTHER ACTIVITIES

At the end of the report period, membership in the Friends of Lowell Observatory had grown to 1,979 members, who contributed $274,247 in unrestricted gifts. This was a 10.9% increase in members over the prior report period. Contributions from the Friends supported purchases of computers and peripherals, installments of the *Palomar/ESO Sky Atlas*, the second Lowell Fellowship, presentation equipment, conference travel, and costs of upgrading the 42-inch Hall Telescope mirror. In addition to support from the general membership of the Friends, corporate supporters were very generous: APS became the presenting sponsor of the Lowell Observatory Public Astronomical Research Center (LOPARC), in addition to contributing a new solar energy exhibit; the Raymond Educational Foundation and the Southwestern Foundation for Educational and Historical Preservation funded work in the Observatory's archives; the BF Foundation and Honeywell/AlliedSignal supported the Navajo-Hopi Outreach Program; and Bank One and Wells Fargo Bank each supported educational outreach programs. Other corporate contributors included Alcoa, Barringer Crater Company, Cerprobe, Loven Contracting, Nackard Companies, Schwerin Boyle Capital Management, Bank of America, Qwest, and the John M. Wolff Foundation.

All contributors were invited to several events on the Observatory campus during the report period, including the VIP Anderson Mesa Tour in August, the *Voices from the Past* Preview in October, a Phoenix Star Party in April, the LOPARC Virtual Groundbreaking in May, and the Annual Member Recognition Open House in June. Presenters at the various events included astronomers and staff: Millis, Hall, Schleicher, Hunter, Koehn, Wasserman, Lockwood, Webster Kanner, W. D. Ferris, Nichols, Spencer, and Bowell.

The Lowell Observatory Advisory Board met in Flagstaff on May 4–6. Presentations to the members covered 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 Giovale, Martin Hecht, John Hendricks, David Henley, James F. Henriot, Gerald Kron, Katherine Kron, Eleanor Libby, W. Jay Lovelace, Frances B. McAllister, James P. McCarthy, Greg Mort, Patrick Nackard, Michael C. J. Putnam, William L. Putnam, Gibson Reaves, John J. Rhodes, Pamela A. Ross, Brad Ryan, William M. Sinton, David Slipher, Earl Slipher, Arthur Szeglin, Marcus R. Van Baalen, and John M. Wolff.

Board members Clifford, Giovale, Hendricks, Putnam, Ross, and Ryan serve as the Executive Committee of the Board. This committee has met quarterly since its creation and is concerning itself with raising funds for the Next-Generation Lowell Telescope.

Fifty planetary scientists from the United States and Europe attended the Observatory's Fourth Annual Fall Workshop, *Pluto and Triton: Comparison and Evolution Over Time*, September 23–24. The meeting was especially timely with the recent announcement by NASA of plans to send a small spacecraft to Pluto and the Kuiper Belt. Most of the world's experts on Pluto and Triton were in attendance and the workshop was an ideal forum for assembling scientific teams and for discussing the scientific goals of the mission in light of the rapidly changing state of knowledge.

Bosh served as a member of the NASA Planetary Astronomy Review Panel.

Bowell served as a member of NASA's Planetary Astronomy Management Operations Working Group and as Vice President of Commission 20 of the International Astronomical Union.

Dunham continues to serve as Co-Investigator on the Kepler mission (a proposed Discovery-class space mission to detect extrasolar terrestrial planets by photometric observation of transits of the planets across the disks of their respective suns); he also serves on the SOFIA Science Steering Committee, which provides advice to SOFIA's Chief Scientist. Dunham served on a NASA Small Explorer proposal review panel and presented a paper on HIPO at the Munich SPIE meeting and a paper on Kepler at the IAU Bioastronomy meeting.

Dunham also worked with Roger Angel (U. Arizona) on a concept for a very ambitious 6.5- to 8-meter telescope with a 3-degree field of view. Their work culminated in a document presented to the decade review panel and an SPIE paper on the instrument concept.

Director of Development Alice Ferris as named ''Outstanding Fund Raising Executive of the Year'' by the local chapter of the National Association of Fund Raising Executives. Alice is widely recognized throughout Flagstaff for her involvement in the community.

Franz, assisted by Wasserman, continued as a member of the *HST* Astrometry Science Team, with primary responsibility for the scientific uses of the FGS in the TF scan mode, particularly the investigation of and search for multiple stars.

Grundy made presentations at Northern Arizona U., Boston U., and U. Alabama, as well as at the Hubble Fellows Symposium in Baltimore and the DPS meeting in Italy.

Hunter continued as a member of the ISO Key Project team to study the interstellar medium of normal galaxies using FIR continuum and ionic fine structure lines.

In September, Hunter gave an invited talk, ''Gas and Star Formation in Irregular Galaxies,'' at the meeting Gas, Dust, and Stars--From Meteorites to Galaxies: A Meeting at Friday Harbor to Honor Paul Hodge. With P. Massey (NOAO), Hunter made a presentation to the Sun City West Astronomy Club in March.

Lockwood continues to represent the Observatory on matters related to light pollution and outdoor lighting. Lockwood gave an invited paper on the role of small telescopes in astronomy at the January meeting of the American Astronomical Society.

Millis continued as chairman of the NASA Keck Telescope Allocation Committee. He also was a member of the NASA IRTF/Keck Management Operations Working Group, NASA Planetary Astronomy Management Operations Working Group, and the Space Commission of Arizona (a gubernatorial appointment). Millis served as chairman of the NASA Planetary Astronomy Proposal Review Panel.

Schleicher was a member of the *Asteroids, Comets, and Meteors 1999* Scientific Organizing Committee, and continued to serve on the NAU/NASA Space Grant Steering Committee. He also served on the 2000 NASA Planetary Astronomy Review Panel.

Shoemaker was featured speaker at many events across the United States and around the world. Of special note were the July meeting of the Meteoritical Society in Johannesburg, South Africa, where she presented a public lecture for 1300 attendees at Rand Afrikaans University and additional lectures at the University of Capetown and the University of Western Cape. In February, in San Salvador, El Salvador, Shoemaker cut the ribbon at the dedication of the first observatory established in that country, followed by a public lecture and participation in the first Central American Conference for astronomy. In March, she attended the Lunar and Planetary Science Conference, during which the NEAR spacecraft was renamed ''NEAR Shoemaker.'' In May, at the National Science Foundation and National Space Board celebration, she presented an asteroid named *Scientia* in honor of the NSF. She also served as a finalist judge for Jumpstart, 2000—Your Chance to Build A Better Century, took part in ''Women in Science,'' a public forum in Cheyenne, WY, and completed eight observing runs at Jarnac Observatory, Vail, AZ. She continues as a Consulting Editor for *Odyssey*, a member of the Advisory Board of the San Juan Capistrano Research Institute (Tucson), the Meteor Crater Board, and the Executive Council of the American Academy Arts and Sciences, Western Region.

Spencer served on the NASA Jupiter System Data Analysis Program and Planetary Astronomy review panels. He gave invited talks on Io volcanism at the 1999 DPS meeting in Italy and invited talks on *Galileo* PPR results and Galilean satellite surface temperatures at the fall meeting of the American Geophysical Union. Spencer also worked with the *Galileo* team to plan future observations of Io during a possible extended mission.

Taylor worked with the SOFIA Mission Control System development staff on definition of the SOFIA Command Language and on testing of prototype software systems.

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

The joint colloquium series sponsored by Lowell Observatory, Northern Arizona University, and USNO Flagstaff Station continues. Speakers are scheduled about twice monthly.

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