The New MMT

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ABSTRACT

Originally commissioned in 1979, the Multiple Mirror Telescope was a highly innovative and successful facility that pioneered many of the technologies that are used in the new generation of 8 to 10 m class telescopes. After 19 years of operations the MMT was decommissioned in March of 1998: the enclosure was modified, the optics support structure was replaced, and a single 6.5-meter primary mirror was installed and aluminized *in-situ*. First light for the new MMT was celebrated on May 13, 2000. Operations began with an *f*/9 optical configuration compatible with existing instruments. Work has continued commissioning two new optical configurations that will serve a suite of new instruments: an *f*/15 deformable secondary mirror and adaptive optics facility that has obtained diffraction-limited images; and an *f*/5.4 secondary mirror and refractive corrector that provides a one-degree diameter field of view. The wide-field instrument suite includes two fiber-fed bench spectrographs, a robotic fiber positioner, and a wide-field imaging camera.

Keywords: MMT, commissioning, adaptive optics, instrumentation

1. INTRODUCTION: WHY DECOMMISSION A PERFECTLY GOOD TELESCOPE?

The Multiple Mirror Telescope (MMT) was dedicated on May 9, 1979 and removed from service on the morning of March 2, 1998. At the time of its dedication, the MMT was the third largest optical telescope in the world. It featured ambitious design innovations including lightweight, multiple primary mirrors, a co-rotating building and an altitude-azimuth mount. In its 19 years of operation 94% of the scheduled time was used for science observations.

With the exception of the Bolshoi Teleskop Azimutalnyi, all major optical telescopes prior to the MMT used equatorial mounts. The success of the MMT heralded a change in telescope design while the technology pioneered at the MMT contributed to the success of the current generation of large telescopes. A few of the more notable technical developments were: high dynamic-range servos for the alt-azimuth mount; highly accurate pointing to about two arcseconds rms all-sky; co-alignment and co-phasing of multiple telescopes; control of local seeing by attention to the thermal environment of the facility and the use of low-emissivity coatings on the telescope and enclosure; many contributions to vacuum coatings deposition, optics cleaning, and maintenance; and early experiments in co-phased adaptive optics.

The success of spin-casting 3.5 m mirrors at the Steward Observatory Mirror Laboratory (SOML) during the 1980s confirmed the feasibility of still larger mirrors, and in 1986 the MMTO and its two parent institutions resolved to replace the six 1.8 m mirrors with a single 6.5 m diameter, *f*/1.25 primary with three interchangeable secondary mirrors: an *f*/9 secondary to allow use of existing instrumentation and for high-resolution narrow-field imaging; an infrared optimized *f*/15 secondary for adaptive optics; and an *f*/5.4 secondary, corrected to *f*/5.27 with a three-element refractive corrector to produce a one-degree field of view. The conversion offered three significant advantages: an increase of more than a factor of two in light gathering power; a factor 15 increase in the diameter of the field of view; and a two-reflection adaptive focus for diffraction-limited imaging in the infrared.

2. DESIGN AND PRE-FABRICATION

The consulting engineering firm Simpson Gumpertz & Heger, which played a major design role in the original MMT, was contracted for the design of the new optics support structure (OSS), mirror cell, elevation trunnion, aluminizing head, and modifications to the building. Smithsonian Astrophysical Observatory (SAO) undertook the design and fabrication of the wide field optics and the suite of instruments that would take advantage of the one-degree field of view, while SOML began the multi-year task of producing a 6.5 m mirror, then the largest single piece of glass ever attempted. Each stage of this task involved the construction of new equipment: a spinning kiln capable of supporting the 21,000 lbs of molten glass; a Large Optics Generator (LOG) for generating, loose-abrasive grinding and final polishing; computer controlled stressed-laps for polishing the steep aspheric surface; a test tower; and an impressive array of handling and test equipment.

In April 1992 the primary mirror was successfully cast, the final design phase was completed, and steel fabrication began. In addition to the new OSS, TIW Fabrication & Machining began construction of the vacuum bell jar for *in-situ* aluminization. The limited space available at the MMT site drove the decision to aluminize in the telescope cell, a new approach never before attempted by any large telescope.

In August 1992 the MMT was closed for 2 months for the first of several telescope and facility modifications needed for the conversion. A new pintle bearing was installed on the azimuth axis. Its installation required the complete disconnection of all cables through the azimuth cable drape, the cutting of two 2 x 8 foot slots through the 1" thick steel of the MMT yoke, and the careful insertion of the 7000 lb, 6-foot diameter pintle bearing into the yoke. This corrected a long-standing problem that compromised the pointing and tracking performance of the telescope and fortified the mount for the increased weight of the new elevation structure. The telescope was re-cabled and put back into operation at the start of September 1992.

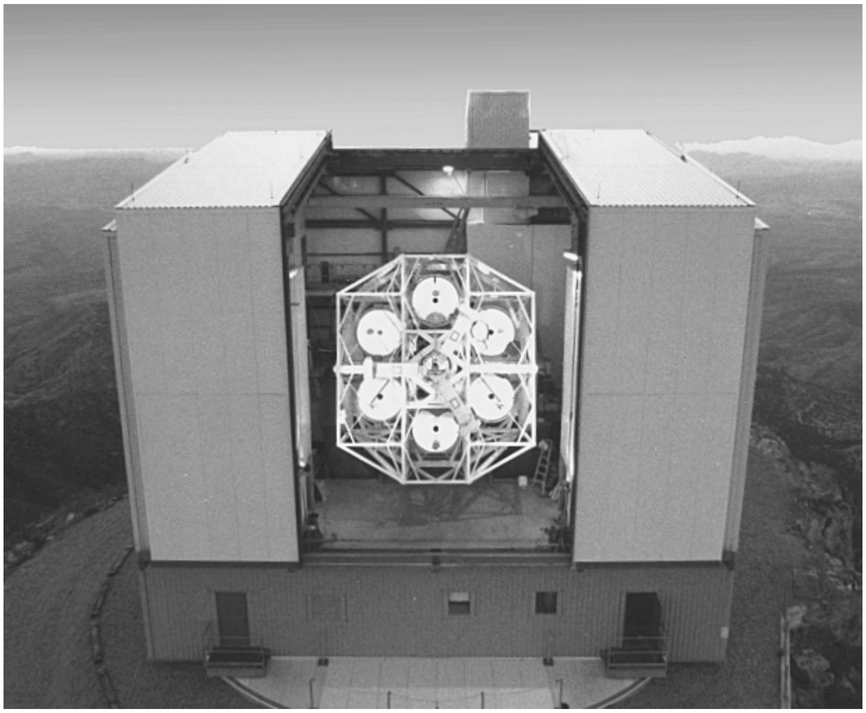


Figure 1: The Multiple Mirror Telescope prior to conversion.

By May of 1994 generation of the primary back plate was complete and 264 pucks and load-spreaders were bonded to the back of the mirror. But there was a setback: pull tests revealed that a large number of pucks failed in adhesion. After a rapid testing program, a second adhesive, Dow Chemical 6093, was selected and the pucks were re-bonded. By November the pucks were in place, and in December the mirror was turned over and lowered into its polishing cell. Generation of the front face was complete by May 1995, and the LOG was modified in preparation for polishing.

In May 1995 the MMT was closed for three months to enlarge the building, extending the front and top of the main shutters by ~two meters to accommodate the new 6.5 m telescope. At the same time the rear wall of the chamber was replaced with a door that could open to allow flow-through ventilation of the chamber. The main doors had to be removed from the building for many weeks, so the telescope was "cocooned" to protect it from the elements. A false floor was built to cover the observing chamber floor, pitched from rear to front to allow for rainwater drainage out the front of the building. By the end of October the new bulged doors were in place on their new tracks, and the rear doors were in operation. The effectiveness of flow-through ventilation was confirmed over the next few months by an improvement in median seeing from 0.79 arcseconds FWHM prior to installation, to 0.71 after.

The primary mirror cell was delivered to SOML in November 1995 and fitted with 1200 air nozzles, 104 support actuators, and six hardpoints that define the mirror's position, together with several miles of connecting hoses and cables. In June 1996 a 10-ton dummy mirror was installed in the cell for testing of the active support system. The entire cell was supported on a temporary trunnion so that it could be tilted for off-zenith testing.

Work continued preparing the MMT site for conversion. In November 1996 a new servo control for the rotating building was installed. Through much of 1997 a new mount servo control was developed and tested. Revisions to the control system were done in preparation for the addition of major new sections: control of the active primary supports and control of the thermal system.

Production of the three-element corrector with ADC wedge prisms, designed by Harland Epps, was contracted to Hughes Danbury Optical Systems (later Raytheon), where polishing was completed in October of 1997. The lenses were coated with anti-reflective Solgel coating at Cleveland Crystals, and assembled into the corrector cell designed and fabricated by SAO.

Polishing of the primary was completed in December of 1997. Redundant testing by Hoffner null lens and CGH confirmed a final surface accuracy of 28 nm rms concentrating 80% encircled energy in 0.14 arcseconds after removal of four "soft" bending modes controllable by the active support system. In January 1998 the mirror was lifted from its polishing cell and installed into the telescope cell. Optimization of the support forces and detailed testing of the primary mirror thermal control system were carried out through the spring. The mirror and cell were returned to the test tower where optical testing confirmed the earlier measurements, now without any post-processing. Following the successful completion of the primary support testing, the mirror was removed from its cell and installed in a shipping box. In July the primary mirror was transported from SOML 50 miles south to the Whipple Observatory base camp where it was stored for the next eight months.

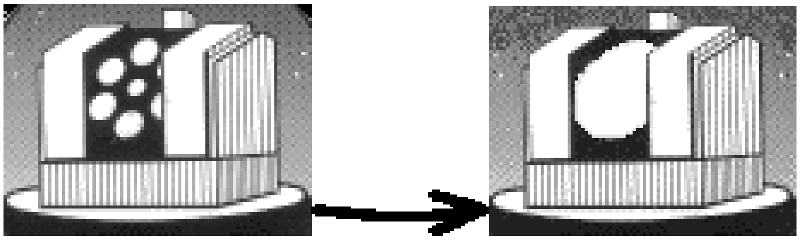


Figure 2: The MMT conversion, in a nutshell. MMTO maintains a World Wide Web site (https://www.mmto.org/) that includes a photo gallery of the Conversion project as well as specifications and documentation related to the Conversion.

A key concern to the project was the safe transport of the 10-ton mirror to the summit of Mount Hopkins. In March 1998 a full-scale test of the transport equipment, including the full-weight dummy mirror instrumented with accelerometers and position transducers, made the trip up the 20 km dirt road to the summit. The instrumentation indicated that the mirror would have a smooth ride.

3. REMOVAL AND REPLACEMENT

When it became clear that the support system was performing to spec, and that the mirror could be safely transported up the tortuous road to the summit, the 4.5 m MMT was decommissioned. Operations ceased on the morning of March 2, 1998. The six-fold optics were removed, packaged, and sent into storage at the Whipple Observatory base camp. The old OSS was dismantled and removed. The new mirror cell and drive arc assemblies were transported to the mountain and installed on the MMT yoke in the summer of 1998. Shortly thereafter, the 21,000 lb steel dummy mirror was installed in the mirror cell on the static primary mirror supports. Next, the forward structure was lifted into the building and attached to the cell. The hardpoints and mirror support actuators were then re-installed in the cell. The drive arc and elevation bearing alignment could then be completed. The active primary mirror support system was installed and tested with the dummy mirror to provide a degree-by-degree map of the actuator and hardpoint forces applied from zenith to horizon pointing, and for accelerations from 0 to the maximum slew speed.

Counterweight drive systems and the elevation brakes were installed and tested. The primary mirror support system, dummy mirror, and the telescope drives were operated simultaneously for the first time in late November 1998. The servo loop for the telescope elevation drive was closed and the two new elevation motors were run simultaneously at slew rates up to 1.5 degrees per second. The azimuth drives were run at similar speeds. Controlled building/telescope collision tests were carried out to verify the safety of the primary mirror under rapid deceleration.

Concurrent with these efforts, SOML continued work on the smaller optics. Jim Burge (UA Optical Sciences Center) developed a new testing technique for convex secondary mirrors using a full-sized CGH in a variation of a Fizeau test. This required the production of transmissive test plates and the development of a CGH writer of unprecedented size. By October of 1996 this effort had produced a 1.2 m diameter holographic test plate for testing the *f/*9 secondary. With the primary mirror in final polish, SOML turned their efforts in earnest to the smaller optics, completing the *f/*9 secondary polishing in August 1998. A day later an accident set the project back several months; a second, even larger, 1.8 m diameter test plate being polished for testing the 1.7 m *f/*5 secondary was shattered during handling. An order for a new fused silica plate was quickly placed. Kodak Special Optics Division was contracted to generate the 1.8 m test optic.

The vacuum head was transported to the mountain in November 1998, test fitted to the mirror cell, and stored on the roof of the nearby support building. The large 50 hp blower for the primary thermal control system was lifted into place while a crane was available on site. Early in 1999 the vacuum head was re-installed on the cell. Large mechanical and turbo molecular vacuum pumps were attached to the cell and the vacuum head. The system was pumped down and deflections of the mirror cell under the pressure load were measured. Satisfactorily low pressures were achieved in the cell, and the cell deflection was within specification. The vacuum bell jar was then removed along with the dummy mirror, and the telescope was prepared for installation of the primary mirror.

4. PRIMARY MIRROR INSTALLATION

On March 22, 1999, the primary mirror was rolled out of the storage facility at the Whipple Observatory base camp and lifted from its lowboy trailer. After mounting on the specially constructed transport trailer, it was rotated to near vertical in preparation for the trip to the summit, and bolted and chained into place. The mirror was driven up the mountain the following day, with the mirror convoy leaving the base camp at about 9:00 AM and arriving at the summit at about noon. Preparations for lifting the primary included the assembly of the lifting fixture, and vacuum tests of the suction pads and associated pumps.

Early in the morning of March 26, 1999, a joint MMTO/Steward Observatory crew assembled at the summit for a pre-lift briefing by J.T. Williams, who directed the lift. At 7:10 AM, a 120-ton crane began to hoist the lifting spider holding the $10 million primary over the top of the building, then gently lowered it into the optics support structure. By 8:40 AM, observatory staff was aligning the mirror to its cell to within an accuracy of a couple of millimeters. At 10:26 AM, the mirror cell supported the entire 10-ton weight of the glass, with the crane holding only the 7-ton lifting fixture. Williams announced that the mirror was wholly free of crane support and cradled only by the cell. A half-hour later, celebratory root beer was popped and passed around among the staff. The mirror had been installed for the life of the telescope, then the biggest single-piece mirror on the North American continent.

On May 24, 1999 first images were obtained at the uncorrected prime focus with the unaluminized primary mirror. To everyone's relief the strongly comatic image field appeared to be free of spherical aberration. Tracking was measured to be quite good at 8 arcseconds rms over the full sky with some clearly systematic errors. Over the next months these were traced to a sticking static support in the primary cell. Testing and refinement of mount and cell control systems continued throughout the summer.

5. IN-SITU ALUMINIZATION

In July 1999 the mirror was carefully cleaned, the cell stripped and fitted with vacuum covers, and the bell jar maneuvered into place. The results of the first *in-situ* aluminizing attempt were mixed. The mechanical pumps worked very well, as did the cryopump. Good deposition rates were achieved, depositing 900 Å of aluminum on the primary. This demonstrated the effectiveness of the power distribution system, which delivered approximately 1100 amps at 36 volts distributed among 200 sources arranged in the lid of the bell jar. However, some sources ran dry during firing and the tungsten rods melted, depositing an overcoat of tungsten on top of the aluminum, resulting in poor reflectance. A second attempt was scheduled for the following April.

Further modifications of the MMT building were carried out through the winter months of 1999, finishing in February 2000. This work included modification of laboratory space to accommodate two large bench mounted spectrographs and a multi-fiber focal plane positioner then in assembly at SAO, reinforcement of the floor in various locations, and relocation of several walls to provide space for storage of the secondary mirrors and the large instruments to be mounted on the telescope. Large white flat-field panels were mounted to the ceiling of the observing chamber doors. The airborne dirt produced by all this activity required that the telescope be tented and therefore not available for observing.

Work continued at SOML preparing the *f/*9 secondary. The optic was mounted and tested in its cell, then removed for aluminization, reassembled, and transported to the mountain. The hexapod positioner that is used to move this secondary in six degrees of freedom was delivered from ADS Italia, assembled and tested at SOML, transported to the mountain, and installed on the telescope.

The 70 cm diameter, 1.6 mm thick *f/*15 Zerodur "shell" for the adaptive *f/*15 secondary was polished at SOML. Polishing this thin shell to a smooth aspheric surface was challenging. To provide polishing support, a convex Zerodur substrate was machined to a close fit, and the back of the proto-shell and front of the substrate were lapped together. They were then bonded with a 100-micron thick layer of pitch to provide rigid support against polishing forces while still allowing the glass to relax under internal stress. The shell was machined to 2 mm thickness, then ground and polished. Polishing was completed in September 1999, achieving a smooth 73 nm rms surface that could be corrected to 8 nm by the 320 voice coil actuators that comprised the adaptive support.

Work also progressed on polishing the *f/*5 secondary mirror. The second 1.8 m fused silica test plate, generated at Kodak, was delivered to SOML where it was polished, coated with chrome, and scribed with concentric rings producing the largest CGH ever produced.

April 2000 saw the second attempt at *in-situ* aluminization of the primary mirror. This yielded a better coating than the previous year's attempt, but the coating was contaminated with copper that had evaporated from the power cables connected to tungsten rods wetted with aluminum. At ~70%, the reflectance was poor but useable at red and longer wavelengths.

Figure 3: The new MMT at sunset. Photo by H. Lester.

6. FIRST LIGHT AT *f*/9

On May 17, 2000, the telescope saw first light at *f*/9 Cassegrain focus. The optical performance exceeded expectation, easily resolving a binary star with 0.7 arcsecond separation and producing images with about 0.3 arcsecond fwhm cores. The thermal control system for the primary mirror had not been installed and only a few aberrations were corrected, and those were assessed "by eye."

The MMT was rededicated on the evening of May 20, 2000. Speeches were given by C. Foltz (MMTO Director), P. Strittmatter (Director, Steward Observatory), and I. Shapiro (Director, Smithsonian Astrophysical Observatory). University of Arizona President, Peter Likins, and the Smithsonian Institution's Undersecretary, Dennis O'Connor, also spoke. At 8:00 PM MST, C. Foltz introduced Project Engineer J.T. Williams, who gave the command by radio to move the telescope and break the ceremonial ribbon that spanned the observing chamber.

From its closure as a 4.5 m Multiple Mirror Telescope to its rededication as the 6.5 m MMT, the conversion took just over two years, certainly the fastest installation of any telescope in its class and a testament to the careful preparation over the preceding years. On the other hand, from the initial commitment in 1986 the conversion took fourteen years. One may well ask, why so long? Clearly there were significant setbacks throughout the history of the project: failure of the first puck bonding; breakage of the 1.8 m diameter test lens; and two unsatisfactory attempts at *in-situ* aluminizing. A less obvious and perennial delay was that the new MMT was a retrofit, designed and built by a staff that was operating a major observatory, itself a full-time job.

A limited amount of scientific observing began on the telescope in June 2000. The first instrument to be mounted was the MIRAC/BLINC mid-infrared camera and nulling interferometer. Observing began in earnest in mid-September with the commissioning of several instruments. The original suite of instruments was upgraded and returned to service one by one: Blue Channel spectrograph, fitted with a new detector, was recommissioned in November 2000; and the Red Channel spectrograph in May 2001. By the last trimester of 2000, sixty percent of the available observing time was available for scientific programs and instrument commissioning, with the remainder going to telescope development and optimization.

An interferometric Shack Hartmann wavefront sensor, developed by Steve West, was used to optimize the mirror's figure. On-axis aberrations were nulled to less than 50 nm rms, producing a point spread function near 0.25 arcsecond. This system was used to optimize the theoretical elevation-dependent force commands derived from FEA. Concurrently Steve began construction of a lenslet Shack Hartmann wavefront sensor that would mount in an existing guider for *f/*9 instruments.

Initial operations were plagued by frequent failures of the primary support actuators that provide the forces to support the primary mirror. The hardpoints that define the mirror position were also problematic, and at first, non-repeatable. Actuator failures were traced to leaks in the pneumatic cylinders. Inspection showed that the leaks were in the internal rubber seals in the pneumatic pistons. The problem was exacerbated at low temperatures and, during the coldest conditions, it became difficult to supply enough air at the requisite pressure to support the primary. The problem was temporarily solved with the installation of Teflon seals; a more permanent solution involving gluing of the seals was devised and tested. The actuators were all removed, disassembled, repaired, and the hardpoints were re-worked, modified, and replaced by March 2001. A further problem developed in the *f/*9 cell, causing erratic collimation. Several sources were identified, and during July 2001 the mirror was removed and the cell was disassembled to replace several components. At the same time, the top end of the telescope was disassembled and the spider turnbuckles replaced. Subsequent tests confirmed that these measures had eliminated the problems, and the tracking improved to ~2 arcseconds rms.

The primary thermal system was installed in the spring of 2001. The design of this system was a departure from those used with other spin-cast borosilicate primaries and was a prototype for the thermal control system to be used with the Large Binocular Telescope. Instead of using distributed liquid-air heat exchangers and fans, the MMT system brings roughly 2200 cfm of conditioned air to the mirror cell from a large remote blower/heat exchanger/chiller via large 24" ducting to the primary cell. Inside the cell the air is piped to a set of jet ejectors that mix with the air in the cell in a semi-recirculating system, which supplies 8 liters/sec of temperature-controlled air to each of the 1020 hex cells in the mirror. With the thermal system in place there was an immediate, dramatic improvement in delivered image quality and in the stability of the wavefront; however, the system did not immediately meet its stringent performance goals and would require further effort to characterize and control.

7. 91% REFLECTIVITY

The telescope was shut down in mid July of 2001 for the third attempt at *in-situ* coating. Preparations included the replacement of the tungsten rod system within the bell jar with coiled tungsten filaments, redesign of the power system to ensure more uniform application of power to the filaments, and installation of a second large cryogenic pump to handle the pressure increase just prior to evaporation. In November 2001 the mirror was stripped and the bell jar maneuvered into place. This time the system performed flawlessly, depositing approximately 1000 Å of Al with 91% reflectance— within two percent of a perfect (92.4%) coating.

The AO mirror was first deployed on the telescope on June 18, 2002 following an extensive testing program at the Steward Observatory Mirror Lab. The run did not achieve first light, due to two problems. The first was a dust contamination of the critical 40 micron air gap behind the deformable optical surface from inadequate shrouding of the mirror. A portable clean room was used to clean the assembly and encapsulate it in Saran Wrap (except the optical surface). This solved the problem, and the mirror went through a full night's operation exposed to the elements. The second was an error in the manufacture of the mechanical structure. As delivered, it was too long and the required motion to focus it correctly was outside the range of its hexapod. This prevented closing the loop during the run. Nevertheless, the secondary was able to hold a rigid figure in the face of a 30 kph wind, and the stability of the optical surface was measured at 20 nm rms or better over periods of ten minutes regardless of elevation angle (to 30 degrees) and orientation with respect to the wind.

In September 2002, the two large optical benches, Hectochelle and Hectospec, arrived from SAO. Installation required the temporary removal of part of the rear wall of the building. The benches and a few of the larger optical components were lifted by crane through the opening into the building. In the following weeks a team of SAO engineers, led by A. Szentgyorgyi and N. Caldwell, began the painstaking process of testing the mechanisms and electronics and aligning the optical components.

In November 2002 SOML completed polish of the 1.7 m *f/*5 secondary mirror, one of the largest optical secondaries ever produced. The final surface figure was measured at 17 nm rms. On completion the mirror was integrated into its support cell and retested against the CGH, this time with the mirror suspended in its use position. Tests showed that the mirror support functioned flawlessly.

8. FIRST LIGHT AT *f/*15 AND *f/*5

During the fall of 2002 the adaptive optics group made corrections to the mechanical structure of the AO secondary, and fitted a new dust shroud. The adaptive secondary was installed for the second time in November 2002. After initial setup and alignment, the system achieved a very impressive first light, reducing ~3/4 arcsecond seeing limited images to just over 1/8 arcsecond with loop closure at 20 Hz and correcting 22 modes. Images were obtained in K-band fully resolving a 0.5 arcsecond binary and achieving a Strehl-ratio of approximately 0.1. These achievements were easily surpassed in January 2003 during the third AO run when full speed loop-closure at 550 Hz yielded Strehl ratios of 0.14 to 0.4 in the H-band, and >0.96 Strehl in N band.

By the start of 2003 the MMT was scheduled ~90% time for science operations and instrument commissioning with the remainder being used for telescope engineering. Throughout January and February the main focus of the MMTO engineering team was the integration and testing of the *f/*5 secondary mirror support and control systems at Steward's Sunnyside vacuum facility. Early results suggested that the positional standard deviation with this setup was about 3 microns rms, well within specification. In March the *f/*5 hexapod controller and its associated electronics completed their integration and testing, and the secondary mirror, cell, and hexapod were delivered to the mountain in early April. Control electronics were installed and a new *f/*5 wavefront sensor, developed by SAO, was transported to the site.

First light in the "naked" *f/*5 configuration occurred early Saturday morning, April 18, 2003. The hexapod performed accurately and reliably, and early images with the *f/*5 wavefront sensor science camera showed images smaller than 0.7 arcseconds on axis. The completed three-element field corrector was delivered and installed for initial engineering trials in May. The 6,000 lb Hectospec fiber positioner arrived in July and was lifted into the chamber. The clearances between the telescope, the massive instrument, and the building were very tight, requiring a coordinated tilt of the telescope while six people pushed the instrument through the narrow gap, all in the face of a thunderstorm that bore down upon the mountain. Over the next five weeks crews from SAO and MMTO uncrated and assembled the instrument and test fit it to the telescope.

With three secondary mirrors to be exchanged on a regular basis, the overhead in collimating by standard methods would have been daunting. During the winter months of 2002 to 2003 MMT staff began development of an alternate method that allowed quick, accurate collimation of each secondary using only an on-axis wavefront sensor. The key to the method was the realization that in any tilted, decentered system with zero coma on axis, the primary optical axis does not coincide with the pointing axis of the telescope. On the other hand, if the primary axis is accurately aligned to the telescope pointing axis, the position of the secondary that produces zero coma on axis must be perfectly collimated. We adopted the basic tenet that the instrument rotator axis defines the pointing direction of the telescope, and developed a method that yielded near-perfect collimation in all three secondaries.

Several engineering nights in the spring of 2003 were devoted to implementing and refining the method. The fast (*f/*1.25) parabolic primary gave us two advantages: prime focus is accessible inside the secondary hub; and it is easy to discern the center of the strongly comatic image field of the uncorrected prime focus. A video camera was mounted at prime focus and an auto-collimating alignment telescope was mounted to the instrument rotator. After alignment to the rotator axis, the collimating telescope projected a target onto the prime focus camera, locating the rotator axis. Pointing to a rich star field, it was easy to discern the center of the coma pattern. The primary tilt was adjusted to place the center of the coma field onto the rotator axis, aligning the primary and rotator axes. Flexure was mapped and found to be sufficiently small that it could be neglected and still give excellent collimation. The video camera was used to build a "first-order" pointing map for the telescope mount. This map assured that the primary optical axis was accurately pointed toward the object.

Secondary changes could now be done with minimum effort. After installing a new secondary mirror, we acquire a star, tilt the secondary about its zero-coma point to move the image onto the center of the instrument rotator axis while setting mount offsets to zero, then tilt the secondary about its center of curvature to eliminate coma as measured with a wavefront sensor located on-axis. As each new secondary was commissioned we used the same first-order pointing map, and built a new elevation-dependent look-up table (called "elcoll") for positioning the secondary mirror. Wavefront analysis and image metrology over the full one-degree field have confirmed that this procedure gives accurate collimation with no detectable anamorphic field aberrations or differential distortion.

With the confirmation of the optical quality of the wide field optics, the telescope commissioning phase was essentially complete. Much work still remained optimizing telescope performance, fabricating baffles for the wide field, and honing the adaptive optics configuration for operations.

9. INSTRUMENT COMISSIONING

In February 2003 a new detector was installed on the Blue Channel of the facility MMT spectrograph. The new detector has 2688 x 512 x 15 micron pixels; read noise was measured at 2.5 electrons rms; full well was 140,000 electrons; cosmetics were nearly perfect; and the QE was superb (~65% at 3200 Å, >90% at 4000 Å and ~65% at 8000 Å). Both Red and Blue channels now had detectors with read noise more than a factor of two smaller than their predecessors.

Blue Channel's new detector saw immediate service: on March 29, 2003 it was used to record the light curve of an extremely bright γ-ray burst. The afterglow from that event was also extraordinarily bright and long-lived, allowing studies from large ground-based telescopes for more than a week following the burst. The MMT and Blue Channel Spectrograph played a crucial role in that follow-up by providing a regular series of spectra of the fading light, revealing for the first time the extraordinarily broad emission lines of elements manufactured during the detonation of a Type 1c supernova at a redshift of 0.17 (Stanek et al. 2003).

By June of 2003 gratings, calibration lamps, and filters had been installed on the bench spectrographs and tests of the alignment and operation completed. Preliminary test images showed that the fiber images had a 98% encircled energy radius of approximately four pixels, about as good as was obtained in laboratory tests. A dark tent was installed around the benches and light-leak tests indicated that most all stray-light sources had been removed. Joe Zajac (SAO) and a team of UA student workers spent the month of August installing 320 fibers from the fiber positioner to the bench spectrograph lab. First astronomical light with the full Hectospec instrument was achieved in August 2003 when 252 fibers were placed on targets in the field of Abell 399. By the end of the run thousands of spectra were recorded during observations of many clusters.

The Arizona Infrared Imager and Echelle Spectrometer (ARIES) obtained first-light images in October 2003 during the fifth adaptive optics run. Point-spread functions show diffraction-limited cores with a FWHM of 2.5-3.5 pixels (0.035 arcsecond/pixel) in the H and K bands. Images were obtained for several scientific and engineering projects relating to the polarization of the double nucleus in M31, the nucleus of NGC 1068, methane-band detection of brown dwarfs, the planetary nebula IC 2149, extragalactic objects such as GC 7252 and Arp 279, and star clusters for isoplanicity measurements (figure 4).

Megacam, SAO's 36-CCD, 340 mega-pixel mosaic imager, was delivered to the site in mid-November 2003. After installing the specially fabricated ~20 inch square Sloan filter set, the imager was installed on the telescope on the 24th. The weather and seeing cooperated to yield some spectacular first light images, with on-axis images of 0.4 arcseconds FWHM for exposures of a few seconds duration. Several targets were imaged for both characterization and science including M1 (the Crab Nebula), M33, M67, M81, Landolt Standard Fields, and Sloan Fields. Extra-focal images were also taken to measure the field-dependent aberrations. Subsequent analysis confirmed the earlier measurements that the field was free of anamorphic aberrations (figure 5).

Megacam was followed by first light for the Hectochelle bench spectrograph in December. Results of the first engineering trials indicated that the spectrograph resolution exceeded expectation; however, the coatings of the bench optics had started to deteriorate, reducing efficiency. In March 2004 the collimator and re-imaging mirrors were removed for recoating.

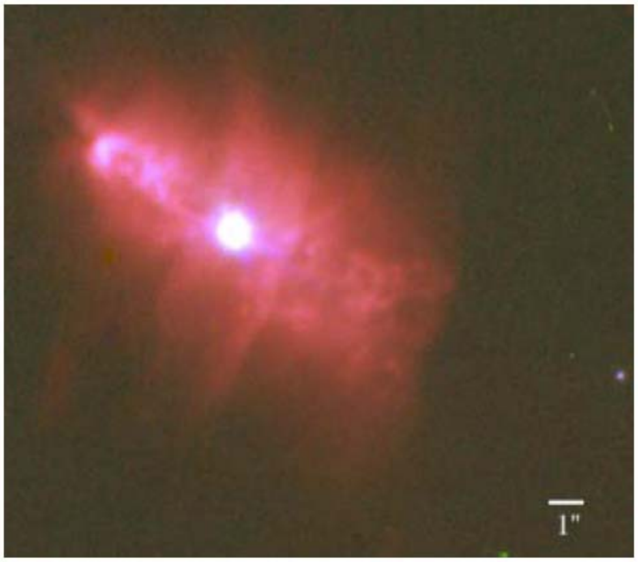
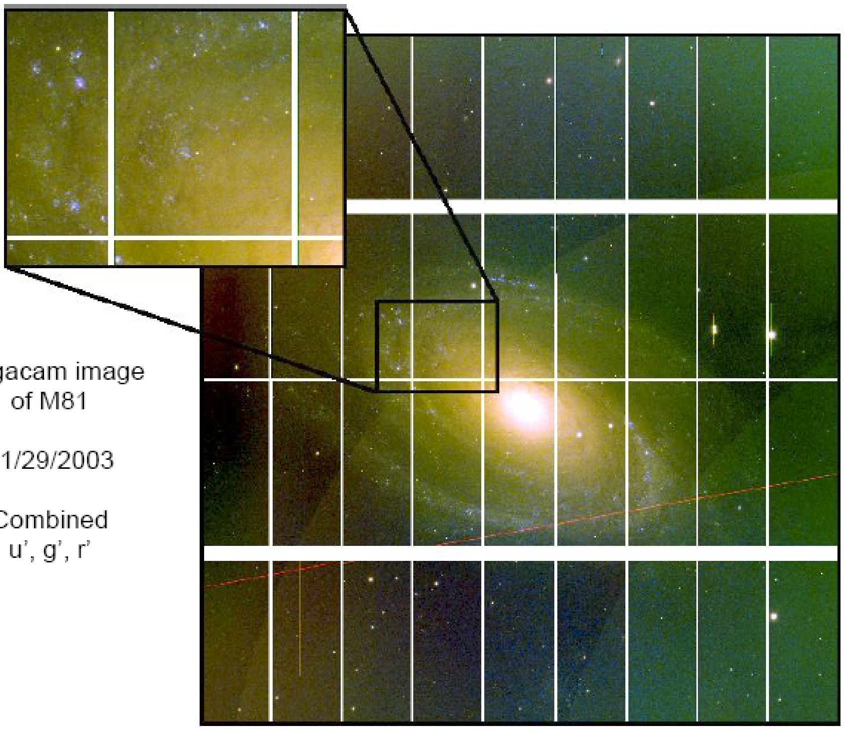


Figure 4: A false-color composite image of the planetary nebula IC 2149 with Adaptive Optics on the MMT. Colors blue, green and red represent 2.088, 2.118, and 2.17 µm wavelengths. The image has a spatial resolution of ~0.1. Image credits: Patrick A. Young, Donald W. McCarthy, Craig Kulesa, Karen A. Knierman, Jacqueline Monkiewicz, Guido Brusa, Douglas Miller, and Matthew Kenworthy.



Megacam image
of M81

11/29/2003

Combined
u', g', r'

Figure 5: Image of M81 taken with the MMT's new f/5 wide-field imager, Megacam, that obtained first light in November, 2003. The instrument uses a mosaic of 36 CCDs, each with 2048 x 4608 pixels, to provide a field-of-view of 24' x 24' at a pixel resolution of 0.08"/pixel. Photo courtesy of B. McLeod (SAO).

The new MMT presently supports a versatile suite of instruments that have been commissioned or are in commissioning. These are briefly described here; further information can be found at the MMT Observatory web page.

f/5 Instruments

- HECTO Fiber Positioner: a twin robotic positioner and 300 fiber head that feeds the two bench spectrographs, HECTOSPEC and HECTOCHELLE. Dual robots, dubbed Fred and Ginger, reconfigure all 300 optical fibers in just 300 seconds.
- HECTOSPEC: a moderate-resolution, multi-object spectrograph fed by 300 optical fibers. The spectrograph offers 5770Å of spectral coverage at ~6Å resolution in the 350 to 1000 nm band. A higher dispersion grating offering ~3Å resolution is in fabrication.
- HECTOCHELLE: a *very* large bench mounted spectrograph using an Echelle grating to attain R~32,000 (sigma~4 km s^{-1}) over single, filter-selected orders. An iodine cell provides wavelength standards.
- MEGACAM: a mosaic camera made up of 36 CCDs each with 2048 x 4608 pixels covering a 24'x24' field with 0.08" sampling on the *f*/5 MMT, eight filter slots, in-dewar guiding, focusing, and low order wavefront sensing,

f/9 Instruments:

- MMT Spectrograph: a two-channel classical single-object spectrograph with Red and Blue optimized channels covering 320 to 1000 nm with resolution R~1,500 to 15,000.
- PISCES: a wide field, 1–2.5 mm camera uses a HAWAII 1024 x 1024 detector covering a 3.16’ field.
- SPOL: a dual-beam imaging polarimeter and grating spectrograph offering spectral resolutions of 4-15Å over a 380-900 nm range. Linear or circular polarization at a level $p < 0.05\%$ is detectable. In the imaging mode, polarization maps can be obtained over a field of view 19” square at the *f/*9 MMT.

f/15 Instruments:

- MIRAC/BLINC: MIRAC3 is a 5-25 micron imager that gives diffraction limited imaging up to 6 microns. BLINC is a nulling interferometer that uses MIRAC as its imager for the nulling mode and provides a focal ratio change for MIRAC in the imaging mode.
- ARIES: the Arizona Infrared Imager and Echelle Spectrometer consists of four cameras optimized for plate scales from 0.019 arcsecond/pixel to 0.102 arcsecond/pixel at the *f*/15 MMT. Each camera uses a 1024x1024 HgCdTe array. The spectrometer (in development) will offer low-resolution spectroscopy with grisms (prisms?) ($\lambda/\Delta\lambda$ from 250 to 500), high-resolution spectroscopy with a cross-dispersed Echelle grating ($\lambda/\Delta\lambda$ from 3,000 to 60,000) and an atmospheric dispersion corrector.

Guiders:

- *f*/5 WFS: a guider and wavefront sensor that can move up to ½ degree off-axis.
- *f*/9 TOPBOX: supporting most *f*/9 instruments including an on-axis wavefront sensor, two guide cameras and calibration lamps.
- *f*/15 TOPBOX: provides high resolution wavefront sensing at >500 Hz for adaptive optics.

In development:

- MAESTRO: the MMT Advanced Echelle Spectrograph, a single-object, high-throughput spectrograph covers 320 to 1000 nm spectral range with R~80,000 for the *f*/5 MMT.
- MMIRS/FLAMINGOES: a NIR (1-2.5 microns) Imager/Multi-object Spectrograph of R~3000 maximum resolution. The final focal scale will be 0.2 arcsecond/pixel, providing a 6.8 by 6.8 arcminute field of view for imaging. With slit masks the field of view will be 2’ by 6.8’ at the *f*/5 MMT.

- BINOSPEC: a moderate-dispersion direct optical spectrograph using up to 150 slitlets located within a 16 by 15 arcminute region. Binospec can cover the spectral range 390 to 1000 nm with 5000Å at 6Å resolution to 2100Å of spectral coverage at 2Å resolution.

- SWIRC: the SAO Wide-field Infrared Camera, a J and H band imager based on a 2048x2048 pixel HAWAII-2 HgCdTe engineering-grade detector. SWIRC will have a 0.15 arcsecond per pixel plate scale, and a field of view of 5 by 5 arcminutes at the *f*/5 MMT

- Rayleigh Laser Beacon: a 30 W pulsed blue laser and gated wavefront sensor that will provide a cluster of five beacons to extend the adaptive optics capabilities beyond the present natural guide star limitations and provide a development path for multi-conjugate adaptive optics.

With so many instruments on site or on the way, storage and handling have become a major issue. We are presently planning further modifications to the facility to provide storage space.

10. CONCLUSIONS AND A LOOK AHEAD

With 2004 marking the 25th anniversary of the dedication of the original MMT, it seems like an appropriate occasion to evaluate our progress. In the four years since its rededication as a 6.5 m facility, the new MMT has transitioned into full operations, now averaging ~90% time dedicated to science use and instrument commissioning. The telescope performance has exceeded our expectations in many areas. The most dramatic evidence of this is undoubtedly the breathtaking first light Megacam image of M81 displaying 0.5 arcsecond FWHM images over the entire 24-arcminute square field. The Steward adaptive optics group has made considerable progress in improving the setup and operation of the unique adaptive secondary mirror and natural guide star system, and we have been rewarded with impressive early results. As this summary is being written, optics for the new Rayleigh laser beacon are being installed that will extend this capability.

Six new instruments have been commissioned or are in commissioning: these provide new capabilities spanning the visible to the thermal IR, and ranging from diffraction-limited resolution to wide-field imagery and multi-object spectroscopy. Four new instruments are presently in construction. Even the stately, twenty-two-year-old facility spectrograph received a face-lift with the installation of state-of-the-art CCDs for both Blue and Red channels. We look forward with anticipation to many future scientific discoveries from these powerful new capabilities.

While we have achieved much, there are many areas that need further improvement. The performance of the tracking servos is less than ideal, and image quality is compromised in even moderate winds. Focus and collimation adjustments can now be applied to correct for known flexure and temperature variations, but the action of the secondary hexapods is not sufficiently smooth to apply them during scientific exposures. Our twenty-five-year-old facility is showing its age and a number of upgrades are needed to improve safety, efficiency of operation, and integrity against the weather. Work is underway on each of these issues: we are close to deploying new encoder readout electronics, a new telescope servo system, a new controller for the hexapods; and improvements and major maintenance of the facility are in contract or are being planned.

Our overall objective is ambitious: to operate what may be the most versatile large telescope in the world on a comparatively Spartan budget, yet with as high a degree of performance and reliability as exists anywhere. This will not be accomplished overnight, nor within a single year. In fact, like scientific research itself, there will be no occasion where we can simply announce the project as “complete.” The satisfaction comes in our dedication to make steady progress, and to take pride in our labors through the astronomical discoveries made along the way.

11. REFERENCES

Hundreds of papers have been published on the MMT conversion and related developments; the list is far too long to include here. The MMT Observatory maintains a partial list of related publications on its website. For more information, please visit https://www.mmto.org/.