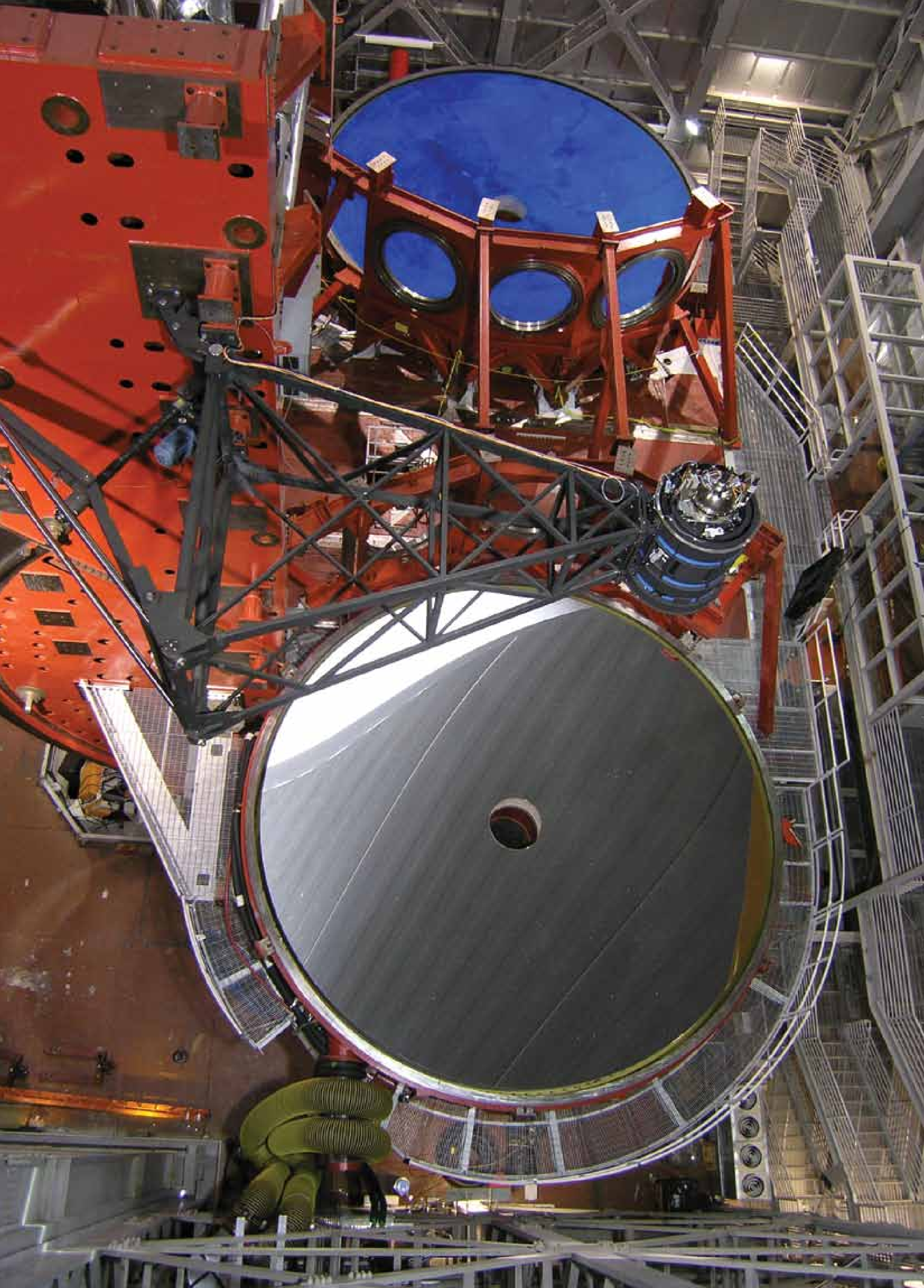

THE LARGE BINOCULAR TELESCOPE

-WORLD'S LARGEST

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As visionary planetary astronomer, Carl Sagan said some thirty years ago, to make extraordinary discoveries requires extraordinary efforts.

The successful creation of great new telescopes to explore the universe requires much planning, design, technological innovation, and construction on remote mountain sites. Building such instruments also require much patience, effort over many years, the formation of international partnerships, and tens or hundreds of millions of dollars in funding. In perspective, the Steward Observatory was established in 1918 with a 36-inch (91 cm) reflecting telescope, funded by the generous gift of Lavinia Steward, and dedicated in 1923. It is still in operation today, 88 years later.

Opposite: This view in the LBT enclosure, seen from overhead, shows a newly aluminized 8.4-m primary mirror with a prime-focus camera above (the barrel-like container with blue stripes supported by a triangular structure). The other mirror has a protective optical coating that will be removed prior to being aluminized. The distance from edge-to-edge (top to bottom) of the two primary mirrors is 23 m, a distance which sets the limit to the angular resolution when the two mirrors are used together.

The LBT is on the summit of Mt. Graham showing the 30-m high shutters open and the two 8.4-m mirrors looking out. The white enclosure is fully rotatable. At left is the Heinrich Hertz 10-m submillimeter radio telescope. This view was taken from a helicopter.

In the 1970s several 4-m telescopes were funded and built in Arizona, Hawaii, Chile, and Australia. When the next generation of larger telescopes, of ~ 8 m aperture, got under way in the 1980s, several different plans arose. The site selection for a major next-generation large telescope was sought in the early 1980s at a time when the Kitt Peak National Observatory and the Steward Observatory were working together. The choice came down to two final sites, Mt. Graham (3200 m) near Safford, Arizona and Mauna Kea (4200 m) on the Big Island of Hawaii. While politics, funding, and location all affected a possible large project, then referred to as the National New Technology Telescope (NNTT), with four 8-m mirrors, , the private-public partnership, supported by the National Science Foundation, became divided. The University of Arizona's Steward Observatory, led by Peter Strittmatter, proposed an alternate plan utilizing two 8-meter mirrors that would be spun cast at the then newly established Steward Observatory Mirror Lab (see AGC, vol. 2, 2010, "Creating the World's Largest Telescope Mirrors").

Subsequently, the Large Binocular Telescope (LBT) was conceived, in the mid-1980s, as a successor to the Multiple-Mirror Telescope that had six 1.8-m mirrors on a common mounting. The MMT served as a demonstration model showing that the light from multiple mirrors could be combined. The effective aperture of the MMT was equivalent to a single mirror of 4.5-m circular aperture but because of its compact design, it required only about 15% the volume compared to the dome of the Palomar 5-m telescope. What Roger Angel, the Mirror Lab Director, proposed were two large mirrors on a single mounting where the light from each large mirror could be combined.

While Angel started out thinking of making two 7.5-m mirrors, other projects of different mirror designs were proposing at least 8-m aperture at the same time. In the course of several years in the early 1990's, the European Southern Observatory decided on four telescopes on separate mountings, each 8.1-m diameter, called the Very large Telescope or VLT. Soon thereafter, the Gemini Project (funded by the National Science Foundation) chose two separate 8.2-m mirrors where one telescope would be located on the summit of Mauna Kea, on the Big Island of Hawaii, and the other would be located on Cerro Pachon, in Northern Chile. At almost the same time, the Japanese funded the Subaru 8.3-m telescope, also located on Mauna Kea. As for the LBT mirrors, Angel subsequently decided on two 8.4-m mirrors on a common (single) mounting.

For the LBT, by installing both mirrors on a single mounting, the images from each huge mirror could be combined to produce images with the angular resolution set by the edge-to-edge distance from one mirror to the other, i.e. 22.4 meters. While the size of the primary mirrors is not limited by the mirror-making technology, the ability to transport these mirrors is set by the dimensions of the roads, bridges, and tunnels along the 250-km delivery route.

The University of Arizona decided on a site for the LBT in October 1984, on Mt. Graham selected for its high elevation, dark skies, clear weather, low water vapor, and the existence of an access road. The formation of a partnership took some ten years to fully realize. By 1994 a parcel of land of 8.5 acres was secured at the summit of Mt. Graham under a lease agreement with the U.S. Forest Service. The LBT partnership involves three US and two European partners, namely Arizona, Germany, and Italy, each with 25%, plus Ohio State University and Research Corporation, each with 12.5%. The Research Corporation participates on behalf of three institutions: the University of Minnesota, the University of Virginia, and the University of Notre Dame.

The upper parts of Mt. Graham, at elevations of ~ 2400 m to the summit there are some 11,000 acres of standing pine forest. Since about 1990 there have been significant changes in the climate resulting in extreme drought conditions. Under these circumstances, bark beetles have moved in and eat the bark destroying the Cambrian layer beneath the bark that otherwise carries nutrients to the tree. A large fraction of the pine forest was decimated first by the bark beetles and then by two major forest fires in 1996 and in 2004. Similar blights have occurred in numerous forests across the western states as a result of climate change.

Ground-breaking on Mt. Graham occurred in 1995. By 1999 the foundation and most of the steel structure of the LBT enclosure was nearing completion. The enclosure is about 45 m high, of which the upper 30 m is the telescope enclosure that is fully rotatable, with a volume of ~ 27,000 m3. In the next five years, the interior of the enclosure, telescope mounting, and optics were assembled. The installation of the major component parts of the mounting each weigh ~ 30-55 tons. Most of the steel parts of the mounting were fabricated by the Ansaldo Steel Works in Milan, Italy.

The two 8.4-m primary mirrors for LBT were spun cast at the Steward Observatory Mirror Lab in 1997 and 2000. They are shown here in the casting lab in January 2003 when rough abrasive grinding had been completed. In the background is a 6.5-m mirror for another project. Note the senior staff technician, Damon Jackson, on the upper right at the top of the stairs.

In 2002-03 these mechanical components were delivered to the site, by ship from Italy to Houston, Texas, and from there overland to Arizona. At the LBT site, they were lifted into place through a hatchway 4x10 m, and assembled. In 2004 and 2006, the 8.4-m diameter primary mirrors, each weighing ~ 17 tons, were transported from the Steward Observatory Mirror Lab at the University of Arizona campus in Tucson to the Mt. Graham International Observatory base camp in Safford (200 km from Tucson). From there each mirror was transferred to a special precision flat-bed trailer-truck and carefully transported from Safford to the summit at ~ 1.6 km/hr, covering the 56 km of the mountain road with many switchbacks in the course of three days.

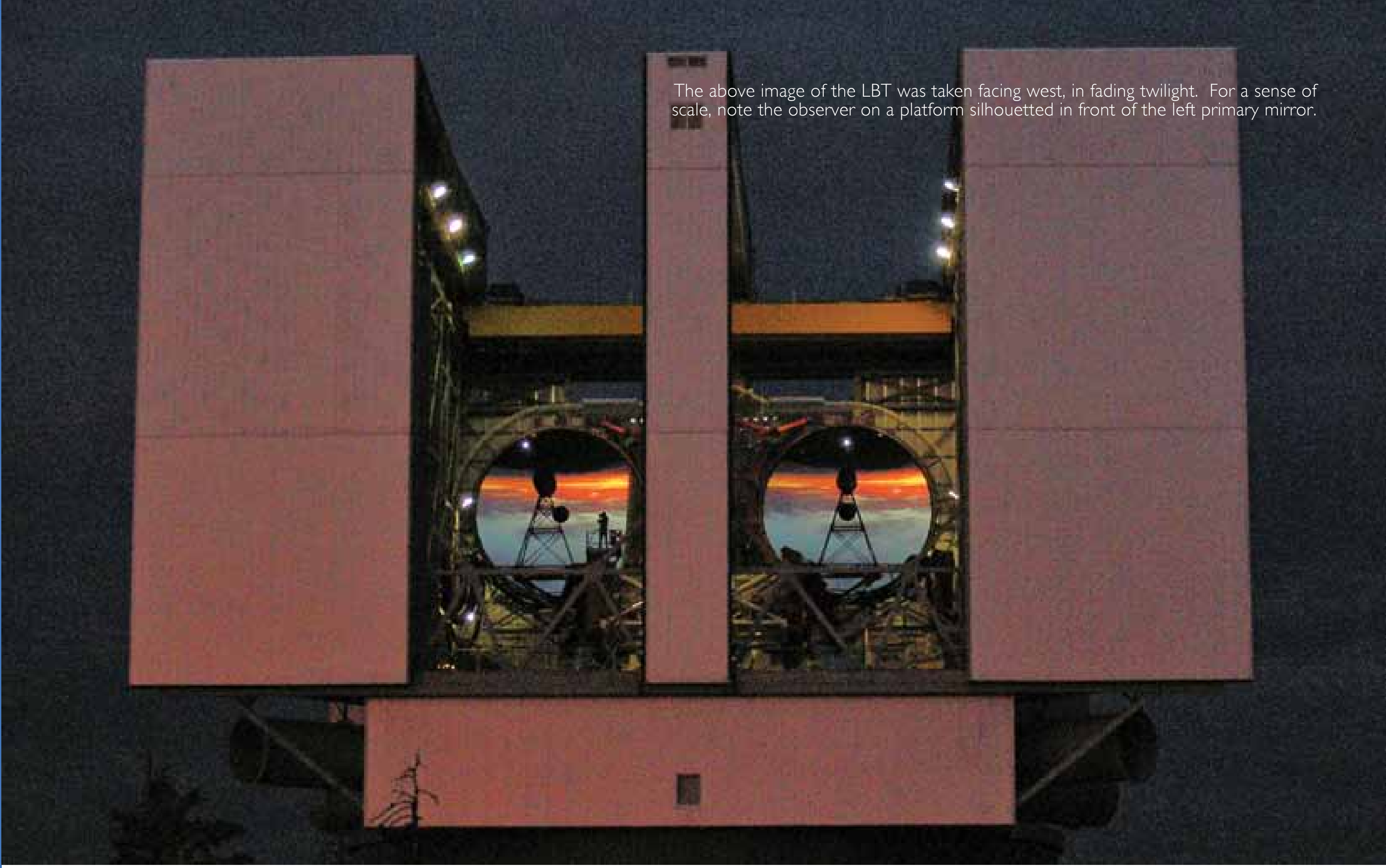
Within the LBT enclosure, each mirror was coated with aluminum in a special vacuum chamber that resides on the site. The thickness of the vapor-deposition of aluminum is ~ 100 nanometers. Aluminum is used rather than silver because it reflects ~ 90% of the light over the full range of visible spectrum (from near ultraviolet, visible, to near infrared) whereas silver has low reflectivity in the violet and near ultraviolet. The first successful operation of acquiring starlight (referred to as "first light" with one 8.4-m mirror was achieved in October 2005 and first binocular light (using both mirrors) was achieved in January 2008. The final optical surfaces of each primary mirror are polished to an accuracy of ▯20 nanometers (about ▯1 millionth of an inch).

INNOVATIVE DESIGN OF THE LBT

The overall design of the LBT includes many innovations in comparison to earlier telescopes. Each of the primary mirrors is actively supported by a series of force actuators that maintain the shape of each mirror regardless of what direction the telescope is pointing. Additionally load cells are used to monitor the force actuators in a kind of feedback loop. This active support system further serves to aid the image quality. The primary mirror requires constant monitoring and updating, to correct for wind loading, for changing gravitational forces as the mirror points in different directions in the sky, as well as convective and radiative thermal changes in the course of the night.

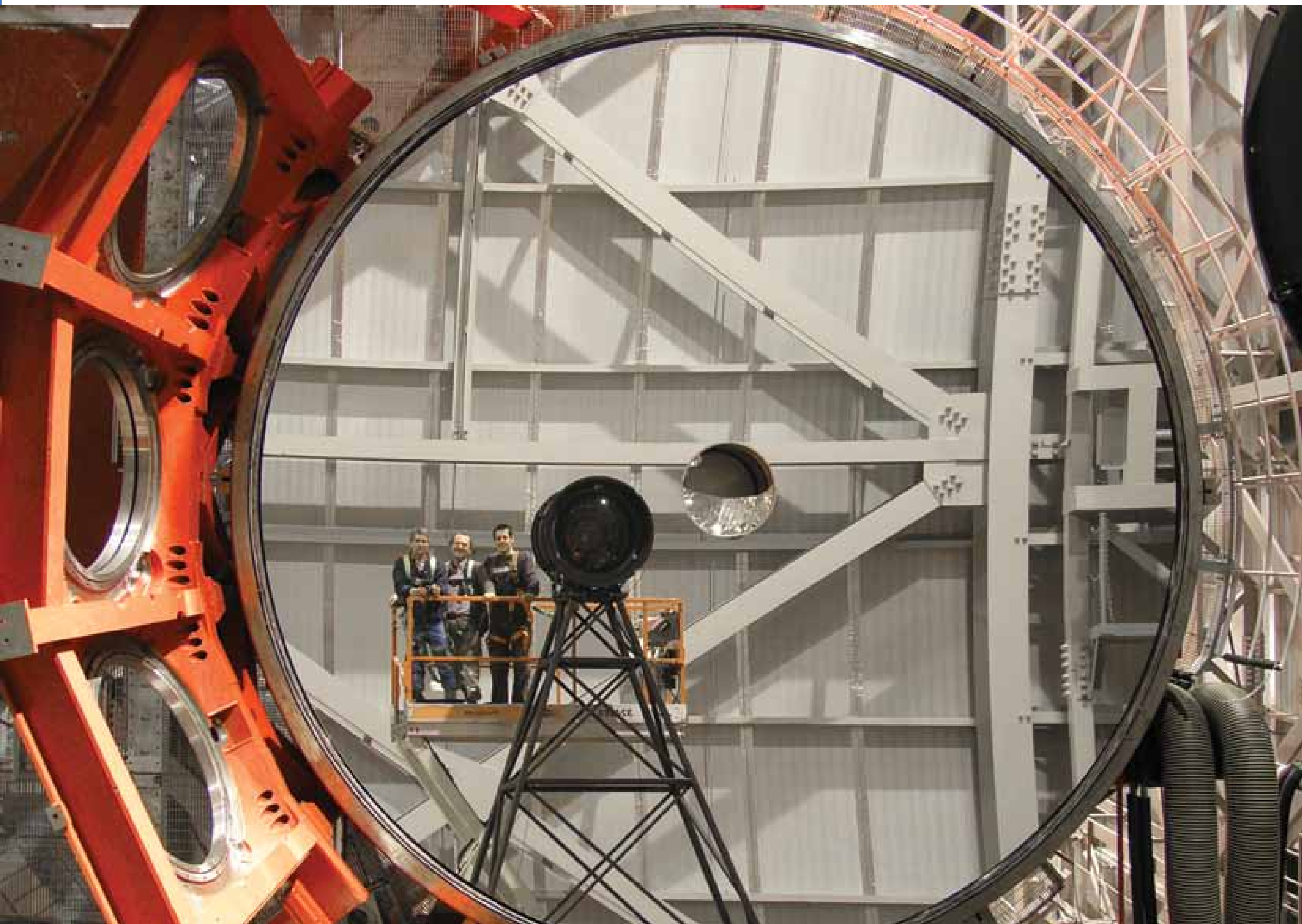
Both primary mirrors are made of Ohara E6 borosilicate glass, manufactured by Ohara Corporation of Japan. When cast, each mirror weighs ~ 20 tons. The high degree of uniformity of Ohara E6 glass and its melting temperature make it ideally suited for spin casting large mirror blanks. Ohara E6 glass has a coefficient of thermal expansion of 2.8 x 10-6/C and this glass has a very high level of homogeneity, essential to spin casting. The mirrors were spun cast with in a honeycomb structure, thus being of relatively light weight. Thermally-conditioned cold night air is circulated through the relatively thin light-weight structure of the glass. The air circulation results in cooling each mirror to the ambient night air temperature in the course of about 30 minutes. In this way air turbulence is minimized just above the mirrors. As a result of the force actuators and load cells to monitor the forces, and the air circulation system, significantly sharper images are obtained, where the seeing (or sharpness) of star images is ~ 0.3 to 0.6 arc seconds in diameter.

Here is one of the two mirror cells being transported to the summit. Note the driver wearing a white helmet at the lower right. Each mirror cell weighs about 56 tons. Each 8.4-meter mirror is also transported on a flat-bed truck to the mountain base camp. From there it is transferred to the flat-bed vehicle (shown above) with 48 independently articulated wheels that is designed to go up mountain roads. The transport is designed so that the mirror is tilted slightly off vertical to make the drive easier on the mountain road with many switchbacks.



The above image of the LBT was taken facing west, in fading twilight. For a sense of scale, note the observer on a platform silhouetted in front of the left primary mirror.

Below: Seen in reflection off of one of the 8.4-m mirrors, LBT team members on a scissors-lift platform complete the installation of the prime-focus camera LBC (the dark circular structure). From left, they are Ray Bertram, Roberto Speziali, and Roberto Ragazzoni.



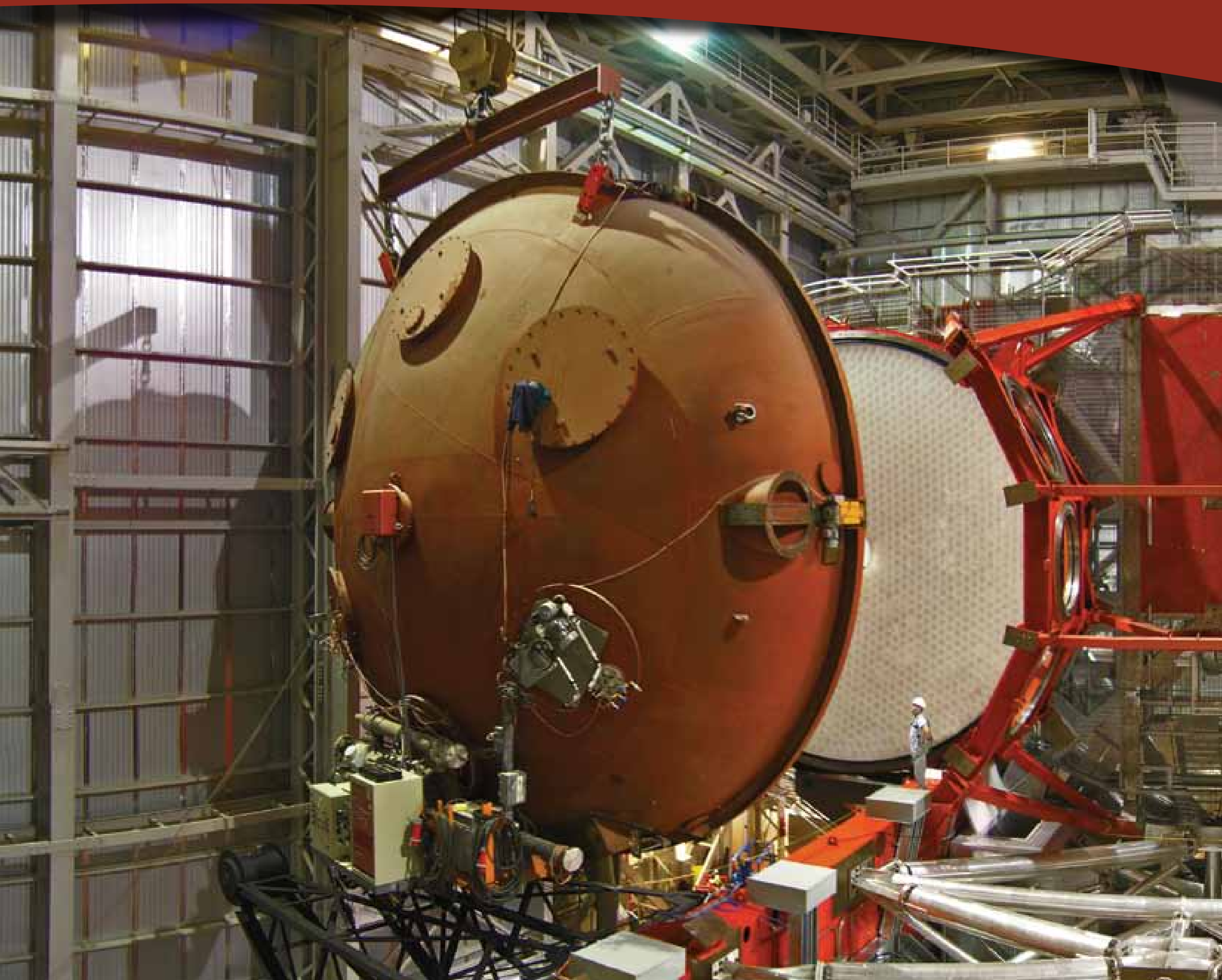
Traditional telescopes built in the period 1930-80 were only able to achieve image quality of ~ 1-2 arc seconds at best. With an improvement in image sharpness by a factor of three, for example, from 1.5 to 0.5 arc sec, stellar images are nine times brighter. While cooling the primary mirrors makes a significant difference, other new technology (adaptive optics, or AO, described below) provides further correction of turbulence in the Earth's atmosphere resulting in even sharper images.

ADAPTIVE OPTICS (AO): CORRECTING FOR ATMOSPHERIC TURBULENCE

While the mechanical components and support of large mirrors were being put into operation, secondary mirrors that will achieve even sharper images are under way. Advances in adaptive optics (AO) have been developing over the past twenty years. Since about 1900, telescopes with apertures of more than one meter have utilized reflecting optics which could be supported below their reflecting surface. In addition to a primary mirror that collects light, there is a secondary mirror that then reflects the light back downward to a focus. In the past, secondary mirrors have been static in their optical shape and function.

With the introduction of adaptive optics (AO), ultra-thin glass mirrors (~ 1.7 mm thick, 91 cm in diameter) have been designed which are flexible. The AO secondary mirrors are made of Schott Zerodur, a zero-expansion glass. Each AO secondary mirror is supported by a series of 672 actuators similar to acoustical voice coils that are magnetically coupled to a rigid reference plate. These very thin glass membranes can change shape to correct for the effects of turbulence in the incoming wavefront in a column of the Earth's atmosphere above the telescope. Corrections in shape occur at rates of 300 to 1000 hertz (cycles per second).

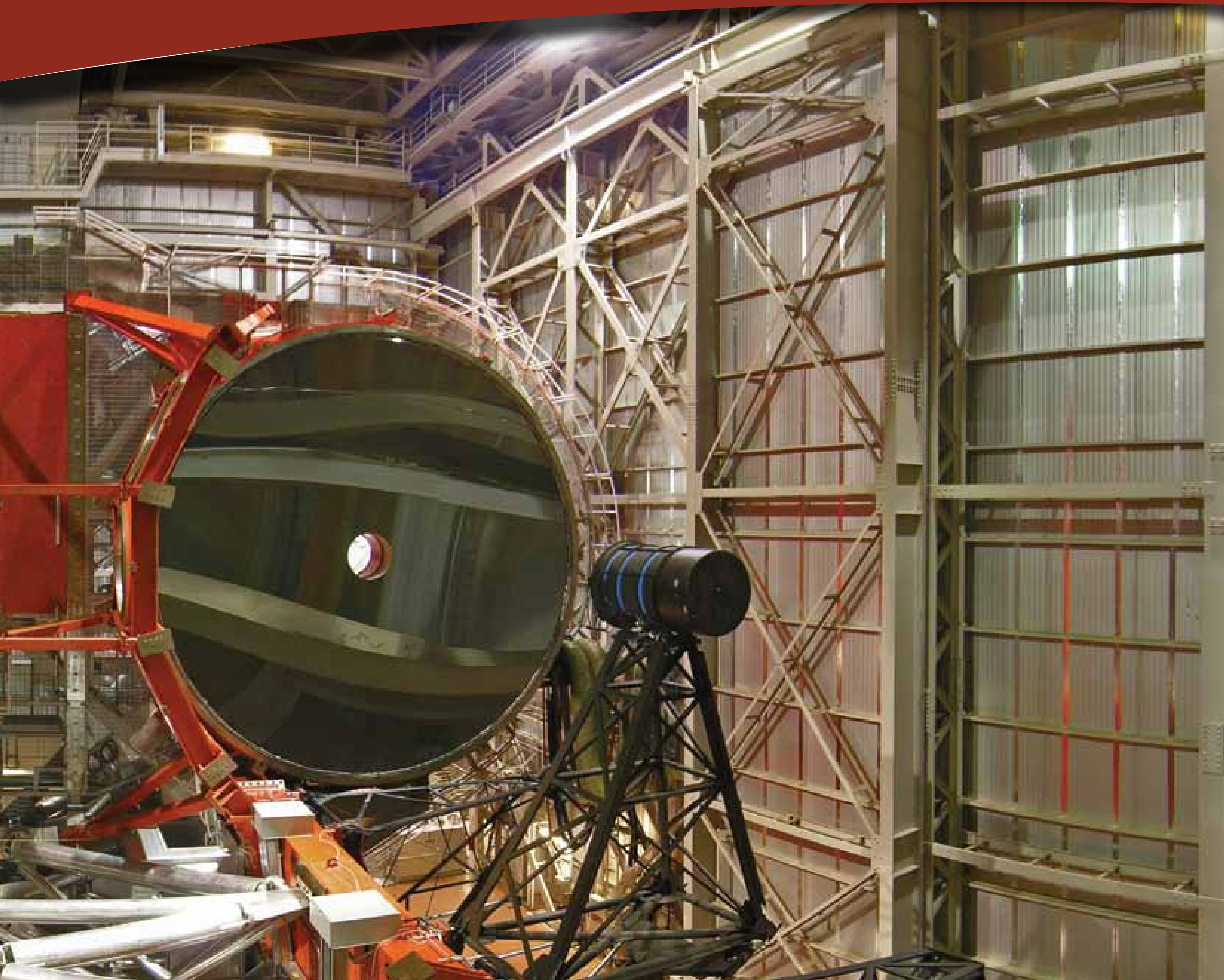
At left the second 8.4-m mirror is about to be aluminized. In the foreground at left is the bell-jar cover that will soon be placed over the mirror to do the aluminizing. Note LBT instrument specialist, Doug Officer below left standing in front of the uncoated mirror.



The AO mirrors can be controlled either passively with natural guide stars (typically ~ 14th magnitude or brighter, i.e. about 5000 times fainter than stars that can be seen by the unaided human eye) or by using a constellation of laser beams that probe the atmosphere at an elevation of 12 km to correct the majority of the turbulence from the air just above the site. The laser beams that originate in the telescope bounce back from the atmosphere and serve as a guide to correct the incoming distorted wavefront. AO corrections can most effectively be made at infrared wavelengths, ~ 1-10 microns. At shorter wavelengths, the rate of change of the distorted wavefront occurs faster than AO corrections can feasibly be made at present. At infrared wavelengths, when both secondary AO mirrors are installed, the LBT is expected to acquire images that are about ten times sharper than the Hubble Space Telescope.

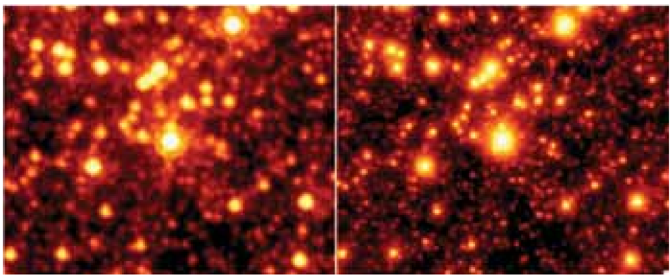
As of this writing (April 2011), one AO secondary mirror has been installed in the LBT and it is achieving images that are ~ 3.5 times sharper than Hubble. A second AO secondary is nearing completion at Arcetri Astrophysical Observatory, in Firenze, Italy. First light adaptive optics (FLAO) images were achieved in May 2010.

At present another secondary mirror – static in shape - is already in place to collect light from the other 8.4-m primary mirror. This static secondary was provided by the Astronomy Department of Ohio State University. Using both the AO and the static secondary mirrors, light from both 8.4-m primary mirrors can be combined. Interference fringes have recently been achieved that demonstrate the optics and the mechanical structure of the telescope and mounting are remarkably stable when directly combining light from the two 8.4-m primary mirrors.

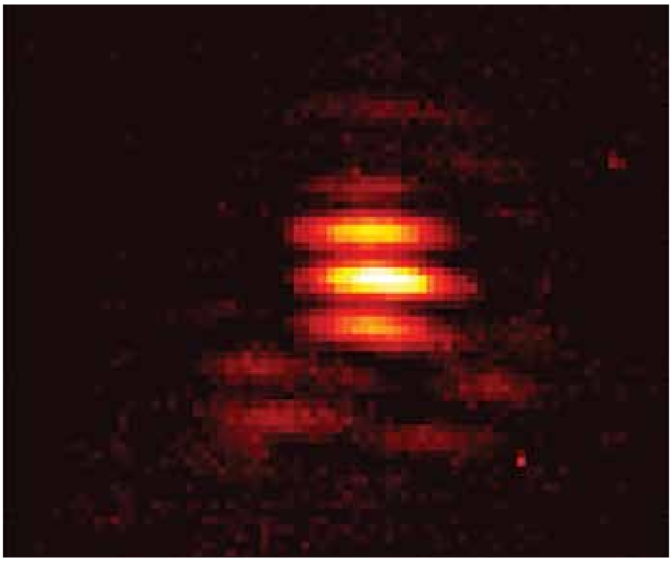


This view from the observing floor, with the building enclosure shutters open, shows two instruments, the prime-focus camera (dark barrel-like structures at upper right), and an f/15 secondary mirror (left of center). The reflections off the 8.4-meter diameter mirror (at right) are the interior walls of the enclosure.

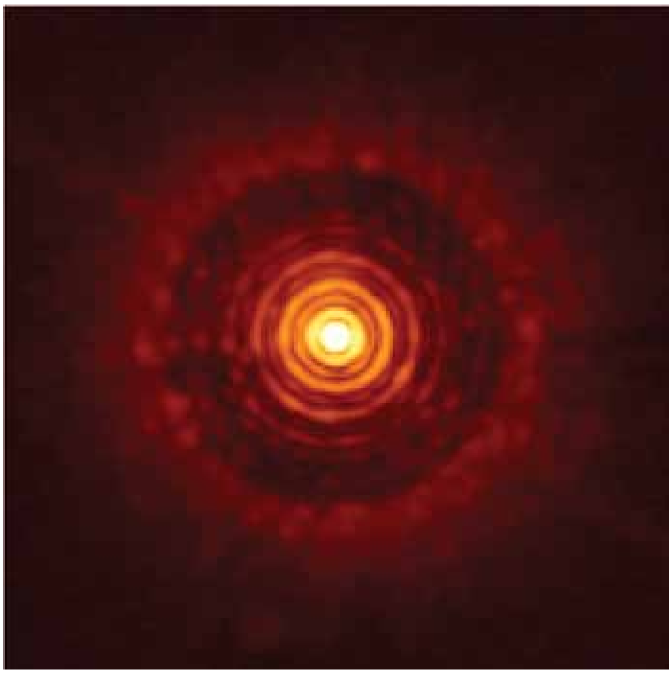
This image of the spiral galaxy NGC 6946, also known as the Fireworks Galaxy, was acquired in January 2006, soon after the first 8.4-m mirror was installed in the LBT with the prime focus camera (LBC). Keep in mind that our Milky Way Galaxy has a similar size and shape as this galaxy, where the Sun would be one faint star out of 100 billion stars in one of the outlying spiral arms. NGC is 22 million light years away. Courtesy of Vincenzo Testa and Cristian DeSantis and the LBTO.



These two images of the central part of the globular cluster M92, at a wavelength of 1.6 microns, show the difference between the Hubble Space Telescope (20 min exposure, at left) and the LBT (10 min). Courtesy of Simone Esposito and the FLAO team.



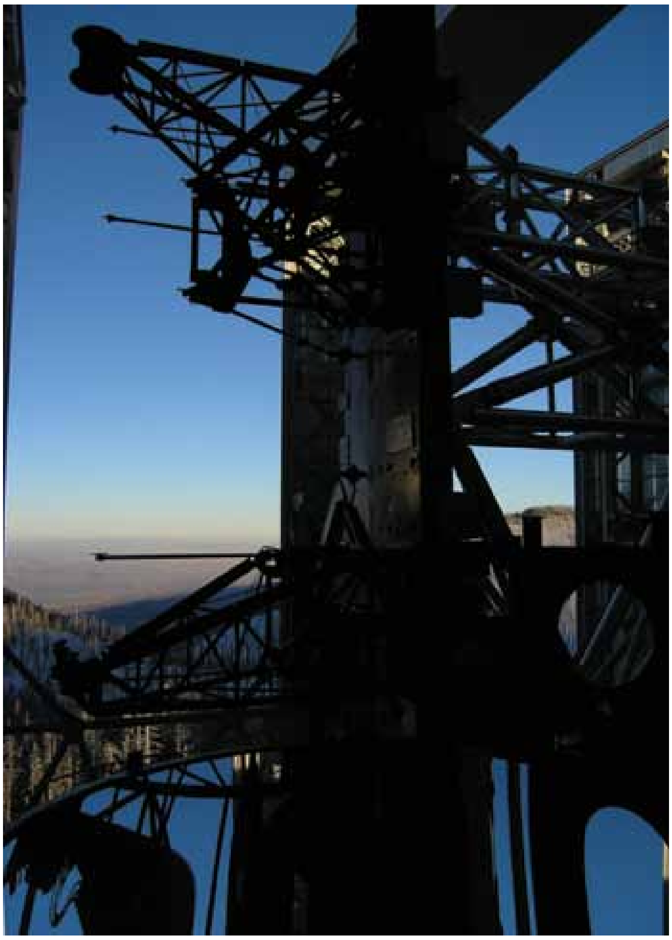
The image shown above was acquired with the LBT Interferometer (LBTI). It demonstrates that the light from both mirrors have been combined interferometrically so that the two images create a fringe pattern at a wavelength, λ ~ 12 microns. . When both AO secondary mirrors are put into operation, LBTI will be capable of acquiring images close to the diffraction limit equivalent to a single mirror of 22.7-m diameter. Courtesy of Phil Hinz and the Steward AO imaging team.



This image of the guide star, HD 175658, shows at least ten diffraction rings, thus demonstrating the high angular resolution of a single LBT mirror using adaptive optics, i.e., 0.025 arc sec at λ ~ 1.6 micron. This image was acquired at the LBT Observatory by Simone Esposito and the AO imaging team from Arcetri Astrophysical Observatory, Firenze, Italy.

PAST, PRESENT, AND FUTURE: MMT TO LBT TO GMT (1977 TO ~ 2020)

The LBT represents an intermediate optical design between the original Multiple-Mirror Telescope (MMT), designed in 1975, and the Giant Magellan Telescope (GMT), currently under construction. The MMT originally had a collecting aperture equivalent to a 4.5-m while the GMT will have an equivalent circular aperture of 21.5 m. When first constructed and put into operation, the MMT (1977-1999) consisted of six 1.8-m mirrors. Starlight was combined by a set of six tertiary mirrors and brought together to form an image, though this image was only stable as a point source for 15-20 minutes. Between 1998 and 2000, the MMT went through a conversion from six 1.8-m mirrors to a single 6.5-m mirror. The MMT is a partnership between the University of Arizona and the Smithsonian Institution. In comparison, the LBT with its two 8.4-m mirrors is in operation and has the light collecting power equivalent to a single 11.8-m mirror and an edge-to-edge aperture of 22.7 m. The GMT will have seven 8.4-m mirrors with an equivalent circular aperture of 21.5 m and an edge-to-edge aperture of 24.5 m.



Just before a night's work is to begin, this view shows a freshly aluminized primary mirror and silhouetted by the secondary support structure and backlit in the twilight. In clear weather on a mountain top in Arizona, looking toward the horizon, one can see ~ 300 km. Observing overhead on a Moonless night, LBT astronomers can nearly see 'forever', i.e., looking back in time ~ 13 billion years or 13 billion light years.

One might ask: what is the importance of the edge-to-edge aperture? When the light from two big mirrors is combined on a stable platform, the effects of optical interference can be achieved which enables the two mirrors to have an aperture equivalent to the distance from the edge of one mirror and the opposite edge of the other mirror. In this configuration, interference or "fringing" can be achieved. As shown above, the LBT has achieved "first fringes" in the infrared at 12 microns. That raw data pattern can be processed to produce image sharpness equivalent to that of a 22.7-m diameter telescope. The second AO secondary mirror is expected to be installed in late 2011.

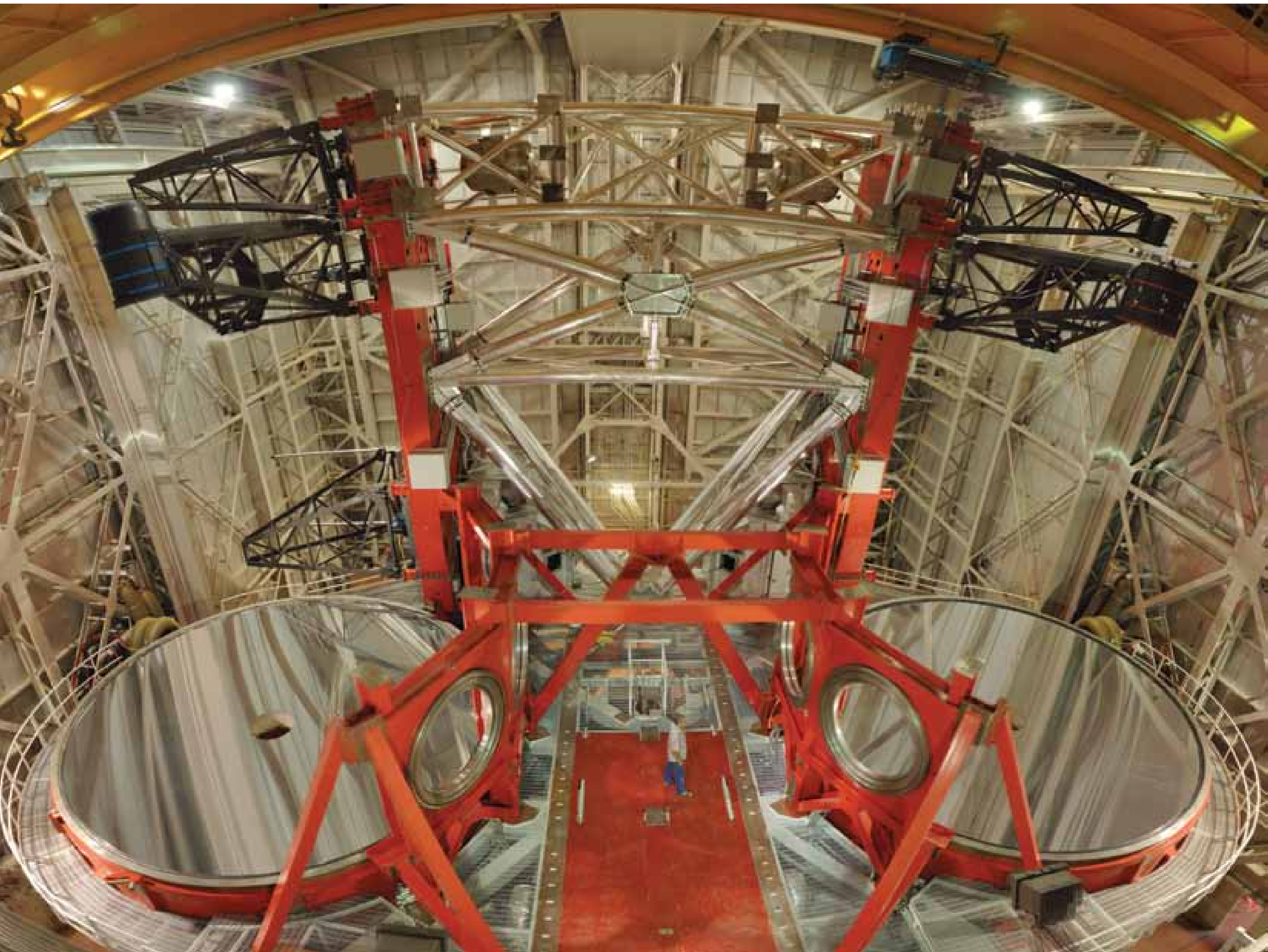
Graphics Editor: Be sure to see three large format (~ 40 MB) images, one of which should go in place of the image directly above. All three images have file names starting with LBT Interior… I like the one with our photographer, Ray Bertram in the center.

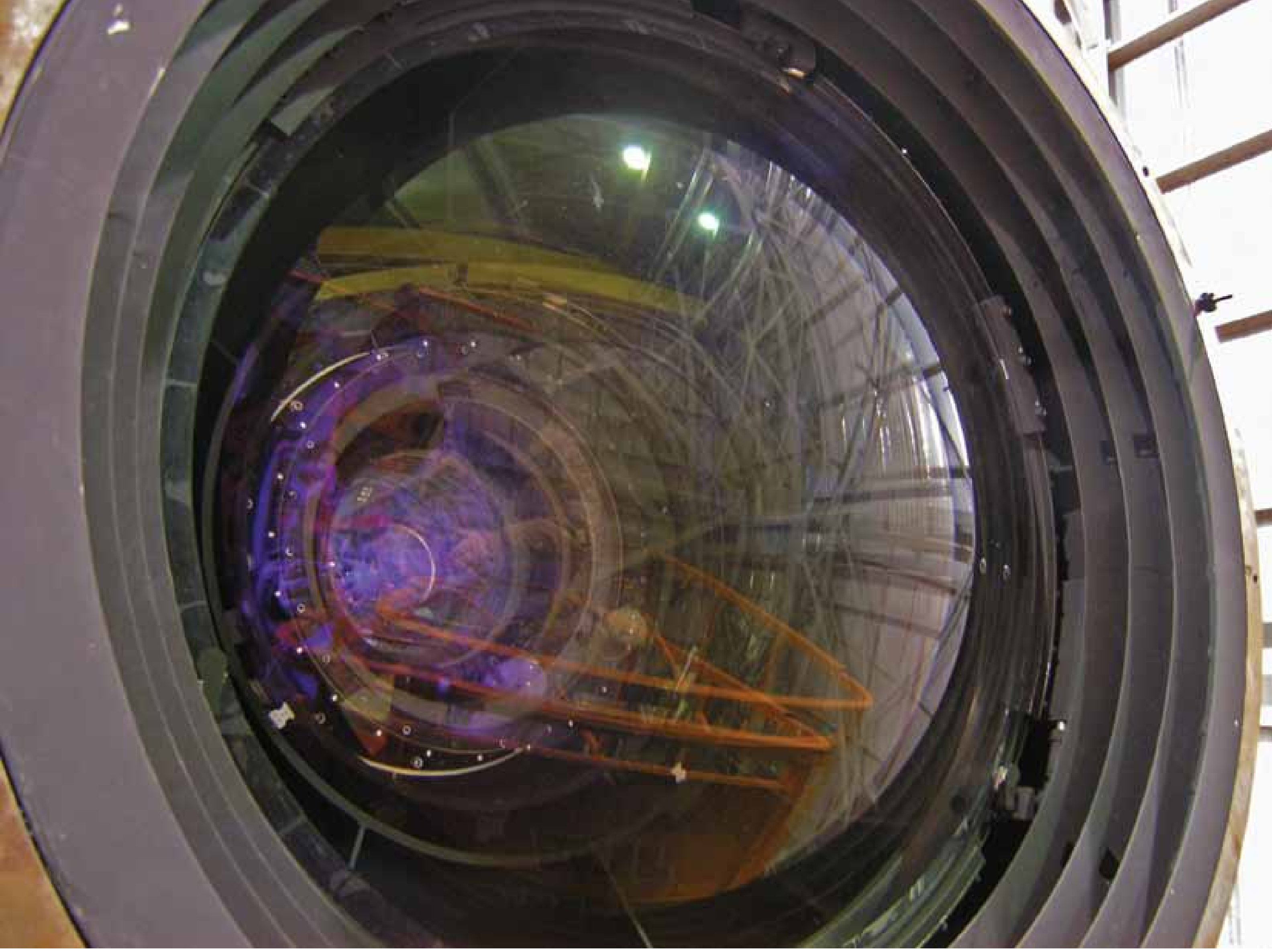
INSTRUMENTS FOR SCIENCE – ANALYZING LIGHT FROM PLANETS, STARS, AND GALAXIES

There are six different instruments that can be utilized with the LBT. Basically we can acquire images of astronomical objects and then those images can be used as a guide to further explorations, primarily involving spectroscopy which is the subject of analyzing the detailed spectral features in the light from these far away objects.

In perspective, the faintest stars that we can see with the unaided eye at a dark site are ~ 6th magnitude. In the logarithmic magnitude scale, commonly used by astronomers, a difference in brightness of five magnitudes corresponds to a factor of 100 in brightness. For LBT, objects can be seen or imaged with the Large Binocular Camera (LBC) about 250 million times fainter, or about 27th magnitude. For imaging, the LBC consists of large-format CCD (charge-coupled

Wide-field view of LBT enclosure with shutters wide open. The distance from the left edge of one primary mirror to the right edge of the other primary is 22.7 meters. The two prime-focus cameras are installed above each primary mirror. Courtesy of Wiphu Rujopakarn, Steward Observatory and the LBTO.





This close-up view of the prime-focus camera shows the set of concentric rings that suppress or mask scattered light off the optical axis. The optical surface in the foreground is a field corrector. When astronomical objects of special interest are identified, by their positions and/or with data acquired using other instruments at various wavelengths, then their light can be analyzed with a spectrograph, which splits the starlight into its component colors of the rainbow.

device) cameras installed at the prime focus of each of the 8.4-m mirrors; one is optimized For the blue spectral region and the other for the red with a field of view of 27 x 27 arc minutes, roughly the size of the Full Moon. Each of the CCD cameras has four sets of CCDs, each containing a CCD array of 2048 x 4608 pixels. In addition, there are two 512 x 2048 CCDs per camera used for guiding the telescope, adjusting the camera focus and making optical corrections to the primary mirrors. The CCDs are cooled with liquid nitrogen to temperatures of ~ -200 C to minimize the electronic read-out noise.

ASTRONOMICAL SPECTROSCOPY – THE ANALYSIS OF STAR LIGHT

Spectroscopy, or the analysis of light in its component colors, provides a powerful means of exploring the physical conditions and chemical composition of astronomical objects, including planets, stars, gaseous nebulae, galaxies, etc. Put simply, a large telescope serves as a light collector that feeds a spectrograph. A whole range of possible scientific measurements can be made with a spectrograph. Here are some examples of information derived from spectroscopy:

- Temperature of the gas in the atmosphere (surface) of a star.
- Identification of atoms and molecules, i.e., chemical composition.
- State of ionization and pressure of the gas.
- Existence and strength of a magnetic field
- Line of sight (i.e. radial) velocity of the object
- Doppler motion of expanding gas shells
- Detection of extrasolar planets (orbiting stars other than the Sun)
- Cosmological distances to galaxies billions of light years away

Astronomers at Ohio State University have designed and built a matching pair of complex Multi-Object Double Spectrographs (MODS) that are fed through an f/15 secondary mirror (at the Gregorian focus). Spectra can be acquired of objects within a field of view of 6 arc minutes with spectral resolutions up to ~ 8000.

Another instrument called the LBT Interferometer (LBTI) will combine light from both primary mirrors in an interferometric manner to null or suppress the light from a bright star and combine the light from the field of view near the star to directly image exoplanets. There is also a fiber-fed spectrograph capable of ultra-high spectral resolution, i.e., = 40,000 to 300,000. The higher the spectral resolution, the more detail can be seen in the spectrum, much like the spatial resolution of a map or aerial photo.

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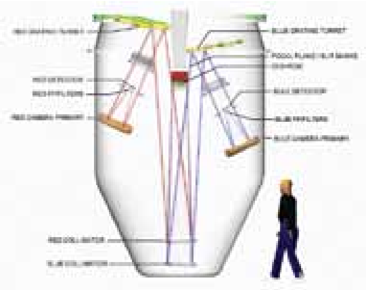
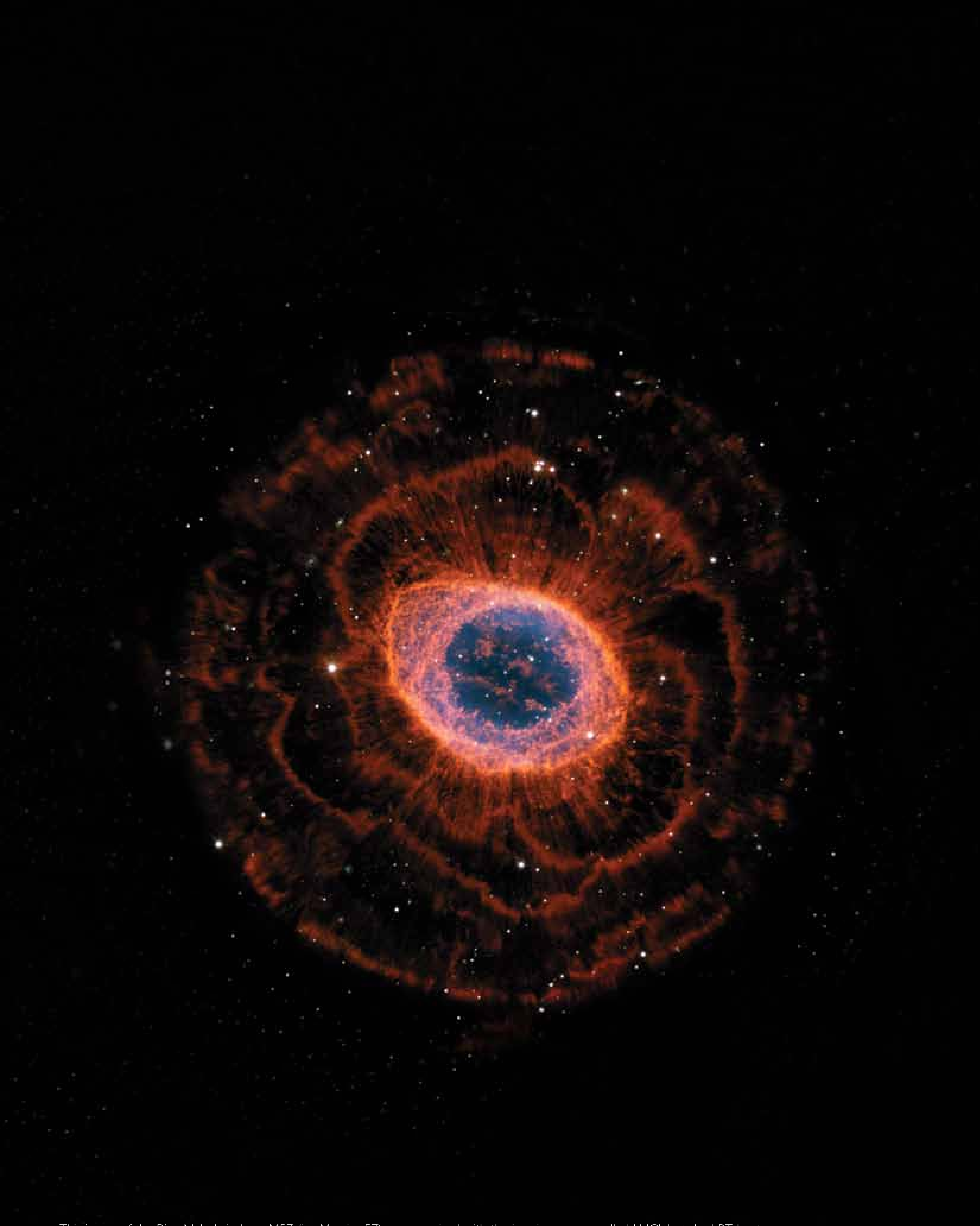
Credit line for all photograph except as noted: Ray Bertram, Steward Observatory

Web sites:
Steward Observatory: http://www.as.arizona.edu
Steward Observatory Mirror Lab: http://mirrorlab.as.arizona.edu
Large Binocular Telescope: http://medusa.as.arizona.edu/lbto/index.htm



This graphic shows the key part of MODS, the Multi-Object Double Spectrograph. Basically, light from the telescope is focused on a narrow slit, and then the light falls on a collimator producing a parallel light beam that is then imaged on a diffraction grating. The light is then dispersed (or split up) into the component colors of the rainbow. Then the light is collected by a camera and comes to a focus where an image is recorded covering some range of wavelengths. MODS is a double-imaging spectrograph with a dichroic beam splitter, reflective collimators, and Maksutov-Schmidt cameras. Graphic courtesy of Richard Pogge, Astronomy Department, Ohio State University.

An astronomer inspects this especially coated 16-cm diameter filter that is used with the prime-focus camera. Interference filters have a narrow wavelength passband that are created by depositing a thin metallic coating on glass.



This image of the Ring Nebula in Lyra, M57 (i.e. Messier 57), was acquired with the imaging camera called LUCI-1 at the LBT bent-Gregorian focus with filters isolating part of the infrared. It dramatically shows structural detail in the expanding shells of gas that are the remnant the outer envelopes of a star that has ejected gases driven by hot winds Earlier photos with 4- or 5-m telescopes only show the brightest central part of this object. LUCI-1 is a near-infrared camera and spectrograph designed and built by scientists and engineers at six research institutes in Germany. This image was acquired by LBTO instrument scientist, David Thompson.