Mount Wilson: Birthplace of Adaptive Optics

By Timothy Thompson

Twinkle, twinkle, little star,
How I wonder what you are!
Up above the world so high,
Like a diamond in the sky.

In the first verse of their famous 1806 poem, "The Star," poet sisters Ann and Jane Taylor wonder what that star really is. Good question. Astronomers have been trying to answer that question in earnest since the dawn of the 20th century, when Mount Wilson founder, physicist and astronomer George Ellery Hale took up the challenge. He forced the new science of astrophysics out of the shadows and into the daylight, for that very purpose. To find out what the stars are.

But there’s a problem. "Twinkle, twinkle, little star," might work for poets, but "steady, steady, little star," while lacking romantic flare, would be a lot better for astronomers. The twinkle is caused by turbulent air.

Unfortunately the atmosphere above always has some level of turbulence, which creates pockets of air of different densities. The time scale for the twinkling comes from the combination of the sizes & speeds of the variable density pockets of air. Larger pockets moving fast have pretty much the same effect as smaller pockets moving slower. The root physical cause is that as light moves from an air pocket of one density, into another air pocket of another density, the light is refracted. In essence, the air pockets act just like lenses floating in the atmosphere. In the jargon of astronomy, this effect is called seeing. If the stars are twinkling madly, then the seeing is bad. The less the stars twinkle, the better the seeing.

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Simulations of what a star field will look like with the future Giant Magellan Telescope without adaptive optics (top) and with adaptive optics (bottom).

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Mount Wilson Observatory Status
As of Tuesday, June 15th, like much of California, the Observatory grounds will be open! The Cosmic Cafe will also reopen during the first weekend: June 19 and 20. Docent tours will resume soon. Please check our website, mtwilson.edu, for more announcements and information about Telescope Rentals, Lectures, Concerts and other activities on the mountain.
NEWS & NOTES

Mount Wilson Observatory Has Reopened!

As of June 15th the Observatory grounds are finally open to the public. The staff and volunteers have been working hard to get all the events up and running. Telescope Reservations for groups have begun. Public Ticket Nights are also ready for individual ticket purchases for up to 4 people. Detailed information about these can be found on the website.

Concerts in the 100-inch Telescope Dome are planned for August 1st and September 5th. Lecture dates are August 28th, September 25th and October 16th. As soon as the programs are finalized, tickets will become available on the website. These generally sell out quickly so check back often.

To find the most current information on all these activities and other announcements please visit our website: www.mtwilson.edu

NOTE: The Observatory Grounds Open at 10:00 AM and Close at 5:00 PM!

The Cosmic Café is open every weekend. Come enjoy a snack or lunch in the Pavilion overlooking the San Gabriel Valley and on a clear day all the way to the Pacific Ocean!

Discovering Mount Wilson

Don’t miss this special series describing the history of the discoveries and the amazing people who made them right here on Mount Wilson! Articles will be arriving weekly throughout the summer in your inbox or they can be found posted on our website. Then join us for “Sundays with Tim” - Zoom gatherings to hear even more at 5:00 PM on the last Sunday of each month.

Supporting Mount Wilson

This past year, with very little revenue coming in due to the pandemic and a major forest fire, we have relied on our many kind donors more than ever. If you are in a position to support science, education, and this remarkable historic site, it would be especially welcome. Visit mtwilson.edu for information on how to support the Observatory through donations and memberships.
Dear Mount Wilson Supporters,

As we track the ever-changing COVID-19 restrictions and guidelines, the Observatory is carefully emerging from more than a year of closure. We recently welcomed our first student STEM group for two days of science instruction, including a night of observing on the historic 60-inch telescope. We were excited to finally see young people again, enjoying the experience of observing celestial wonders with a large and historic telescope, the one used to measure and map our galaxy for the first time. And now we gearing up to welcome back the general public.

Our next step will be to reopen the Cosmic Café which serves food and drink to Observatory visitors and is the point of departure for most of our public and private tours. We hope the tours will be going on some limited basis soon, but we need to make sure they comply with health guidelines and may be restricted in size for a number of months. Likewise telescope sessions. Science lectures and concerts in the 100-inch Telescope dome will probably not be possible anytime soon. As the Observatory reopens in stages, we will post the information at the top of our website: www.mtwilson.edu

The long hiatus in most of our public activities, since December 2019, has been used well (although obviously we would have rather been open). It has been when we could focus on many of the restoration jobs and improvements to our facilities that we have been too busy to tackle in normal years.

Our maintenance staff and a volunteer have finished the complete repainting of the metal components of the Snow Solar Telescope (see photo opposite). Stripping the iron and steel of three or four layers of old paint and rust was not easy, but our crew now has a rock hard layer of enamel paint on it that will keep this historic telescope looking new for years. We thank the Ludwick Family Foundation and the Norris Foundation for funding the preservation of this famous scientific instrument and major component of our STEM program.

Along with countless smaller projects, we have repainted a large section of the Monastery’s dorm rooms. The restored bedrooms, hallway, and stairway once again look as good as they did when many of the most famous astronomers of the 20th century made it their temporary home on the mountain. This historic building will continue to house students, telescope observers, and other guests for many years in the same style as Edwin Hubble.

Like many areas on the fringes of the Observatory property close to the Bobcat Fire, the Monastery narrowly escaped the inferno. We survived the fire with the assistance of our mountain staff and an overwhelming response by Cal Fire and the Forest Service in fielding an army of firefighters on the mountain. As we reopen we are redoubling our efforts to keep the Observatory safe from future and likely more frequent, fires. Due to the lowest precipitation in history this winter (under 12 inches), the forests of the San Gabriel Mountain were as dry in May as they normally this is shaping up to be a very bad fire year.

During the pandemic and Bobcat Fire, the Observatory has been sustained financially by donations from a few large benefactors, but mostly from the general public and our own people. The programs we offer would not be possible without the many unselfish volunteers who staff our events. I am confident that we can soon re-engage all those who share our love for this beautiful world class science and historic site. Mount Wilson is after all the place where humanity finally discovered the true scale of our Milky Way Galaxy and then the Universe beyond.

We look forward to welcoming you all back soon! Bring friends and family and share the amazing experience of being on this special mountain, day or night.

Tom Meneghini
Executive Director, Mount Wilson Institute

The newly restored Snow Solar Telescope, the first large telescope Hale installed on the mountain (in 1904), was ready for our first “post-pandemic” STEM group. The coelostat’s flat mirrors send sunlight into the telescope building so students view a detailed solar spectrum. The spectral lines seen with this instrument provided the first evidence that sunspots are relatively cool regions on the surface of our star.
Alas, condemned to life at the bottom of the atmosphere, which causes all that twinkling, astronomers had no choice but to put up with it the best they could.

Of course, the Hubble Space Telescope solved that problem by going all the way to space. Old time astronomers obviously could not do that. But they could get up on high mountains, to get above as much of the air as they could. Indeed, Isaac Newton suggested this, in his famous book *Opticks* (1704). The first observatory to do this in the USA was Lick Observatory, 4200 feet above San Jose, California, on Mt. Hamilton. One of the places they tested, as a good site for an observatory, was Mount Wilson, 5700 feet above Pasadena, California. And so did Harvard College Observatory, in 1889/1890, when George Ellery Hale was studying there. So it’s no surprise that he settled on Mt. Wilson for his observatory.

The seeing at Mt. Wilson Observatory is the best in North America, and among the best in the world. This is due to simple geography. Mt. Wilson is on the leading edge of the San Gabriel Mountains, where air flowing from the west, after thousands of miles over the Pacific Ocean, is flowing smooth and without turbulence. But of course, even Mt. Wilson has nights of poor seeing and it would be nice to remove the remaining effects of upper atmospheric turbulence from a great seeing night.

An opportunity to do just that came in the late 20th century, with the advent of the new technology of adaptive optics (AO). There are two problems to solve, both of which contribute to the twinkling of stars. One is fluctuations of the apparent position of a star, and the other is the smearing of the image of a star.

No doubt many readers are at least aware of this technology, and some may even know a fair amount about how it works. But perhaps most don’t know that AO technology was invented at Mount Wilson Observatory (MWO). This should come as no surprise, since MWO is the place where so many advances in astrophysics were pioneered. In addition to fundamental discoveries about the Universe, many of the technologies and techniques of the new science were first developed here.

The person who started AO in both practice and theory, was Horace Babcock (1912-2003) who grew up at MWO, where his father, Harold Babcock (1882-1968), had joined the staff in 1909. Harold made his mark primarily in the field of precision spectroscopy, and officially retired in 1948, although retirement did not keep him from continuing his astronomical research. Horace is best known for measuring the general magnetic field of the Sun, along with his father, in the 1950s. MWO Founder George Ellery Hale had discovered localized magnetic fields in sunspots in 1908. And he thought he had observed the general magnetic field, outside of sunspots, in 1912-1913. But in fact, his results were ambiguous. But the magnetic maps made by father & son Babcock were not at all ambiguous, and nailed down the general magnetic field of the Sun, for sure.

Horace Babcock’s bachelor’s degree was in physics, and his PhD in astronomy. But he was always inclined towards mechanical engineering, and was highly talented at developing, designing & building instruments. In 1947, he hit on the idea of using a knife-edge, as found in the well-known Foucault knife-edge test for mirrors, to compensate for the apparent motion of a star.

He didn’t have the technology to do tip-tilt correction by rapidly moving a mirror, as adaptive optics systems do today. That’s where a single flat mirror is rapidly wiggled around, so that the image of the star remains, as closely as possible, at one fixed place on the focal plane.

So instead, Babcock built an autoguider, and corrected for the wiggling of the star, by moving the entire telescope. He started by pointing the telescope, so that the position of the star was aligned on the optical axis, and was intercepted by the knife-edge, which covered about half of the image of the star. If the star wiggled around, then the light from the star would get brighter if it moved away from the knife-edge, and dimmer if it moved towards the knife edge. His key insight was to then rotate the knife-edge, so that its frequency was faster than the wiggling frequency of the star. Since the rotation of the knife-edge is known, and therefore its position as a function of time is known, both the distance and direction, in which the star wiggles can be retrieved. Then the autoguider moved...
In 1947, Babcock constructed this device to detect movements of a star. Its light, entering through the brass ring, would encounter a rapidly rotating “knife edge” blocking the light from different quadrants. The photodetector (the black cylinder) would then measure the light and sense any changes in amount of light if the star moved off center. A feedback loop would then move the telescope to keep the telescope on the star. It was astronomy’s first autoguider in two dimensions.

The diagram below shows how a modern AO system works, with all the elements Babcock envisioned. Light entering the telescope is intercepted by a beam splitter, which sends half of the light to a wavefront sensor, and the other half to a wavefront corrector. The light from the wavefront corrector goes to your detector, or science instrument, or even a photographic plate (if anyone still uses them). The wavefront sensor detects both the smearing, and the wiggling motions of a star, calculates appropriate corrections, and then sends the instructions to the wavefront corrector. The corrector is a thin, flexible mirror, with a large number of electronically driven pistons behind it. They push against the back of the mirror, deforming the front surface, roughly 1000 times per second. The result is that most of the blurring and wiggling of the star image is removed, and the image projected onto the detector is what it would look like, if there were no seeing effects at all, like being in space.

Following Babcock’s seminal AO paper in 1953, astronomers continued to try to tackle the AO problem, but with limited success. The first published application of AO to astronomy does not show up until 1989, when the COME-ON (CGE Observatoire de Meudon ESO ONERA) system achieved diffraction limited imaging, on the 1.5 meter telescope, at the Observatoire de Haute Provence, in France. This was what we now call a natural guide-star AO system, where the seeing correction is applied to a star in the same field of view as your science target. (Hopefully there is a suitably bright one to use.)

After the success of 1989, the technology developed by experts in astronomical optics, combined with declassified systems that the U.S. military had been working on, sparked a sudden surge in research into AO systems. This resulted in a quick series of advances for the new technology. A race to eliminate atmospheric distortion.

Observatories all over the world went to work on testing & adapting the newly declassified technology, and MWO was certainly one of them. In the post-Babcock era, the first
adaptive optics system at MWO appeared on the 60-inch telescope in 1991. The Atmospheric Compensation Experiment (ACE) had been designed by Lincoln Labs, for the Department of Defense, starting in the 1970s. It was declassified, and installed at the coudé focus of the 60-inch (Baliunas, et al., 1994). The system was designed to enhance the relative brightness of the object of interest (the Strehl ratio in astronomy jargon), whereas astronomical applications primarily seek to enhance the angular resolution. But, of course, it’s a rare astronomer who will complain about objects being brighter as well.

In the words of Sallie Baliunas (1994), “With careful attention to thermal control, on nights of good seeing, we have been able to obtain stellar images that are within 25% of the telescope diffraction limit at 700 nm. ... The ACE system operating at the 60-inch telescope has demonstrated great success in employing an early adaptive optics system to an historic telescope. A modern adaptive optics system designed for astronomical use could be efficient, relatively inexpensive and robust.” The diffraction limit of a telescope is the theoretical limit of its resolution, with zero atmospheric interference, tied to the size of its mirror. If you can tackle the seeing problem, the bigger your mirror the better your resolution will be.

The success of ACE on the 60-inch led to the system being ported to the 100-inch, where it was adapted to the north cassegrain position. On the 100-inch, ACE was used to investigate binary stars. In 1999, ACE was used to disprove the Hipparcos mission determination that Arcturus was a binary. And in the same year, ACE was used to study the atmosphere of Titan.

Meanwhile, another team, lead by astronomer Laird Thompson at the University of Illinois and electrical engineer Scott Teare at New Mexico Tech, went to work on a second AO system for the 100-inch. This was the University of Illinois Seeing Improvement System (UnISIS). Unlike ACE, which used a star in the field of view for its seeing corrections, UnISIS used an artificial star, created by projecting a 35-watt ultraviolet laser into a layer in the upper atmosphere which reflects its light back down to a detector to monitor the turbulence above. So, ACE is an example of natural guide-star AO, while UnISIS is an example of laser guide-star AO.

UnISIS was set up at the coudé focus of the 100-inch telescope. The simple AO diagram included here shows how such systems work in a very general manner, but leaves out the fine details of the optics needed in a real instrument. The UnISIS optics sat on an optical bench that measured 5 x 16 feet, with a large number of optical components, including mirrors, collimating lenses, beam splitters, and of course, the deformable mirror that is the heart of the system. The laser was generated at the ground level of the 100-inch telescope building, and projected out through the 100-inch telescope itself, with the focus point set at 18 km (11.2 miles). The laser creates an artificial star, simply by scattering light off of air molecules in the upper atmosphere. And as you might guess, this requires FAA approval, and a person acting as spotter, to make sure there are no visible aircraft that might intercept the laser beam.

Although the literature includes numerous technical descriptions of UnISIS (e.g., Thompson & Teare, 2002; Thompson, et al., 2009), I can find no indication that the system was ever used for science observations. It appears to have been primarily an engineering & technology test instrument. It certainly influenced the laser guide-star AO systems that are increasingly used for large telescopes.

And finally, I will point out that if you really want to go all the way to the frontier of science & engineering, to achieve high angular resolution, then interferometry is the way to go. The world’s first successful stellar optical interferometer went to work at MWO in 1920 (Michelson & Pease, 1921), and produced the first apparent angular diameter measurements for stars. Continuing in the tradition of biggest & best, that permeates MWO, the Center for High Angular Resolution Astronomy at Georgia State University, chose MWO as the host facility for the world’s largest optical astronomical interferometer, the CHARA Array. They have been doing science observations at MWO since 2002, with a vast array of significant achievements to their credit so far. But even for an interferometer, seeing is an issue. So the CHARA array is currently in the process of being upgraded with adaptive optics on all 6 telescopes. This will improve efficiency, and allow the array to observe dimmer stars. It’s the perfect marriage of interferometry and adaptive optics, both of them fundamental astronomical technologies, and both invented & first tested, at Mount Wilson Observatory.
The mission of the Mount Wilson Institute is to manage and promote the Mount Wilson Observatory for scientific research, historic preservation, education, public engagement, and the arts.

The Observatory relies solely on the generosity of our many supporters, to whom we are always extremely thankful, to accomplish our goals. This year, with our revenue from tours, events, and telescope rentals cut off, we are especially grateful to those who have helped us with a donation or a membership. If you would like to join in giving, please visit our website at: www.mtwilson.edu.
HOW TO GET TO MOUNT WILSON OBSERVATORY

From the 210 freeway, follow Angeles Crest Highway (State Highway 2 north) from La Cañada Flintridge to the Mount Wilson–Red Box Road; turn right, go 5 miles to the Observatory gate marked Skyline Park, and park in the lot below the Pavilion. Visit the Cosmic Café at the Pavilion, or walk in on the Observatory access road (far left side of parking lot) about 1/4 mile to the Observatory area.

WELCOME, VISITORS!

The Observatory is open from 10:00 a.m. to 5:00 p.m. daily, and until 4:00 p.m. in the off-season. The Cosmic Café at the Pavilion offers sandwiches and Observatory memorabilia on Saturdays and Sundays from 10:00 A.M. to 5:00 PM.

SELF-GUIDED TOURS

When grounds are open, you are welcome to walk around the outside public areas of the Observatory. Our website has printouts for self-guided tours. The Observatory and the CHARA array both have small museums, and the 100-inch Telescope dome has a visitor's gallery to view the famous 100-inch Telescope.

DOCENT-LED WALKING TOURS

On weekends at 1:00 P.M. docents generally lead two-hour tours. Suspended due to COVID, these will resume soon. Please see our website for up to date information and details.

PRIVATE GROUP TOURS

Group daytime tours are also available. Advance notice and reservations are required and a modest fee is charged.

PARKING AT THE OBSERVATORY

We are open almost everyday of the year. The U.S. Forest Service requires those parking within the Angeles National Forest and the National Monument (including the Observatory) to display a National Forest Adventure Pass. For information, visit www.fs.usda.gov/angeles/. Display of a National Parks Senior Pass or Golden Age Passport is also acceptable.