

Ground-Based Telescopes and Instruments

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By 1916, the American astronomer George Ellery Hale (see Fig. 1), a founding member of The Optical Society (OSA), had designed and built an optical solar telescope on Mt. Wilson and measured the strength of magnetic fields on the Sun using his new invention: the solar magnetograph. This opened a new era in astronomy and demonstrated to all the merits of adding optical physics to astronomy. In 1916 the Mt. Wilson Observatory, under the direction of Hale, had just completed the 60-inch reflecting telescope and it was becoming productive. Hale hired George Ritchey to figure the 60-inch mirror with a hyperbolic primary and secondary to extend the field of view (FOV) of the standard Cassegrain telescope. Most astronomical telescopes today use this optical configuration.

Hale's career started out at the University of Chicago, where he met A. A. Michelson (OSA Honorary Member) in 1889 when he arrived at the University of Chicago. Hale nominated Michelson for the Nobel Prize in Physics in 1907. In 1916 Hale, director of Mt. Wilson Observatory, was elected vice-president of OSA. Later (in 1935) he would be awarded the Frederic Ives Medal. Obsessed with optical astronomy since childhood, Hale graduated from MIT in physics and studied solar physics at Harvard. Hale recognized the advantages of reflectors and in 1908 used a 60-inch-diameter glass disk given to him by his father to build the world's largest telescope on Mt. Wilson in southern California. By 1916 Hale had obtained funds from John D. Hooker, a Chicago philanthropist, and he was building, once again, the world's largest telescope: the 100-inch, dedicated in 1917. The 100-inch Hooker ground-based telescope is the same size as the Hubble Space Telescope of today. By 1935, Hale had sold the Rockefeller Foundation on supporting the design and construction of a 200-inch telescope and set off for a third time to build the world's largest telescope. George Ellery Hale engaged private financial support for optical telescopes from wealthy barons of the industrial revolution: Yerkes, Carnegie, Hooker, and Rockefeller. Figure 2 shows Hale with Andrew Carnegie in 1910. Hale established the tradition of private support that continues today with the Keck telescopes, Sloan Digital Sky Survey, and others.

Using new sensitive photographic emulsions developed by C. E. K. Mees (for whom the OSA Mees Medal is named), Edwin Hubble (shown in Fig. 3) imaged several Cepheid variables in the Andromeda Galaxy (M-31). The average luminosity of these variables is constant. Therefore, a measurement of the brightness of these very faint objects in M31 gives a direct measure of the distance. The measured distance was well outside our galaxy, demonstrating that spiral nebulae were outside our galaxy and thus proving that the universe was very large indeed! Hubble went on to show that the universe was expanding, thus providing fundamental evidence for today's "big bang" cosmology.

In 1930 an Estonian optician, Bernard Schmidt, developed his Schmidt camera for the imaging of large areas of the sky. For the first time, astronomers could make wide-FOV surveys needed to study the large-scale structure of our galaxy and to create catalogs of spectral types and variable stars in an efficient manner. The first large-aperture Schmidt cameras were the 40-cm-aperture at Mt. Palomar (1936) and the 60-cm at Case Western Reserve University (1939).

In 1946 Aden Meinel (1982 Ives Medalist, 1952 Lomb Medalist, and OSA President) built the first high-speed Schmidt camera and discovered the OH bands in the IR spectrum of the atmosphere using recently declassified infrared-sensitive photographic emulsions. James Baker (OSA Ives Medalist) improved on Schmidt's design to create the Baker–Nunn camera for wide-angle observations of artificial satellites passing rapidly overhead.

Hale conceived the 200-inch telescope shortly after the dedication of the 100-inch telescope in 1917. The task of raising funds, keeping the vision alive, and preparing conceptual designs occupied most the 1920s. By 1928 Hale secured a grant of \$6 million from the Rockefeller Foundation to complete the design and begin construction of the 200-inch telescope on Mt. Palomar. The Corning Glass Works, an OSA Corporate Member, working over a ten-year period, developed the technology and cast the Pyrex primary mirror. Construction of the observatory facilities began in 1936 but was interrupted by the onset of World War II. The telescope was completed and dedicated in 1948. Ira Bowen (1952 Ives Medalist) refined the optical system and the grating spectrographs and rebuilt the mirror support system. The telescope was not open for scientific use until 1949, and the first astronomer to use it was Edwin Hubble.

John Strong (1956 Ives Medalist and OSA President), demonstrated the advantages of using an evaporative aluminum coating on the 100-inch telescope in 1936. Before this, chemically deposited silver was used, which degraded rapidly to limit the faintest magnitude that could be recorded. The reflectivity of silver degrades significantly within a few days. Al coatings on mirrors are robust and with proper care retain high reflectivity for years. This increase in telescope transmittance enabled astronomers to record stars several magnitudes fainter than before.

During World War II, most optical astronomers were involved in the war effort. Scanners, detectors, photomultipliers, mirror coatings, manufacturing methods for large glass mirrors, and high-speed cameras were just a few of the technologies developed by optical astronomers during this period.

At the end of the war optical astronomers returned to civilian jobs. The new infrared-sensitive photographic films developed during the conflict were now used to extend astronomical discoveries into the infrared. Photomultipliers were used to make precision measurements of stellar brightness and color. These data improved our understanding of stellar evolution and reddening (absorption) due to interstellar matter.

The National Science Foundation was founded in 1950. Its earliest research center was the Kitt Peak National Observatory founded in 1955 operated under a board of directors from several university astronomy departments. Aden Meinel, an astronomy professor and optical scientist from the University of Chicago, was selected to be the founding director. The purpose of the observatory was to provide astronomical telescope time on a peer-review selection basis to all astronomers in the U.S. Under Meinel's direction the observatory developed the process for the thermal slump of a Pyrex mirror around a conformal mold (used in the 82-inch telescope), created a rocket program for UV spectroscopy of stellar objects, developed the world's largest solar observatory (the 60-inch McMath–Pierce), developed a 50-inch robot telescope for photoelectric photometry, and laid the groundwork for the first program in observational infrared astrophysics.



▲ Fig. 1. George Ellery Hale, astronomer and founding member of the OSA. Credit Huntington Library, San Marino, California. (The University of Chicago Yerkes Observatory, courtesy AIP Emilio Segre Visual Archives.)



▲ **Fig. 2.** George Ellery Hale (right) possibly discussing future telescopes with Andrew Carnegie (center) in 1910. (Image courtesy The Observatories of the Carnegie Institution for Science Collection at the Huntington Library, San Marino, California.)

In 1960 Meinel left the Kitt Peak National Observatory to become the director of Steward Observatory. There he led the academic program, developed a 92-inch telescope for the University of Arizona on Kitt Peak Mountain and led an initiative to establish a national center of excellence in optical sciences and engineering, focused on many issues related to technology for astronomical telescopes and instruments. In 1964 funding became available, and the University of Arizona established the Optical Sciences Center under Aden's leadership. Aden established a distinguished faculty composed of A. F. Turner (Ives Medalist), R. R. Shannon (1985 OSA President), R. V. Shack (David Richardson Medalist), J. C. Wyant (2010 OSA President), and Roger Angel (OSA Fellow). Figure 4 shows Aden Meinel in 1985 while at NASA/JPL. In 1973 Aden resigned from the directorship to continue research in solar thermal energy, and Peter Franken (OSA Wood Prize and OSA President) became director.

In the late 1970s Roger Angel (OSA member) experimented with spin casting Pyrex mirrors for astronomical telescopes. This development has led to a family of 8-meter ground-based telescopes, which are revolutionizing our astrophysical understanding of the universe around the world.

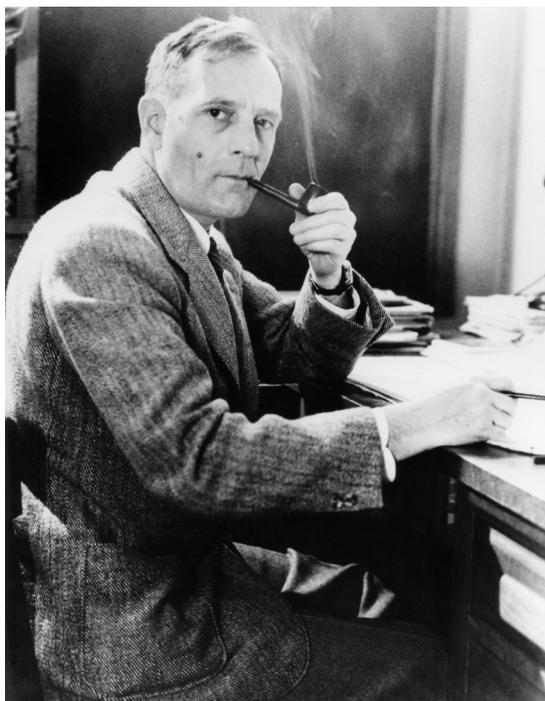
In 1920 optical physicist A. A. Michelson (OSA Honorary Member) made the first measurements of the diameter of a star using a white-light spatial interferometer mounted to the top of the 100-inch telescope. Atmospheric seeing and telescope stability prohibited useful data using the photographic plates of the time, and both he and his colleague F. G. Pease resorted to visual observations of flickering fringes to measure the diameter of stars. Breckinridge (OSA Fellow) recorded the first direct images of the fringes more than 50 years later. C. H. Townes (1996 Ives Medalist and Nobel

Laureate) developed the heterodyne-interferometer method and made early measurements of details of stellar atmospheres. Townes also invented the laser, which astronomers use in conjunction with adaptive optics to provide reference laser guide stars to remove atmospheric turbulence and enable diffraction-limited imaging from large-aperture ground-based astronomical telescopes. Over the past 30 years stellar optical interferometry has advanced to become a highly useful tool for the astronomy community. Today, several ground-based observatories use optical interferometry to measure high-angular-resolution (<0.001 arc sec) details across the surfaces of stars in the presence of Earth's atmospheric turbulence.

This 25-year period from 1975 to 2000 in the history of the OSA saw an explosive growth in technologies to make very large mirrors, long-baseline interferometers, large-area detectors, and space telescope systems. Angular resolution on the sky went from 0.5 arc sec to 0.001 arc sec and the surfaces of hundreds of stars were resolved. The high-speed electronics developed for military and commercial applications and innovative optical systems enabled long-baseline Michelson stellar interferometers for high-angular-resolution astronomy. Astronomers used atmospheric-turbulence-induced speckle patterns to create diffraction-limited images at large optical telescopes and thus make the first direct images across the surfaces of stars. The Orbiting Astronomical Observatory (OAO) was built and launched, and the Hubble Space Telescope (HST) was built and corrected.

Mt. Wilson astronomers discovered that larger telescopes, while collecting more photons than smaller telescopes, did not necessarily mean observing fainter objects. Atmospheric turbulence introduces wavefront errors as a function of time. Three major problems confronted the implementation of a system to correct atmospherically induced time-dependent phase perturbations. These were the need for (1) wavefront sensing, (2) a deformable mirror, and (3) signal and control processing.

Several OSA members pioneered practical solutions to these problems to increase the angular resolution on the sky from the seeing-limited 0.5 arc sec to 0.005 arc sec for a gain of 10,000 in area resolution. Although no one person was responsible for the invention of adaptive optics, OSA Fellows John Hardy and Mark Ealey and others from ITEK Optical Systems (OSA Corporate Member at the time) led the technology development of ground-based telescope systems to image distant objects



▲ Fig. 3. Edwin Hubble, who proved that the universe is much larger than we thought and is expanding. (Hale Observatories, courtesy AIP Emilio Segre Visual Archives.)



▲ Fig. 4. Aden Meinel in 1985 while at NASA/JPL. (Courtesy NASA/JPL-Caltech P-31041A.)



▲ **Fig. 5.** A laser guide star tuned to the wavelength of sodium atoms in the atmosphere, providing information on atmospheric turbulence to allow for adaptive optics to compensate and enable improved telescope resolution. (©Laurie Hatch.)

through atmospheric turbulence for the Air Force. At Kirtland Air Force Base Bob Fugate (OSA Fellow) demonstrated laser guide star adaptive optics, a technology in common use today at the Keck Telescope and a critical part of the new very large 30-meter-class telescopes. Figure 5 shows a laser guide star being used to compensate for atmospheric distortion.

Today there are four optical telescopes with apertures over 10 meters and nine 8-meter-class optical telescopes in operation nightly recording faint radiation from the cosmos. The Keck Ten-Meter-Diameter Telescope Project, under the technical leadership of Jerry Nelson (OSA Senior Member) pioneered the large aperture segmented phased telescope in common use today. OSA Corporate Members Corning Glass and Schott Glass and the University of Arizona under the leadership of OSA Fellow Roger Angel pioneered the design and cost-effective manufacture of monolithic mirror blanks 8 meters in diameter.

In 2016, on the occasion of the 100th anniversary of the OSA, there are three very ambitious projects underway to build astronomical optical telescopes with 30-meter-aperture-class phased primary mirrors. Each of these will be equipped with laser guide star adaptive optics to remove the effects of atmospheric turbulence and thus enable diffraction-limited imaging at resolutions approaching 3 milliarcsec steerable over a FOV on the order of 20

arc min. The Thirty Meter Telescope (TMT) will have over 500 phased mirror segments. The Giant Magellan Telescope (GMT) will have seven 8-meter mirrors in a hexagonal pattern with one of the mirrors at the center. The Extremely Large Telescope (ELT) will have 798 hexagonal segments each 1.45 meters across to create a 40-meter-diameter primary mirror.

The past 100 years of optical telescope development has led to profound changes in our understanding of the universe. The next 100 years of optical astronomy may reveal that mankind is not alone in the universe and that life exists and flourishes on planets around distant stars—stars so far away that our only contact will be with the optical photons reflected from the surface of exoplanets. Innovative spectrometers and polarimeters will be used to estimate the presence of life. Only if humans invent a way around the limits of speed-of-light travel will two-way communication with exoplanet life be possible.