BUILDING LARGE TELESCOPES:
II- REFLECTORS

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On the turn of the twentieth century the refractor was rapidly approaching its limits in terms of aperture. The main reason for this was the difficulty in manufacturing discs of crown and flint glass with diameters greater than 100 cm. Manufactures of plate-glass could however cast large disks of ordinary crown glass, of lower optical quality, that were suitable for mirrors. It was also known that the light losses in lenses of more than 100 cm would be much greater that those in mirrors of equal aperture, especially in the blue region of the electromagnetic spectrum where the highest sensitivity of the first photographic plates lay. Lenses with diameters of more than 1 m were also very difficult to mount and flexure was a major drawback. Mirrors were easy to mount, the focal ratios were smaller and there were no residual chromatic aberrations. Astrophysicists aimed at the largest possible aperture and perfect color correction. The reflector was the way to go. The lower focal ratio of the reflector meant shorter tubes, smaller domes and lower overall costs. Reflectors were, in spite of all, considered by the majority of astronomers around the turn of the century, as imprecise and difficult to use instruments. The mounts of the first big reflectors were imperfect and the mirrors sagged under their own weight. For this reason the reflector was being mainly used by amateur astronomers.

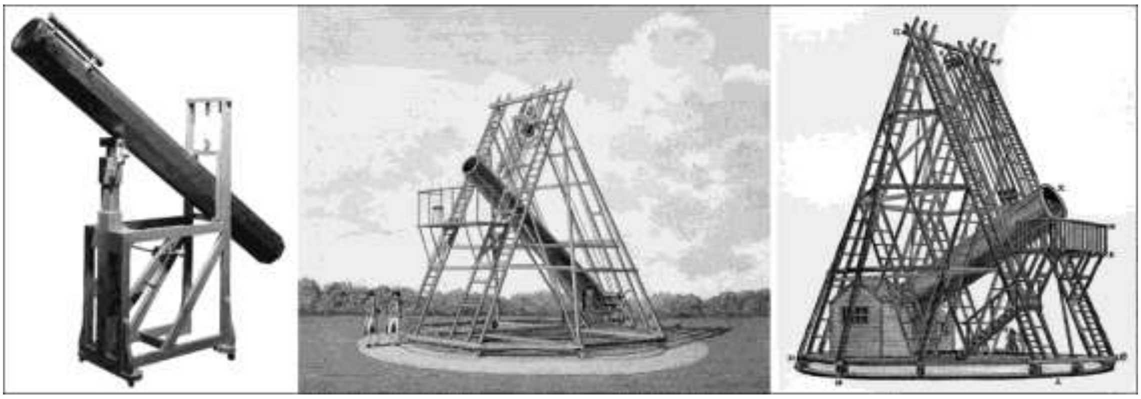

Figure 1- William Herschel's telescopes. From left to right: seven-foot reflector, twenty-foot reflector and forty-foot reflector.

First big reflecting telescopes

The first big reflectors were built by William Herschel (1738-1822). During the course of his career, Herschel constructed more than four hundred telescopes. The largest of these reflectors was the 40 ft (12 m focal length) telescope. This telescope with a primary mirror with a diameter of 126 cm was very difficult to use and most of W. Herschel's observations were conducted with smaller instruments (15 and 48 cm apertures) (Figure 1).

Herschel cast his first solid speculum mirror in late October 1773. These consisted of a compound of copper, tin and antimony. Its surface was shaped and finally polished to a high gloss. Most of Herschel's telescopes were mounted in wooden tubes and alt-azimuth mounts (Figure 1). Herschel became the greatest telescope maker of the eighteenth century (between 1773 and 1795 he casted and polished 430 telescope mirrors). Herschel used no scientific approach to test his mirrors. The mirrors were tested on a distant object and then tried on the sky. In 1774, Herschel began his systematic survey of the heavens, observing and keeping a log book of all his observations (planets, double stars, cluster of stars and nebulae). On March 13, 1781, observed a "star" that he "perceived as larger than the rest". It had a perceptible disk with a sharp border. This object was no comet but a new planet (Uranus). According to Herschel logbook:

"It was a lucky accident that brought this star to my view (…) in the regular manner I examine every star of the heavens, not only of that magnitude but far inferior, it was that night its turn to be discovered (…) had business prevented me that evening, I must have found it the next".

In 1783, Herschel completed a twenty-foot reflector (48 cm aperture) that he used to sweep the heavens for the next three decades. This telescope was suspended within a rotating wooden frame operated by assistants that raised or lowered the tube by hand. Herschel used no secondary mirror; instead he observed near the periphery of the tube opening, on a platform, fifteen-feet above the ground (Figure 2).

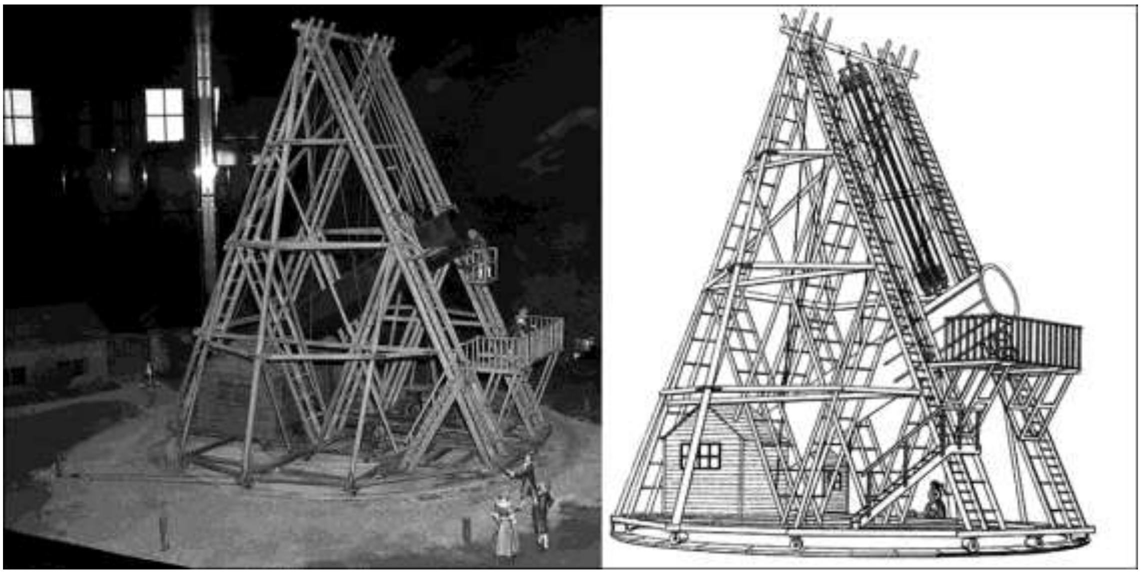

Figure 2- Herschel forty-foot reflector.

According to William Herschel sister (Caroline) astronomy was a dangerous business:

"I could give a pretty long list of accidents of which my brother as well as myself narrowly escaped of proving fatal; for observing with such large machineries, when all round in darkness, it is not unattended with danger".

Caroline impaled her leg when she tripped over a metal hook hidden under a blanket of snow. On another night the entire mounting of the twenty-foot reflector collapsed moments after Herschel had climbed down from the observing platform.

In 1876, the Herschel moved to Slough in pursue of a drier climate and more space to mount their telescopes. The forty-foot telescope was completed in 1789. This big reflector never lived up to Herschel's expectations. The mirror required frequent repolishing and sagged under his own weight, giving imperfect images at the eyepiece. The preparation for an observing night took many hours. Taking this into account, Herschel used mainly the twenty-foot for most of his observing sessions. Herschel's telescopes were capable of looking deeper into space than any other telescope to date. With these instruments, Herschel collected an amazing number of discoveries that according to his son John Herschel (1792-1871) include: the discovery of Uranus and two of its satellites; the measurement of the rotation period of Saturn's rings; measurement of the height of lunar mountains; confirmation of the gaseous nature of the Sun; discovery of almost 1000 double stars and more than 2000 nebulae and star clusters; discovery of infrared light and the determination of the solar system movement thought space.

Herschel also used the twenty-foot for "star gauging". With this project he hoped to determine the shape of the local universe. Herschel counted (gauged) the number of stars in 3400 different star fields. He assumed that the fainter stars were farther from the Earth and was able to produced a three dimensional model of our Galaxy[1] (Figure 3).

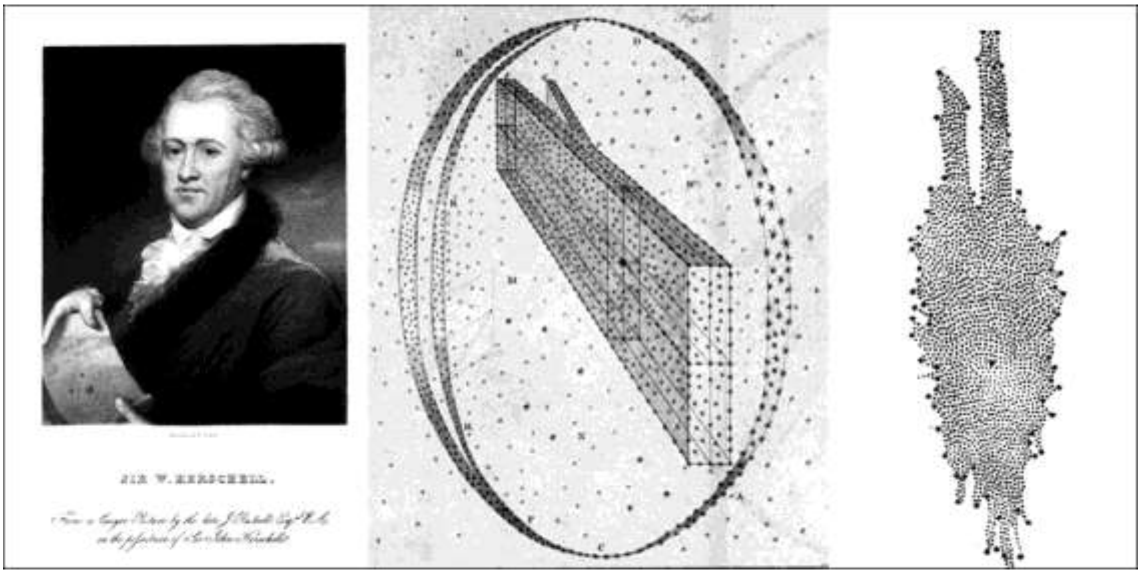

Figure 3- William Herschel depiction of the shape of our Galaxy.

During the first half of the nineteenth century several large reflectors were built by William Parsons (Third Earl of Parsonstown, Lord Rosse) (1800-1867), William Lassel (1799-1880), Thomas Grubb (1800-1868) e Howard Grubb (1844-1931) (Figure 4, 5, 6 and 7). These first big reflectors were also very difficult to use, its weight was enormous and tracking was deficient (see below).

[1] Star gauging was performed under the wrong assumption that all stars are identical in their light output.

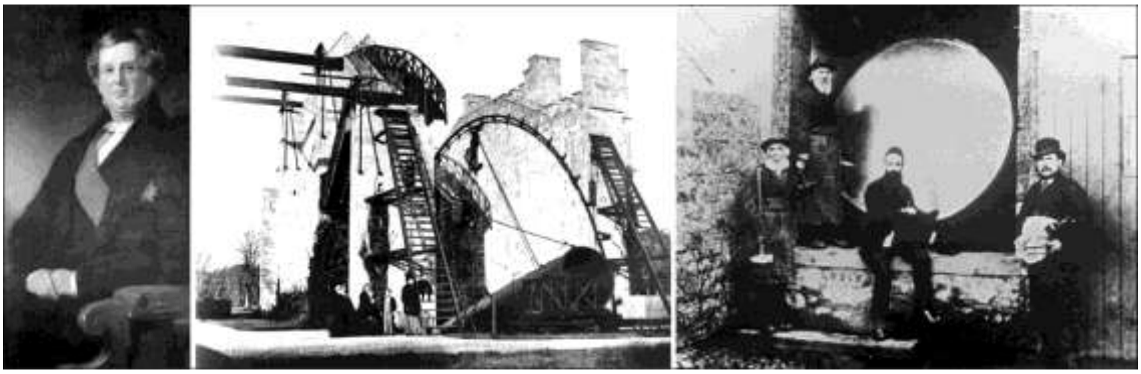

Figure 4- Lord Rosse and the Leviathan of Parsonstwon (*ca.* 1845).

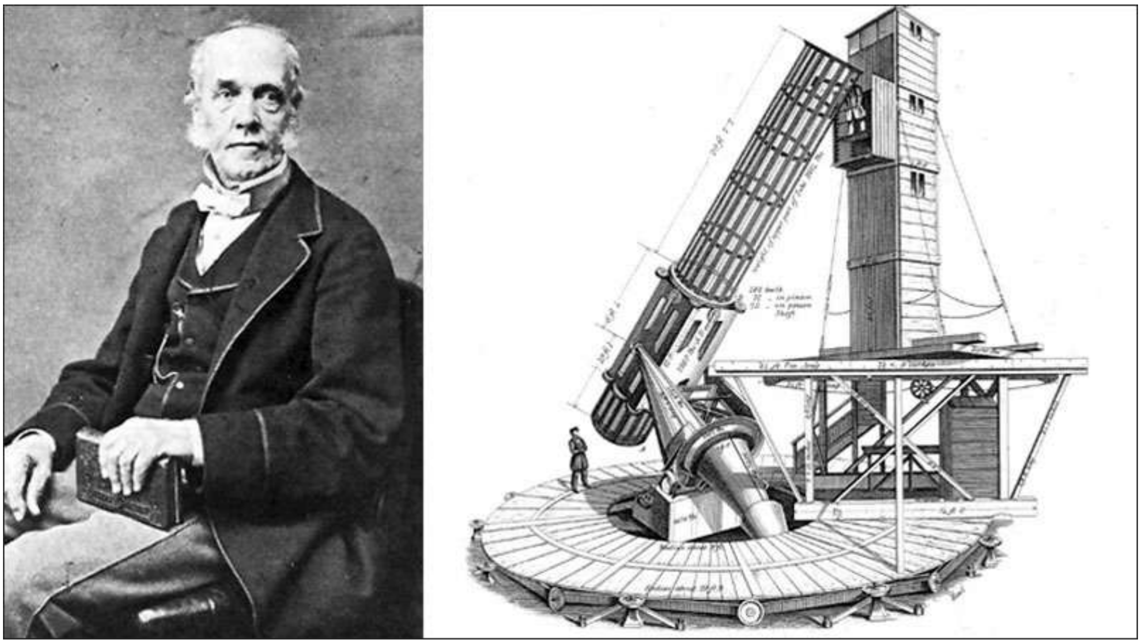

Figure 5- William Lassel and the 48-inch (122 cm) equatorial telescope (*ca*. 1852).

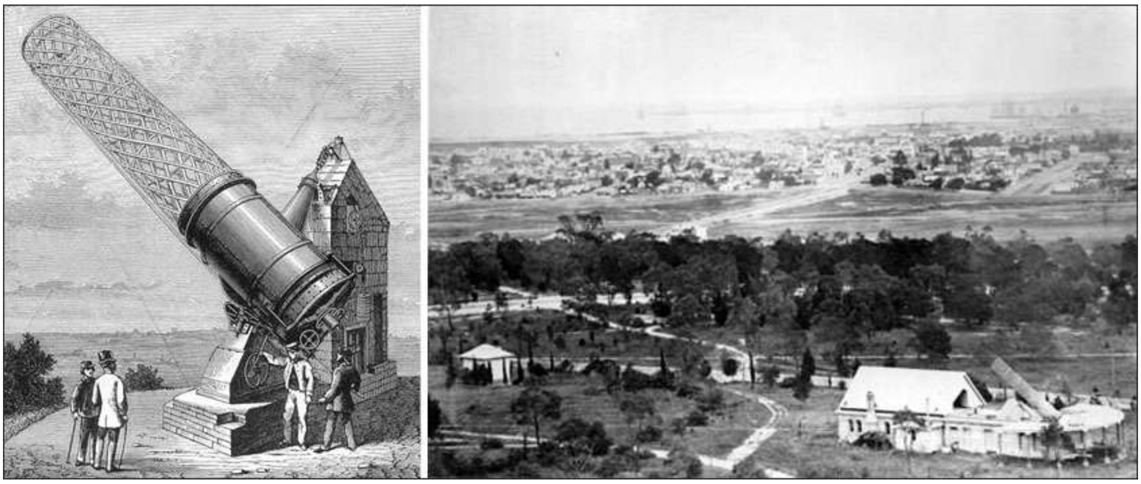

Figure 6- The Great Melbourne Telescope and its roll-of-roof observatory (*ca*. 1869).

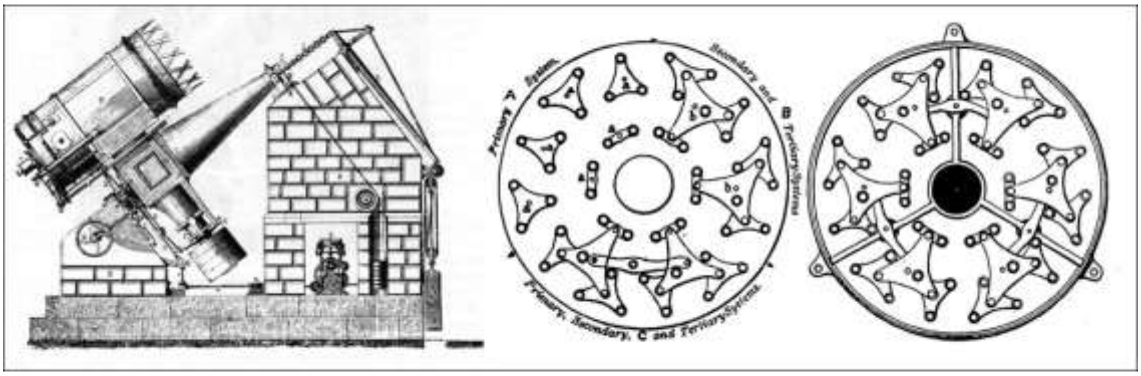

Figure 7- Equatorial Mount and mirror support of the Great Melbourne Telescope.

William Parsons, third Earl of Rosse was the first to surpass Herschel telescopes. Rosse experimented with compound specula and eventually was able to cast several mirrors with increasing diameters. In 1840, a three-foot mirror was mounted in a similar way to Herschel's telescopes. This telescope was used with a Newton configuration (plane secondary mirror). Rosse was able to produce highly reflective surfaces. He considered that the three-foot reflector was "the best ever produced". Shortly after, Rosse drew planes for a reflector of double the size. The six-foot reflector mount was erected from 1842 to 1844 (Figure 4). It featured parallel piers of solid masonry that carried several observing platforms. This telescope had very limited movements (limited to an observing window of about 15^{o}). To raise or lower the tube the assistance of two workmen was required. Slow motions were assured by turning two small hand wheels on the observing platform. The mirror weighted four Tons. Observations started in 1845. In April of the same year, Lord Rosse described for the first time spiral structures in M 51. Together with his assistants, Rosse described these structures in a considerable number of nebulae.

William Lassel was the first to apply Franhofer's equatorial mount to large reflectors. In 1844 Lassel visited Parsonstown were he inspected the erection of the Leviathan. Lassel added a small quantity of arsenic to his specula, but the reflective power was mainly due to the purity and correct proportions of copper and tin. In 1861, Lassel erected a 48-inch equatorial in the isle of Malta (Figure 5). This telescope had two alternative mirrors weighting over a Ton. The telescope had a fork mount and an open tube. Slow motions were assured by an assistant that turned a winch handle once every second.

The Great Melbourne Telescope (GMT) was the last great reflector that was fitted with a speculum-metal mirror. It went into operation in 1869 and was not only the biggest equatorial telescope in the world but also the largest and most expensive scientific equipment ever built in the Australia (Figures 6 and 7). The telescope was built by Howard Grubb and was mainly used to produce sketches of nebulae first discovered by John Herschel in the southern hemisphere. George Willis Ritchey (1864-1945) published the following statement in 1904:

"I consider the failure of the Melbourne Instrument to have been one of the greatest calamities in the history of instrumental astronomy; for by destroying confidence in the usefulness of great reflecting telescopes, it has hindered the development of this type of instrument, so wonderfully efficient in photographic and spectroscopic work, for nearly a third of a century".

Recent evidence has shown that the failure of the Great Melbourne Telescope should be associated with the fact that it was built to produce drawings of nebulae: direct photography and spectroscopy were precluded.

In 1862, Leon Focault (1819-1868) completed an 80 cm reflector with a silvered-on-glass mirror (Figure 8). It was also the first large mirror that was figured using a novel approach: Foucault's knife edge test. It had a fork mount and tube made of wood. The total weight of the telescope was 1.5 Tons (much less than the GMT that weighted 8.3 Tons). This telescope was very successful in a number of different fields: observation of faint nebulae, first application of the Fizeau interferometer and the Fabry-Perot etalon and double star measurements.

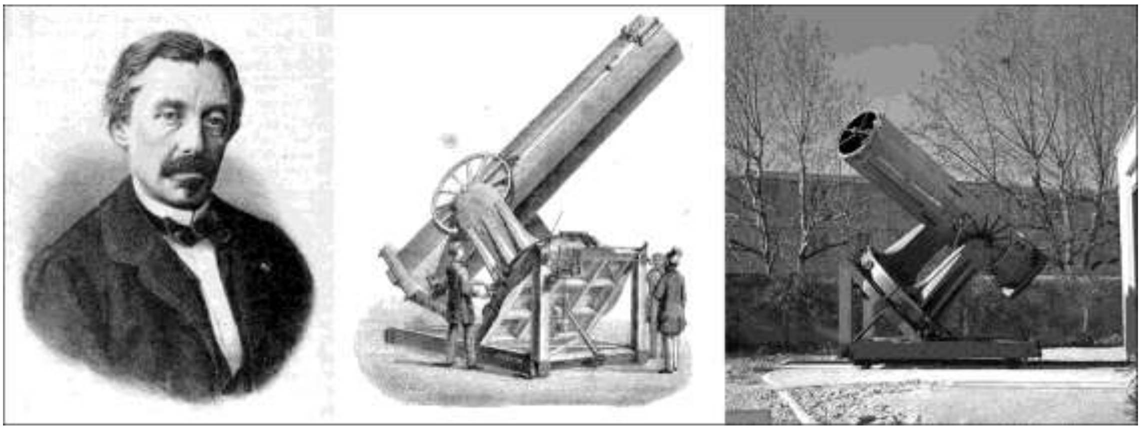

Figure 8- Leon Focault and the 80 cm reflector.

Silver-on-glass mirrors were suggested as early as 1827 by George Biddel Airy (1801-1892). It was only in 1856 that C.A. Steinheil and L. Focault produced independently small parabolic glass mirrors with a thin coat of silver deposited by precipitation. Producing a good parabolic surface in glass mirrors proved to be more difficult that in speculum-metal mirrors. These first difficulties were overcome and the silver-on-glass mirrors became standard equipment from 1870 onwards. The advantages were obvious. Once the optical surface was produced, the silver coating had to be renewed from time to time without the need to repolish the surface.

The reflectors were free from chromatic aberrations and its shorter focal ratios proved to be invaluable for astrophysical work. These advantages were very instrumental for the development of astrophotography and spectroscopy.

Henry Draper (1837-1882) started by grinding metal mirrors but soon changed to silver-coated glass mirrors. Draper obtained the first photograph of a nebula in September 30, 1880 using an 11-inch Clark refractor. In 1864, Draper wrote an extensive monograph entitled "*On the construction of a silvered glass telescope, fifteen and a half inches in aperture, and its use in celestial photography*".

Andrew Ainslie Common (1841-1903), a wealthy engineer and amateur astronomer, was mainly interested in producing astronomical photographs. Common started with refractors around 1870, but soon changed to silver-on-glass reflectors that were built by G. Calver (1834-1927). Common used two Newton reflectors with apertures of 46 and 91 cm provided with fork mounts. These mounts had several important innovations. One of these was a mercury floating device for the polar axis to reduce friction.

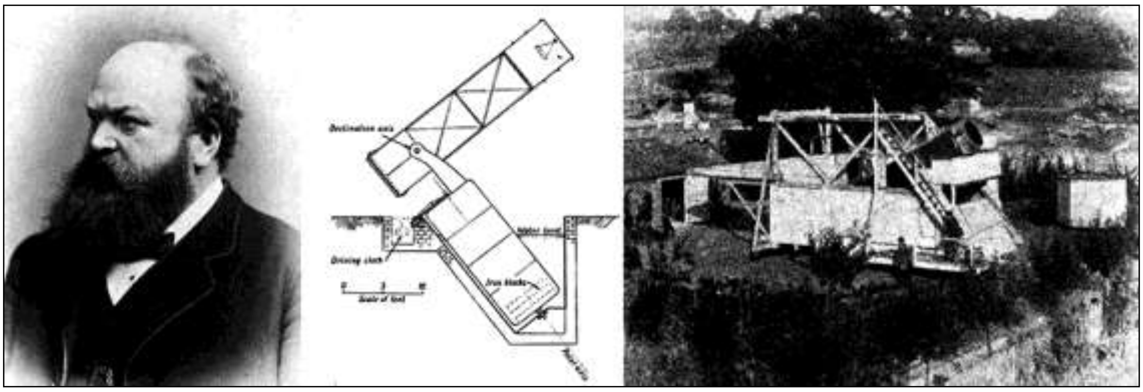

Figure 9- Andrew Ainslie Common and the five-foot reflector.

Common used his instruments mainly as photographic telescopes. Several photographs of the Orion nebulae were obtained with considerable success. In 1883, Common produced images that showed for the first time, stars that were not seen by visual observation. In 1885, the 91 cm reflector was sold to Edward Crossley (1841-1905) and Common started to work on a 5-foot disk (155 cm) (Figure 9). The instrument was finished in 1889. The polar axis (hollow cylinder) floated in a tank of water. This telescope in spite of its good optical quality produced few results.

Crossley, after retiring from astronomy in 1893, offered the 91 cm Common reflector to the Lick observatory. This instrument was extensively used by James E. Keeler (1857-1900) for nebular photography between 1898 and 1900. After Keeler's death, Charles Dillon Perrine (1867-1951) completed the project and renewed the telescope in 1902 and 1905 (Figure 10). These first successful photographic results helped to establish the reflector as the preferred observatory instrument.

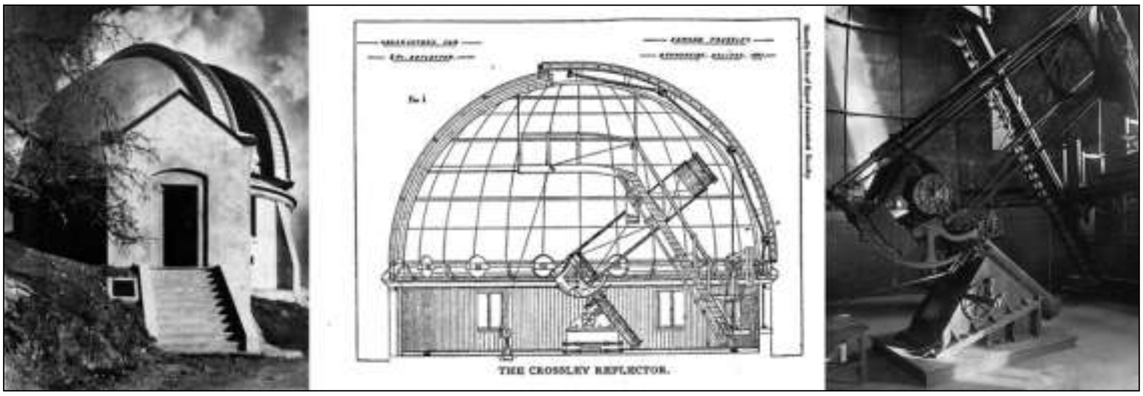

Figure 10- Crossley reflector at Lick observatory (*ca.* 1900).

Modern reflectors

The next big reflecting telescopes were built by George Willis Ritchey (1864-1945). Ritchey was the prophet and builder of the first large successful American reflecting telescopes. He was also a master of astronomical photography. Ritchey worked at Yerkes observatory at the turn of the nineteenth century, a well established leading center for astrophysical research, and was in charge of the optical and instrument shops. There he designed and produced auxiliary equipment for the 40-inch Yerkes refractor and also grinded and finished a 60-inch disk. His first big mirror was a 24-inch of 8-foot focal length that was also used at Yerkes (Figure 11).

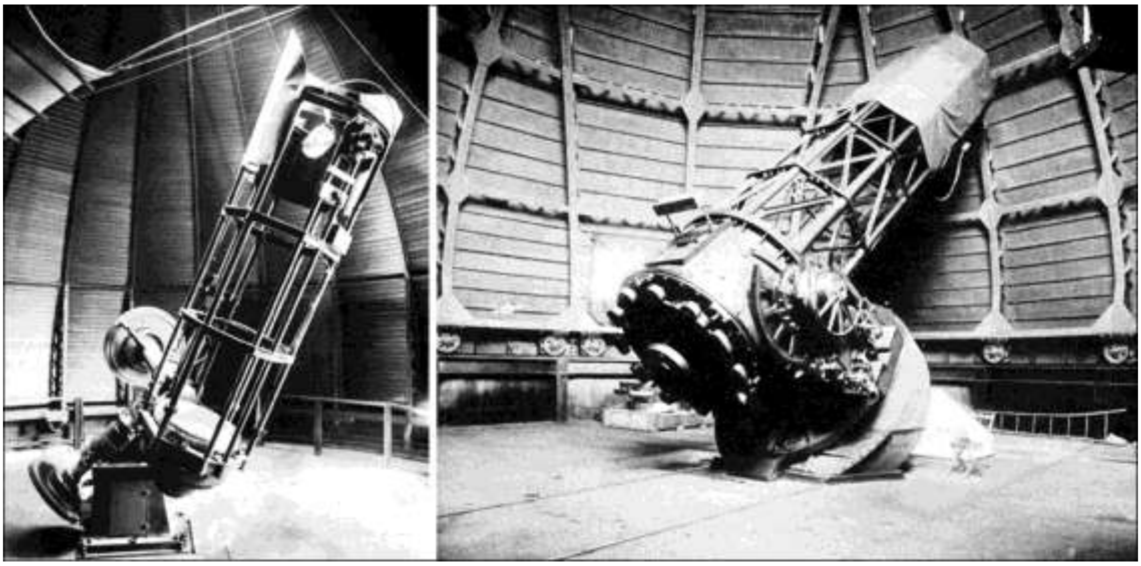

Figure 11- Yerkes 24-inch (left) (*ca.* 1900) and Mount Wilson 60-inch (right) (*ca.* 1908) reflectors built by G.W. Ritchey.

In 1904, Ritchey publishes an extensive work entitled "*On the Modern Reflecting Telescope and the Making and Testing of Optical Mirrors*" that quickly became an essential reference. In the introduction Ritchey refers:

"The present paper describes the methods employed by the writer in the optical laboratory of the Yerkes Observatory in making and testing spherical, plane, paraboloidal, and (convex) hyperboloidal mirrors. On account of the very great importance of supporting mirrors properly in their cells when in use in the telescope, a chapter is devoted to the description of an efficient support system for large mirrors. Intimately related to this, and equally important, is the subject of the mounting, the mechanical parts, of a modem reflecting telescope (…)".

Ritchey was one the first telescope makers to use standard methods at the optical shop. Every precaution was used to exclude dust. The walls and ceiling were varnished, and the floor was kept wet during polishing operations. Double sealed widows were also used and the incoming air was filtered. A canvas was suspended over the mirror to protect the surface from falling particles. Room temperature was kept constant and the optician was properly dressed with cap and gown. The mirror was tested using the Foucault method that required the use of a plane mirror of great precision.

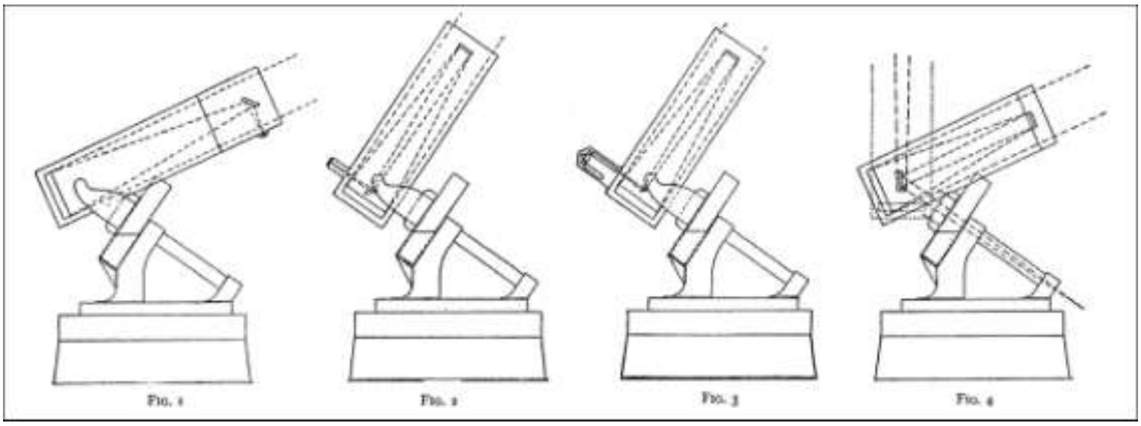

Figure 12- The four possible optical configurations of the 60-inch Mount Wilson reflector.

The Mount Wilson 60-inch reflector had an innovative design with an open tube and a fork mount. Four optical arrangements were possible: Newton; two modified Cassegrain and a polar or Coudé Cassegrain (Figure 12).

The first visual and photographic observations with this instrument were made in 1908. George Ellery Hale (1868-1938) wrote in a 1909 report:

“Visually the images of stars, planets and nebulae obtained with it on a good night are excellent. The star images are very small and sharp and can be observed with great precision. Such an object as the Great Nebula in Orion shows bewildering variety of detail. Globular clusters are especially remarkable because of the large number of stars visible by the great light-gathering power”.

The first photographic tests with this instrument were conducted by Ritchey in 1908. Several nebulae and star clusters were imaged at the Newton and Cassegrain focus. These first results were described in 1909:

“The new plate-carrier (...) takes plates 3 ½ inches (89 mm) square. This small size is chosen because it allows the guiding eyepiece to be near the center of the field. It includes a clear field about 36 minutes of arc square, and fully covers the entire central region which is free from objectionable distortion. A second guiding eyepiece is also used, the two being on opposite sides of the center. Each gives a magnification of about 750 diameters. This allows any slight rotation of the field to be detected immediately; such rotation is corrected by rotating the bronze plate which carries the guiding eyepieces and plate-holder; two fine screws with graduated heads are provided for effecting this rotation. The small metal plate-holder, is so designed that it can be quickly removed and replaced as frequently as desired during long exposures, thus allowing access to the focal plane for the purpose of refocusing by means of the knife-edge. The position of the plate-holder is defined by small hardened steel surfaces so that when replaced it returns accurately to its original position with reference to the guiding eyepieces. With the small apparent change of focus which takes place since the canopy has been in use, it is found that refocusing every 25 or 30 minutes in the early part of the night, and every 40 or 45 minutes after 11:00 P.M., is usually sufficient. With the new plate-carrier, all of the uncertainties which usually occur in making long exposures with very large telescopes are eliminated. A plate can be exposed night after night, if desired, with the assurance that no error in focus greater than one or two thousandths of an inch can occur, and that no rotation of field can take place without immediately being detected and corrected. Both of these conditions are absolutely necessary for the finest results with an instrument as powerful and sensitive as the 60-inch. With these conditions no injury or elongation of the star-images or nebular details can occur and the full effect of the prolonged exposure is secured. All of the negatives which have been secured with the new plate-carrier show perfectly round star-images. On the best negatives, with exposures of eleven hours, the smallest star-images are 1.03” in diameter”.

Even before the 60-inch first light, George Ellery Hale was already planning the constructing of a 100-inch reflector. The mirror was casted after several failures by the same firm that supplied the 60-inch (St. Gobain Glass Company). The disc arrived at Mount Wilson in December 1908 but was discarded by Ritchey since it was filled with gas bubbles. In spite of this drawback Ritchey was able to start grinding in 1911. The English yoke mount was also designed by Ritchey and further refined by Hale and Francis Gladheim Pease (1881-1938) (Figure 13).

By the end of 1914 a near perfect spherical curvature was obtained, the mount was finished in 1917 and the telescope was in regular use in 1919.

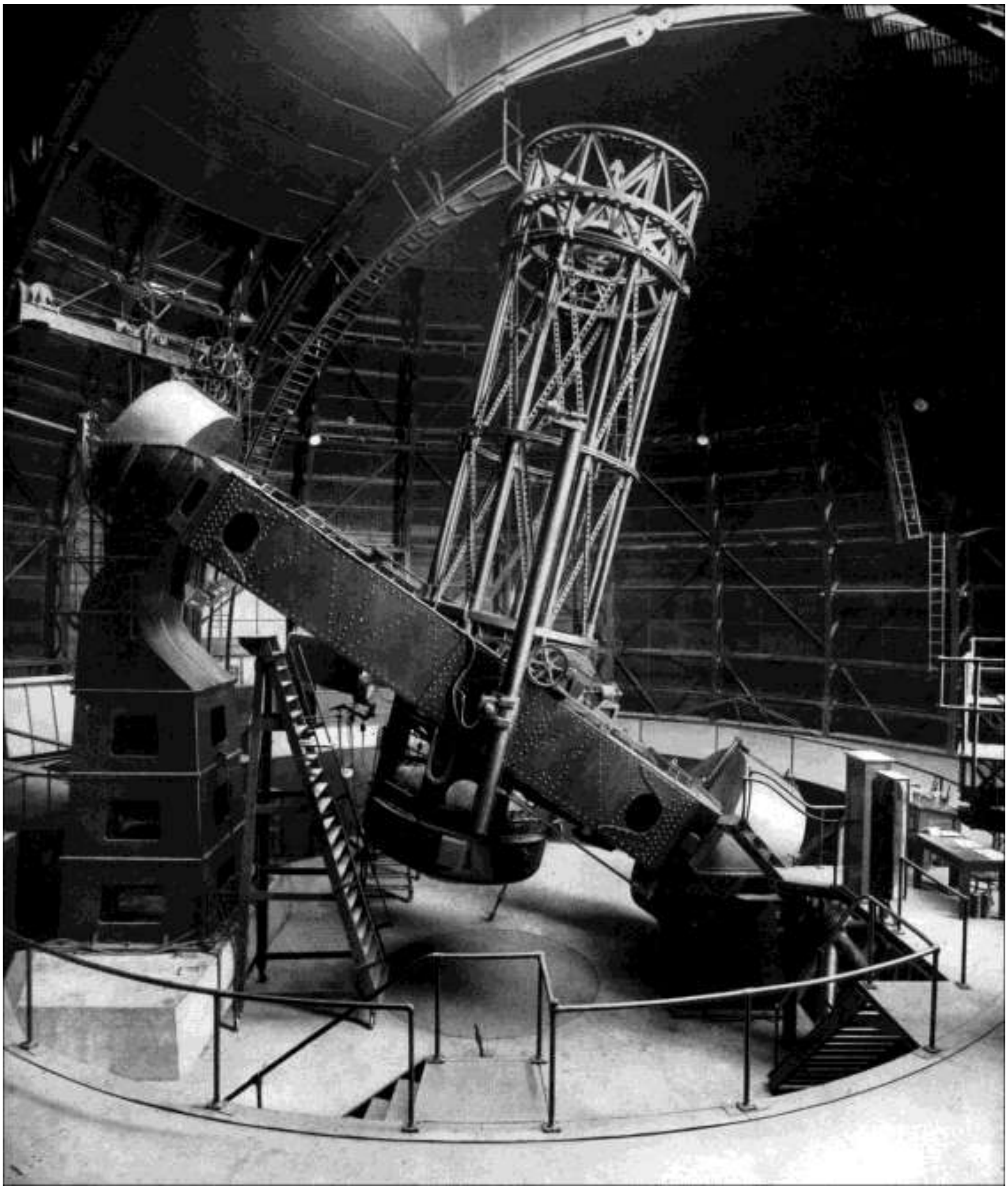

Figure 13- 100-inch Hooke telescope (Mount Wilson observatory) (*ca.* 1919).

The Hooker telescope is similar in optical design to the 60-inch. It can be used as an *f*/5 Newton, as an *f*/16 modified Cassegrain and as an *f*/30 Coudé. The 100 Ton English yoke is supported by means of mercury flotation bearings. The dome is also similar to that of the 60-inch.

Edwin Hubble (1889-1953) used the Hooke telescope to determine for the first time the distances and red shifts of neighboring galaxies. In 1929 Hubble's proved that the universe was expanding in all directions at a constant speed (Hubble's constant).

In 1928, Hale started a campaign to gather funds for a larger telescope. His article "The possibilities of large telescopes" published in the Harper's Magazine was very instrumental.

Hale started the article with a prophetic phrase:

“Like buried treasures, the outposts of the universe have beckoned to the adventurous from immemorial times. Princes and potentates, political or industrial, equally with men of science, have felt the lure of the unchartered seas of space, and through their provision of instrumental means the sphere of exploration has rapidly widened (…)”.

In a letter to the International Education Board Hale stated:

“No method of advancing science is as productive as the development of new and more powerful instruments and methods of research. A larger telescope would not only furnish the necessary gain in light space-penetration and photographic resolving power, but permit the application of ideas and devices derived chiefly from the recent fundamental advances in physics and chemistry (…)”.

Hale and its staff began to consider a telescope with an aperture of 200 or 300 inches. After some initial difficulties, the Rockefeller foundation awarded (autumn of 1928) a sum of $6 million dollars to the California Institute of Technology to build the giant telescope.

The design and construction of the 200-inch telescope was not an easy task. The first major problem was the cast of the primary mirror. After a series of trials with fused quartz, the mirror was made of Pyrex with a ribbed structure by Corning Glass Works. The mount was also another challenge. The first options were between an open-fork (preferred because it allowed access to the North Pole) and a yolk type equatorial. In 1932 a new yolk design (horseshoe) was adopted with considerable success. After approval, the Westinghouse Company (Philadelphia) started work on the mount in 1936. The primary mirror has a short focal ratio (*f*/3.3). This low focal ratio meant that a Field-Flattener had to be built. Frank Elmore Ross (1874-1960) of Yerkes observatory was selected to design and built the corrector. Ross corrector lenses made for the 60-inch and 100-inch were very successful. Ross correctors became standard equipment for large reflectors.

The 200-inch (Figures 14 and 15) was the first telescope large enough to allow an observer to ride in a cage at the primary focus of the telescope. The observing cage is 72-inch in diameter and carries the secondary mirrors and the Ross correctors (Figure 16). The only other large telescope featuring an observer’s cage is the 120-inch Shane reflector (Lick observatory), completed in 1959 (Figure 18). The 120-inch primary mirror of the Shane reflector was originally a glass test blank cast in Corning Labs for the Palomar Observatory 200-inch reflector.

In 1934, Palomar Mountain in Southern California was chosen to install the 200-inch reflector. When G.E. Hale died in 1938, the 200-inch mirror was still in the figuring process. The 42 m dome designed by Russell Porter (1871-1949) was already erected at Palomar. The mirror was only finished in 1947 and "first light" photographs were taken by Edwin Hubble on January 26, 1949 (Figure 17).

The 200-inch telescope optically is similar to the 100-inch and 60-inch reflectors. At the prime focus with the two most frequently used Ross correctors focal ratios vary (*f*/3.6 and *f*/4.7). In the Cassegrain configuration it has a focal ratio of *f*/16. The 200-inch reflector was named after G.E. Hale. It was dedicated on June 3, 1948. Most of the large reflectors that followed (third quarter of the nineteenth century) incorporated many features of the 200-inch design.

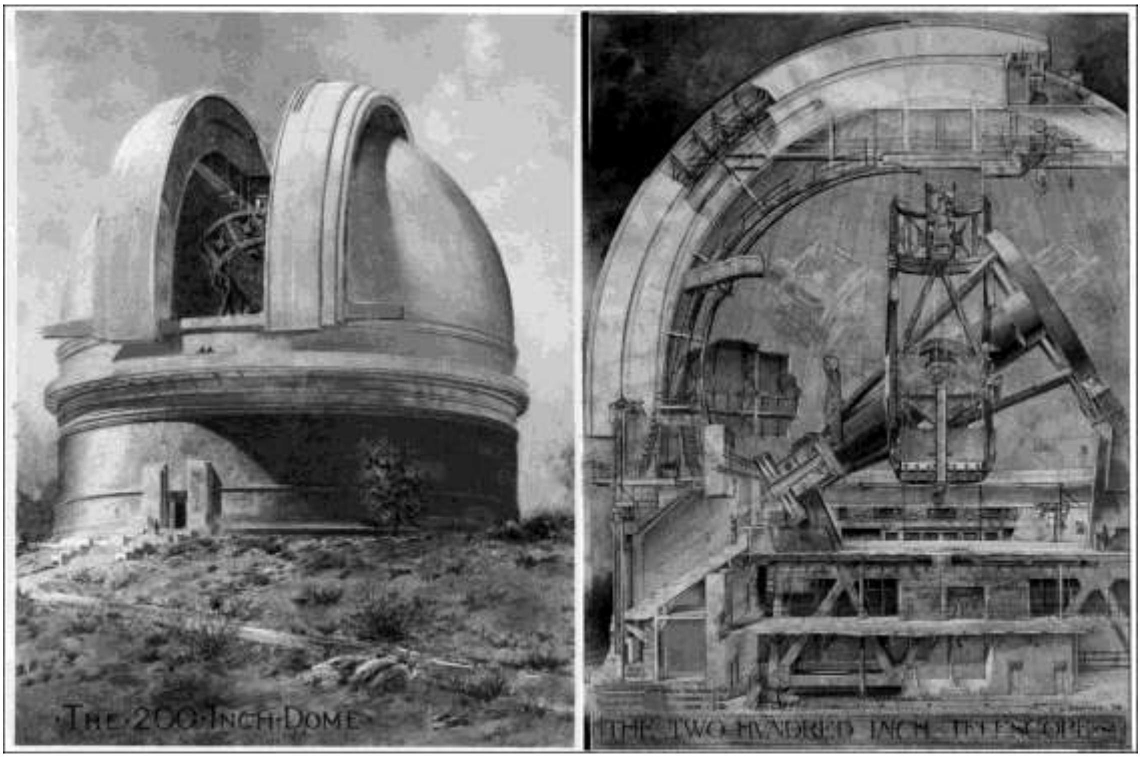

Figure 14- 200 inch (5.08 m) Hale telescope. Cutaway drawings by Russell W. Porter.

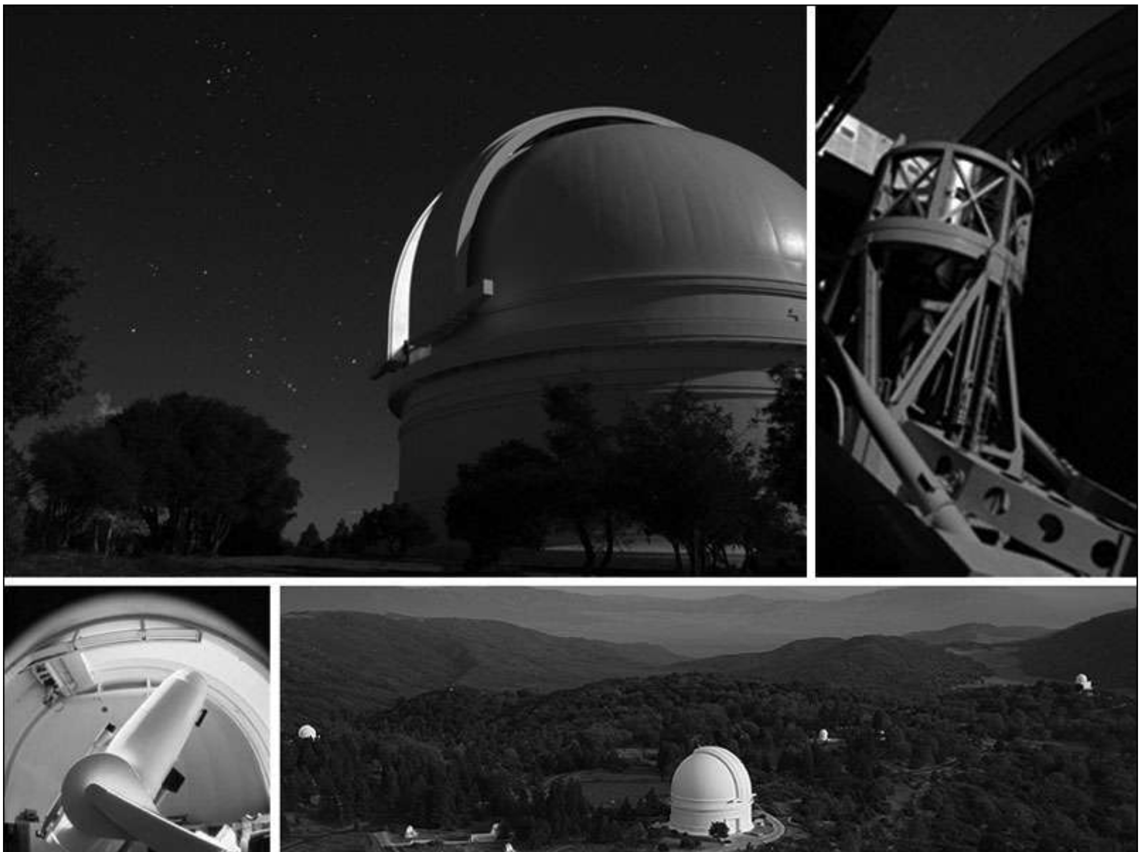

Figure 15- Palomar observatory.

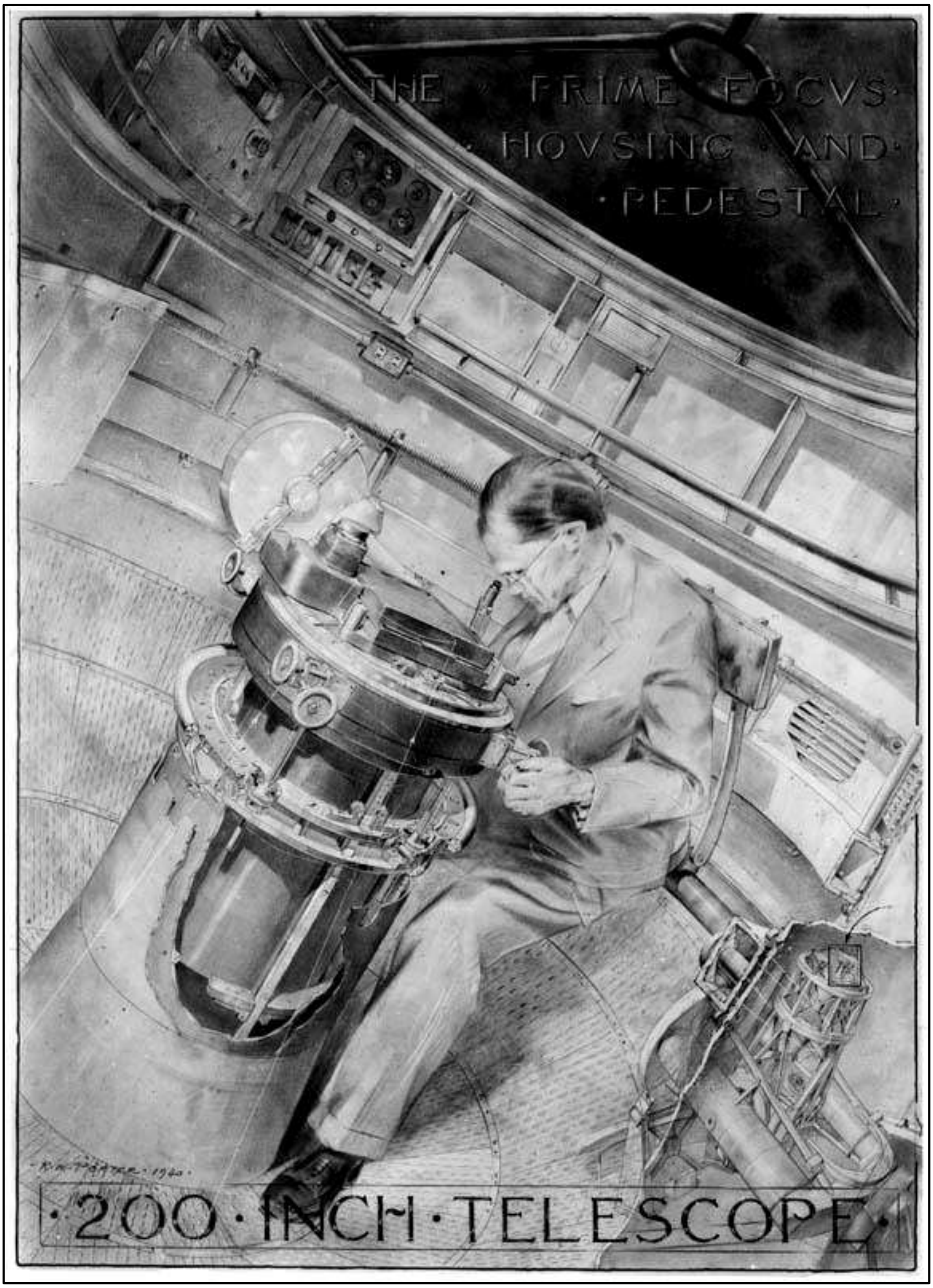

Figure 16- Observing in the prime-focus capsule. As astronomer is shown seated in the adjustable chair with the photographic plate-holder locked to the pedestal, and his eye at the guiding eyepiece. Exposures range from a few minutes to several hours. The astronomer's seat can travel completely around the capsule and tilt through a large angle to compensate for any position to which the telescope may be tipped. Dials on the wall above the astronomer's head tell him exactly where the telescope is aimed, and switches below allow him to activate essential equipment. The plate-holder can be changed for a spectrograph or a photoelectric photometer. Cutaway drawing by Russell W. Porter.

Figure 17- First-light image (200-inch reflector), taken by Edwin Hubble on January 26, 1949 (NGC 2261).

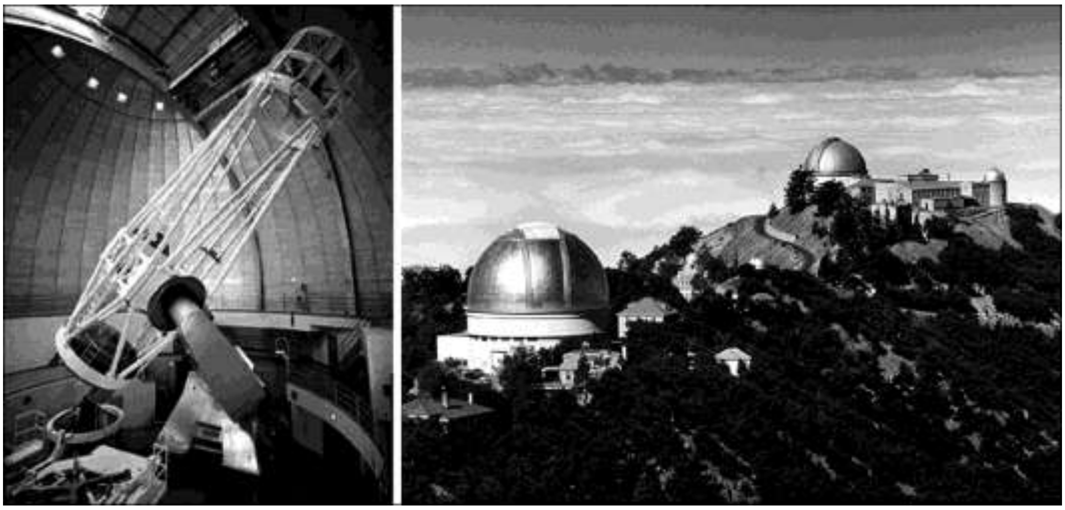

Figure 18- 120-inch Shane reflector (*ca.* 1959).

Sources:

- Danjon, A. & A. Couder (1935). *Lunettes et Télescopes.* Livrarie Scientifique et Technique, Paris.
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