Part 1

Optical Observatories

1

Palomar Mountain Observatory

1.1 The 200 inch (5.1 m) Hale Telescope

The early twentieth century had seen the emergence of the United States as the world leader in the construction of large optical telescopes.[1] For example, two large solar telescopes had been built on Mount Wilson, California before the First World War. In addition, George W. Ritchey had also completed a 60 inch (1.5 m) reflector at the same observatory in 1908, and nine years later Ritchey and W. L. Kinney had completed the 100 inch (2.5 m) Hooker reflector there. As a result by the early 1920s Mount Wilson was also the premier observatory in the world.

No sooner had the 100 inch telescope been completed than George Ellery Hale, the director of the Mount Wilson Observatory, began to consider building an even larger instrument.(1) He mentioned his ideas to Francis Pease, who had recently joined the staff on Mount Wilson. By 1921 Pease, who by then had outlined the design for a 300 inch (7.5 m), was convinced that a 100 ft (30 m) telescope was feasible. But Hale was much more cautious, partly because of the difficulties that he had already experienced with building the 100 inch, and partly because of the difficulty he anticipated of raising the money to build such an enormous telescope. In fact, as he recognised, the time was not ripe for raising finances for even a 300 inch.

Nevertheless, Pease continued with designing his 300 inch. Then in 1926 he and Walter Adams took H. J. Thorkelson of the General Education Board of the Rockefeller Foundation on a tour of the Mount Wilson Observatory. During the tour, Pease showed him his design of the 300 inch. This design impressed Thorkelson so much that he mentioned it to Wickliffe Rose of the Rockefeller Foundation's International Education Board shortly afterwards.

[1] It could be argued that the United States had become dominant in the construction of large optical telescopes by the end of the nineteenth century. On the other hand, the Mount Wilson Observatory had had to purchase optical blanks for their 60 inch (1.5 m) and 100 inch (2.5 m) telescopes from France in 1895 and 1906 as they could not be produced in the United States at the time.

Two years later Hale wrote an article for Harper's Magazine on 'The Possibilities of Large Telescopes' in which he outlined their importance. He also floated the idea of finding a donor to back the financing of a new large telescope, following on the path already trodden by Messrs Lick, Yerkes, Hooker and Carnegie in funding telescopes. Hale arranged for a proof of his article to be sent to Rose, which he backed up with a long letter asking if the Rockefeller Foundation's General Education Board would consider making a grant to determine the maximum size of mirror that could be made. Rose, a supporter of big science, was interested in Hale's proposed project.

In March 1928, Hale followed up his letter with a visit to Rose where he explained the difficulties that he foresaw in building a 200 inch (5.1 m) telescope. This may have made Rose think twice about being involved in funding such a large telescope but, rather than being put off, Rose asked if a 300 inch was feasible. Hale suggested that the jump from 100 inch to 300 inch was probably too large and a 200 inch was a much safer alternative. The only disagreement between the two men at that time was which organisation should be given the telescope in the event that the Rockefeller Foundation agreed to fund it. Hale naturally thought that that should be the Carnegie Institution's Mount Wilson Observatory, which had experience of building and running their 60 inch and 100 inch telescopes. Rose disagreed and suggested that an education establishment like the California Institute of Technology (Caltech) should be the recipient. This ought not to have surprised Hale bearing in mind Rose's membership of Rockefeller's Education Board. But Rose then went on to suggest that the staff at Mount Wilson should, under Caltech's guidance, build the telescope and run its research programme.

The problem with Rose's idea was that John C. Merriam, the president of the Carnegie Institution, was not willing to enter into such an agreement with an organisation like Caltech who had no experience of running a great observatory. In fact Caltech did not even have a department of astrophysics.

In the end, after a convoluted set of negotiations between the Rockefeller Foundation, the Carnegie Institution and Caltech, the Rockefeller trustees agreed in 1928 to pay the estimated construction cost of $6 million for the 200 inch telescope and ancillary equipment. But they were not willing to finance the annual running costs and Caltech could not afford to pay for them. Fortunately Henry Robinson, a wealthy Los Angeles businessman and Caltech trustee, agreed to cover them. So the Rockefeller Foundation agreed to give the construction money to Caltech who were to build and operate the telescope, whilst the Carnegie Institution and the Mount Wilson Observatory agreed to provide assistance. Or as Elihu Root, chairman of the Carnegie trustees, put it – the Carnegie Institution would furnish the brains while the Rockefellers provided the funds.

A four-member Observatory Council was set up with Hale as chairman to direct the planning, construction and operation of the 200 inch. This was assisted by an Advisory Committee consisting of members of the observatory and institute staffs, as well as external astronomers, physicists, chemists and mathematicians. There were also committees set up to cover the mirror, the mounting and the site. In one way or another Hale managed to involve the best American scientists and engineers in this great undertaking.

Light pollution was already becoming a problem at Mount Wilson in the late 1920s and Rose's decision to give the telescope to Caltech also meant that a new location was required. So alternative sites in the south-western United States, as close as possible to Caltech in Pasadena, were tested for weather conditions and seeing starting in 1928.(2) At this stage, Hale already favoured Palomar Mountain as it had been recommended by the Lick astronomer William J. Hussey in 1903 as the most promising site in the San Diego area. But it was too inaccessible then and Hale had decided to locate the Carnegie observatory on Mount Wilson instead. Now in 1928 the inaccessibility problem was not as severe.

Following the site survey Palomar Mountain and Table Mountain behind Mount Wilson were considered to be the best sites with Palomar receiving the final decision in 1934 as the location for the 200 inch observatory. This was mainly because of Palomar's dark skies compared with those of the Mount Wilson area which was now too close to Los Angeles and its surrounding towns. The land to build and protect the new observatory consisted of 120 acres (49 hectares) purchased from private individuals and 40 acres which were transferred from the Cleveland National Forest to Caltech. Construction of a road to the observatory was begun by the County of San Diego the following year.

Initially it was thought that the equatorial mounting system for the primary mirror should be either an open-fork or an English yoke type.(3) At first, the fork design was preferred as it allowed access to the sky's polar regions, but in 1932 a new yoke design was proposed that also allowed such access. This was in the form of a horseshoe in which the telescope tube was lowered into the horseshoe far enough for it to be able to point to the pole. Unfortunately calculations indicated that the horseshoe was not sufficiently rigid for it to remain circular when the telescope tube moved over to the east or west. But this problem was solved by prestressing the horseshoe structure during manufacture.(4)

The 200 inch was large enough to allow an observer's cage to be fitted in the telescope tube at the primary focus (see Figure 1.1) without cutting off any more light than a Newtonian mirror. This 72 inch (1.8 m) diameter cage carried the secondary mirrors. But the weight of this system at the top of the tube and that of the primary mirror at the bottom caused the telescope tube to flex too much. This would have been a particular difficulty for the Ross corrector lens (see later) as it had to be collimated very accurately with the primary mirror. But that problem was

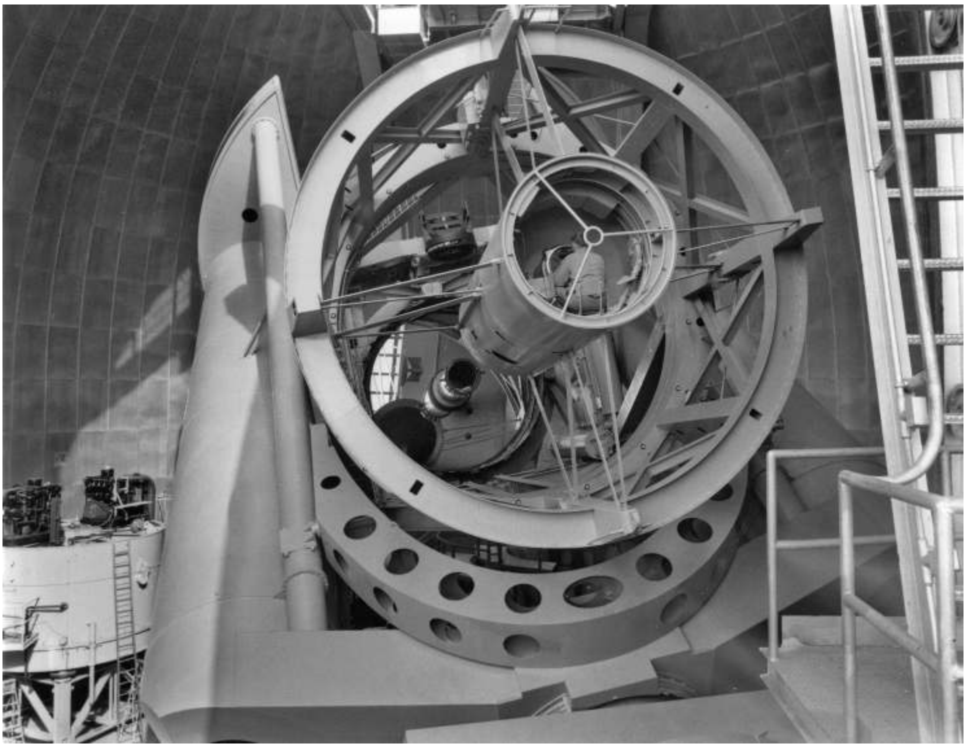

Figure 1.1. The 200 inch (5.1 m) Hale reflector which was completed on Palomar Mountain in the late 1940s. The observer is seen sitting in the prime focus cage. (Courtesy Palomar Observatory and California Institute of Technology.)

solved by Mark Serrurier who designed a parallelogram of trusses to connect the top and bottom rings of the tube to the section housing the bearings of the declination axis. This system allowed both ends of the telescope to move by virtually the same amount as the telescope moved. So the focus of the primary mirror did not deviate from its mean position on the plate in the observer's cage by more than about 0.01 inch (0.25 mm). Called the Serrurier truss, this solution has since been adopted for other large telescopes.

The most difficult problem facing Hale and the telescope team was how to make a 200 inch diameter mirror. After consulting experts worldwide Hale and the Observatory Council decided to ask the General Electric (GE) Company to make the mirror blank of fused quartz[2] at an estimated cost of about $250,000.[3] This

[2] Other materials that were considered at this time included Pyrex, stainless steel or some other metallic alloy, and metal with a glass surface of the same expansion coefficient. (See George E. Hale, The Astrophysical Observatory of the California Institute of Technology, *Astrophysical Journal*, 82, 1935, pp. 111–139.)

[3] The agreement with GE was that they would be paid at cost, excluding profit and overhead, so this $250,000 estimate was seen, at the time, to be on the high side of the possible cost of a 200 inch. See Donald E. Osterbrock, *Pauper and Prince; Ritchey, Hale and Big American Telescopes*, University of Arizona Press, 1993, p. 234.

was because fused quartz has an expansion coefficient of about one-fifteenth that of plate glass that had been used for the primary mirror of the Mount Wilson 100 inch.(5) But by late 1928 only small quartz discs had been produced and even in these it had proved impossible to eliminate bubbles from the molten silica. So GE decided to melt clear quartz plates onto the surface of the discs.(6) In the event that did not work for large diameter discs, so GE tried spraying the disc surfaces with molten quartz instead. By mid 1931, after a considerable effort, only two 60 inch discs had been produced. The first had a crack caused by an operative opening the furnace cover too early, and the other was unsuitable as pieces of fire brick had fallen from the cover of the furnace.(7) Yet over $600,000 had been spent. Possible timescales for production of the required 200 inch blank were anyone's guess, and the extra cost was estimated to be at least $1 million. Consequently Hale cancelled the contract.

In the meantime, Hale and Pease had decided to make the mirror a relatively fast *f*/3.3 because this allowed shorter exposures for nebula photography. It also enabled the tube to be made relatively short, allowing the dome to be made smaller also. The mirror was lightened by more than half by having an hexagonal pattern of ribs on its back to provide stiffening. This design also substantially reduced the annealing time of the mirror blank. The main problem caused by having such a relatively fast mirror was that the diameter of the field of good definition was only about 0.4 inch (1 cm) for the 200 inch because of coma. A similar but less severe problem had occurred with Mount Wilson's 60 inch f/5 and 100 inch f/5 telescopes. But this had been solved by Frank Ross of the Yerkes Observatory who designed corrector lenses for them. So Hale asked Ross to design similar corrector lenses for the 200 inch. This resulted in a series of two and three component lenses which produced well-corrected fields up to 15 cm in diameter. They also provided a choice of aperture ratios from f/3.6 to f/6.0. Which of these was used depended on the type of object being observed and the seeing conditions.

The primary mirror was not rigid enough to avoid bending under its own weight, even with the hexagonal pattern of ribs at the back. Consequently the mirror was carried on thirty-six support mechanisms inserted into the hexagonal holes. These elaborate lever-based mechanisms balanced the changing forces as the mirror was moved relative to gravity. But problems with friction within the mechanism caused its lever arm to be redesigned in 1948.(8)

Returning to the problem of making the 200 inch primary mirror, following the problems experienced by GE in producing the blank in fused quartz, Corning was contracted to produce one in Pyrex as, although the expansion coefficient of Pyrex was about five times that of fused quartz, it was only about one-third that of plate glass.(9) Corning produced a set of increasing diameter mirrors to adjust the quartz content of the Pyrex and to develop new methods of casting, preliminary cooling

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and annealing. First of all they produced a 26 inch (66 cm), followed by a 30 inch (76 cm) which was used for the Coudé flat, a 60 inch (1.5 m), and finally a 120 inch (3.0 m), all with ribbed backs. Unfortunately some of the cores required to produce the ribs at the back of the 60 inch mirror came loose during the mirror's production in July 1932. But the quartz content of the Pyrex was then changed to produce a material with a lower expansion coefficient,[4] and a 120 inch disc successfully cast in the summer of 1933.

The first attempt to produce a 200 inch disc was begun in March 1934 but, unfortunately, several cores came loose and rose to the surface as molten Pyrex was being ladled into the mirror mould. Attempts to break up the loose cores failed so a decision was taken to cool the blank relatively quickly to see if its quality was acceptable. Although this rapid cooling did not result in any cracks, polarised light tests indicated strains and the loose cores were embedded in the Pyrex.[5] Consequently it was decided to have another attempt to produce a satisfactory 200 inch blank, whilst retaining this first attempt as a spare.

The cores had come loose in producing the first 200 inch blank as the steel bolts that were designed to retain them had melted in the intense heat. So the bolts were replaced for the second attempt by those made of chrome-nickel steel, and a special air-cooling system was introduced beneath the mould to keep the interior of every core at an acceptable temperature. The new casting attempt took place in December 1934. After the glass had solidified the blank was moved to an electric annealing oven where it stayed at a steady temperature for two months. Its temperature was then gradually reduced at less than 1°C per day to produce a strain-free disc. But two-thirds of the way through this cooling process the Corning plant was flooded by its adjacent river and the electricity had to be cut off for three days. However, much to everyone's relief this had no adverse effect on the blank which turned out to be fine. Subsequently it was transported to Pasadena by train in April 1936, taking two weeks to cross the country.(10)

On receipt at the Pasadena optical shop, the front and back surfaces of the mirror blank were first ground flat. Then the front surface was ground to approximately the correct curvature by deepening the centre by nearly 4 inches (10 cm) and removing about 5 tons of glass. In total 31 tons of abrasive were used during this process and the subsequent polishing. The mirror was mounted on its 36-lever support system during figuring and testing. But this showed a problem with the outer 20 inches (50 cm) of the mirror that had been purposely produced with a slightly turned-up

[4] This Pyrex had an expansion coefficient of just three times that of fused quartz.
[5] Hale, who was not present as he was ill at the time, says in his 1935 Astrophysical Journal paper (7) that the floating cores were fished out. But both King (4) and Wright (1) say that it proved impossible to either break them up or fish them out.

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edge as it was expected to sag slightly in operation. Unfortunately the mirror was too stiff and so it did not sag enough. But the error was only about one wavelength of green light. So the mirror was sent to the new observatory on Palomar Mountain in this condition, hoping to rectify the problem in situ.

In the meantime, Hale had died and the Second World War had interrupted work. So it was not until November 1947 that the mirror was finally transported to its observatory where it was placed in the telescope for the first time. The telescope was subsequently dedicated to Hale on June 3 of the following year in a ceremony presided over by Vannevar Bush, president of the Carnegie Institution, and Lee Du Bridge, president of Caltech. The Palomar Observatory was then administratively joined to Mount Wilson to become the Mount Wilson and Palomar Observatories. So Hale had got what he wanted in the end.[6]

It turned out to be impossible to rectify the problem of the raised edge of the mirror in situ, so in 1949 it was decided to remove the mirror from the telescope and repolish the offending edge on the dome floor. This delicate task was undertaken by Don Hendrix, the chief optician of the Mount Wilson observatory, assisted by Mel Johnson who had previously worked on the mirror in the Pasadena optical shop.(11) Following a successful operation, the telescope became available for regular scheduled observations in November 1949.

The Hale Telescope's design with its massive mirror and support system, low expansion glass, lensed field correctors, Serrurier truss design, equatorial mount, oil-pad bearings and hemispherical dome had a major effect on the design of other large telescopes for the next twenty years or so. In fact there was no major push to design a more mass-efficient large telescope for some time as the Hale telescope design was so successful with its oil-pad bearings and Serrurier truss design which were able to support such enormous weights.(12)

The Hale telescope remained the largest and most productive optical telescope in the world for many years. In the 1950s observations with it confirmed the linear relationship between redshift and distance to greater distances than previously possible. It also showed that the Andromeda nebula was twice as far away as previously thought, and that the value of the Hubble constant needed substantial revision. The Hale telescope also played an important role in understanding stellar evolution and in the discovery of quasars in the early 1960s.[7]

[6] In 1969, the Las Campanas Observatory in Chile became part of the group that was renamed the Hale Observatories. Then in 1980 it was decided to split the Palomar observatory from the Mount Wilson and Las Campanas observatories, with Caltech operating Palomar (except for the 60 inch [1.5 m] reflector which was still jointly operated) and the Carnegie Institution, the other two observatories. Subsequently Carnegie handed over the Mount Wilson Observatory to the non-profit making Mount Wilson Institute, and in 1989 the Las Campanas Observatory became part of the Observatories of the Carnegie Institution of Washington, see *Sky and Telescope*, October 1980, p. 280 and February 1996, p. 8.

[7] Sandage gives an excellent overview of the cosmological and astrophysical discoveries made with the 200 inch telescope in his Annual Reviews of Astronomy and Astrophysics article of 1999 (11).

Eventually, in 1976, the 5.1 m Hale telescope's position as the largest optical telescope in the world was finally lost to the 6.0 m (236 inch) Bolshoi Teleskop Altazimutalnyi[8] (BTA) that was built at the Special Astrophysical Observatory near Zelenchukskaya in the Caucasus. The BTA was the first modern large telescope to have an altazimuth mount (see Section 5.3), rather than the equatorial of the previous large reflectors. Unfortunately, the BTA's performance was poor because problems with its mirror were compounded by relatively poor seeing conditions at the observatory.

The design of the Hale telescope itself has been gradually improved over the years. For example in 1965 an observer's cage was fitted at the Cassegrain focus underneath the primary mirror's structure. This not only made it easier for astronomers to observe at the Cassegrain focus but also allowed the installation of larger and more complex instrumentation there. The Ross corrector lenses were also replaced by a Wynne corrector that provided a much wider usable field of view at the prime focus. But probably the largest change in using the 5 m Hale, like that with other large telescopes of the time, occurred in the recording and analysis of images. In the late 1940s, almost all observations had been made on the Hale using photographic plates. But by 1978, for example, photographic plates were used on only 15% of observing nights.(13) This was because they had been gradually replaced by image intensifiers, television cameras, imaging pulse-counting systems and finally CCDs (see Section 5.4), even though the photographic plates of the late 1970s were much better than those available in the late 1940s.[9]

In 1998 a Shack-Hartmann adaptive optics system[10] called PALAO (Palomar Adaptive Optics), developed by the Jet Propulsion Laboratory (JPL), was fitted to the Hale 5 m. It was produced as part of an agreement between Caltech and JPL which allowed JPL access to the telescope in return for their support with instrumentation.(14) PALAO was operated with PHARO (Palomar High Angular Resolution Observer) a dedicated near infrared science camera which had been designed and built by Cornell University under a cooperative agreement between Cornell and Caltech. The system produced near infrared images with a resolution of about 20 mas (milliarcsec).

Eight years later LuckyCam, which had been developed by Cambridge University in the UK, was installed on the telescope. It took images at a rate of about 20 per second, allowing the best to be added together to produce very sharp results. Unusually for modern high-resolution systems, LuckyCam operated in the

[8] Translates as 'Large Altazimuth Telescope'.
[9] The last photographic plate to be exposed on the 5 m Hale was a 1 hour exposure of the supernova remnant 3C 58 by Sidney van den Bergh on September 29 1989, see *Sky and Telescope*, February 1990, p. 134.
[10] Shack-Hartmann arrays are outlined in Section 5.2.

visible waveband. Operating with an adaptive optics system it produced images with a resolution of 35 mas.

1.2 Palomar Schmidt Telescopes

The Mount Wilson 60 and 100 inch f/5 reflecting telescopes had been built in the early twentieth century to photograph dim objects. But, as mentioned above, they initially had relatively narrow, corrected fields of view owing mainly to off-axis coma. In the late 1920s/early 1930s when the f/3.3 Palomar reflector was being planned it was clear that it would have an even worse problem as coma was known to vary inversely as the square of the focal ratio.(15) At about this time Ross was designing coma correctors for these large reflectors, but their corrected field of view would still be rather small.

But in 1931 John Anderson, the Mount Wilson instrumental physicist, became aware of a radical new design of telescope produced by Bernhard Schmidt of the Hamburg Observatory that could be used for very wide field photography. It was clear that such a telescope would be a valuable complement to the large reflectors on Mount Wilson and Palomar as it could find and accurately locate the faint stars, nebulae, and galaxies that these telescopes could then study in more detail.(16) Schmidt's design had a spherical rather than a parabolic primary mirror and an aspherical glass plate to correct for spherical aberration. This aspherical corrector plate was smaller than the primary mirror and was placed at its centre of curvature to eliminate coma. The main problem was that the focal plane was curved, so the photographic plate which was placed in the focal plane had to be curved to keep the image in focus.

John Anderson on hearing of Schmidt's radical design suggested to Hale that they should build a Schmidt telescope or camera[11] at Palomar. Shortly afterwards Russell Porter was commissioned to design such an instrument which was built in the Mount Wilson optical shop. It had a 26 inch (66 cm) *f*/2 primary mirror and an 18 inch (46 cm) corrector plate. With its 8° field of view, it was used by Fritz Zwicky and Joseph Johnson from 1936 to 1939 to produce 1625 photographs of 175 regions of the sky that contained nearby galaxies. They were looking for supernovae, twelve of which they discovered over that three year period.(17)

The early success of the 18 inch Schmidt, as it was called, persuaded Hale to ask the Rockefeller Foundation for funding to construct a much larger Palomar Schmidt. Corning made the blank for its 72 inch (1.8 m) *f*/2.4 spherical primary mirror. This was then ground and figured by Don Hendrix and Ralph Dietz in the Mount Wilson optical shop where it was completed in 1940. Hendrix then started

[11] Some authors use the term 'telescope' and some 'camera' when describing Schmidts.