



400 Years of the Telescope

Professor Ian Morrison

26 November 2009

In October 1608, a Flemish spectacle-maker by the name of Hans Lipperhey had applied for a patent for his spyglass which allowed distant objects to be seen as distinctly as if they were nearby. Knowledge of it quickly spread around Europe and such telescopes could be bought quite easily. In England, the mathematician Thomas Harriot used one to make what are believed to be the first telescopic observations of the Moon. The first known (rather crude) drawing was dated the 26th July 1609, followed later with an impressive map of the Moon. Harriot did not publicise his observations and, as a result, it is widely thought that the first astronomical made using a telescope were made by Galileo Galilei.

Thomas Harriot's Moon map of 26th July 1609 (left) and his later, impressive, map of the Full Moon.

The spyglass came to the attention of Galileo in July 1609; he quickly worked out the principle of the telescope and built himself an eight-power telescope. Grinding his own lenses and optimising the shape of the objective lens, he gradually improved the power and image quality of the telescope and began to observe the heavens making his first astronomical observations in the autumn of 1609. In March 1610, he published the "The Starry Messenger" which described his observations of the Moon and planets - particularly those of Jupiter and its moons:

"On the seventh day of January in this present year 1610, at the first hour of night, when I was viewing the heavenly bodies with a telescope, Jupiter presented itself to me; and because I had prepared a very excellent instrument for myself, I perceived (as I had not before, on account of the weakness of my previous instrument) that beside the planet there were three starlets, small indeed, but very bright. Though I believed them to be among the host of fixed stars, they aroused my curiosity somewhat by appearing to lie in an exact straight line parallel to the ecliptic, and by their being more splendid than others of their size. . . . There were two stars on the eastern side and one to the west. The most easterly star and the western one appeared larger than the other. I paid no attention to the distances between them and Jupiter, for at the outset I thought them to be fixed stars, as I have said. But returning to the same investigation on January eight -- led by what, I do not know -- I found a very different arrangement. The three starlets were now all to the west of Jupiter, closer together, and at equal intervals from one another

On the tenth of January . . . there were but two of them, both easterly, the third (as I supposed) being hidden behind Jupiter There was no way in which such alterations could be attributed to Jupiter's motion, yet being certain that these were still the same stars I had observed . . . my perplexity was now transformed into amazement. I was sure that the apparent changes belonged not to Jupiter but to the observed stars, and I resolved to pursue this investigation with greater care and attention

I had now decided beyond all question that there existed in the heavens three stars wandering about Jupiter as do Venus and Mercury about the sun, and this became plainer than daylight from observations on similar occasions which followed. Nor were there just three such stars; four wanderers complete their revolution about Jupiter"

Galileo continued his observations and conveyed some of them in ciphers to Johannes Kepler. These included his observations of Saturn which showed "handles" (the ring system) and those of Venus which when decoded said "The mother of lovers (Venus) imitates the shapes of Cynthia (the Moon)) - Galileo had observed that Venus showed phases.

In the Ptolemaic model, in which the Earth was at the centre of the universe and around which the Sun, Moon and planets revolve, Venus lies between the Earth and the Sun and hence it must always be lit from behind, so could only show crescent phases whilst its angular size would not alter greatly. In contrast, in the Copernican model Venus orbits the Sun. When on the nearside of the Sun, it would show crescent phases whilst, when on its far side but still visible, it would show almost full phases. As its distance from us would change significantly, its angular size (the angle subtended by the planet as seen from the Earth) would likewise show a large change.

The figure shows a set of drawings of Venus made by Galileo in parallel with a set of modern photographs which illustrate not only that Galileo showed the phases, but that he also drew the changing angular size correctly. These drawings showed precisely what the Copernican model predicts: almost full phases when Venus is on the far side of the Sun and has a small angular size coupled with thin crescent phases, having a significantly larger angular size, when it is closest to the Earth.

Galileo Galilei, his telescope and his drawings of the planet Venus.

So Galileo's observations, made with the simplest possible astronomical instrument, were able to show which of the two competing models of the Solar System was correct.

In order to produce acceptable images, the length of these simple telescopes had to be very long compared to the diameter of their objective lens. They thus became very unwieldy! The problem is that an objective made of a single lens gives red and blue focuses that are widely separate from the green focus. Using such a lens in a telescope and trying to get the best image - probably where the green light comes to a focus - one would see the sharp green image on top of out of focus blue and red images which surround the image with a purple glow. This is chromatic aberration!

The Achromatic Doublet and Giant Refractors

By combining a biconvex crown glass lens with a plano-concave flint glass lens, it is possible to make what is called an achromatic doublet or achromat - implying that the problem of chromatic aberration is at least largely eliminated. Such a doublet lens was first patented by John Dolland in 1758 but it is believed that the first achromatic lenses were made by Chester Moore Hall in about 1733. This allowed refractors to be made with far larger aperture objective lenses. These not only collected more light and so were able to detect fainter objects, but also improved the image quality or "resolution" of the telescope and so began the era of the giant refractors which culminated in the construction of the 40" aperture Yerkes telescope.

In the mid 1700's using a refracting telescope of just 4 inches aperture, the French Astronomer, Charles Messier, produced a catalogue that eventually numbered 103 celestial objects. These were largely "nebulous objects" such as galaxies and small star clusters, but it was "packed out" a little to, in partial form, exceed the number of objects in a rival catalogue! The Pleiades cluster, M45 and the Beehive Cluster, M44, were added when he was about to publish his first catalogue of 45 objects in 1774! He published his catalogue largely to help comet hunters (a major astronomical pursuit in those days) so that they would not be confused with the sometimes comet-like objects such as galaxies that it included. Today the catalogue provides a wonderful set of objects for amateur astronomers to observe, and there are many beautiful books available to help them locate and learn about them.

Though larger aperture telescopes will theoretically give higher resolutions, in practice the resolution is usually limited by what is called the "seeing" - a function of turbulence in the atmosphere. The atmosphere contains cells of gas with slightly differing refractive indices which are carried high above the telescope by the wind and act rather like the glass used for screens which blur what is seen beyond. A star is effectively a point source and should theoretically give an image (a central disc surrounded by some faint rings, called the Airy disc) determined by the telescope aperture. In practice a stellar image as seen from the UK will probably be or order 2 to 3 arc seconds across and is highly unsteady. This is one reason why professional telescopes are located on high mountains on islands such as La Palma in the Atlantic Ocean and Hawaii in the Pacific Ocean or high in the Chilean Andes. There is far less atmosphere above the telescope and the air tends to be less turbulent as it has been flowing over the sea. Under the best conditions the seeing might limit the resolution to half an arc second, so larger aperture telescopes will see more detail but not significantly more than a telescope whose aperture is ~ 400cm across. The best

location for an optical telescope is in space, as in the case of the Hubble Space Telescope, where its full resolution of 1/20th of an arc second at visible wavelengths may be realised. The turbulence of the atmosphere and hence seeing varies from night to night. In bad seeing the image of a star will appear bloated and the Moon can appear to be boiling! On such nights the image quality will be totally determined by the atmosphere. But rarely, the atmosphere can be still and then the aperture, type of telescope and the quality of the optics will determine what you can see.

When the giant refractors were the prime astronomical instruments, they tended to concentrate on stellar observations - the fact that there were external galaxies was not known. Then, galaxies were called "white nebulae" and it was generally thought that they were clouds in our own galaxy. Precise observations of the star Sirius showed that it was following a sinusoidal path across the sky. In 1844 German astronomer Friedrich Bessel realised that this must be due to the fact that it had a companion star in orbit around it. In this case, it is the barycentre (centre of gravity) of the star system that follows a linear path (called the system's proper motion) with the two stars oscillating on either side. By analyzing the path it was possible to deduce the presence of a star, now called Sirius B and of just 0.06 solar masses, orbiting Sirius A. It had not been directly observed, as with telescopes of the time it would be lost in the glare of Sirius due to light scatter within the telescope. When, in 1862, Alvin Clarke was testing the pristine optics of an 18.5 inch refractor by observing Sirius to carry out a "star test", he spotted the 9th magnitude companion for the first time. It is now known to be a "White Dwarf" star - similar to the final state of our Sun.

One of the most important set of observations using a refractor were made by Vesto Slipher at the Lowell Observatory where Percival Lowell had used the observatory's 24 inch refractor to draw the canals on Mars. Slipher made spectroscopic observations of 24 "white nebula" which showed that they were moving at high speed relative to our Galaxy. Some of the nearby galaxies were coming towards us (gravity is making the members of our local group of galaxies collapse down to eventually form one giant amorphous galaxy) but the majority were moving away from us. For example, in 1913 he had discovered that the Andromeda galaxy had a blueshift of 300 km/s. This implies that Andromeda and the Milky Way galaxies are approaching each other due to the gravitational attraction between them but not, as might first appear, by 300 km/sec. Our Sun is orbiting the centre of our galaxy at about 220 km/second and taking this into account, the actual approach speed is nearer 100 km/sec.

By 1915 Slipher had measured the shifts for 15 galaxies, 11 of which were redshifted. Two years later, a further 6 redshifts had been measured and it became obvious that only the nearer galaxies (those within our local group) showed blueshifts. From the measured shifts and, using the Doppler formula, he was able to calculate the velocities of approach or recession of these galaxies. As we will see, these data were used by Edwin Hubble in what was perhaps the greatest observational discovery of the last century, and it is perhaps a little unfair that Slipher has not been given more recognition.

Percival Lowell observing Mars with the 24 inch refractor and the redshift of spectral lines in distant galaxies as observed by Vesto Slipher.

Reflecting Telescopes

The Newtonian reflecting telescope was invented by Sir Isaac Newton who did not believe that the problem of chromatic aberration that was suffered by simple refracting telescopes of the time could be overcome. Sadly, it is not thought that he made any astronomical observations with it. In the Newtonian, a primary mirror reflects the light to a focus that would lie in the centre of the tube so, to avoid obstructing the light path with one's head, a secondary mirror, often called the flat, reflects the light sideways to form an image just outside the tube where the focuser and eyepiece are placed.

Discovery of Uranus

William Herschel came to England from Germany and became the organist at the Octagon Chapel in Bath. His father has given him an interest in astronomy and this increased whilst he was at Bath. He became very unsatisfied with the telescopes that he could buy so decided that he would make a reflecting telescope of his own. In those days, the mirrors were cast in speculum metal - an alloy of two parts copper and one of tin - and he made the castings in the kitchen of his house. Occasionally the mould would break and the molten metal would crack the stone floor!

By 1778, he had built an excellent telescope having a mirror of just over 6 inches (150 mm) in diameter and began to make a survey of the whole sky. On the night of 13th March 1781 he observed an object that did not have the appearance of a star and he first thought that it was a comet. Observations over the following months showed that it did not have the highly elliptical or parabolic orbit of a typical comet and that it was in a nearly circular orbit having a semi-major axis of just over 19 AU - it was a planet!

It soon became apparent why Herschel had seen that that it was a planetary body whilst others had not. Side by side comparisons with telescopes in use by others confirmed its far higher image quality - Herschel had proven to be a superb telescope maker! Uranus has a maximum angular size of 4.1 arc seconds and, as the author has observed with an excellent telescope just a little smaller than Herschel's, it appears as a tiny greenish-blue disk. But unless a telescope has well figured optics this disk would be very hard to distinguish from a star.

The Leviathan of Birr Castle

During the 1840's William Parsons, the Third Earl of Rosse, built the mirrors, tube and mountings for a 72 inch reflecting telescope that was erected in the grounds of his castle at Birr Castle in County Offaly, Ireland. This was, for three quarters of a century, the largest optical telescope in the world. With this instrument, Lord Rosse made some beautiful drawings of astronomical objects. Perhaps the most notable was that of an object which was the 51st to be listed in Messier's catalogue and known as the "Whirlpool Galaxy". It was the first drawing to show the spiral arms of a galaxy and bears excellent comparison to modern day photographic images. [The galaxy is interacting with a second galaxy, NGC 5195, seen at the lower left of the drawing.

M51, The Whirlpool Galaxy, as drawn by the Third Earl of Rosse using the 72 inch telescope at Birr Castle in County Offaly, Ireland along with a CCD image of M51 .

Cassegrain and Ritchey-Chrétien Telescopes

Though Newtonian telescopes are still widely used by amateur astronomers, the majority of professional telescopes are a variant of a type of telescope called the Cassegrain telescope. In these telescopes, the secondary mirror is a hyperboloid which reflects the light down through a central hole through the primary mirror below which lies is the focal plane. This a far better place to locate heavy equipment such as a spectrometer. The image quality of a parabolic primary mirror (as used in Newtonian and Cassegrain telescopes) falls off rather rapidly away from the optical axis due to the optical aberration called coma. If instead, the primary is also a hyperboloid in what is called a Ritchey-Chrétien Telescope, coma is eliminated making it well suited for wide field and photographic observations. It was invented by George Willis Ritchey and Henri Chrétien in the early 1910s. The vast majority of all professional telescopes are Ritchey-Chrétiens. The Birr Castle 72 inch and Mt Wilson 100 inch telescopes.

The 100" Hooker Telescope at Mount Wilson

The "Leviathan of Birr Castle" was the largest telescope in the world for a quarter of a century and it was not until 1917 that the 100" Hooker Telescope was built at the Mt Wilson Observatory in the mountains above Los Angeles. (The increasing light pollution from LA is a problem!) Edwin Hubble became a staff astronomer at Mt Wilson and used it to make one of the most important discoveries of the last century. In the 1920's he measured the distances of galaxies in which he could observe a type of very bright variable star, called Cepheid Variables, which vary in brightness with very regular periods. Their period is related to their brightness and so, by measuring the period, it is possible to derive the absolute brightness of such a star in a distant object, such as a galaxy. From its observed (apparent) brightness it is then possible to calculate its distance and hence the distance of the galaxy in which it resides. He combined these measurements with those of their speed of approach or recession (provided by Slipher as described above) of their host galaxies to produce a plot of speed against distance. All, except the closest galaxies, were receding from us and he found that the greater the distance, the greater the apparent speed of recession. From this he derived "Hubble's Law" in which the speed of recession and distance were directly proportional and related by "Hubble's Constant" or H_0 . The value that is derived from his original data was ~500 km/sec/Mpc (a Mpc is a distance of 3.26 million light years). Such a linear relationship is a direct result of observing a universe that is expanding uniformly, so Hubble had shown that we live within an

expanding universe. The use of the word "constant" is perhaps misleading. It would only be a real constant if the universe expanded linearly throughout the whole of its existence. It has not - which is why the subscript is used. H_0 is the current value of Hubble's Constant!

Hubble's plot of Recession Velocity against Distance.

Consider the very simple one dimensional universe shown below. Initially the three components are 10 miles apart. Let this universe expand uniformly by a factor of two in one hour. As seen from the left hand component, the middle components will have appeared to have moved 10 miles in one hour whilst the right hand component will have appeared to move 20 miles - the apparent recession velocity is proportional to distance.

If one makes the simple assumption that the universe has expanded at a uniform rate throughout its existence, then it is possible to backtrack in time until the universe would have had no size - its origin - and hence estimate the age, known as the Hubble Age, of the universe. This is very simply given by $1/H_0$ and, using 500 km/sec/Mpc, one derives an age of about 2000 million years. In fact, the real age must be less than this as the universe would have been expanding faster in the past. In the case of the "flat" universe the actual age would be 2/3 that of the Hubble Age or ~1300 million years old.

This result obviously became a problem as the age of the solar system was determined (~ 4,500 million years) and calculations relating to the evolution of stars made by Hoyle and others indicated that some stars must be much older than that, ~ 10 to 12 thousand million years old. During the blackouts of World War II, Walter Baade used the 100" Hooker Telescope to study the stars in the Andromeda Galaxy and discovered that there were, in fact, two types of Cepheid variable. Those observed by Hubble were 4 times brighter than those that had been used for the distance calibration, and this led to the doubling of the measured galaxy distances. As a result, Hubble's constant reduced to ~250 km/sec/Mpc. There still remained many problems in estimating distances, but gradually the observations have been refined and, as a result, the estimate of Hubble's constant has reduced in value to about 70 km/sec/Mpc - corresponding to an age of ~14 billion years when the varying expansion rate of the universe over time is taken into account.

The 200 inch Hale Telescope at Mt Palomar

The next, and one of the most significant telescopes ever built, was the Hale Telescope that was built at Mt Palomar Observatory. In 1928, Ellery Hale of Mt Wilson Observatory had secured a grant of six million dollars from the Rockefeller Foundation for "the construction of an observatory, including a 200-inch reflecting telescope... and all other expenses incurred in making the observatory ready for use." With the increasing light pollution from Los Angeles, Mount Wilson was no longer regarded as an ideal site for an observatory so a site at an elevation of 5,600 feet on Palomar Mountain, 100 miles southeast of Pasadena, California was selected.

Following unsuccessful efforts at making the primary mirror out of quartz, Corning Glass Works were able to cast a mirror out of Pyrex - a low expansion glass that expands and contracts far less than ordinary glass - hence its use in kitchen ware. Engineers then started designing the telescope's structure that would weigh hundreds of tons, but be capable of moving smoothly and accurately to follow celestial objects across the sky. While tracking, the mirror must maintain its shape to a few millionths of an inch. Several revolutionary and ingenious engineering concepts were implemented into the design to meet these requirements, including a Serrurier truss open telescope structure, and oil bearings. Russell Porter produced a wonderful set of drawings of the telescope.

Construction of the dome began in 1936 with telescope foundations anchored 22 ft into the bedrock. The 135ft tall and 137 ft diameter dome was completed in two years. Also in 1936, the mirror blank was transported by rail to Pasadena (at no more than 25 mph!) taking 16 days. It then spent 11 years in the Caltech Optical Laboratory where 10,000 pounds of glass are ground and polished away to give the required surface accuracy. The extended time was partially due to World War II during which time all work on the telescope stopped, finally to restart in September 1945. The completed mirror was transported from Pasadena to Palomar in November 1947 and then a further two years were spent to finish polishing, aligning, and adjusting the mirror before its dedication, before final completion in June 1948. In January 1949, Edwin Hubble took the first photographic exposure with the 200-inch, 21 years after the grant for its construction had been given. An interesting fact was that, due to its size, an observer could sit just behind

the prime focus to take the (then) photographic plates. It was the world's largest optical telescope for 45 years!

The 200 inch and Edwin Hubble sitting at the prime focus.

The Hale Telescope played an important role in the study of Quasars - Quasi Stellar Objects - so called because on an optical photograph they appear like stars. They had been first discovered in a set of radio observations at Jodrell Bank Observatory which had shown that a small number of the then known radio sources had angular sizes less than 1 arc second. As the atmosphere caused even point objects to have an angular size of ~ 2 arc seconds when observed optically, these could well have been nearby star-like objects. A very accurate position of the brightest, called 3C 273 (as it was the 273rd object in the 3rd Cambridge Catalogue of radio sources), was found when it was occulted by the Moon. As the precise position of the Moon's limb at the time of immersion and emersion was known, the position was found to an accuracy of a few arc seconds. It was then possible to use the 5 m Hale Telescope to take a photograph of the object. Though its image looked very like a star, a jet was seen extending ~ 6 arc seconds to one side so it was certainly not a star! Maarten Schmidt, a Dutch astronomer who had emigrated to the USA and worked at CalTech, used the Hale Telescope to take a spectrum of the object. It was unlike any spectrum that had been observed up to that time and it took some time for Schmidt to realise that the lines that he could see in the spectrum had been redshifted by 16%. This indicated that its distance was about 611 Mpc or 2,000 million light years - it was then the most distant object known on the Universe. But 3C273 is one of the closer quasars to us and the most distant currently known lies at a distance of $\sim 4,000$ Mpc, or 13 billion light years! So, quasars are some of the most distant and most luminous objects that can be observed in the Universe.

The Schmidt Camera

The Schmidt Camera was invented in 1930 by Bernhard Schmidt. He wanted to design a new type of instrument which would have a very large field of view yet be free of aberrations such as coma and would have a short focal ratio so allowing fainter stars to be observed for a given exposure time. To eliminate chromatic aberration the new design would use a mirror as the primary, but to give a large field of view and eliminate coma a spherical mirror would be needed. But spherical mirrors suffer from spherical aberration. He realised that he could correct for spherical aberration if a corrector plate were placed at the radius of curvature of the spherical mirror. This has a varying thickness across its aperture to compensate for the path length difference between the parabolic and spherical mirrors.

The Mount Palomar 48 inch Schmidt Telescope.

Schmidt cameras have become one of the most useful tools of modern astronomy, ideally suited to photographing large star fields in the Milky Way - showing maybe 10,000 stars on one negative! Surveys of the sky have been made using such cameras, notably the 48 inch Samuel Oschin Schmidt Telescope at Mount Palomar which produced the Palomar Sky Survey which was completed in 1958. The film plates were 14 inch square and covered an area of sky six degree across! The survey initially covered the whole of the northern sky down to a declination of minus -27 degrees. Plates were made with both blue and red sensitive emulsions and are sensitivity to $+22$ magnitudes (about 1 million times fainter than the limit of human vision). In 1973, The United Kingdom built a similar telescope at the Siding Spring Observatory in Australia which produced a matching survey of the southern sky. On a personal note, an asteroid numbered 15727, now named after the author, was discovered in 1990 by the 2 meter diameter Alfred-Jensch-Telescope at Tautenburg Observatory in Germany, the largest Schmidt camera on the world.

The Mt Palomar Schmidt is now playing an important role in the detection of Near Earth Objects (NEO's) which are asteroids whose orbit brings them within the orbit of the Earth so making it possible that at some future date they might impact with the Earth. The orbits of the majority of those which might pose a major threat to us because of their size (>1 km diameter) have now been determined so allowing the possibility of changing their orbits slightly to avoid impact. A spin off from such observations is the detection of Trans Neptunian Objects which have included the discovery of the dwarf planet, Eris, the outermost member of our solar system.

Ways of improving the image quality of ground based telescopes

Given a perfect telescope used in space, resolution is directly proportional to the inverse of the telescope diameter - a bigger telescope giving finer resolution. A plane wavefront from distant star would form an image, with an angular resolution limited only by the diffraction of light so the telescope is said to be diffraction limited.

In practice however, for ground based telescopes, turbulence in the atmosphere distorts the wavefront, creating phase errors across the mirror. Even at the best sites, ground-based telescopes observing at visible wavelengths cannot achieve an angular resolution better than telescopes of about 20 cm diameter. Wavefront errors are also caused by inaccuracies in the mirrors surface and effects caused by gravitational and thermal changes in the mirror and its support structure.

The wavefront errors are thus of two types:

- 1) Slowly changing errors due to gravitational and thermal effects on the mirror. These are corrected by what are called Active Optics systems.
- 2) Rapidly changing errors due to the turbulence in the atmosphere. These are corrected by Adaptive Optics systems.

Active Optics

This is the term used to describe the methods used to correct for slow changes in the mirror and its telescope structure. In a typical system the mirror - which is relatively thin - is supported by a large number of actuators (perhaps 150 in number) which can be moved to apply forces to the rear surface of the mirror and so adjust the surface profile.

Periodically the image of a star is analysed, taking about 30 seconds, and a computer calculates the errors in the surface that would give rise to the observed image. The computer then calculates the force correction which each actuator has to perform to achieve optimal image quality.

Adaptive Optics

This is the term used to describe the correction of phase errors caused by the atmosphere: across a large mirror, rapidly changing phase errors of a few micrometers equivalent path length result. If there is a reasonably bright star in the field of view (which should give an image which is that of an Airy disk whose angular size is determined by the aperture of the telescope) its actual, distorted, image can be analysed in a computer and corrections applied to correct for the waveform errors and so produce a diffraction limited image. It would be quite impossible to correct the primary mirror at the required rate of every few milliseconds to the required precision of $\sim 1/50$ th of a micrometer, so instead, a small (8 to 20cm) deformable mirror is used in the light path whose surface profile is controlled by hundreds of piezoelectric actuators to compensate for the atmospheric effects. It is easier to fully correct the wavefront and so give a diffraction limited performance for observations in the near infrared but such systems can still provide an improvement of perhaps ten times at visible wavelengths.

Often a suitable reference star will not be found in the field of view that includes the target object, so artificial reference stars are now being created by firing a laser which excites sodium atoms in the upper atmosphere at an altitude of ~ 90 km. Such an artificial reference star can be created as close to the astronomical target as desired, but a lookout has to kept for high flying aircraft!

Spun cast telescope mirrors in Alt Azimuth mounts

A major development in the manufacture of large telescope mirrors was the practice of spinning the mold containing molten glass whilst in the furnace. By spinning the furnace at the proper speed while the glass is molten, the surface takes on a paraboloidal shape and, when the cooling process is complete, this surface is accurate to a small fraction of an inch. This avoids the removal of large amount of glass from the centre of the mirror (c.f. the Hale 5 m mirror) and so both greatly reduces the cost and time required to produce a parabolic mirror. Given the approximately correct shape, the precise paraboloidal shape is then ground using a spinning tool impregnated with diamond particles in a numerically-controlled milling

machine. The process gives a surface accuracy to about 50 microns (0.002 inch) which is then polished to the final surface shape using a very fine polishing compound to give an accuracy of better than 25 nanometers (1 millionth of an inch).

This technique has enabled a large number of 8 m class telescopes to be built over the last 20 years. Due to advances in drive systems and their computer control, these telescopes use alt-azimuth mounts. This is a simple two-axis mount for supporting and rotating the telescope about two mutually perpendicular axes; a vertical (altitude) axis, and a horizontal (azimuth) axis. The biggest advantage of an alt-azimuth mount is the simplicity of its mechanical design resulting in a far reduced cost. To follow an object across the sky, as alt-azimuth mounts need to be rotated at variable rates about both axes and it is also necessary to rotate the photographic plate (or now CCD camera) to compensate for the rotation to the field of view that is a consequence of this type of mounting. An alt-azimuth mount also reduces the cost of the dome structure covering the telescope since the telescope structure is more compact. All current and proposed large optical telescopes use this type of mounting.

Multiple and Segmented mirrors.

It appears that 8.4 m seems to be about the maximum size that single mirrors can be made, so other techniques are now being employed to give large effective apertures using two or more smaller mirrors whose light is combined to form one image. An early example was the Multiple Mirror Telescope (MMT) which used six, 1.8 m diameter, ex-surplus mirrors which had been originally manufactured to be incorporated into US spy satellites! Completed in 1979 it had an effective aperture of 4.5 m, almost as big as the Hale Telescope. However it was always a challenge to keep the individual mirrors perfectly aligned so in 1999 they were replaced by a single 6.5 m mirror made using the spin technique described above.

In 2008, the Large Binocular Telescope was completed. This uses two 8.4 m mirrors operating in tandem to give an effective aperture of 11.8 m and so is currently the world's largest optical telescope within a single dome. However the overall size of the pair is 22.8 m, and for some applications it will have an effective resolving power of a telescope this size - about 1/200th of an arc second!

Gemini North and South

The Gemini Observatory comprises two 8.1-meter telescopes; Gemini North, is located on Mauna Kea, Hawaii at a height of 4214m whilst Gemini South is at a height of 2737m on Cerro Pachón, Chile. Together, the twin telescopes can give full sky coverage with both sites giving a high percentage of clear weather and excellent atmospheric conditions. They have been designed to operate especially well at infra red wavelengths and to this end, their mirrors are coated with silver which reflect significantly more infrared radiation than the aluminum used to coat most other telescope mirrors. As atmospheric water vapour absorbs infrared radiation both telescopes are located on high mountain tops where the air has a very low water vapour content.

Segmented mirrors

The twin Keck Telescopes, located at a height of 4200 m at the top of Mauna Kea, Hawaii, are the world's largest optical and infrared telescopes. They have primary mirrors of 10 m diameter each composed of 36 hexagonal segments whose positions are adjusted (using active optics) to act as a single mirror. Telescopes can take time to thermally stabilize to the nighttime temperatures when the domes are opened, so to minimize these effects, the interior of the Keck domes are chilled close to freezing point during the day.

Twice a second when observing, the active optics system controls the positions of each mirror segment to a precision of 4 nanometers to compensate for thermal and gravitational deformations. The Keck Telescopes also use an adaptive optics system using 15 cm diameter deformable mirrors that changes their shape by up to 670 times per second to cancel out atmospheric distortion, improving the image quality by a factor of ten.

The Keck Telescopes have made a notable contribution to the detection of extra-solar planets by the "doppler wobble" method.

The Very Large Telescope

The Very Large Telescope (VLT) is operated by the European Southern Observatory (ESO) and consists of four 8.2-m telescopes which can either work independently or in combined mode when it is equivalent to a single 16 meter single telescope - making it the largest optical telescope in the world. The light from four auxiliary 1.8 m telescopes may also be combined with that from the 8-m telescopes to give high angular resolution imaging. It can observe over a wavelength range from the near UV up to 25 microns in the infrared.

The VLT is located at the Paranal Observatory on Cerro Paranal in the Atacama Desert, northern Chile at a height of 2600 m, one of the best observing sites in the world. The four main telescopes have been given the names of objects in the sky in the Mapuche language: Antu - the Sun, Kueyen - the Moon, Melipal - the Southern Cross - and Yepun - the star Sirius.

One notable achievement was the first visual image of a planet, albeit around a brown dwarf rather than a normal star, which was observed in the infra red when using an adaptive optics system. Recent discoveries have also included the discovery of the farthest gamma-ray burst and the evidence for a black hole at the centre of our Galaxy, the Milky Way.

Optical Interferometers

In radio astronomy, many observations have been made by combining the signals from two separated telescopes in what is called an interferometer. This has been extended in the form of arrays of antennas to synthesise a telescope which has a resolution equivalent to a single telescope whose diameter is the size of the array. This has enabled radio astronomers to achieve the same, or greater, resolution than optical telescopes. These techniques are now being applied to infrared and optical observations but, due to the far shorter wavelengths involved, the technique is difficult to apply. At Cambridge, an optical interferometer called COAST currently combines the light from four 40 cm diameter mirrors to give the equivalent resolution of a 22 m diameter optical telescope. This gives it a resolution of 1/200th of an arc second in comparison to that of the Hubble Space Telescope of 1/20th of an arc second. It has, for example, been used to observe the very close double star Capella showing the rotation of the two stars about each other. A similar array is in operation at Mt Wilson Observatory.

On a far larger scale, the light from two or more telescopes of the VLT, described above, which comprises four 8.2m telescopes and four auxiliary 1.8 m telescopes, can be combined in an interferometric array which has a resolution of ~ 1 milliarcsecond!

The four 8.2 m VLT telescopes with two of the auxiliary 1.8 m telescopes in the foreground.

A second major interferometer links the two 10m KECK telescopes on Mauna Kea, Hawaii. Combining the light from the two telescopes, which span a distance of 85 m, it can provide a resolution of 5 milliarcseconds. It had been hoped to build a number of smaller telescopes to build a similar array to that at the VLT, but currently there is a ban on building any further telescopes on the mountaintop site. A recent use of the interferometer has been to "null" out the light from a bright star, 51 Ophiuchi that is 410 light-years from Earth, and so be able to image an extended, double layered disc of dust - called a protoplanetary disc - orbiting the star. Here lies a solar system in the making!

Robotic telescopes

With the use of sophisticated computer systems and high speed connections over the internet, it is possible to operate telescopes remotely (as we did in the October 2009 lecture "The Hunt for Planet X."). Such "robotic" telescopes, often with mirrors of about 2m in diameter such as the two Faulkes Telescopes in Hawaii and Australia, are now spreading around the world. A particularly interesting use is that of observing the effect of gravitational lensing by a foreground star of a more distant one. Observations are usually performed using networks of robotic telescopes which continuously monitor millions of stars towards the center of the galaxy in order to provide a large number of background stars. In the same way that a convex lens can concentrate the light from a distant object into the eye and so make it appear brighter, if a foreground star passes behind one of greater distance, the brightness of the distant star will undergo a temporary increase in brightness which can last for many days. The peak brightness can be up to 10 times (2.5 magnitudes) that normally observed. Several thousand such events have now been

observed.

If the lensing star has a planet in orbit around it, then that planet can produce its own microlensing event, and thus provide a way of detecting its presence. For this to be observed, a highly improbable alignment is required so that a very large number of distant stars must be continuously monitored in order to detect such "planetary microlensing" events.

Observations by the OGLE consortium showing the microlensing caused by a planet of 5.5 earth-masses.

If one of the telescopes finds that the brightness of a star is increasing, then the whole network, spaced around the world for continuous observation, will provide unbroken monitoring. The presence of a planet is shown by a very short additional brightening appearing as a spike on the flanks of the main brightness curve.

On January 25, 2006, the discovery of OGLE-2005-BLG-390Lb was announced. This planet is estimated to have a mass of ~5.5 earth-masses and orbits a red dwarf star which is around 21,500 light years from Earth, towards the center of the Milky Way galaxy. The planet lies at a distance of 2.6 AU from its sun. At the time of its discovery, this planet had the lowest mass of any known extra-solar planet orbiting a main sequence star. By the end of August 2009, eight extra-solar planets had been discovered using the microlensing technique.

Robotic Observations of Gamma Ray Bursts

Gamma-ray bursts are very bright transient events that are observed primarily in gamma rays (hence their name) but some have extremely luminous optical counterparts as well. The fact that they can be observed from Earth despite lying at immense distances implies a massive energy output. The recent burst from GRB 080319B was accompanied by an optical counterpart that peaked at a visible magnitude of 5.8 comparable to that of the dimmest naked-eye stars despite the burst's distance of 7.5 billion light years. Had anyone on a dark location been looking in the right direction at the right time they would have seen an object over half way to the visible edge of the universe! Gamma-ray bursts are thought to be highly focused explosions, with most of the explosion energy collimated into a narrow jet traveling at speeds exceeding 99.995% of the speed of light. Because their energy is strongly beamed, most gamma rays bursts will never be detected, but when the beam is pointed towards Earth, the focusing of its energy causes the burst to appear much brighter than it would have been were its energy radiated uniformly. The calculated energy is comparable to the energy released in a bright supernova or may result from the coalescence of two neutron stars to form a black hole.

The bursts are very short and are initially detected in gamma rays with, for example, the Swift orbiting gamma ray telescope. The position is immediately sent around the world using the internet to robotic telescopes that can quickly move to the gamma ray burst's position. The Robotic Optical Transient Search Experiment has placed 0.45m reflecting telescopes in four locations on Earth to cover the entire sky in search of gamma-ray bursts. One of these, ROTSE IIIb, is located at McDonald Observatory in the USA whilst, at Los Alamos National Laboratory, RAPTOR-T uses 4 co-aligned 0.4 m telescopes that are capable of slewing to anywhere in the visible hemisphere in just 10 seconds following a gamma burst alert. The response and subsequent observations are carried out without any human intervention - its designers call it a "thinking telescope". When not responding to alerts it, along with two further RAPTOR telescopes located some distance away, is continuously scanning the sky searching for transient events. The use of three telescopes can eliminate cosmic ray or terrestrial effects that would only affect one of the three telescopes.

The Hubble Space Telescope (HST)

The HST, named after Edwin Hubble, was launched in April 1990 to observe the universe over a wavelength range that extends from the ultraviolet, through the visible to the near-infrared. That is, from 0.12 microns in the ultraviolet to 2.4 microns in the near-infrared. (One micron is 10^{-6} m.)

The HST's primary mirror is 2.4 m and has a resolution of ~1/20th of an arc second at visible wavelengths. However, this resolution would have only been met if the mirror was ground to such a precision that it would be diffraction limited and to achieve this, the mirror was one of the smoothest ever made.

When placed in its orbit some 600 km above the Earth, the astronomers commissioning the HST were

mortified to find that it could not be focused. The full optical system had not been tested on the ground and a problem in the test rig that controlled the shape of the primary mirror meant that the mirror suffered spherical aberration that gave very bad images. The centre of the mirror was just 2 microns too shallow, and as a result, rays from the edge of the mirror came to a focus 4 cm behind that from the centre. An ideal mirror will put 84% of the light into the central disk, but the HST mirror put only ~15% of the light in the central disk with most of the light spread over a region 1.5 arc seconds across, comparable to ground based telescopes! However, rather than being a badly made mirror of the correct shape, it was a perfectly made mirror of the wrong shape! This meant that it was possible to correct the spherical aberration by introducing a correcting lens or mirror into the optical path, and this was achieved in the first servicing mission that was carried out in 1993.

The Hubble Telescope relies on the use of gyros to orientate itself in space and these have a limited life. It was thus designed so that it could be serviced by astronauts who could replace the gyros but also install new instruments. The last (and final) of the five servicing missions took place in May 2009 when two new instruments were installed and numerous repairs made. This last servicing mission should allow the telescope to function until at least 2014, when its successor, the James Webb Space Telescope (JWST), is due to be launched. The JWST will only observe in infrared, so it will complement rather than replace Hubble's ability to observe in the visible and ultraviolet parts of the spectrum.

Since 1993, it has been a virtually perfect telescope and its contribution to our understanding of the universe has been immense. One of its main legacies to astronomy will be the images of the distant universe in what are called the Hubble Deep Field and the Hubble Ultra Deep field showing galaxies close to the time of their formation just a billion years after the origin of the universe.

The Future:

The Thirty Meter Telescope (American spelling!)

The Thirty Meter Telescope (TMT) will be a ground-based astronomical observatory with a 30 metre (98 foot) diameter segmented mirror capable of observations from the near-ultraviolet to the mid-infrared. An adaptive optics system will correct for image blur caused by the atmosphere of the Earth to enable observations at the longer wavelength end that have ten times the spatial resolution of the Hubble Space Telescope. The TMT will be more sensitive than existing ground-based telescopes by a factor of 10 when used without adaptive optics in use and 100 when used. If completed on schedule in 2018, the TMT will be the first of the new generation of Extremely Large Telescopes.

The design of the TMT descends from the successful KECK telescopes and will use a Ritchey-Chrétien telescope with a 30 metre diameter primary mirror. This segmented mirror will consist of 492 smaller (1.4 m), individual hexagonal mirrors whose shape as well as their position relative to neighboring segments, will be continuously controlled by computer. The altitude-azimuth telescope mount will be capable of moving between any two points of the sky in less than 5 minutes to precision of ~2.0 arcseconds and can then track the motion of a celestial body with a precision of a few milliarcseconds.

The Extremely Large Telescope (ELT)

The European Southern Observatory (ESO), in which the UK has a stake, is designing a telescope with a mirror 42 m in diameter which will be capable of covering a field on the sky about a tenth the size of the full Moon. The primary mirror will consist of almost 1000 segments, each 1.4 m wide, but only 50 mm thick. The optical design calls for an immense secondary mirror 6 m in diameter, comparable in size to the biggest primary telescope mirrors in operation today. It will use adaptive optics to compensate for atmospheric turbulence using a mirror in the optical path that is supported by more than 5000 actuators that can distort its shape a thousand times per second. The ELT will be capable of observing over a wide range of wavelengths from the optical to mid-infrared enabling astronomers to exploit the telescope's size in a very wide range of observations. The site for the ELT is still under consideration, but if all goes well it could, along with the TMT, be completed around 2018.

Optical astronomers have an exciting future!