Chapter 12: Astronomy from the Renaissance to the mid-twentieth century

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The period from the European Renaissance to the middle of the 20th century was an extremely rich one for the history of astronomy. The heliocentric paradigm of Copernicus (mid 16th century) followed by the techno-scientific revolution of Galileo's refracting telescope (1609) initiated a tremendous movement for revival and progress in astronomical observations and theoretical understanding of the sky that favoured the construction and development of many new observatories with successive generations of completely new instruments. In the late 19th century, astronomical observations were strongly transformed by the methods of astrophysics following the discovery of the wave nature of light and emission spectra from heated materials.

The astronomical heritage of the four centuries in question is huge, mainly and firstly in European countries and later in others parts of the world. It involves several different categories of heritage simultaneously: moveable instruments, fixed instruments, observatories, and records of original observational data.

The sheer size of this topic presents us with a problem in the context of this Thematic Study, since it must aim to achieve balance over a very wide range of themes without letting any one of them dominate. This problem would have been impossible to resolve but for the timely publication of a separate volume wholly dedicated to the theme *Astronomical Observatories: From Classical Astronomy to Modern Astrophysics*, edited by Gudrun Wolfschmidt (Berlin, 2009: ICOMOS, Monuments and Sites XVIII). The volume represents the proceedings of an international symposium on "Cultural Heritage: Astronomical Observatories (around 1900)" organized by ICOMOS Germany together with the University of Hamburg in October 2008 and contains 40 articles on classical observatories and their heritage. Instead of duplicating this effort by trying to present a complete overview of the theme of astronomy from the Renaissance to the mid-twentieth century, we refer the reader to the Hamburg symposium publication and simply offer here a brief chronological survey whose length is consistent with the other chapters.

Similarly, the five case studies have been chosen as far as possible to complement rather than to reproduce the information available in the Hamburg book. They are: the Royal Observatory, Greenwich, UK; the Royal Observatory, Cape of Good Hope, South Africa; the Observatory of Paris–Meudon, France; the Mount Wilson Observatory, California, USA; and the Einstein Tower in Potsdam, Germany. Greenwich and Cape Town are featured in the Hamburg volume but included here in the interests of balance, Greenwich because it is part of a World Heritage Site and exemplifies several important issues, and Cape Town Observatory because of its special significance due to its position both in the South Hemisphere and in Africa.

Sometimes, the heritage approach in modern and contemporary astronomy focuses strongly on a given instrument. Historically, this was often the essential reason for the creation of the observatory itself, so that a remarkable instrument is considered the core part of the place, giving it all its value. The scientific requirements and the technical capacities at a given moment come together to create a high-performance instrument: in scientific/technological terms this, rather than its architectural context, is the real work of genius. We have addressed this issue in Introduction and Conclusion of the Thematic Study, and discuss there the difficulties in keeping in strict accordance with the application of the World Heritage Convention. To do that we must consider a site, in the sense of a whole property; in other words, the instrument cannot be separated from its direct surroundings or from its material environment considered as a totality. The accordance between an instrument and a site (fixed tangible heritage) and between an instrument and its scientific uses and results (intangible heritage) are essential issues if the aim is to develop a definition of a property with a view to a viable nomination.

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Researched and written around 1530, *De revolutionibus orbium cœlestium,* the reference book by Nicolaus Copernicus (1473–1543), was published in the year of his death. Within the history of cosmogony and European thought, this book carried an outstanding change of paradigm. The Ptolemaic description of a geocentric world (2nd century AD) was replaced by a heliocentric system that conserved circular orbits and uniform motions.

During the second half of the 16th century, the positions of celestial objects were determined by the naked eye, using classical instruments inspired both by the European medieval and the Arabic-Islamic traditions (see Chapters 10 and 11). In Europe, the most important astronomical project was the construction of the Uraniborg observatory complex. Funded by the king of Denmark, it was built on a small island by the astronomer Tycho Brahe (1546–1601) between 1576 and 1580. Equipped by large new instruments, it permitted Tycho and his group of astronomers to work over a long period to establish new astronomical tables for more than 1000 stars. These tables were later published by Johann Kepler (in 1627). Tycho also improved the quality of the measurements, reaching a precision of less than one arc minute, and permitting the accurate prediction of celestial events.

An important social event of the period linked with astronomy and cosmology was the reform of the calendar adopted by the Catholic Church in 1582 under the rule of Pope Gregory XIII. The difficulties in changing the cosmological paradigm during the late Renaissance are illustrated by Tycho Brahe's ambivalent attitude in trying to keep the Earth at the centre of the universe, with the planets circulating around the Sun and the Sun around the Earth. Giordano Bruno's (1548–1600) concept of the infinite universe illustrates the general flowering of ideas in science and cosmology during the Humanist period and also the difficulties hindering their social and cultural recognition.

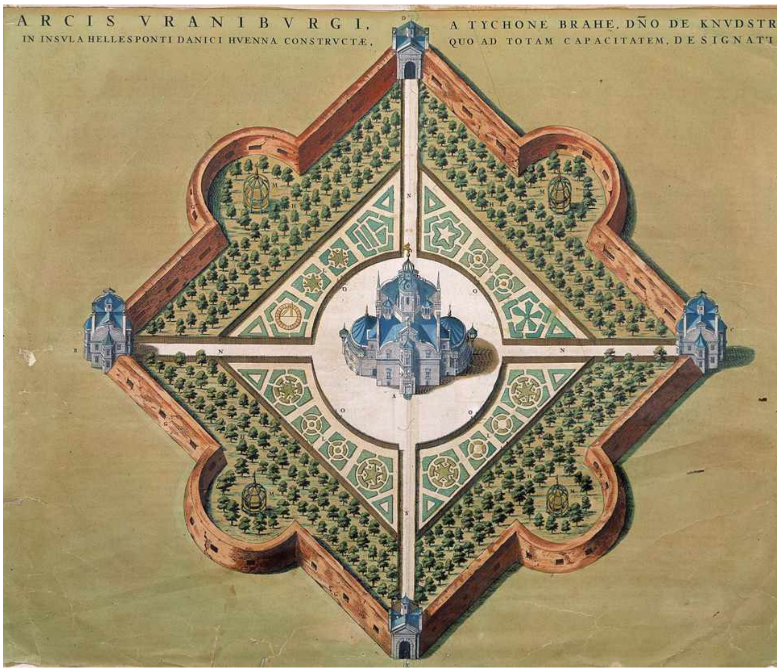

Fig. 12.0.1. "Uraniborg", in Tycho Brahe, *Astronomiae instauratae mechanica* (1598). It was demolished during the 17th century. Wikimedia Commons (Public domain)

Johannes Kepler (1571–1630) continued Tycho Brahe's work, using the results to support Copernicus's propositions concerning the celestial movements by means of his famous three laws: that planetary orbits are elliptical, that the line from the Sun to a planet sweeps out equal areas in equal times, and that a simple formula links the period of revolution to the dimensions of the orbit. Kepler launched the 'modern scientific revolution' by formulating extremely simple mathematical laws that have universal consequences. However, Kepler remained a man of his time, publishing popular almanacs and compiling horoscopes and astrological prognoses for his clients.

Copernicus's heliocentric system took time to be fully recognised as a completely new description of the sky: Galileo Galilei's (1564–1642) famous controversy with the Catholic Church lasted from the 1610s until his death. In the process of reaching his own certitude in support of the Copernican model, Galileo radically changed the capacities of astronomical observations by the use of the refracting telescope—two convex lenses mounted in a tube that magnified the field of vision. From 1609 onwards, astronomical knowledge was suddenly transformed, as telescopes started to reveal a multitude of celestial objects that no human being had ever seen before. One of Galileo's earliest and most significant discoveries was the existence of Jupiter's four (largest) moons, showing that the Earth was not unique among the planets in having a moon and hence supporting the Copernican model. Another was the discovery of mountains on the Moon, demonstrating its materiality and its similarities with the Earth.

A new epoch began in the middle of the 17th century following the development of reliable and efficient refracting telescopes. Scientists and craftsmen improved their know-how and built better instruments, for example adding angular measurement systems to the telescope. Such devices leaded to numerous new discoveries: for example in the 1650s Christiaan Huygens (1629–1695) discovered Saturn's rings and its moon Titan and made the first known sketch of the Orion nebula. They also offered improvements in transoceanic navigation since astronomical observations could be used to determine one's position at sea. This period was characterised by observation programmes and the exchange of information through networks of European scientists. The powerful kingdoms of the time chose to construct major observatories, using the latest technological improvements to create new instruments, and funding professional astronomers recruited from all over Europe. In 1641, Johannes Hevelius (1611–1687) founded an observatory at Danzig (Gdańsk) equipped with a large telescope. The Paris Observatory was founded in 1667 by Louis XIV, with a range of astronomers centred at first around Jean Picard (1620–1682) and then around Jean-Dominique Cassini (1625–1712), who became the first director. The Royal Observatory at Greenwich (see Case Study 12.1) was commissioned by the English king Charles II in 1675 and directed by the 'Astronomers Royal' John Flamsteed (1646–1719) followed by Edmund Halley (1656–1742).

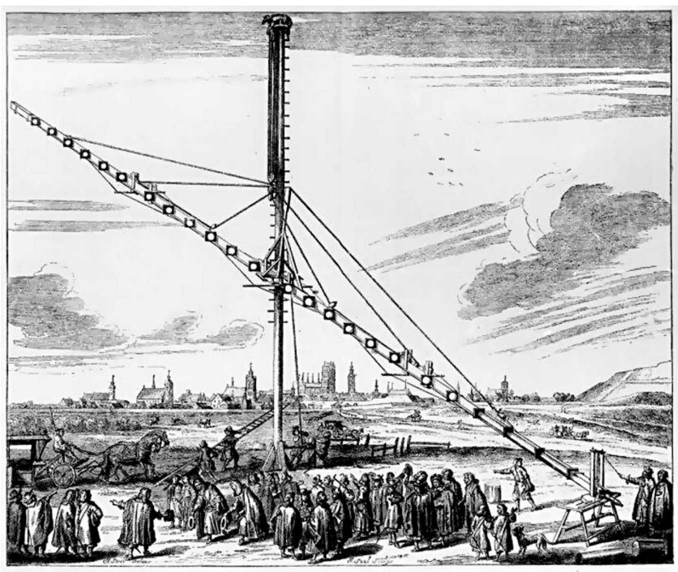

Fig. 12.0.2. The 140ft telescope of Johannes Hevelius (from *Machina coelestis*, 1673). Wikimedia Commons (Public domain)

The availability of all this new equipment and the increasing number of astronomers led to many crucial discoveries, and generated a completely new view and understanding of the sky. Specific events such as the appearance of Halley's comet (1680–84) engaged a wide public and offered many opportunities for discussion among the elite in salons. Astronomers published revised catalogues of stars and updated ephemerides.

With his *Principia* (1687), Isaac Newton (1643–1727) produced the greatest theoretical achievement of the 17th century, unifying celestial science and terrestrial physics. The concept of universal gravitation and the three laws of motion formed the basis of a complete and coherent mathematical model underlying what became known as 'celestial mechanics'.

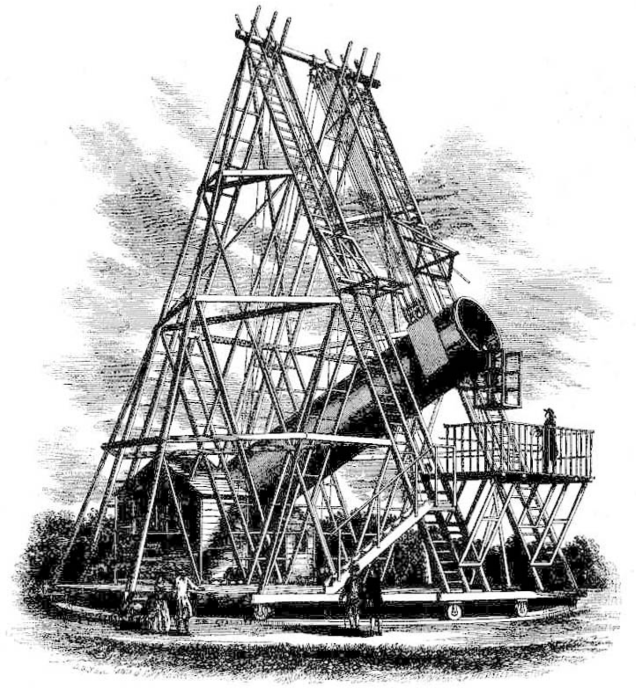

Fig. 12.0.3. William Herschel's 40ft reflector, completed in 1789. (Public domain)

This period also marked the appearance of new associated fields of experimental discovery such as the determination of the finite speed of light in 1676 by Ole Christensen Rømer (1644–1710), while at the Paris Observatory. An apparent variation in the position of stars observed at the end of the 17th century gave hope of determining their parallax (the annual variation in their position caused by the earth's motion around the sun), and hence their distance. Instead, it led James Bradley (1693–1762) to discover the aberration effect (1727), which is a consequence of the finite speed of light, and confirmed Rømer's theory. Bradley also discovered the nutation of the Earth's axis in 1738.

Improvements in instruments and theory brought about many further developments in the astronomical sciences during the 18th century. New accurate instruments were invented, such as Rømer's meridian telescope (1704) equipped with micrometers, and Pierre Bouguer's heliometer (1748). Techniques of fabricating parabolic bronze mirrors were improved, so that reflecting telescopes became viable, while in 1758 John Dollond (1706–1761) discovered a way to largely eliminate the chromatic aberration of lenses in refractors. By the end of the century, these improved instruments had led to the completion of a number of substantial catalogues and ephemeredes. Thus:

- in 1764, Jérôme Lalande (1732–1807) published his *Traité d'Astronomie*, a compendium of astronomical knowledge of the time, in the rational and pedagogic manner of the Enlightenment;
- in 1771, Charles Messier (1730–1817) published his catalogue of celestial bodies outside the solar system;
- in 1776, the first edition appeared of the *Berliner Astronomisches Jahrbuch*, an annual ephemeris and astronomical periodical that continued until 1960; and
- in 1801, Jérôme Lalande (1732–1807) published the *Histoire Céleste Française*, which contained a catalogue of over 47,000 stars.

William Herschel (1738–1822), who discovered Uranus in 1781, started a family dynasty of astronomers. His high-precision instruments marked the beginning of a new generation of great reflecting telescopes.

During the 18th century a number of scientific expeditions were organised in order to determinate the size and true shape of the Earth. The measurement of the Paris meridian from one end of France to the other, a project begun by Picard, was pursued by J.-D. Cassini and his son Jacques. Expeditions to Peru and Lapland, coordinated by the *Académie des Sciences* in Paris in the mid-1730s and involving numerous astronomers and other scientists, established that the Earth was flattened at the poles. The transits of Venus (across the solar disc) in 1761 and 1769 led to the organization of scientific expeditions involving international cooperation and the coordination of observations in different parts of the World, the main aim being to obtain a more accurate measurement of the distance of the sun and hence to 'scale' the solar system.

Another important question deriving from the new astronomical possibilities arose at the beginning of the 18th century: could longitude be determined by astronomical observations at sea and/or by time measurements using accurate and sustainable maritime clocks? Solutions were mainly developed in England and France. Octants usable for navigation started to be produced in the early 1730s, portable sextants followed in the 1750s, and an improved reflecting circle (essentially an octant extended to a full circle) was invented by Jean-Charles Borda in 1787. The last aspect of the solution of the quest for longitude at sea was the production of tables of lunar motions in 1752 by the German astronomer Tobias Mayer (1723–1762).

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The construction of new observatories continued and even accelerated in the 19th century, creating not only a sizeable international network in Europe but also, and for the first time, a significant scattering of modern observatories all around the world. Between 1830 and 1840, the classical architecture of the dome observatory arose, producing a specific and popular landmark that is easily recognizable. It still remains today emblematic of astronomy and astronomers. Of the many such constructions of that period, the Pulkovo Observatory in St Petersburg, Russia, constructed by order of the Tsar Nicolas I and opened in 1839 under the directorship of Friedrich Georg Wilhelm Struve (see Case Study 14.1), was probably one of the most typical and the most complete. The Harvard College Observatory in the USA, founded in 1839, and the Royal Observatory at the Cape of Good Hope in South Africa (see Case Study 12.2) are good examples of permanent sites constructed outside Europe.

Fig. 12.0.4. Pulkovo Observatory. Photograph © Vladimir Ivanov; Creative Commons licence

At the same time, the efficiency of the instruments continued to increase in various ways: in terms of the quality of the metal, the mechanical capabilities of the builders, the workmanship of the lens-makers and the precision of the mirror polishing. For example, the availability of achromatic homogeneous glass allowed larger objective lenses to be built, so that large refracting telescopes could be constructed for the first time; and equatorial supports and mechanical drives allowed the telescope to follow stars in the sky, thus permitting an extended survey of a single field with the precision of observation being limited only by external factors such as diffraction and air turbulence. One effect of all these improvements was that pride of place in the observatory now went to the refracting telescope. Another was that smaller objects were now visible, so that, for example, many 'double stars' (binaries) could now be resolved. The theoretical capacities of astronomers of this period are illustrated by Carl Friedrich Gauss (1777–1855) successfully predicting in 1801 the sky position of the asteroid (now dwarf planet) Ceres by calculation; and later in 1846 by the discovery of Neptune by Urbain Le Verrier (1811–1877) using calculations based on perturbations in the position of Uranus.

The middle of the 19th century is characterised by large systematic surveys of the sky. International projects were producing large catalogues and maps, listing an increasing number of celestial objects, together with their position, magnitude, and other details. The New General Catalogue (NGC), produced in 1880, listed 7840 'non-stellar objects'—star clusters and nebulae, many of which we now know to be other galaxies. It was the beginning of a deeper understanding of the Universe.

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In the late 19th century, the use of spectroscopy and photography triggered a fundamental shift in emphasis from mapping the skies to understanding the physical processes going on in space. The origins of astronomical spectroscopy go back to the mid-1810s, with Joseph Fraunhofer's (1787–1826) observation of dark spectral lines in the solar spectrum, but its implications for astronomy were only followed up seriously in the 1850s and 1860s, and in 1868 Pierre Janssen (1824–1907) and Norman Lockyer (1836–1920) discovered a new element, helium, in the Sun. Spectra rapidly led to an understanding of the chemical structure not only of the sun but of other stars.

Janssen was a pioneer in astrophotography, taking early photographs of the sun and introducing technical innovations that enabled large numbers of photographs to be taken in quick succession. From the 1870s onwards, new photographic emulsions and improved accuracy of movement in equatorial drives enabled magnificent photographs to be taken, and this led to the creation in 1885 of a global international programme for mapping the sky, the *Carte du Ciel*.

The new field of astrophysics connected astronomy to physics and chemistry, and led to the creation of specific communities of practitioners in the 1860s and 1870s such as the Italian Society of Spectroscopists. Two complementary improvements permitted spectrometry to become standard practice in systematic studies of the sky: the replacement of glass prisms by high-density diffraction gratings and the use of fine-grain photography to record the spectra. Specific centres for astronomical spectroscopy were set up during the 1870s at Greenwich, Potsdam (see also Case Study 12.5) and Meudon (see Case Study 12.3), close to the great scientific cities of the time. Programmes were initiated to catalogue stellar spectra and to work towards a better understanding of stellar structure.

By the end of the 19th century the Universe was understood to be a complex and dispersed ensemble of galaxies of different types containing an incredible number of stars, their interdependent movements following the laws of celestial mechanics and their light providing information on their chemical structure and temperature. Successful methodologies had been developed for systematic astronomical studies involving worldwide networks of observatories and the international community of astronomers.

Nonetheless, instrumental performance remained limited at the turn of 20th century by the size of the telescopes and by physical limits such as air turbulence and diffraction. Furthermore, artificial lighting and urban fogs were detrimental both to direct observation and spectrometry. Added to this, astrophysicists began to realise the importance of the new information that could be obtained by observing radiation outside the visible range. The problem was that such radiation was badly affected by the Earth's atmosphere, especially at low levels. The solution was to displace some observatories to new, more isolated locations and to construct new ones in mountain sites with high-quality, stable atmospheric conditions.

Two new observatories that overcame these dual limitations—the dimensions of the reflectors and air perturbation—were built during the first half of the 20th century in the USA, under the conception of George Ellery Hale (1868–1938). The Mount Wilson Observatory, on which construction started in 1904, was built in California at an elevation of 1740m. It was equipped with a high-quality 1.5m reflector in 1908, and with a 2.5m reflector in 1917 (see also Case Study 12.4). A technical innovation invented by Bernhard Schmidt (1879–1935) in 1930 corrected the problem of off-axis aberrations that restricted the field of view of large telescopes, thus facilitating surveys covering large areas of the sky. The Hale observatory that opened in 1936 on Mount Palomar, also in California, contained a 46cm Schmidt telescope. The 200in (5.08m) reflector known as the Hale telescope, which was installed in 1948, remained the largest aperture optical telescope in the world until 1976.

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