ISTITUTO E MUSEO
DI STORIA DELLA SCIENZA

Galileo's telescope

Here you will find all of the texts on application,
compiled by the *Institute and Museum of the History of Science*, Florence.

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1 HISTORY

1.1 THE INVENTION

The question of who was the first to invent the telescope is as old as the instrument itself. On October 2, 1608, the Dutch Estates General examined an application for a patent for "a device to observe things at a distance" presented by a certain Hans Lipperhey (?-1619), an obscure spectacles-maker from Middelburg, in southwestern Holland. The patent application was rejected on the grounds that, although the usefulness of the device was recognised, especially for military purposes, it was deemed impossible to keep the secret of its construction for very long. And especially considering that, in those same days, another instrument-maker – a certain Sacharias Janssen (1588-1630), he too a spectacles-maker in Middelburg, indicated by Pierre Borel (c. 1620-1671) a few decades later as the true inventor of the telescope – declared that he knew how to build the instrument.

News of the invention spread rapidly throughout Europe, and already by April 1609 little telescopes about thirty centimetres long were to be found on sale, at the shops of spectacle-makers, in Paris and presumably in London. In Italy, the new instrument made its appearance at Milan in May of the same year, and two or three months later in Rome, Naples, Padua and Venice, where Fra Paolo Sarpi (1552-1623), a friend of Galileo, had heard news of it already by November 1608.

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1. Galileo's telescope, late 1609 - early 1610, Florence, Institute and Museum of the History of Science.
This is one of the only two surviving telescopes from the vast Galilean production, now conserved at the Institute and Museum of the History of Science, Florence.

2. Report of the October 2, 1608 session of the Dutch Estates General.
On October 2, 1608 the Dutch Estates General discussed the patent application made by Hans Lipperhey (?-1619), a spectacles-maker in Middelburg, for the construction of telescopes. The Dutch government commissioned him to make six telescopes, but refused to grant him a patent.

3. Portrait of Hans Lipperhey.
Pierre Borel, *De vero telescopii inventore*, The Hague, 1656.

A native of Wesel in western Germany, and spectacles-maker in Middelburg, southwestern Holland, Hans Lipperhey (?-1619) is considered one of the possible inventors of the telescope.

4. Geographical chart of Holland.
Both Hans Lipperhey (?-1619) and Sacharias Janssen (1588-1630), by many deemed the real forerunners of the telescope, worked as spectacles-makers in Middelburg, southwestern Holland.

5. Diego Velasquez, *The Surrender of Breda*, 1635, Madrid, Prado Museum.
The painting represents the surrender of Breda, which took place in 1625, after a long siege. Justin de Nassau consigns the keys of the city to the commander of the Spanish troops, Ambrogio Spinola (1569-1630), shown holding a field telescope.

6. *Portrait of Sacharias Janssen*.
Pierre Borel, *De vero telescopii inventore*, The Hague, 1656.
A spectacles-maker in Middelburg, southwestern Holland, Sacharias Janssen is indicated by Pierre Borel as the true inventor of the telescope.

7. Pierre Borel, *De vero telescopii inventore*, The Hague, 1656 - frontispiece.

8. Johannes Collarts, *Plate depicting a sixteenth-century optician's shop*, engraving, 1582.
Already by April 1609 in the spectacles-makers' shops of Paris, and probably of London as well, small telescopes about thirty centimeters long were being sold.

9. Luigi Catani, *Galileo with some of his pupils in Piazza San Marco, Venice, as he tests the first lenses with which he will construct his telescope*, 1816, Florence, Palazzo Pitti, Gallery of Modern Art.

10. *Portrait of Fra Paolo Sarpi*.
Natale Schiavoni, *Cento ritratti di illustri italiani* [One hundred portraits of illustrious Italians], Calcografia Bettoni, Milan, 1824.
The Venetian Servite Fra Paolo Sarpi (1552-1623) met Galileo, probably in late 1592, and was in contact with him, actively following his research activities, until 1606, when the city of Venice was struck by an interdiction for heresy.

1.2 FROM THE WORKSHOP TO THE STARS

Galileo (1564-1642) fabricated his first telescope, with only three magnifications, in the summer of 1609. But already on August 21 of that year, in the bell tower of San Marco, in the presence of the Doge and other Venetian notables, he presented an instrument that had eight magnifications, and that won him a lifetime appointment to the Padua Chair of Mathematics at a salary of one thousand florins a year. In November, Galileo had at his disposal a telescope with twenty magnifications, that is, more powerful by far that all the others circulating through Europe at the time, which utilised ordinary lenses made for spectacles, of low quality and with unsuitable focal lengths. The instruments developed by Galileo were highly superior in performance, for example, to the telescope with six magnifications with which the Englishman Thomas Harriot (1560-1621) had conducted observations and made drawings of the lunar surface in July 1609. Thanks to the power of his instrument, Galileo achieved exceptional results in his observations of the moon, demonstrating, in fact, that its surface is not perfectly spherical nor immaculate and even managing to calculate the height of the lunar mountains. Subsequently, Galileo was to make the exceptional series of astronomical discoveries, described in the Sidereus Nuncius [The Starry Messenger] published in March 1610, and destined to revolutionize forever the traditional view of the cosmos. He was to discover, first of all, the existence of a myriad of new stars, showing that the Milky Way is "no other than a mass of innumerable stars scattered in clusters". And again, he was to observe the strange appearance of Saturn, whose true cause, the presence of a ring around the planet, was to be found by Christiaan Huygens (1629-1695) nearly half a century later. He was the first to observe the phases of Venus, which conclusively demonstrated that the planet moved, orbiting around the Sun. But the discovery that brought him immortal fame, in January 1610, was that of the four satellites of Jupiter, which Galileo, in homage to the dynasty that ruled Tuscany, named Astri Medicei, or Medicean Planets.

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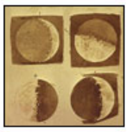

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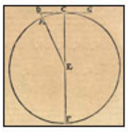

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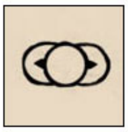

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1. Justus Suttermans, *Portrait of Galileo Galilei*, 17th century, Florence, Uffizi Gallery.
In the summer of 1609 Galileo (1564-1642), a reader in mathematics at the University of Padua, developed his first telescope, with a power of only three magnifications.

2. Guglielmo De Sanctis, *Galileo Galilei showing his telescope to the Signoria of Venice*, printed reproduction, Rome, Museum of Rome, detail.
On August 21, 1609, on the bell tower of St. Mark's in the presence of the Doge of Venice and other Venetian notables, Galileo (1564-1642) presented a telescope with eight magnifications, which won him a lifetime appointment to the Chair of Padua and a salary of 1000 florins.

3. Engraving showing the University of Padua (in the background).
Galileo Galilei's wooden professorial chair at the University of Padua (in the foreground).

4. Galileo's telescope, late 1609 - early 1610, Florence, Institute and Museum of the History of Science.

This is one of the two surviving telescopes from the vast Galilean production, now in the Institute and Museum of the History of Science, Florence.

5. Drawing of the lunar surface done by Thomas Harriot on July 26, 1609.

6. *Portrait of Thomas Harriot.*
In 1609 Harriot (1560-1621) fabricated a telescope with six magnifications, with which he could observe the surface of the Moon.

7. Galileo Galilei, *Sidereus Nuncius* [Starry Messenger], autograph sketch, Mss. Gal. 48 –Div. 2a – Part III, tome 3, c. 28r.
Representation in tempera of the lunar surface.

8. Galileo Galilei, *Sidereus Nuncius* [Starry Messenger], Venice, 1610.
Drawing showing the Moon in the first quarter.

9. Galileo Galilei, *Sidereus Nuncius* [Starry Messenger], Venice, 1610.
Drawing illustrating the method used to calculate the height of the mountains on the Moon.

10. Galileo Galilei, *Sidereus Nuncius* [Starry Messenger], Venice, 1610 - frontispiece.

11. Galileo Galilei, *Sidereus Nuncius* [Starry Messenger], Venice, 1610.
Drawing of the Pleiades.

12. Letter from Galileo to Belisario Vinta, Padua, July 30, 1610.
Drawing of "three-bodied" Saturn: "[…] the star of Saturn is not one alone, but is composed of 3, which almost touch one another, nor do they ever move or change position among themselves; […] the one in the middle being about 3 times larger than the two at the sides."

13. Letter from Galileo to Fortunio Liceti [in Padua], Florence, January 11, 1620.
Drawing showing one of the aspects of Saturn.

14. Christiaan Huygens, *Sistema Saturnium*, The Hague, 1659.
Diagram explaining the appearance of Saturn due to the presence of the ring.

15. Galileo Galilei, *Il Saggiatore* [The Assayer] Rome, 1623.
Drawing showing the phases of Venus.

16. Galileo Galilei, *Autograph diaries of observations on the positions of Jupiter's satellites*, 1610-1613.

17. Justus Suttermans, *Portrait of Grand Duke Cosimo II de' Medici and his wife Maria Maddalena d'Austria and his son Ferdinando II*, c. 1640, Florence, Vasari Corridor.

1.3 THE KEPLERIAN TELESCOPE

The Galileian telescope furnishes erect images, but has an extremely narrow field of view, which rapidly diminishes with increasing magnification. If, in fact, the field of view of a Galileian telescope with twenty magnifications is indicatively 15 minutes, that is, about half the apparent diameter of the Moon, it decreases to the order of only 5 minutes in a telescope with fifty magnifications. Such limited fields not only made the Galilean telescope unfeasible for civil and military purposes, but above all prevented, in the astronomical field, increments in performance over a few tenths of a magnification.

Johannes Kepler (1571-1630), the German astronomer famous for his three laws on planetary motion, had however demonstrated, since 1611, the possibility of replaced the diverging eyepiece of the Galileian telescope with a converging lens, with the ensuing advantage of a much vaster and more highly contrasted field of view. But this optical combination, known today as the Keplerian (or astronomical) telescope, furnished upside-down images that made it unsuitable for terrestrial use. Galileo (1564-1642) was to remain always faithful to the optical combination that bears his name. However, in the 1630s, the Keplerian telescope began to be widely used, mainly due to the work of the Neapolitan optician Francesco Fontana (c. 1580-1656), to the point of entirely superceding the Galileian one toward the middle of the century. The last great astronomical achievement made with a telescope of this type, published by Hevelius (1611-1687) in 1647, was the representation of the lunar surface. Moreover, the Keplerian telescope soon predominated for terrestrial purposes as well, thanks to the introduction of the so-called erector, an optical device, usually consisting of two convex lenses with the same focal length, which turned the image produced by the objective upright.

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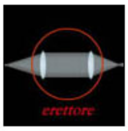

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1. *Portrait of Johann Kepler*, copy from the Jovian Collection, Florence, Institute and Museum of the History of Science.

The so-called Jovian Collection is a series of portraits of illustrious men, begun by Cosimo I (1519-1574), modelled on the museum of the erudite Paolo Giovio (1483-1552) and enriched over the centuries. Among the personages portrayed are Dante (1265-1321), Marsilio Ficino (1433-1499), Giovanni Alfonso Borelli (1608-1679), Robert Boyle (1627-1691), Thyco Brahe (1546-1601), Galileo (1564-1642), Isaac Newton (1642-1727), Evangelista Torricelli (1608-1647) and Vincenzo Viviani (1622-1703).

2. Johann Kepler, *Dioptrice, seu Demonstratio eorum quae visui et visibilibus propter conspicilla non ita pridem inventa accidunt*, Augsburg, 1611 – frontispiece.
In his *Dioptrice,* Kepler (1571-1630), famous for his three laws on planetary motion, demonstrated the possibility of replaced the diverging eyepiece of the Galilean telescope with a converging lens. This optical combination, known today as the Keplerian telescope, furnishes upside-down images but provides a much larger and more highly contrasted field of view.

3. Justus Suttermans, *Portrait of Galileo Galilei*, 1636, Florence, Uffizi Gallery.
Justus Suttermans (1597-1681), a Flemish artist, was the portrait painter of the Medici family at the time of Cosimo III (1642-1723). This work is perhaps the best-known and most intense portrait of Galileo (1564-1642), over seventy at the time. Around 1639, Suttermans painted another oil portrait of Galileo, now in the Greenwich Maritime Art Museum, London.

4. *Portrait of Francesco Fontana.*
Lorenzo Crasso, *Elogii d'hvomini letterati*, Venice, Combi & La Nou, 1666, p. 296 – Florence National Central Library, Palat. 12.B.A.6.3.7.
The Neapolitan Francesco Fontana (c.1580-1656) is known for having fabricated and marketed the first examples of the Keplerian telescope. In his *Novae coelestium terrestriumque rerum observationes* (Naples, 1646), Fontana claims that he has invented the telescope, according to him as early as 1608.

5. Johannes Hevelius, *Selenographia: sive, Lunae descriptio*, Gdańsk, Andreas Hünefeld, 1647 - frontispiece.
Published at Danzig in 1647, the *Selenographia* of Hevelius (1611-1687) includes, in addition to four general cartographies of the Moon, 40 splendid plates of the satellites in their various phases. The work, a compendium of the selenographic knowledge of the age, unrivalled by any previous work on this subject, encountered immediate success all over Europe.

6. *The Moon in the plenilunal phase*.
Johannes Hevelius, *Selenographia: sive, Lunae descriptio*, Gdańsk, Andreas Hünefeld, 1647, fig. P.

7. Diagram of Keplerian telescope fitted with erector unit.
The erector unit with two lenses, widely used in seventeenth-century telescopes of the Keplerian type, has two converging lenses, placed between the focal point of the objective and the eyepiece. Their mutual distance is equal to the sum of their respective focal lengths. The unit inverts, erecting it, the upside-down image formed by the objective. If the two lenses have the same focal length, the device does not alter the magnification of the optical system.

8. Christiaan Huygens, *Oeuvres Complètes*, Société Holladaise des Sciences, La Haye 1888-1950, pl. Ft pp. 118-9.
In 1664 Giovanni Domenico Cassini (1625-1712), utilizing a telescope made by Giuseppe Campani (1635-1715), observed the shadow of the Galilean satellites on the disc of Jupiter. This discovery was a further confirmation of the extraordinarily high quality of the optical components produced by Campani, who had this sheet printed, on which the Saturn he had observed himself also appears.

1.4 THE TUBE AND THE HOUSING OF THE OPTICAL PARTS

Various materials and techniques for making the tube were experimented by the first telescope makers. The little telescope examined by Giovambattista della Porta (c. 1535-1615) in Naples in the summer of 1609 had, for example, a tube made of tin. To build his first telescope, Galileo (1564-1642) used instead a lead tube, while that of the instrument he presented to the Venetian government was made of tin plate covered in *rascia*, a fabric made of raw wool that was to be used in Venice to cover gondolas up the end of the 19th century. The only two surviving examples of Galileo's vast production, now in the *Institute and Museum of the History of Science* in Florence, both have wooden tubes: one is made of two hollow half-cylinders covered in paper and held together by four copper wires; the other is made of twenty strips of wood glued onto paper and covered in red leather with gold tooling.

Later the tube became standardised. As telescopes grew in size, it became *telescopic*, that is, made of several sections sliding into one another, to reduce its size when not in use. The preferred material became cardboard, lightweight but able to provide the necessary rigidity. The secondary sections were often covered in marbled paper and the main section in finely decorated leather. In the telescopes of English make, the eyepiece was usually housed in the tube of largest diameter.

The housing of the optical parts also became more sophisticated. Often fabricated by lathing fine cabinet woods, either domestic like boxwood or exotic like guaiacum, they were fitted with screw caps to protect the optical components.

IMAGES AND CAPTIONS

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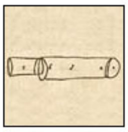

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1. Giovanni Battista della Porta, Biblioteca dell'Accademia dei Lincei, Mss n° 12, c. 326 – Autograph

This sketch, found in a letter from Giovanni Battista della Porta (c.1535-1615) dated August 28, 1609 to Federico Cesi (1585-1630), is the first known representation of the telescope: "It is a tube made of silver-plated tin, with length of a palm *ad*, three fingers in diameter, which has a convex eyepiece at end *a*: there is another canal [*c*] in the same tube, 4 fingers long, which enters into the first, and has a concave [lens] at the top."

2. *Portrait of Giovanni Battista della Porta*.
Thomas Young, Samual Speed, *Natural Magick*, London, 1658, English translation of the *Magiae naturalis sive de miraculis rerum naturalium*, Naples, in aedibus Ioannis Steelsij, 1588.

3. Justus Suttermans, *Portrait of Galileo Galilei*, 1636, Florence, Uffizi Gallery.

Justus Suttermans (1597-1681), a Flemish artist, was the portrait painter of the Medici family at the time of Cosimo III (1642-1723). This work is probably the best-known and most intense portrait of

Galileo (1564-1642), over seventy at the time. Around 1639, Suttermans painted another oil portrait of Galileo, now in the Greenwich Maritime Art Museum, London.

4. Guglielmo De Sanctis, *Galileo Galilei showing his telescope to the Signoria of Venice*, photographic reproduction, Rome, Museum of Rome, detail.
The original painting displayed by De Sanctis in 1867 at the Bologna exhibition and in 1883, at the International one in Rome, was purchased by Prince Giovannelli of Venice. Of this canvas, dispersed in 1927 with the sale of the Giovannelli collection, there remain in the Museum of Rome a sketch on wood and a model on canvas.

5. Galileo's Telescopes, 1609-1610, Florence, Institute and Museum of the History of Science.
Of Galileo's vast production of telescopes, many of them produced for sale, only these two examples have survived, along with an objective lens, it too conserved in the Museum of the History of Science in Florence, which was accidentally broken and glued back together already during the lifetime of Galileo.

6. Terrestrial telescope by Giuseppe Campani, c.1664, Florence, Institute and Museum of the History of Science.
Terrestrial telescope consisting of eight cardboard sections. The objective lens is signed by the maker. The smaller section consists of two parts, the outer one being reversible. Depending on which side is inserted in the tube, the magnification is either 29 or 36. This is very probably the telescope that Campani (1635-1715) sent to Ferdinando II de' Medici (1610-1670) in 1664.

7. Galilean type telescope, middle of the 17th century, Florence, Institute and Museum of the History of Science.
Although the maker of this telescope is unknown, the wording in Latin and Italian appearing on the papers lining the inside of one of the nine sections, made of cardboard, indicates that he was probably Italian. The objective is lacking. The eyepiece consists of a biconcave lens with focal length of around 50 mm, and the instrument thus represents a late example of the Galilean telescope.

8. Terrestrial telescope by Eustachio Divini, 1660-1670, Florence, Institute and Museum of the History of Science.
Telescope made of seven cardboard sections. The main one is covered in green leather tooled in gold, the others in red marbled paper. The instrument was built by Eustachio Divini (1610-1685) probably for experimental purposes. The eyepiece and the erector unit do not consist of three individual lenses, in fact, but of three pairs of plano-convex lenses. The objective is missing.

9. Terrestrial telescope attributed to John Marshall, late 17th century, Florence, Institute and Museum of the History of Science.
Terrestrial telescope made of eight cardboard sections, all covered in white vellum except for the first, which is coloured red and green with gold decorations. The arrangement of the optical components — with the eyepiece placed in the main tube and the objective lens in the smaller section — make it a typical English telescope, perhaps attributable to John Marshall (1663-1712).

10. Terrestrial telescope by Jacques Tendre de Moulina, first half of the 18th century, Florence, Institute and Museum of the History of Science.
The arrangement of the optical components — with the objective lens placed in the smallest section and the ocular lens in that of largest diameter — seems to indicate an instrument of English make; however, the second section bears the name "Anthoine Dumner" and the smallest one "Jacques Tendre Iray [?] de Moulina", suggesting a French provenance instead.

11. Terrestrial telescope by Giuseppe Campani, c. 1664, detail of eyepiece, Florence, Institute and Museum of the History of Science.
Starting from the middle of the 17th century, the housings of the optical elements in telescopes were produced by lathing precious woods, such a guaiacum, or domestic woods such as box, of which the eyepiece housing and the screw cap of this telescope by Campani (1635-1715) are made.

12. Terrestrial telescope attributed to John Marshall, 1690-1720, Florence, Institute and Museum of the History of Science.
Attributed to John Marshall (1663-1712), this telescope is undoubtedly of English make, as shown by the arrangement of the optical component, with the eyepiece placed in the main tube and the objective lens in the smallest section. It consists of 10 cardboard sections, all covered in white velum except for the main one, coloured and decorated with gold tooling. The erector unit is missing.

1.5 CHROMATIC ABERRATION

A ray of light traversing the surface separating two mediums of different density is refracted, that is, deviated. But light is composed of various colours, and the angle at which the colours are refracted differs for each of them. For this reason, in a positive lens the light rays do not all converge exactly at the same point, but the radiations of shorter wavelength focalize closer to the lens and those of longer wavelength further away from it. This phenomenon is known as chromatic aberration. The lack of a single focal point provokes a phenomenon of iridescence, which significantly impairs the quality of the images. Already the first telescope makers had empirically realised that the effects of chromatic aberration in a telescope substantially diminished when the ratio between the focal length and the diameter of the objective was increased. Seventeenth-century telescopes, in fact, not only had relatively long focal lengths but were also usually fitted with a diaphragm to reduce the aperture. But the focal length required to limit the effects of chromatic aberration is not proportional to the diameter of the objective, but to its square. If, for example, an objective with aperture of 2 cm shows no appreciable chromatic aberration for focal lengths of at least 75 cm, an objective having double the diameter, i.e., 4 cm, must have a focal length 4 times greater, or nearly 3 m. This circumstance profoundly conditioned the subsequent evolution of the telescope. On the one hand, progressive increase in the diameter of the objectives led to the construction of increasingly longer telescopes, to the point of reaching the practical limits of fabrication; on the other, it stimulated the search for solutions based on the utilisation of mirrors, which, working by reflection, are not affected by chromatic aberration.

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1. Justus Suttermans, *Portrait of Galileo Galilei*, 1636, Florence, Uffizi Gallery.

Justus Suttermans (1597-1681), a Flemish artist, was the portrait painter of the Medici family at the time of Cosimo III (1642-1723). This work is probably the best-known and most intense portrait of Galileo (1564-1642), over seventy at the time. Around 1639, Suttermans painted another oil portrait of Galileo, now in the Greenwich Maritime Art Museum, London.

2. *Portrait of Eustachio Divini*.
Carlo Antonio Manzini, *L'occhiale all'occhio: Dioptrica Pratica*, Bologna, Herede del Benacci, 1660
Around the middle of the 17th century, Eustachio Divini (1610-1685) was considered the best maker of optical instruments in all Europe. His fame was to be obscured, some ten years later, by that of Giuseppe Campani (1635-1715).

3. Caspar Netscher, *Portrait of Christiaan Huygens*, 1671, The Hague, Haags Historisch Museum.
Christiaan Huygens (1629-1695), famous Dutch physician and mathematician, fabricated, in collaboration with his elder brother Constantijn, some telescopes of outstanding quality. Among these is the telescope with aperture of approximately 5 cm (whose objective lens has survived) with which, on March 25, 1655, he discovered Titan, a satellite of Saturn, and later came to understand the true nature of the ring around the planet.

4. Terrestrial telescope by Paolo Belletti, 1689, detail of the objective, Florence, Institute and Museum of the History of Science.
Paolo Belletti was an optician active in Bologna during the second half of the 17th century.

5. *Aerial telescope*.
Christiaan Huygens, *Astroscopia compendiaria*, 1684
The striking length of the big telescopes produced in the second half of the 17th century posed serious problems in building mounts capable of ensuring the necessary stability. The telescope 123 feet long (over 37 m) built by Christiaan Huygens (1629-1695) was entirely without a tube, and the optical components were aligned by mean of a cable, held taught by the observer, which joined the eyepiece to the objective.

6. Johannes Hevelius, *Machinae coelestis, pars prior*, Gdańsk, Simon Reiniger, 1673, fig Y.
Telescope 60 feet (approx. 18 m) long built by Hevelius (1611-1687). The big seventeenth-century telescopes were first roughly aimed by means of a cable connected to a pulley on top of a pole, after which the final aiming and tracking of the stars was effected through a mobile fulcrum situated in the vicinity of the eyepiece.

7. Johannes Hevelius, *Machinae coelestis, pars prior*, Gdańsk, Simon Reiniger, 1673, fig. AA.
This plate — engraved, like most of the others, by Isaak Saal, to a drawing by the Polish artist Andreas Stech (1635-1697) — represents the famous telescope 150 feet long (approx. 45 m) built by Hevelius (1611-1687). Note the so-called "à jour" tube, open to make it lighter, which is suspended by cables at several points and stiffened by a complex system of tie rods to keep it from bending.

1.6 REFLECTING TELESCOPES

A concave mirror focuses the rays of light exactly like a converging lens, and can thus be utilised as objective. In 1663, the Scottish mathematician James Gregory (1638-1675) proposed an instrument consisting of a main parabolic mirror, and an elliptical secondary one, which sent the optical beam back behind the primary mirror, which had a hole in it. The Gregorian reflecting telescope, which furnishes erect images, met with great success in the 18th century thanks above all to the famous Scottish optician James Short (1710-1768).

In 1668, Isaac Newton (1642-1727) designed a telescope in which a plane mirror of elliptical shape, inclined by 45°, reflected the optical beam laterally, outside of the tube, where the eyepiece was positioned. A second version, still existing today, was presented to the Royal Society in 1672.

In that same year the Frenchman Laurent Cassegrain (c. 1629-1693) proposed an instrument in which the secondary mirror, a convex hyperbolic one, was placed in front of the focus of the primary, focusing the image, as in Gregory's telescope, in back of the latter.

The first truly efficient reflecting telescope was a Newtonian one with a 6-inch aperture presented in 1721 to the Royal Society by the Englishman John Hadley (1682-1744). Its performance equalled that of Huygens' (1629-1695) refracting telescope 123 feet long. Although reflecting telescopes of large size were built during the 17th century, the poor reflecting power of the mirrors of the time, made of a copper and tin alloy called *speculum* that reflected only about 60% of the incident light, prevented the success of the reflecting telescope. The problem was solved in 1856, when Léon Foucault (1819-1868) and Karl August von Steinheil (1801-1870) invented the process of silver-plating that allowed the utilisation of mirrors made of glass covered with a very fine layer of the purest silver.

IMAGES AND CAPTIONS

Fig.1

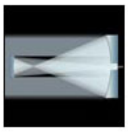

Fig.2


Fig.3


Fig.4


Fig.5


Fig.6


Fig.7


Fig.8


Fig.9


Fig.10


Fig.11


Fig.12


Fig.13


Fig.14


Fig.15


1. William Holl, *Portrait of James Gregory*, engraving, Oxford, Museum of the History of Science.

In the *Ottica promota* (London, 1663), published in 1663, the Scotsman James Gregory (1638-1675) presented the reflector telescope that bears his name. In the field of mathematics, Gregory is known for his *Vera Circuli et Hyperbolae Quadratura* (Padua, 1667), published in 1667, in which he demonstrates the squaring of the circle and of the parabola by means of converging series.

2. Diagram of Gregorian telescope.
This reflector has a concave parabolic primary mirror and a secondary mirror, also concave, but elliptical, that sends the optical beam back, through a hole in the primary mirror, to the eyepiece. The Gregorian telescope furnishes erect images. No longer in use today, this optical combination was highly succession in the 17th century, especially due to the work of the Scottish optician James Short (1710-1768).

3. James Short's Gregorian telescope, second half 18th century, Florence, Institute and Museum of the History of Science.
The Scotsman James Short (1710-1768) built nearly 1400 telescopes, almost all of them of the Gregorian type. This example bears on the breech the inscription "1/1309 = 61", which, according to the system used by Short, means that the telescope is the first one of this size out of a total of 1309 built up to then, and that the focal length of the primary lens is 61 inches (approx. 155 cm).

4. James Short's Gregorian telescope
The instrument, built entirely of brass, has a sophisticated universal equatorial mount. The outer rod of the tube is used to vary the distance between the primary and the secondary mirror, allowing the telescope to be focussed.

5. *Portrait of James Short*, Oxford, Museum of the History of Science.

6. John Vanderbank, *Portrait of Sir Isaac Newton*, c. 1726, oil on canvas, London, National Portrait Gallery.
In 1668 Isaac Newton (1642-1727) built the first example, now lost, of the telescope he had designed. In autumn 1671, he built a second one, which, on January 11 of the following year, he presented to the Royal Society, where it aroused great interest. During the same session Newton was named a member of the Royal Society.

7. Diagram of Newtonian telescope.
This reflector consists of a concave parabolic mirror and an elliptical plane mirror. The secondary mirror is inclined 45° degrees from the optical axis and serves the function of intercepting the rays of light coming from the primary, deviating them laterally outside the tube, where the eyepiece is positioned. Thanks to its simplicity, this telescope is still today widely used by amateur astronomers.

8. Drawing of Newtonian telescope.
This drawing — sent by Henry Oldenburg (c.1615- 1677), Secretary of the Royal Society, to Christiaan Huygens (1629-1695) in Paris — is the first representation of a Newtonian telescope. The two crowns at the lower left represent the decoration of a water clock, located at a distance of 300 feet (approx 90 m) and observed (letter A) through Newton's telescope and (B) through a refractor telescope 25 inches (approx. 64 cm) long.

9. Newton's telescope, London, Royal Society.
The first two telescopes built by Newton (1642-1727) have not survived. However, parts of a third instrument he built in the winter of 1671-1672 are believed to have been reused in a telescope presented in 1766 to the Royal Society, where it is still found today. Note the wooden ball-and-socket joint for aiming the telescope, and on the breech, the screw for focussing it.

10. Diagram of Cassegrain type telescope.
This telescope, named for the Frenchman Laurent Cassegrain (c. 1629-1693), consists of a primary parabolic mirror and a secondary hyperbolic convex mirror, placed before the focal point of the

primary. The secondary sends the optical beam in back of the primary mirror, through a hole in the latter. Since the secondary mirror, diverging, multiplies the focal length of the primary, the Cassegrain provides relatively long focal lengths with compact tubes.

11 John Bradley's telescope, London, Science Museum.
This Newtonian telescope — fabricated by John Bradley, who presented it to the Royal Society, of which he was a member, in the session of January 12, 1721 — was the first example of a reflector for practical use ever made. The aperture was about 6 inches (approx. 15 cm) and its performance equalled that of the famous 123-foot long refractor made by Christiaan Huygens (1629-1695).

12. Bartholomew Dandrigde [attr.], *Portrait of John Hadley*, London, National Maritime Museum.
This portrait is presumed to be that of John Hadley (1682-1744). Corroborating this hypothesis is the fact that the person portrayed is shown holding an octant — the instrument, precursor of the sextant, that Hadley presented to the Royal Society in 1731. But some doubt still remains as to the identity of the portrait, since by that time Hadley was 49, while the person portrayed seems younger.

13. William Herschel's reflector telescope 20 feet long (approx. 6 m), Royal Astronomical Society.
In his great telescopes, to compensate for the poor reflectivity of the mirrors of the time, Herschel (1738-1822) — famous for having discovered the planet Uranus in 1781 — eliminated the secondary mirror, inclining the primary away from the optical axis. The observer stood on a platform at the mouth of the tube, in an off-centred position so as not to obscure the aperture.

14. *Portrait of Jean Bernard Léon Foucault.*
A French physicist, author of the famous pendulum experiment that demonstrated the rotation of the earth, Jean Bernard Léon Foucault (1819-1868) — a little after Steinheil (1801-1870), in 1857, but independent of the latter — applied to telescope mirrors the method of silverplating the glass developed by Liebig (1803-1873). A crater on the Moon is named for Foucault.

15. J.C. Battre (after a portrait by Franz Hanfstaeng), *Portrait of Carl August von Steinheil*, engraving.
The German Carl August von Steinheil (1801-1870) made major contributions to various fields of applied physics. In optics, in 1856, he applied to telescope mirrors the method of silverplating the glass, invented a few years earlier by the German chemist Liebig (1803-1873), allowing the fabrication of mirrors with high reflectance. A crater on the Moon is named for Steinheil.

1.7 CHRONOLOGY

1608: THE INVENTION OF THE TELESCOPE

On October 2 the Dutch Estates General discuss the patent application presented by a certain Hans Lipperhey (?-1619), an optician in Middleburg who came from Wesel (western Germany), for the production of "a device to observe things at a distance". This is the first certain source testifying to the invention of the telescope. The patent is denied because the Estates General deem that, due to the intrinsic simplicity of the instrument, which consists of only two lenses, it would be impossible to keep the secret of its construction for long. However, the Dutch government commissions a certain number of these instruments from Lipperhey, specifying that they are to be of the binocular type with lenses made of rock crystal.

1609: THE FIRST TELESCOPES

In the month of April, rudimentary examples of the telescope with magnification of 3 or 4 are on sale in Paris, and probably in London as well, at opticians' shops.

1609: GALILEO'S FIRST TELESCOPE

In May, Galileo (1564-1642) first hears of the invention of the telescope. The news is confirmed to him a few days later in a letter from Paris written by the Frenchman Jacques Badovere (1570/1580-c. 1620), already his disciple.
In July and August Galileo builds his first telescope, which has a magnification of 3.

1609: THOMAS HARRIOT OBSERVES THE MOON

On August 5 the English mathematician and astronomer Thomas Harriot (c. 1560-1621) observes the Moon with a 6-power telescope, making a sketch of the lunar surface that has come down to us. It is a rather rough representation, testifying to the poor quality of Harriot's instrument.

1609: IN VENICE GALILEO DEMONSTRATES AN 8-POWER TELESCOPE

On August 21, on the bell tower of St. Mark's, in the presence of the Doge and other Venetian notables, Galileo (1564-1642) gives a demonstration of a telescope made by him with magnification of about 8. This will win him a lifetime appointment to a university chair, and a raise in salary from 520 to 1000 florins a year.

1610: GALILEO'S DISCOVERIES

On January 7, Galileo (1564-1642), using a 20-power telescope fabricated by him, discovers three of Jupiter's satellites. A fourth satellite is then discovered on the night of January 10.

1610: THE *SIDEREUS NUNCIUS*

The *Sidereus Nuncius* [Starry Messenger] by Galileo (1564-1642), dedicated to Grand Duke Cosimo II de' Medici (1590-1621) is published in Venice.

1610: THE “THREE-BODIED” NATURE OF SATURN

On July 30, in a letter to Belisario Vinta (1542-1613), the Secretary of State to Grand Duke Cosimo II (1590-1621), Galileo (1564-1642) — while awaiting the publishing of his discovery in a planned new edition of the *Sidereus Nuncius* (Venice, 1610) — announces the "three-bodied" nature of Saturn.
In August, in a letter to Giuliano de' Medici, Tuscan ambassador to Prague, Galileo announces the discovery of the "three-bodied" nature of Saturn, in the form of an anagram that Kepler (1571-1630) tries in vain to decipher. He had already informed Belisario Vinta of his discovery on July 30.

1610: THE PHASES OF VENUS

In a letter to Giuliano de' Medici dated December 11, Galileo (1564-1642) announces under the form of an anagram, which Kepler (1571-1630) tries in vain to decipher, his discovery of the phases of Venus.

1611: GALILEO IN ROME

In late March Galileo (1564-1642) goes to Rome to demonstrate the discoveries he has made with the telescope to the ecclesiastical authorities.

1611: KEPLER'S *DIOPTRICE*

In Augsburg the *Dioptrice* by Johann Kepler (1571-1630) is published. In this text the author suggests, among other things, replacing the diverging eyepiece of the Galilean telescope with a converging lens (Keplerian telescope).

1611: GALILEO MEMBER OF THE ACADEMY OF THE LINCEI

In Rome Galileo becomes a member of the Academy of the Lincei in a convivial meeting held on April 14 in the villa on the Janiculum owned by Cardinal Cesi, the uncle of Prince Federico, founder of the Academy.

1612: SUNSPOTS

Under the pseudonym of *Apelles latens post tabulam* (Apelles hidden behind the painting) the Jesuit Father Scheiner (1573-1650) publishes three letters, sent to Marc Welser (1558-1614), on sunspots.

1613: THE *ISTORIA E DIMOSTRAZIONI INTORNO ALLE MACCHIE SOLARI*

Under the title of *Istoria e dimostrazioni intorno alle macchie solari e loro accidenti* [History and demonstrations concerning sunspots and their characteristics], the three letters written by Galileo (1564-1642) to Marc Welser (1558-1614) are published in Rome under the aegis of the Academy of the Lincei.

1613: THE *DISPUTATIO DE COELO*

The *Disputatio de coelo* by Cesare Cremonini (1550-1631) is published in Venice.

1616: BELLARMINO'S ADMONITION TO GALILEO

The so-called first trial of Galileo (1564-1642) takes place. The *De revolutionibus orbium coelestium* of Copernicus (1473-1543) is prohibited *donec corrigantur* (pending correction). Galileo, who is informed of this measure by Cardinal Bellarmino (1542-1621), is ordered not to hold or defend the heliocentric theory. The proposition, "Sol est centrum mundi et omnino immobilis motu locali" is censured by the Holy Inquisition, insofar as deemed philosophically absurd and formally heretical; the proposition "Terra non est centrum mundi nec immobilis, sed secundum se totam se movere etiam motu diurno" is censured on the grounds that it is erroneous in faith at least.

1618: THE *TELESCOPIUM SIVE ARS PERFICIENDI*

The *Telescopium sive ars perficiendi* by Girolamo Sirtori is published in Frankfurt.

1621: SNELL FORMULATES THE LAW OF SINES

Willebrord Snell (1580-1626) formulates the law of sines.

1623: THE *SAGGIATORE*

Edited by the Academy of the Lincei and dedicated to the new Pope Urban VIII (1568-1644) *Il Saggiatore* [The Assayer] by Galileo (1564-1642) is published in late October in Rome.

1630: THE *ROSA URSINA* AND THE *COMMENTATIONES IN MOTUM TERRAE DIURNUM & ANNUUM*

Father Christoph Scheiner (1573-1650) publishes the *Rosa Ursina* at Bracciano.
The *Commentationes in motum Terrae diurnum & annuum* by Philip Landsberg (1561-1632) is published at Middelburg.

1630: THE DARK BANDS ON JUPITER

On May 17, 1630 the Jesuit priest Niccolò Zucchi (1586-1670), professor of theology and mathematics at the Collegio Romano, discovers the dark bands on the disc of Jupiter. A crater on the moon is dedicated to Father Zucchi.

1632: THE *DIALOGO SOPRA I DUE MASSIMI SISTEMI DEL MONDO*

In February the *Dialogo sopra i due massimi sistemi del mondo* [Dialogue on the Two Great World Systems]by Galileo (1564-1642) is published in Florence by G. B. Landini. It had been finished two years earlier, after having been interrupted several times.

1633: GALILEO'S TRIAL

On April 12 the first hearing of the so-called second trial of Galileo (1564-1642) is held, in which he appears before the Holy Office.

On June 22 of the same year, the trial concludes with Galileo's abjuration and sentencing to prison. The prison sentence is mitigated into a sort of house arrest and in July Galileo goes to Siena where he stays as guest of Archbishop Ascanio Piccolomini (1597-1671). In December he obtains authorization from the Pope to return to the villa “Il Gioiello” at Arcetri, in the vicinity of Florence, where he remains in confinement until his death.

1636: THE *HARMONIE UNIVERSELLE*

The *Harmonie Universelle* by Marin Mersenne (1588-1648) is published in Paris.

1637: THE *DIOPTRIQUE*

The *Dioptrique* is published in Leyden. Based on the law of sines, formulated in 1621 by Willebrord Snell (1580-1626), Descartes (1596-1650) demonstrates in 1621 that a plano-convex lens whose surface is of hyperbolic section would be free from spherical aberration. But despite various attempts, neither Descartes nor any of his contemporaries were able to produce lenses with hyperbolic surfaces.

1639: THE MICROMETER

The Englishman William Gascoigne (1612-1644) introduces the micrometer, a device to be applied to the eyepiece of a telescope to measure angular distances.

1642: DEATH OF GALILEO

On January 8 at Arcetri, near Florence, in the villa "Il Gioiello" where he is confined, Galileo (1564-1642) dies.

1642: THE *OCULUS ENOCH ET ELIAE SIUE RADIUS SIDEREOMYSTICUS*

The *Oculus Enoch et Eliae siue Radius sidereomysticus* by Anton Maria Schyrleus de Rheita (1604-1660) is published in Antwerp. This treatise contains a large section dedicated to binocular telescopes.

1646: THE *NOVAE COELESTIUM TERRESTRIUMQUE RERUM OBSERVATIONES*

The Neapolitan Francesco Fontana (c.1580-1656) publishes the *Novae Coelestium Terrestriumque Rerum Observationes* in Naples. Fontana was probably the first, starting in the early 1630s, to systematically utilize and market the Keplerian telescope, (which he even claims, in the *Observationes*, to have invented in 1608) and his instruments soon became renowned all over Italy and France. This work contains 28 plates of the Moon observed in its various phases and, although surpassed already in the following year by the famous *Selenographia* (Gdańsk, 1647) of Hevelius (1611-1687), Fontana's text is the first selenographic work having a certain organic structure. The treatise also includes observations on Mars, on whose surface Fontana observed a great dark patch, probably the Syrtis Major.

1655: THE DISCOVERY OF TITAN

On March 25, utilizing a telescope he had built himself having an aperture a little over 5 cm, Christiaan Huygens (1629-1695) discovers Titan, the largest of Saturn's satellites. This was the first discovery of a new celestial body after that of the four satellites of Jupiter made by Galileo 45 years before.

1656: THE *DE SATURNI LUNA OBSERVATIO NOVA*

The *De Saturni luna observatio nova* is published in the Hague. In this brief treatise, dedicated to the discovery of Titan the year before, Huygens (1629-1695) includes an anagram on the discovery of Saturn's ring. The anagram, whose meaning was to be disclosed only in 1659, when Huygens divulged his discovery, reads in fact: "Annulo cingitur, tenui, plano, nusquam cohaerente, ad eclipticam inclinato" ([Saturn] is surrounded by a slender ring, flat, which does not touch [the planet] at any point and is inclined in respect to the ecliptic).

1659: THE *SYSTEMA SATURNIUM*

Christiaan Huygens (1629-1695) publishes the *Systema Saturnium* in The Hague.

1660: THE *BREVIS ANNOTATIO IN SYSTEMA SATURNIUM CHRISTANI EUGENII*

Eustachio Divini (1610-1685), the most famous optician in all Europe around the middle of the 17th century, publishes in Rome the *Brevis annotatio in Systema Saturnium Christani Eugenii*, dedicated to Leopoldo de' Medici (1617-1675), the brother of the Grand Duke of Tuscany. In this work Divini claims that he, not Christiaan Huygens (1629-1695), had been the first to discover the satellites of Saturn.

1663: GREGORY'S TELESCOPE

The Scotsman James Gregory (1638-1675) designs a reflecting telescope with a primary mirror (objective) of parabolic section and a secondary one of elliptical section, situated beyond the focal point of the primary. This optical combination furnishes erect images without the need for an erector. For this reason too, the Gregorian telescope met with great success around the middle of the 18th century, above all thanks to the work of the famous Scottish optician James Short (1710-1768), who made over a thousand of these telescopes, some of them very large, during the course of his career.

1666: THE *THEORICAE MEDICEORUM PLANETARUM EX CAUSIS PHYSICIS DEDUCTAE*

Giovanni Alfonso Borelli (1608-1679) publishes the *Theoricae Mediceorum planetarum ex causis physicis deductae* in Florence.

1666: THE *MARTIS CIRCA AXEM PROPRIUM REVOLUBILIS OBSERVATIONES*

The *Martis circa axem proprium revolubilis observationes* by Giovanni Domenico Cassini (1625-1712) is published in Bologna. Cassini, using telescopes built by the famous optician Giuseppe Campani (1635-1715), had observed Mars, making drawings of its surface and determining its orbital period, which he estimated as 24hr 40min (a value less than 3min greater than the one accepted today) on an axis that was almost perpendicular to its orbital plane. An orbital period very close to the one assumed by Cassini had been determined in 1659 by Christiaan Huygens (1629-1695) who however, being unsure of the result, had failed to publish his discovery.

1668: NEWTON'S REFLECTING TELESCOPE

Isaac Newton (1642-1727) builds a reflector with parabolic objective and a plane secondary mirror of elliptical section that sends the light beam laterally outside of the tube.

1671: THE DISCOVERY OF IAPETUS

In December, utilizing a 17-foot telescope built by Giuseppe Campani (1635-1715), Giovannni Domenico Cassini (1625-1712) discovers a second satellite of Saturn, Iapetus.

1671: THE SECOND EXAMPLE OF NEWTON'S REFLECTING TELESCOPE

Isaac Newton (1642-1727) builds a second example of the telescope he has designed. The instrument is presented to the Royal Society of London, where it arouses great interest.

1672: CASSEGRAIN'S REFLECTING TELESCOPE

The Frenchman Laurent Cassegrain (c. 1629-1693), at the time professor of physics at Chartres, designs a reflector with a parabolic objective and a hyperbolic secondary, placed in front of the focal point of the primary, which focuses the image behind the latter, passing through a hole in it. Thanks to the diverging element, consisting of the hyperbolic secondary, this optical combination, still in use today, especially for amateur telescopes, provides for relatively long focal lengths (typically f/15) with tubes of limited dimensions.

1672: THE DISCOVERY OF RHEA

In December, utilizing a 34-foot telescope built by Giuseppe Campani (1635-1715), Giovanni Domenico Cassini (1625-1712) discovers a third satellite of Saturn, Rhea.

1673: THE *HOROLOGIUM OSCILLATORIUM SIVE DE MOTU PENDULORUM*

The *Horologium oscillatorium sive de motu pendulorum* by Christiaan Huygens (1629-1695) is published in Paris. In it the author describes the application of the pendulum to the measurement of time.

1684: THE DISCOVERY OF TETHYS AND DIONE

In March, utilizing the 100-foot and 136-foot telescopes of Giuseppe Campani (1635-1715), Giovanni Domenico Cassini (1625-1712) discovers two more satellites of Saturn, Tethys and Dione. The incredible series of discoveries made by Cassini using telescopes built by Campani sanctioned the latter's fame as Europe's finest optician.

1687: THE *PHILOSOPHIAE NATURALIS PRINCIPIA MATHEMATICA*

The *Philosophiae naturalis principia mathematica* by Isaac Newton (1642-1727) is published in London.

1721: HADLEY'S REFLECTING TELESCOPE

On January 12, John Hadley (1682-1744) presents to the Royal Society, of which he is a member, a Newtonian reflector fabricated by him with an aperture of 6 inches (approx. 15 cm) and a focal length of 62 inches (approx. 157 cm). This is the first example of a reflector with performance levels comparable to those of the refracting telescopes of the time. The technical solutions adopted were numerous and innovative, such as a screw focus mechanism, a checker and micrometric movements that greatly facilitated the sighting and tracking of celestial bodies. As compared to the refractor 123 feet long (approx. 37.5 m) of Huygens (1629-1695), Hadley's reflector, although less luminous (the mirrors of the time were made of a copper and tin alloy called speculum metal, which reflected only about 60% of the incident light), had virtually the same definition, with the difference that, being only about 1.8 m long, the Newtonian telescope was vastly easier to use.

1729: THE ACHROMATIC OBJECTIVE

Chester Moor Hall (1703-1771) invents the achromatic objective.

1.8 TEST

You can accede to the complete version of the test from the Resources section of the site "Galileo's telescope". Open the PDF file or download the RTF file. Good luck!

2 EXPLORE

2.1 THE INSTRUMENT

Name: Galileo's telescope
Inventor and maker: Galileo Galilei
Place: Italian
Data: Late 1609 - early 1610
Materiali: Wood, leather

DIMENSIONS

Total length: 980 mm
Length of the tube: 835 mm
Eyepiece
diameter: 22 mm**; aperture:** 15 mm**; thickness at the center:** 1,8 mm**; focal length:** -47.5 mm
Objective lens
diameter: 37 mm**; aperture:** 15 mm**; thickness at the center:** 2 mm**; focal length:** 980 mm

COMPONENTS

Tube
The bearing structure is formed of 20 strips of wood, glued onto a sheet of paper and covered in red leather with gold tooling. At each end the strips of wood are left bare of the leather covering to allow the cylinders containing the optical parts to be inserted by pressure. The overall length is 835 mm.

Housing of the objective lens
The housing consists of a wooden cylinder, covered in the same leather as the tube, 45 mm long with outside diameter of 61 mm. One end is inserted by pressure into the tube, the other, with inside diameter of 52 mm, houses the objective lens, protected by a wooden ring.

Objective lens
This is a plano-convex (converging) lens with the convexity facing outside. It has a focal distance of 980 mm, a diameter of 37 mm and a thickness at the centre of 2.0 mm. A cardboard diaphragm limits the aperture to 15 mm.

Eyepiece tube
It consists of a wooden cylinder, covered in the same leather as the tube, 40 mm long. One end is inserted by pressure into the tube, while the other, whose inside diameter is the same as the outside diameter of the eyepiece housing, allows the latter to slide in order to bring the object observed into focus.

Eyepiece housing

The housing of the eyepiece lens consists of a cardboard cylinder 30 mm long with outside diameter of 40 mm. The lens is situated a little less than one centimetre from the outer end of the housing.

Eyepiece

The original eyepiece has been lost. It has been replaced by a biconcave lens with focal length of -47.5 mm (the minus sign indicates that the lens is diverging). Its diameter is 22 mm and its thickness at the centre 1.8 mm. A cardboard diaphragm limits the aperture to 15 mm.

2.2 HOW IT WORKS

In any telescope system the objective — even when made up of several elements, both converging and diverging — must always be converging as a whole. The Galilean and the Keplerian telescopes thus differ only in the eyepiece, which is diverging in the former, converging in the latter.

The Galilean telescope (fig. 1) consists of a converging lens (plano-convex or biconvex) serving as objective, and a diverging lens (plano-concave or biconcave) serving as eyepiece. The eyepiece is situated in front of the focal point of the objective, at a distance from the focal point equal to the focal length of the eyepiece. Since converging lenses are conventionally positive (or of positive optical power) and diverging ones negative (or of negative optical power), we can also say that the distance between the objective and the eyepiece is equal to the algebraic sum of their focal lengths. The negative eyepiece intercepts the converging rays coming from the objective, rendering them parallel and thus forming, to the infinite (afocal position), a virtual image, magnified and erect. The magnification of the system is determined by the ratio between the focal length of the objective and that of the eyepiece. The Galilean telescope, although it furnishes erect images with the aid of erector devices, has the severe drawback of an extremely narrow field of view (which makes it, in practice, usable only for magnifications up to around thirty).

The principle of operation of the Keplerian telescope (fig. 2) is relatively simple. The objective forms a real image, diminished in size and upside-down, of the object observed. The eyepiece — which, consisting of a converging lens with short focal length, is actually a magnifying lens — enlarges the image formed by the objective. The image observed is however upside-down, so that the Keplerian telescope, at least for terrestrial use, must be fitted with some kind of erector device which, by inverting the image again, erects it. But this disadvantage is amply compensated for by a much greater and more evenly illuminated field of view than that of the Galilean telescopes.

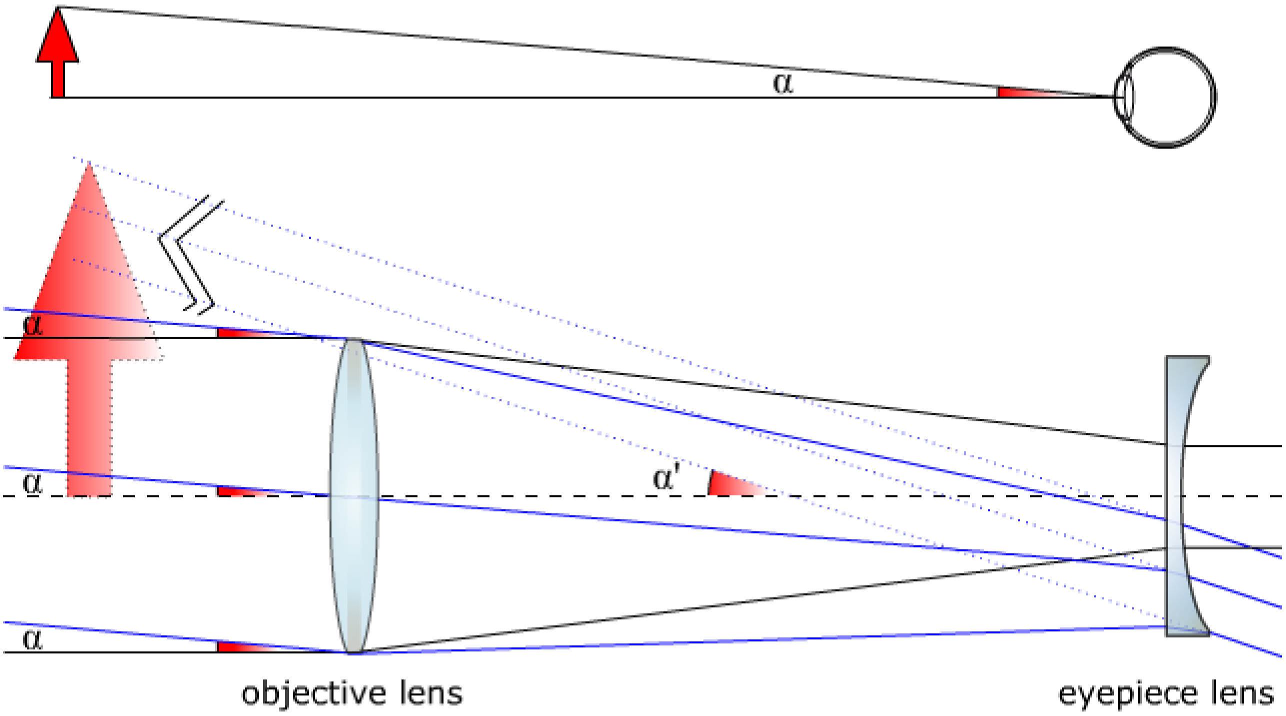


Fig.1 Optical diagram of Galilean telescope

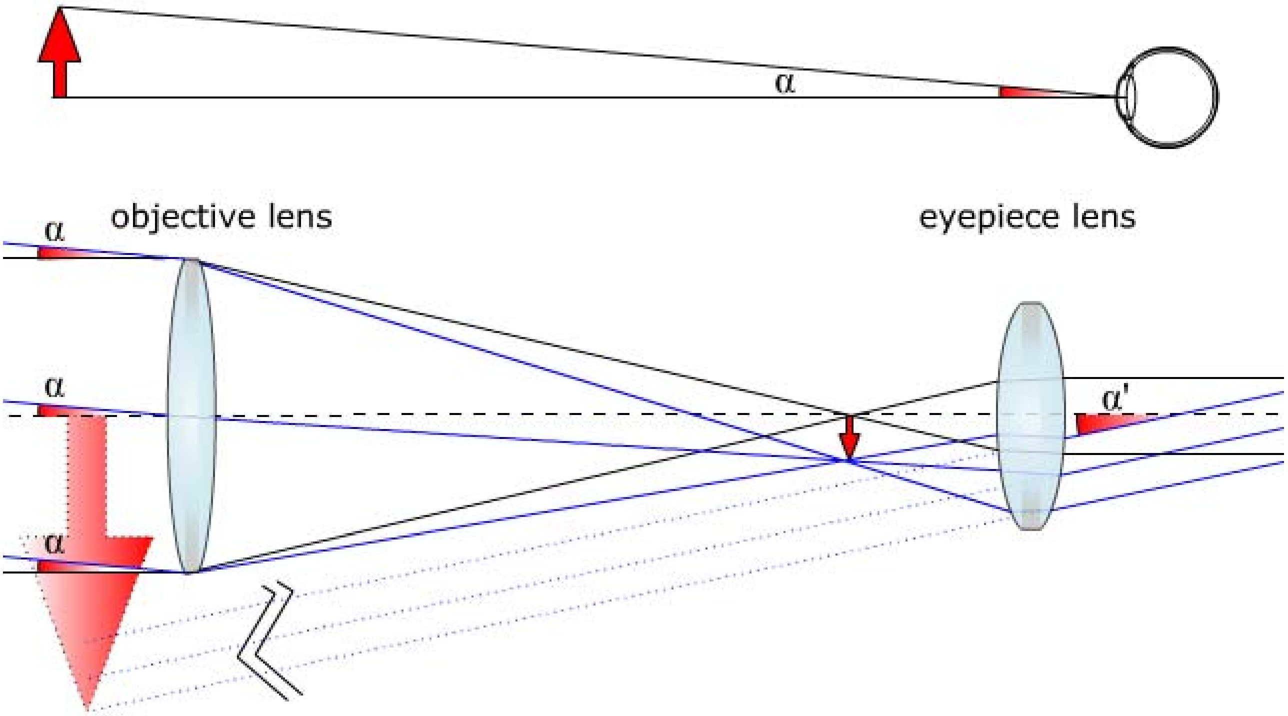


Fig.2 Optical diagram of Keplerian telescope

2.3 THE MODERN TELESCOPE

Components

Column
Objective lens
Checker
Lens hood
Balance weight
Zenith prism
Straight ascension axis
Declination axis
Eyepiece
Cradle
Tube
Focuser
Latitude adjustment

2.4 TEST

You can accede to the complete version of the test from the Resources section of the site "Galileo's microscope". Open the PDF file or download the RTF file. Good luck!

3 SIMULATION

3.1.1 THE HEIGHT OF THE MOUNTAINS ON THE MOON

Starting in autumn of 1609 Galileo (1564-1642) conducted observations of the Moon, of which he made some drawings of striking impact.

In open contrast to the Aristotelian tradition, which held that the celestial bodies are perfectly smooth and spherical, the surface of the Moon, observed through the telescope, showed cavities and prominences. Galileo had also noted the presence of small luminous zones in the dark part of the lunar disc in proximity to the terminator, the line of separation between the lighted part and the one in shadow. As dawn broke over the lunar surface, the luminous spots melded with the illuminated zone. Galileo correctly attributed this phenomenon to the presence of mountains, whose high peaks are touched by the sun's rays before the terrain below them, exactly as happens on the Earth when, at dawn, the mountain tops are already lit by the rays of the Sun while the valleys are still shrouded in darkness. With a simple but ingenious method, Galileo was able to calculate the height of the mountains on the moon. He estimated the distance of a mountain from the terminator as about one twentieth of the apparent diameter of the Moon. Then dividing by 20 the length of the true lunar diameter, known since antiquity, he obtained the length of the segment FA. By applying Pythagoras' theory to the right triangle GAF, he found the hypotenuse FG. It represented the distance of the top of the mountain from the centre of the Moon. By subtracting from this the radius of the Moon, he obtained the height of the mountain.

3.1.2 THE SATELLITES OF JUPITER

On the night of January 7, 1609, while observing Jupiter with his telescope, Galileo (1564-1642) noticed in the vicinity of the planet three "small but very bright" stars. On the next evening he found the little stars occupying a different position in respect to Jupiter, as if the planet have moved eastward, but since in those days, according to the astronomical tables, the planet should have been retrograde and thus moving to the west, he decided to observe the phenomenon systematically. On the 10th, Galileo understood that the positions observed could be explained only by admitting that the three little stars were moving around the planet. Then on the night of the 13th he discovered a fourth celestial body orbiting around Jupiter. The discovery constituted an argument in favour of the Copernican system, or rather, it eliminated what had by some been considered an anomaly, a jarring note in the elegant heliocentric architecture. If in fact, for Copernicus (1473-1543), the Sun was the new centre around which the planets moved, then why should the Earth alone have a satellite, the Moon, orbiting around it? The satellites of Jupiter demonstrated, on the contrary, that other planets too can have celestial bodies orbiting around them and thus be, in turn, the centre of astral motions.

3.1.2.1 MICROMETER

After discovering Jupiter's moons, Galileo (1564-1642) tracked their movements for several days. To measure with precision the distance of each satellite from the planet, Galileo designed a device known as a micrometer.

Giovanni Alfonso Borelli (1608-1679) described the micrometer as a rule with twenty equal divisions. The device was fitted on the telescope and could slide along the body tube.

Galileo observed Jupiter's system through the telescope with one eye, while his other eye watched the micrometer lit by a lantern. He then set the micrometer distance so as to make the interval between two divisions of the graduated scale coincide with the planet's apparent diameter.

This procedure enabled Galileo to superpose the telescope's field of view on the micrometer. He could thus determine the distance of each satellite from the planet, with the radius of Jupiter as the unit of measurement.

3.1.2.2 JOVILABE

In January 1610, while exploring the heavens with his telescope, Galileo (1564-1642) discovered four small star-like objects around Jupiter. Having soon concluded that these were the planet's satellites or moons, he sought to establish their orbits and periods.

The velocities of orbital motion decrease from the innermost to the outermost moon. All four display almost the same brightness. It was difficult, therefore, to work out which was which and calculate how long they took to complete their orbits around the planet.

To determine the positions of the moons without having to perform complex calculations each time, Galileo developed a diagram—a sort of analog calculator—called the Jovilabe. The design shows Jupiter and the orbits of the four moons to scale. The orbits are placed in a grid of parallel vertical lines spaced at intervals equal to the radius of Jupiter.

While making his telescopic observations, Galileo would estimate the apparent distance of a moon from the planet in units equal to Jupiter's radius. The intersection between the vertical line corresponding to this distance and the circle representing the moon's orbit gave its position instantly. By means of a thread, one could read the value on the marked scale drawn in the margin.

However, the moons' observed positions vary with the relative positions of Jupiter and the Earth in the course of their revolutions around the Sun. For example, the timing of a moon's passage in front of Jupiter, as seen from the Earth, differs from the timing of the same phenomenon if it were observed from the Sun. The time difference depends on the Earth-Jupiter-Sun angle, known as the annual parallax.

To cancel this continuously variable effect, Galileo recorded the motion of the moons relative not to the Earth, but to the Sun. To avoid complicated calculations, he developed a second diagram consisting of a representation, to scale, of the orbits of Jupiter and the Earth around the Sun. Jupiter is assumed to be immobile at the moment of the observation. The diagram features a graduated scale giving the Earth's position relative to Jupiter. The parallax value could be read instantly on another graduated scale.

The two diagrams were combined into a single instrument, known as the Jovilabe. Jupiter's position at the moment of observation was computed by means of a rotating disk. A moving pointer, fixed with an arm to the instrument's plate, served to determine the Earth's position at that same moment. The arm thus represents the Earth-Jupiter link, i.e., the observer's continually changing line of sight. The parallax value for any position of the Earth relative to Jupiter could be read directly on a scale on the upper rim of the instrument.

3.1.2.3 CELATONE

To use Jupiter's moons as a clock for determining longitude at sea, observing them through a telescope on the deck of a continuously moving ship, Galileo (1564-1642) designed a device that he called *celatone* (from *celata*, a type of helmet called a "sallet" in English). It consisted of a metal helmet with a visor carrying a small telescope. The visor was hinged to the side of the helmet and could be adjusted to align the axis of the telescope with the eye of the observer. The wearer could thus continuously adjust the aim to the ship's pitch and roll, and the planet would always remain within the telescope's field of view. Galileo later came up with a different solution. He imagined a hemispheric vessel in which the sailor assigned to the observation would be seated. The vessel floated on oil in a tub that was also shaped like a hemisphere. Its diameter was only slightly larger, so as to minimize the quantity of oil required. Like gimbals, the oil bath would have neutralized the ship's oscillations, keeping the observer in a stable position.

3.1.3 THE PHASES OF VENUS

In a letter to Giuliano de' Medici (1574-1636), Tuscan ambassador to Prague, dated December 11, 1610, Galileo (1564-1642) made the announcement of a sensational astronomical discovery by means of a complex anagram that Kepler (1571-1630) tried in vain to decipher. The enigma was then revealed in another letter to Giuliano de' Medici dated January 1, 1611: the mother of Love, that is, Venus, imitates the configurations of Cynthia, that is, the Moon. In other words, the planet Venus, exactly like the Moon, presented phases.

This discovery held great cosmological implications. In the Ptolemaic system, in fact, each planet moved in a circle, the epicycle, whose centre rotated in a larger circle, called deferent, around the Earth, immobile at the centre of the universe. To explain the fact that Venus and Mercury never moved beyond a certain angular distance from the Sun, the Ptolemaic model held that the centre of the epicycle had a period of one year and was always centred on the Sun. The two planets were thus perennially found below the solar orb and consequently would have been obliged to show the phenomenon of the phases without every exceeding a narrow sickle.

In the Copernican system instead, the Sun is immobile at the centre of the universe, while all of the planets, Earth included, rotate around it. The orbits of Venus and Mercury are thus found within the Earth's orbit. For this reason, they should show the entire range of phases, which is what Galileo managed to observe for the first time.

The discovery of the phases of Venus reinforced Galileo's conviction of the truth of the Copernican system.

3.1.4 SATURN'S SYSTEM

In 1610, Galileo (1564-1642) observed Saturn with his telescope and found it to be "triple-bodied," i.e., composed of a central body flanked by two smaller lumps. About two years later, however, Saturn appeared to be "solitary"; in 1616, Galileo again observed the presence of the planet's two companions, which seemed much changed from the first time he saw them.

In the following decades, many authoritative observers described Saturn in sharply differing ways. It was only in 1659 that Christiaan Huygens (1629-1695) formed the hypothesis that the planet was surrounded by a ring that always remained parallel to its equator. Huygens' theory was challenged by the Jesuit Honoré Fabri (1607-1688), who claimed that Saturn was accompanied by four satellites, two dark and two light. The satellites would have moved in pairs, on orbits situated beyond Saturn, and their shifting combinations would have produced the observed appearances.

In summer 1660, the Accademia del Cimento, invited by Prince Leopold (1617-1675) to settle the dispute, built a small model of Saturn that was observed from about 75 meters away with two telescopes of differing strength and quality. The test showed that Saturn could indeed appear "triple-bodied": when the ring was slanted at certain angles, the sections furthest from the planet could still be seen, while the closest sections grew thin, and — when observed with a telescope of insufficient strength — would disappear altogether.

3.1.5 SUNSPOTS

Observed through the telescope, the surface of the Sun shows dark spots, due – as we know today – to intense magnetic fields that block the convective movement of the underlying layers. These areas, receiving a lesser quantity of energy, have a lower temperature and thus appear darker.

Thomas Harriot (1560-1621) was the first to observe this phenomenon, which was divulged in a publication by Johann Fabricius (1587-c. 1615) in 1611.

Galileo (1564-1642) had a heated argument on the nature of sunspots with the Jesuit priest Christoph Scheiner (1573-1650), who, in 1612, under the pseudonym of *Apelles hidden behind his painting*, had published three letters on the subject. To salvage the Aristotelian dogma of the immutability of the celestial bodies, Scheiner had hypothesised the existence of clusters of small planets orbiting around the Sun, which, interposed between the latter and the Earth, appeared as dark spots against the background of the solar disc. Galileo sustained instead that the phenomenon took place on the surface of the Sun or in its immediate vicinity, attributing the motion of the sunspots from east to west to the rotation of the Sun in a period of about one month. To back up this hypothesis, he adduced numerous observational proofs. The spots in fact showed no periodicity, appearing and dissolving continuously, even in proximity to the centre of the solar disk, assuming irregular shapes that changed from day to day. Furthermore, the movement of a planet orbiting at a great distance from the Sun would have proceeded against this background at a practically constant speed. Galileo had observed, on the contrary, a gradual slowing of the spots as they approached the edge of the Sun, in perfect compliance with the hypothesis that they were contiguous to its surface.

3.1.5.1 THE HELIOSCOPE

Some of the pioneers of telescopic observation made systematic observations of the Sun directly through the telescope without any protection, thus damaging their eyesight, often irreversibly.

Galileo (1564-1642) adopted instead a method devised by his pupil Benedetto Castelli (1577/8-1643), which consisted of projecting the image of the Sun through the telescope onto a sheet of paper placed about one meter from the eyepiece. To augment the contrast of the image, it is advisable to darken the room or at least to apply to the telescope tube a large cardboard shield that attenuates the light coming directly from the Sun. With this method, effective and perfectly safe, it was possible to draw the sunspots with great precision directly on the sheet of paper. For this purpose Galileo first traced a circle on the sheet, which he placed at a distance from the telescope's eyepiece where the dimensions of the image of the solar border exactly matched those of the circle previously drawn. The image thus obtained is however a mirror image; to obtain a correct representation of the solar disc, the sheet had to be placed frontally, turned over vertically and then rubbed or traced against the light onto another sheet.

The projection method, which was to be widely used later, was adopted also by Christoph Scheiner (1573-1650), who substantially improved the apparatus by providing it with a plane of rest for the sheet of paper integral with the telescope and, above all, by introducing a new type of mount, known today as the equatorial mounting, which allowed the Sun, once it had been centred in the instrument's field, to be followed in its daily motion by moving a single axis.

3.1.6 THE STARS AND THE MILKY WAY

By means of the telescope Galileo (1564-1642) discovered the existence of a quantity of stars much greater than those observable to the naked eye. In his *Sidereus Nuncius* [The Starry Messenger] he included two engravings: one of the zone of Orion's belt and sword, which, in addition to the stars already known, showed 80 new ones; the other of the Pleiades, with 30 stars invisible to the naked eye.

For centuries philosophers had hotly debated the true nature of the Milky Way, which Galileo revealed with the force of "reasoned experimentation". Thanks to the telescope, in fact, he demonstrated that it is a mass of innumerable stars, which cannot be individually distinguished by the naked eye.

3.2 THE PERFORMANCE OF THE TELESCOPE

The most characteristic element of a telescope is its aperture, that is, the effective diameter of the objective, which determines its power and performance. On the aperture, in fact, depend both the brightness of the faintest stars that can be detected by the telescope, the so-called **limit magnitude**, and the **resolving power**, that is, the size of the smallest details that can be discerned through the instrument. If a telescope's magnification is forced beyond the limits imposed by its aperture, details smaller in size than its resolving power cannot be discerned, and the images appear dark and blurred.

MAGNIFICATION

In a telescope, the magnification — given by the numerical relationship between the focal length of the objective and that of the eyepiece — can be augmented to very high values by adopting objectives of great focal length combined with eyepieces of very short focal length (modern eyepieces are interchangeable and have focal lengths as short as 4 mm). However, exasperating the magnification beyond a certain limit only causes deterioration in the quality of the images. With the same aperture, refracting telescopes can support higher maximum magnifications than reflectors, which, normally having the primary mirror partially obstructed by the secondary, have an effective aperture lower than the theoretical value. The maximum effective magnification generally adopted, for apertures ranging from 6 to 100 cm, is $I = 100\sqrt{(D - 3)}$ for refractors, and $I = 70\sqrt{(D - 1)}$ for reflectors, where D is the aperture expressed in centimeters.

Conversely there exists, for a given aperture, a minimum magnification, the so-called **resolving magnification**, below which it is impossible to distinguish all of the potentially visible details. This magnification — which depends basically on the resolving power of the eye, which differs from one individual to another and according to the lighting conditions, contrast, etc. — can be considered equal to half of the aperture expressed in millimeters.

THE LIMIT MAGNITUDINE

The objective serves as collector of light. The larger its size, the more light it can receive and convey toward the focal point, enabling it to detect the fainter stars. The quantity of light intercepted by the objective is proportional to its surface, and thus to the square of the aperture. For example, an objective with a diameter of 10 cm receives four times the amount of light of an objective of 5 cm, which, in turn, receives about 50 times more light then the human eye, whose pupil, in the darkness, has a diameter of around 7 mm. This means that, if with the naked eye stars up to the 6th magnitude can be observed (the brightness of stars is measured in magnitudes, on a scale in which the higher the number, the lesser the brightness), with a telescope having an aperture of 5 cm, stars up to the magnitude of 10.3 can be seen, and with a telescope of 10 cm, up to the magnitude of 11.8 con.

RESOLVING POWER

The resolving power (or separator) of a telescope can be defined as the minimum angular distance that must exist between two stars for them to be distinguishable as distinct celestial bodies, with a very narrow dark gap still perceptible between them. Its value is given by the formula Pr = 12 / D, where Pr is the resolving power expressed in seconds of an arc and D is the aperture expressed in centimetres. An objective with aperture of 15 cm, for instance, can separate two stars that have an angular distance of 0".8 (= 12 / 15). If we observe through it two stars having an apparent distance less than this value, regardless of how much the magnification is augmented, they will appear as a single body, which may appear oblong or in the shape of an 8 (an expedient employed to identify twin stars whose separation is less than the resolving power of the instrument adopted).