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A HISTORY OF ASTRONOMICAL OPTICS IN FRANCE

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Abstract: In this paper, we explore the advances made in France in astronomical optics. They were quite important in the seventeenth century thanks to Mersenne, Auzout and Picard. Progress in the eighteenth century was less remarkable and many instruments had to be imported from England, but in the following century the developments were again significant thanks in particular to Arago, Foucault, Fizeau, Lœwy and the Henry brothers, working with very competent instrument builders. The French school of optics flourished at the end of the nineteenth century and during the twentieth century, thanks to Fabry, his collaborators and successors, as illustrated by Perot, Chrétien, Lyot, Danjon, Paul, Couder, Courtès, Connes, Labeyrie, Baranne and Lemaitre, among others. However, from time to time there was a trend to build instruments that were too original and with little or no future, at the expense of more conventional but better-adapted instruments.

Keywords: adaptive optics, Cassegrain telescope, cœlostat, coronagraph, coudé equatorial, Danjon astrolabe, instruments for astrometry, interferometer, Lyot's polarizing filter, photometer, polarimeter, quadrant, Richey-Crétien telescope, siderostat, speckle interferometry, spectrometer

This paper is dedicated to the memory of the great optician André Baranne (1931–2021).

1 INSTRUMENTS FOR ASTROMETRY, 1610-1800

The announcement in 1610 of Galileo's discoveries with his new telescope spread rapidly within Europe. As early as May 1610, Nicolas Fabri de Peiresc (1580–1637) was informed in Aix-en-Provence, by a letter from Italy, that "Galileo, with a recently invented telescope, had discovered great things in the sky." (Georgelin and Arzano, 1997: 161; our translation). He managed to obtain several such telescopes, and observed the satellites of Jupiter for the first time on 24 November 1610, determining their period of revolution with remarkable accuracy. He discovered the Great Orion Nebula on 26 November of the same year, and the Præsepe star cluster on 15 January 1611. With a similar telescope, Pierre Gassendi (1592–1655) observed the transit of Mercury on 7 November 1631 from Paris. Between 24 September and 7 November 1636, Peiresc and Gassendi observed the Moon from the summit of Montagne Sainte-Victoire near Aix-en-Provence (the one so often painted by Cézanne), with telescopes offered by Galileo and Hevelius respectively. They took with them the famous engraver Claude Mellan (1598–1688): this resulted in the first engravings of the Moon, better than those made by Hevelius for his 1647 *Selenographia*. They discovered the libration of the Moon during these observations.

These are amongst the most remarkable observations that mark the first use of refracting telescopes in France (for details and references, see Georgelin and Arzano, 2002). All these telescopes were certainly of Galileo's type, with a single-lens diverging eyepiece. However, Kepler's type telescopes with a converging eyepiece were just appearing elsewhere: the earliest written mention of such an optical combination dates from 1616, but it was only introduced as an observational instrument around 1640 (del Santo, 2021).

When the Keplerian telescope appeared in France is not known. However, the crossed wires and the micrometers of William Gascoigne (1612–1644) and of Adrien Auzout (1622–1691) obviously required this optical combination, because they have to be placed on a real image. A paper by Auzout describes his movable-thread micrometer (Figure 1); it was actually written in 1665 but published only in 1729 (Auzout, 1666), and the text says that the micrometer was invented "… long ago" (our English translation).

New instruments (Figures 2 and 3) were described in detail in Picard's *Mesure de la Terre*, a part of a magnificent and very rare book published in 1671 (but without the author's name) under the auspices of the French Academy of Sciences. Because of this rarity, it was reproduced in the *Mémoires de l'Académie*

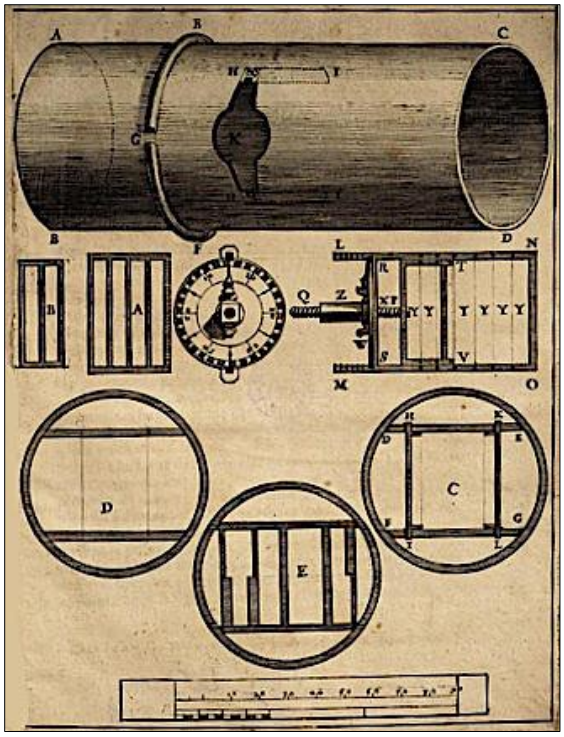


Figure 1: Auzout's micrometer, before 1665 (Wikimedia Commons).

Royale des Sciences (Picard, 1671). These instruments represent a considerable progress and have certainly influenced English instrument-makers. Wolf (1902) gives a detailed account of the instruments and their builders at Paris Observatory from its foundation in 1667 to 1693. More information can be found in Le Monnier (1791).

Mobile quadrants, sextants, octants and zenith sectors were used during a century for positional astronomy and geodesy with no major changes. The first 'modern' instruments were two quadrants constructed around 1670 for La Hire and Picard by Gosselin, an armourer who produced also scientific instruments with the help of Philippe Lebas (ca. 1637–1677) and Pierre Sevin (ca. 1638–1686) (Wolf, 1902: 137). Many more were built later, especially by Jean Chapotot (active from 1670 to 1700) and his son until 1721. One of their quadrants is preserved in Strasbourg and several in Beijing, where they were brought by Jesuits. A list of quadrants is given by Turner (2002: 378). There are no less than 6 mobile quadrants in the collections of Paris Observatory: four by Claude Langlois (1690–1756), dated 1730, 1730, 1746 and 1757, an English one by John Bird (1709–1776) dated 1775 and one by Pierre Mégnié (1751–1807) dated 1784; these last two have an azimuth circle. Langlois was arguably the first specialized instrument-maker in France. A beautiful large sextant by him (Figure 4) was used by La Caille for building up his stellar catalogues at the Cape of Good Hope and in Paris (Glass, 2013). The r.m.s. internal errors in right ascension and declination of La Caille's fundamental catalogue compiled using this instrument are 4–5″, comparable to those of the best other measurements of the time (Lequeux, 2014: 2–4).

Le Monnier (1791: LXXV) describes "… a new instrument consisting in a telescope movable around an horizontal axis …" (our translation), a meridian (or transit) telescope. Ap-

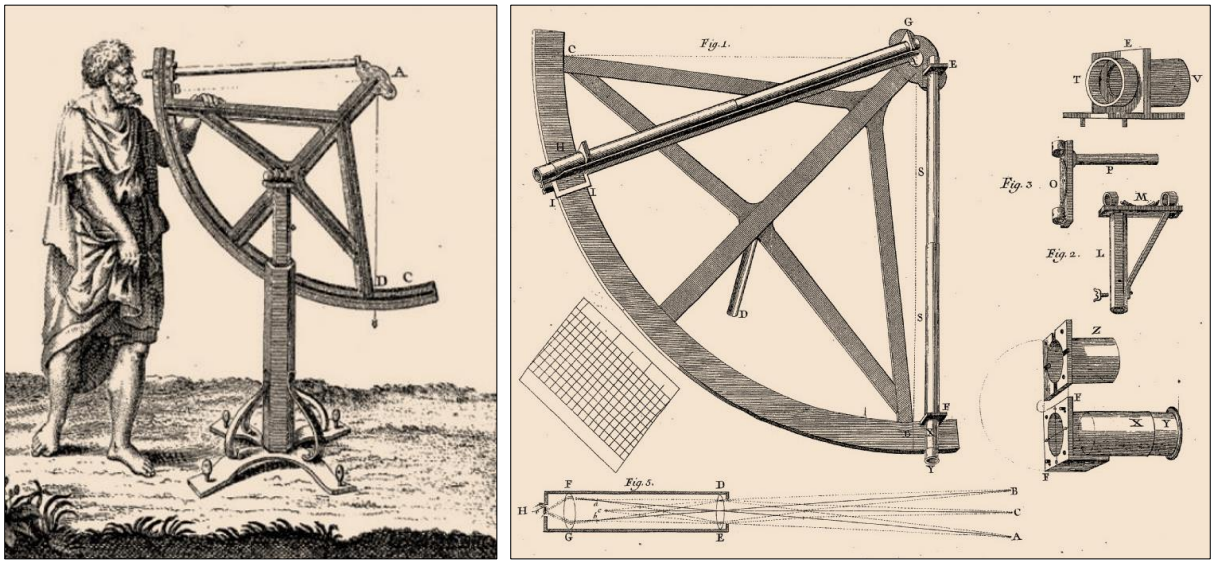


Figure 2: Picard's quadrant (ca. 1666). Right: a quadrant for geodesy, used in horizontal position. It is equipped with two telescopes, EF being fixed on the quadrant and GH mobile so that the angle between the two is read on the circle transversal graduations, represented at the bottom left, which gave the minute of degree. The optical design of the telescope is represented, as well as various parts of the eyepiece and supports on the right. Left: a quadrant for measuring heights, equipped with a plumb line (courtesy: Paris Observatory).

parently it was invented in London by George Graham (1673–1751), probably inspired by Rømer's instruments. The first one in France was acquired and described by Le Monnier; it was very probably built by Graham in 1735. In 1760, La Caille acquired one constructed by John Dollond (1706–1761), with an achromatic objective (Glass, 2013: 135; see for a description Lalande, 1792, t. 2, part 2: 615 and plate XXIII). This is one of the very first instruments in France benefitting from an achromatic lens. It is lost but two similar, later ones are in the collections of Paris Observatory (Figure 5). They were used for transit observations either in the meridian plane, or in the first vertical plane, perpendicular to the meridian.

In 1683, La Hire had a mural quadrant installed at Paris Observatory, derived like the mobile quadrants from Tycho Brahe's instruments (Le Monnier, 1791: XLII–XLIX). Picard

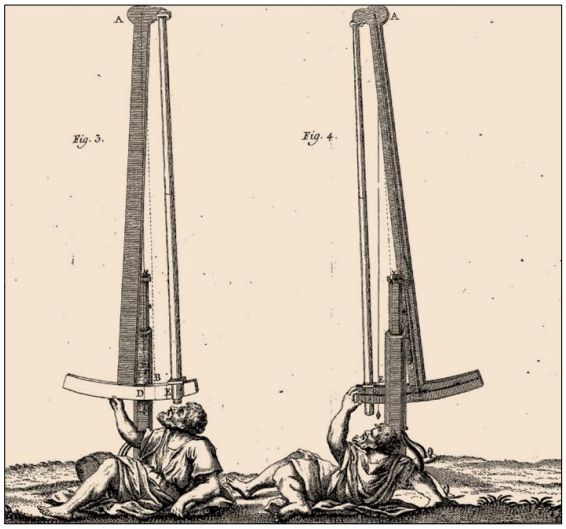


Figure 3: Picard's zenith sector. It was used for determining latitudes (courtesy: Paris Observatory).

had another one, 5 pieds[1] in radius, installed the same year and in operation until 1719 (Wolf, 1902: 139). These fixed instruments were supposed to be more accurate than the mobile ones to measure the time of meridian crossing of the Sun, stars or planets. A new large mural quadrant, 6 pieds in radius, was installed by Langlois in 1732 at Paris Observatory, as well as a smaller one in 1738 for observations to the north of zenith (Wolf, 1902: 176–177). The Duc de Chaulnes (1714–1769), a competent amateur, had constructed in 1765 a small but very accurate astronomical half-circle that was not much used because of its complexity; it had the particularity to have two telescopes with achromatic objectives built by another amateur, Charles François Gouverneur l'Estangt (ca. 1720–1800). They are probably the first achromatic objectives made in France



Figure 4: La Caille's sextant by Langlois, dated 1750. Its radius is 1.9 m. It has two orthogonal telescopes, used according to the elevation of the target. The plumb line is protected by a square tube (courtesy: Paris Observatory).

for an astrometry instrument (Wolf, 1902: 181). All these instruments have disappeared.



Figure 5: A movable transit instrument dated 1774, and built in Paris by Louis Pierre Florimont Lennel (1743–1781). It was used at Toulouse Observatory and sent to Paris in 1883 for the museum created by Admiral Mouchez. Note the large bubble level under the axis (courtesy: Paris Observatory).

Two novel instruments were constructed for the Paris Observatory at the end of the seventeenth century: an alt-azimuthal circle and an equatorial (Wolf, 1902: 147–149). The first one was built by the surveyor Migon in 1678: it had two circles, one horizontal and the other vertical, and could be turned so that the vertical axis became a polar axis. Grant's (1852; 465) claim, repeated in King (1955: 106), that "Roemer was the first person who constructed an altitude and azimuth circle …" is thus wrong. Rømer, who was in Paris at the



Figure 6: Amongst various astronomical instruments, the Huygens-Thuret clock is depicted in the bas-reliefs by Francesco Temporiti (1634–1674) that since 1670 decorate the south façade of Paris Observatory and feature various astronomical instruments (courtesy: Paris Observatory, J.-M. Kollar).

time, was certainly aware of this instrument and decided to have a similar one made around 1690 (see Horrebow, 1735: Plate II). However, the vertical axis could not be turned in Rømer's instrument.

The other instrument was a very advanced equatorial mount built by Claude Couplet (1642–1722)

> … similar to that I [Cassini] used in Italy for observing eclipses and the difference of the right ascensions of celestial bodies close to the same parallel. (Wolf, 1902: 47; our translation).

It had a clock mechanism acting on the polar axis to follow the target in its diurnal motion, and a binocular telescope could be adapted to it. The invention of the driving clock mechanism for equatorials is generally attributed to Passemant (1702–1769), but this is clearly wrong as the mechanism for this equatorial is considerably earlier. Rømer was probably inspired by Cassini's equatorial for the one he installed in Denmark in 1690, which however had no clock drive (see the figure in King, 1955: 105, from Horrebow, 1735: Plate I). The famous Flamsteed equatorial sextant of 1677 was probably less perfect and more difficult to use than Cassini's equatorial. Unfortunately, all of these instruments have disappeared, and there are no pictures of the French ones.

Amongst the instruments for astrometry, we should not forget the 'méridiennes', although they do not involve any optics. The large one of the Observatory was finished in 1729. Another famous one was completed in 1748 and installed in the Saint-Sulpice Church in Paris. There is a third large méridienne in France, installed in 1747 in the Saint-Étienne Cathedral of Bourges, and several smaller ones, in particular in Notre-Dame Cathedral and Saint-Eustache Church in Paris. These all consisted of a north-south line on which the image of the Sun was projected through a small hole to the south: from it, the time of the true noon and the elevation of the Sun at noon could be determined. Later, a lens was installed in some of these instruments in place of the hole

Astrometry also required clocks (often set from these méridiennes or smaller gnomons). The first good astronomical clock was invented by Christiaan Huygens (1629–1695) and is first described in his *Horologium* of 1658 and later in more detail in his *Horologium Oscillatorium* of 1673, published in Paris (see Huygens, 1934: 27). Huygens was in Paris from 1666 to 1681 and several astronomical clocks were built as early as 1667 by Isaac Thuret (ca. 1630–1706) according to his principles, and were probably the first accurate ones in the world. This improvement was considered so important that a Huygens-Thuret clock is depicted in one of the two bas-reliefs that decorate the south façade of the Observatory (see Figure 6).

Isaac Thuret was the only astronomical clock-maker who worked for Paris Observatory during the end of the seventeenth century. He was followed in France by his son Jacques (1669–1738) and by other clock-makers who flourished during the following century, in

particular Julien Le Roy (1686–1759) and Ferdinand Berthoud (1727–1807).[2]

2 REFRACTING TELESCOPES, 1610–1800

Aside from the small telescopes used in the instruments for astrometry, larger ones were required for other observations. The construction of such telescopes encountered a major difficulty: chromatic and spherical aberrations of the single lenses used as objectives could only be sufficiently reduced if the focal lengths were extremely large. There are 25 seventeenth-century lenses preserved at Paris Observatory. The larger ones (>13 cm in diameter) have an average focal ratio f/117, while the smaller ones are on average f/81. The largest of the set, 26 cm in diameter, has a focal length of 50 m. One of these lenses, with a focal ratio f/80, bears the signature of Giuseppe Campani and is dated 1672 (Figure 7): it was thus purchased by Cassini after his arrival in Paris, as were many others.

Indeed, several lenses were sent to Paris from Rome by Giuseppe Campani (1635–1715) and Eustachio Divini (1610–1685), sometimes inserted in a telescope tube (see Wolf, 1902: 156–159). But, as these lenses were very expensive, some people started producing them in France, in particular Auzout, Jacques Borelly (?–1689), Philippe Lebas (1637–1677) and Nicolaas Hartsœker (1656–1725), a Dutch optician who had come to Paris, accompanying Huygens; he stayed there in 1678, and again from 1684 to 1696. The glass came generally from French factories in Nevers, Orléans and Paris, where the secrets of the glassmakers of Murano in Italy were known (Véron, 2009: Chapter 3). The optical quality of several lenses has been checked at various epochs and is in general satisfactory, but the Italian lenses have always been considered superior to the French ones.

The long focal ratio of these lenses made observation very difficult. Figure 8 shows what was done in Paris at the time of Cassini: when the focal length was not too large, conventional telescopes with a tube could be used, but they were not easy to handle. Lenses with larger focal lengths were placed on the edge of the terrace or on a wooden tower, and the observer standing on the ground had to find the object through the lens, and then to track it by moving. Cassini describes how he achieved this feat (Wolf, 1902: 164–167), but his successors were not as good and the long-focus lenses were abandoned at the beginning of the eighteenth century. Consequently, the fainter satellites of Saturn discovered by Cassini with his long telescopes were not seen again for several decades.

Several tricks were invented to bypass the difficulties with these giant telescopes (King, 1955: 60). A man named Boffat, in Toulouse, proposed a polar siderostat, with the telescope fixed and parallel to the polar axis and a plane movable mirror reflecting the light to the objective (Boffat, 1682: 339–341). Claude Perrault (1613–1688), the architect of Paris Observatory, proposed a horizontal siderostat (Perrault, 1735; Figure 9). However, as indeed feared by Perrault, it was not possible to produce a plane mirror with sufficiently good optical quality, and no siderostat was constructed. We had to wait for Léon Foucault to successfully build such a device.

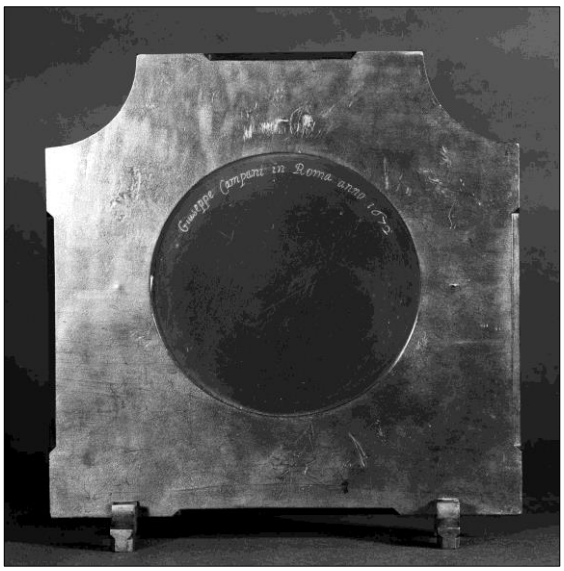


Figure 7: A 13.7 cm diameter lens signed by Campani. Its focal length is 11 m. Cassini discovered Rhea, a satellite of Saturn, with a telescope equipped with this lens (courtesy: Paris Observatory).

Nothing of real importance in French refracting telescope design is to be mentioned after the abandonment of the long telescopes. Smaller refracting telescopes with simple, not achromatic lenses, were used for observing the satellites of Jupiter, comets, etc., in the many amateur observatories that flourished in France in the eighteenth century. Huygens' two-lens eyepiece (King, 1955: 54), introduced in France in the 1660s (van Helden, 1977), was sometimes used but not always, in spite of its larger field and achromatic property (Lalande, 1792, t. 2 part 2: 573).

An interesting invention with a long future is the heliometer, due to Pierre Bouguer (1698–1758) in 1748 but also attributed by Short to the Englishman Servington Savery. A controversy followed (Delisle and Folkes, 1983). Whatever its origin, this instrument, initially conceived to measure the diameter of the Sun,

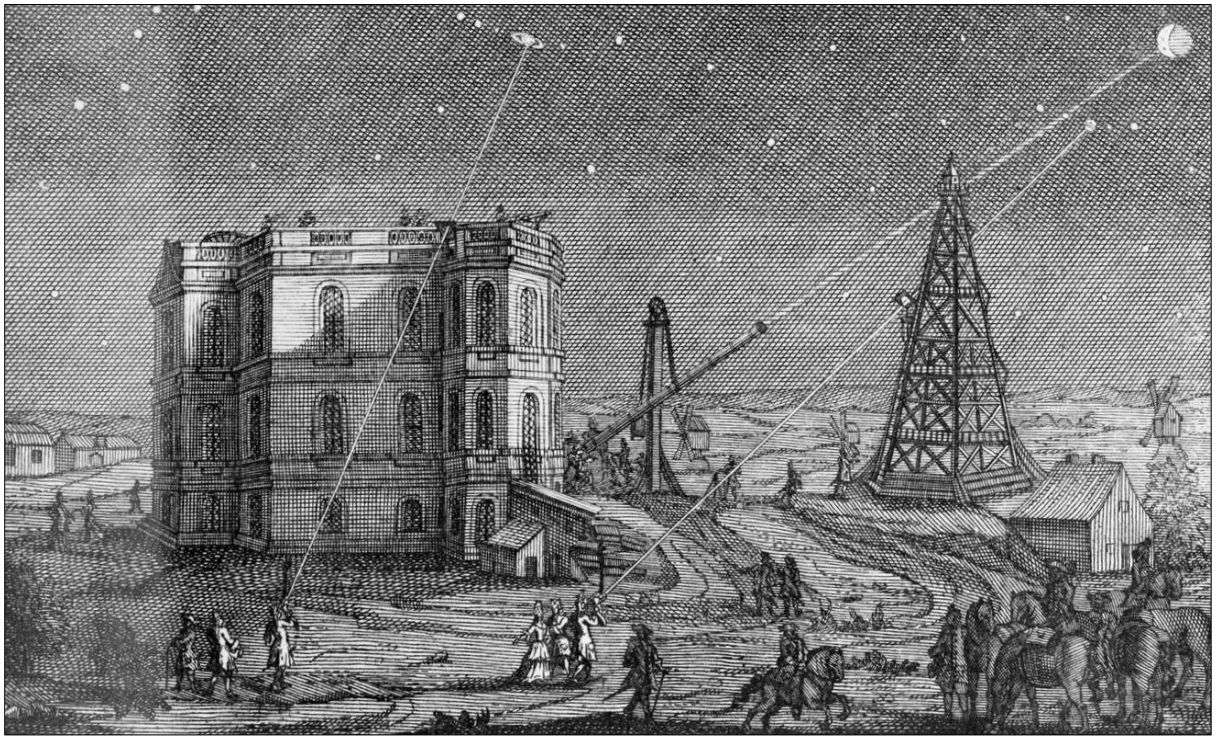


Figure 8: Three ways of observing at the Paris Observatory, engraving by Thomassin in Jacques Cassini (1691; Aij). The west side of the Observatory is shown. A long telescope is used to observe the Moon, and lenses are placed on the edge of the terrace and on the wooden 'Marly tower'. Satellites of Saturn discovered in this way by Jean-Dominique Cassini are symbolized (courtesy: Paris Observatory).

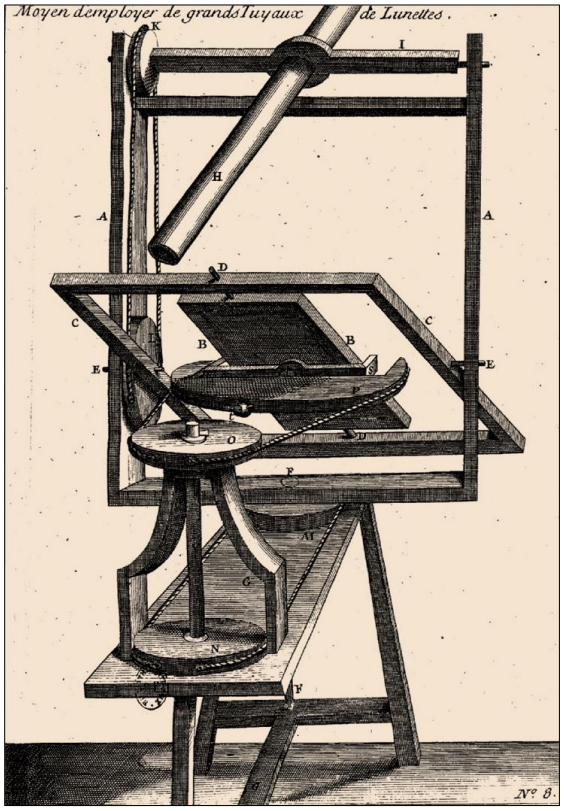


Figure 9: A primitive siderostat invented by Claude Perrault before 1688. The light from the object is reflected to a horizontal, fixed telescope by the rectangular plane mirror BB, whose orientation can be changed by moving the lever H (courtesy: Paris Observatory).

hence its name, was also suited to measure accurately distances between nearby stars. It consists of two half-lenses each giving an image (Figure 10); the separation and position angle of the two images can be measured accurately. It was described for the first time in 1755 by Father Esprit Pézenas (1692–1776), who directed Marseilles Observatory from 1728 to 1763 (Pézenas, 1755: 62–79, 87–136; see also Lalande, 1795: 811–824). Fraunhofer built several heliometers, one of which was used by Bessel to discover the parallax of 61 Cygni in 1838.

In France, achromatic objectives were constructed as early as 1763, by the afore-mentioned Gouverneur l'Estangt, Passemant, Anthéaulme and Raymond-François Bourriot (1734–1796). It was difficult and expensive to obtain, generally from England, good-quality flint glass for the objectives. Flint was also produced in France, but with much difficulty (see Véron, 2009: Chapter VII). This was one of the reasons that led to the construction of achromatic objectives with two crown lenses separated by a liquid: a rather long adventure, but with no future (Véron, 2009: 167–172). There were also various attempts to use rock crystal (natural quartz) to replace flint, but it was even more expensive. And reflecting telescopes were now competing with refractors.

3 REFLECTING TELESCOPES, 1636–1795

The idea of replacing by mirrors the lenses so affected by chromatic aberrations is older than Newton, although he was the first to produce a working reflecting telescope. The first mention can be seen in Volume 1 of the famous book by Father Marin Mersenne (1588–1648), *Harmonie Universelle* (Mersenne, 1636: 61–62). Like many scientists of the time, Mersenne was interested in the properties of conic sections, and produced the drawings represented in Figure 11. He considered that they could find applications for sound and for light, and wrote (our English translation): "One can make excellent telescopes with these two parabolas, which will allow to see quite distinctly very remote objects." However, he did not mention the need for an eyepiece.[3]

Mersenne was at the center of European science, and it is likely that the Scottish James Gregory (1638–1675) was aware of his writings when he proposed in 1663, in his *Optica Promota*, a reflecting telescope with a concave secondary mirror (and an eyepiece!). However, he does not cite Mersenne. This is also probably the case for the French Laurent Cassegrain (ca. 1629–1693). Although his name is known to all astronomers, it is only recently that André Baranne and Françoise Launay have discovered many facts relevant to his life and work (Baranne and Launay, 1997).

Cassegrain was a priest and teacher in Chartres with a good knowledge of physics. In April 1672 another priest, Claude Estienne, intervened. Estienne (1640–1723) was the Prior of Bercé, a sort of correspondent of the Academy of Sciences in Paris, knew Huygens, and was to build a small meridian line at Chartres Cathedral. Under the sole name of Bercé, Claude Estienne sent from Chartres a letter that was published in the *Recueil de Memoires Concernant les Arts et les Sciences* (here in the *Huitieme Memoire* dated 15 April) published instead of the *Journal des Sçavans* during the interruptions of this publication. In this letter, he described a telescope "… almost similar to that of Newton …", invented at least three months before by Cassegrain (Figure 12).

Newton's telescope had just been described in the 29 February issue of the *Journal des Sçavans*. On 20 May 1672, a translation of a part of Bercé's letter was published in the English *Philosophical Transactions*, accompanied with a harsh criticism by Newton (Newton, 1672), who wrote:

> That design of it … I fear will not answer Expectation. … Mr. Gregory's Optica Promota … being fallen into my hands, where there is an Instrument … like that of Monsieur Cassegrain's with a hole in the midst of the Object-Metal to transmit the Light to an Eye-glass placed behind it … I found their disadvantages so great, that I saw necessary, before I attempted any thing in the Practique, to alter the design of them, and place the Eye glass at the side of the Tube rather than at the middle.



Figure 10: Two heliometers built by Short in 1753 from a design by Dollond, having belonged to Pézenas. Their two half-lenses have a focal length of about 99 m. One is attached to Pézenas' 11-cm diameter English Cassegrain telescope (photograph: M. Marcelin, courtesy Marseilles Observatory).

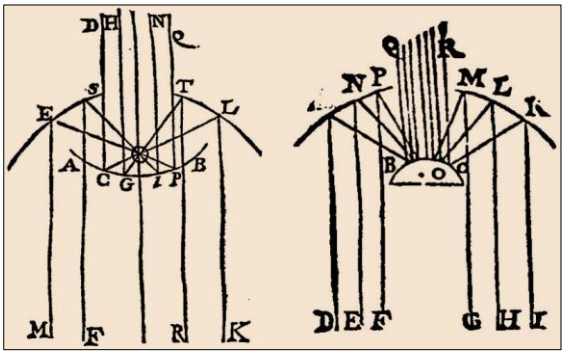


Figure 11: Two drawings in Mersenne's *Harmonie Universelle*. We recognize at left the principle of the Gregorian telescope, and at right that of the Cassegrain one (Lequeux Collection).

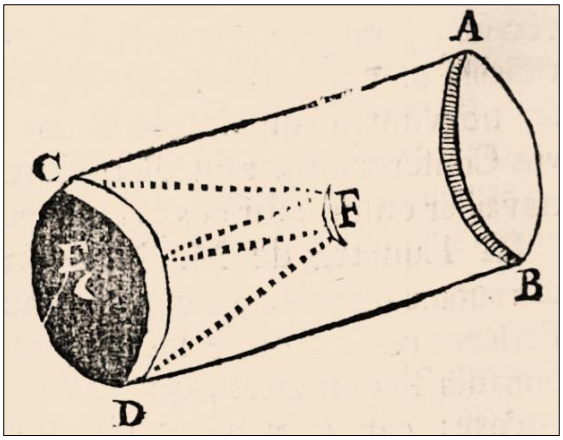


Figure 12: The Cassegrain telescope as represented in *Recueil de Memoires Concernant les Arts et les Sciences* of April 1672 (courtesy: Paris Observatory).

Then he went into detail: his main arguments were the difficulty to produce small convex or concave mirrors, and the fact that Mr Reive, although a skillful artist, did not succeed in producing a good 6-ft (length) Gregorian telescope. And Newton (*ibid.*) concluded:

> I could wish therefore, Mr. Cassegrain had tryed his design before he divulged it: But if, for further satisfaction, he pleases hereafter to try it, I believe the success will inform him, that such projects are of little moment till they be put in practice …

which was justified but not encouraging. And Huygens supported strongly Newton, writing (our translation):

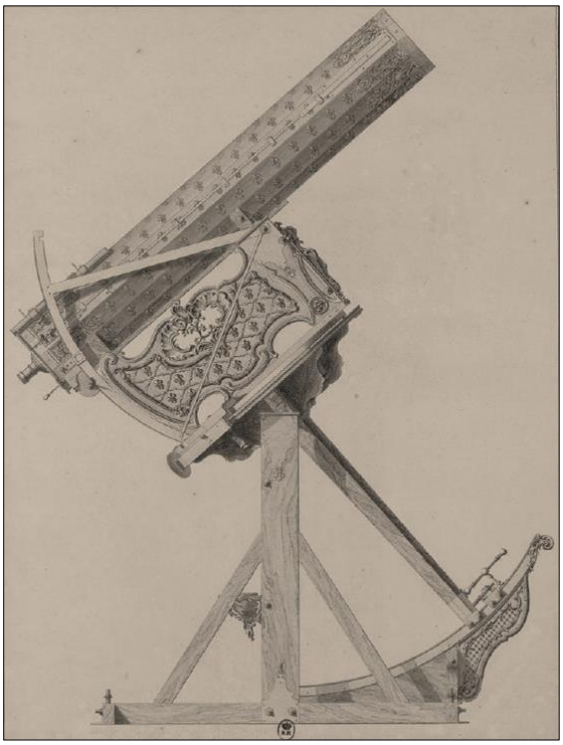


Figure 13: This is not the great 24-pieds Dom Noël's reflecting telescope but a smaller one, 8 pieds long. It is likely that the great telescope was similar, but no image of it exists (courtesy: Bibliothèque Nationale de France).

> Mr. Newton treats him more gently than he deserves in my opinion … because it is a temerity to want to bid on the inventions of others which are proven, by others which are not … (Baranne and Launay,1997: 161).

No wonder that in front of such authorities, the Cassegrain design had no future for half a century. A better reason, however, is that it was more difficult to produce a strongly convex mirror than a concave one, so that the Gregorian design was generally preferred throughout the eighteenth century.

The reflecting telescope was developed in England thanks to Hadley, Molyneux, James Short (1710–1768) and a few others (King, 1955: Chapter V). France was not very active until late in the eighteenth century, but a few Gregorian telescopes were purchased from Short: a 24-cm diameter equatorial built around 1753, bought by Le Monnier and acquired in 1807 from his heirs for 3000 francs (equivalent to about $11,000) by the *Bureau des Longitudes* for Paris Observatory (Lequeux, 2016: 180), and a smaller one for Marseilles. They are still there, and the Parisian one was used until about 1820.

However, there was an ambitious project. In Paris in 1772 Dom Noël (1712–1783) (Launay, 2009), a Benedictine priest who was the curator of King Louis XV's private collection of scientific instruments located in the *Cabinet de Physique de la Muette*, west of the Paris city, finished a large Cassegrain telescope "… double de ceux d'Angleterre …" (twice as large as the English ones; those by Herschel were not yet constructed). This monster (see Figure 13) had a 59 cm diameter speculum mirror with a focal length of 24 *pieds* (8.0 m) and had cost a fortune, 500,000 francs (about $1.6 million) according to Lalande. The mirror was very bad and in about 1788 another one was produced by Noël-Simon Caroché (1744–1813), who transformed the telescope into a Newtonian. Lalande and Méchain tested the new mirror and found it "… as good as those of Herschel …" (Lalande, 1805: 253). This telescope was transported to Paris Observatory and was housed inside the building. The central door on the garden terrace had to be enlarged to roll the telescope outside for observations (one of the few changes made to the historical building), but it was very cumbersome and difficult to use, so it did not produce any significant results. It was only preserved in order to be shown to the public, which had no access to the other instruments, until it was dismantled in 1841 (Lequeux, 2016: 179).

Caroché worked at the Cabinet de la Muette under Abbé Alexis-Marie de Rochon (1741–1817), the successor of Noël, and he produced a few other reflecting telescopes, in particular a large one, 22 pieds long, similar to Herschel's telescopes, i.e. without a secondary mirror.

As the speculum mirrors tarnished rapidly and had to be often resurfaced, platinum—which did not alter—was sometimes used instead, in spite of its very high price. Around 1785 Caroché produced a Gregorian telescope with a platinum primary mirror 20 cm in diameter, weighting about 7 kg, mounted "… according to Herschell's method." Indeed, he was well aware of what Herschel was doing and was even able to pay him a visit in 1787.

After the success of Caroché's platinum mirror, the authorities envisaged constructing a much bigger telescope with a mirror 4 pieds (1.3-m) in diameter, able to rival those in Herschel's telescopes. There were discussions with Spain, which would supply the platinum if the French would agree to make two mirrors, one of them for Madrid. In 1796, 103 kg of platinum from Spain arrived in France, but the telescope would have needed almost a metric ton, so the project was abandoned. The whole story of this aborted project, which took place during troubled times, can be found in Chapin (1972).

While two quadrants by Bird and Jonathan Sisson (1690–1747) had been installed at Paris Observatory, Jean-Dominique Cassini (Cassini IV, 1748–1845), who ran the Observatory from 1784, had plans to train new French builders and to have a workshop at the Observatory approved by the government. But this failed for various reasons, so that Cassini had to order from Jesse Ramsden (1735–1800) a mural circle and a meridian telescope. He had visited Ramsden and Herschel in England and held them in high regard. It is remarkable that this visit and the transactions had taken place at a time when the relations between France and England were very bad. Only the meridian telescope was delivered, in 1803. It had been finished by Matthew Berge (ca. 1753–1819) after the death of Ramsden. It rested on two stone pillars for stability, and the weight on the horizontal axis trunnions was partly compensated by levers. The English meridian telescopes like this one were models for the future French instruments.

4 A NEW ERA, 1795–1900

A big problem at the end of the eighteenth century was that, aside Caroché, there were no good astronomy instrument-makers in France after the death of Langlois in 1756 and of his talented successors Jacques Canivet (1714–1773) and Lennel, deceased in 1781 (Rocca and Launay, 2017). Cassini IV wrote (Cassini, 1810: 4; our English translation):

> From the beginning to the middle of the reign of Louis XV … the Observatory housed mural instruments and large mobile quadrants due to Langlois, Canivet and Lennel, who were the most famous builders of astronomy instruments of the time. But when I took the directorship of the Observatory [in 1784], these old talents were superseded by Bird and Ramsden. These English artists raised their art to perfection, leaving far behind the French, from whom they had taken off almost entirely the commerce of instruments of optics and mathematics."

Still, Cassini was too pessimistic. Several new instrument builders emerged, like Étienne Lenoir (1744–1832) who had produced a mural circle for the Observatory before the 1789 Revolution, Jean-Nicolas Fortin (1750–1831), Noël Jean Lerebours (1761–1840), Robert Aglaé Cauchoix (1776–1845) and Henri Prudence Gambey (1787–1847). Lenoir, Fortin and others built several repeating circles according to guidelines given by Jean Charles de Borda (1733–1799). They were beautiful instruments for geodesy (Figure 14), which were also occasionally used for astronomy.



Figure 14: A repeating circle of Borda, built by Lenoir around 1795, set in the horizontal position for triangulation (left) and in the vertical position for measuring zenith distances and latitudes (right). This is one of the four circles used by Delambre and Méchain, and it was also used by Biot and Arago in Spain. Paris Observatory preserves another circle by Fortin, which was also used by the latter (photographs: M. Marcelin, courtesy Marseilles Observatory).

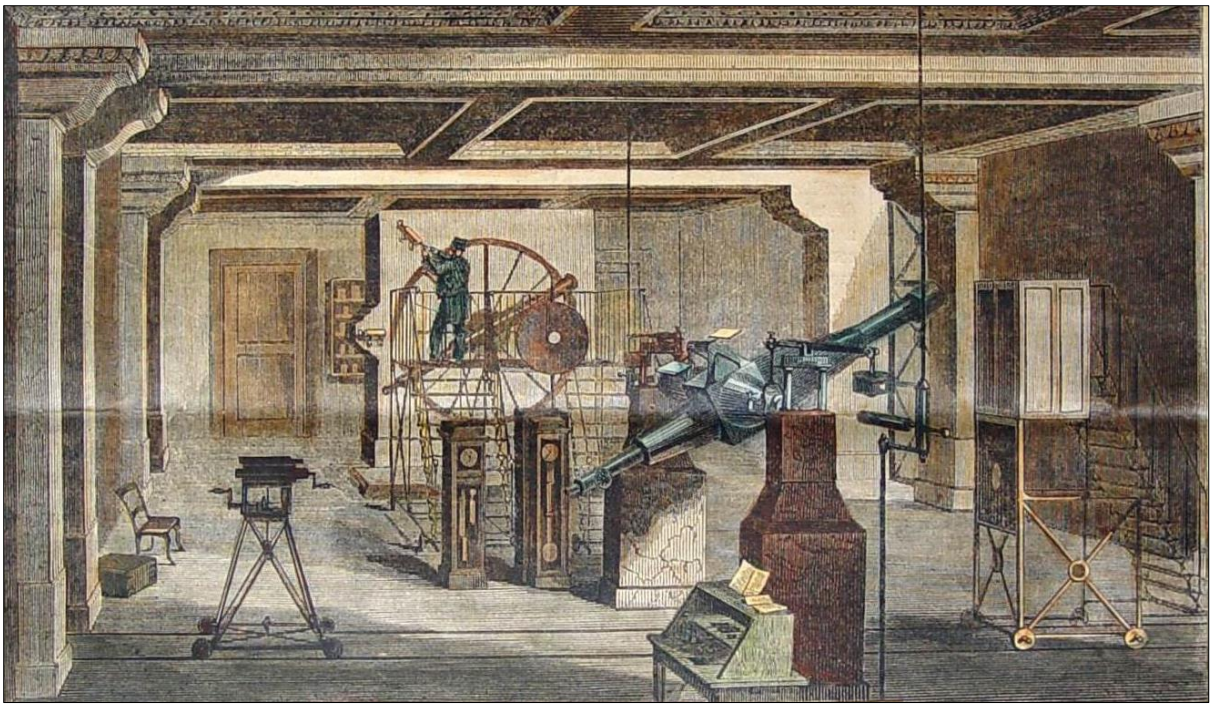


Figure 15: The meridian room of the Paris Observatory, with Gambey's meridian telescope and mural circle (courtesy: Paris Observatory).

Gambey produced for Paris Observatory a new meridian telescope with a 15-cm diameter objective by Cauchoix. In 1834 it replaced the Ramsden-Berge one whose optics was poor, which was transferred in 1839 to Toulouse Observatory, where it is preserved. Gambey also built a mural circle in 1843 (Lequeux, 2016: 180–184). Figure 15 shows these instruments installed in the meridian room, located in the east wing of the Observatory.

A more original instrument was the equatorial telescope of Gambey, with two graduated circles almost 1 m in diameter and a Lerebours 10-cm objective (Figure 16). It replaced in the small observatory on the terrace a 'parallatic machine' by Bellet, which was sent to Marseilles and has since disappeared. These instruments served to measure the positions of planets, asteroids and comets with respect to neighboring stars, but of course their accuracy was lower than that of meridian instruments.

Lerebours and Cauchoix produced several refractors for the Observatory. The main difficulty they encountered was to obtain the flint and crown glass for the objectives (see Véron, 2009 for details). None of these refractors was of the same quality as the famous 23-cm diameter equatorial installed in 1824 in Dorpat (Tartu) by Joseph von Fraunhofer (1787–1826), which marked the beginning of the supremacy of Germany in astronomical instrumentation during most of the nineteenth century. Moreover, Georg Merz (1793–1867) and Franz Joseph Mahler (1795–1845), successors of the Fraunhofer and Utzschneider Company, were building in 1839 a still larger equatorial telescope (38 centimeters in diameter) for Pulkovo Observatory in Russia, where Struve was named Director in 1834. Another 38-centimeter equatorial telescope was installed in Cambridge, England, in 1835, with an objective by Cauchoix[4] and a mounting designed by Airy. France could not stay behind and the *Bureau des Longitudes* decided that a similar instrument would be constructed for Paris Observatory, in order to observe double stars, a weak point of the Observatory.

Both Cauchoix and Gambey would have been able to build this large telescope, but they were dead. It is thus a newcomer, the Austrian Johann Brunner (1804–1862), who had been working in Paris since 1828, who produced the mount, with driving clockwork built by Louis Breguet (1804–1883). The telescope needed a dome. A large one, with a floor rotating with the dome, was installed at great cost on the eastern tower of the Observatory (Figure 17). It was the largest astronomical dome of the time.

The 38-cm objective had been purchased in 1849 from Lerebours father and son, but when it was to be installed on the telescope tube in November 1855, it was discovered that the surface of the crown glass was damaged by humidity; a large number of very small

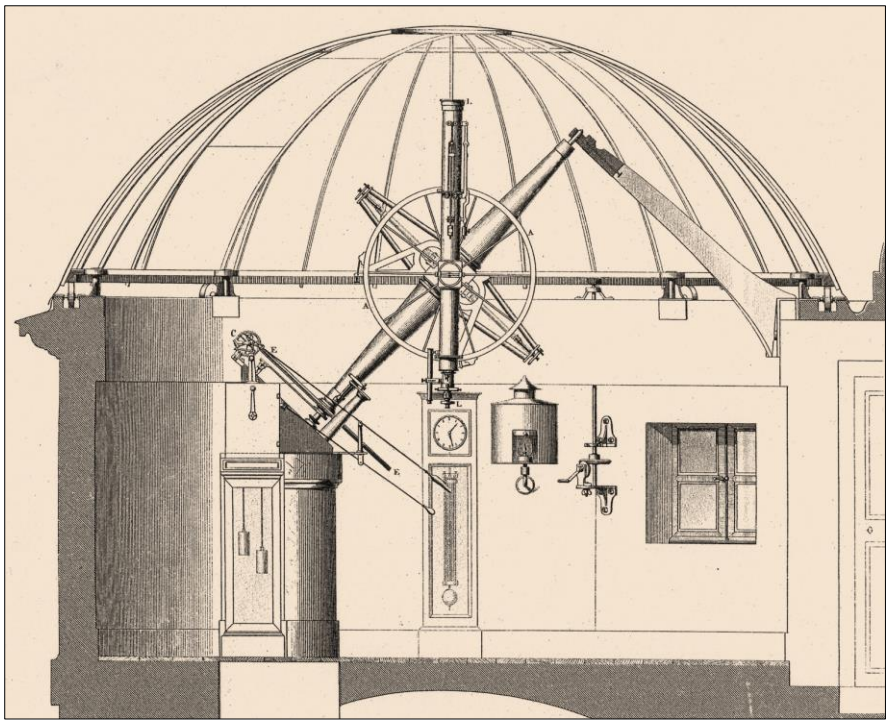


Figure 16: Gambey's equatorial telescope (1826). Note the large equatorial and declination circles, and the driving clockwork with its weights on the left (after Arago's *Astronomie Populaire*, Lequeux Collection).

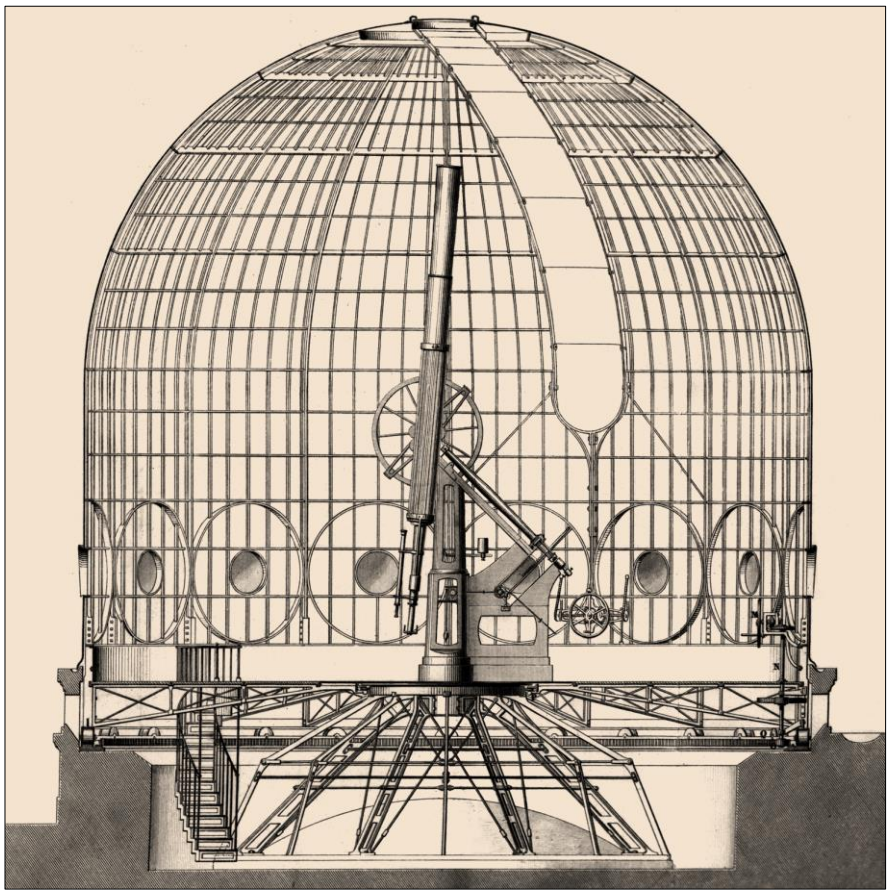


Figure 17: The large dome of the Paris Observatory, built by the architect Henri Alphonse de Gisors (1796–1861) and the engineer Louis Travers (1814–1886) in 1847, housing the Brunner telescope. The telescope is supported by a metallic spider that rests on the tower walls, and lacks stability (after Arago's *Astronomie Populaire*, Lequeux collection).

cracks were visible, preventing its use. As for the equatorial mount, it was only delivered in 1859. The objective was not installed. After partial re-polishing, it was used by the physicist Alfred Cornu (1841–1902) for his measurement of the velocity of light in 1874, then after re-installation, for a few observations. The original wooden tube was then replaced by an iron one and a new objective was built by the brothers Paul Henry (1848–1905) and Prosper Henry (1849–1903), but only in 1881. This instrument is still operational.

In the meantime, an equatorial with an iron tube, built by Friedrich Wilhelm Eichens (1820–1884), a German instrument builder based in Paris, had been placed in 1858 on the east tower of the Observatory, under a more satisfactory dome due to the engineer Joseph Jean. It had an objective of 5.25 meters focal length and 31.6-centimeter diameter, perhaps one built in 1834 by Lerebours father for one of his telescopes. This instrument and its dome have disappeared.

In the early 1870's, the French Government realized that France was very behind in astronomy compared to Germany and England: there were only two well-equipped observatories, Paris and Marseilles, compared to a large number in those two countries. It was decided to renovate the existing observatories in Toulouse and Algiers (then a French colony), and to create new ones in Besançon, Bordeaux and Lyons. In parallel, a large observatory was financed in Nice by the banker Raphaël Bischoffsheim (1823–1906), an observatory was created for Jules Janssen (1824–1907) in Meudon and a private one by Antoine d'Abbadie (1810–1897) in Hendaye. Germany installed in Strasbourg—which had been conquered from France in 1870—the best observatory in the whole country; France recovered Strasbourg and its Observatory in 1919. All this resulted in a frenzy of construction of new astronomical instrumentation, which is detailed in Table 1.

One cannot be but amazed by the enormous work required to build all these instruments, which were in general of excellent quality. This instrumentation is generally classical in its principle, with the exception of the reflecting telescopes, which will be discussed in Section 5, and of some strange instruments that will be presented in Section 6.

However, photography introduced some novelties. In France, astronomical photography was introduced by the Henry brothers. They were initially opticians in Nancy, and were 'discovered' by Le Verrier who, struck by their skill, invited them to Paris Observatory. They started by working on visual observations of zodiacal stars, but soon realized that photography would considerably ease their task.

As the achromatic objectives of refractors were optimized for visual observation, thus for yellow, and the photographic plates were sensitive to blue, Paul Gautier (1842–1909) and the Henry brothers constructed a double refractor with two parallel tubes, a photographic tube with a 33 cm objective and 343 cm focal length, and a visual tube with a 24 cm visual objective (Figure 18). This arrangement was needed as the photographic plates were sensitive to the blue-violet and required an optimized achromatic objective different from the visual one. The telescope has an equatorial English mount. The first photographs taken with this instrument were a great success, and triggered the gigantic project of the *Carte du Ciel*, which involved 18 observatories worldwide, equipped with photographic refractors similar to the Parisian prototype (Lamy, 2008). There were four French participating observatories: Paris, Bordeaux, Toulouse and Algiers.

The Great Meudon Equatorial (Figure 19), built in 1896 by Gautier with optics by the Henry brothers, is also a double refractor with a photographic and a visual tube. It is one of the last large refractors of the nineteenth century. For details and history, see Dollfus (2006).

5 THE BIRTH OF THE MODERN REFLECTING TELESCOPE

The development of the reflecting telescope had been hampered by the low reflectivity of speculum mirrors and the need to resurface them when tarnished. A number of attempts have been made to solve these problems, as we have seen. Huygens (1916: 805) had imagined that the mirror could be replaced by a lens with the convex surface made reflecting with the usual tin-mercury process, but this was only done much later (see the end of Section 8). We have mentioned the platinum mirrors of Caroché. Other unsuccessful attempts are described by King (1955: 261). Thus, the large reflectors before 1850 all had speculum mirrors. When Léon Foucault (1819–1868) visited Ireland in 1857 and inspected the famous 'Leviathan' telescope with its 6-foot metal mirror, he wrote "Lord Rosse's telescope is a joke." (Tobin, 2003: 204). The reason is that Foucault had just made a small glass mirror with a silver layer deposited according to Liebig's chemical process, and knew that he could make large mirrors in this way. He was

Table 1: List of astronomical instruments installed in French observatories between 1860 and 1900. This list is slightly incomplete as only a few private observatories are mentioned, and small instruments are not included. The dates of foundation or renovation of the observatories are given in the leftmost column. The dates of installation in the second column are approximate. Italics indicate instruments that have disappeared or been strongly modified. Many data come from Grillot (1986), Le Guet Tully and Davoigneau (2005) and Véron (n.d.).

Observatory	Date	Instrument	Mount	Objective	Note
Paris	1859	Reflecting telescope	Eichens	40 cm, Foucault	
	1863	*Meridian circle*	Secrétan	24 cm, Secrétan	
	1870	Reflecting telescope	Eichens	40 cm, Martin	
	1876	*Reflecting telescope*	Eichens	120 cm, Martin	
	1877	Meridian circle	Eichens	20 cm, Martin	
	1884	*Small Coudé equatorial*	Gautier	27 cm, Henry Brothers	
	1885	Photographic equatorial	Gautier	33 cm photo, Henry Bros. 24 cm visual, Martin	
	1891	*Large Coudé equatorial*	Gautier	60 cm photo, Henry Bros. 60 cm visual, Henry Bros.	1
Meudon (1875)	1891	*Reflecting telescope*	Gautier	100 cm, Henry Bros.	2
	1895	Photovisual equatorial	Gautier	62 cm photo, Henry Bros. 83 cm visual, Henry Bros.	
	1896	Photographic equatorial	Gautier	13.5 cm, Prazmowski	3
Marseilles (1864)	1862	Reflecting telescope	Eichens	80 cm, Foucault	
	1872	Equatorial	Eichens	26 cm, Merz	
	1876	*Meridian circle*	Eichens	19 cm, Martin	
	1883	*Comet finder*	Eichens	18 cm, Foucault/Henry Bros.	
Lyons (1878)	1881	Meridian circle	Eichens	15 cm, Martin	
	1882	Equatorial	Brunner	18 cm, Brunner	
	1888	Coudé equatorial	Gautier	35 cm, Henry Bros.	
Bordeaux (1878)	1881	Meridian circle	Eichens	19 cm, Henry Bros.	4
	1882	Equatorial	Gautier	22 cm, Henry Bros.	
	1883	Equatorial	Gautier	38 cm, Merz	
	1890	Photographic equatorial	Gautier	34 cm photo, Henry Bros. 24 cm visual, Henry Bros.	
Besançon (1878)	1884	*Equatorial*	Eichens?	25 cm, ?	
	1887	Meridian circle	Gautier	19 cm, Henry Bros.	
	1890	*Coudé equatorial*	Gautier	33 cm, Henry Bros.	
	1890	Alt-azimuthal	Gautier	10 cm, ?	
Nice (1879)	1883	Equatorial	Gautier	38 cm, Henry Bros.	
	1887	Meridian circle	Brunner	20 cm, Brunner	
	1888	Equatorial	Gautier	76 cm, Henry Bros.	
	1892	Coudé equatorial	Gautier	40 cm, Henry Bros.	5
	1895	*Equatorial*	Gautier	38 cm, Henry Bros.	6
Toulouse (1872)	1860	*Reflecting telescope*	Secrétan	33 cm, Foucault	
	1875	Reflecting telescope	Secrétan	83 cm, Henry Bros.	7
	1880	*Equatorial*	Brunner	25 cm, Brunner	8
	1888	Photographic equatorial	Gautier	33 cm photo, Henry Bros. 24 cm visual, Henry Bros.	
	1891	Meridian circle	Gautier	19 cm, Henry Bros.	
Hendaye (1870)	1880	Meridian circle	Eichens	15 cm, Henry Bros.	9
Juvisy (1882)	1886	Equatorial	Gaussin	24 cm, Bardou	10
Paris, Sorbonne	1900?	*Photo/visual equatorial*	Mailhat	25 cm visual, Mailhat 24 cm photo, Mailhat	
Algiers (1858–1873)	1859	*Reflecting telescope*	Secrétan	33 cm, Foucault	11
	1861	Reflecting telescope	Secrétan	50 cm, Foucault	12
	1888	Meridian circle	Gautier	19 cm, Henry Bros.	
	1888	Coudé equatorial	Gautier	32 cm, Henry Bros.	
	1890	Photographic equatorial	Gautier	33 cm photo, Henry Bros. 24 cm visual, Henry Bros.	
Strasbourg (1881)	1876	Equatorial	Repsold	16 cm, Reinfelder/Hertel	13
	1877	Equatorial	Repsold	49 cm, Merz	
	1879?	Comet finder	Repsold	16 cm, Merz	
	1879	Alt-azimuthal	Repsold	14 cm, Merz	
	1880	Meridian circle	Repsold	16 cm, Merz	

Notes to Table 1. 1: Disassembled, building in bad condition. 2: Replaced by a 1-m Cassegrain reflector in 1971. 3: Used for the beautiful photographs of solar granulation; there were three other refractors. 4: Automated in 1980. 5: Modified in 1972. 6: In mountain station (Mont Mounier). 7: New mount in 1889. 8: New tube with 38-cm objective on same mount in 1902. 9: D'Abbadie's private observatory; meridian circle with decimal graduations. 10: Flammarion's private observatory. 11: Algiers was then a French colony; the Observatory at Bouzareah is well preserved. 12: New mount in 1920. 13: Strasbourg was then in Germany (in France since 1919).

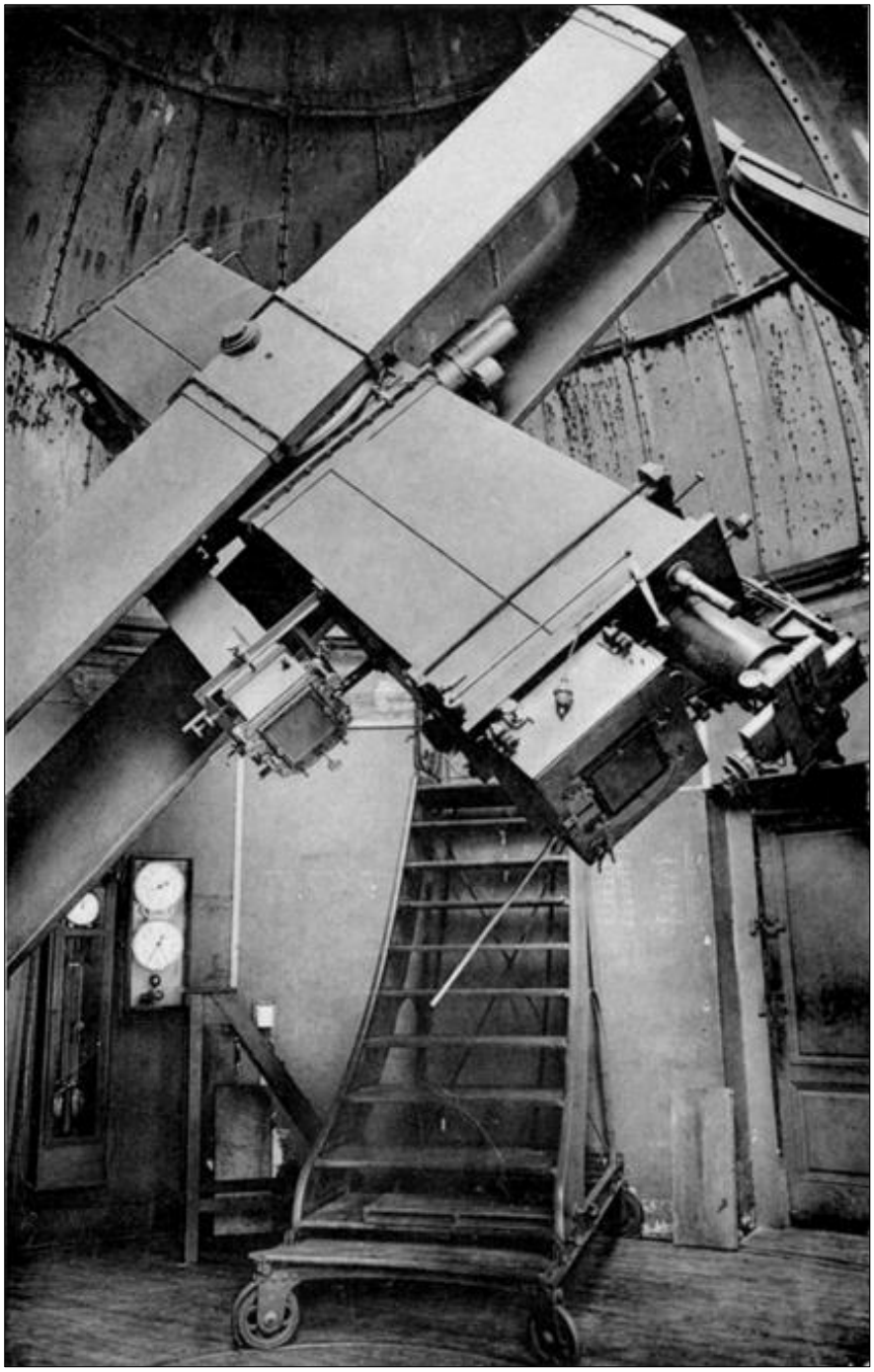


Figure 18: The *Carte du Ciel* photographic equatorial at Paris Observatory made by Gautier and the Henry brothers (courtesy: Paris Observatory).

not first, as Karl Steinheil (1801–1870) had already produced in Munich a silvered glass mirror the previous year, and even produced a 12-inch one in 1859; however, despite his predictions of a great future for this invention, Steinheil devoted most of his further energies to refractors and did not produce many more mirrors (Tobin, 2003: 202 and note 16).

The silvered glass mirrors have decisive advantages with respect to the speculum ones. The silver layer is highly reflective, tarnish slowly (at least, at the time of Foucault) and can be dissolved and replaced easily. Consequently, no large reflecting telescope with a speculum mirror was produced after Foucault, with the exception of the 4-feet diameter Great Melbourne Telescope, erected in 1867, which for various reasons did not fulfill the evolving needs of astrophysical research (Gascoigne, 1996; Gillespie, 2011), and, according to Ritchey, unfortunately destroyed confidence in reflecting telescopes,

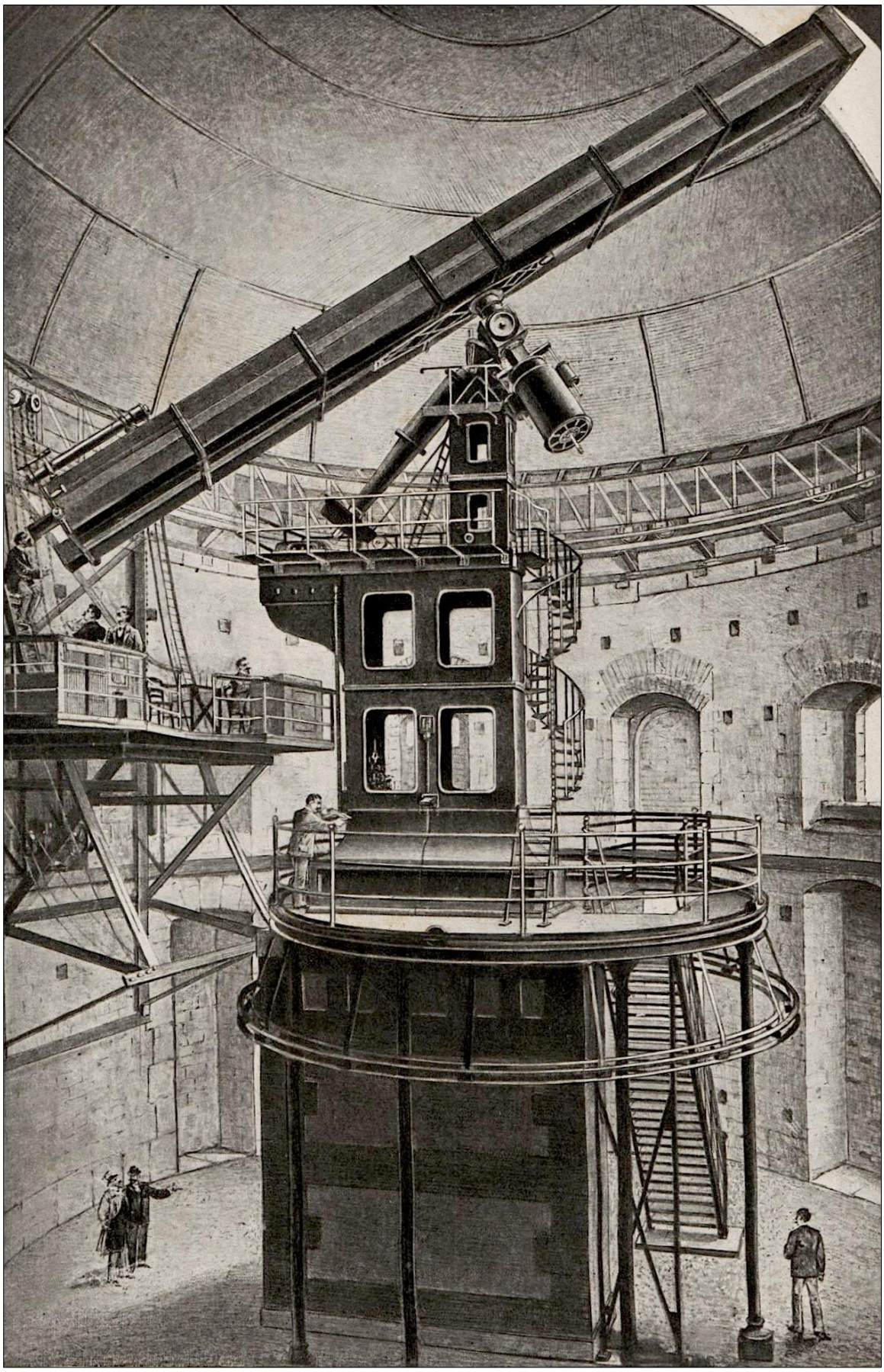


Figure 19: The Great Equatorial at Meudon (courtesy Paris Observatory).



Figure 20: Four telescopes by Foucault. Top: 10 cm (1857), 20 cm (1858); Bottom: 40 cm (1859; photograph: Sylvain Peilly), and 80 cm (1862). The mirror of the 20-cm telescope is lost. For images of the 80 cm telescope in place and in its shelter see Georgelin and Lequeux (2021: Figure 5) (courtesy: Paris Observatory).

"… so wonderfully efficient in photographic and spectroscopic work, for nearly a third of a century." (King, 1955: 267).

For testing his mirrors, Foucault invented several processes that are still in use today, the most important one being the Foucault knife-edge test. He also showed how to safely parabolize a mirror. After his first experimental telescope, 10 cm in diameter, he produced a dozen parabolic mirrors, and in particular three of increased size mounted by Wilhelm Eichens (1818–1884) of the firm of Marc Secretan (1805–1867) for Paris and Marseilles Observatories (Figure 20).

The mirrors of the 40-cm and 80-cm telescopes have a meniscus shape, and not a flat back as most later mirrors (see Georgelin and Lequeux, 2021: Figure 6). Foucault placed on the back a rubber bag linked by a tube to a stopcock near the eyepiece; it could be inflated by the observer to ensure that the back of the mirror was entirely supported by the bag and to produce a limited deformation (Figure 21), although the shape of the mirror was such that its surface remained approximately correct when inclined: this is an early precursor of active optics.

The back face of the mirror is polished so that Foucault could monitor by its colour the thickness of the silver layer during its deposition (0.1 to 0.2 μm). The 80-cm telescope was a Newtonian, the beam being reflected on the side by a total reflection prism; Foucault introduced in the reflected beam an 'optical vehicle' with two lenses, increasing the focal length to 15.95 m, comparable to that of the largest refractors. As these lenses produced spherical aberration, Foucault retouched the primary mirror to correct it. The original optical vehicle was lost in 1905 during the transportation of the telescope to Guelma (Algeria) for the observation of a total solar eclipse, and later was replaced in an imperfect way, until André Couder (1897–1979) calculated a new vehicle. The shape of the mirror is close to that of a Ritchey–Chrétien primary mirror, and tests have shown that it is perfect except for the edges.

Foucault's telescopes immediately attracted the attention of astronomers and amateurs worldwide. Secretan and his successors, in particular Mailhat, produced a number of small Foucault-type telescopes for amateurs until 1940 (Tobin, 2016, with photographs of instruments still in existence). The silver-on-glass reflector was introduced in America by Henry Draper (1837–1882), who learnt through John Herschel about the work of Foucault. He polished more than a hundred glass mirrors until he could produce two good 40-cm mirrors in 1862, with which he took many photographs of the Sun and Moon, and in 1878 a 70-cm mirror (King, 1965: 268–270). The silvered glass mirror became also popular in England, often also for photography.

In France, several relatively large reflecting telescopes followed Foucault's 80-cm one. Foucault began another 80-cm mirror for the Toulouse Observatory, which after his death was polished unsatisfactorily by Adolphe Martin (1824–1896), the only pupil of Foucault. It was placed in an Eichens' wooden mount similar to that at Marseilles, but with a new 84-cm mirror figured by the Henry brothers (see Tobin, 2016: Figure 37). In 1889 the wooden mount was replaced by a metallic one due to Paul Gautier (this has never been done for the Marseilles telescope in spite of the fact that the wooden mount was declared 'provisional'). Contrary to the Marseilles telescope, the Toulouse one has never been used extensively.

In Paris, a giant 120-cm diameter Newtonian telescope was built by Eichens; the mirror was polished by Martin in 1876, but it was a failure, so this telescope was essentially used as a light collector for spectroscopy, before being dismantled. The mount was adapted for the 120-cm telescope at Haute-Provence Observatory and thus survives.

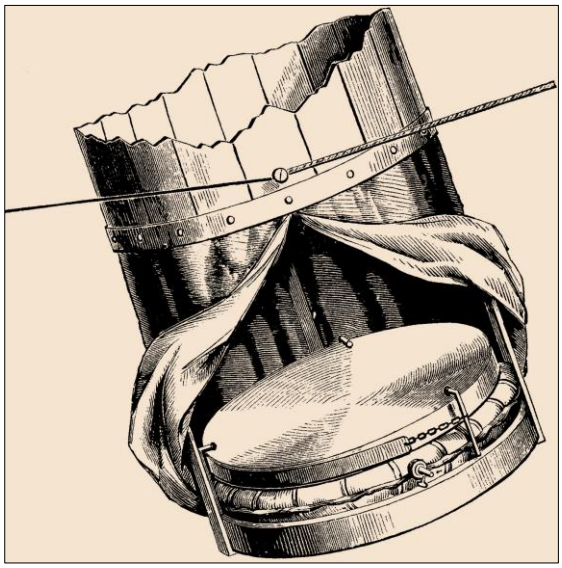


Figure 21: Like Foucault, Henry Draper used a rubber cushion to support the mirrors of his telescopes (courtesy: Paris Observatory).

Another reflecting telescope was ordered by Janssen to equip his observatory in Meudon. It was built by Gautier, with a 1-m mirror by the Henry brothers, and installed in 1891 (Figure 22). It was a Newtonian telescope with an f/3 mirror, thus very compact. Its equatorial mount was conceived for transportation and adaptation to different latitudes (for details on the instrument and its history, see Dollfus, 2000). Unfortunately, there was little interest in this pioneering telescope at the time. It was not used very much, except for a series of photographs taken by Louis Rabourdin (1858–1936) in 1897–1899. The telescope was replaced in 1971 by a Cassegrain one with a new mirror made by the REOSC Company and a new mount, so that only a few mechanical parts survive of the original instrument. This was the last relatively large reflecting telescope built in France before the

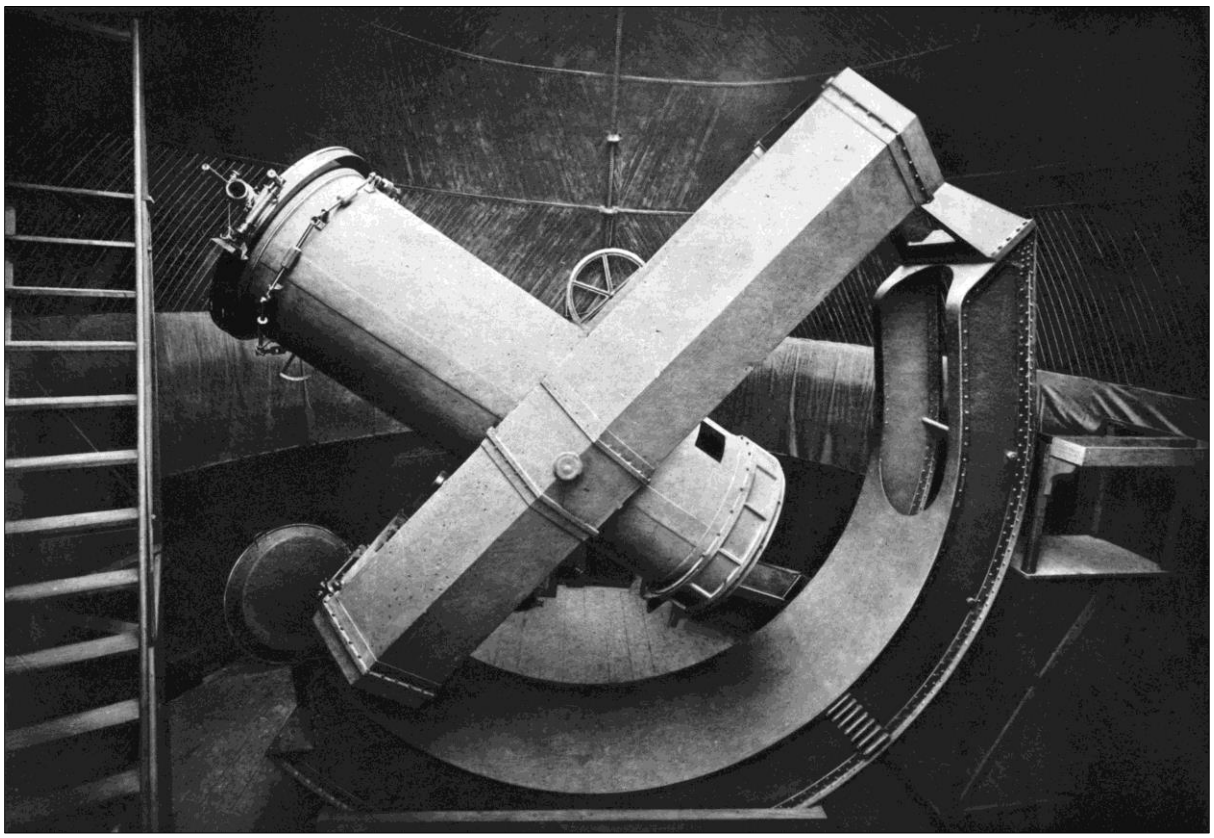


Figure 22: The Gautier-Henry reflecting telescope at Meudon Observatory (1891). The telescope was conceived as transportable, and its semi-circular support allowed adaptation of the inclination of the equatorial mount to different latitudes (courtesy: Paris Observatory).

creation of Haute-Provence Observatory (OHP) in the late 1930's.

All of the telescope mirrors were covered chemically with a silver layer that tarnished in a few years and had to be replaced periodically. Aluminizing was only introduced in 1932–1934 in the USA (King, 1955: 382) and simultaneously in France by Louis Dunoyer de Segonzac (1880–1963). Dunoyer had succeeded in aluminizing glass by deposition in a vacuum as early as 1911 and gave instructions that were soon adopted by Lyot and Couder (Dunoyer, 1936).

6 CURIOSITIES AND ODDITIES

Foucault was a fertile inventor. He not only invented the modern reflecting telescope, but also his famous pendulum and the gyroscope, with which he demonstrated the rotation of the Earth, and the siderostat, an instrument used to send continuously the light from a celestial object to a fixed, horizontal direction. To tell the truth, he did not start from nothing for this last invention, as the siderostat derives directly from heliostats, which were used in the laboratory to send via a flat mirror the light from the Sun to a fixed target, compensating for its diurnal motion thanks to clockwork. Foucault succeeded in polishing large silver-on-glass, optical quality flat mirrors and designed a relatively large instrument that could be used to send the light from the sky to a fixed, horizontal refracting telescope. This instrument was constructed by Eichens and Gautier in 1868, just after Foucault's death (Figure 23). It was used for several decades at Paris Observatory, where it can still be seen.

Similar siderostats were also used by two groups to observe the 1874 transit of Venus at Mauritius (King, 1955: 279). In 1899, a polar siderostat with a single mirror rotating around a polar axis was installed at Meudon Observatory to feed Deslandre's spectroheliograph. A large Foucault siderostat with a 1-m diameter mirror replaced it later (Deslandres, 1910: 28). A variant, called a cœlostat, with two flat mirrors, was invented in 1839 by the Frenchman K. August, and its properties studied by another, better known Frenchman, Gabriel Lippmann (1845–1921; Lippmann, 1895). It has the advantage of avoiding the field rotation present with the siderostat, but can only be used at relatively low declinations. A cœlostat with 50 cm and 30 cm mirrors was built in 1905 for the total solar eclipse of that year and was installed at Meudon in 1906 to feed a

spectroheliograph (Deslandres, 1910: 18). A larger one, with 80 cm and 60 cm mirrors, was placed in 1972 on the top of the solar tower, also at Meudon, to feed a large spectrograph.

The apogee of the siderostat was reached in the monster instrument presented at the 1900 Universal Exhibition in Paris, the largest refracting telescope ever built (Launay, 2007). It was not an initiative of astronomers, but of an influential political man. This instrument consisted of a Foucault-type siderostat feeding a fixed horizontal refractor (Figure 24). This should have been a double refractor, but only the photographic part was completed.

The construction of this instrument was a formidable challenge to the French glass-makers, opticians and mechanical engineers. Gautier built all the mechanics, and curiously was also in charge of grinding and polishing (successfully) the huge plane mirror, using specially designed machinery. Édouard Mantois (1848–1900), the successor of Henry Guinand and Charles Feil who had supplied most of the glass for the nineteenth century French instruments, cast the crown and flint blanks for the objective, and was also responsible for mechanically figuring the lenses; however, only



Figure 23: Foucault's siderostat (1868). The mirror was 30 cm in diameter and fed a 20-cm diameter horizontal refractor. The clockwork with centrifugal regulator was designed by Foucault himself (Paris Observatory collections, photograph Sylvain Peilly).

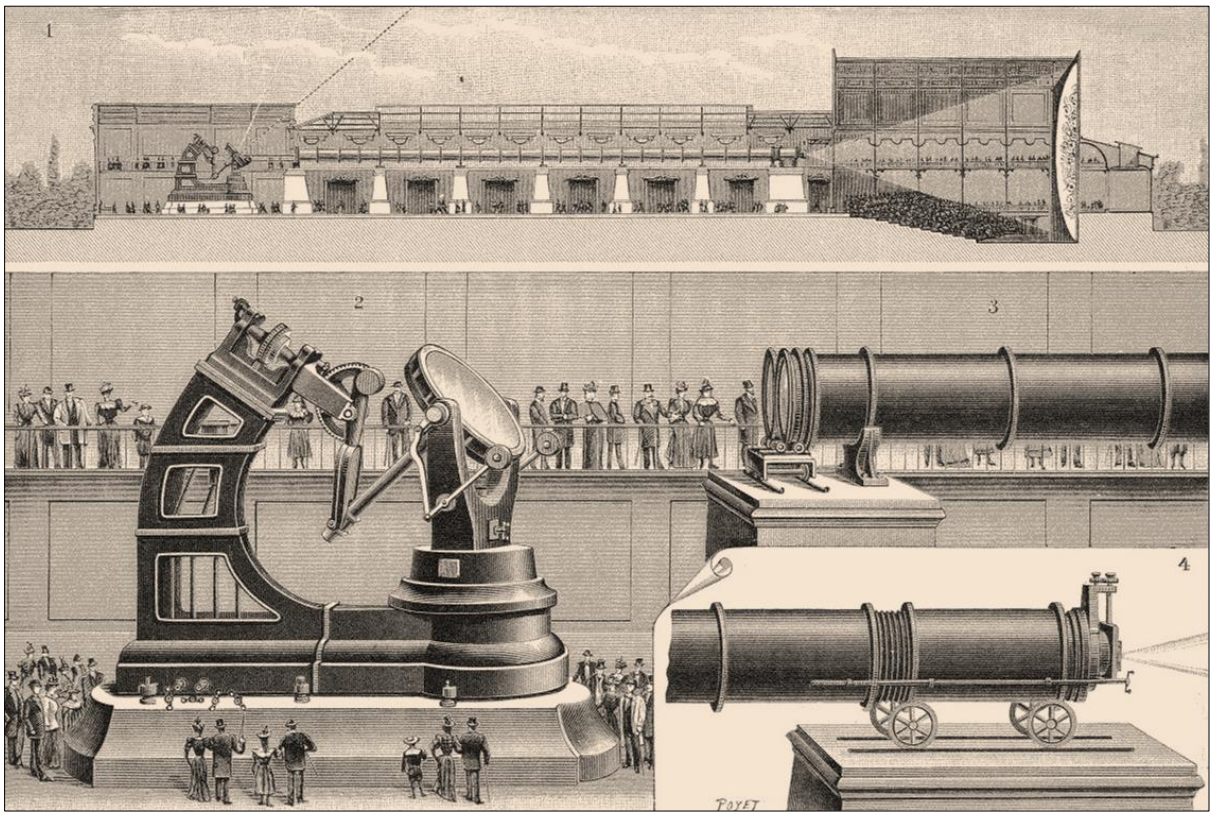


Figure 24: The great horizontal refractor of the Paris Universal Exhibition of 1900. Built by Gautier, including optics, it consisted of a 2-m diameter siderostat feeding a 125-cm diameter, 58-m long refractor. The top picture represents the instrument as planned, with an enormous image of the Moon projected on a screen by the visual telescope. The bottom picture shows details. However, only the photographic part was built, with a single objective and tube. The mechanics of the siderostat were said to be reliable, and the optics fairly good (after Barré, 1899). For various photographs, see Launay (2007).



Figure 25: The large coudé equatorial at Paris Observatory (1891, 60 cm, f/d = 30; Gautier/Henry brothers). The observer sits in a fixed position in the building and looks along the polar axis. The objective is on the side of the cube at the end of the shorter tube. Inside this cube, a flat mirror at 45° sends the light into the tube; another 45° flat mirror at the intersection of the two tubes reflects this light to the eyepiece or to the photographic plate. The whole instrument rotates around the polar axis, and the cube can rotate upon itself. In other models, the objective is behind the cube (courtesy: Paris Observatory).

the photographic doublet was in time for the exhibition. Some photographic and even visual observations were secured with this instrument before it was dismantled in 1910 after an unsuccessful auction, everyone judging the instrument too cumbersome for practical use. The mirror and the two lenses of the photographic objective survive at Paris Observatory. The optical quality of the lenses has not been tested, but the glass is of excellent transparency, better than that of the yellowish doublets of the large Meudon equatorial. The fate of the uncompleted lenses made for the visual objective is unknown. A walnut and brass model is kept in the Science Museum in London (object number 1993-740).

Another strange instrument, designed for the comfort of the observer, was the coudé equatorial of Maurice Lœwy (1833–1907) (Lequeux, 2011). After the success of a 27-cm diameter prototype built in 1882, a large instrument was built in Paris in 1890 (Figure 25). It had two interchangeable 60-cm objectives, for visual and photographic observations respectively. Strangely enough, the coudé

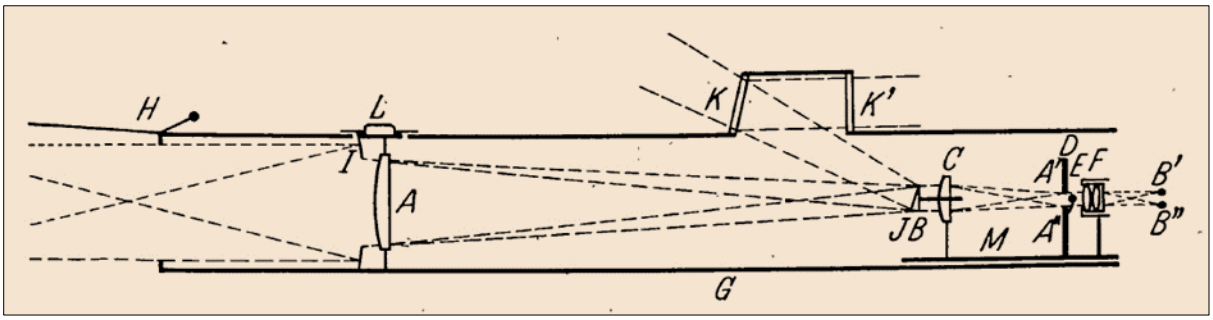


Figure 26: Lyot's coronagraph. *A* is a simple lens, which gives in *B* an image of the Sun. The light is sent laterally to *K* in order to avoid heating the instrument. The field lens *C* produces an image *A'A"* of the lens *A* (a pupil) on a diaphragm *D* that eliminates the light diffracted by the edges of the first lens. A small central screen *E* eliminates the light reflected on the faces of this lens. The objective *F* produces the image of the corona in *B'B"* (after Lyot, 1932: 77).

equatorials were originally conceived as astrometry instruments for building a star catalogue with the possibility "… to study the zones on the right and the left of the meridian." (Lequeux, 2011: 193). They soon showed themselves to be unsuitable for this and were mainly used for photography and other purposes. The principle had much success and seven coudé equatorials were built in total: the two in Paris already mentioned, one in Besançon (dismantled), one in Lyons (very well preserved), one in Algiers (also preserved), one in Nice (still visible), and one in Vienna (which has disappeared). The weaknesses of the coudé equatorials were their excessive mechanical complexity and the thermal deformation of the flat mirrors. Indeed, in 1971–1972 the two flat glass mirrors in the Nice instrument were replaced by ceramic (cervit) mirrors less susceptible to thermal deformation. This served for solar observations until 1975, and is now used by amateur astronomers.

7 AFTER 1900: STAGNATION AND RENEWAL

After the considerable instrumental effort of the years 1870–1890, it is not surprising that little new instrumentation was built in France for some time. Astronomers were busy observing with their new telescopes and, above all, obtaining and measuring the photographic plates from the *Carte du Ciel* project. Moreover, WW1 had a very negative impact on scientific activities in France. Important exceptions were the Perot–Fabry spectrographs (Georgelin and Lequeux, 2021) and the spectroheliograph, invented in 1893 by Henri Deslandres (1853–1948) quite independently from George E. Hale (Deslandres, 1910: 13–42), to be discussed in Section 11. Later exceptions were the coronagraph and monochromatic filter of Bernard Lyot (1897–1952), and the astrolabe of André Danjon (1890–1977).

Bernard Lyot is the only French astronomer cited in the *Source Book of Astronomy and Astrophysics, 1900–1975* by Lang and Gingerich (1979: 108–110), for his work on the polarization of the Moon, Mars and Mercury. Even taking into account some American nationalism in this book, this testifies for the poor state of French astronomy between WW1 and WW2 and somewhat beyond.

Lyot had been assistant to Alfred Perot (1863–1925), one of the inventors of the Fabry–Perot interferometer; as such, he can be considered as a member of the French optical school. He was a very imaginative instrumentalist, who was first to photograph and film with his coronagraph (Figure 26) the solar corona outside of a total eclipse. The coronagraph, used for the first time in 1931, had, and still has, a very important posterity, in particular for observing exoplanets. In 1933 Lyot also designed a very narrow band filter (Figure 27), which progressively replaced the spectroheliograph for imaging the chromo-

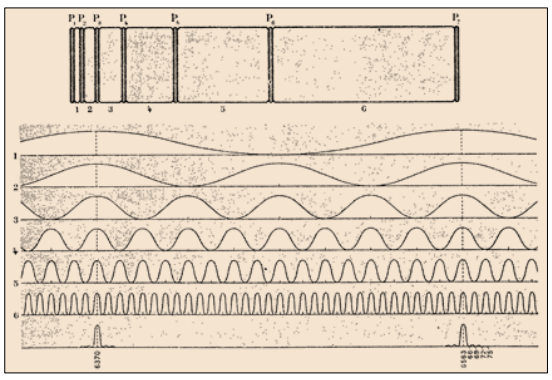


Figure 27: Principle of Lyot's polarizing filter. It consists of a series of birefringent plates of quartz or feldspar separated by polaroids (top). The thickness of the plates increases by a factor 2 from one to the next. Each plate produces a channeled spectrum (bottom). The figure shows how the light is progressively filtered as a narrower and narrower spectrum at well-separated wavelengths. The exact filtered wavelength can be adjusted by changing the temperature of the filter (after Lyot, 1944: 36).

sphere of the Sun through its emission lines. Associated with the coronagraph, it produced images of the corona in various emission lines. Curiously, this filter was the source of inspiration for the solar grating radio array built in 1952 by W.N. 'Chris' Christiansen (1913–2007) in Australia, the first of a long series of similar instruments. Christiansen wrote (cited in Wendt et al., 2008: 174):

> The idea occurred while reading a description of Bernard Lyot's optical filter in which narrow frequency pass-bands are produced at widely different frequencies. This may seem particularly indirect when the analogy which is more obvious is the optical diffraction grating, but to me as an antenna designer the cos*n*.cos*2n*.cos*4n* series of the Lyot filter immediately suggested an antenna array and an array of arrays.

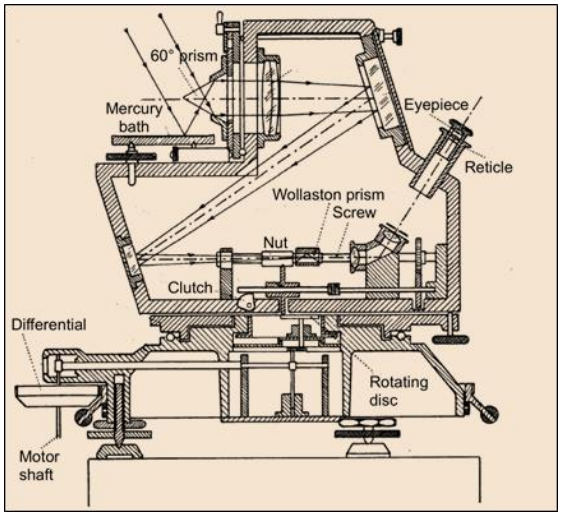


Figure 28: Danjon's astrolabe. It measures the time of passage of a star at 60° elevation from the coincidence of a direct ray and a ray reflected on a mercury bath, both being reflected in a 60° prism. A Wollaston prism produces double images to ensure a better coincidence, and the phenomenon is followed for some time by moving the prism by a motor so that the images stay in coincidence, its position being marked by contacts on the drive screw (adapted from Danjon, 1955a: Figure 9).

Later, Lyot (1950) built a coronal spectrophotometer able to observe the emission lines of the corona within 1 arc minute of the edge of the solar disk.

André Danjon has also several inventions to his credit. We will mention later the interferential micrometer. The most important one is the impersonal astrolabe (Figure 28). This astrometry instrument is derived from a geodetic one, the astrolabe of Claude and Driencourt, and is made impersonal (independent of the observer) because the passage of the star is followed for 10 to 20 seconds. It was conceived in 1938, but only realized as a prototype in 1953 (Danjon, 1955a), then built and commercialized by the *Société Optique et Précision de Levallois* (later absorbed by SAGEM, now a part of SAFRAN). It allowed a very precise determination of the time of the passage of stars at an elevation of 60°. Danjon's astrolabe enjoyed considerable success, as no fewer than 45 instruments were supplied to observatories around the world.

Another important improvement in ground-based astrometry was the tracking photoelectric micrometer installed on the Bordeaux Observatory meridian circle in 1971 (Requième, 1972). It was replaced in 1994–1996 by a much more sensitive CCD working in scanning mode (Viateau et al., 1999), which was still in operation in 2014.

8 REFLECTING TELESCOPES

Let us return to reflecting telescopes. A decisive improvement is the Ritchey–Chrétien telescope, a wide-field, short focal-length Cassegrain telescope with deformed mirrors, whose principle is due principally to the French optician Henri Chrétien (1879–1956). At the time he was an adjunct-astronomer at Nice Observatory. This telescope design is detailed in a remarkable paper (Chrétien, 1922), that unfortunately has never been translated into English. In 1908–1910, Chrétien visited several observatories worldwide, and at Mount Wilson Observatory he met George W. Ritchey (1864–1945), and the two men started to discuss a new type of telescope. Ritchey came to France in 1924 to work on an (aborted) project, an observatory on the Salève mountain close to the Swiss border, and he and Chrétien met again. Ritchey was enthusiastic about the telescope concept and proceeded to build a 50-cm diameter prototype (see Figure 29). In 1927, this was presented to the Academy of Sciences (Ritchey and Chrétien, 1927).

The advantages of the Ritchey–Chrétien design are so considerable that many recent telescopes and the Hubble Space Telescope are of this type. A small problem is the curvature of the image, which can be made flat by a corrector, as calculated by the unjustly forgotten optician Maurice Paul (1890–1981; Paul, 1935). Often, a flat, 45° mirror sends the final beam to one side, along the horizontal axis of the alt-azimuth mount (Nasmyth configuration). However, it took many years before the Ritchey–Chrétien concept was generally adopted: George E. Hale (1868–1938) rejected it for the Mount Wilson 100-inch and the Mount Palomar 200-inch telescopes, in spite of the insistence of Ritchey. As we will see now, it was also rejected in France: no

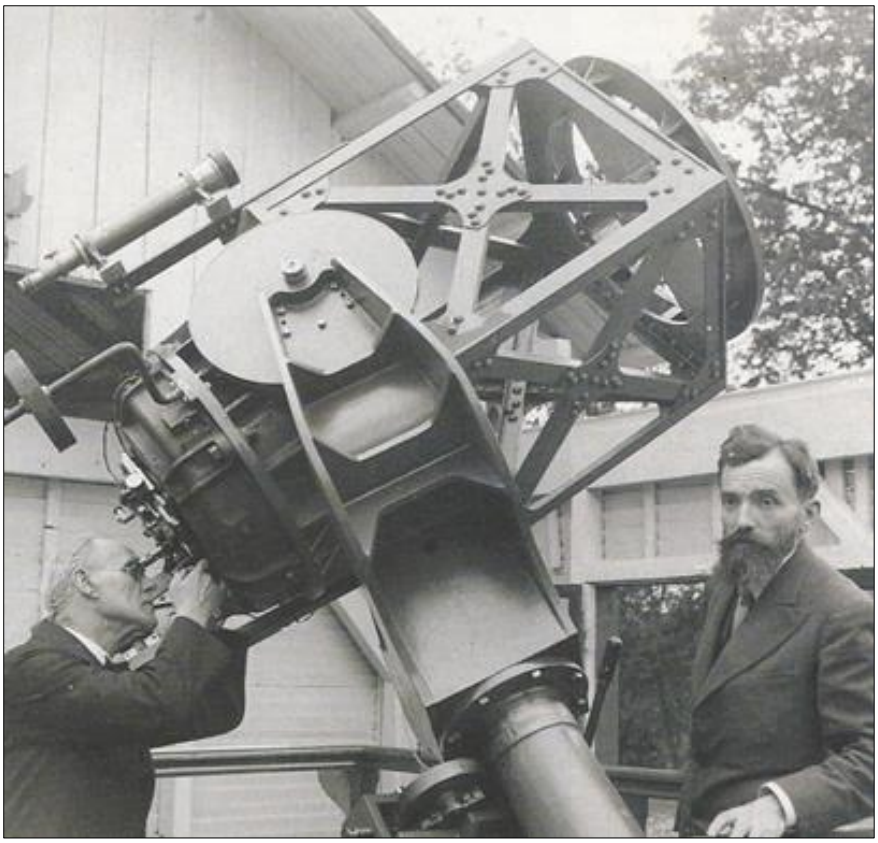


Figure 29: George Ritchey (left) and Henri Chrétien (right) in 1927 with their 50-cm diameter prototype telescope. The primary mirror was open at f/3 (courtesy: Linda Hall library).

man is a prophet in his own country! As an excuse, one must acknowledge that the 1-m diameter Ritchey–Chrétien telescope built by Ritchey in 1964 for the Flagstaff Naval Observatory was not a success, essentially due to mechanical deficiencies.

The first reflecting telescope of some importance built in France after the Meudon 1-m one of 1891 is the 120-cm diameter Newtonian telescope of the Haute-Provence Observatory, created in 1939. It used the mount of the failed 120-cm Parisian reflector, whose mirror was polished anew by André Couder. It was operational in 1942 but unfortunately the main mirror was damaged in 1945 and was finally replaced by a new one in 1953, also polished by Couder. Another telescope, 1.93 m in diameter, was constructed in 1957 by Grubb-Parsons in England for this observatory, with a parabolic mirror by Couder. It had initially three foci: Newtonian, Cassegrain and coudé, but only the Cassegrain focus is used at present. This telescope (Figure 30) is famous as it served, with the spectrograph ELODIE designed by André Baranne (see Section 12), to discover the first exoplanet.

Two larger telescopes became available in the 1970s: the 2-m Bernard Lyot Telescope at Pic du Midi Observatory, in the French Pyrenees at 2870 m elevation, and the 3.60-m Canada–France–Hawaii telescope in Hawaii at 4200 m. Both testify to the qualities of French optics, but also the lack of pragmatism of their designers.

The 2-m telescope was conceived around 1964 following the model of the Kaj Strand 1.55-m diameter astrometric telescope, which saw its first light that same year. The Strand instrument has a removable flat mirror half way between the primary mirror and its very long focus (f/9.9), giving the image at the level of the central hole of this mirror. However, probably through lack of interest of French astrometrists and the difficulty of polishing a good flat mirror of 1 meter diameter, the idea was abandoned; but the primary mirror was already polished. The telescope, completed in 1980, became a Cassegrain open at f/25, excessively long hence the need for a large dome, 15 m in diameter (Figure 31). Inspired by the previous turret-dome at Pic du Midi (Roudier et al., 2021), this dome was supposed to be entirely closed, with a 2.2-m diameter optical window facing the telescope, hence a rather strange structure likely to be blocked



Figure 30: The 193-cm diameter telescope of the Haute-Provence Observatory (courtesy: OHP/CNRS).

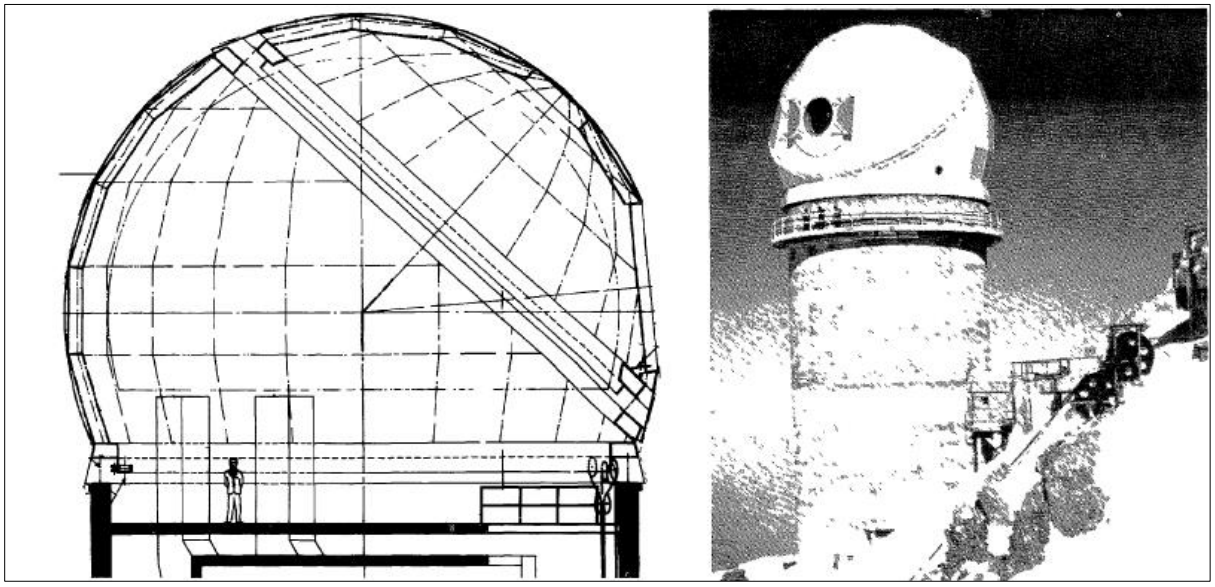


Figure 31: The dome of the 2-m telescope of Pic du Midi Observatory. The 45° rotating cap is pierced by a 2.2-m diameter hole through which the telescope points (after Rösch, 1982: 82).



Figure 32: The 3.6-m diameter Canada–France–Hawaii telescope (courtesy: CFHT).

by frost. However, it turned out that it was impossible to produce such a plane-parallel piece of glass with optical quality, and the hole in front of the telescope was left open. As could be expected, hot air escaping through the hole produced bad images. Three fans were installed to draw air from outside, but resulted in no improvement. The final solution was to have a cooled floor! To make matters even worse, the concrete of the high pillar supporting the dome and the telescope turned out to be defective and needed significant repairs.

The Canada–France–Hawaii 3.6-m Telescope (Figure 32), at 4200 m on top of Mauna Kea in Hawaii, was less problematic. When the Canadian and French astronomers decided to build a large telescope together in 1967 there was a controversy about the choice of the optical combination. Baranne (1966) had already published a comprehensive study of the Ritchey–Chrétien concept, with application to a 3.5-m diameter telescope. He showed that such a telescope can even be used at the prime focus with a suitable corrector. Charles Fehrenbach (1914–2008), who was then Director of Marseilles Observatory and OHP, and one of the authors of this paper (J.L.), were sent to Tucson in April 1968 to discuss the Ritchey–Chrétien 4-m telescope that was under construction for Kitt Peak Observatory. They were very well received by David Crawford, who even proposed to give blue-prints of the telescope to France. However, several French and Canadian astronomers wanted a telescope with a parabolic mirror that would give perfectly stigmatic images at the prime focus, and they won. As a result, the 3.6-m telescope has a parabolic, f/3.8 primary mirror, while it would have been shorter with a f/3 mirror in the Ritchey–Chrétien combination. Ironically, to our knowledge, the 3.6-m has never been used at the direct prime focus because the stigmatic field is very small, of the order of one arc minute. Fortunately, it was possible to calculate correctors giving a 1° field at the prime focus, and in this configuration the telescope has been used satisfactorily.

One of the authors (J.L.) knew that it was possible to use an alt-azimuth mounting and a computer-controlled drive (the Russian 6-m telescope was the first of those), and in 1968 he and Michel Combes (1939–2017) proposed an alt-azimuth mount for the 3.6-m CFH Telescope. However, this was flatly rejected, and as a result this telescope, which saw its first light in 1979, was the penultimate one with an equatorial mounting and a very large dome (the last one being the German 3.5-m telescope in Calar Alto, with first light in 1984).

Thanks to the great optician Raymond Wilson (1928–2018), a real breakthrough came

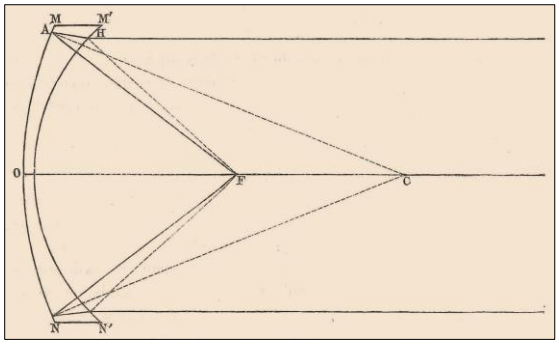


Figure 33: Mangin's projector for geodesy. It is a meniscus with two spherical surfaces. The rear, convex one with center in C is silvered, hence reflecting. The lamp is placed at the focus F, which is also the center of curvature of the inner surface (after Ibáñez and Perrier, 1886: 15).

with ESO's 3.5-m New Technology Telescope (1989), a Ritchey–Chrétien with f/2.2 thin, deformable primary mirror and alt-azimuth mount, which is housed in a dome a factor of two smaller than that of the 3.6-m.

With the previous three telescopes and also with the 3.6-m ESO Telescope completed in 1976, the French REOSC Company (now SAFRAN-REOSC), founded in 1937 under the impetus of Henri Chrétien and Charles Fabry (1867–1945), acquired considerable expertise in polishing large mirrors. It has polished four single-piece 8-meter mirrors for ESO's Very Large Telescope and two more for the Gemini telescopes, segments of the 11-meter mirror for the Gran Telescopio de Canarias (2000), and mirrors for the GAIA astrometry satellite and the James Webb Space Telescope. It won the contract to polish all the mirrors and segments for ESO's Extremely Large Telescope (ELT), to be completed in 2024.

Aside from classical telescopes, instruments with unconventional, aspherical optics were conceived in France, in particular at Marseilles Observatory. The story begins with the correcting plate of the Schmidt wide-field telescope (1929). The German optician Bernhard Schmidt (1879–1935) imagined that this

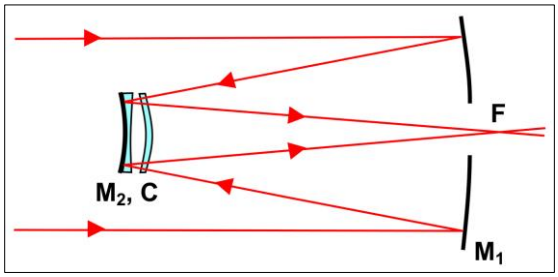


Figure 34: The Klevstov–Cassegrain telescope. The secondary mirror M_2 is a modified Mangin mirror, and the corrector C allows a larger field. All surfaces are spherical (after Wikipedia).

optical piece could be produced by surfacing a plane-parallel plate bent by partial vacuum while supported at its edge, then releasing it; however, he did not use this method himself, probably because of difficulties in producing a well-controlled pressure (Lemaitre, 2009: 265). This method only requires the use of a full-size spherical tool. Couder (1940) solved the theoretical problem, but the first practical realizations date only from the mid-1960s. Since that time, many aspherical mirrors, lenses and diffraction gratings have been produced, in particular in France, for telescopes and spectroscopes on the ground and in space (Lemaitre, 2009); see for example Lequeux (2021: Figure 8).

To end this section, we wish to mention two interesting and original discoveries.

The first one, from 1876, is by a French military man, colonel Alphonse Mangin (1825–1885). He built an aplanatic light projector for geodesy, made of a curved diopter whose convex surface is reflecting (Figure 33). This device had already been imagined by Huygens (see the beginning of Section 3), but it is very unlikely that Mangin was aware of this. With two spherical surfaces it is exactly equivalent to a parabolic mirror, for one wavelength. Mangin (1876: 252) proposed a Cassegrain telescope with a spherical primary mirror and a 'Mangin' secondary, which would be very open. This was not constructed, but in 1978 the Russian optician Yuri Klevstov built the so-called Klevstov–Cassegrain catadioptric wide-field telescope (Figure 34) along this principle (for details and variants, see Rydel, n.d.).

The second discovery dates from 1935 and is due to Maurice Paul: the three-mirror anastigmatic telescope (Paul, 1935: Figure 35). This is the only all-mirror combination that gives almost perfectly stigmatic images over a large field, with a short focal ratio (see Lemaitre, 2009: 392). Several recent telescopes have been constructed or are under construction using this combination, in particular the Vera Rubin (ex-Large Synoptic Survey) 8.4-m diameter telescope, which is expected to give images of 0.2 arc second over a field of 3.5° diameter.

9 INTERFEROMETRY AND ADAPTIVE OPTICS

In 1970, Antoine Labeyrie invented speckle interferometry (Labeyrie, 1970). Let us recall briefly its principle. Atmospheric turbulence affects the incoming wave front of the light from a star so that it is decomposed into

rapidly variable coherent zones of about 10 cm size with random phases. In a telescope, the instantaneous image is formed of speckles resulting from the interferences between all pairs of these coherent zones.[5] As the lifetime of these speckles is very short, of the order of 10 milliseconds, they can only be seen with very short exposures, requiring a fast detector like a movie camera. With a slow detector like the eye, only a seeing spot is observed.

The minimum size of the speckles is of course equal to the diffraction limit of the telescope at the observing wavelength. A restricted spectral bandwidth is necessary to make visible high-contrast speckles. If we observe a double star with spacing smaller than the seeing spot, the instantaneous image consists of the superposition of two identical speckle patterns, shifted by an amount smaller than the image size. The 2-D Fourier transform of this image exhibits interference fringes corresponding to the separation of the two components. In order to improve the signal-to-noise ratio, it is possible to superimpose the Fourier transforms of many short-exposure images. If we observe a single unresolved star, the Fourier transform is that of the Airy pattern of the unperturbed telescope; if the star has a significant angular diameter, the Fourier transform lacks high spatial frequencies. Figure 36 shows these different cases. The Fourier transforms can be obtained in an analogic way with a laser-illuminated

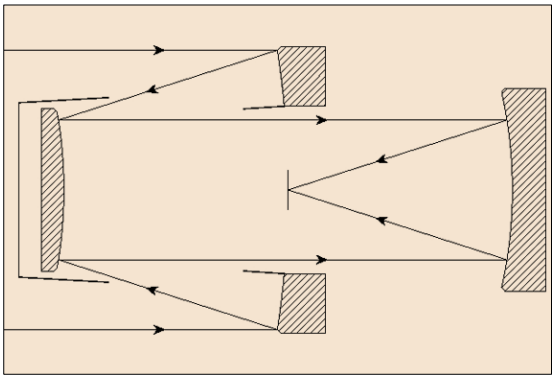


Figure 35: The Paul–Baker three-mirror anastigmatic telescope. The pierced primary mirror is parabolic, the secondary is a convex sphere, the tertiary is also spherical with its center at the vertex of the primary. This gives a curved image. James G. Baker (1914–2005) modified the second mirror to make this image plane. This can also be done with a lens corrector (adapted from Wikimedia Commons).

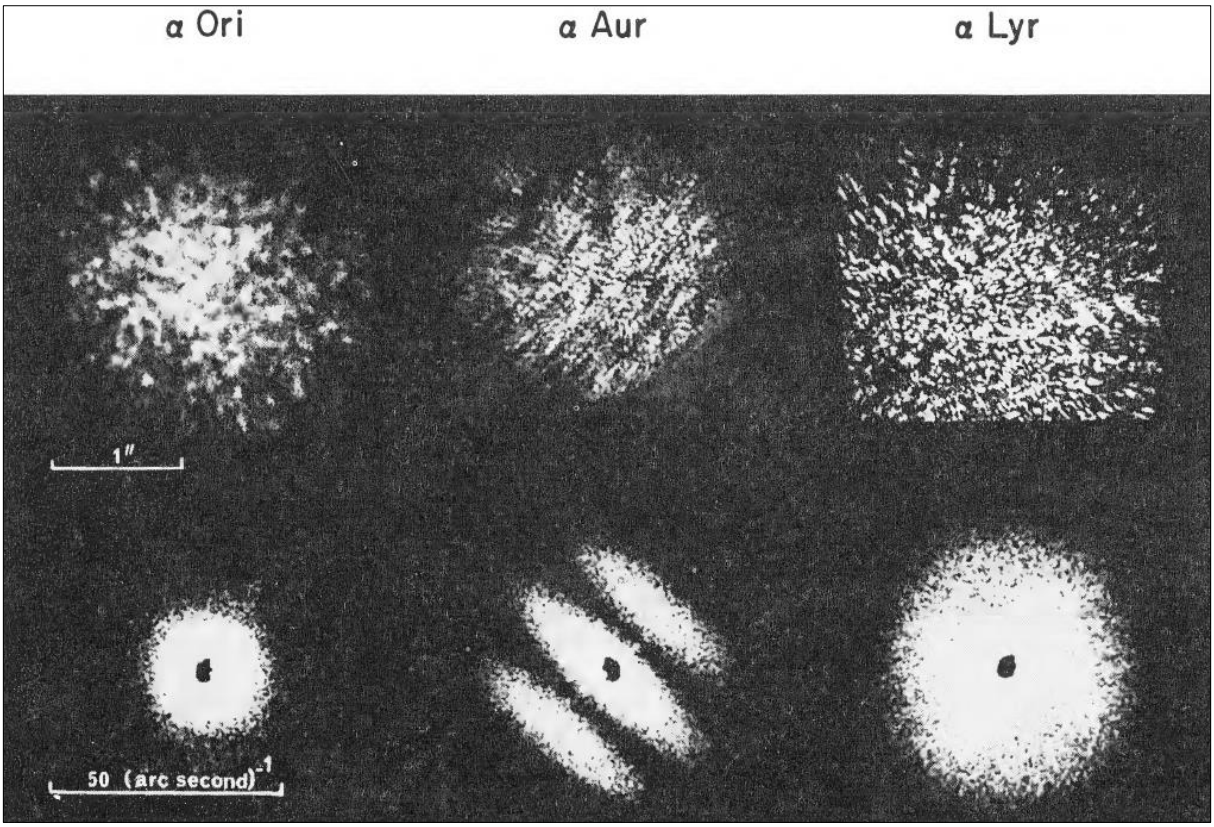


Figure 36: Top row: images of three stars taken with the 5-m Palomar telescope with 0.010 s exposure, bandwith 20 nm at 500 nm wavelength. The seeing was 2″. Bottom row: co-added Fourier transforms of the stellar images in the top row. α Lyr (right) is an unresolved star, the Fourier transform is that of the Airy disk of the telescope. α Ori (left) is resolved, the speckles are enlarged arising from the convolution of the true image (0.06″) with the point spread function. α Aur (middle) is a double star with unresolved components separated by 0.055″, and the Fourier transform shows a fringe pattern, which defines the position angle and the separation of the binary system (after Labeyrie et al., 1974: Plate L11).

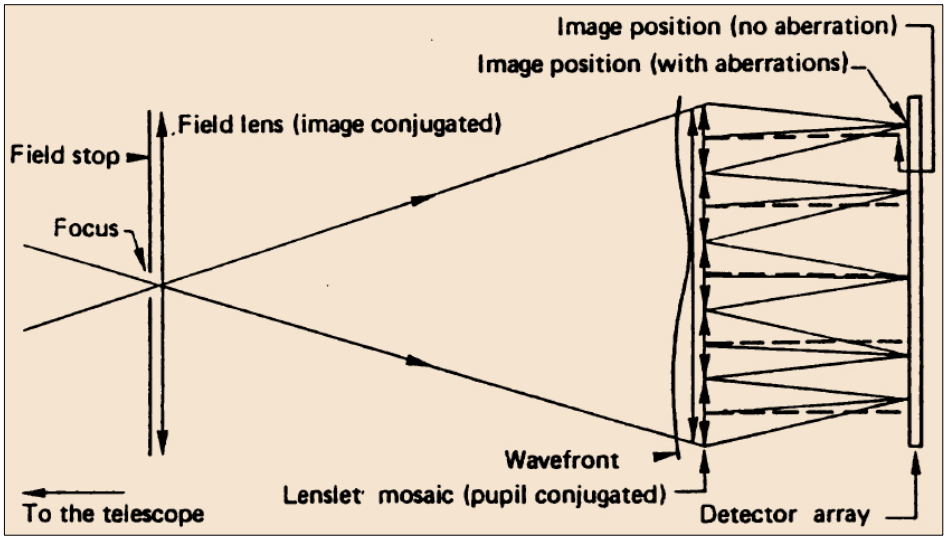


Figure 37: Shack-Hartmann wavefront sensor principle, adapted to OHP's 1.52-m telescope. A mosaic of 5 x 5 holes is placed on a pupil (image of the telescope aperture), which form a series of spots on the detector array. The size of these spots is analyzed by a Reticon array of 100 × 100 photodiodes (after Rousset et al., 1990: 337).

optical system employing the classical aperture/image relationship of coherent optics, or numerically with a fast-Fourier-transform computer algorithm (Bonneau and Labeyrie, 1973: 180). An alternative is to use the autocorrelation of the instantaneous image, which provides a direct, diffraction-limited, image of the source.

Speckle interferometry has been and is still used intensively, including by amateurs, for studying binary stars, and also to observe the limb darkening of resolved, supergiant stars. However, the importance of speckle interferometry is declining in the infrared, because adaptive optics now makes it possible to benefit from the full resolution of big telescopes.

Adaptive optics is a method to correct in real time the effect of atmospheric turbulence on telescopic images. For the moment, this is possible only in the infrared where the turbulence effects are less severe than in the visible, due to the longer wavelength. Adaptive optics was initially implemented in the late 1970s by US Air Force in order to obtain from the ground images of Soviet satellites. As this was a classified subject, astronomers had to work from scratch to build an adaptive optics system.

This was first achieved in October 1989 by a consortium of European Southern Observatory, Paris Observatory and two French laboratories, LASERDOT and ONERA. An analysis of the incoming instantaneous wave front coming from a sufficiently bright star is performed every 1/100 second in visible light by a Shack-Hartmann sensor (Figure 37). This works even if the observations are in infrared because atmospheric fluctuations are achromatic.

A thin mirror on the optical path is deformed by actuators controlled by an on-line computer, in order to compensate for the deformations of the wave front. Another, tiltable mirror on the optical path compensates for the large-scale wave-front deformation due to the refraction index gradient across the telescope aperture. Figure 38 is the optical scheme of the initial adaptive optics system, and Figure 39 shows one of the first results.

Initially, only a small field around the reference star could be observed. In order to observe an arbitrary field, one or several artificial reference stars are created by a laser beam emitted near the telescope, which excites the sodium atoms located in the upper stratosphere. This possibility is at present implemented on all large telescopes. Adaptive optics is an absolute necessity for the giant telescopes presently under construction.

Astronomical applications of interferometry other than speckle interferometry were developed very early in France (their application to spectroscopy will be discussed in Section 12). As early as 1851, Hippolyte Fizeau (1819–1896) imagined that the apparent size of stars can be obtained by interferometry, and Édouard Stephan (1837–1923) applied this idea in 1873 to all bright stars visible from Marseilles, using the 80-cm Foucault telescope with a two-slit screen placed on the mirror (Georgelin and Lequeux, 2021: 253).

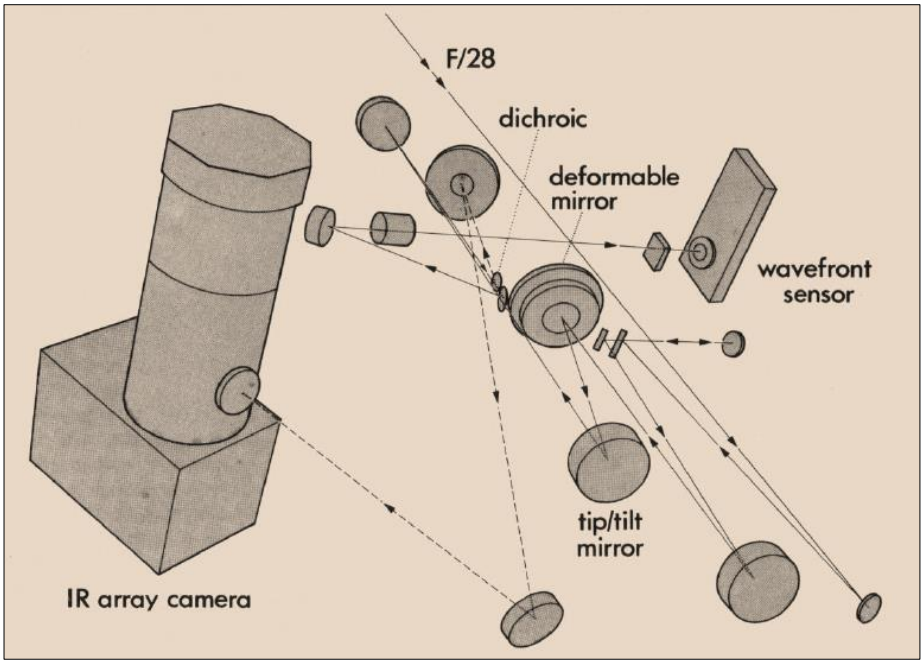


Figure 38: Optical scheme of the first adaptive optics system, adapted to the coudé focus of OHP's 1.52-m telescope. The f/28 beam enters from the top, a focal reducer changes the aperture ratio to f/8, and an off-axis parabolic mirror collimates the beam to the deformable mirror. After this mirror, the beam is reflected to a gimbal-mounted mirror that corrects for the gradient of refraction index through the telescope aperture, and a second off-axis parabola refocuses it. The infrared and visible parts are separated by a dichroic mirror. The infrared part is sent to the IR array camera, while the visible part is reflected to the wavefront sensor (after Merkle et al., 1989: 3).

None of the stars was resolved, and he concluded that their apparent diameters were smaller than 0.16 arc second. This method was used by Albert Michelson (1852–1931) in the USA and by Maurice Hamy (1861–1936) in Paris to obtain the diameter of Jupiter's Galilean satellites and of Vesta. It is well-known that the first positive measurement of a star's diameter was obtained by Michelson and Francis Pease (1881–1938) in 1920.

In 1895, Karl Schwarzchild (1873–1916) in Munich measured the separation of binary stars with an interferometric method derived from that of Fizeau. His instrument was the first of a series of interferometers with different principles dedicated to the measurement of binary stars (Bonneau, 2019: Chapter 5). Amongst them, the interferential micrometer of André Danjon (Figure 40) was particularly ingenious because of its luminosity (Danjon, 1933; 1937; 1955b); for a description, see (Bonneau, 2019: 66). These interferometric methods have been later superseded by speckle interferometry.

The diameter measurements of Michelson and Pease were followed by measurements by Pease alone with a new 50-ft interferometer. Due to various difficulties, only seven star diameters were measured from 1931 to

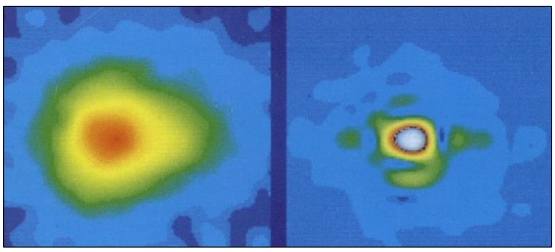


Figure 39: Images of Deneb in the infrared K-band without (left) and with (right) the adaptive optics feedback loop activated. The image diameter shrinks from 1.0 to 0.37 arc second, the diffraction limit of the 1.52-m telescope (after Merkle et al., 1989: 1).

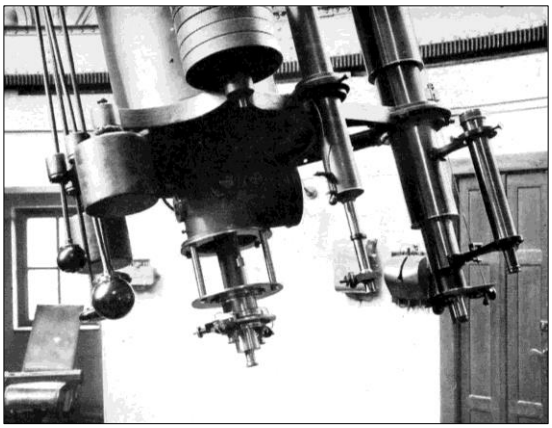


Figure 40: Danjon's interferential micrometer mounted on the 49-cm Merz equatorial in Strasbourg (after Danjon, 1937: Plate 194.1).

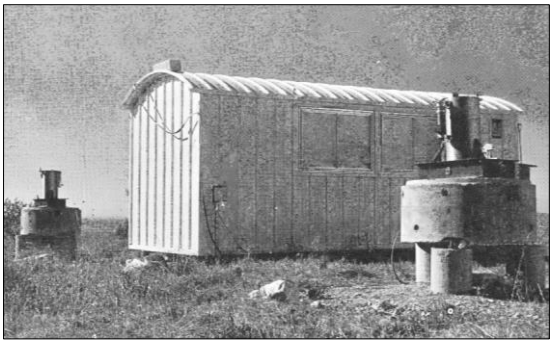


Figure 41: The first two-telescope interferometer installed by Labeyrie at Nice Observatory (after Labeyrie, 1975: Figure 2).

the death of Pease in 1938 (Bonneau, 2019: 37). Then the method was abandoned, until Robert Hanbury Brown (1916–2002) and Richard Q. Twiss (1920–2005) built their intensity interferometer at Narrabri (Australia) in 1964. With it, they measured until 1974 the diameter of 32 stars with a high accuracy, but they could not go beyond this number because of the intrinsic lack of sensitivity of this method. It was thus necessary to come back to Fizeau's concept. The main difficulty with the Michelson–Pease interferometers, as well as with the derived interferometer built in 1968 in the USSR by Evgeni Kulagin and Vladimir Linnik (1889–1984), was the vibration of the long beam that supported the base. Moreover, the length of this beam was necessarily restricted, limiting the angular resolution of the instrument. It is probably this limitation that convinced Antoine Labeyrie to propose collecting the light with two independent telescopes, each reflecting the light to a fixed laboratory where the beams would interfere.

After some trials in Meudon, Labeyrie and his students installed the first two-telescope interferometer at Nice Observatory in 1974 (Figures 41 and 42). Fringes were regularly obtained on Vega in summer 1974, and the star was found unresolved while the fringes could not be observed with Pease's 50 ft interferometer because of vibrations of the beam (Labeyrie, 1975). This success can be considered as the triggering event for the development of long baseline optical interferometry. Labeyrie and his collaborators made successive improvements to the technique, which are described in detail by Bonneau (2019: Chapter 7). Their first interferometer was transported in 1976 to a better site, the Calern Observatory near Grasse, at 1250 m elevation; the two telescopes could now move on a 60-m long North–South rail track. The fringes were observed in light dispersed by a spectrograph, allowing the study of the morphology of close binaries like Capella, or that

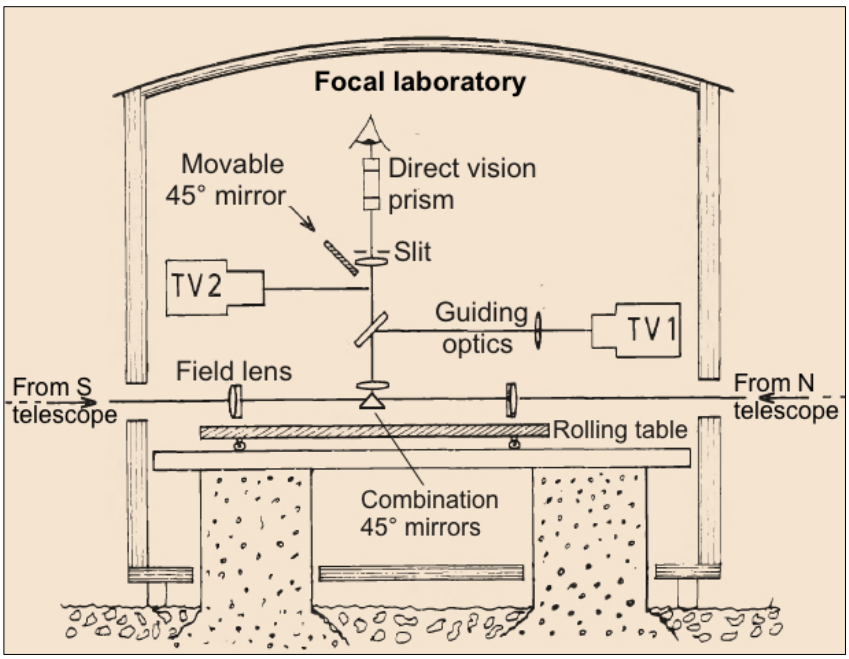


Figure 42: Optical scheme of the 2-telescope interferometer. The observation was made during the meridian transit of the star in order to minimize the change in the difference between the two optical paths, which was compensated by the rolling table holding the focal equipment. The guiding optics with the TV1 camera allowed piloting the 25-cm diameter telescopes. The two pupils were combined and the fringes modulating the focal image were searched visually in the spectrum of the star formed by a direct vision prism; then the 45° mirror was inserted and the fringes registered by the TV2 camera (adapted from Labeyrie, 1975: Figure 1).

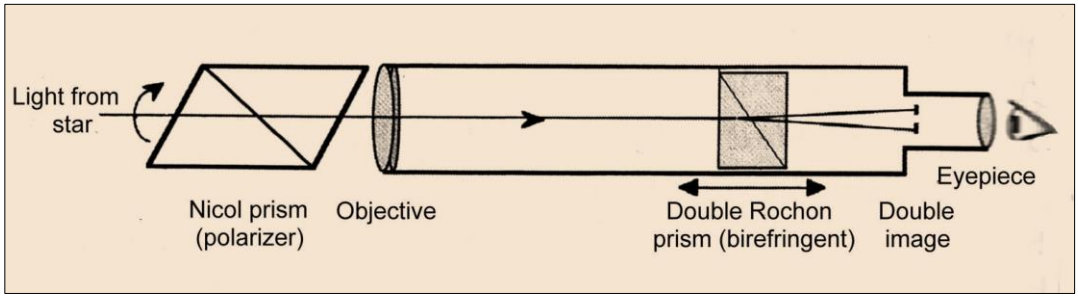


Figure 43: Principle of Arago's photometric apparatus. A polarizer is placed in front of the objective (it could also be on the back), and the analyzer is a birefringent Rochon prism producing two images polarized in perpendicular directions. One could change the separation of the images by displacing the Rochon prism along the axis of the telescope, and the relative intensity of the images by turning the polarizer by a known angle (authors' drawing).

of the immediate surroundings of supergiant or Be stars. The 25-cm diameter telescopes were replaced by 1.5 m ones, with the inconvenience that the fringes were visible on each of the numerous speckles.

Interferometry is presently flourishing, with about ten interferometers in operation worldwide (Bonneau, 2019: 163). The first ones used small-diameter telescopes in order to limit the problems with atmospheric turbulence, but it is presently possible to use efficiently larger telescopes equipped with adaptive optics, at least in the infrared. An example is the GRAVITY instrument of the VLTI (2016), which combines the light of either the four VLT 8.2-m diameter telescopes or the four 1.8-m auxiliary telescopes, all with adaptive optics (GRAVITY collaboration, 2017). To end this section, let us mention the infrared interferometer SOIRDETE, which involved heterodyne detection with a 11-μm CO_2 laser as the local oscillator (Assus et al., 1979). This instrument with two 1-m diameter telescopes on a 15-m baseline was installed in 1974 by Jean Gay, Alain Journet (1941–2007) and collaborators at Calern Observatory and used for a few years until the accidental destruction of the laser.

10 PHOTOMETRY AND PHOTOGRAPHY

Photometry began with Huygens: he was first to compare the optical flux of Sirius to that of the Sun. The problem was that only visual observation was possible, while the eye can only compare equal luminous intensities. It was thus necessary to attenuate in a known way the comparison light, which had the higher intensity, so that it was equal to that with the fainter intensity. This is what Huygens did using geometry, as did his successors Pierre Bouguer (1698–1758) and Jean-Henri (or Johann Heinrich) Lambert (1728–1777); their results were rather inaccurate. They also wondered if the disc of the Sun was uniform or presented a limb brightening or darkening, with contradictory results.

Arago was probably the very first to enter quantitative photometry in the 1810s by attenuating the light from sources by a polarizer/analyzer pair, a method used by most later nineteenth century photometers. He went to great pains, with a special instrument preserved at Paris Observatory, to verify the cosine-squared law that gives the attenuation of light as a function of the angle α between the planes of the polarizer and of the analyzer: $I = I_0 \cos^2\alpha$, where I_0 is the incoming intensity and I that after the analyzer. He then built a photometer (now lost) based on this principle (Figure 43) and tried to use it to attack the problem of the limb of the Sun, but with no conclusive result.

For stellar photometry, Arago turned the polarizer until the fainter image of the star disappeared. Repeating the observation for another star, he could get the ratio of their fluxes providing that the background had not changed between the two observations and the stars were not polarized. A few such observations were made around 1850 by Ernest Laugier (1812–1872), a colleague of Arago who was by then almost blind. The results were somewhat scattered because of variations in seeing and background (see Lequeux, 2016: Figure 8.18), but they were unbiased. This method would have been useful for rapid photometry of many stars, even if distant from one another. Unfortunately, it was never used, due to a lack of interest from Le Verrier, who succeeded Arago in 1854.

The problem of the limb darkening of the solar disc was finally solved by photography. The first successful astronomical photographs are daguerreotypes of the Sun taken by Fiz-

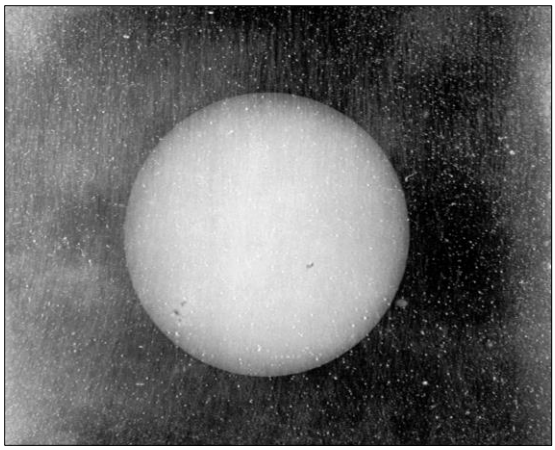


Figure 44: The first large photograph of the Sun, a daguerreotype obtained in 1845 by Fizeau and Foucault. The diameter of the disc is 90 mm. Notice a few sunspots and the limb darkening of the disc (courtesy: Musée des Arts et Métiers-CNAM).

eau and Foucault after 1843 (Tobin, 2003: Chapter 4). The largest one (Figure 44) was obtained on 2 April 1845 and is preserved in the *Musée des Arts et Métiers/CNAM* in Paris. In spite of the low sensitivity of the daguerreotypes, the exposure time had to be as short as 1/100 second. As there was no fast shutter at the time (the hand of the photographer was placed on the objective and removed during the exposure), they imagined a "*rather original*" shutter made of a board with a horizontal slit falling in front of the objective. This photograph shows clearly the limb darkening of the solar disc, which was still controversial at the time.

The next important French astronomical photographs were taken in the 1880s by the Henry brothers in Paris. One of these is reproduced as Figure 45. As already mentioned

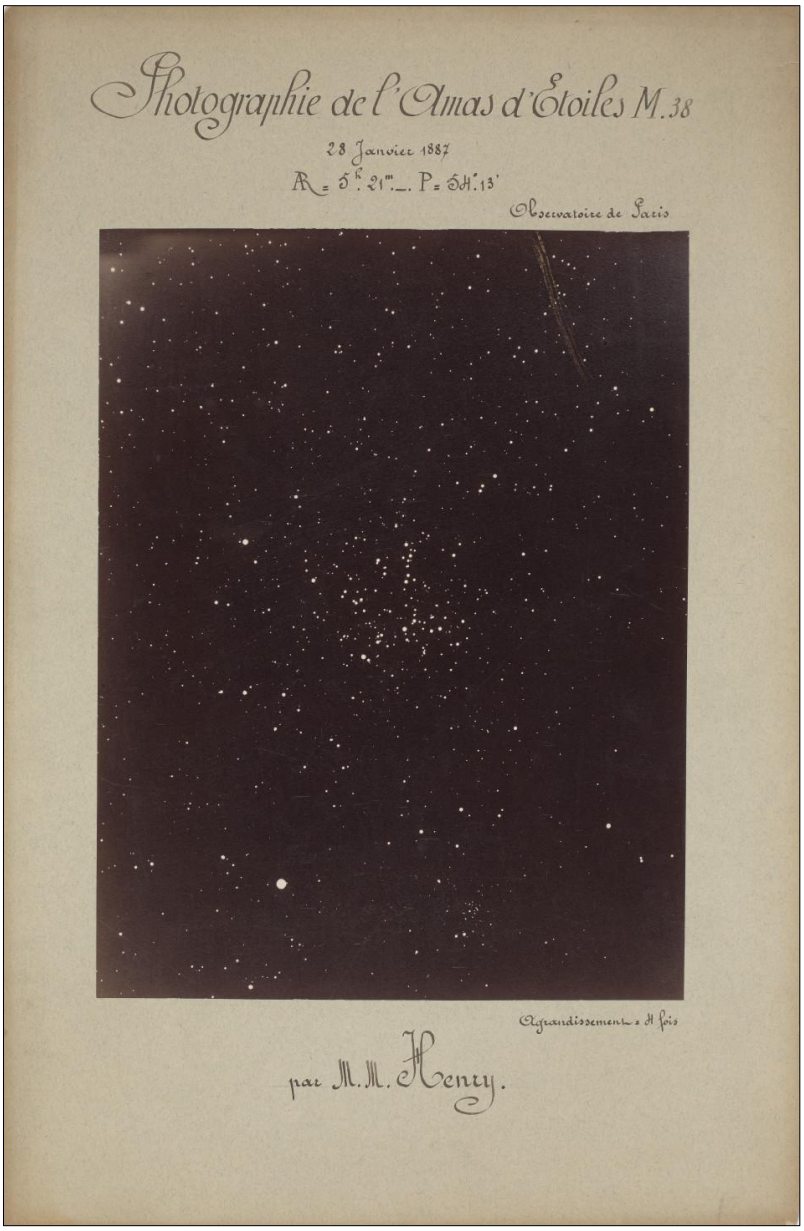


Figure 45: A photograph taken in 1887 by the Henry brothers (courtesy: Paris Observatory).

in Section 4, their quality was noticed by astronomers worldwide and triggered in 1887 the enormous project of the *Carte du Ciel,* that was to take most of the strengths of French astronomy for decades (Lamy, 2008). Photography was also used extensively for the search for asteroids, in particular at the Nice Observatory.

Let us return to photometry. After Arago, a number of stellar photometers were constructed in which the light of the star was compared visually to that of a lamp attenuated by a polarizer/analyzer pair. The best known are those of Zöllner (ca. 1860) in Germany and Pickering, used to measure magnitudes of stars of the Harvard catalogue. In Paris, in 1909 Charles Nordmann (1881–1940) built a multi-color photometer on a similar principle. It had blue and red filters, calibrated using the radiation of solids at different temperatures, and was used to apply Planck's formula for the first time in measuring the temperature of the Sun and stars (Lequeux, 2010). The well-known measurement of the temperature of the Sun by Charles Abbott came later (in 1913).

Charles Fabry was also interested in astronomical photometry and invented a simple, ingenious method to compare the flux in any circular region of the sky with that of a reference star (Fabry, 1915). The observed region was limited by a diaphragm in the focal plane of a telescope, and a short-focus system produced on a photographic plate a pupil (image of the objective), small and uniformly illuminated. It was thus possible to compare the total flux of the region with that of a reference star observed with a diaphragm set as small as possible. This method has often been employed since.

But the time had come to use detectors other than the human eye and photography. In fact, thermometers with blackened reservoirs had long been used to detect infrared radiation: it is in this way that William Herschel discovered the infrared in 1800. Then came thermocouples, bolometers, radiometers, etc. for the same purpose (for a history see Lequeux, 2009). However, for visible light, the first photocell, using selenium, was only applied to astronomy in 1894 (Minchin, 1895).

Because the selenium photocell was not very sensitive, soon photocells were built using photoemission from alkaline metals, generally with a thick potassium photocathode treated with hydrogen, sensitive to the blue (see e.g. Kemp, 1913). These cells contained a low-pressure neutral gas multiplying the free electrons by ionization. The current was measured by an electrometer or a galvanometer. The first such French photoelectric cells were constructed in the early 1920s by Dunoyer de Segonzac, whom we already encountered with respect to mirror aluminizing (in Section 5). Gilbert Rougier (1886–1947) was doing similar work at Strasbourg Observatory (Rougier, 1925). He used these cells in a photometer whose principle is displayed in Figure 46. It is photographed in Figure 47.

Photoelectric cells were also used in microphotometers for scanning photographic spectra. Rougier (1925: 74) describes a micro-

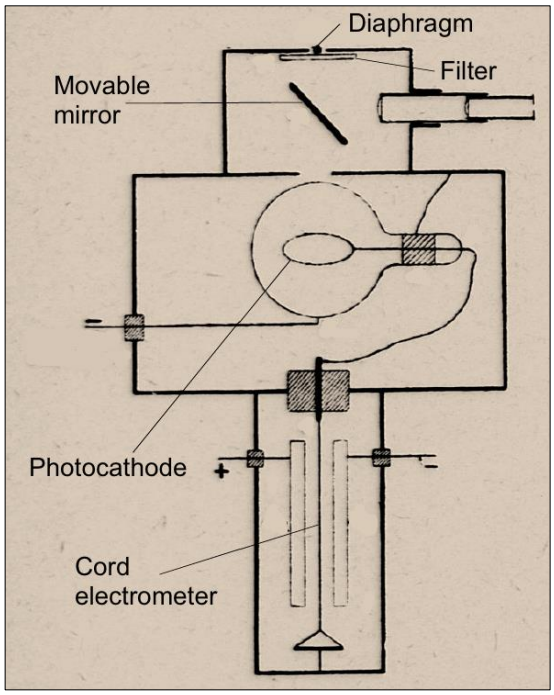


Figure 46: Rougier's photometer. The positive charges accumulated on the illuminated photocathode produce a potential measured by an electrometer whose cord is deflected, its deviation being measured by a microscope with a micrometer (adapted from Rougier, 1925: Figure 21).

photometer where the photocell signal was amplified by a triode. It was recorded by a galvanometer whose mirror reflected light rays that exposed a photographic plate displaced in synchronism with the scanning photocell.

The thick photocathodes of the first photocells were replaced in the early 1930s by the thin photocathodes we know now. Photomultipliers invented soon after increased their sensitivity considerably. Excellent photomultipliers were produced at different epochs by André Lallemand (1904–1978).

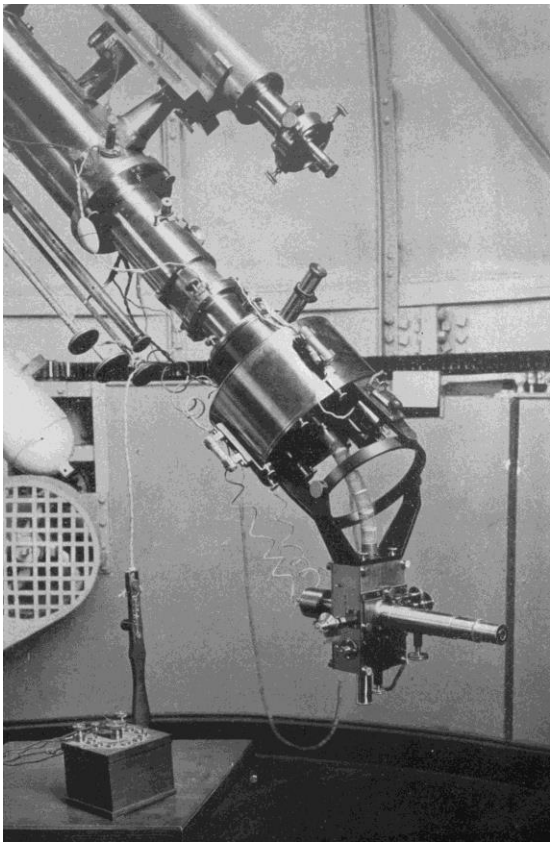


Figure 47: Rougier's photometer (ca. 1925) attached to the 16-cm diameter Repsold equatorial at Strasbourg Observatory. The cord electrometer, which has to stay vertical, is the gimbal-suspended box at the bottom with its measuring microscope (after Bosler, 1928: Plate III).

The electronic camera was the life work of Lallemand (1964). As early as 1936, when at Strasbourg Observatory, he had built a prototype in which the telescopic image was formed on a photocathode which emitted electrons, accelerated to 22,000 volts and producing thanks to a magnetic lens an electronic image on a zinc sulfur screen or a photographic plate (Lallemand, 1936a; 1936b). Several improvements were made in Paris after WW2 by Lallemand and Maurice Duchesne (1913–2004) (Lallemand, 1955). A photocathode contained in a thin glass capsule was introduced in the instrument, a magnetic manipulator broke this capsule and moved the photocathode in place. Several photographic plates were placed on a rotating support, allowing a number of exposures. All this was in a very good vacuum. A major inconvenience was that the instrument had to be opened to recuperate the exposed plates, with the consequence that the photocathode was destroyed. The instrument had the quantum efficiency of the photocathodes, of the order of 10% against 1% for photographic plates, and a good linearity; but it was cumbersome, fragile, difficult to use and many failures were encountered, so that relatively few results were obtained in spite of enormous efforts. Figure 48 shows an electronic camera in its transportation case.

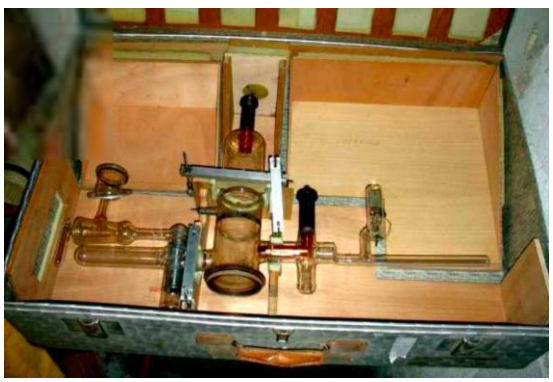


Figure 48: An electronic camera in its transportation case (ca. 1963). The accelerating electrodes and the electronic optics have been removed. The lateral dimension is 96.5 cm (courtesy: Paris Observatory).

Paul Felenbok (1936–2020) and collaborators built a metal–ceramic camera with a valve that preserved the photocathode (Figure 49); the first observations with this new electronic camera were made in 1980—at the same time as the arrival of CCDs that were more sensitive and considerably easier to use—so it was rarely used (Baudrand et al., 1982). Just like the *Carte du Ciel*, the endless saga of the electronic camera took a large part of the forces of French astronomy, but with little reward.

The first CCDs had a very limited number of pixels. The first French observations with CCD date from 1980 (Dreux et al., 1981). Arnaud et al. (1994) describe a rather heroic effort to build a camera with a 20-cm^2 mosaic of sixteen 579 × 400-pixel CCDs. The next difficulties were with the mosaics of infrared detectors necessary for ISOCAM, the camera of the European Infrared Space Observatory (ISO) launched in 1995, for which France was mainly responsible. Such detectors were made in the USA and classified, and new ones had to be produced by the LETI, a subsidiary of the *Commissariat à l'Énergie Atomique* (CEA). Since that time, large mosaics have been constructed in France for the visible and the infrared, and installed in particular at the prime focus of the Canada–France–Hawaii telescope.

11 POLARIMETERS

In 1808, the French physicist Étienne Louis Malus (1775–1812) discovered by chance the polarization of light. Arago and Biot were interested and soon became specialists of polarization, without rivals except for David Brewster (1781–1868) in Scotland. In 1811, Arago

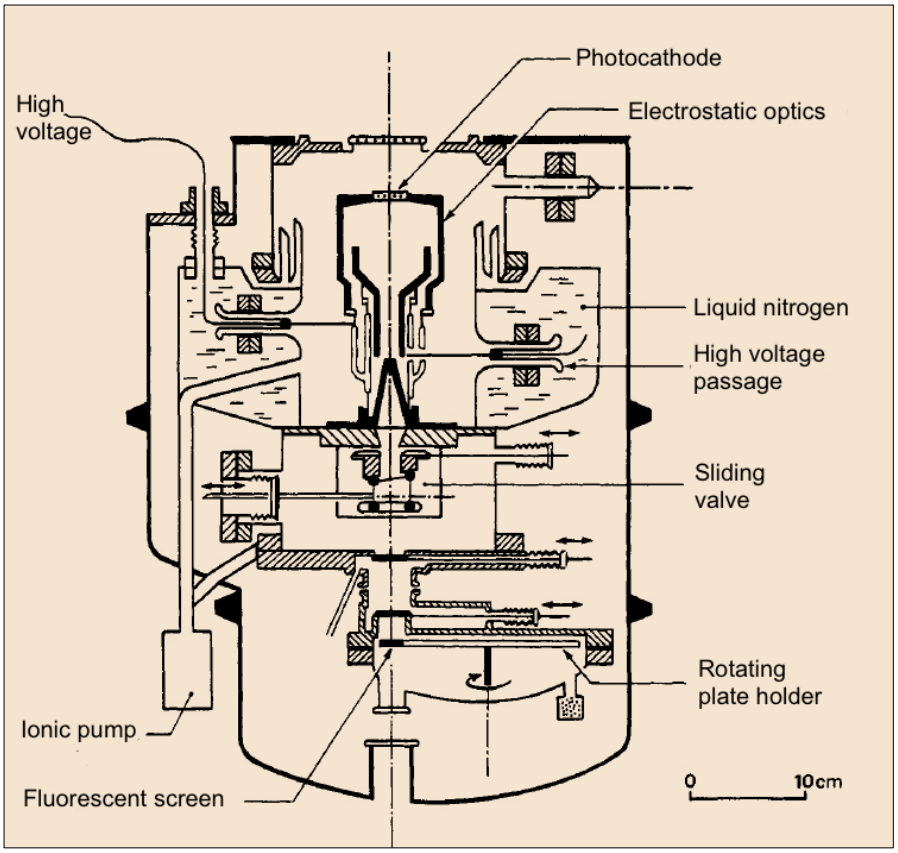


Figure 49: A schematic view of the valve electronic camera (adapted from Baudrand et al., 1982: 296).

discovered chromatic and rotational polarization, and had a polarimeter built on this principle (Figure 50): for details see Lequeux (2016: Chapter 3). With this instrument, Arago discovered the polarization of the blue sky, that of the Moon and of the tails of comets, and showed in 1811 that the photosphere of the Sun was made of incandescent gas, and could not be solid or liquid. For this, he observed that the disk of the Sun was nowhere polarized, while the light emitted obliquely by red iron or molten platinum was polarized. As this was the first time that one could affirm something about the physical nature of a celestial body, this can be considered as the birth of astrophysics.

Very little happened after these measurements (for a history, see Lyot, 1929: 3), and no polarization had been detected on planets except for a narrow zone around Mars' polar caps until around 1920, when Bernard Lyot built a very sensitive polarimeter (Lyot, 1923; 1929: 12). This instrument is too complicated to be described here. It was used for very interesting studies of the nature of the surfaces of the Moon, Mars and Mercury, of the rings of Saturn and of aerosols in the high at-

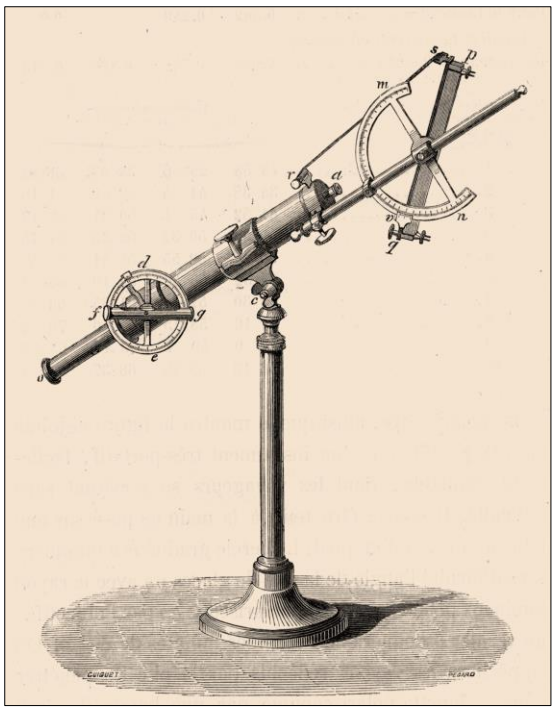


Figure 50: Arago's polarimeter. The oblique glass plates in front of the polariscope can be used to measure the degree of polarization of the incoming light, by compensating for it by a suitable inclination. This instrument had much success and several samples survive (courtesy: Paris Observatory).

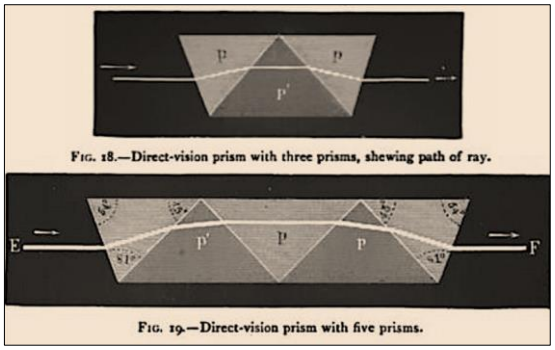


Fig. 18.—Direct-vision prism with three prisms, shewing path of ray.

Fig. 19.—Direct-vision prism with five prisms.

Figure 51: Direct-vision prisms. Top: Amici's prisms; bottom: Hofmann's prisms. The flint prisms are in dark grey, the crown ones in light gray (after Barnard, 1869: 528).

mosphere of Venus. These results, obtained by comparison with terrestrial substances, were published by Lyot (1929).

This instrument was visual. In 1948, Lyot presented to the Academy of Sciences a note describing an extremely sensitive photoelectric polarimeter, which was the basis of most modern instruments (Lyot, 1948).

12 SPECTROGRAPHS

It is well known that Joseph von Fraunhofer observed—perhaps after Wollaston but independently—lines in the spectrum of the Sun formed by a prism. This marked the beginning of astronomical spectroscopy. In France, Edmond Becquerel (1820–1871) obtained, probably for the first time, photographs of the UV-green solar spectrum on daguerreotypes, extended to the red using phosphorescence (Becquerel, 1842). These results raised the enthusiasm of Joseph Norman Lockyer (1836–1920) who wrote:

> [Becquerel] did what has never been done since, so far as I know. He photographed the whole solar spectrum with nearly all the lines registered by the hand and eye of Fraunhofer. I do not mean merely the blue end of the spectrum, but the complete spectrum, from the "latent light" – the ultra violet rays of Draper – to the extreme red end. (Lockyer, 1878: 81).

Becquerel used a simple prism, but this device is not well suited for astronomical observation through a telescope because of its deviation; so, astronomers preferred to use the direct-vision prisms of Giovanni Batista Amici (1786–1863); they were improved by the Parisian optician Jean Georges Hofmann (or Hoffmann, 1823–1892) who added two more prisms (Figure 51).

A three-element Amici's direct-vision prism was used by Charles Wolf (1827–1918) and Georges Rayet (1839–1906), at the focus of Foucault's 40-cm diameter telescope (see Figure 20), for their 1867 discovery of the emission-line stars that bear their names. More sophisticated spectroscopes (Figure 52) were conceived by Janssen and built by Hofmann (Launay, 2012). In 1863, Janssen carried his 'pocket spectroscope' to the Vatican Observatory. With Father Angelo Secchi (1818–1878), he observed a wide variety of stars with this spectroscope, which was adapted to the Vatican 24-cm Merz equatorial. Secchi became jealous of these results and forbade Janssen to use his telescope anymore, while publishing under his sole name in *Astronomical Nachrichten* (Secchi, 1863).[6]

Important progress in high-resolution spectroscopy was due to Louis Thollon (1829–1887), an astronomer at Nice Observatory. He designed a double-passage instrument,[7] which was built by Léon Laurent (1840–1909) (Figure 53). Its prisms could be rotated in order to stay at the minimum deviation what-

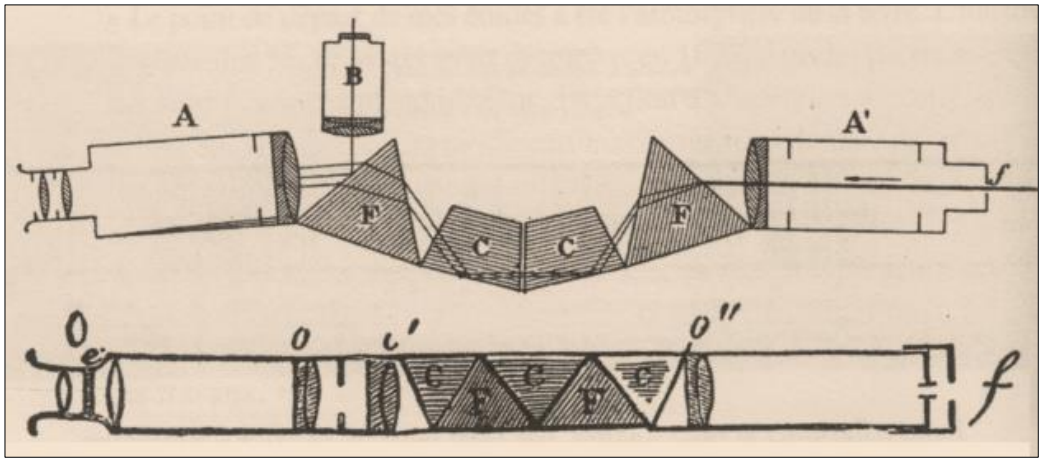


Figure 52: Two spectroscopes of Janssen, built by Hofmann (ca. 1862). Light enters from the right, through a slit. The prisms C are in crown, F in flint. The spectroscope at the bottom is a 'pocket spectroscope' that was very successful (after Janssen, 1862: 73).

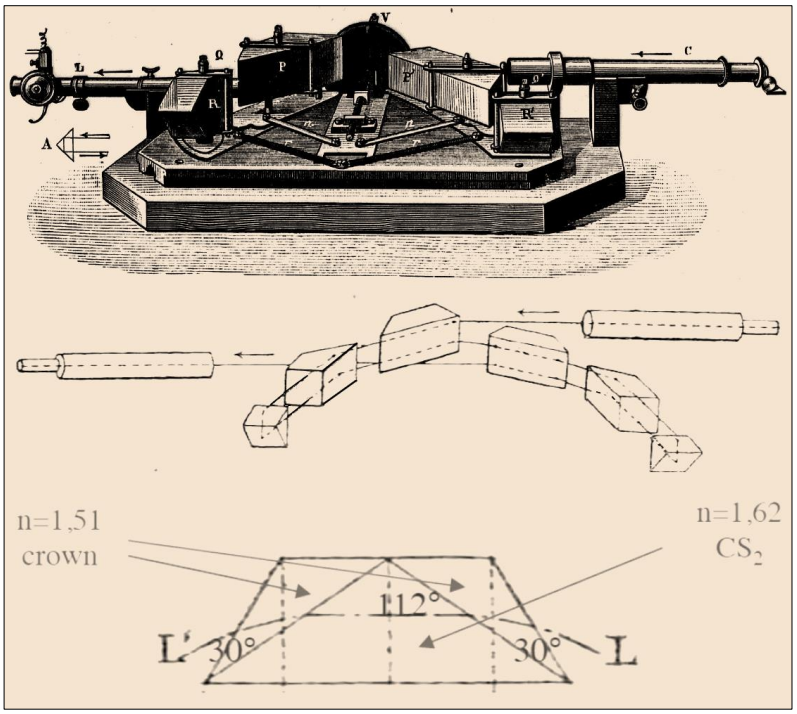


Figure 53: Thollon's high-dispersion spectroscope. Top: general view (after Thollon, 1890: A.9). The direct vision prisms P and P' can be oriented to stay at the minimum deviation for the observed wavelength. R and R' are semi-prisms followed by a prism reflecting the light to the other level. Middle: principle, adapted from Salet (1888: 42); the semi-prisms and the reflecting prisms are separated for clarity. Bottom: principle of the direct vision prisms of crown and carbon disulfide; the light ray L L' is at the minimum deviation.



Figure 54: The auto-collimation spectroscope of Fabry and Jobin (1904: 203). The light from the slit F is sent by the total reflection prism R to the flint prisms T_1 and T_2, and back to the eyepiece or a photographic plate in S after reflection by mirror M. This mirror is slightly turned in order that the reflected light is not obstructed by R. A mechanism orients T_1 and T_2 so that they give the minimum deviation for the mean observed wavelength.

ever the wavelength, so that the central wavelength was centered in the eyepiece. The resolution was considerable, three times better than that of the contemporary concave Rowland grating in the third order. It allowed Thollon to draw 4000 lines in the solar spectrum compared to 1200 by Ångström in 1868. Thollon was also able to verify the Doppler–Fizeau principle, observing the rotation of the Sun by comparing the spectra of the disc edges.

Another interesting double-passage, high-resolution prism spectroscope was built in 1904 by Fabry and Amédée Jobin (1861–1945), the founder of the celebrated Jobin–Yvon firm. This time, it used auto-collimation, the reflected and dispersed light following backwards the same path as the incident one (Figure 54). Its wavelength resolution was very high, and its luminosity superior to that of a grating spectrograph with the same resolution.

However, the gratings won in the end: in 1895, Rowland, who had modified the grating by ruling it on a spherical mirror, enlarged Ångström's tables to about 20,000 lines.

It is worth noting that after the first ruled gratings made by Fraunhofer in the early

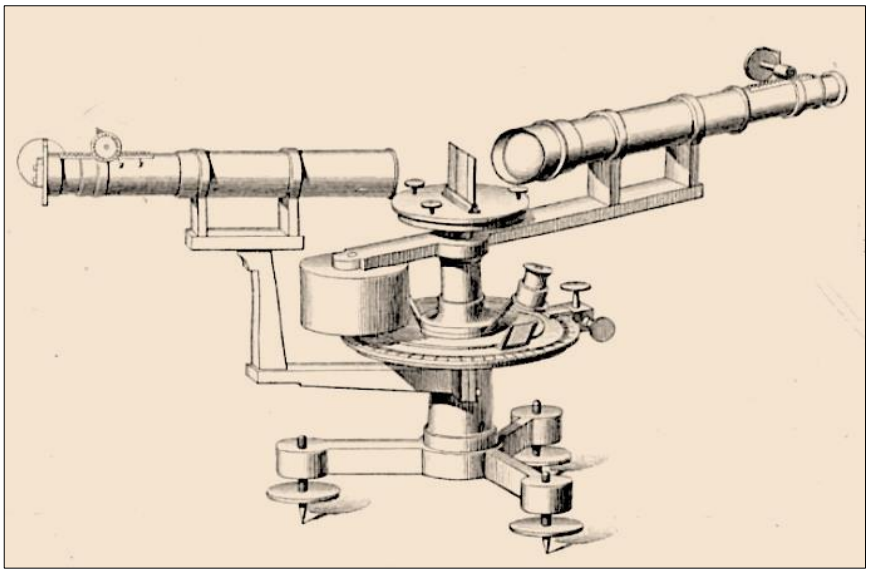


Figure 55: Mascart's grating spectroscope (1864). A goniometer measured the deviation of the light from the transmission grating at the middle. A similar device was used by Ångström four years later to build his atlas of solar lines (after Mascart, 1864: Figure 1).

1820s, little happened until Friedrich Adolph Nobert (1806–1881), an optical instrument-maker of Pomerania, produced gratings ruled on glass in the 1850s. In France, it seems that the physicist Eleuthère Mascart (1837–1908) was first to use one of these gratings for astronomy, in order to determine accurately the wavelengths of the UV lines of the Sun (Mascart, 1864; Figure 55). The physicist Jacques Babinet (1794–1872) and Mascart fully understood, but after Fraunhofer, that the grating uses a combination of diffraction and interference (Figure 56).

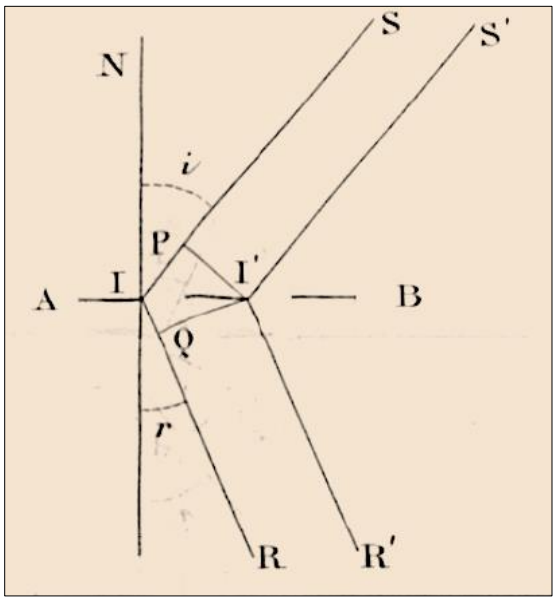


Figure 56: Principle of the transmission grating, according to Babinet and Mascart. The incident light S S' (assumed here to be monochromatic) is diffracted by the grating and interferes in the direction R R' such that the optical path PIQ is equal to one wavelength for the first order, or two wavelengths for the second order, etc. The deviation is minimum when the direction of arrival is such that the angles *i* and *r* are equal (after Mascart, 1864: Figure 4).

However, grating spectroscopes and spectrographs seem to have been neglected in France for several decades, perhaps due to the difficulty of producing the gratings that had to be purchased at high cost from the USA (Rowland, 1882).

The spectroheliograph was invented independently around 1891 by Henri Deslandres (1853–1948) in France and by the young George E. Hale (1868–1938) in the USA. The two men knew each other well and the competition was friendly at the beginning, although their relation became strained after some time, both claiming priority. Figure 57 illustrates the principle of this instrument.

Deslandres was an expert spectroscopist, and he built several spectroheliographs at Meudon Observatory of increasing complexity (Deslandres, 1906; 1910, 13). Figure 58 is a view of the 1908 very complex instrument, which consisted of four spectroheliographs with prisms or grating, fed as desired by the same objective. Figure 59 shows the great optician Alfred Perot (1863–1925) near the cœlostat of the Meudon spectroheliographs.

A spectroheliograph is still in use today at Meudon, with elements from Deslandres' original ones (see https://observations-solaires.obspm.fr/Le-spectroheliographe).

Just before WW1, Henri Chrétien designed for Nice Observatory a simpler spectroheliograph, which was built by Jobin (Figure 60). It was transferred in 1928 to Marseilles

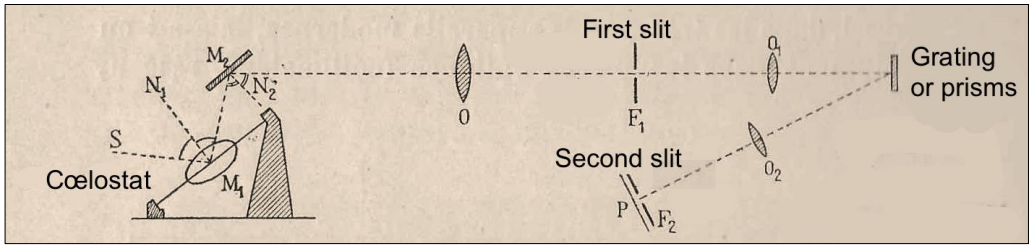


Figure 57: Principle of the spectroheliograph. A fixed image of the Sun is formed on a first slit, sometimes directly by a telescope or by a Foucault siderostat (see Figure 22), or by a cœlostat like here; the cœlostat is generally preferred to the siderostat because it causes no field rotation. A high-resolution spectrograph gives a dispersed image of the first slit F_1 on a second slit F_2 that selects a part of the observed line. A simultaneous motion of the image on F1 and of the photographic plate is used to scan across the solar disk or protuberance (adapted from Bosler, 1928: Figure 54; Georgelin Collection).

Observatory and fed by a Gautier cœlostat (Figure 61) with flat mirrors polished by the Henry brothers (Bosler, 1929).

The chase for high spectral and angular resolution resulted in the astronomical use of the Fabry–Perot interferometer, which we shall call the Perot–Fabry interferometer as more historically justified. This is a long story that we have recently developed in this journal (Georgelin and Lequeux, 2021) and needs not to be reproduced here. Figure 62 shows the interferometer installed on the 80-cm Foucault telescope. With this set-up, the motions and the temperature of the ionized gas of the

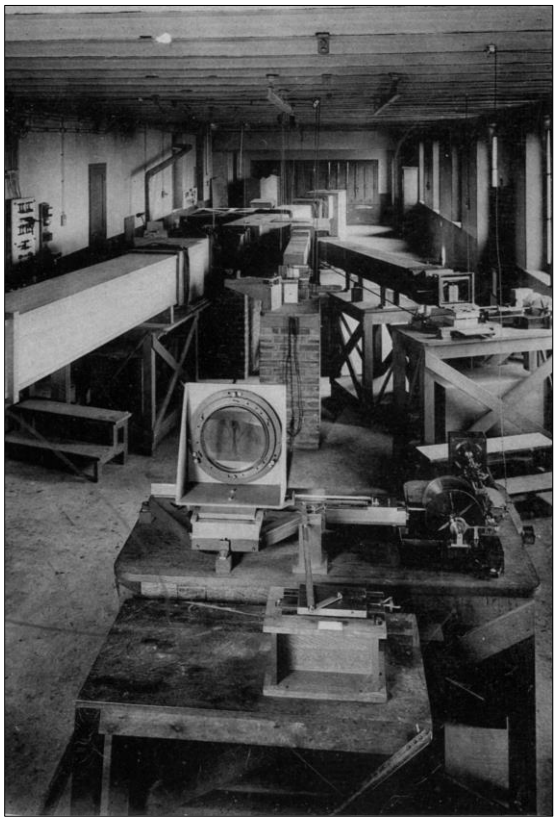


Figure 58: The spectroheliographs of Meudon Observatory, 1908 version. The drawing in Deslandres (1910: 37) shows the optical design of this complex instrument (courtesy: Paris Observatory).

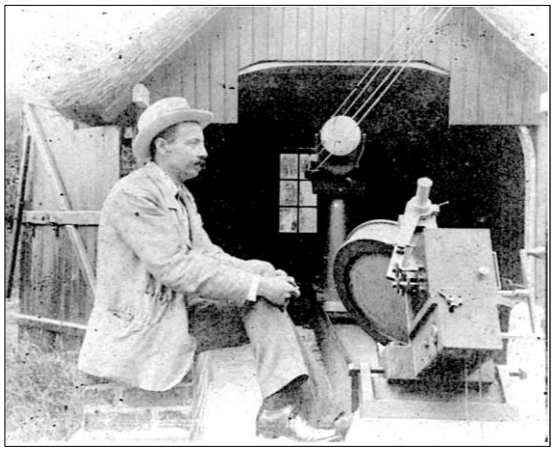


Figure 59: Alfred Perot in 1914 sitting near the Meudon cœlostat. Perot was from 1908 the physicist at Meudon Observatory (courtesy: Jacques Perot).

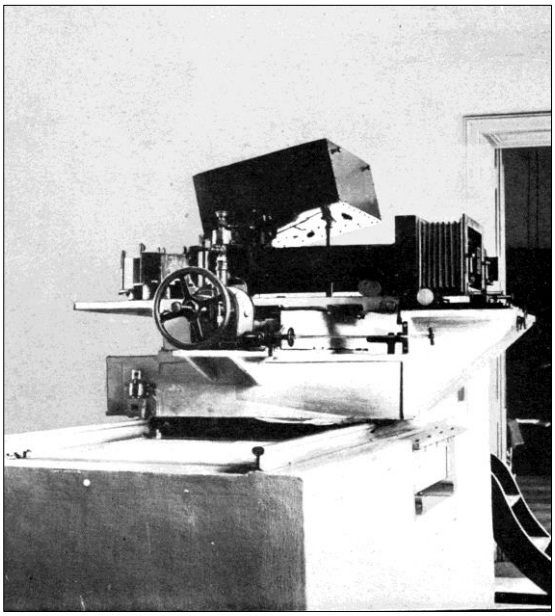


Figure 60: The Chrétien spectroheliograph at Marseilles Observatory (ca. 1930). The dispersive system consisted of two prisms and a mirror such that the beam was deviated by 180° for the K line of ionized calcium. The whole instrument was displaced laterally on rails to scan the disk of the Sun in front of the fixed photographic plate, hence the bellows (courtesy: Marseilles Observatory).

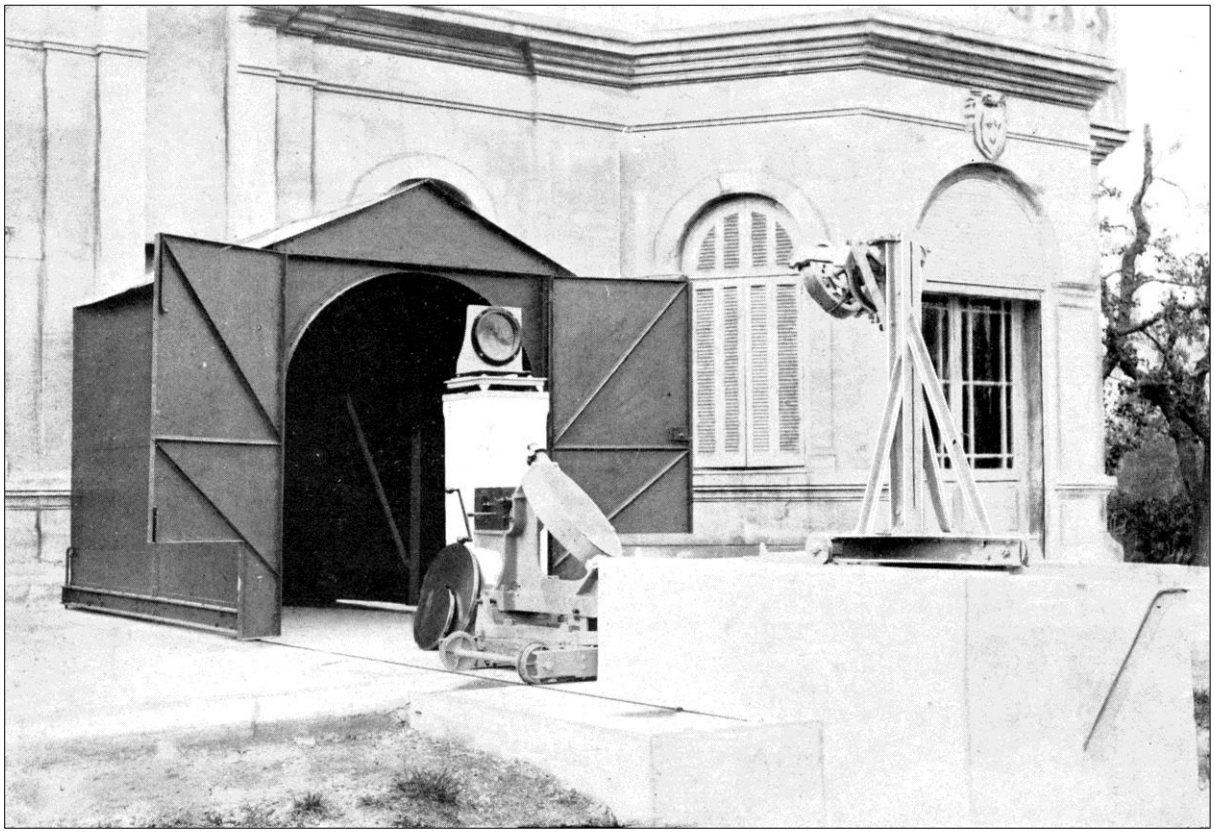


Figure 61: The cœlostat of Marseilles Observatory (ca. 1930). The 25-cm diameter Zeiss objective feeding the spectro-heliograph is visible on a pillar (courtesy: Marseilles Observatory).

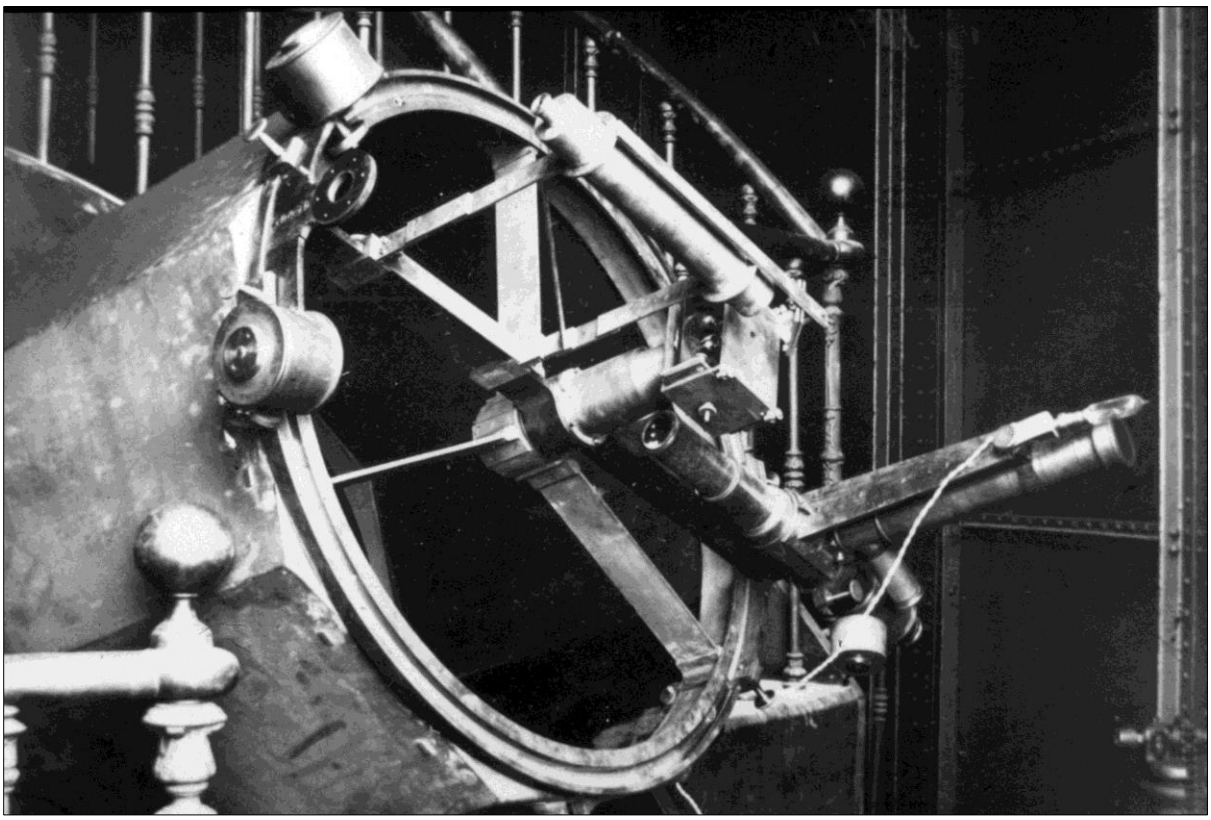


Figure 62: The Perot–Fabry interferometer installed at the prime focus of the Foucault 80-cm telescope of Marseilles Observatory. On the right, a hydrogen lamp gave a wavelength reference (from Album du Laboratoire de Physique de l'Université de Marseille. Georgelin collection).

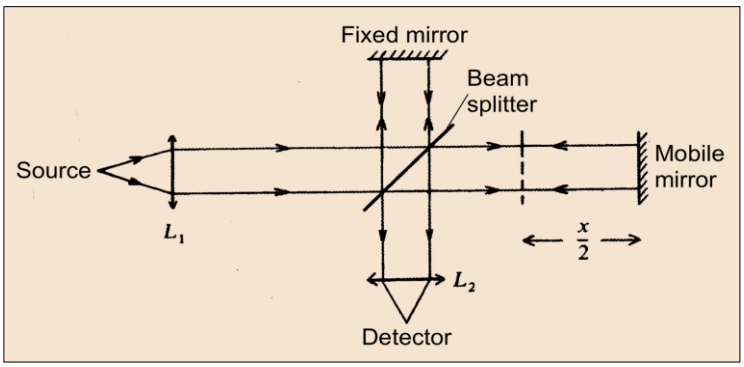


Figure 63: Principle of the Fourier-transform spectrometer. The light enters a Michelson interferometer, with one arm terminated by a fixed mirror and the other by a mobile mirror. By scanning the mobile mirror, the path difference x varies, and one can show that the spectrum is the Fourier transform of the signal $I(x)$ received by the detector (adapted from Léna et al., 2008: Figure 8.22).

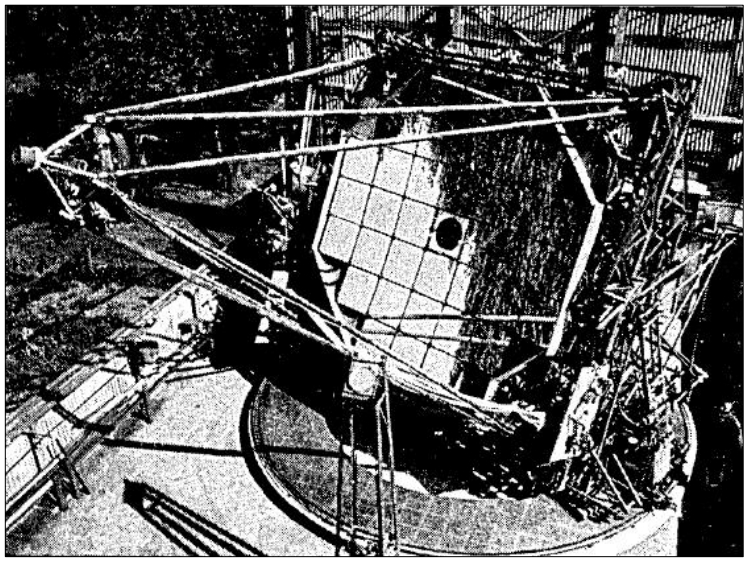


Figure 64: Pierre Connes' light collector, ca. 1974 (after Chevillard et al., 1977, Figure 16).

Orion nebula were observed for the first time (Buisson et al., 1914).

Fourier-transform spectroscopy is another way to reach high spectral resolution. The principle (Figure 63) is very simple, but the realization is not.

Fourier-transform spectroscopy was first developed for laboratory work, especially in England by Peter Felgett (1922–2008) and in France by Pierre Jacquinot (1910–2002) and collaborators. After a few rather inconclusive adaptations to astronomical observation, it was finally used successfully for high-resolution spectroscopy of planets in the near-infrared by Janine Connes and her husband Pierre Connes (1926–2019) (Connes and Connes, 1966).[8] Their instrument was built at the Jet Propulsion Laboratory in California during their stay there and taken to Haute-Provence Observatory where they obtained most of their results. Fourier-transform spectroscopy is not easily applicable to the visible because of technical difficulties. At the beginning, a big problem was the need for computers necessary to calculate the Fourier transform with thousands of entries: this was only possible in US computing centers and was one of the main incentives that led Jacquinot, who became the scientific director of the *Centre National de la Recherche Scientifique*, and Janine Connes to create in 1969 the French national center of scientific computing.

As stigmatic images are not necessary for single-object Fourier-transform spectroscopy, Pierre Connes and collaborators built around 1974 at Meudon Observatory a low-cost, 4-m diameter light collector for the near-infrared (see Figure 64). This was an alt-azimuthal mounted Cassegrain telescope whose prim-

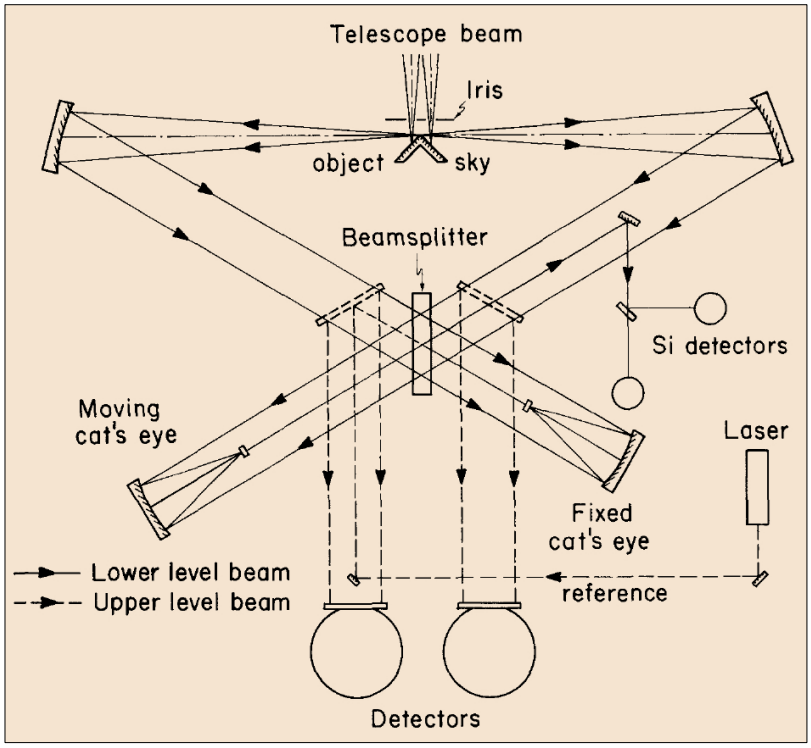


Figure 65: The CFHT Fourier-transform near-infrared imaging spectrometer. The mirrors at the end of the two arms have been replaced by cat's eyes. This instrument provided simultaneous 2-D interferograms of the target and the sky (after Maillard and Michel, 1982: Figure 1).

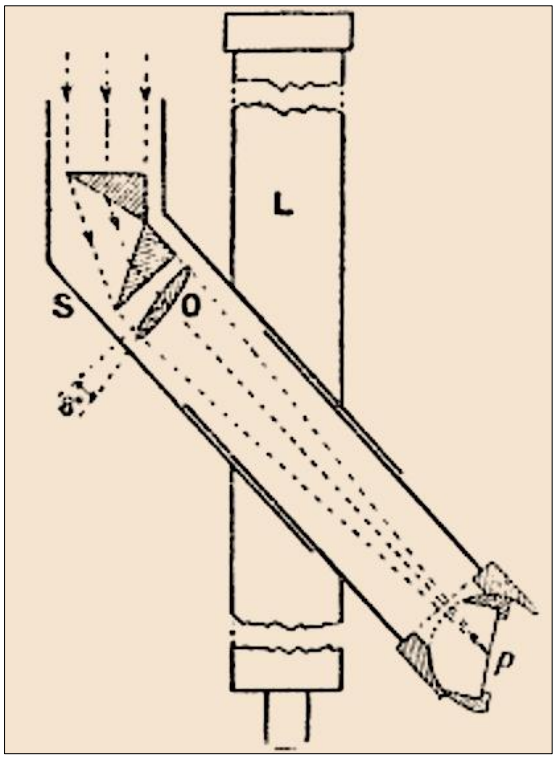


Figure 66: Arnulf's ultraviolet spectrograph (1934). **L** is the guiding telescope, to which the spectrograph **S** is attached. It is an objective-prism spectrograph, with optics in quartz. The objective **O** is inclined in order to ensure stigmatism in the ultraviolet part of the spectrum. ***p*** is the photographic plate (after Arnulf et al., 1936: Figure 1).

ary mirror was made of 36 identical spherical mirrors, adjusted by an active optics system. In spite of its novelties, this instrument was never used due to human difficulties and has been dismantled.

Fourier-transform spectroscopy had much success until about 2000, when the progress in infrared detectors made it partly obsolete, except for space because of compactness and multiplex character. Imaging Fourier transform spectrometers like the BEAR instrument on the CFH Telescope (Figure 65) have survived for a longer time. BEAR was decommissioned in 2001, but others have been constructed since.

Let us return to more conventional spectrographs. In the course of the nineteenth century, the first notable progresses were the spectrometers conceived for the ultraviolet by Albert Arnulf (1898–1984). Figure 66 shows the principle of the spectrometer that served to elaborate the classification of hot stars by Daniel Chalonge (1895–1977) and his collaborators.

A considerable advance in the design of astronomical spectrographs was due to Baranne in 1965: the white pupil spectrograph (Figure 67). Many spectrographs have been constructed by him according to this principle. The first one, inspired by the photoelectric rad-

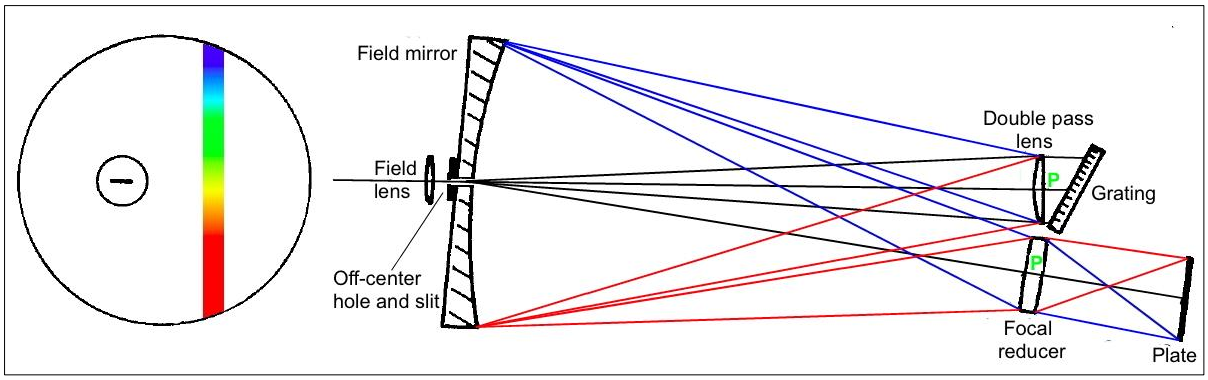


Figure 67: Principle of the 'white pupil' spectrograph of André Baranne (1965). A field lens near the entrance slit forms a pupil P (an image of the telescope mirror, in green) near the grating. The grating forms a spectrum that is reflected by the spherical field mirror on a focal reducer, which is thus conjugate to the grating and is in consequence located on another pupil P. The slit is placed in a hole of the collecting mirror, slightly eccentric so that the spectrum does no project on the hole (left). There is no obstruction anywhere, and the grating can be small whatever the required dispersion. A prism can produce a cross dispersion, perpendicular to that of the grating, allowing the use of several grating orders (not represented); this idea had a considerable future (adapted from Baranne, 1965: 1).

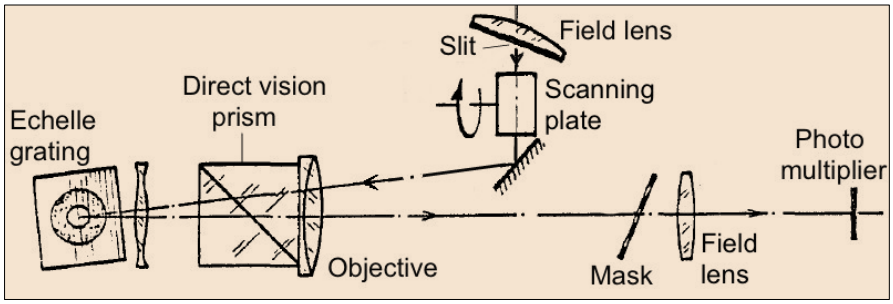


Figure 68: Simplified layout of the CORAVEL spectrometer. The field lens forms a pupil on the echelle grating through the achromatic objective and a correcting plate. The spectrum is imaged at the level of a mask (represented in Figure 69), and the light crossing this mask is projected as a second pupil by the second field lens on a photomultiplier. The direct-vision prism gives a cross dispersion of the different orders of the grating, hence of the different consecutive parts of the spectrum, resulting in a spectrum similar to that of the mask. The scanning plate displaces the spectrum with respect to the mask in a known way, allowing the measurement of the radial velocity of the observed star. As there are many lines in common between the two spectra, the precision is very high (adapted from Baranne et al., 1979).

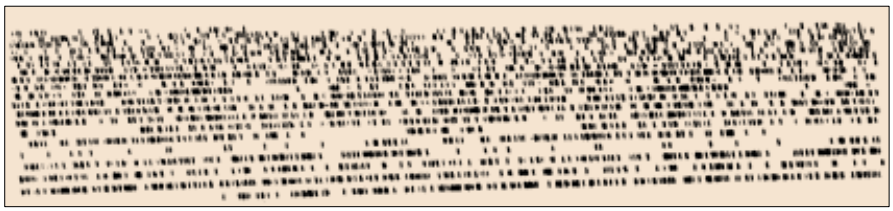


Figure 69: The mask built from the CORAVEL spectrum of Arcturus (negative image). All the different orders of the echelle grating have the same linear shift for a given radial velocity. Consequently, the correlation with the spectrum of the observed star is achieved by simple translation and allows a very accurate measurement of its radial velocity (after Baranne et al., 1979: 308).

ial-velocity spectrometer of Roger Griffin (1935–2021; Griffin, 1967) and the Leiden radial-velocity instrument (Walraven and Walraven, 1972) was named CORAVEL (Figure 68).

Successive versions of correlation spectrographs have been built. The second one was ELODIE on the Haute-Provence Observatory 1.93-m telescope (Figure 70), and its twin CORALIE on the 1.2 m Swiss telescope at ESO La Silla. They are fed by an optical fiber, and the spectrum is recorded on a 1024 × 1024 pixel CCD, the correlation with the template spectrum being performed by computer (Baranne et al., 1996). The wavelength calibration is ensured either by a reference thorium–argon spectrum, as usual, or by a Perot–Fabry etalon illuminated by white light

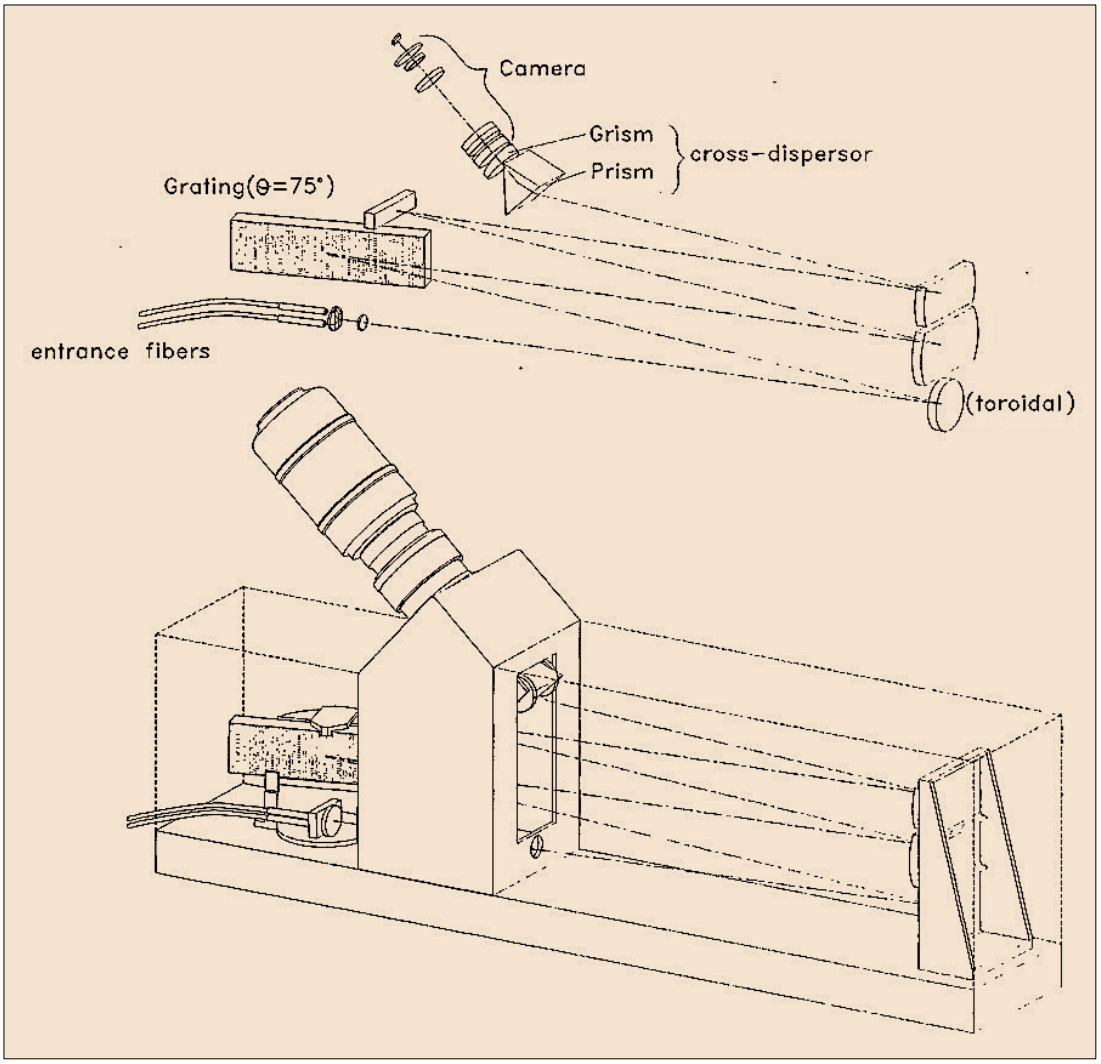


Figure 70: The ELODIE spectrograph. Top, principle; bottom, general view. It is fed by two optical fibers, for the star and for the sky nearby. 67 orders of the echelle grating are used, with a resolution of 100 000 over a 300 nm wavelength range (adapted from Baranne et al., 1996).



Figure 71: From left to right: André Baranne and the Nobel Prize winners Michel Mayor and Didier Queloz (courtesy Marseilles Observatory).

that provides a dense comb of emission lines. The latter set-up was based on a principle and experiment of Perot (1908), and was to replace progressively the iron or other atomic spectra for calibration of spectrometers.[9]

It is this extremely successful spectrograph that allowed the discovery of the first exoplanet by Michel Mayor and Didier Queloz (Mayor and Queloz, 1995), who obtained for this the Nobel Prize for Physics in 2019. Figure 71 shows Baranne, Mayor and Queloz at the time of the discovery. ELODIE was replaced in 2006 by a similar, more sensitive spectrograph named SOPHIE.

Baranne has conceived a number of other spectrometers, and succeeded in convincing other astronomers to build white pupil spectrometers. Examples are the high-resolution part of the coudé spectrograph of the 1.93-m Haute-Provence Telescope, the coudé echelle

spectrometer of ESO, fed by the Coudé Auxiliary Telescope (CAT) of the 3.6-m telescope at La Silla (Énard, 1982), and the KiwiSpec of the Magellan telescope (Barnes et al., 2012). Baranne was less lucky with the HARPS spectrometer of ESO, with its enormous and expensive two-piece 840 × 240 mm grating, which gives a wavelength resolution of 120 000, not appreciably better than the twice smaller echelle grating of ELODIE. The major advances are not always well followed.

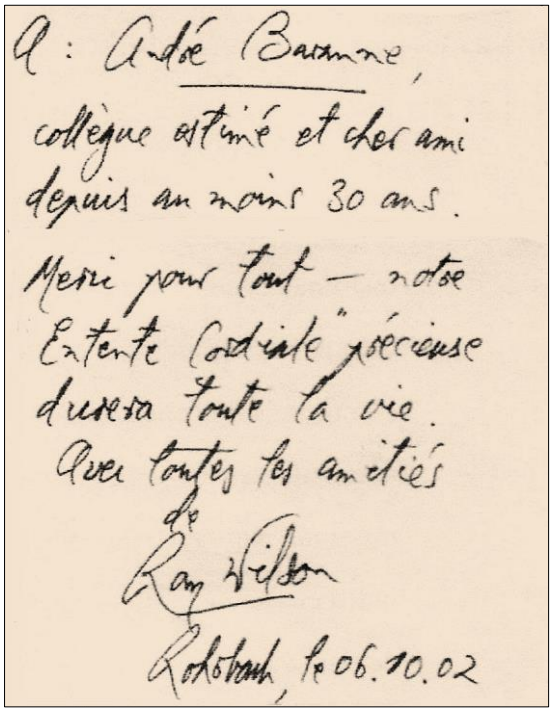


Figure 72: A message from Ray Wilson sent to Baranne in 2002. Translation: "To André Baranne, esteemed colleague and dear friend for at least 30 years. Thank you for everything — our precious cordial understanding will last our lifetime. With the very best wishes from Ray Wilson. Rohrbach, 6 October 2002." (courtesy: Marseilles Observatory).

André Baranne was very devoted to his work, but also full of humor. He was much appreciated by his colleagues worldwide, and had a great influence on astronomical optics in general. For this he received in 1998 the *Prix du Rayonnement Français* (French Influence Reward) of the French Senate. Still more precious to him was the friendship of Ray Wilson who directed for a long time the Optics Group of the European Southern Observatory (Figure 72). He was also proud to be cited in the book of Erwin Loewen (1921–2016) and Evgeni Popov, two world experts on diffraction gratings (Loewen and Popov, 1997).[10]

13 NOTES

1 The Frence *pied* and *pouce* used by astronomers from the seventeenth to the nineteenth centuries are equal to respectively 324.8 mm and 27.07 mm. They are thus larger than the English foot and inch (respectively 304.8 mm and 25.40 mm). The French *toise* contains 6 *pieds*.

2. Many astronomical clocks were built in France during the eighteenth century for the observatories or to be carried during the numerous scientific expeditions. Some were exported and others were purchased, in particular from Graham in London. Not many have survived, and there are none at Paris Observatory. At Marseilles Observatory we can still see a clock by Graham given by Laplace, two clocks by Louis Berthoud (1754–1813) and several later astronomical clocks, including one by Pierre-Michel Lepaute (1785–1849).
3. Mersenne had a good understanding of geometrical optics. In a letter from him to Peiresc dated 1635 (Mersenne, 1959: 374), we read (our English translation):

   > I have learnt that three glasses of same size, matter and shape, one without silvering, the second with metal deposit on its convex side and the third with deposit on its flat side, that the first one burns [has its focus] at a distance of two feet by refraction, its convex side being part of a sphere with a diameter of 2 feet. The metal deposit on the flat side makes it burn [gives a focus] at one foot by reflection, and that on the convex side makes it burn at half a foot. You can experiment this by yourself in having three similar glasses made on the same mold. The man who had made this experiment is M. de la Roche-Maillet [Gabriel Michel, sieur de la Roche Maillet, 1562–1642], quite curious about mirrors and telescopes, who is a lawyer at the Parliament, and still produces beautiful children at 70 years [sic!].

   A complete Cassegrain reflecting telescope could have been made with these glasses, provided that their sizes were different, but we have no indication that this has been done.
4. Cauchoix produced many large and good objectives, generally tested at Paris Observatory, but most went abroad, in particular to England (Launay, 2018).
5. François Arago (1786–1854) had understood as early as 1814 that scintillation is an interference phenomenon (Arago, 1858: 40–47 and 97–98). However, his theory was rightly criticized by Danjon (1955b: 379): Arago wrote: "It might happen that the rays of the left side destroy in totality the rays of the right side." (our English translation); the star might there-

fore be extinguished. Danjon remarks that this is absurd and contrary to the principle of conservation of light: the light will simply go elsewhere.

6. This paper gives Secchi's version of the dispute between Janssen and himself, as well as an image of another direct-vision spectroscope inspired by Janssen. In Secchi's *Les Étoiles* (Secchi, 1879: 68–86) one finds again his version, together with an interesting history, a scheme of the 'pocket spectroscope' and the designs of a wide-field one and an objective prism.
7. The idea of increasing the dispersion, not by adding more prisms, but by passing the light through the prisms twice after reflecting it back on itself, seems to be due to the Paris optician Jules Duboscq (1817–1886) in about 1860, or perhaps also to Otto von Littrow (Richards, 1912: 556). This idea had a considerable future: for example, the multichannel subtractive double-pass spectrograph of Meudon Observatory and its derivatives (Mein and Mein, 2020: Figure 26).
8. Pierre Connes had previously invented a variant with spherical mirrors of the Perot–Fabry interferometer, which is in current use in gas lasers. With collaborators, he has also produced an Absolute Astronomical Accelerator (Connes, 1994) which was later coupled to a spectrograph named EMILIE, rather similar to ELODIE, on the Haute-Provence Observatory 1.52-m telescope (Bouchy et al., 1999). Not many results have been obtained with this instrument.
9. A similar calibration system is implemented on the HARPS and ESPRESSO spectrographs of ESO and on the Maroon-X echelle spectrograph of the 8.1-m diameter Gemini North telescope. Such systems are themselves progressively being replaced by a laser frequency comb (Steinmetz et al., 2008), which is already operational in HARPS.
10. The Bulgarian scientist Evgeni Popov spent several years in the Laboratory of Electromagnetic Optics at Marseilles University and knew Baranne well.

14 ACKNOWLEDGEMENTS

We thank the referees for improving the language, correcting some errors and providing complementary information on several instrument constructors cited in this paper.

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