The Heliometer:
Instrument for Gauging Distances in Space

Rolf Willach
Staudenhofstrasse 10
CH-8274 Tagerwilen, Switzerland
Work: 41-71-669-16-11 Home: 41-71-669-24-55
Fax: 41-71-669-25-12 E-mail: rwillach@hotmail.com

Rolf Willach studied physics, astronomy and mathematics at the Universities of Bern (Switzerland) and Göttingen (Germany), and then served as an assistant at the Astronomical Institute of Bern for five years. Since 1976, he has been self-employed in developing infrared sensor techniques.

Abstract

For more than a century, the heliometer was astronomy's classic instrument for measuring interplanetary and interstellar distances. Invented in the 18th century, during the 1769 transit of Venus across the face of the sun, the heliometer enabled astronomers to determine the solar parallax with the highest accuracy yet achieved. Improvements in the heliometer by John and Peter Dollond and Josef Fraunhofer culminated in the first successful determination of the parallax of a fixed star by Friedrich Wilhelm Bessel. By the late 19th century, the Hamburg firm of A. and G. Repsold had so perfected the instrument that astronomical distances could be measured up to thousands of light years. Superseded by photographic means of distance determination in the late 19th century, by 1910 this exquisite instrument of precision had fallen into undeserved obscurity.

The principle of the heliometer—also called the divided object-glass micrometer—is easily understood [Fig. 1]. The objective lens of a telescope is divided into two semicircular halves. Each half focuses a separate image onto the focal plane. When both halves of the lens exactly coincide, we see a single image. But if one half is displaced along its diameter relative to the other, we see two images of the same object. How is that useful? If we look through a heliometer at a double star, we see four star images. Now, let us shift the objective halves until the image of star 1 coincides with the image of star 2. If we carefully measure how much the two halves of the heliometer's objective are shifted, and if we know the focal length of the divided objective, we can calculate the angular separation of the double star with great precision.

Since antiquity, astronomers have wanted to measure small angles precisely. The original 17th-century Dutch or Galilean form of the astronomical telescope was unsuitable for micrometer measurements because its double-convex objective combined with its negative eyepiece created an erect virtual image (an upright image, such as the reflection of one's face in a plane mirror, that cannot be focused onto a surface). The Keplerian form of the telescope with its double-convex eyepiece as well as double-convex objective, however, forms an inverted real image (one that can be focused onto a surface). In 1640, William Gascoigne of Leeds (1619–1644) introduced a crosshair into the image plane of his Keplerian telescope; he also developed the first screw micrometer to measure small angles such as the diameters of planets, the separations of double stars, or the varying distances between the moons of Jupiter.

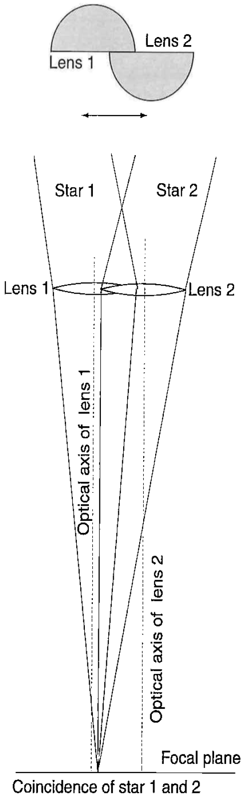

Figure 1 *A heliometer consists of an objective lens divided into two semicircular halves, or semi-lenses. Each semi-lens focuses a separate image onto the focal plane. When both semi-lenses exactly coincide, the objective produces a single image. But if one half is displaced along its diameter relative to the other, the instrument produces two images of the same object. An observer trying to measure the separation of two stars would thus see four star images. If the observer now shifts the semi-lenses until the image of star 1 coincides with the image of star 2 (shown in the diagram), and then carefully measures how much the two semi-lenses are shifted, knowing the focal length of the divided objective, the observer can calculate the angular separation of the double star with great precision.*

As early as 1675, the Danish astronomer Olaf Roemer (1644–1710) suggested building a telescope with two objective lenses that could be moved with respect to each other, to measure the varying apparent diameter of the moon as its orbital distance varies from the earth, and to measure the progress of eclipses by dividing the diameters of the sun and moon into 12 equal parts. But his invention appears to have been forgotten for close to 70 years. In 1743, Servington Savery of Exeter, England, sent a paper to James Badley to read before the Royal Society of London in which he described a double–object-glass micrometer for measuring the diameter of the sun at apogee and perigee. But that paper, too, was forgotten and not published for a decade, by which time Savery had died.[1]

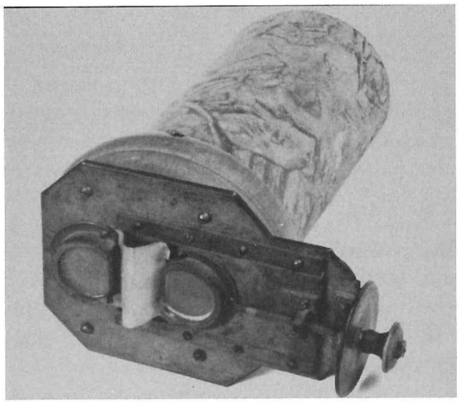

Figure 2 *An early heliometer was designed by French geodesist and astronomer Pierre Bouguer (1698–1758) in 1748, using two whole telescope object glasses of equal diameter and equal focal length but one eyepiece. Shown is one of the few surviving examples of a Bouguer heliometer (indeed, Bouguer was the one who gave the instrument that name) at the observatory of Göttingen in Germany from circa 1750–55, whose objective lenses each were 25 mm (1 inch) in aperture. But with a Bouguer heliometer not only was it impossible to superimpose both images of a single object (such as a star), but also the calibration of the distance between the two objective lenses was difficult and inexact. Photo credit: University of Göttingen.*

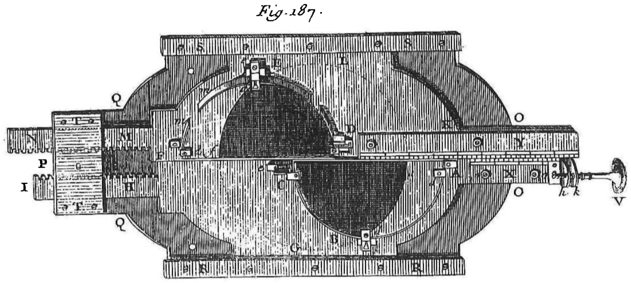

Figure 3 *The idea of using half-lenses or semi-lenses was that of British optician and inventor John Dollond (1706–1761). He showed that if the optical axes of both semi-lenses coincide exactly, both images also will coincide and therefore the instrument will have a well-defined zero point. The separation of the two semi-lenses along their common diameter could be measured with a precision divided ruler. Source: Lalande,* Astronomie

Meanwhile, in 1748 the French geodesist and astronomer Pierre Bouguer (1698–1758) informed the Royal Academy of Sciences in Paris about his own independent invention of a telescope consisting of two object glasses of equal diameter and equal focal length but one eyepiece, which he called a "héliomètre."[2] Bouguer apparently constructed several of these instruments and gave one to the French astronomer Joseph Jérôme Le François de Lalande (1732–1807), who described it in his book *Astronomie* [Fig. 2].

But the design of Bouguer's two-objective heliometer was imperfect. Not only was it impossible to superimpose both images of a single object (such as a star), but also calibrating the distance between the two objective lenses was inexact and difficult.

Dollond precision heliometers

The first inventor who turned the heliometer into a true precision astronomical instrument was the English optician John Dollond (1706–1761), well known for his later improvements of the achromatic objective. In 1753 and 1754, Dollond presented two papers to the Royal Society,[3] showing that the purpose of the instrument would be fulfilled much better if a single objective were to be divided into two semi-lenses (or half-lenses) along its diameter [Fig. 3]. If the optical axes of both semi-lenses coincide exactly, both images also will coincide and therefore the instrument will have a well-defined zero point. The separation of the two semi-lenses along their common diameter could be measured with a precision divided ruler.

John Dollond developed his heliometer not as an independent instrument, but as a supplementary part of a telescope. In its early form, it was usually attached at the front end of a Gregorian or Cassegrain reflecting telescope, where its divided, long-focus, positive single lens shortened the distance of the focal point from the main mirror. The heliometer's positive lens in front of the reflecting telescope made it necessary to shorten the distance between the secondary and the main mirror. But because 18th-century reflecting telescopes were focused by sliding the secondary mirror, it was possible to adapt the focal length of the telescope over a wide range.

What is presumably the oldest Dollond heliometer is on a reflecting telescope made by Scottish optician James Short (1710–1768) in 1754, which has a mirror with a focal length of 9.6 inches. This telescope with its heliometer is now in the George III collection of the Science Museum in London, and other early ones also survive at the National Maritime Museum in Greenwich, at the Harvard Collection of Historical Scientific Instruments in Massachusetts, and at the Paris Observatory [Figs. 4 and 5].

Both John Dollond and his son Peter (1730–1820) came to realize that early heliometer designs had three principal disadvantages.

First, early models used a rack and pinion to move the two halves of the divided lens symmetrically. Such symmetrical shifting was very important, especially if the instrument was used in connection with a reflecting telescope, in which the parabolic mirror has an extremely narrow usable field of view. Only a few arcminutes off a reflector's optical axis, the undesirable aberration of coma becomes pronounced, which—if lens shifting were at all asymmetrical—would lead to significant errors in measurement. But in the late 18th century, the precision with which the amount of shifting could be measured using a gear was very limited (for the Cambridge heliometer I found an error in the gear of at least 0.2 mm). Thus, it was impossible to exploit a heliometer's true optical precision with such a crude mechanical device as a rack and pinion.

Peter Dollond solved the problem by rejecting the rack and pinion and replacing it by a precision ruler [Fig. 6]. The reading accuracy of the ruler of a Dollond 4-inch heliometer was 1/500 of an inch, which translated to an angular measurement of an accuracy of 0.9 arcsecond. To maintain such accuracy, symmetrical shifting of both semi-lenses was crucial. Therefore, with the improved heliometers one semi-lens was shifted via a wheel (governed by a long handle directly next to the eyepiece), while the other was shifted by a rack and pinion on the heliometer itself.

The second disadvantage of early designs arose from their use of a single positive divided lens. One lens introduced chromatic

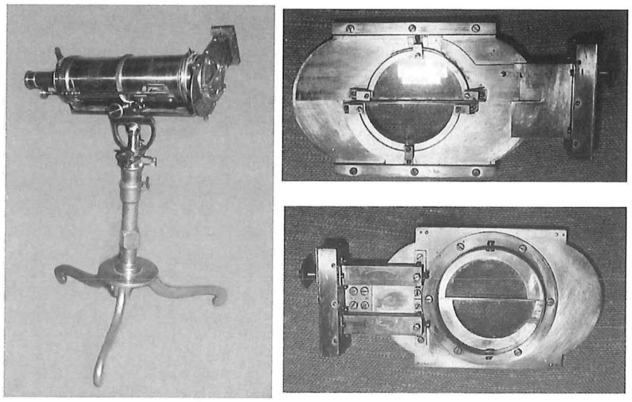

Figure 4 *This 18th-century heliometer by John Dollond is in the collection of the National Maritime Museum in Greenwich. The reflecting telescope is a Cassegrain whose main mirror has a focal length of 305 mm (12 inches)* (left). *Because it is signed J.DOLLOND AND SON LONDON, it must have been made before John Dollond's death in 1761. The two semi-lenses, which have an aperture of 58 mm (2.28 inches), are slightly positive with a focal length of several meters. The front is shown top right and the back, bottom right. They are made of English crown glass, with a faint greenish tinge and some air bubbles. The shifting of the two semi-lenses is measured by gears with a precision of 0.01 mm for 1 scale division. Photo credit: Rolf Willach, courtesy Greenwich Observatory*

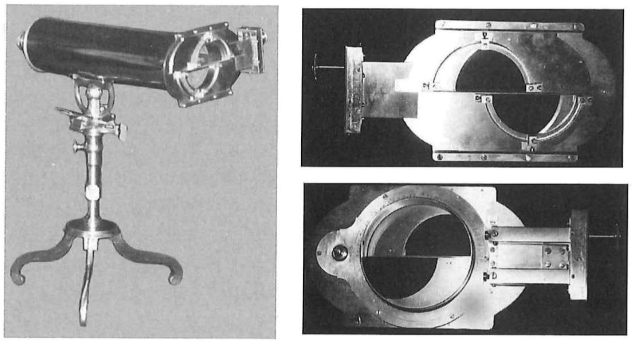

Figure 5 *A very similar 18th-century Dollond heliometer, made circa 1758–64, is in the Harvard Collection of Historical Scientific Instruments in Cambridge, Massachusetts (left). The telescope, another Cassegrain with a focal length of 305 mm (12 inches), was made by James Short in 1755 (both telescope and heliometer were purchased together by Harvard in 1765). The aperture of the heliometer is 61 mm (2.4 inches), and its slightly positive half lenses are made of Venetian glass, with a yellow tinge and numerous air bubbles. The accuracy in measuring the shifting is 0.063 mm for 1 scale division and is therefore less than for the Greenwich instrument; the front is top right and the back, bottom right. Photo credit: Courtesy the Collection of Historical Scientific Instruments, Harvard University. All rights reserved.*

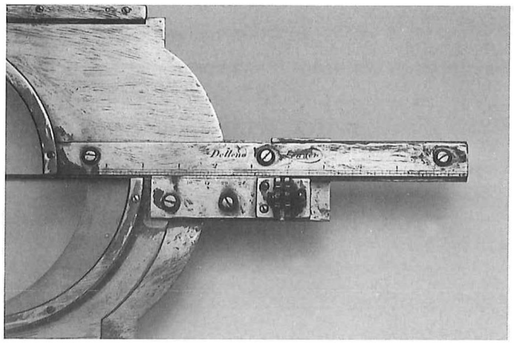

Figure 6 *To increase the accuracy of measuring the amount the semi-lenses were shifted, Peter Dollond (1730–1820) replaced his father John's rack and pinion with a precision ruler. The reading accuracy of the ruler of a Peter Dollond 4-inch heliometer was 1/500th of an inch, which for a refractor of 1.5-meter focal length translated to an angular measurement of an accuracy of 0.9 arcsecond. This was one of three principal improvements he made to the design of heliometers. Photo credit: Peter Louwman*

aberration, surrounding every object viewed with undesired rainbow-colored fringes of unfocused light, thus reducing the precision of the measurement. Peter Dollond therefore replaced the single divided lens by an achromatic (color-free) doublet [Fig. 7]. Dollond apparently began to make achromatic heliometer lenses shortly after 1770, around the time he was also producing an increasing number of refracting telescopes with achromatic objective lenses having relatively large apertures between 3 and 4 inches (in the late 18th century, for a variety of reasons, achromatic refractors became more attractive to observers than reflectors).

The third problem was that each image focused by each semi-lens was only half as bright as an image produced by an unmodified lens of the same diameter. Worse, shifting the semi-lenses reduced the effective aperture, further reducing the image brightness. Dollond's solution, after about 1785, was to give each semi-lens a length in the shifting direction that was more than double the telescope's nominal aperture. For a typical Dollond heliometer of 90 mm (3.5 inches) diameter, the semi-lenses were given a dimension of 210 mm (8.3 inches) in the shifting direction. So the loss of image brightness when shifting the lens remained negligible [Figs. 8 and 9].

With these three innovations, Peter Dollond believed he had perfected the heliometer. From 1785 until his death in 1820, he made no further improvements to it.

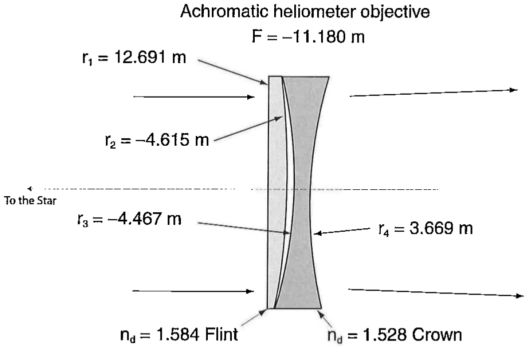

Figure 7 *Peter Dollond's second improvement to the design of heliometers was to use achromatic (color-free) doublet semi-lenses. Because 18th-century heliometers were built as accessories for pre-existing telescopes, for refractors Dollond made the achromatic semi-lenses with a negative focal length to elongate the total focal length of the combination heliometer-refractor, to avoid having the focal point brought inside the refractor's tube. The positive front element of the lens was made of flint glass and the negative element of crown.*

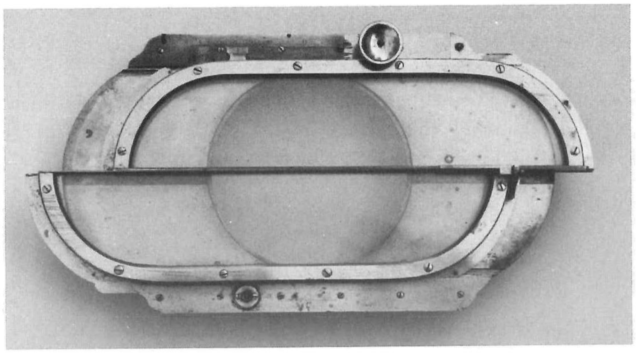

Figure 8 *Making the objective semi-lenses more than twice as wide in the shifting direction as their nominal aperture was Peter Dollond's third improvement to the heliometer. That ensured there would be no dimming of the image of the objects whose separations were being measured. Photo credit: Rolf Willach, collection*

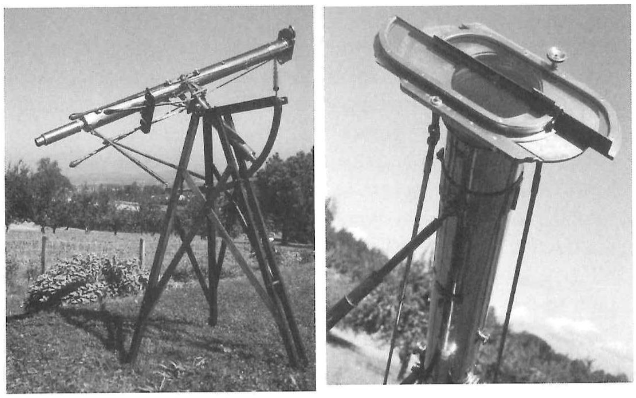

Figure 9 *A portable 18th-century astronomical refractor by Peter Dollond is shown together with its mounted heliometer (left). It is an instrument made for expeditions, packed in two large wooden boxes and can be totally assembled in less than one hour. The telescope's objective is an achromatic doublet with an aperture of 96 mm (3.8 inches) and a focal length of 1.5 m (59 inches). It has long handles for adjusting tooth-wheels in right ascension and in declination. Parallel to those are similar-handled shafts for the heliometer: One handle adjusts the separation of the semi-lenses while the other can rotate the whole micrometer part of the heliometer around its axis in position angle. The maximum separation angle that can be measured is 40 arcminutes. The heliometer lens (right) is an achromatic doublet with the positive flint lens forward and with a negative focal length of slightly more than 11 m. It extends the focal length of the telescope by 240 mm (9.4 inches). Therefore, an extending tube has to be screwed on at the eyepiece. Photo credit: Rolf Willach collection*

Despite its high cost and difficulty in manufacture, the heliometer became very popular for precision measurements of small angles. It offered two main advantages over the use of conventional telescopes equipped with filar micrometers at the eyepiece.

First, the distance separating the images of two stars depended only on the linear shift of the lens parts. That separation remained absolutely stable and unaffected by the rotation of the earth—a very important factor in an era where precision clock-drives in right ascension did not yet exist.

Second, the heliometer was remarkably insensitive to air turbulence. In an eyepiece micrometer, the star image jumped from side to side behind the eyepiece's crosshair in a statistical way as a consequence of turbulence, which therefore limited the accuracy attainable in measuring the apparent separation of double stars. True, star images seen through a heliometer were also jumping—but for relatively closely-spaced doubles, the jumps of the image of star 1 were nearly synchronous with the jumps of the image of star 2. The smaller the separation between the two stars, the closer their synchronization and the higher the resulting accuracy of the coincidence. It was due primarily to this advantage that the heliometer became by far the best instrument for measuring small angles in the 19th century.

Indeed, with a Peter Dollond heliometer, distance measurements with an accuracy of one arcsecond or better were made possible—improving the precision of 18th-century astronomical angular measurements by a factor of 10.

The heliometer and the solar parallax

The greatest problems of 18th-century astronomy were to measure the shape of the earth's orbit and to determine actual distances in the solar system. That required finding the length of the astronomical unit—the mean distance from the earth to the sun.

Since the early 17th century when Kepler articulated his laws of planetary orbits, astronomers have known that the earth traveled around the sun in an elliptical orbit and not in a circle, with the sun at one focus of the ellipse. To define the orbit's eccentricity (amount of "ovalness"), it was necessary to measure the sun's angular diameter with the highest possible precision at the earth's annual perihelion (closest approach in January) and aphelion (greatest distance in June). By the late 18th century, astronomers had determined a very good value for the eccentricity of the earth's orbital ellipse by measuring how much the sun's diameter varied during the course of a year, coming up with a value of 0.017.

But knowing the shape of the earth's orbital ellipse was only half the problem; the other half was determining its absolute size. The first astronomer who estimated the distance of the sun on the basis of correct principles was the Greek Aristarchus, who concluded the earth was 19 times farther from the sun than the moon is from the earth. Unfortunately, his numerical result was way off because of his lack of precision measuring instruments. Although Kepler suspected that Aristarchus's value was far too low, it was not until after 1650 that the Flemish astronomer Godefroi Wendelin (1580–1667) repeated the Greek's measurements, obtaining a much better ratio of 229, or 92 million km—still only 61 percent of the modern measurement of 150 million km. In 1671, the Italian-French astronomer Giovanni Domenico Cassini (1625–1712), director of the Paris Observatory, equipped an expedition to Cayenne in French Guiana in South America under the direction of the French astronomer Jean Richer (ca. 1630–1696). Richer's goal was to observe a favorable opposition of the planet Mars in 1672, and to compare his observations in Cayenne with those of Cassini made from Paris, so as to measure the parallax of Mars, from which (from Kepler's third law) they could trigonometrically calculate the solar parallax [Fig. 10]. Their result was 9.5 arcseconds, corresponding to a distance of 138 million km—92 percent of the modern value, and not improved upon for the next century.

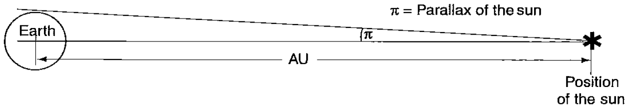

Figure 10 *The solar parallax, π, is the angle subtended by the radius of the earth seen from the distance of the sun. In principle, the sun is close enough that observers on opposite sides of the earth could detect its slight displacement against a background of stars, but measuring that displacement angle is extraordinarily difficult, not least of all because the sun's brilliance obscures background stars.*

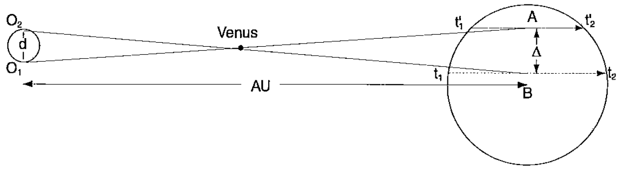

Figure 11 *Edmond Halley in 1716 proposed using transits of Venus to measure π. He recommended observing from stations that were as widely separated in latitude as practicable, because the distance between them was to be the baseline of a trigonometric measurement. Each observer O_1 and O_2 would measure the duration of Venus's transit across the sun's disk, defined as the time elapsed between the two inner contacts of the planet with the sun's limb. From the well-known orbital motions of Venus and earth, it would then be possible to calculate the angular length of the chords A and B across the apparent disk of the sun, then their angular separation Δ, and with this knowledge the distance of the astronomical unit (the mean sun-earth distance).*

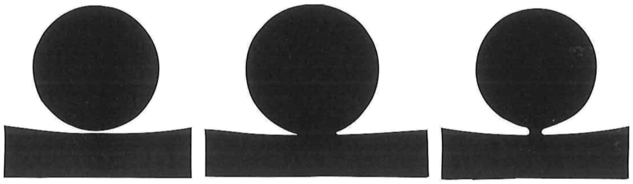

Figure 12 *During the transits of Venus as seen in both the 18th and 19th centuries, most observers did not see the black disk of Venus detach from the sun's limb at a definite instant of time at second contact (left). Instead, the planet's silhouette appeared to cling to the limb with a black ligament (center) that, with growing distance, became thinner and thinner (right) and disappeared only after several minutes, causing the timings of observers even at the same location to differ by as much as half a minute. The reverse was seen to happen at third contact. The phenomenon came to be called the "black drop effect." Source: Newcomb, Simon,* Popular Astronomy *(New York: Harper & Bros., 1878), pp. 178–179*

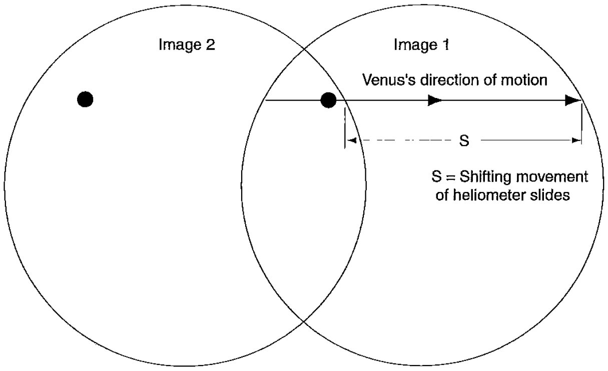

Figure 13 *During the 1769 transit of Venus, heliometers were used to measure the angular distance of Venus's disk from the limb of the sun. The heliometer semi-lenses were shifted until image 1 of the black disk of Venus nearly touched the sun's limb of image 2. Now Venus was observed to move slowly in the direction of the limb of image 2; and as soon as it touched, a timing was made. No "black drop effect" disturbed this method, and the artificial contact of the disk with the sun's limb could be measured to a very high accuracy. This measurement was repeated during the transit as often as possible. Such heliometer measurements yielded the most accurate values of the solar parallax π.*

In 1716, Edmond Halley (later the Astronomer Royal) published a proposal for determining the solar parallax by timing the passage of the planet Venus across the face of the sun during the extraordinarily rare transits of Venus.[4] From the differing durations of the transit as seen by widely separated observers in the northern and southern hemispheres—ideally at the two latitudes where the transit would be either shortest or longest—Halley showed it would be possible to calculate the earth's distance in kilometers using trigonometry [Fig. 11]. The observations needed only a time measurement accurate to 2 seconds, which Halley believed could be made to very high accuracy using small telescopes and common clocks. His paper strongly advocated using the Venus transits in 1761 and 1769 for this purpose.

In 1761, expeditions were sent out to widely separated locations of the world. But the results didn't have the expected accuracy, primarily because of the so-called "black drop effect," which caused the black disk of the planet Venus to appear to cling to the limb of the sun instead of detaching at a clearly defined instant, thereby reducing the accuracy of the timings [Fig. 12]. The results of the different observers differed greatly, therefore affecting the calculated parallax of the sun, which ranged from 8.5 arcseconds (corresponding to a distance of 154 million km or 96.2 million miles computed by James Short) to 10.5 arcseconds (corresponding to a distance of 125 million km, computed by French astronomer Alexandre Guy Pingré [1711–1796]).[5]

Now all hopes were placed on the transit of June 3, 1769. Because astronomers realized that exact time measurements of the inner contacts were so difficult, the observing strategy was changed to that of measuring the angular distance of Venus's disk from the sun's limb as accurately as possible during the whole transit time. The duration of this transit was several hours, long enough to repeat measurements several times and thus calculate an average value for the first and the second contact to a much higher degree of accuracy.

The best instrument for making such angular measurements was the heliometer [Fig. 13]. Few observer teams were equipped with them, but the heliometer measurements gave by far the best results. In 1835, using the complete observations from 1761 and 1769 expeditions, the Berlin astronomer Johann Franz Encke (1791–1865) calculated the sun's parallax to be 8.571 arcseconds, corresponding to a mean distance of 153 million km (94.9 million miles). In comparison, the 20th-century value obtained by interplanetary radar is 8.794148 arcseconds, corresponding to a mean distance of 149.6 million km (92.8 million miles). Thus, 18th-century measurements with Dollond heliometers and telescopes differ only in fractions of an arcsecond from modern values.

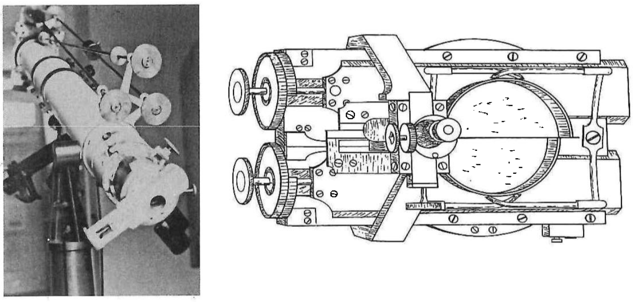

Figure 14 *The heliometers made by Munich optician and scientist Joseph Fraunhofer (1787–1826) were complete telescopes, not just accessories for pre-existing telescopes. Fraunhofer's first one, at the left, was made in 1814 for mathematician and astronomer Karl Friedrich Gauss (1777–1855) in Göttingen. Details of the micrometer part are shown on the right. The microscope was a later addition by German instrument-maker Johann Georg Repsold (1770–1830). Originally the shifting of the two semi-lenses was measured only with two micrometer screws, both turnable with a handled shaft near the eyepiece. This design was in principle a step backwards compared to Dollond's use of the precision ruler, although the accuracy of Fraunhofer's mechanical work was significantly higher than was possible in the 18th century. Credits: Astronomical Institute University of Göttingen*

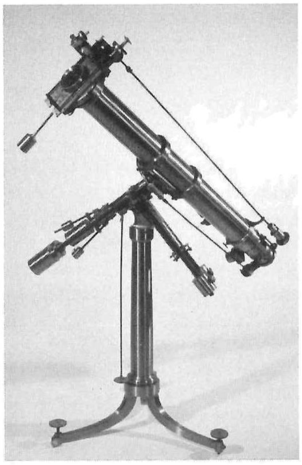

Figure 15 *Fraunhofer made this heliometer in 1815 for German astronomer Heinrich Wilhelm Matthäus Olbers (1758-1840) in Bremen. It has an aperture of 76 mm (3 inches), smaller than the 4-inch aperture characteristic of Dollond heliometers. Credit: Deutsches Museum, Munich*

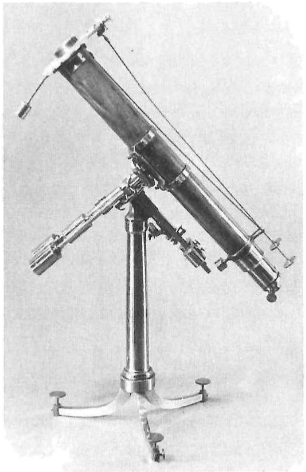

Figure 16 *Also in the Deutsches Museum is the only Fraunhofer heliometer that remains totally in its original state. Fraunhofer made it in an unknown year for mathematician, ordnance surveyor, and member of the Royal Academy, Johann Georg von Soldner (1776–1833). Like all the others of the eight known to be made by Fraunhofer, it has an aperture of 76 mm (3 inches). Credit: Deutsches Museum, Munich*

The heliometer's Golden Age

In the early 19th century, the famous Munich optician and scientist Joseph Fraunhofer (1787–1826) further improved the heliometer. The most advanced Dollond heliometers consisted of a divided negative achromatic lens mounted in front of the objective of a preexisting telescope. The main disadvantage of this construction was that optimum stability—and thus reproducibility of results to less than 0.1 arcsecond—was not guaranteed. Fraunhofer overcame that difficulty by dividing a refracting telescope's achromatic objective itself. Thus, Fraunhofer's heliometers were complete telescopes in and of themselves—not supplemental accessories.

As far as is known, Fraunhofer made a total of eight small heliometers: one in 1814 for mathematician and astronomer Karl Friedrich Gauss (1777–1855) in Göttingen [Fig. 14], one in 1815 for German astronomer Heinrich Wilhelm Matthäus Olbers (1758–1840) in Bremen [Fig. 15], one of uncertain date for Fraunhofer's friend Johann Georg von Soldner (1776–1833) [Fig. 16]. Fraunhofer also made a heliometer in 1817 for Baron Bernhard August von Lindenau (1780–1854) in Gotha, two in 1819 for the observatories in Berlin and Breslau (modern Wroclaw, Poland), and one in 1824 for the Finnish astronomer Halstroem in Abö (who then moved to Helsinki), and one of uncertain date for Johannes Pasquich in Ofen (now Budapest). At least seven Fraunhofer heliometers still survive. All eight instruments had an aperture of 76 mm (3 inches), smaller than the 4-inch aperture characteristic of Dollond heliometers.

Unfortunately, no important results were obtained with any of them. Not even Gauss used his excellent instrument for serious observations, and the seven other heliometers suffered the same fate, merely being admired by their owners as incomparable works of optical and mechanical art. That happened primarily because of a change in the interests and problems of the astronomers of that period. In principle, 18th-century observers had solved the astronomical problems that had been in question since antiquity concerning the size of the solar system, but the innumerable fixed stars seemed to be at an immeasurable distance.

It was William Herschel (1738–1822) with his giant telescopes who opened the eyes of astronomers to the vast universe beyond the solar system, essentially becoming the founder of sidereal astronomy. The results of his many years of "gauging" the stars led him to the conviction that our sun with its planetary system is only one of billions of similar suns in a flat disk, and that the Milky Way we see arching across the sky is the plane of that disk of stars projected onto the celestial sphere. Furthermore, Herschel speculated that the thousands of faint nebulae visible through his big telescopes were stellar systems similar to our galaxy distributed around the whole universe at, he thought, distances of tens of thousands of astronomical units (actually, a vast under-estimation). With such revolutionary insights, Herschel shattered the constraints of solar system-bound 18th-century astronomy, raising entirely new questions that would not be solved until the first decades of the 20th century.

One of the first who thought seriously about possibilities for the exact measurement of stellar distances was the astronomer and mathematician Friedrich Wilhelm Bessel (1784–1846), director of the Königsberg Observatory in East Prussia (now Kaliningrad on the Baltic). Bessel hypothesized that brighter stars, and stars with

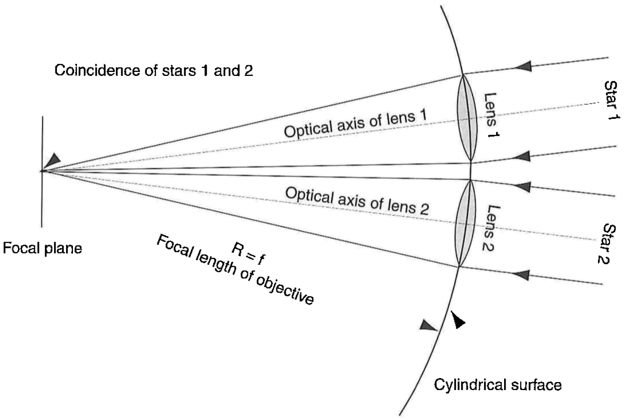

Figure 17 *Astronomer and mathematician Friedrich Wilhelm Bessel (1784-1846) proposed shifting a heliometer's semi-lenses along the surface of a cylinder whose radius coincided with the focal point of the objective. In a heliometer of this design, the images of the two stars whose angular separation was to be measured would remain on optical axis of both semi-lenses, thereby avoiding the aberrations and distortion of the star images that arise from moving the images away from the optical axis.*

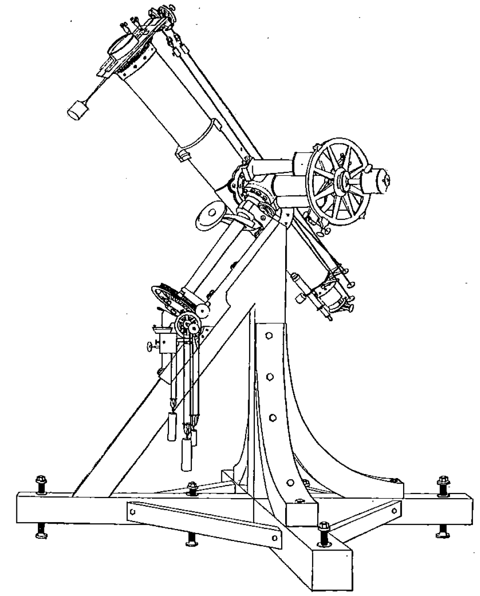

Figure 18 *Copperplate of the Fraunhofer/Merz heliometer at the observatory at Königsberg, East Prussia (now Kaliningrad on the Baltic), shows that it had a wooden tube. Of the three controls near the eyepiece, two are used to shift the two semi-lenses and one to turn the whole micrometer in position angle. Credit: Deutsches Museum, Munich*

higher proper motions, were nearer the earth than fainter ones. Thus, if one were to measure the angular separation of two neighboring stars—a bright one and a faint one—over the course of a year, he thought it would be possible to detect angular position changes that would take the form of a closed ellipse. That ellipse would be nothing less than the projection of the earth's orbit onto the celestial sphere—a parallactic ellipse. Bessel also realized that if Herschel's estimate of 80,000 AU was indeed the absolute minimum distance to the nearest fixed star, then that star's annual angular variation (or annual parallax) would be minuscule—at most only a few tenths of an arcsecond.

In the first half of the 19th century, before reliable photography, the only instrument capable of measuring such small angular variations with high precision was the heliometer. But to obtain reliable measurements to a hundredth of an arcsecond, such a heliometer would have to be larger than any yet built. It would also, Bessel calculated, have to overcome one serious disadvantage of any heliometer: the fact that shifting the semi-lenses in a plane perpendicular to the optical axis inevitably moved the image of a star away from the optical axis of the telescope, with attendant coma, astigmatism, and defocusing (enlarging of the star's diffraction disk). To eliminate those aberrations, Bessel proposed shifting both semi-lenses along a cylindrical surface concentric with the focal point of the objective [Fig. 17]. Bessel also wanted an objective aperture of at least 150 mm (6 inches), almost as large as Fraunhofer's largest telescope objective up to that time—180 mm (7 inches).

Around 1817, Bessel contacted Fraunhofer and informed him about his plans for a heliometer. At first, Fraunhofer was reluctant, especially rejecting Bessel's idea about moving the semi-lenses along a cylindrical surface on the grounds that the construction of such cylindrical surfaces would be too difficult. Negotiations went on for years as meanwhile Fraunhofer was constructing the 244-mm (9.6-inch) refractor for Friedrich Georg Wilhelm von Struve (1793–1864) in Dorpat (modern Tartu, Estonia), which at the time of its completion in 1824—and for many years thereafter—was the largest refracting telescope in the world.

Shortly thereafter, Fraunhofer began construction of Bessel's big heliometer. Because Fraunhofer resisted Bessel's idea of cylindrical slides for the divided objective, he tried to minimize the effects of off-axis aberrations by equipping the instrument with an eyepiece that could be shifted in a plane exactly parallel to the movement of each of the objective semi-lenses. Fraunhofer never lived to complete it, however, as he succumbed to tuberculosis on 7 June 1826 at the young age of 39. Bessel's heliometer was finished by Georg Merz, and delivered to Königsberg in 1829.[6] Unfortunately, although the instrument survived at the observatory there until the last days of World War II, no existing photograph of it is known. But a fairly detailed copperplate reveals that the instrument looked very similar to the Dorpat refractor [Fig. 18].[7]

For the next five years, Bessel made a detailed analysis of the heliometer's instrumental errors. Although Fraunhofer's modifications had improved the instrument, they did not wholly eliminate aberrations. Modern recalculations of the objective indicate that coma is reduced but not perfectly corrected, and that astigmatism is impossible to mitigate with a two-lens objective. Bessel tabulated the errors for different angular separations of stars and found that they worsened nonlinearly with increasing separation; for example, while an angular separation of 24 arcminutes had an error of 1.7 arcseconds, an angular separation of 48 arcminutes had an error of fully 5.1 arcseconds.

How could such severe errors be tolerated if the goal were to make measurements accurate to a *hundredth* of an arcsecond? For measuring the separation of two stars, Bessel circumvented the difficulty very cleverly. He knew that if one semi-lens were shifted until the images of both stars coincided, the optical axes of the semi-lenses were separated but parallel. All star images from the unshifted semi-lens would remain round points. But the star images from the shifted semi-lens would look like small comets, because its optical axis lies outside that of the eyepiece, thereby introducing coma. Now, if Fraunhofer's movable eyepiece were slid until the optical axis of the eyepiece fell exactly *between* the optical axes of both semi-lenses, the images produced by both semi-lenses would be affected with coma, but in only half the amount and in opposite directions (that is, the apparent "comet tails" point in opposite directions, each tail pointing away from its respective optical axis). And since position errors worsened *non*linearly with the degree of shifting off the optical axis, then for equal separations the ability to superimpose two sets of slightly off-axis images allowed measurements with significantly higher accuracy than superimposing one on-axis image with one off-axis image.

In August of 1837, Bessel began using the Königsberg heliometer to measure the position of the double star 61 Cygni with respect to several 10th-magnitude comparison stars; by October 1838 he had derived an annual parallax of 0.3136 arcsecond, corresponding to a distance of 10.3 light years. Bessel's result—the first truly reliable star parallax in the history of astronomy—was published in the December 1838 issue of *Astronomische Nachrichten*[8] and it created a sensation. The modern value is 0.2871 arcsecond, corresponding to a distance of 11.4 light years.

Other astronomers tried to test Bessel's results and measure other star distances. Because they had no heliometers, they used eyepiece micrometers in conventional telescopes. But their measurements were seriously affected by air turbulence and thus suffered in accuracy. For example, Struve using Fraunhofer's Dorpat refractor and its eyepiece micrometer reported finding a parallax for the bright star Vega (Lyrae) of 0.26 arcsecond, corresponding to 12.5 light years.[9] The modern value is 0.13 arcsecond, corresponding to 25 light years, or exactly double Struve's value. Other 19th-century attempts at parallax measurements (involving Arcturus, Sirius, Capella, as well as fainter stars) all showed the same trend: when results are compared with modern determinations, by far the most accurate pre-photographic measurements were those by Bessel with the Fraunhofer heliometer.

In 1839, Struve moved from Dorpat to Pulkowa (near St. Petersburg), where Tsar Nicholas I (1796–1855) planned to build an observatory. Struve was appointed its director, and as at Dorpat, he chose Munich as the source for instruments for the new observatory. In 1840 Merz and Mahler delivered a refractor with an aperture of 380 mm (15 inches), then the largest refractor in the world. That same year, they delivered to Pukowa a heliometer with an unprecedented aperture of 200 mm (nearly 8 inches), but otherwise it differed little from the instrument in Königsberg.[10] Like Fraunhofer, Merz did not risk making a cylindrical guide for the sliding semi-lenses. Merz divided the micrometer screw drums into 500 parts, theoretically enabling an observer to read a thousandth part of a revolution (corresponding to an angle of 0.05 arcsecond). But in practice, the accuracy of the screws was not so high. Indeed, Merz himself did not wholly trust them, so as a backup he equipped the objective slides with soldered silver strips whose precision divisions were readable with microscopes to an accuracy of 0.01 arcsecond. Also in 1839, Merz made a similar heliometer for the German astronomer Friedrich August Theodor Winnecke (1835–1897) of the Bonn Observatory with an aperture of 160 mm (6.3 inches).

Those were the only heliometers made by the company Merz and Mahler in Munich. The future belonged to another star in the trade of astronomical high-precision instruments.

The Repsolds of Hamburg

Adolf (1806–1871) and Georg (1804–1885) Repsold, the sons of Johann Georg Repsold (1770–1830), the founder of the famous firm, carried the heliometer from a high-precision but nonetheless imperfect instrument to its highest perfection. Struve came up with a list of desiderata for future heliometers based on his evaluation of the Merz heliometer at Pulkowa.[11] Specifically, Struve recommended that future heliometers have:

1. Cylindrical slides for objective semi-lenses whose radius centers in the semi-lenses' focal point (the unfulfilled request Bessel had made to Fraunhofer);
2. Symmetrical shifting of both objective semi-lenses;
3. Ability to rotate the entire telescope tube around its optical axis to obtain the correct position angle;
4. Highly stable connection between the eyepiece and the objective semi-lenses;
5. All-metal telescope tube;
6. Precision rulers for reading the shifting amount;
7. Ability to read the precision rulers from the eyepiece without moving the instrument, because even small movements can lead to changes in the position of the semi-lens slides;
8. Restriction of the eyepiece movement to along the optical axis and not at right angles to it, as was done for the Königsberg and the Pulkowa heliometers.

The first heliometer the Repsold brothers made was for the Radcliffe Observatory in Oxford, England, erected by Adolf Repsold in October 1849[12] [cover illustration]. The objective, fashioned by Merz, had a diameter of 190 mm (7.5 inches) and a focal length of 3.2 m (10.5 feet). This instrument was noteworthy for fulfilling nearly every one of Struve's recommendations. The shift of both objective semi-lenses was measured with a precision ruler at the objective slides, which were illuminated by electrically heated platinum wires and read with a telescope fixed beside the main telescope eyepiece; thus, it was never necessary to lower the telescope to a horizontal position to read the rulers. Most important, the Repsolds finally fulfilled the demand that the objective semi-lenses be shifted along cylindrical slides whose radius centers at their mutual focal point; thus, both stars being measured remain exactly in the optical axis of the objective semi-lenses and their images are not degraded by either coma or astigmatism. Struve's only point still unfulfilled was the desideratum that both semi-lens slides should move symmetrically rather than independently.

The Oxford heliometer was used for nearly three decades, primarily by Manuel John Johnson (1805–1859), who measured stellar parallaxes, the separations of double stars, and the variations of planets' diameters; and then by Robert Main (1808–1878) especially for the separations of double stars. But after the late 1870s, the instrument gradually fell into disuse.

After erecting the Radcliffe instrument, the Repsolds received no new orders for heliometers for two decades. But as the next pair of Venus transits (1874 and 1882) approached, astronomers began to look for suitable expedition instruments. For the 1874 transit, James Ludovic Lindsay (later Earl of Crawford and Balcarres, 1847–1915), owner of the private Dun Echt Observatory near

Aberdeen, Scotland, ordered a heliometer with an aperture of 107 mm (4.2 inches) and a focal length of 1.6 m (5.3 feet) [Fig. 19].[13] As with the Oxford heliometer, the telescope tube rotated around its optical axis and position angle could be read with two small telescopes fixed near the eyepiece.

Most significant, the shifting of the objective semi-lenses was exactly symmetrical owing to a high-precision diagonal lever acting equally on both objective slides. The shifting angle of the semi-lenses was read with another telescope focused on the scale. In short, with this instrument for Lord Lindsay, the Repsolds had reached the acme of mechanical perfection for the heliometer, finally fulfilling all of Struve's desiderata. Indeed, this instrument was an absolute masterpiece of compactness and mechanical high precision, and became an archetype for several larger heliometers produced by the firm in the following years.

The Repsolds made two further, nearly identical instruments for the Russian government for transit expeditions. Heliometers proved so successful during the 1874 event that they received orders from eight different observatories. For the 1874 transit, photography—in which American astronomers had great hope—gave very poor results. The wet collodion plates proved to be too unstable and produced serious nonlinear distortions. In contrast, heliometer measurements gave by far the best results. Nonetheless, although the Repsold heliometers had an accuracy at least 10 times greater than the Dollond heliometers of the 18th century, the final 19th-century results were not equivalently better. It therefore became clear that measurements were limited not by the precision of the instruments, but much more by the enormous difficulty of making measurements through a turbulent atmosphere against the sun's brilliant disk.

The Repsolds' next heliometer, with an aperture of 152 mm (6 inches) and a focal length of 2.6 m (8.5 feet), went to Yale College Observatory in New Haven, Connecticut [Fig. 20] in 1882. Its design removed a long-standing inconvenience of earlier instruments. For fully a century, astronomers had wrestled with the difficulty of precisely measuring the separation of two stars that differed widely in brightness, because light scattered from the brighter star obscured the fainter star during attempts to superimpose their images. Therefore, in front of one of the objective semi-lenses, the Repsolds fixed a wheel divided into several sectors, each sector having a screen mesh of different fineness. The screens enabled an observer to reduce the brightness of a star seen through one of the objective semi-lenses, and thus adapt it to the brightness of its partner seen through the other semi-lens, so their angular separation could be measured accurately. The Repsolds used mesh because large plane-parallel tinted optical glass was not available at that time. Such mesh-screen wheels were standard on all subsequent heliometers.

In the 1880s, Repsold heliometers became progressively more sophisticated. The only heliometer at a major southern hemisphere observatory was one of 178-mm (7-inch) aperture, installed in 1887 at the Royal Observatory, Cape of Good Hope, South Africa [Fig. 21]. It was used by director David Gill (1843–1914) in 1889 to make further determinations of the solar parallax by observations of asteroids (7) Iris, (80) Sappho, and (12) Victoria. Also participating in these measurements with heliometers in the northern hemisphere were observatories in Leipzig, Königsberg, New Haven, and Göttingen. The last and largest heliometer the Repsolds made was for the Moritz von Kuffner Observatory in Vienna in 1894, with an aperture of 217 mm (8.5 inches) and a focal length of 3 m (9.8 feet) [Fig. 22].

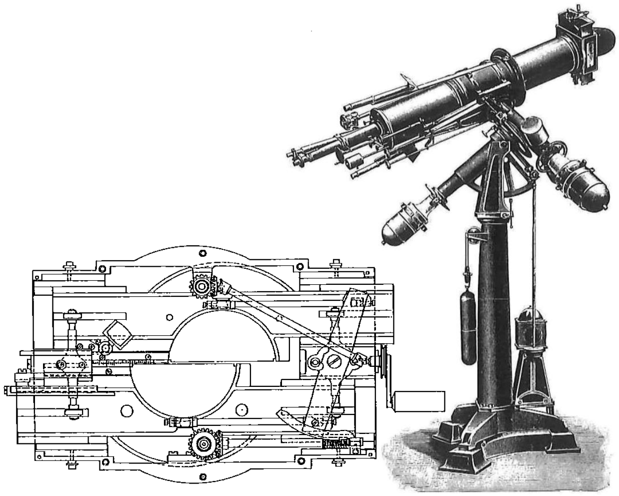

Figure 19 *This 107-mm (4.2-inch) heliometer (focal length of 1.6 m or 5.3 ft) by the Repsolds was made for James Ludovic Lindsay (later Earl of Crawford and Balcarres, 1847–1915), owner of the private observatory Dun Echt in Aberdeen, Scotland. Finished in 1873, it was designed for astronomical expeditions to different locations, so its polar axis could be adjusted according to latitude. It was used by David Gill to measure the position of the planet Venus with respect to the solar limb during its transit in December 1874, observed from Mauritius. The two objective semi-lenses were shifted symmetrically by a high-precision diagonal lever acting simultaneously on both objective slides; the shifting angle was then read through another telescope focused on the scale. With this instrument, the Repsolds fulfilled all Struve's desiderata for heliometers. Source: Dun Echt Observatory Publications; Ambronn*

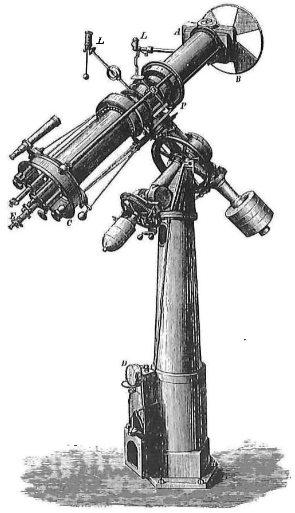

Figure 20 *The Yale College Observatory heliometer, mounted in 1882, had an objective with an aperture of 152 mm (6 inches) and a focal length of 2.6 m (8.5 feet). The wheel in front of the objective carried screens of various mesh size, arrayed in sectors, which enabled an observer to reduce the intensity of a bright star seen through one semi-lens to make it more equal to that of a fainter one imaged by the other, when measuring a pair of unequal brightness. Source: Ambronn*

Wedding "Old Astronomy" with "New Astronomy"

Heliometers were particularly well-suited for the parallax measurements and were used with success in determining the distances of the sun and the nearest fixed stars. But gauging the distances of all but the closest fixed stars is extremely difficult,

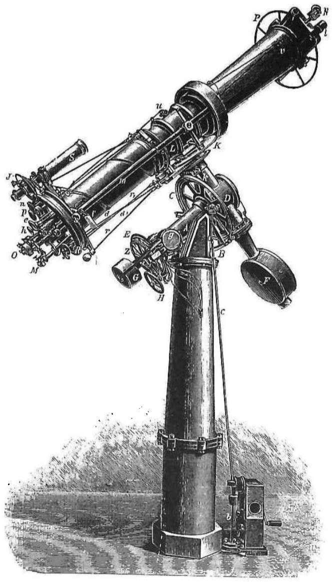

Figure 21 *The Repsolds' heliometer for the Royal Observatory, Cape of Good Hope, South Africa, was the only heliometer installed at a major observatory in the southern hemisphere. It had an aperture of 190 mm (7.5 inches) and a focal length of 2.6 m (8.5 feet), and was used by Gill to refine measurements of the solar parallax by measuring the distances to asteroids.Source: Ambronn*

because even the nearest ones have an annual parallax of only a few hundredths of an arcsecond. Moreover, the parallaxes of merely the nearest stars cannot yield information about the large-scale distribution and motions of the stars comprising our galactic system. To probe the farther reaches of the galaxy, late 19th-century astronomers thus wedded the "Old Astronomy" (positional technique of the heliometer) with the "New Astronomy" (astrophysical technique of spectral analysis) to create a brand new technique called "star-stream parallax."

How does the method work? It depends on the fact that all stars are physically moving through space relative to the sun (e.g., around the center of our galaxy), quite apart from any annual parallax they might appear to exhibit as a result of the earth's own orbit around the sun. Astronomers resolve any star's physical motion through space into two vectors: proper motion (angular motion across the line of sight) and radial velocity (motion along the line of sight directly toward or away from the earth).

By the late 18th century, William Herschel knew about proper motion. More important, he had observed during his sky survey that the stars of several open clusters—such as the Pleiades, the Hyades, or Praesepe—seemed to form their own gravitationally bound systems and to be traveling together through space. That being the case, the movements of stars in such a cluster through space would be parallel. Now, if an astronomer uses a heliometer to determine the annual proper motion of each star in such a cluster, and if the directions and amounts of all those proper motions are plotted on a star map, a highly interesting phenomenon is revealed. Although all the stars are moving parallel to one another in space, the plotted measurements are not parallel lines; instead, they converge to a single point—a perspective effect, exactly equivalent to the way the parallel rails of a railroad track appear to converge to a single "vanishing point" at the horizon [Fig. 23]. In astronomy, that point of convergence is called the "vertex" of a star cluster, and is enormously helpful in revealing the three-dimensional structure of the galaxy beyond just the nearest stars.

Proper motion as measured by the heliometer, however, comprises only half the star-stream parallax technique. Radial velocity is the other half—requiring the spectroscope. In the last two decades of the 19th century, spectral analysis was a young, pioneering science, and astronomers were busily mapping the bright and dark lines seen in the spectra of stars and identifying them as belonging to elements known on the earth. British astronomer Sir William Huggins (1824–1910) and others began to apply the principle first articulated in 1842 by Austrian physicist Christian Doppler (1803–1853) that lines that were shifted from their normal positions toward the blue end of the spectrum indicated that a star was moving toward the earth along the line of sight, while those shifted toward the red indicated that a star was receding.

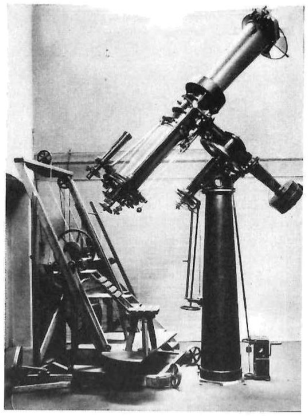

Figure 22 *The biggest heliometer ever made was also the Repsolds' last. Built for the Moritz von Kuffner Observatory in Vienna in 1894, its aperture was 217 mm (8.5 inches) and its focal length was 3 m (9.8 feet). Source: Ambronn*

Combining heliometer measurements of angular proper motion with spectroscopic measurements of radial velocity in kilometers per second enabled *absolute* distances to be determined for star clusters thousands of light years away [Fig. 24]. Such measurements for clusters all over the sky allowed 19th-century astronomers to determine their distances, and thereby to map the larger extent of the Milky Way.

No wonder that many astronomers devoted years to making heliometer measurements of different star clusters with the highest possible accuracy! Most notable among the pioneers of the star-stream parallax method were William Lewis Elkin (1855–1933) who measured the Pleiades in Taurus with the Yale heliometer in the late 1880s, Wilhelm Schur (1846–1901) who measured the Praesepe in Cancer with the Göttingen heliometer from 1889 to 1893, and Bruno Peters (1853–1911) who measured the Hyades in Taurus with the heliometer at Leipzig in 1899–1904 (this instrument, delivered in 1886, had an aperture of 6.4 inches or 162 mm).

But by the close of the 19th century, the era of the heliometer—this star of highest precision instruments—was waning. The technique of astrophotography, with its ability to preserve an image of the sky for all time, was developing very rapidly and just as rapidly replacing the heliometer. Indeed, after about 1910 no further measurements with heliometers were made, and most of those exquisite instruments were dismantled.

2004 measurements with a 225-year-old heliometer

On 8 June, 2004, Venus once again transited the sun, its conditions closely resembling those of the transit of 3 June, 1769. Therefore, armed with only 18th-century optical equipment, I set out to try and replicate 18th-century accuracy in timing the contacts

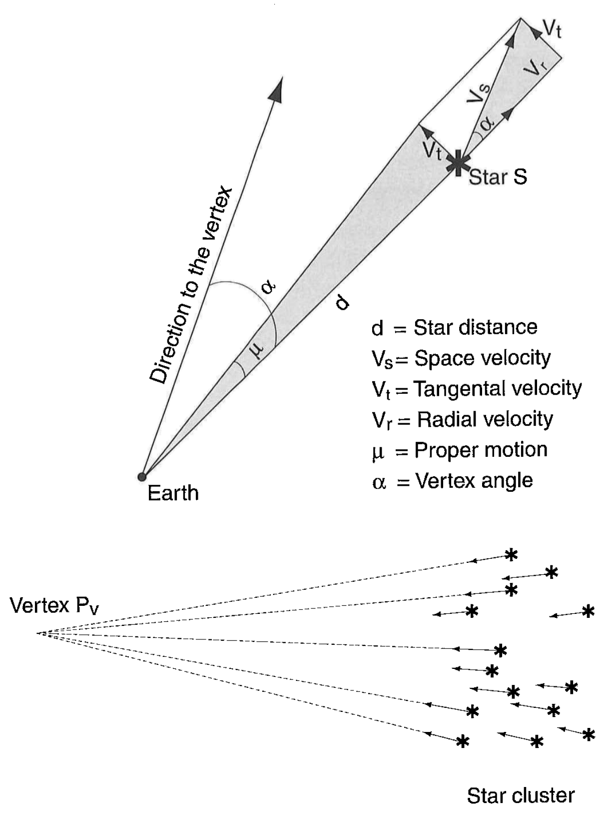

Figure 23 *The principle of star-stream parallax is readily understood from a simple diagram. Point S is a star at an unknown distance d. Vs is its velocity vector in space and it is at the moment an unknown parameter. The components of this vector are the radial velocity Vr and the tangential velocity Vt. The determination of Vr is straightforward with a spectroscope, as the red shift (in this particular case) of the spectral lines can be correlated directly to kilometers per second. The component Vt is less easy to find. If the star is not too far away, then a survey over several years would allow astronomers with a heliometer to measure the star's proper motion μ (direction and angular displacement across the line of sight). But angular displacement is still not enough information to determine Vs in kilometers per second, which is impossible to find with a single star if the star is too distant to exhibit annual parallax. If the star S is part of a gravitationally bound cluster of stars, however, then all the stars are moving together through space. Plotting the magnitude and direction of all their proper motions onto a star map will, however, show not parallel lines but lines that converge due to perspective. This point of convergence Pv is called the vertex of the star cluster, and is the solution to the problem. Suppose now that the proper motion of each star in the cluster is measured relative to the direction of the vertex—that is, the "vertex angle" α. With the knowledge of the radial velocity Vr and α, the vector diagram is defined. Thus, now it is possible to calculate for every star its actual space velocity Vs and its* absolute *tangential velocity Vt in kilometers per second. Moreover, since we now know both the proper motion μ and the absolute length of the triangle's side Vt in kilometers per second, it is possible to calculate the star distance d in kilometers. The accuracy of the "star stream parallax method depends critically on the precision of measuring both the location of the vertex Pv and the direction and angular displacement of the proper motion μ with the heliometer, as well as on measuring the radial velocity Vr with the spectroscope.*

of Venus with the sun's limb. The day dawned with cloudless weather and the best observing conditions possible across the whole of continental Europe.

For all my observations, I used a Peter Dollond equatorial built around 1780 [Fig. 9]. All four contacts were observed directly through the telescope with a magnification of 200 and a red eyepiece filter (eyepiece and filter are part of the telescope's original accessories). The rest of the transit, more than five hours, I measured with a Dollond heliometer [Fig. 8] installed in front of the objective, using eyepiece projection onto a white screen. I broke with the 18th century only in timing the events using a modern quartz stopwatch.

Using present-day knowledge of the sun's distance, first contact was predicted to occur at my location at 7:20:07 AM MEST (middle European summer time), but I timed it to be 7:20:18, 11 seconds late. The sun was then at 16 degrees altitude. Second contact was predicted for 7:39:45 but I timed it to be 7:39:48, 3 seconds late.

Then I installed the heliometer and the projection screen. Until the middle of the transit I made 20 distance measurements toward the sun's eastern limb (where Venus had entered) using the technique shown in Fig. 13; during the second half, I made 20 measurements toward the western limb (where Venus would exit).

A few minutes before the last two contacts, I dismounted the heliometer and again looked directly through the telescope with the 200-power eyepiece and the red filter. Third contact I timed as 10 seconds before the predicted time and the fourth 25 seconds early. I did not have much confidence in my measurements, though,

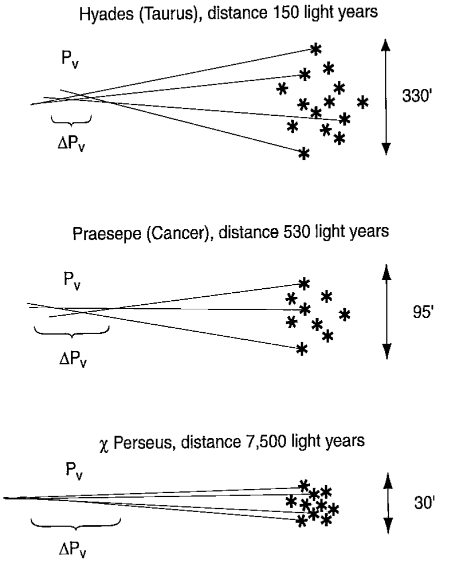

Figure 24 *The farther the distance of the cluster, the smaller is its angular diameter and the higher is the uncertainty in the vertex determination. But the star-stream parallax method for measuring stellar distances was an enormous step forward in the late 19th century. Whereas the limits for the distance measured via annual parallax was approximately 300 light years, the limit with the star-stream parallax method was about 15,000 light years.*

as by this time, the sun was at 66 degrees altitude; its observation, without a right-angle zenith eyepiece, was inconvenient and exhausting.

Although I have not yet completely reduced the heliometer observations to the sun's limb, my initial approximate calculations indicate they were better than my timings of third and fourth contacts, but not of first and second contacts.

What is my 21st-century evaluation of the 18th-century Dollond telescope and heliometer?

One significant difficulty was the evident secondary spectrum of the telescope's objective. Although the heliometer's negative focal length diminished the rainbow-colored fringes, they were clearly visible in the projected image; they reduced the definition of the sun's limb and therefore the precision of the contact measurements. The chromatic aberration would have been negligible had I made the heliometer measurements using the red eyepiece filter rather than in white light. But concentrated direct observing proved to be unexpectedly tiring, so I preferred the projection method.

Secondly, my Dollond equatorial refractor is mounted and equipped with gears in right ascension and declination, a remarkable help in manual tracking of the sun. But such convenient mechanical helps were not available on telescopes in 1769. Most telescopes then had altazimuth mounts, so tracking the sun required turning two different wheels, which in turn can cause the tube to tremble slightly—an effect that could diminish accuracy even at relatively low magnifications.

Thirdly, I was fascinated by how effectively the heliometer cancelled out the effects of air turbulence, especially near the sun's limbs. When I projected an image of Venus on the sun onto the screen using the telescope's normal eyepiece, the micrometer thread in the eyepiece appeared as an absolutely quiet image, behind which Venus jumped about according to the scintillation of the air. Therefore, it was not possible to secure an exact timing of the instant Venus touched the thread. With the heliometer installed in front of the objective, however, each semi-lens projected its own separate image of Venus and the sun's limb. When the image of Venus through semi-lens 1 was brought over the sun's limb through semi-lens 2, however, the scintillation distortions between the two were almost identical; the images moved together in virtual lock-step, and good timings were possible. But this homogeneity in air turbulence lessened with growing angular distance between Venus and the sun's limb, and after about 10 minutes disappeared—so through the heliometer the image of Venus seemed to jiggle around with respect to the sun's limb, as it did with respect to the micrometer thread. As third contact neared, however, the reverse happened, and the closer Venus approached the solar limb the better the heliometer timings became.

Lastly, because of the rarity of transits of Venus, it was (and perhaps still is) difficult to train observers how to anticipate all accuracy-reducing circumstances. The fact that I had some doubt about the exact moment of contact (especially for the third and fourth contacts) suggested to me that great differences in timings between observers may well be at least partially due to differences in their observing skills.

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