# Theme 5: The Rise of the Telescope:

## the role of instrumentation in astronomical advance

The 17th century marked a break with the past in the theoretical sense, as descriptive geometrical models of the solar system gave way to physically-motivated dynamical theories. It also marked a break in the observational sense: the end of the era of naked-eye astronomy. Through the 18th and 19th centuries, there is a good case for arguing that advances in astronomy were largely driven by improvements in technology.

Telescope technology provides two key improvements to observational data:

- greater light gathering power, allowing the observer to detect fainter objects or features;
- greater resolution, allowing the observer to detect finer details and make measurements with greater precision.

The former advantage leads to qualitatively new discoveries, which will be discussed in the next topic. The latter leads to better understanding, usually of existing phenomena. In this topic we focus on the effect of increased precision on our understanding of the scale and structure of the universe.

Astronomical technology does not consist purely of telescopes. Two 19th-century advances in technology/physics, photography and spectroscopy, have produced as great a revolution in astronomy as the invention of the telescope. In 1835, 12 years after Fraunhofer published his spectrum of the Sun with 574 measured spectral lines, the logical positivist philosopher Auguste Comte thought it self-evident that "never, by any means, shall we be able to study the chemical composition or mineralogical structure of the stars." Perhaps fortunately, Comte died in 1857: Kirchhoff and Bunsen demonstrated the identification of chemical elements by their spectral lines in 1859.

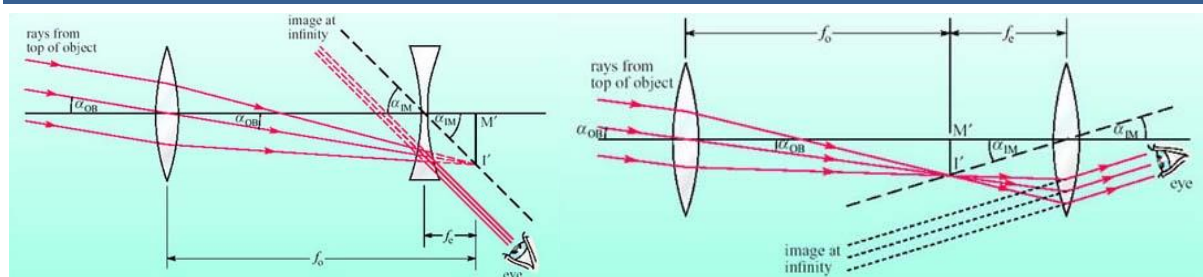## 5.1 Development of the telescope from 1600 to 1900



*Figure 5.1: refracting telescopes. Left, Galilean telescope producing upright virtual image; right, Keplerian telescope producing inverted real image. Any object placed in the focal plane M'I' of the Keplerian telescope will be in focus for the observer, hence the ability to introduce focal-plane instrumentation.*
*Images from http://www.open.edu/openlearn/ocw/mod/oucontent/view.php?id=2722&printable=1*

### 5.1.1 Technical developments

The early telescopes all consisted of a convex objective and a concave eyepiece, producing an upright virtual image, but a poor field of view. In 1611, Kepler suggested replacing the concave

eyepiece with a convex lens, producing a real inverted image which offered a larger field of view and could be projected on to a screen, e.g. for sunspot observations. Kepler never built his design, but various astronomers in the next few decades adopted it; by the middle of the 17th century it was the standard astronomical telescope.
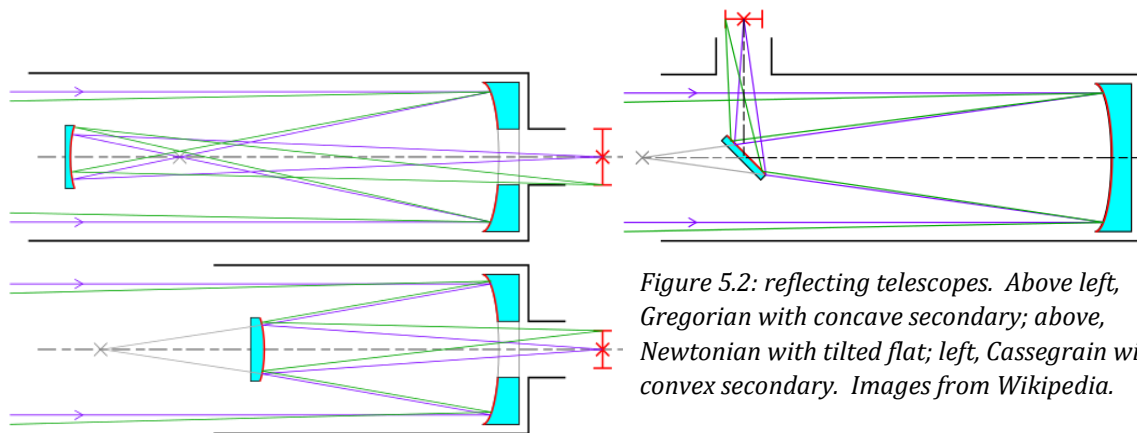


Figure 5.2: reflecting telescopes. Above left, Gregorian with concave secondary; above, Newtonian with tilted flat; left, Cassegrain with convex secondary. Images from Wikipedia.

Since only single ("simple") lenses were used, all early telescopes suffered from **chromatic aberration**. In 1672 Newton published his studies of the composition of white light, which showed that this was intrinsic to glass lenses; the only way to minimise it seemed to be to make very long focal-length lenses, and therefore extremely long telescopes. **Gregory** (1663), **Cassegrain** (1672) and Newton himself (1668) all suggested avoiding chromatic aberration by using a mirror as the objective instead of a lens; their designs differed in the shape of the secondary mirror (concave, convex and tilted flat, respectively, as shown in figure 5.2). Newton's design, which required only one curved face, was the most successful (though the Cassegrain design, which produces a shorter tube and better image quality, is more common nowadays). Reflecting telescopes could be much shorter, owing to shorter focal lengths, and have larger aperture, since mirrors can be supported at the back whereas lenses can only be held at the edges. However, early reflecting telescopes used metal mirrors (made of speculum alloy), which were difficult to cast, tarnished easily, had poor reflectivity by modern standards, and deformed with changing temperature; their technical superiority was by no means clear-cut until the 20th century.

In the 17th century the best telescopes were very long Keplerian refractors, which were difficult to align and awkward to use. Indeed, Huygens decided to dispense with the tube altogether, producing "aerial telescopes" which consisted of separately supported objective and eyepiece. Huygens also developed an improved doublet eyepiece and a reliable pendulum clock (valuable for positional astronomy because it allows better measurement of right ascension through transit observations). Positional astronomy also benefited from the realisation that wires could be placed in the focal plane of a Keplerian telescope and would then appear in focus on the observed image. In 1667, Adrien Auzout used one fixed and one movable wire to measure distances in the field of view (a **filar micrometer**); the same year, Jean Picard used cross-hairs to improve position measurement. He used this technique in surveying as well as pure astronomy, producing an improved determination of the size of the Earth by accurately measuring the length of one degree of latitude. Picard's measurements were good enough to observe seasonal shifts of 15–20" in stellar positions, but his friend Römer had not yet provided the necessary information to interpret these—definitive proof of the Copernican system was therefore delayed for another 60 years. Good, stable transit mounts completed the requirements for precision positional astronomy; the first precision transit mount was built by Römer at Copenhagen in the 1680s.
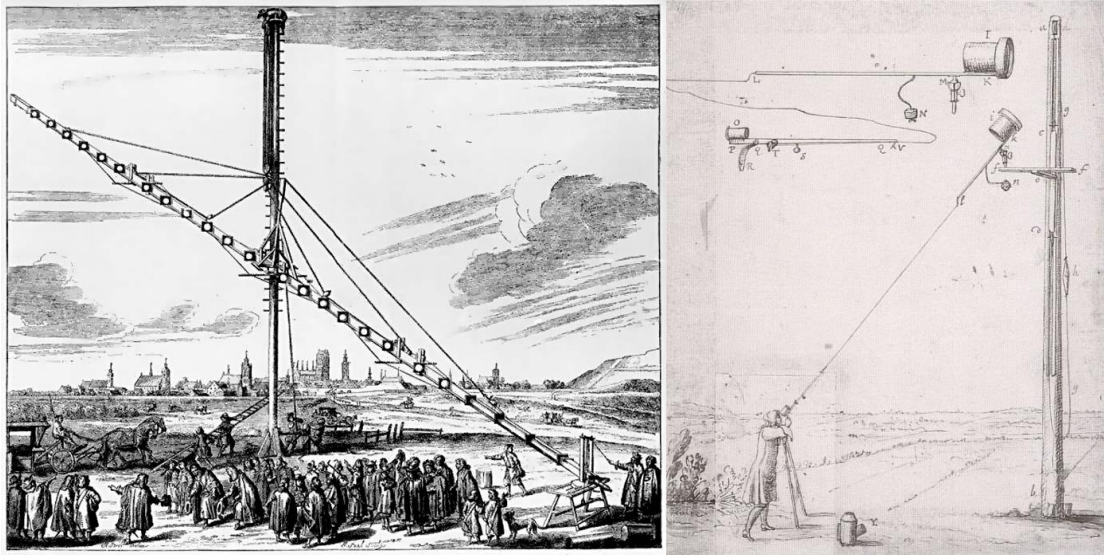
*Figure 5.3: 17th century telescopes. Left, Hevelius' 140-foot tubed telescope; right, Huygens' 210-foot aerial telescope with eyepiece and objective connected by a piece of string. Images from Wikipedia.*

In the 18th and 19th centuries, telescope technology split into two distinct directions. The largest telescopes were speculum reflectors, most notably those built by **John Hadley** (1682–1744), and later by **William Herschel** (1738–1822). These were the faint-object discovery machines of their day: Herschel discovered Uranus, planetary nebulae and the spiral structure of some nebulae, catalogued nebulae (the original New General Catalogue), and attempted to map the Milky Way. He also built and sold a phenomenal number of reflecting telescopes (around 400!).

Speculum mirrors, however, tended to distort with temperature and produced a fair amount of scattered light. In 1757 **John Dollond** designed a lens triplet of crown and flint glass[1] which reduced chromatic aberration to nearly negligible (for visual use) levels: the **achromatic lens** made it possible to build good, high precision, refracting telescopes of manageable size. At the same time, the start of the Industrial Revolution improved precision engineering, leading to better mounts (especially equatorial mounts). The Dollond family (John, his son Peter, and his son-in-law Jesse Ramsden) were the leaders in the 18th century, but the Germans, especially **Joseph Fraunhofer**, overtook the English in the 19th century. The highest precision instruments were **heliometers**, high-quality achromatic refractors with a split objective, where one half of the lens could be moved relative to the other, producing two displaced images of the same field. The movement needed to superimpose a target object on a known reference star provided a very accurate measurement of the position of the target. The instrument with which Friedrich Bessel finally cracked the stellar parallax problem was a Fraunhofer achromatic heliometer on a German equatorial mount: the Hubble Space Telescope of its day.

### 5.1.2 Early astronomical observations and consequences

**Galileo** did not invent the telescope, and was not even the first person to make astronomical observations with it (the English mathematician **Thomas Harriot** made observations of the Moon a few months before Galileo did so), but he was the first person to publish telescopic observations and relate them to current astronomical theory. Galileo's observations included the following:

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[1] A barrister named Chester Moor Hall designed an achromatic doublet earlier, but had not published his invention. Dollond's patent was later contested, but was upheld by a judge who argued that the person who published the invention was the person who should profit from it (I doubt this argument would stand legal scrutiny!).

- mountains and craters on the Moon, showing that it was not a perfect sphere as Aristotle would have expected;
- the phases of Venus, which were consistent with a Copernican (or Heraclidan, or Tychonic) system rather than the Ptolemaic;
- the four large satellites of Jupiter, showing that at least some celestial bodies orbited objects other than the Earth.
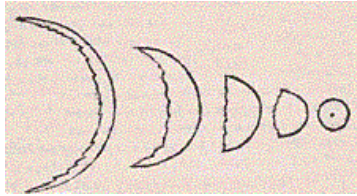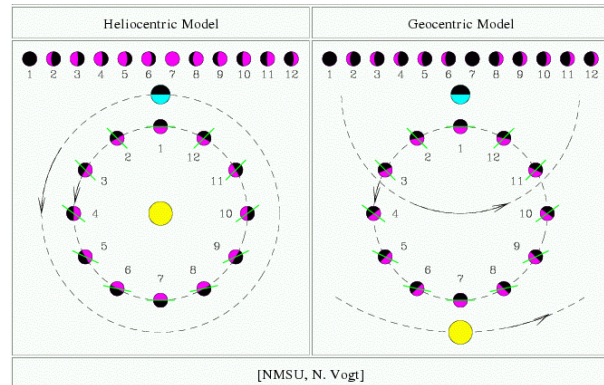


Figure 5.4: the phases of Venus, as drawn by Galileo (above).  Right, diagram showing that the full range of phases seen by Galileo requires Venus to be orbiting the Sun (note that the variation in the image size also matches expectation).

These observations did not themselves require any radical revision of established astronomical theory.  They did require the adoption of a heliocentric orbit for Venus, and by analogy for Mercury (the observations themselves were not so conclusive for Mercury, because it is too close to the Sun to observe near conjunction), but this is an old idea, as we have seen, and does not imply the abandonment of the rest of Ptolemy's system.  The Tychonic system is geometrically equivalent to the Copernican and cannot be disproved except by direct evidence of the Earth's motion (not forthcoming until **Bradley**'s discovery of aberration in 1729).  However, they were clearly in conflict with Aristotelian ideas, and when coupled with Kepler's three laws (which appeared at about the same time) they made a clear case for a mechanistic interpretation of the solar system in terms of "ordinary" mass and force.

### 5.1.3 Telescope technology and astronomical distance measurement

At the dawn of the telescopic age, astronomers had only one secure distance measurement: the distance between the Earth and the Moon, which had been known at least approximately since Hipparchos' calculations from eclipses.  Tycho had tried and failed to measure the parallax of Mars; the distance of the Sun had been attempted since the days of the Greeks, but universally underestimated.  Kepler's laws provided an accurate *relative* scale for the solar system, but no absolute distances.  Meanwhile, there was still little if any concept of stellar distances.

### The astronomical unit

Because of Kepler's laws, measuring any solar system distance is equivalent to measuring the **astronomical unit**, or equivalently the **solar** (diurnal) **parallax** (defined as $R_\oplus/d$, where $R_\oplus$ is the Earth's radius and $d$ is the distance to the Sun).  In antiquity, Aristarchos concluded that the Sun was 18–20 times as far away as the Moon, i.e. about 1100–1200 Earth radii; Hipparchos seems to have concluded that it was at least 490 Earth radii (probably on the grounds that any smaller distance would produce a detectable solar parallax); Ptolemy went for 1210 Earth radii. These numbers all stem from theoretically valid methods (Aristarchos' from the lunar terminator, Hipparchos' and Ptolemy's from eclipses), which are simply too difficult to apply accurately using the naked eye. Eratosthenes is quoted by Eusebius as measuring a distance of "stadia myriads [tens of thousands] 400 and 80000", which is apparently as ambiguous in the Greek as it is in translation: does it mean 4,080,000, or 804,000,000? There are various defi-

nitions of the stadion, and authorities disagree about which one Eratosthenes used; if instead we scale to his value of 252000 stadia for the Earth's circumference, we get about 100 Earth radii for the former value (much too small) and about 20000 for the latter (within 20%). It is tempting to credit Eratosthenes with the right answer, but there is sadly no obvious way he could have achieved this except by luck. (In contrast, his equally good value for the size of the Earth rests on measurements which were quite within the capacities of his technology.)

Ptolemy's and Aristarchos' estimates were believed up to the dawn of the telescope era: Tycho's search for the parallax of Mars rested on the assumption that the solar parallax was the corresponding 3', and therefore that Mars' parallax would be a reasonably detectable (if you happen to be Tycho) 6' or so at opposition. Kepler deduced from the good fit of his calculated orbit to Tycho's observations that the parallax of Mars is actually not more than 1' or 2', so the Sun's is 1' at most: this was the first real revision of the Greek estimates. (In India around AD 500, Āryabhaṭa estimated 5500 Earth radii, much better though still far too small; but the Indian theories had little influence on the Western tradition.)

Telescope technology offered a possible solution. Around 1630, **Vendelinus** applied Aristarchos' method using a telescope to locate the lunar terminator: he concluded that the elongation of the Sun at half moon was 89½° (as opposed to Aristarchos' 87°); therefore the Sun's distance is about 230 times the Moon's distance, about 60% of the correct value. The dominant source of error is the irregularity of the lunar terminator caused by the lunar relief, so this method cannot be greatly improved by enhanced technology.

Attention switched back to the parallax of Mars. In 1672 there was a favourable opposition, with Mars only 0.37 AU from the Earth; **Jean Richer** in Cayenne and **Gian Domenico Cassini** in Paris measured the position of Mars, and found that the difference in positions was comparable with the accuracy of their measurements. Cassini concluded that the parallax of Mars was not more than 25", and therefore the solar parallax not more than 10"; he took 9½" (with a large uncertainty) as a final result. [This suggests that he must have felt that the difference in positions, though consistent with the observational uncertainty, was in fact real.] Note that the greater ease of travel also played a role: in earlier centuries it would not have been possible to make coordinated observations over such a long baseline. The invention of the pendulum clock, by Huygens in 1656, had also contributed greatly to the accuracy of positional measurements, by allowing more accurate timing of stellar transit times (and hence measurement of right ascension).

Ease of travel also threw up another promising method. In 1676, Edmund Halley was sent to St Helena—not in exile, as per Napoleon, but to catalogue southern hemisphere stars. He observed a transit of Mercury across the Sun, and realised that a series of such observations from different places would provide data for the parallax of Mercury relative to the Sun. Mercury is not in fact the best planet for this purpose, because the key datum is the difference in parallax between the planet and the Sun; Halley realised that transits of Venus were much more appropriate. Unfortunately, they are also much less common: they typically occur in pairs 8 years apart, with a gap of over a century between pairs, and Halley was in the middle of the gap. Being a forward-looking individual, he suggested that a future generation of astronomers should mount an observing campaign for the next pair of transits, due in 1761 and 1769. The results were less good than Halley expected, because of optical illusions (the "black drop" effect) caused by looking at a black spot against a very bright background, but still produced results consistent to a few tenths of an arc-second (the calculated solar parallaxes ranged from 8.28" to 10.6" in 1761, and from 8.43" to 8.80" in 1769). The next pair of Venus transits, in 1874 and 1882, were studied with even more care, and the use of early photographic techniques: they yielded results

varying from 8.76" to 8.88". The probable cause of the difficulty is the high level of atmospheric turbulence inherent in making observations towards the Sun.

Meanwhile, the discovery of aberration by Bradley in 1728 (see below) offered an entirely independent method of measuring distances. The amount of aberration is given by $v/c$, where $v$ is the Earth's orbital velocity. Initially this was seen as a method of determining the speed of light, having determined $v$ from the astronomical unit and the length of the year; however, given a good laboratory measurement of the speed of light, it can be applied backwards to determine $v$, and hence the astronomical unit. The first reliable laboratory measurement of $c$ was made in 1849 by **Fizeau**, using a toothed wheel; it was improved by **Foucault** in 1862 using a rotating mirror. These results suggested a solar parallax of about 8.8", which was in conflict with an 1835 reanalysis of the 1761/9 Venus transit data by Encke which had come down towards the lower end of the range, at 8.57".

In view of this discrepancy (resolved in 1864 by yet another reanalysis of the old transit data, which yielded a result at the top end of the original range), more attention was given to parallax measurements, first of Mars, and then later of asteroids (the first asteroid, Ceres, was discovered in 1801 by Piazzi). The advantage of asteroids was that they have star-like images and brightnesses, which means that it is much easier to measure their positions accurately with respect to comparison stars (this is true both for visual observation and for photography). Even better measurements were possible when the first near-Earth asteroid, **Eros**, was discovered in 1898: because it approaches within 0.2 AU, its parallax is significantly larger than Mars' or Venus' and much larger than those of main belt asteroids. Pannekoek, writing in 1951, cites Eros' parallax and measurements from celestial mechanics (the "parallactic anomaly" in the Moon's motion depends on the ratio of the Moon's distance to that of the Sun, and was first used to determine the Sun's distance in 1805) as the most accurate, and cites values of 8.790" (Eros), 8.796" (lunar motion), 8.799" (Eros' perturbation by the Earth) and 8.802" (Earth's velocity, measured spectroscopically) as best recent measurements. They all have quoted errors of 0.001" or 0.002", which shows that even seasoned professionals frequently underestimate their systematic errors.
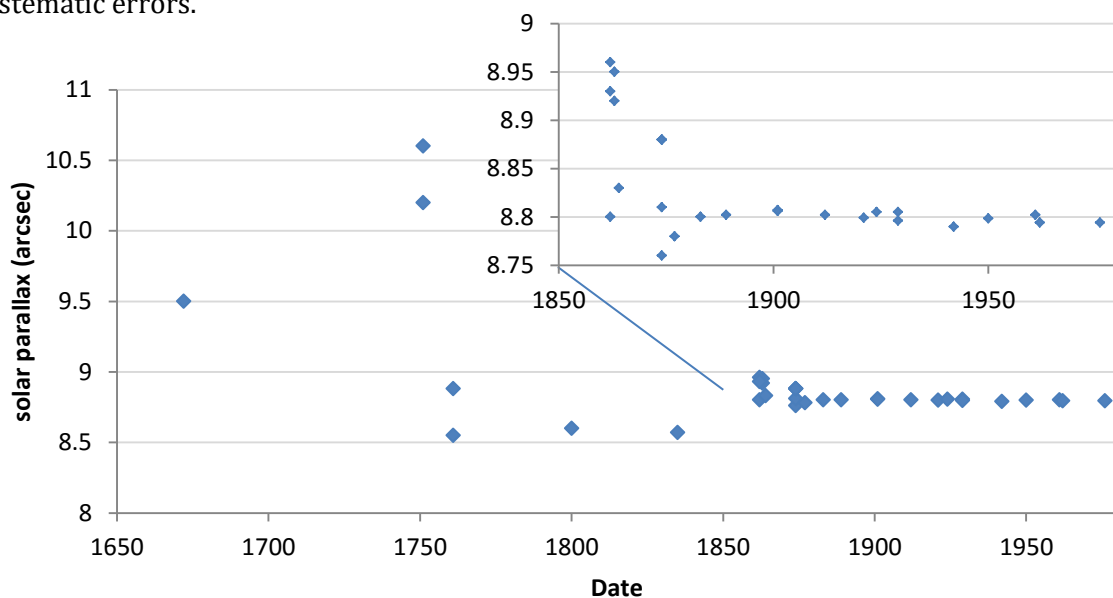


Figure 5.5: History of the astronomical unit. See text for details.

The final chapter in the measurement of the astronomical unit depends on a technological advance of a completely different nature: the invention of radar during WWII. In 1961,

astronomers successfully detected radar reflections from Venus, and later from Mercury. This allowed them to measure both the rotation rates of both planets (by the Doppler splitting of the beam) and, from the time delay between sending and receiving, the distance of the planets with an accuracy limited only by the measurement of time and the speed of light. Later, the transmissions from spacecraft such as Viking were used; this removes the effect of the planet's topography, which blurs the returning signal. The astronomical unit then became one of the best known numbers in astronomy, and indeed in all of physics: the IAU quoted it in 2009 as 149597870700±3 m, and decided in 2012 to fix it at 149597870700 m *exactly*, and absorb the tiny uncertainty into $G$ (actually, into the *Gaussian gravitation constant* $\sqrt{G}$).

Improvements in the measurement of the astronomical unit depended mainly on technology (the greater angular resolution of telescopes; improvements in positional astronomy created by better telescope design and improvements in time-keeping; ease of travel and communications; laboratory measurements of the speed of light; photography for use in parallax measurements; finally radar), and somewhat also on techniques (the transit method; the mathematical understanding of the lunar orbit). The more challenging problem of stellar distances was driven, for 300 years from 1600 to 1900, almost entirely by a single technology: the refracting telescope.

## Stellar parallax

Stellar parallax was a major concern of 17th century astronomers, because of the controversy over the Copernican system. Copernicus himself still saw the sphere of fixed stars as a thin shell, probably not far beyond Saturn, but the idea that stars were other Suns was gaining ground. In *Sidereus Nuncius*, Galileo suggested using double stars of contrasting brightness to measure the stellar parallax; he assumed that the fainter star would be more distant, and would provide a near-stationary reference. He did not, however, follow up on this. Other 17th-century astronomers assumed that all stars were similar to the Sun, and attempted to deduce their distances by comparing brightnesses. Huygens attempted this by comparing Sirius with the Sun viewed through a small pinhole; Gregory suggested using a planet such as Saturn instead (compare the brightness of Saturn to the star; calculate, from Saturn's known diameter and distance, what fraction of the Sun's light Saturn reflects). Gregory got 83190 AU for the distance of Sirius; Newton, using the same method, got 1,000,000. These estimates, while rough, at least give the right order of magnitude (Sirius is actually about 600,000 AU away, but is brighter than the Sun so appears nearer with this method).

This method is subject to the untested assumption that stars are indeed similar to the Sun, and therefore is no substitute for a real measurement. In 1669 **Robert Hooke** built a zenith telescope, with a fixed vertical mount: this allows accurate alignment (with a plumb line), and removes the effect of atmospheric refraction (because the light it sees is normally incident on the atmosphere), but severely restricts the choice of stars. Hooke picked γ Draconis, but made only a few measurements before the telescope met with an accident.

About 50 years later, **Samuel Molyneux** and **James Bradley** resurrected this technique. Using the same star, they found a displacement of about 20"—but it was three months out of phase with that expected from parallax. Further studies, with a telescope offering a wider field of view, showed that all stars displayed a similar effect. This clearly was *not* parallax, but it turned out that it *was* a proof of Copernicus.

In 1676 Ole Römer had explained irregularities in the timing of occultations of Jupiter's satellites (which were consistently early at opposition and late at conjunction) by arguing that light travelled at a finite speed and took about 13 minutes [actually, about 16m 38s] to cross the Earth's orbit. Bradley realised, by analogy with the weather-vane on a moving boat, that this

could explain his effect: the deflection of the light was a result of the Earth's velocity through space (since velocity in a circular orbit is perpendicular to radius, this explains why the ellipse traced was perpendicular to that expected). This phenomenon is now called **stellar aberration**, and clearly proves that the Earth is in motion. Bradley calculated from the size of the effect that light takes 8m 12s to travel 1 AU; this is only about 8 seconds out. (Note that aberration had been seen before by good observers, e.g. Picard, but not recognised as a genuine physical effect. This is not uncommon with unexpected discoveries—for example, several observers recorded Uranus before Herschel identified it as a planet, and Galileo even saw Neptune.)

The precision of Bradley's measurement was such that he could confidently state that the parallax of the stars he had observed was less than 1". This rendered the technical challenge too severe for 18th century instrumentation. In 1779, Herschel began to collect double stars, in the hope that Galileo's method could be used; but **John Michell** had already pointed out in 1767 that double stars were too common to be chance alignments, and must be real physical associations. Indeed, when Herschel re-examined his collection in 1802, he found that several of them had moved relative to each other as expected from Newtonian orbits. This unfortunately also demonstrated that all stars do not have equal brightness, undermining the previous idea that bright stars were the best parallax targets (and indeed they aren't—of the 20 brightest visible stars, only α Centauri and Sirius are less than 10 light years away, and of the 20 nearest systems, only seven are even visible with the naked eye).

Meanwhile, the advent of achromatic lenses had greatly enhanced the image quality of Keplerian refracting telescopes, the onset of the Industrial Revolution had provided higher precision engineering for both telescopes and, especially, mounts, and mathematicians such as **Gauss** (1777–1845) and **Poisson** (1781–1840) had put statistics on a firm mathematical footing, so that scientists were getting to grips with the quantitative treatment of experimental error. These were the necessary ingredients for a successful measurement of stellar parallax.

First, a combination of natural ability and strong government support allowed **Joseph Fraunhofer** (1787–1826) to develop a world-leading optical instrumentation lab at the Mathematical-Mechanical Institute in Munich. He produced ultra-high-quality achromatic lenses (some of them split for heliometers), and developed an excellent version of the equatorial mount (the **German equatorial**). Secondly, **Friedrich Wilhelm Bessel** (1784–1846), mathematician and astronomer, recognised the importance of understanding the telescope: he said in 1848 that the telescope has to be built twice, "once in the workshop of the artisan, from brass and steel, and again by the astronomer, on paper, through the application of necessary corrections"[2]. Thirdly, thanks to Herschel's demonstration that stars do not all have equal brightness, astronomers had realised that choosing targets by their brightness was not a good idea, and had instead moved to considering stars of high proper motion.
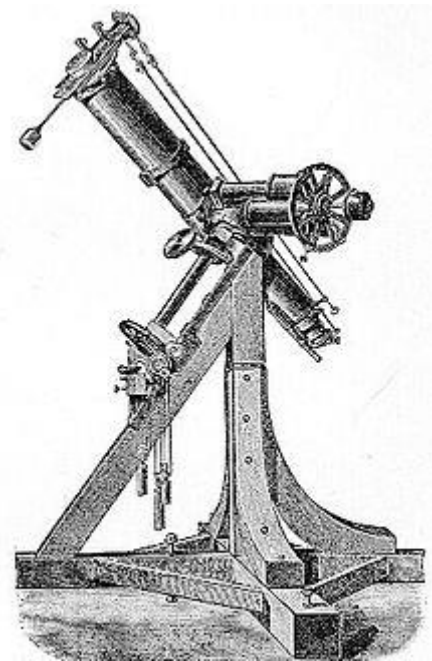


*Figure 5.7: Bessel's heliometer. Image from Wikipedia.*

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[2] Bessel, 1848, quoted by AW Hirshfeld, *Parallax: The Race to Measure the Cosmos* (Henry Holt, 2001), p214.

Putting these ingredients together, Bessel used a Fraunhofer 6-inch heliometer, properly calibrated by himself, to observe 61 Cygni, a rather faint binary star with exceptionally high proper motion. The resulting paper (*MNRAS* **4** (1838) 152–161) is a model of careful analysis, and concludes that the parallax of 61 Cygni is 0.3136±0.0202 arc seconds. The current best value is 0.2872±0.0015, only just outside Bessel's error bar.

Just to demonstrate that parallax was a measurement whose time had come, two other measurements were reported within the year. Neither was as accurate, as carefully justified, or as convincing as Bessel's, because the vital ingredients were not fully in place. **Wilhelm Struve**'s value for Vega was out by a factor of 2: he did have a high-quality Fraunhofer refractor (the Dorpat refractor), but had not chosen a good star (Vega's true parallax is only 0.129"), largely because the small field of view of the Dorpat refractor limited his choice of candidates (you must have a more distant reference star in the field). **Thomas Henderson** in South Africa had made the ideal choice of star (α Centauri, the nearest system available, with a true parallax of 0.742"), and had worked diligently to calibrate his instrument, but had only a Troughton mural circle which was known to be damaged (it had collided with the dock during unloading).

After the first few measurements, the improvement in stellar parallax continued to be technology driven. The first advance, not long after Bessel's triumph, was the advent of astrophotography, which allowed star fields to be recorded for later measurement; this was followed by automatic plate measuring in the 1960s and CCD imaging in the 1990s. The current state of the art is of course dominated by space-based measurements (Hipparcos (1989-1993), and Gaia, launched in December 2013 and scheduled to publish its first data release in September 2016), which have much better angular resolution as a result of being outside the atmosphere.

## 5.2 Photography

Up to the middle of the 19th century, all astronomical data were taken using the human eye as a detector. The eye is a very good optical instrument: it has good resolution, is capable of good dynamic range, and requires no special equipment. However, it has two serious drawbacks: it does not make a permanent, objective record of what is actually observed, and it uses a fixed exposure time of around 1/20 second. Photography addresses these issues: the photograph records the image formed by the telescope, whereas the observer's drawing records the image processed by the visual centres of the brain; and photographic exposures can be varied from small fractions of a second up to hours. The photograph also allows far more measurements to be taken: the observer can only concentrate on one measurement at a time, whereas the photograph records all the objects in the field of view, and can be measured at leisure afterwards.

Photography was invented in the 1830s, by a number of people, though the least impractical technique was the **daguerreotype** invented by **Louis Jacques Daguerre** in 1839. This process was extremely slow, and not at all suited to photographing the night sky, although a number of pioneering astronomers used it to image the Sun and a few bright stars. The **wet collodion process**, invented in 1850 by **Frederick Scott Archer**, was much better, and was used by numerous astronomers including **Lewis Morris Rutherfurd**, who built the first telescope designed specifically for photography (early photographic plates were sensitive to blue light, rather than the yellow-green of the dark-adapted eye, and so needed a slightly different focus—even achromatic lenses do not get blue light to the same focus as yellow-green).

In 1871 **Richard Leach Maddox** invented the **dry gelatine** plate, which was enormously more convenient than the wet collodion process (in particular, wet collodion plates have to be produced immediately before use and developed immediately afterwards, which is very inconvenient for astronomers), and astrophotography took off. Henry Draper took the first "deep-sky" image, of the Orion Nebula, in 1880; Huggins photographed its spectrum in 1882.



*Figure 5.8: the value of photography. Top left, drawing of the Orion nebula by Sir John Herschel in the 1830s; top right, drawing of the Orion nebula by William Parsons, 3rd Earl of Rosse, in the 1840s; bottom, photograph of the Orion nebula by Andrew Ainslie Common using the dry gelatine process and the 36" reflector later known as the Crossley Reflector, 1883. Common's image covers a larger field of view than Herschel's and Rosse's: the white box roughly denotes the area that corresponds to Herschel's drawing. Note that the long exposure image (37 min) shows nebulosity extending over a much wider area. Also note how different the two drawings—both by experienced astronomers—are from each other and from the photograph. (Upper two images from David Malin's introductory essay for RIT's Images from Science exhibition of 2002; bottom image from Malin and Murdin, Colours of the Stars (CUP 1984), p29.)*

The Henry brothers made the first unambiguously photographic discovery, of the nebulosity around the Pleiades, in 1885. In 1887 the Paris Observatory planned a photographic atlas of the whole sky, carried out by a consortium of 18 observatories. The scientific cost-effectiveness of this project, which was never fully completed, is debated, but it demonstrates the speed with which astronomers adopted the new technology. A much more lasting contribution was the **Henry Draper catalogue**, which used objective prism plates taken around the turn of the 20th century to produce spectroscopic classifications of around 225000 stars; paid for by Henry Draper's widow, this introduced the Harvard spectral classification still used today.
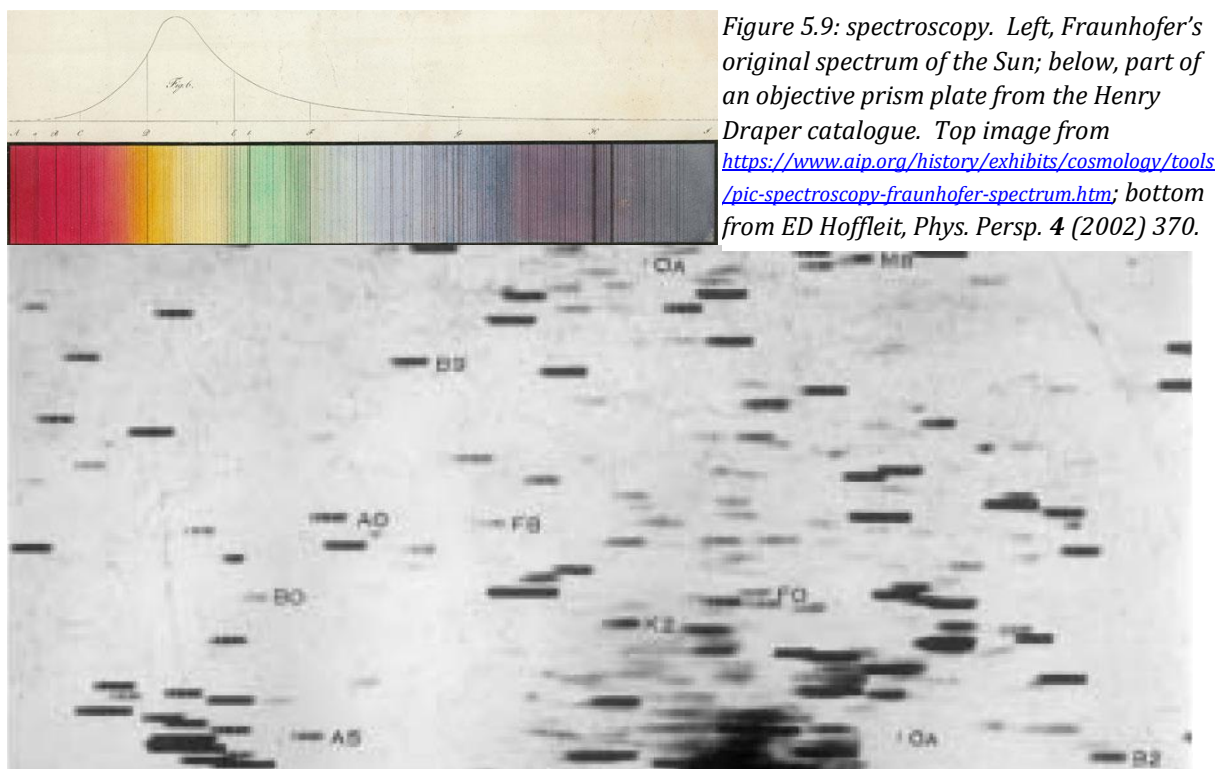
It is remarkable how long it took before photography completely ousted the naked eye as the detector at the eyepiece of the telescope: as late as 1951, Anton Pannekoek wrote in his *History of Astronomy* that the best photographs of planets "show almost the same amount of detail as the best drawings" (i.e. the drawings were still superior, though Pannekoek does go on to say, "it may be expected that [photographs] will surpass [drawings] after further improvement has been made").

## 5.3 Spectroscopy

In 1671, Newton's famous prism experiment demonstrated that sunlight was made up of light of different colours, and that an individual colour passed through a second prism was not further split up (this is important, because it confirms that the rainbow effect is not simply created by the prism). At the time, this effect was simply a nuisance for astronomers, since it caused

chromatic aberration in refracting telescopes. Spectroscopy as such did not begin until 1802, when **William Wollaston** observed dark lines in the Sun's spectrum, which he interpreted as boundary lines between discrete colours of light. Searching for a method of defining wavelength standards, Fraunhofer repeated this experiment in 1823, incidentally creating the modern spectroscope by using a small telescope instead of the naked eye to view the spectrum. He observed 574 lines, of varying width and intensity, and labelled the strongest with the letters still used today (e.g. the sodium D lines).

Fraunhofer simply used his lines as wavelength standards. Over the next couple of decades, physicists and chemists began to correlate flame colours with chemical composition of salts, until in 1859 **Kirchhoff** and **Bunsen** demonstrated that individual elements create individual line spectra, either in emission or in absorption depending on conditions (**Kirchhoff's rules**). In 1872, Henry Draper took a stellar spectrum which showed absorption lines, Comte was proven wrong, and the study of the chemical composition of celestial bodies was born.



*Figure 5.9: spectroscopy. Left, Fraunhofer's original spectrum of the Sun; below, part of an objective prism plate from the Henry Draper catalogue. Top image from* https://www.aip.org/history/exhibits/cosmology/tools/pic-spectroscopy-fraunhofer-spectrum.htm*; bottom from ED Hoffleit, Phys. Persp.* **4** *(2002) 370.*

## 5.4 Summary: the role of instrumentation in the advance of astronomy

The telescope, photography and spectroscopy are responsible for the development of astronomy as we know it today, and particularly for the existence of the sub-disciplines of astrophysics and cosmology. It is hard to imagine how we could go about studying the structure and evolution of the stars without some method of determining their chemical composition, or how observational cosmology could have developed without the Hubble diagram. These advances did not originally come about because of their applications in astronomy: telescopes were invented in the Netherlands for terrestrial use; photography's applications have always been more terrestrial than celestial; Fraunhofer originally used his solar spectrum as a source of wavelength standards (though it *is* fair to say that Kirchhoff's realisation that emission and absorption lines at the same wavelength were produced by the same element came directly from his studies of the spectrum of the Sun). However, all were rapidly adopted by astronomers, and all led to new

discoveries, and indeed entire new fields of study, in astronomy. Thus, in all three cases the improvements in instrumentation drove the scientific advance, and not *vice versa*.

To a great extent, this has remained true ever since, although the traffic is not entirely one-way: sometimes the needs of observers stimulate technological progress, as in the case of gravitational-wave astronomy, where the required sensitivity could be estimated from Einstein's calculations; sometimes technological advances open up new fields of astronomy, as in the case of radio astronomy after the development of radar in World War II. The dialogue between technology and observation is as fruitful for astronomy as that between theory and observation.

Of course, technology as a driver for discovery is not unique to astronomy: in high-energy physics, $E = mc^2$ ensures that the discovery reach of an accelerator is limited by its beam energy, which in turn is limited by some combination of technology and budget. Similar examples could be cited from other fields. However, astronomy stands out for the number of times that entire subdisciplines have been revolutionised by technological advances—especially in the era of space-based instrumentation where the opening up of new regions of the electromagnetic spectrum has led to enormous changes in our understanding of many types of astrophysical object.