Christmas Lecture

Tycho Brahe – Instrument designer, observer and mechanician

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Accustomed as modern astronomers are to thinking of their science as progressive, and based on an ever-improving instrument technology, it is hard to envisage a time when astronomy was seen as a conservative discipline. Yet if one believed that the principal features of the heavens had already been catalogued by the ancients, then one could do little more than make adjustments for precession and other quantities. Medieval astronomers regarded the heavens as a great clock, the workings of which were generally understood, and which were read periodically with astrolabe and quadrant to keep the calendar in adjustment.[1]

Not until the fifteenth and sixteenth centuries did new scientific circumstances demand a change of approach. The Julian Calendar was running into error, the Earth's motion around the Sun was being seriously proposed, while the new star of 1572 demonstrated that change could take place in space, beyond the 'sphere of the Moon'. Astronomers were also coming to challenge the very existence of the crystal sphere of heaven, while comets were being considered as astronomical, rather than meteorological bodies. None of these questions could be answered by simply adjusting existing observations, but demanded a fresh examination and measurement of all bodies in the sky. Though Tycho Brahe was not the first Renaissance astronomer to observe the heavens, he was the first to realise that long-term, systematic observation was required, and that the quality of these observations – and the cosmological conclusions which could be drawn from them – depended on the improving accuracy of instruments.

The main event which compelled this new way of thinking upon Tycho was a new astronomical phenomenon, for which there was no precedent in existing catalogues: the New Star of 1572.[2]

When the New Star appeared, in November 1572, it was confidently expected by astronomers to display a parallax. It was assumed, in accordance with prevailing cosmological beliefs, that no new phenomenon could occur beyond the Moon on the grounds that only the terrestrial regions were subject to change, so the star must be in the upper atmosphere. As the Moon, which was considered to occupy the extreme upper limit of the atmosphere, displayed an obvious parallax, the essentially meteorological New Star, being closer than the Moon, should show an even bigger one. Tycho set about measuring the New Star's position from its adjacent stars in Cassiopeia during the winter of 1572–73, observing as it transited the northern meridian.

The conclusion delivered a serious blow to classical cosmology, by demonstrating that there could be changes and new stars in deep space. Equally important was the avenue via which Tycho arrived at this conclusion: not by the rules of logic or philosophical abstraction, but by mathematical data yielded by a precise measuring instrument. In many ways, one might say that it was Tycho's observation of the New Star of 1572, even more than Copernicus's theory, which saw the birth of modern astronomy, for it identified the essential working ingredients of a scientific problem:

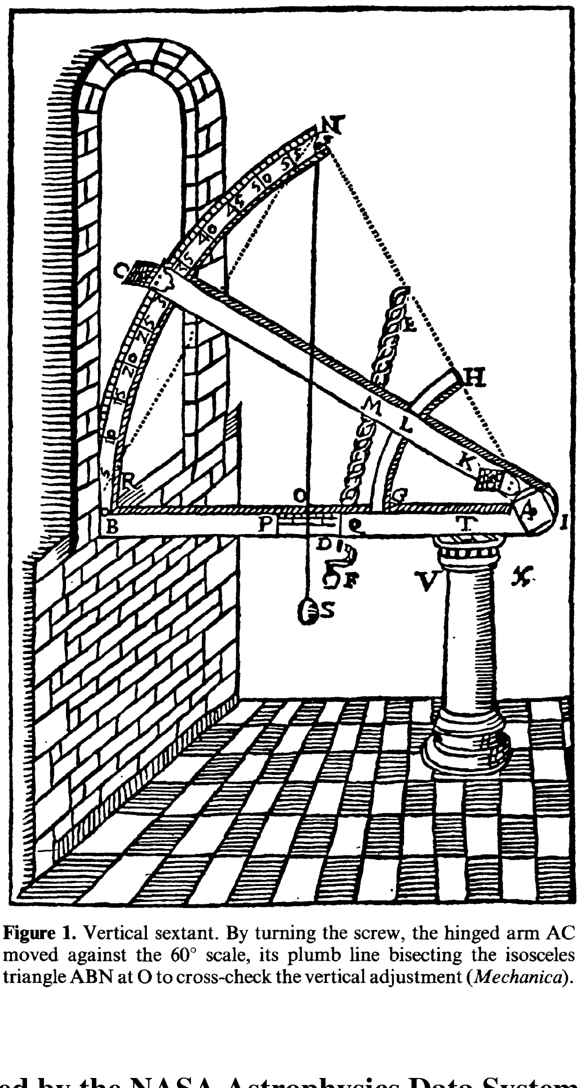

Figure 1. Vertical sextant. By turning the screw, the hinged arm AC moved against the 60° scale, its plumb line bisecting the isosceles triangle ABN at O to cross-check the vertical adjustment (*Mechanica*).

the need for accurate observation, exact instrumentation and conclusions based on careful measurements as opposed to purely theoretical criteria. Over the next twenty-five years, Tycho was to devise a new working method for astronomical research, grounded in the systematic use of instrumental evidence, and described in detail in his *Mechanica* and *Progymnasmata*.[3] These two books, along with Tycho's other published works, established a new way of doing science, searching for, and utilising new knowledge, which was to be as important for the philosophy of science as Kepler's Laws or Newton's gravitation.

Tycho's observations of the New Star were performed with an instrument of his own devising, comprising a hinged pair of six-foot beams, opening like a pair of compasses against an accurate scale of 60°, controlled by a fine screw. Unlike most of the instruments of his day, this 'sextant' was designed to fulfil one single function – the precise measurement of a vertical angle.[4] Most sixteenth-century instruments were devised to be multi-purpose, and could measure a variety of different types of phenomenon, such as the time, vertical and horizontal angles. Tycho established a fundamental principle of instrumentation: the more functions you expected an instrument to perform, the less accurately will it do each one of them. Supreme accuracy depended on an instrument that was designed to fulfil only one specialised task, and which could be left in one critical adjustment (Fig. 1).

The New Star, and the major book in which he published his conclusions and observing methods, made Tycho's astronomical reputation by the time that he was twenty-seven. Following an invitation from King Frederick II of Denmark, he set up his famous observatory of Uraniborg, on the island of Hven, off Copenhagen, to commence a quarter-century research programme which was to change the course of astronomy. Fortunate insofar as he had ample Royal funds to back him during King Frederick's life, Tycho set about a complete revision of the northern heavens to become the first European since antiquity to re-map the sky from scratch.

Tycho's work was original not only in the way in which it stressed the use of specialised instruments to attack specific astronomical problems, but because of his wider contributions to the process of technological research and development. Uraniborg was more than just the first well equipped observatory in Europe – it was also a workshop and testing ground for new ideas in astronomical hardware. Tycho's skills as an observer are well known, but we often forget his perhaps greater skills as a mechanician and engineer. Though he did not make equipment with his own hands, he did *design* it, and between 1573 and 1597 evolved several 'families' of instruments, individual members of which he improved, re-built and perfected until he was able to obtain the extreme limit of accuracy possible to the naked eye. The modern scholar, Victor Thoren, has worked out a detailed chronology for the invention, use and superceding of many of Tycho's instruments, from the observing logs included in the astronomer's *Opera*

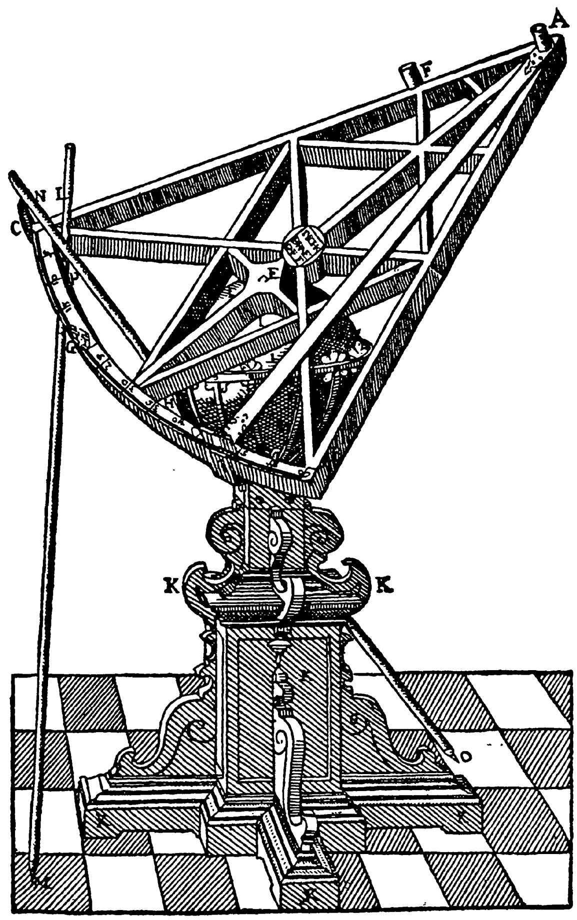

Figure 2. *Sextans trigonicus*; horizontal angles were read against the peg A (*Mechanica*).

Omnia.[5]

Tycho's main instruments fell into three groups, each devised to fulfil a particular purpose, comprising the sextants, armillaries and quadrants. The sextants represented Tycho's most original and structurally significant instruments. They were used for measuring either vertical or horizontal angles between pairs of objects in the sky, and comprised a 60° arc, which was produced naturally by striking off the radius of any circle against its own circumference, in accordance with Euclidean procedures.[6] Though not the first astronomer to use a 60° instrument, Tycho was certainly the first to see the wide possibilities which this natural geometrical shape, and its enclosed isosceles triangle, afforded. His first instrument of this type had been a portable 'half sextant' of 30° made when travelling in Germany in the late 1560s.[7] It had been with such an instrument, and with a full sextant of 60°, that he had observed the New Star of 1572, as mentioned above.

Once this hinged two beam design had been realised, Tycho improved it, to produce a series of sextants with rigid 60° frames of wood and metal, equipped with pairs of sights to enable two observers to read off large horizontal angles against a central sighting peg. In his six-foot radius 'Sextans Trigonicus' of 1584, the body of the sextant could be locked by a ball and claw to any

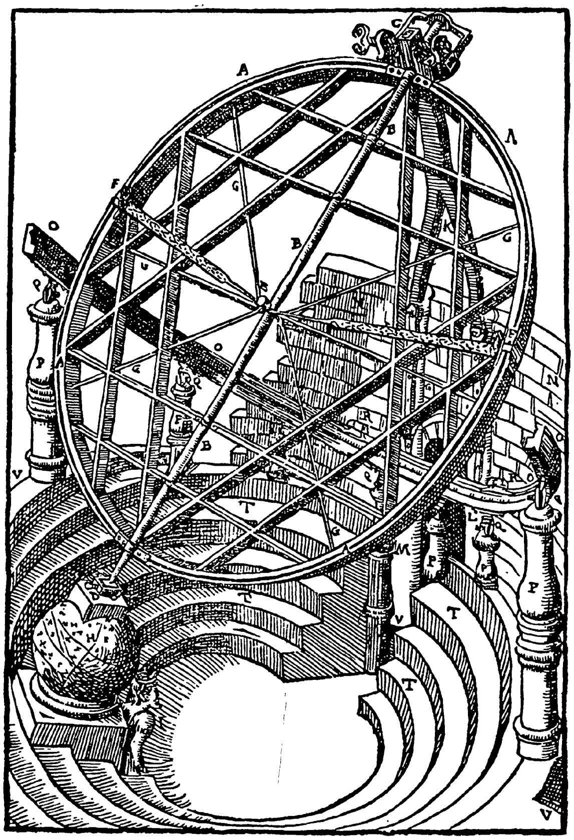

Figure 3. The Great Armillary of one ring, set upon a polar axis, for the measurement of declination angles across the central peg (*Mechanica*).

plane in the sky to observe a series of great interlocking spherical triangles around the zodiac or celestial equator.[8] Though accurate to about one minute of arc for a single observation, Tycho greatly refined his values by regularly repeating the same observation over months or years, so that when his observations were reduced in the nineteenth century, his standard stars were found to be accurate to 24 seconds of arc.[9] these were the stars which formed the foundation positions from which everything else was measured in the construction of his catalogue (Fig. 2).

The armillaries were large circular instruments, based on ancient Greek prototypes, in which great rings around six-feet in diameter were set up to form skeleton spheres, to demarcate the zodiac, equator, meridian and pole. By taking sightings across the accurately graduated rings, one could observe Right Ascension angles, measure the Sun's daily coordinates and fix the First Point of Aries. Because classical and medieval astronomers used the zodiac as their fundamental celestial plane, Tycho found it awkward to integrate ecliptic coordinates with latitude measurements made from the pole. In consequence, he simplified the armillary sphere by reducing its plane to that of the equator, thereby improving its ease of operation by simulating the daily rotation of the heavens. By this act, we must also remember, he also 'invented' the equatorial mount.[10]

Tycho built several armillaries at Uraniborg, each one more specialised and exact in its function, until he reduced the design to a single ring ten feet in diameter, moving around a polar axis, within a semicircle set within the equatorial plane. This instrument was so large that the observer stood *inside* it to make an observation, while it was mounted on one of the earliest sets of self-centering bearings in the history of precision mechanics (Fig. 3).[11]

The traditional problem with armillary spheres derived from the fact that the cental axis upon which the heavy rings were mounted, moved in a simple plug socket, which had to be fairly loose to permit the rings to turn. Tycho realised that the instrument could never be exact so long as the inevitable 'play' in the sockets remained. On his ten-foot armillary, however, he terminated the lower end of the polar axis with a specially machined conical point bearing, which rested inside a corresponding conical hole cut inside an adjustable steel block. At the same time, the upper end of the polar axis was secured by a matching bearing. This design successfully eliminated play, for the weight of the instrument inevitably forced the pointed end into the cone bearing, while the upper axis was also self centring. The resulting instrument would have been in perfect balance, easily moved, yet centering itself dead in any position. After a succession of design experiments with armillaries over a ten year period, Tycho had evolved the ideal combination of specificity of

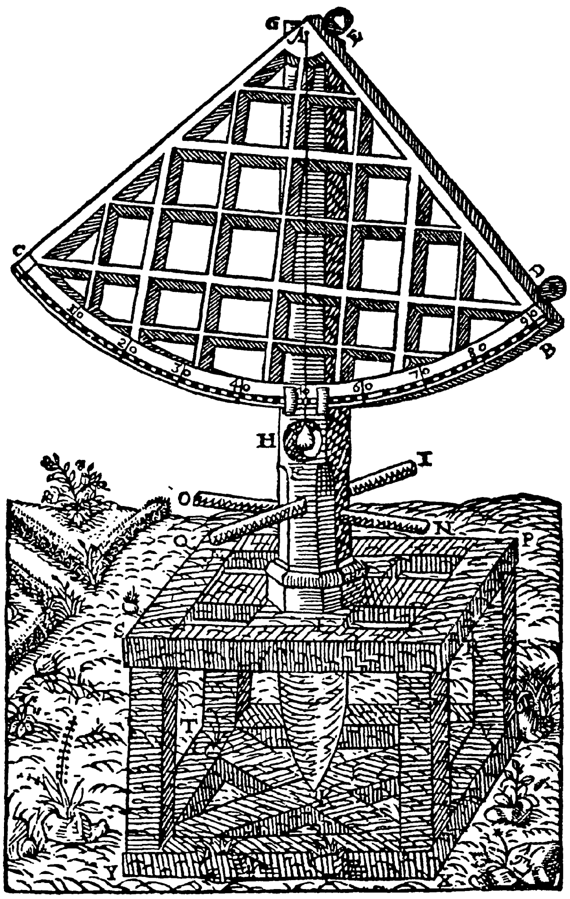

Figure 4. Fourteen-cubit radius wooden quadrant for Paul Hainzel (*Mechanica*).

function, lightness, accuracy and stability.

The third of Tycho's principal instrument types was the quadrant. While the quadrant, like the armillary, had a lineage extending back to antiquity, its construction had always presented problems, for a 90° scale was not easy to divide and had to be produced by a combination of elaborate geometrical techniques.[12] While nothing is known of the way in which Tycho obtained his individual degree divisions, he nonetheless made several innovations in the overall design of the quadrant as a mechanical structure. Most of this work was concerned with attempts to solve two basic problems: (a) how to make an instrument where the degree divisions were physically large enough to allow accurate sub-division into minutes, and (b) how to achieve the same on a structure which was not physically cumbersome and likely to distort under its own weight.

In the past these two requirements had been irreconcilable within the same instrument, for if one built a quadrant that was large enough to show single minute subdivisions, it must, perforce, be as large as a house, and hence be too crude for those delicate adjustment necessary to effectively use its small graduations. This had formed a barrier to improved accuracy before Tycho, and his own solution to the problem was a classic in geometrical and engineering innovation.

In the *Astronomia Instaurate Mechanica* (1598), where Tycho described the functions of his major instruments, it is clear that more effort was devoted to devising the perfect quadrant than to any other instrument. He describes nine quadrant designs, as opposed to five sextants and four armillaries. The purpose of the quadrant was simple in theory, but exacting in practice; it had to measure vertical angles between horizon and zenith. Without a reliable quadrant, it was impossible to fix any of the cardinal points of the sky, such as the latitude, solstices and equinoxes, or derive the exact time. It provided the fundamental vertical angles of bodies, from which the sextants and armillaries could next measure the horizontals, for a good set of declination angles was an essential pre-requisite to measuring RAs.

Tycho's first attempt at a scale showing small subdivisions had been made in Augsberg, Germany, in the early 1570s, when he designed a nineteen-foot radius instrument for his astronomical friend Paul Hainzel, who was also Burgomaster of the city. This massive instrument was built of wooden beams, so that the nineteen-foot radius quadrant could be made to move

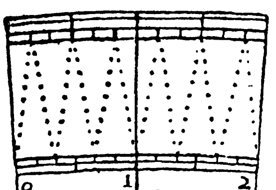

Figure 5. Transversal dot scale, or Diagonal, used on all of Tycho's major instruments (*Mechanica*).

in the vertical plane, while rotating to face any part of the sky on its great timber support pole.[13] Though its brass scale was big enough to be divided into individual minutes, the sheer bulk of the thirty-foot high structure obliterated that delicacy of touch necessary to use them (Fig. 4).

Tycho experimented with various ways of dividing a degree space, including the 'Nonius' scale, which was a complicated ancestor of the Vernier, but it was not until he hit upon the use of transversal, or diagonal lines, that his desired solution was found. While Tycho did not invent the diagonal scale, he was the first to develop and apply it to major astronomical instruments. The principle of the scale lay in utilising not the circumference edge of a degree division, but a diagonal line drawn on the surface of the quadrant between a consecutive pair of degrees. In this way, it was possible to draw a line that was much longer than the circumference edge line, and divide it into a greater number of fractions.[14] When an observation was made, one obtained the eventual angle by first reading the nearest whole degree, and then by counting which diagonal dot had been cut by the sighting arm edge, and adding the same number of minutes to obtain the complete angle. The diagonal scale made it possible to have an instrument divided down to single minute intervals or less, yet still have a quadrant that was small enough to be physically compact and easy to manage. It formed an elegant example of precision miniaturisation (Fig. 5).

From a variety of intermediary models, Tycho evolved two major quadrants, both of which incorporated his new diagonal divisions. Maximum rigidity in quadrant design was achieved in the mural quadrant of 1582, when he reduced the instrument to a heavy brass arc fastened to a masonry wall, to make the first scientifically significant mural quadrant set in the meridian.[15] With its radius of almost $7\frac{1}{2}$ feet, it carried a diagonal scale divided down to 10 arc second spaces to delineate the fundamental plane of the sky. Tycho was now able to take his principal observations as objects culminated in the meridian, to commence a procedure which would become standard in positional astronomy down to the twentieth century (Fig. 6).

His second major quadrant, of the same radius as the mural (so that their scales carried equal proportions), was his 'Steel quadrant in a square' of 1588.[16] While the mural quadrant provided an excellent absolute standard, he still needed an instrument which he could use outside the meridian, especially to observe the Sun's position in any part of its orbit. The steel quadrant obtained maximum rigidity by its metallic structure, braced as it was within a six-foot square. The whole instrument stood on a strong vertical axis of steel, which was both self centring and capable of rotation to face any part of the sky. In many ways, the Steel quadrant in a square was Tycho's masterpiece, demonstrating as it did an understanding of light girder bracing, versatility and accuracy. Having experimented with wood and brass, and abandoned them where critical accuracy was necessary, he settled on the properties of steel as the ideal material for a light

Figure 6. Tycho's Great Mural Quadrant. The portrait and view of the inside of Uraniborg were added, so Tycho said, to fill up the blank wall space (*Mechanica*).

weight, rigid frame. It was made with the same radius as the mural quadrant, moreover, so that the paired 10 arc sec divisions on the two instruments could be interchanged (Fig. 7).

Much of Tycho's significance in the history of science comes from his quest to find the perfect shape, material and design for each type of observation. He also realised the importance of having several different instruments utilising different geometrical principles, such as those used in the sextants, armillaries and quadrants, to make the *same* observation. Crucial constants, such as the solar altitude or First Point of Aries, would be observed with a battery of instruments, both to obtain the best average value, and to cross-check the strengths and weaknesses of different designs.

Cross-checking and error analysis formed a major component in Tycho's working method, and he was a leading pioneer of its development. Almost every instrument which Tycho designed possessed an internal cross-check against itself, along with divisions of similar proportions to those on other instruments. Thus, his earliest vertical wooden sextant of 1572, exploited its sixth part of a circle shape to produce an isosceles triangle which was bisectable by a plumb line in accordance with a Euclidean proposition.[17] His armillaries could read the same angles in either clockwise or anticlockwise directions around the sky to see if they always closed to zero at the First Point of Aries, while the steel quadrant was enclosed inside a square, the straight edges of which were engraved with a sine table, to cross-check the circular degrees.[18] Armillaries could also be tried against sextants when reading the same horizontal angle, and circular degrees against a linear sine scale when reading a vertical one.

Early in his career, about 1573, he came to realise that otherwise well-made instruments could be spoiled if their naked eye sights were not precise. Up to Tycho's time, astronomers had used 'pinhole' or 'pinnule' sights on their instruments with which to sight the stars, but he came to realise that as an observer would never be certain of having the star at the centre of the sight hole, it was possible to introduce random errors up to eight minutes in an observation.[19] It was absurd, therefore, having an instrument with scales graduated to single minutes if the sights contained an eight minute error.

His solution was to invent a parallax-free sight, wherein he observed a star through a pair of fine slits across opposite edges of a cylindrical brass pivot.[20] When he saw the star equally well through each slit on each pivot edge, he knew that he had a perfect alignment. This sight became standard on all of his instruments, and remained in use amongst astronomers for the next hundred years, until the development of the telescopic sight in the 1660s. Though Tycho had no way of knowing it, his improved sights and scale divisions exceeded in accuracy the capacities of the astronomers using them, for while his great quadrants carried divisions down to 10 arc sec, the unaided human eye cannot resolve angles less than one minute.[21] Tycho had

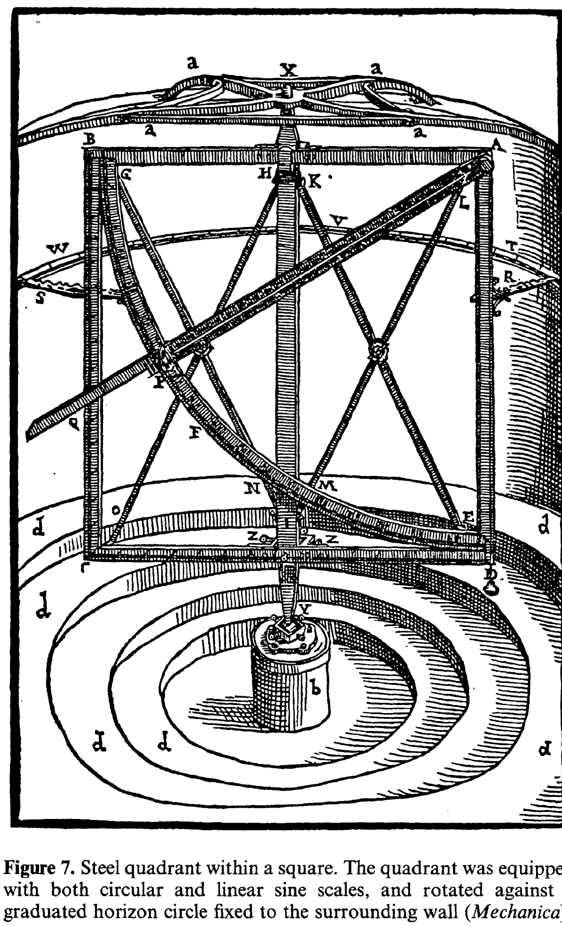

Figure 7. Steel quadrant within a square. The quadrant was equipped with both circular and linear sine scales, and rotated against a graduated horizon circle fixed to the surrounding wall (*Mechanica*).

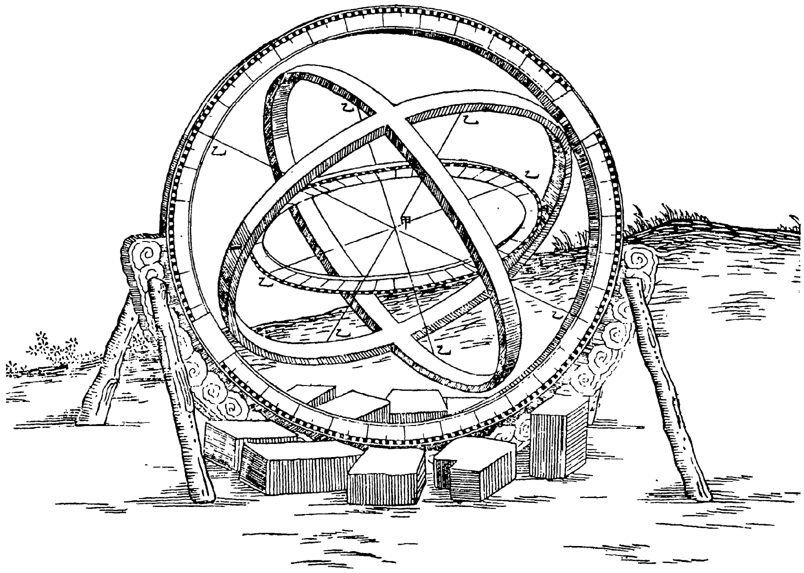

Figure 8. Assembled rings of Ferdinand Verbiest's half-completed Equatorial Armillary, after Tycho (*Astronomia Europaea, Museum of the History of Science, Oxford*).

taken pre-telescopic astronomy as far as it could go, and any significant improvement had to wait until the resolving power of the human eye could be increased. It was a tribute indeed to Tycho's meticulous observing techniques, that his constant revision of the same fundamental observations enabled him to get *average* values that vastly exceeded the angular resolution of the naked eye, for when astronomers in the nineteenth century, reduced Tycho's determinations for the First Point of Aries, they obtained a value which was within 6 arc sec of the correct one.[22]

Though Tycho published detailed illustrated accounts of his instruments, it is unfortunate that he said nothing about the processes of manufacture on a workshop level. This should not be interpreted as secrecy on Tycho's part, however, for his stress was always on the openness of astronomical knowledge, but a lack of awareness that such things needed to be discussed at all. With the well-established metallurgical craft tradition which existed in northern Europe, he probably felt that when his designs and researches were published, existing craftsmen would have no trouble in duplicating them. This belief was no doubt well founded, for Tycho's instruments had been made by craftsmen from various lands, for while his earliest pieces were made in Germany, and his main Uraniborg instrumens in Denmark, he found no difficulty in getting the famous Czech craftsman Erasmus Habermal to make extra ones when he was exiled in Prague, shortly before his death in 1601.[23]

It is only now, after an interval of four hundred years, and the passing away of that tradition, that we ask exactly *how* did one make the rings for an armillary sphere or graduate a scale? Ironically, such information is only available from Oriental sources, for when European Jesuit astronomers re-built the Imperial Observatory in Peking in the 1670s, they made duplicates of Tycho's Uraniborg instruments copied from the *Mechanica*.[24] Because the Emperor, K'ang Hsi, was interested in western technology, the Jesuit scientist Ferdinand Verbiest obligingly provided a detailed set of one hundred and seventeen engravings and text, which included the main processes of workshop manufacture. These European missionary scientists would have been

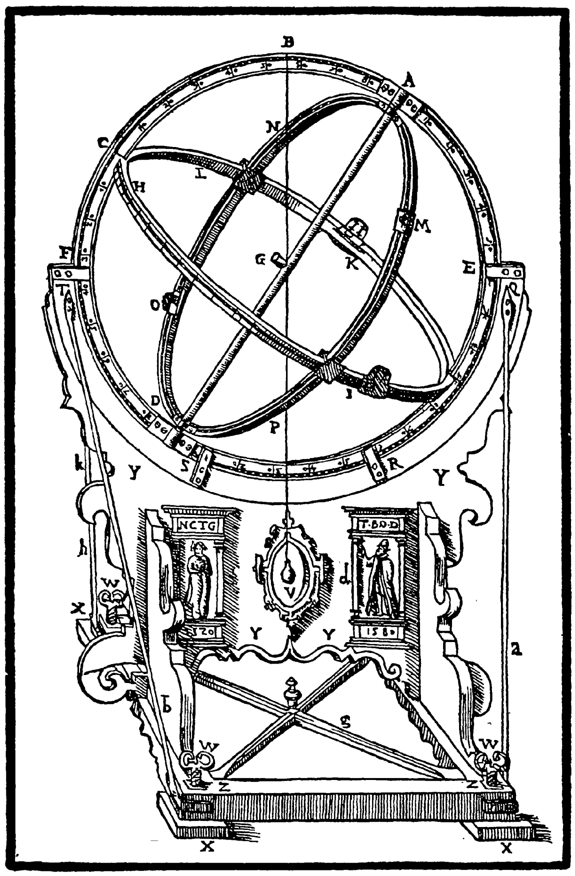

Figure 9(a). Tycho's Equatorial Armillary (*Mechanica*).

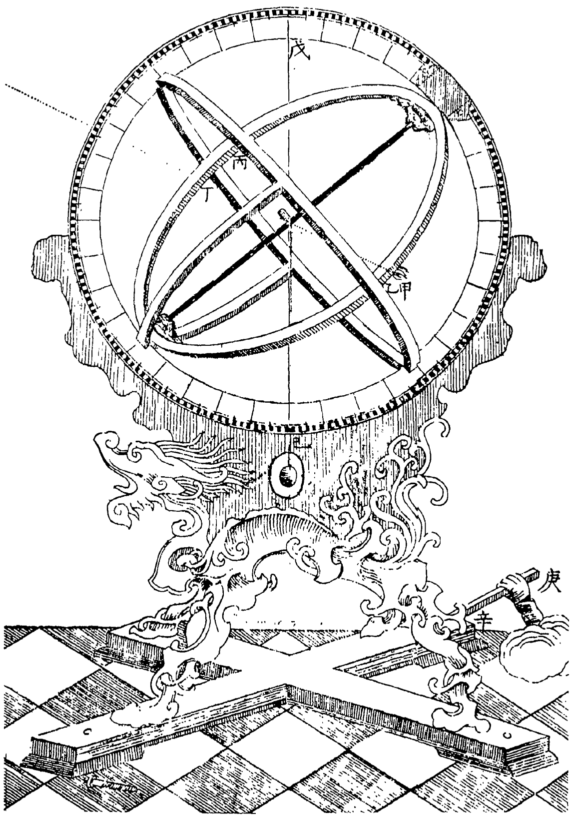

Figure 9(b). Verbiest's Equatorial Armillary (complete) after Tycho, 1674 (*Astronomia Europaea, Museum of the History of Science, Oxford*).

sufficiently familiar with instrument-making processes to enable them to instruct Chinese craftsmen, and record them in a sumptuous work for the Emperor, whereas in Europe, the knowledge would have been commonplace enough to make 'workshop manuals' unnecessary (Fig. 8).

Political circumstances forced Tycho to leave Denmark in 1597, and it is sad to reflect that all his major instruments were lost soon after. It is in China,however, with its great sextants, armillaries and quadrants built by the Jesuits, along with their treatise *Astronomia Europaea* describing their manufacture, that one comes closest to a surviving physical memorial to Tycho Brahe today.[25] Fortunately, the old Imperial Observatory weathered war, invasion and the Cultural Revolution, to provide the only direct descendent of Tycho's Uraniborg to survive to the present day. These great bronze instruments have survived in astonishingly good condition, moreover, and make it possible to compare a modern photograph with a seventeenth-century engraving, and place both alongside Tycho's own illustrations of the *Mechanica* pieces (Fig. 9).

Yet Tycho's real memorial lies not in any set of artefacts, but in a new approach towards the study of the heavens based upon progressive instrumentation and systematic observation. Though he died nine years before the first astronomical use of the telescope by Galileo, it had been Tycho who provided so much of the context in which telescopic evidence could be intelligently interpreted. For when Tycho's eccentric and brilliant life ended prematurely following a bout of over-indulgence at a feast in Prague in Autumn 1601, he had already created the foundation for a reformed science of astronomy.

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References

1 A. C. Crombie, *From Augustine to Galileo*, Peregine (Ed. (1969), vol. 1 pp. 89–110.
2 Tycho Brahe, *De nova stella* (1573). See also J. L. E. Dreyer *Tycho Brahe, a picture of scientific life and work in the sixteenth century* (1890) pp. 38–69.
3 Tycho Brahe, *Astronomia Instaurate Mechanica*, (1598), translated by H. Raeder, E. & B. Strömgren as *Tycho Brahe's description of his instruments and scientific work* (Copenhagen, 1946), cited hereafter as *Mechanica.* Also, Tycho Brahe, *Astronomia Instaurate Progymnasmata* [Astronomical Exercises] (1610). Many of Tycho's principal works were published shortly after his sudden death.
4 *Mechanica*, pp. 84–87.
5 Victor E. Thoren, 'New light on Tycho's instruments', *Journal for the history of astronomy*, **4**, 1 (1973) pp. 25–45. Also, *Tychonis Brahe Dani, Opera Omnia*, Edited J. L. E. Dreyer, (Copenhagen, 1923–6).
6 *Mechanica*, pp. 85–86.
7 *Mechanica*, pp. 80–83.

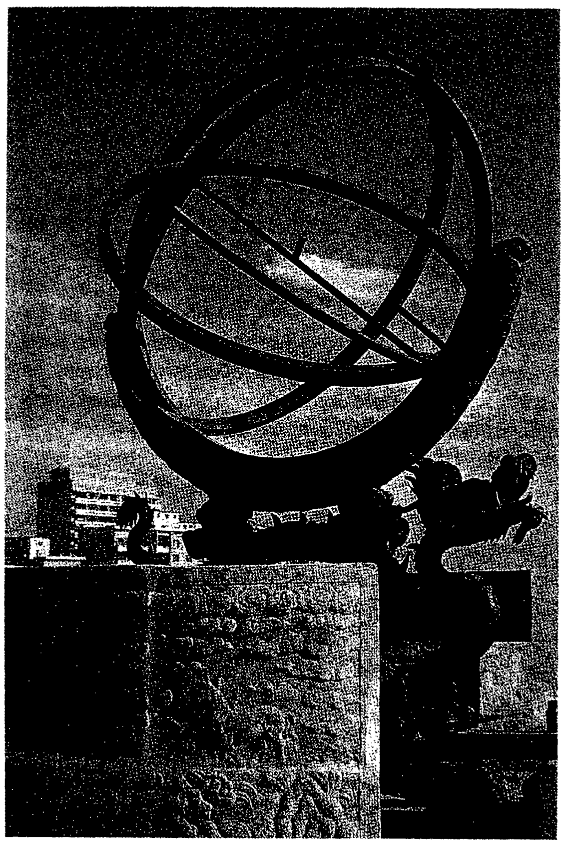

Figure 9(c). Modern photograph of Verbiest's Equatorial Armillary, Peking.

8 *Mechanica*, pp. 72–75.
9 Dreyer, *Tycho Brahe*, (see ref. 2), p. 351.
10 *Mechanica*, pp. 60–63.
11 *Mechanica*, pp. 64–67.
12 Allan Chapman, 'The astronomical art – the reconstruction and use of some Renaissance instruments', *J. Br. Astron. Assoc.*, **96**, 6 (1986) pp. 353–357.
13 *Mechanica*, pp. 88–91.
14 *Mechanica*, p. 141.
15 *Mechanica*, pp. 28–31.
16 *Mechanica*, pp. 36–39.
17 Euclid's *Elements*, Bk. IV, theorem 15.
18 Two of the straight edges of the square, enclosing the quadrant, carried a 5-figure sine table; *Mechanica*, p. 37.
19 This derived from an eight minute of arc sight error which he found in one of Copernicus's instruments; *Mechanica*, p. 46.
20 *Mechanica*, p. 141–143.
21 This was first demonstrated by Robert Hooke in *Animadversions on Hevelius, his 'Machina Coelestis'*. (1674), p. 7. Hooke's value is borne out by modern physiology, as in Sir Stuart Duke Elder, *System of opthalmology*, V (1958), p. 148.
22 Reductions of Tycho's observations were made by Peters, Argelander, Le Verrier and others; see Dreyer, *Tycho Brahe*, p. 351. Also, G. L. Tupman, 'A comparison of Tycho Brahe's meridian observations', *Observatory*, **23** (1900) pp. 132–135; 165–171.
23 The Habermal sextant still survives in Prague, and a photograph is included in Dr Hubert Slouka (Ed.) *Astronomy in Czechoslovakia from its early beginning to the present times*, (Prague, 1952) p. 102.
24 Allan Chapman, 'Tycho Brahe in China; the Jesuit mission to Peking and the iconography of instrument making processes', *Annals of Science*, **41** (1984) pp. 417–443.
25 Ferdinand Verbiest, *Astronomia Europaea sub imperatore Tartaro-Sinico...*, (1687), was the first European printing of this work, though it was based on an earlier text first produced in China. The sets of original Chinese plates are rare, though copies exist in the British Library (Oriental Division), the School of Oriental and African Studies, and the Museum of the History of Science, Oxford. Some copies also survive in European collections.

A note on Tycho's units of linear measurement

I have cited the dimensions of Tycho's instruments in English feet. These figures have been rounded up, however, as Tycho gave them in Cubits, and there is some contradiction in the length of that value. Dreyer in *Tycho Brahe* (1890) p. 39, footnote, gives it as 16.1 English inches, while D'Arrest and Charlier in 1868 determined it to be 388 mm. [15.25 inches]; see Raeder & Strömgren's translation of *Mechanica* (1946) p. 9. This would mean that a 'six-foot' instrument was in reality about 5ft 4.4. inches.

The Phantom Ring of Neptune

William Lassell, brewer and part-time astronomer, created a minor sensation in 1846 when he reported observations with the most powerful telescope in England, a 24-inch f/10 Newtonian, housed at Starfield, his private observatory near Liverpool; they suggested Neptune had a ring system.

His suspicions were first aroused on October 2, nine days after Neptune itself was discovered. Twenty-four hours later, they were verified and confided to his diary. The succeeding days were cloudy and a week elapsed before he could follow up the observation. When he did, in a clear, moonless sky on October 10, all doubt vanished; Neptune had the look of a ringed planet almost edge-on to Earth. On the 12th he voiced his findings to Sir John Herschel and went public by sending a full account to the London *Times*, where it appeared on the 14th.

More sightings were logged before bad weather and Neptune's proximity to the Sun brought the series to a close on December 15. Over the next six years, Lassell would often see the ring, always fleetingly, but never again with the confidence of 1846. In the meantime he submitted two papers to the Royal Astronomical Society. The tone was decisive, the message clear. As a result, the Annual Report of the Society dated 1847 February 12, claimed the 'existence of the ring seems almost certain.'

Others endorsed that view. To J. R. Hind, Neptune presented an oblong appearance in the 7-inch South Villa refractor. From Cambridge, James Challis reported a stubby ring visible in the Northumberland telescope on two nights in January 1847, and further impressions later in the year. There were also vague rumours of confirmation abroad. While back in England, W. R. Dawes and James Nasmyth nodded their assent.

Conscious of discovery, ever cautious of deception, Lassell hesitated. The most careful observer could be led astray, he knew. After all, William Herschel gave up as illusion the ring he first saw around Uranus in 1787. Still, Lassell was unable to reject what he had seen 1846 October 10. The succession of strong, distinct images then received suggested more than a possibility. That night he closed the main dome at Starfield convinced '...that could the planet be seen in a perfectly pure atmosphere ... with more powerful instrumental means, it would put on the appearance of Saturn when his ring is nearly closed.'

And so it was. Exasperated by the effects of urban encroachment and the indifferent seeing generally encountered at Starfield, his wish for limpid skies was realised in the autumn of 1852 when he set up the 24-inch in Malta.

He was not disappointed. As predicted '... the indication of the supposed ring immediately struck,' he wrote on his first night of observation, October 5, and once more a month later. The next night the impression was 'remarkably strong'. Before dawn, however, doubt had interceded. Exactly what induced the change is unknown. But, having measured the ring's position by rotating the telescope tube and repeating the measurements, Lassell concluded on 1852 December 15 that, whatever its cause, the ring was more intimately related to the telescope than the planet. The hypothesis withered. The strange fancy from which it sprang disappeared into what Alexander von Humboldt called 'the astronomical myths of an uncritical age.' Never again did Lassell indicate or even suggest Neptune had a ring system.

There can be no doubt he was misled. Tempting though it is to associate the phantom with the current debate about arcs or ring segments. If Neptune has such features, they will most probably not be seen by Earth-based telescopic observers.

What, then, is to be made of the ring observations? Throughout the 1840s and 1850s, Neptune had a low southern declination and was badly placed for observation from high northern latitudes. In 1846 its declination was $-13°$ and, at Liverpool, stood but 22° above the horizon when on the meridian – too low for the 24-inch. The problem, however, had nothing to do with differential refraction or indeed the poor atmospheric conditions which preclude effective observation at such low altitudes. It was the fact that, with the telescope tube at a small angle to the horizon, the speculum metal primary would be subject to distortion or flexure which, as Lassell apparently knew, could produce a defective image, either linear or highly elliptical in form.

In 1848 the Astronomer Royal, G. B. Airy, described some observations he had made with Lord Rosse's 72-inch speculum, the 'Leviathan of Parsonstown': 'Upon directing the telescope to an object very near the zenith, it was seen very well-defined; or, at least, with no discoverable fault ... But when the telescope was directed to a star as low as the equator its image was very defective.' This defect is astigmatism. Airy noted when the eyepiece was thrust in the image of a star was a well-defined straight line of a certain length. When the eyepiece was drawn out a particular distance

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