Tycho Brahe's Earliest Instruments

By John Robert Christianson

Tycho Brahe (1546–1601) became fascinated with stargazing at the age of thirteen and pursued astronomy-astrology in secret throughout his eight years of university studies, when he was supposed to be studying jurisprudence. In 1564, a fellow student in Leipzig helped him make his first instrument, and when his university studies were over in 1569–1570, he began to design innovative instruments, including a gargantuan quadrant that was clumsy but extremely accurate. Because he was self-taught, he developed his own empirical methods instead of following the theoretical and astrological approach taken by most contemporary astronomer-astrologers.

Tycho Brahe's instruments were at the heart of his contribution to the invention of modern empirical science. For twenty years, he kept turning out astronomical instruments with a profligacy that seemed to make little sense until Victor E. Thoren in 1973 began to document the experimental process in which one instrument led to the next and they kept getting better.[1]

Tycho fell in love with the stars as a young student. He entered Copenhagen University at the age of twelve and studied the *trivium* for three years before he was sent abroad at fifteen with a tutor—first Anders Sørensen Vedel, and later, Hans Hansen Aalborg—to study jurisprudence in Leipzig, Wittenberg, and Rostock. During eight years of university studies in Denmark and abroad, his tutors and preceptors never allowed him to attend lectures in astronomy.

Tycho first became a stargazer after a partial solar eclipse occurred in 1560, during his student days in Copenhagen. He purchased Sacrobosco's textbook of astronomy and began to study it secretly on his own. The preface was written by Philipp Melanchthon, and in this preface, Tycho read that God gave humans eyes in order to observe the beauty of the stars and marvel at their motions, and also that astronomy and astrology were inseparable, and

[1] Thoren 1973. Thoren 1990.

that each individual is a microcosm, a little universe, with stars of his or her own. Melanchthon even said that astronomy could reveal the mind of the Creator to a person who searched assiduously for the "manifest footprints of God in nature".[2] Tycho's fascination with the stars was validated by Melanchthon's praise of celestial regions and his explanation of the profound wisdom they could reveal. Tycho was drawn into the study of astronomy-astrology. "I learnt this by myself, without any guidance," he later wrote, "in fact I never had the benefit of a teacher in Mathematics (Astronomy), otherwise I might have made quicker and better progress in these subjects."[3]

If he had attended lectures and studied astronomy-astrology under the tutelage of a university professor, however, Tycho would have learned to focus upon calculation and not observation. No new catalogue of the stars had been compiled since the ancient Greeks, when Claudius Ptolemy had revised an earlier catalogue by Hipparchus, which in turn was largely based on a recalculation of Babylonian observations.[4] No astronomer of Tycho's day, except perhaps the Landgrave of Hesse-Cassel, felt that a new database was needed, although astronomers revised the old data from time to time in order to keep up with a languid rotation of the stars caused by the precession of the equinoxes. Most astronomer-astrologers of Tycho's day did not even own or use observational instruments, although Tycho remained innocently unaware of this fact until his student days were over and he was finally able to meet some of these leading astronomers. The fact that he was self-taught meant that he pursued astronomy in his own way, and his way was to observe.

Observational Notebook 1563

In 1563, Tycho was a student of jurisprudence in Leipzig when he came to realize that his habit of stargazing was not only enjoyable but also important. An event of great astrological significance was due to occur in that year: a conjunction of the outer planets, Jupiter and Saturn. These planets appear to conjoin every twenty years as they circled the skies in the same "trigon" of three zodiacal signs for 200 years, then moved to the next three, passing in turn through the Fiery, Earthly, Airy, and Watery Trigons before returning after 800 years to their starting point in the sign of Aries. Tycho knew that this conjunction of 1563 would be the last one before the whole cycle came to an end in 1583 and a new cycle began in 1603. He also knew that six such cycles had occurred since God created Adam and Eve, and that every one marked a turning point in affairs on earth. Jesus of Nazareth had lived at the

[2] Melanchthon 1999. Sacrobosco 1549, [A5v], "manifesta Dei uestigia in natura".
[3] Brahe 1598, 24.
[4] North 2008, 36–66, 94–133.

time of the fifth cycle, the Empire of Charlemagne marked the sixth, and this coming one would bring the Sabbath of all Creation.[5]

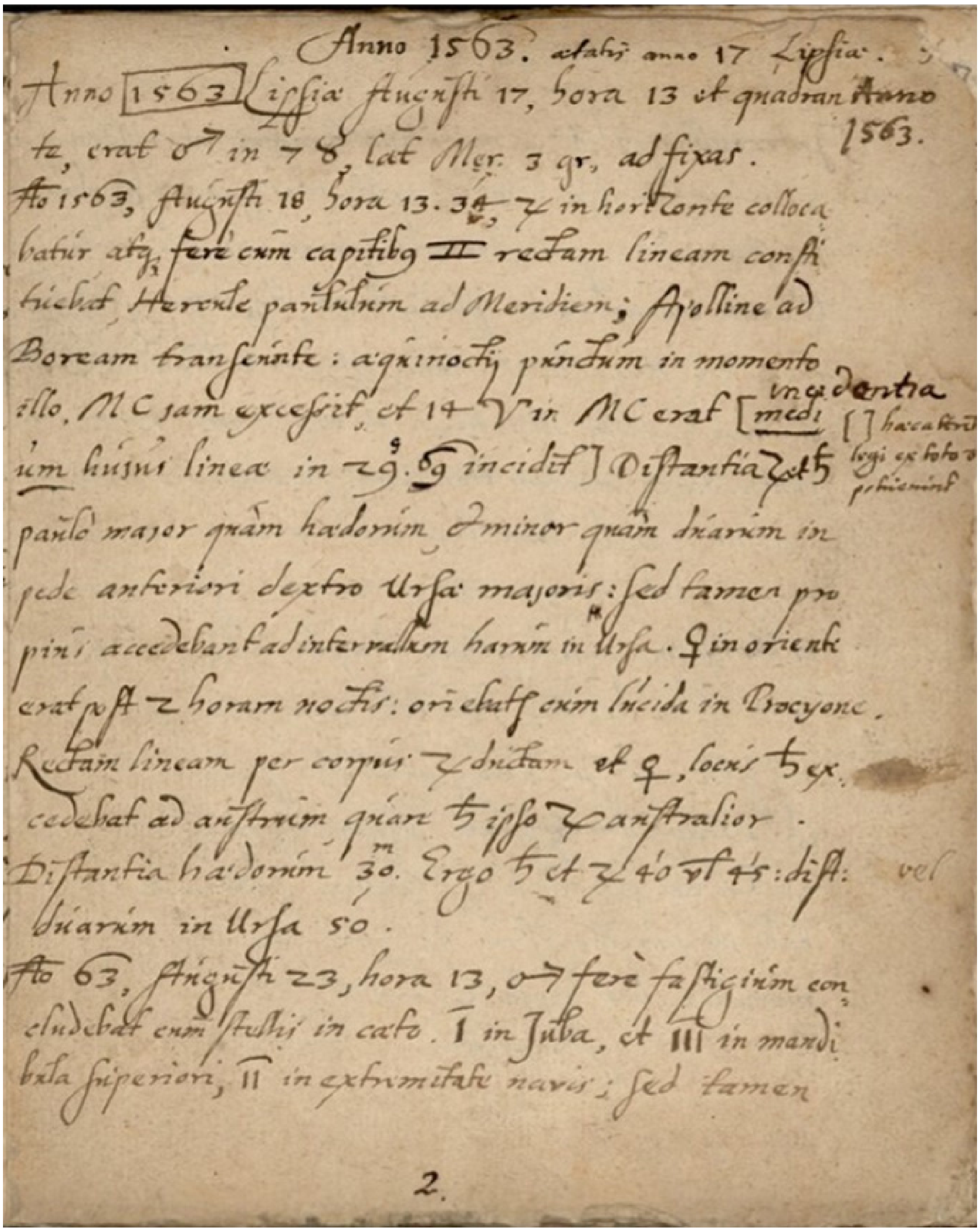
Tycho had already used a celestial globe the size of a fist and Albrecht Dürer's engraved star maps to memorize the names of all the stars and had taught himself to use *ephemerides* containing tables that showed planetary, solar, and lunar locations at any given time. He looked up the conjunction of 1563 in his two ephemerides and went outside to observe the planets as they slowly approached each other.[6]

Tycho had no observational instrument, but he invented a new tool, not for looking at the stars, but for recording observations. This was the *observational notebook.*[7] It was different from a *table of numbers* like an ephemeris or star catalogue, which was a very old astronomical tool. Tycho's notebook did not simply contain rows and columns of numbers but combined narrative, data, and occasional illustrations to describe a series of observations as they took place. Tycho Brahe's original observational notebook in the Royal Library in Copenhagen is one of the great icons of modern science. The first page is headed, "Anno 1563, seventeen years of age, Leipzig." At 1:34 a.m. on 18 August 1563, he began to record observations of Jupiter and Saturn as the Great Conjunction took place before his very eyes (**Fig. 1**). Observations over the course of many nights led Tycho to conclude that the conjunction occurred on or very near the leading edge of the sign of Leo shortly before sunrise on 26 August 1563. According to his Ptolemaic ephemerides, however, the conjunction was not due to occur until 17 September, while his Copernican ephemerides showed it occurring on 24 August. How could they be so different, and so wrong? "I no longer trusted the ephemerides," Tycho later wrote, because they "suffered from intolerable errors."[8]

At this point, celestial observation took on a new significance for him. It was no longer a secret hobby that gave him a sort of intellectual and spiritual pleasure but became something that was essential to the reformation of astronomy-astrology. It was no longer enough to stand outside and gaze at the stars while softly reciting their names. Tycho needed to observe positions of stars, planets, sun, and moon with instruments and record more precisely than ever before their positions within networks of astronomical coordinates. He needed to establish the position of every object in the heavens by means of precise quantitative observation and compile more accurate tables of celestial positions. Only then would it be possible to build new theories of the sun, moon, and planets to replace the erroneous ones of the past. Tycho Brahe

[5] Ptolemy [1822] 1893, 44–46. Aston 1970, 161 n. 9.
[6] Brahe 1598, 24. Brahe 1913–1929, 10, 3.
[7] Daston 2011, 95–99.
[8] Brahe 1598, 24.

conceived of his return *ad fontes* as a return, not to classical literature, but to the stars themselves.



Anno 1563. aetatis anno 17 Lipsiae.
Anno 1563 Lipsiae Augusti 17, hora 13 et quadran- Anno
te, erat ♂ in 7 ♉, lat Mer. 3 gr, ad fixas. 1563.
A° 1563, Augusti 18, hora 13.34 ♃ in horizonte colloca
batur atque fere cum capitibus ♊ rectam lineam consti
tuebat Herculis paululum ad Meridiem; Apolline ad
Boream transeunte: aequinoctii punctum in momento
illo, MC iam excesserat et 14 ♈ in MC erat [medi- incedentia
um huius lineae in 29. ♋ incidit] Distantia ♃ et ♄
paulo maior quam haedorum et minor quam duarum in
pede anteriori dextro Ursae majoris: sed tamen pro
pius accedebant ad intervallum harum in Ursa. ♀ in oriente
erat post 2 horam noctis: oriebatur cum lucida in Procyone.
Rectam lineam per corpus ♃ ductam et ♀, locus ♄ ex
cedebat ad austrum quare ♄ ipso ♃ australior.
Distantia haedorum 30. Ergo ♄ et ♃ 40 vel 45: dist: vel
duarum in Ursa 50.
A° 63, Augusti 23, hora 13, ♂ fere fastigium con
cludebat cum stellis in caelo. I in Iuba, et III in mandi
bula superiori, II in extremitate navis; sed tamen
2.

Fig. 1. Tycho's observations of the Great Conjunction of 1563. Brahe 2012, 9. Source: www.kb.dk.

The Cross-Staff 1564

Tycho owned books that told how to make and use observational instruments.[9] These instruments were mainly used by surveyors and cartographers to measure angles between two landmarks such as church towers and then pace off the distance from the vantage point to one of the towers and use trigonometry to find the angles and distances between all three points. An astronomer could use similar instruments and the same trigonometry to find distances between the stars and then "pace off" the distance from earth to a given celestial object by methods going back to Hipparchus, Ptolemy, and modern authorities like Johannes Regiomontanus.

One of the instruments for observing angles was the "cross-staff," sometimes called a radius or Jacob's staff (**Fig. 2**). It consisted of a calibrated wooden staff around one metre in length, with a shorter, sliding staff attached at right angles. One end of the long staff was held against the cheek and the short staff was moved back and forth until two objectives appeared at its ends, and calibration on the long staff showed the angle between them.

ſunt computatæ atq; verificatæ: inſuper gradum longitudinis alicuius ſtellæ fixæ parũ aut nihil ab ecliptica recedentis, quę motũ Lunæ proximè præcedit ſubſequitúrve. Deinde quære motus Lunæ, eiuſdemq; fixi ſyderis interſtitium vel ſegmentũ. Interſtitio itaq; hoc inuento, applica radium hũc viſorium, ſeu baculũ extremitate vna quæ F. ſignũ tenet oculo, (altero clauſo) moueatur pinnacidium volubile ſuper radium, donec per terminũ vnũ eiuſdẽ pinnacidij intuearis centrũ corporis lunæ: per terminũ verò alterũ dictã ſtellam cuius & lunę interſtitium ſupputaſti. Diſtantiã igitur lunæ & ſtellæ fixæ pro loco tuæ conſiderationis in gradib. & min. pinnacidium ipſum patefacit: quo peracto, recollige diſtantiam lunę & ſtellæ fixæ prius ſupputatã, deme igitur minorẽ de maiori, reſiduabis differentiam vltimam, quæ diuerſitas aſpectuũ iure dici poteſt, qua quidem diuiſa per motũ lunę in vna hora, prodibit tempus quo Luna cũ priori ſtellæ diſtantia cõiungitur aut coniuncta fuerat. Rurſus, tempus ſic elicitum in gradus & grad. minuta conuertito, vt ſuprà docuimus in obſeruatione ecliptica. Poſtremò adde aut ſubtrahe numerum graduum & minutorum iam productum ad meridianum, ad quem tabulæ (ex quibus Lunæ motum computaſti) ſunt verificatæ. Vt ſi intercapedo Lunæ & ſtellæ fixæ tuæ conſiderationis fuerit minor, adde gradus & minuta ad meridianum notum, hoc eſt, ad longitudinem notam, & locus tuæ conſiderationis erit orientalior. Si verò maior, aufer gradus
&

GRAPH. PETRI AP. Fo. 14.

& minuta à longitudine nota, hoc eſt, à meridiano ad quem tabulæ ſunt verificatæ, & erit occidentalior locus tuæ conſiderationis.

GEMMA FRISIVS.

TOtum iſtud verum, cùm Luna plus verſus occaſum eſt quàm ſtella. Alioqui ſi orientalior eſt, totum contrarium eſt, id eſt, ſi intercapedo Lunæ & ſtellæ fixæ fuerit minor, ſubtrahe gradus & minuta à longitudine nota, & locus tuus erit occidentalior: Si verò maior, adde gradus & minuta ad longitudinem notam, & locus erit orientalior.

ALIQVORVM FIXORVM SYDERVM vera in Zodiaco loca, quæ parùm aut nihil à Solis orbita recedunt, cum magnitudinib. eorundem, rectificata per Petrum Apianum ad An. Christi. 1525. completum.

✱ 14 ♉ Aldebaram. i. oculus ſeu cor Tau. ♊. 2. gra. 57. mi. Mag. 1.
✱ 30 ♉ Extremitas ſep. lateris ante-pleiadũ ♉. 22. gr. 27. mi. Mag. 5.
✱ 1 ♋ Præſepe quæ eſt in pectore Cancri ♌. 0. gr. 37. mi. Nebuloſa.
✱ 2 ♋ Iſtarum Septentrionalis habet gra. 27. mi. 57. Mag. 4.
✱ 3 ♋ Septentrionalis aſellus. ♌. 0. gra. 37. mi. Mag. 4.
✱ 4 ♋ Decliuior harum duarum ad meri. ♌. 1. gra. 37. mi. Mag. 4.
✱ 8 ♌ Regulus ſeu cor leonis q̃ baſiliſcus dr̃ ♎. 22. gr. 47. mi. Mag. 1.
✱ 14 ♍ Aſtræa ſeu Spica virginis ♎. 16. gra. 57. mi. Mag. 1.
✱ 1 ♎ Luminoſior lancis meri. ♏. 8. gra. 17. mi. Mag. 2.
✱ 8 ♏ Cor Scorpij, & dicitur Calbalatrab. ♐. 2. gra. 57. mi. Mag. 2.
✱ 4 ♐ Decliuior duarum ab arcu in latere ſeptentrionali ab arcu ad meridiem ♐. 29. gra. minu. 17. Mag. 3.
✱ 23 ♑ In radice caudæ, & dicitur denebalchedi ♒. 15. gr. 7. Mag. 3.
✱ 24 ♒ Et eſt ſeunda ſtella poſt effuſionem. ♓. 5. gr. 7. mi. Mag. 4.
✱ 20 ♓ Et eſt ãtecedẽs ſup nodũ torcularis ſep. ♈. 20. g. 47. m̃. Mag. 4

GEMMA FRISIVS.

Ab Anno. 1525. vſq; ad annum. 1540. ſtellæ fixæ promotæ ſunt. 8. minutis. Hinc facilè erit loca eorum corrigere pro annis venturis.

DE PARTIBVS MENSVRAE, ſeu ſpeciebus Geometriæ practicæ. CAP. XI.

MEnſura eſt longitudo finita, quæ ignotam locorũ diſtantiam ſenſibili experimento metitur. Cuius partes ſeu famoſæ quantitates, quibus Geometer vtitur, ſunt: Granum hordei, Digitus, Vncia, Palmus, Dichas, Spithama, Pes, Seſquipes, Gradus, Paſſus ſimplex, Paſſus duplex, quem Geometricum appellare libuit, Cubitus ſeu vlna, Pertica, quã plures Radium vocant, Stadium, Leuca, Miliare Italicum, Miliare Germanicum. &c.
Gra-

Fig. 2. Using a cross-staff to measure an astronomical angle. Apian 1564, 34. Source: archive.org.

[9] Apian 1553.

In the spring of 1564, a fellow student and aspiring cartographer named Bartholmæus Scultetus, who had made such instruments, helped Tycho to make a cross-staff. Scultetus had studied with the late Professor Johannes Homelius, who had constructed observational instruments to explain Vitruvius, Hero of Alexander, Ptolemy, and Archimedes of Syracuse.[10] Bartholomæus showed Tycho how Homelius made very fine subdivisions by placing dots at regular intervals along transversal lines behind a calibrated scale, and they did this on Tycho's cross-staff.[11]

Tycho's first recorded observations with the cross-staff were made on the evening on 1 May 1564.[12] He could hardly contain his excitement:

> When I had got this radius, I eagerly set about making stellar observations whenever I enjoyed the benefit of a clear sky, and often I stayed awake the whole night through, while my [tutor] slept and knew nothing about it; for I observed the stars through a skylight and entered the observations specially in a small book, which is still in my possession.[13]

In the past, *observatio* had meant a "normative observance" like the observance of a monastic rule, but in the late Renaissance, it was beginning to mean the "empirical study of phenomena" in subjects like astronomy, astrology, meteorology, and medicine.[14] Georg Peurbach had introduced *observatio* to Renaissance astronomy-astrology in Vienna in the 1450s, and his student, Johannes Regiomontanus, had observed the sun and stars with Berhard Walther in Nuremberg in the years 1471–1500. Now, young Tycho was teaching himself to develop what Katherine Park described as "the habitus of an observer: consistent, disciplined, highly attuned to sources of error, and constantly seeking to improve the quality of his records."[15]

In his self-taught enthusiasm, Tycho began to innovate without realizing it and discovered previously unknown anomalies that needed to be explained. Observing with his new cross-staff,

> I noticed that angular distances, which by the radius had been found to be equal, and which with the help of a mathematical calculation of proportions had been converted into numbers, did not in every respect agree with each other. After I had found the cause of the error, I invented a table by which I could correct the defects of this radius.[16]

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[10] On Homelius, Ramus 1569, 67; Zedler 1735.
[11] Brahe 1598. Scultetus, 1572, described Homelius' method of dividing an arc on Bij–[Bij^{v}. Karrow 1993, 464–471.
[12] Brahe 1913–1929, 10, 5.
[13] Brahe 1598, 24. Tycho called Vedel his *pædagogus,* see Brahe 1913–1929, 5, 106.
[14] Park 2011.
[15] Park 2011, 34.
[16] Brahe 1598, 24.

Tycho Brahe thus discovered the phenomenon of "instrumental error" and realized that he needed to take it into consideration, so he invented a way to do so. His nineteenth-century biographer, the astronomer, J. L. E. Dreyer, commented, "This is deserving of notice as the first indication of that eminently practical talent which was in the course of years to guide the art of observing into the paths in which modern observers have followed."[17] Tycho was seventeen years of age.

Quadrants and Compasses 1568

The notebook and cross-staff remained his only tools of observation throughout his student years. When he came home during the summer holidays of 1567, he announced to his family that he did not intend to become a royal jurist but planned to be a natural philosopher and student of the muses. His foster uncle, Peder Oxe, was sympathetic and arranged for him to receive the promise of a canonry in the chapter of Roskilde, which would allow him to pursue such a course in life. Tycho immediately broke off his juridical studies in Rostock and began to travel Germany and visit learned astronomer-astrologers. Eventually, he settled for the winter of 1568 in Basel, the city of Erasmus and of Paracelsus.

Tycho wanted an instrument more accurate than the cross-staff. His experiments began with quadrants, which were small, hand-held quarter-circles of wood or brass with a calibrated 90º scale on the arc and a plumb line that dangled from the centre. When a star was in the sights along one edge, the plumb line was pinched against the scale to mark the angle of altitude. Quadrants were mainly used by travellers and navigators to measure altitudes, but Copernicus and Ptolemy (**Fig. 3**) had used them to measure the inclination of the ecliptic to the celestial equator, and Peurbach had invented an improved model, which Tycho knew from a published description by Regiomontanus.[18] Quadrants were usually less than a foot in diameter, but Tycho wanted to make bigger ones in order to calibrate the scale more finely, so he and his assistant made some as large as four or five feet (1–1.5 m) in diameter. He soon discovered how hard it was to keep these larger instruments stable in the wind.[19] In solving one problem, he created another. He had to try something else.

Early on, before he made his cross-staff, Tycho had used a large pair of compasses as an improvised observational instrument, "placing the vertex close to my eye and directing one of the legs towards the planet to be observed

[17] Dreyer 1890, 20.
[18] Włodarczyk 2010. Regiomontanus 1544, 61–79, ill. between 62–63.
[19] Brahe 1913–29, 2, 343 & 7, 328.

Fig. 3. Urania the Muse of Astronomy instructing Ptolemy in the use of a quadrant. Reisch 1503, 260. Source: archive.org.

and the other towards some fixed star near it."[20] He constructed an instrument on this pattern but with arms a metre long and found that it was portable, fairly stable in the wind, and large enough to be calibrated for rather precise measurement, but too big to be held without some support (**Fig. 4**).

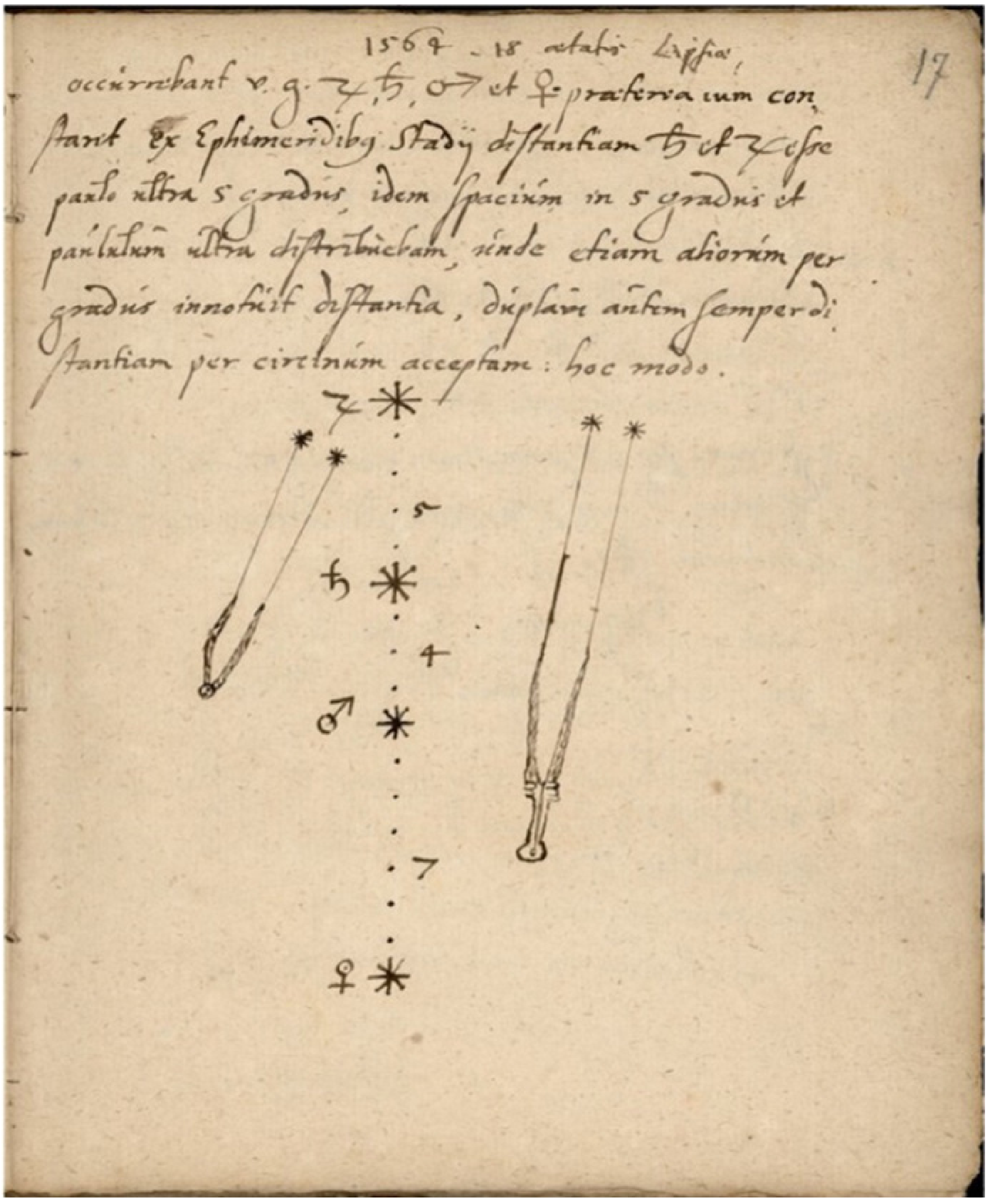

Fig. 4. Tycho's sketch of two pairs of compasses used as observational instruments. Brahe 2012, 9. Source: www.kb.dk.

[20] Brahe 1598, 24.

Quadrans Maximus 1570

In the spring of 1570, Tycho rode into the great imperial city of Augsburg, where he soon gained admission to a circle of humanist friends who were Lutherans like himself and held informal symposia centred on good food, music, and learned conversation. These Augsburg patricians and their friends had studied in Wittenberg, took Melanchthon's approach to astronomy and astrology, and combined solid learning and Philippist values with the lavish tastes of a rich and sophisticated city. Hieronymus Wolf was a renowned humanist scholar, and the brothers Johann Baptist and Paul Hainzel belonged to Augsburg's leading Protestant family.[21]

Some time after he had arrived in Augsburg and had found good friends in this circle, Tycho was in his rooms one day, sketching plans for a very large astronomical instrument, when Paul Hainzel came to visit. Tycho explained what he was doing, and they discussed it at some length. If I ever settle long enough in one place, Tycho said, I intend to build an instrument immense enough to accommodate calibration down to one minute of arc. This had become his seemingly unattainable criterion of observational precision.

Why not here and now, Paul Hainzel asked? He proposed that Tycho design the instrument and that it be built in the garden of his estate in Göggingen outside the city.[22] Tycho quickly agreed, and the leviathan he named Quadrans Maximus came into being (**Fig. 5**). A large pit was dug for a heavy frame of oaken beams and then filled with boulders and buried. An immense oaken post turned on an iron-clad point below ground and rose from the centre of the frame. A crew of twenty sturdy workmen suspended a gigantic oaken quadrant from this post on a massive iron ring. The instrument was like a hand-held quadrant expanded to gargantuan size and weight, with a radius of nearly five-and-a-half metres and a brass arc calibrated to ten *seconds* of arc: every one of the ninety degrees on the scale was calibrated into 360 precisely uniform divisions.

The observer measured altitudes of the sun by directing a beam of sunlight through pinnules along one side of the instrument (D, E), as with a hand-held quadrant, and stars were sighted through these same pinnules. The immense frame of the quadrant had to be moved up or down for every observation and was rotated into position by four strong assistants pushing and pulling on handles attached to the centre post. Angles were marked against the long brass scale by a thin brass wire dangling from the top and kept taut by a heavy weight on the lower end. This instrument stood in the open air but had a cover that could be placed over the scale. It was a classical instrument torn out of

[21] Mezger, 1875–1900. Keil 2013. Häberlein 2013.
[22] Brahe 1913–1929, 2, 343–344.

Ptolemy's *Almagest*, pulled from the hands of navigators, and blown up to the scale of a colossus. It was cumbersome and lacked the ease of operation that Tycho now realized was essential for a truly successful instrument, but it certainly had the quality of extreme accuracy when used with care. Tycho later wrote,

> The use of the instrument was exclusively for observations of the altitudes of the sun and the planets, and that with the greatest accuracy, in fact within one-sixth of a minute of arc, provided the observer exercised the necessary care. A similar accuracy had hardly ever been reached by our predecessors.[23]

Tycho recorded his first observations with Quadrans Maximus on 1 April 1570, observing the meridian altitude of the sun in order to determine the exact latitude.[24] During the following weeks, Tycho, the Hainzels, and their crews were sighting it in when the renowned French philosopher, Petrus Ramus (Pierre de la Ramée), who had friends in Tycho's circle, passed through Augsburg, and they gathered to dine in his honour. After the meal, they went outside to see Quadrans Maximus and stood in its shadow as Ramus conversed with the young Danish inventor, whose name he mentioned in his next publication. With this recognition by one of Europe's leading humanists, Tycho was launched on his path to "measure all things," especially the sun and stars, in order to comprehend the microcosm of Man and the mind of their divine Creator.

[23] Brahe, Tycho 1598, 7.
[24] Brahe 1913–1929, 5, 36.

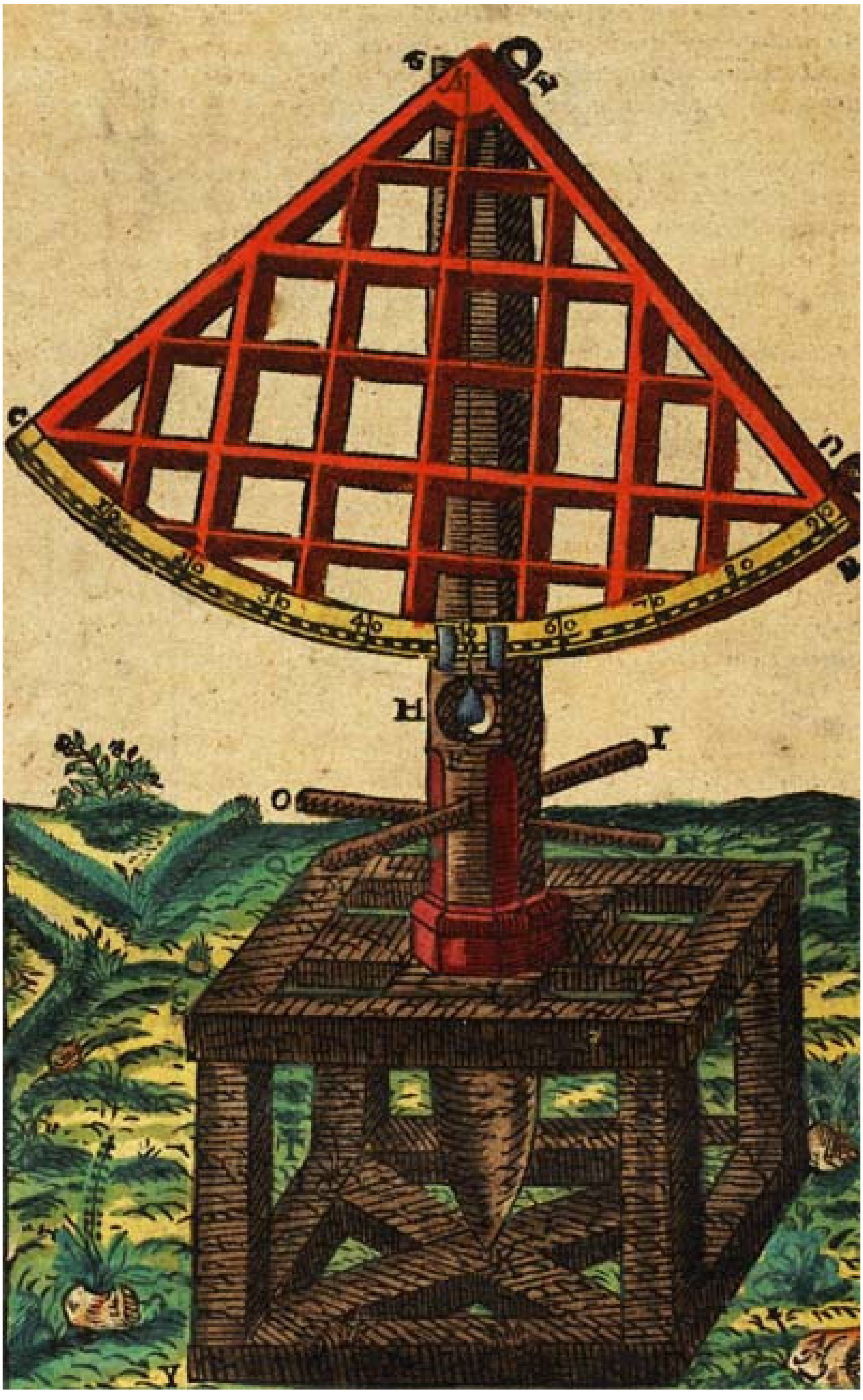

Fig. 5. Quadrans Maximus. Brahe 2005. Source: commons.wikimedia.org.

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