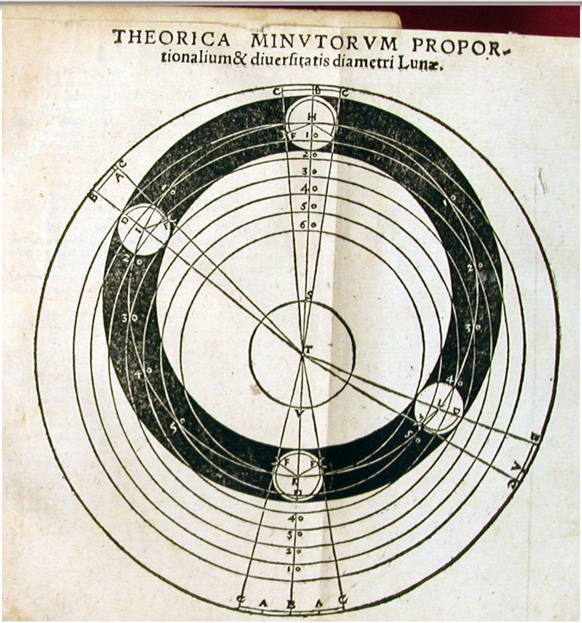
The New Astronomy

Heliostatic and heliocentric astronomy:

Copernicus, Tycho Brahe, Kepler

Waseda University, SILS,
Introduction to History and Philosophy of Science

Peurbach (1423–1461), *New Theory of the Planets* (1454)



Nicholas Copernicus (1473–1543)

- Educated in Cracow, Bologna and Padua; doctor of Canon Law (a lawyer).
- Made his living as canon of the Cathedral of Frauenburg.
- He was a lawyer, practiced medicine, wrote a book on coins, served as a clerical administrator and diplomat, painted his self-portrait, made his own astronomical instruments and established a mathematical theory of a heliostatic cosmos.
- *Commentariolus* (The Little Commentary, manuscript copies), Rheticus' *Narratio Prima* (First Report, 1541), *De revolutionibus orbium coelestium* (On the Revolutions of the Heavenly Bodies, 1543).

Nicholas Copernicus (1473–1543)

Quid tum? si mihi terra movetur,
Solque quiescit, ac coelum?
Constat calculus inde meus.

What then? if for me the earth moves, and while the sun and the heavens are still – my calculations thence are constant.

Copernicus' Hypotheses

Commentariolus, in manuscript

1. "There is no one center of all celestial circles or spheres.
2. The center of the earth is not the center of the cosmos, but only of *gravity* and the *lunar sphere*.[1]
3. All the spheres revolve about the sun as their midpoint, and therefore the sun is the center of the cosmos.
4. The ratio of the earth's distance from the sun to the height of the firmament is so much smaller than the earth's radius to its distance from the sun that the distance of the earth to the sun is imperceptible in comparison with the height of the firmament.[2]

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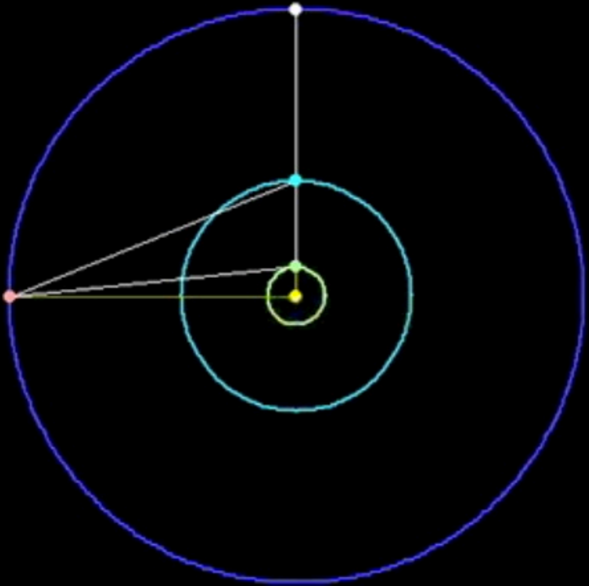
[1] Notice that there is a *different* center for the cosmos and for gravity.

[2] This means there will be no stellar parallax.

No Stellar Parallax

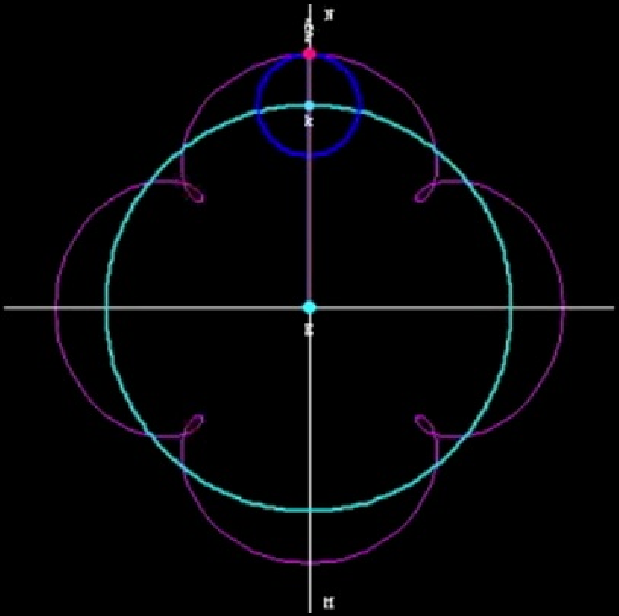


Copernicus' Hypotheses (continued)

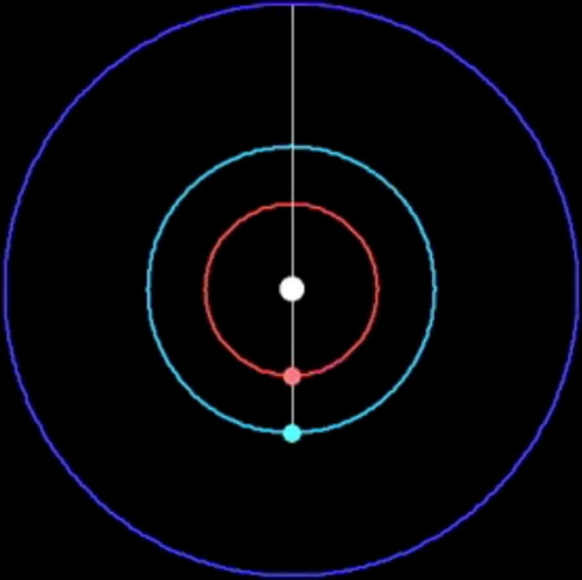
Commentariolus, in manuscript

5. "Whatever motion appears in the firmament arises not from any motion of the firmament itself, but from the earth's motion. The earth, with the nearby elements, performs a complete rotation on its fixed poles in a daily period.
6. What appear to us as the motions of the sun arise not from its motion but from the motion of the earth and our sphere, with which we revolve about the sun like any other planet. The earth has more than one motion.
7. The apparent retrograde motion and direct motion of the planets arises not from their motion, but from the earth's. The motion of the earth alone, therefore, suffices to explain so many apparent inequalities in the heavens."

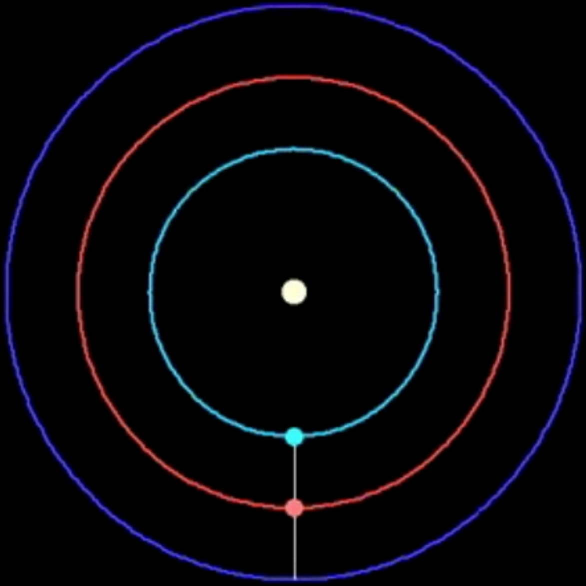
Epicyclic Retrogradation



Heliostatic Retrogradation: Inner Planets



Heliostatic Retrogradation: Outer Planets

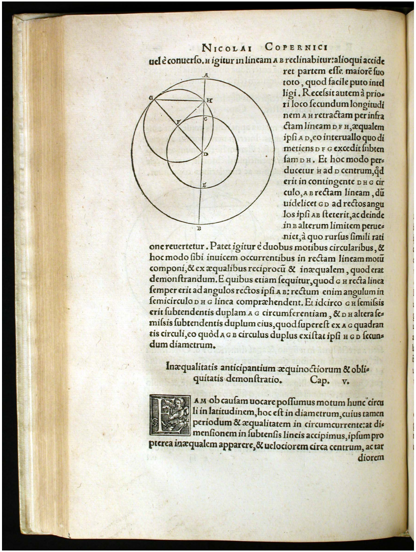


In order to avoid the *equant*, Copernicus introduced the same devices as the *Maragha School astronomers*.

Hence, his final models were as complicated as ash-Shatir's.

Historians are still uncertain how he learned about these methods, or whether he rediscovered them.

(Compare this diagram with that for the Tusi Couple in the lecture on medieval Islamic science.)

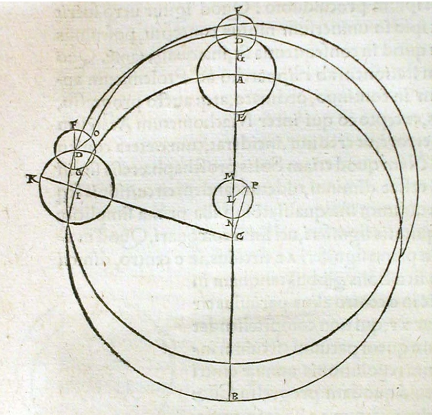

NICOLAI COPERNICI

uel è conuerſo. H igitur in lineam A B reclinabitur: alioqui accideret partem eſſe maiorẽ ſuo toto, quod facile puto intelligi. Receſsit autem à priori loco ſecundum longitudinem A H retractam per infractam lineam D F H, æqualem ipſi A D, eo interuallo quo dimetiens D F G excedit ſubtenſam D H. Et hoc modo perducetur H ad D centrum, q̊d erit in contingente D H G circulo, A B rectam lineam, dũ uidelicet G D ad rectos angulos ipſi AB ſteterit, ac deinde in B alterum limitem perueniet, à quo rurſus ſimili ratione reuertetur. Patet igitur è duobus motibus circularibus, & hoc modo ſibi inuicem occurrentibus in rectam lineam motũ componi, & ex æqualibus reciprocũ & inæqualem, quod erat demonſtrandum. E quibus etiam ſequitur, quod G H recta linea ſemper erit ad angulos rectos ipſi A B: rectum enim angulum in ſemicirculo D H G linea compræhendent. Et idcirco G H ſemiſsis erit ſubtendentis duplam A G circumferentiam, & D H altera ſemiſsis ſubtendentis duplum eius, quod ſupereſt ex A G quadrantis circuli, eo quòd A G B circulus duplus exiſtat ipſi H G D ſecundum diametrum.

Inæqualitatis anticipantium æquinoctiorum & obliquitatis demonſtratio. Cap. V.

EAM ob cauſam uocare poſſumus motum hunc circuli in latitudinem, hoc eſt in diametrum, cuius tamen periodum & æqualitatem in circumcurrente: at dimenſionem in ſubtenſis lineis accipimus, ipſum propterea inæqualem apparere, & ulociorem circa centrum, ac tardiorem

Copernicus' Full Model for Mars



The center is *a point that moves around the sun on a sort of crank* – not the sun itself.

The planet moves on an epicycle, which itself moves on an epicycle – like the Maragha School models.

The final model is even more complicated than Ptolemy's model.

Sizes and Distances of the Planets and Luminaries

Copernicus, *De revolutionibus*, 1453

"Having thus assumed the motions which I ascribe to the earth … by long and intense study I finally found that if the motions of the other planets are correlated with the orbiting of the earth, and are computed for the revolution of each planet, not only do their phenomena follow from thence, but also the order and sizes of all the planets and spheres, and heaven itself is so linked together that in no portion of it can anything be shifted without disrupting the remaining parts and the universe as a whole."

Relative and Absolute Distances


NICOLAI COPERNICI

net, in quo terram cum orbe lunari tanquam epicyclo contineri diximus. Quinto loco Venus nono mense reducitur. Sextum denique locum Mercurius tenet, octuaginta dierum spacio circũ currens. In medio uero omnium residet Sol. Quis enim in hoc

pulcherimo templo lampadem hanc in alio uel meliori loco poneret, quàm unde totum simul possit illuminare? Siquidem non inepte quidam lucernam mundi, alij mentem, alij rectorem uocant. Trimegistus uisibilem Deum, Sophoclis Electra intuentẽ omnia. Ita profecto tanquam in solio regali Sol residens circum agentem gubernat Astrorum familiam. Tellus quoque minime fraudatur lunari ministerio, sed ut Aristoteles de animalibus ait, maximã Luna cũ terra cognationẽ habet. Concipit interea à Sole terra, & impregnatur annuo partu. Inuenimus igitur sub hac

Given the geometric configuration of Copernicus' model, the relative distances are a direct result of the periods of the celestial bodies.

This means that the 'real' configuration is a natural consequence of the observations.

We could then calculate *absolute distances*, although Copernicus does not.

The Planetary Distances

The distances were calculated by a number of his successors. Here is an example:

Body	Mean Distance (er)
Mercury	340
Venus	821
Earth	1,142
Mars	1,736
Jupiter	5,960
Saturn	10,477
Stars (1st m)	"immense"

Although the size of the sphere of the fixed stars was very large (depending on the assumed least value for an observable angle), the size of the planetary orbits was smaller than it had been in previous, Ptolemaic models. Saturn's orbit was about half as small as the whole Ptolemaic system (20,000).

The Simple Model and the Complicated Model

The primary difference in the way Copernicus' work has been assessed depends on whether one focuses on basic ideas or the technical, mathematical model.

- On the *intuitive level*, his work is usually seen as innovative and revolutionary.
- On the *technical level*, his work is seen as mathematically conservative and physically unjustifiable.

The Reception

Most people, of course, did not think that he was right.

The majority of mathematical astronomers who read his work were Jesuits who wanted to use his models to make non-equant, *geocentric* models.

Those who embraced his ideas focused on the simple model – people such as, Bruno, Galileo, etc. Others changed his models in fundamental ways – people such as Tycho Brahe, Kepler.

Almost no one ever accepted his complete models.

Tycho Brahe (1546–1601)

Non haberi sed esse.

Not to seem, but to be.

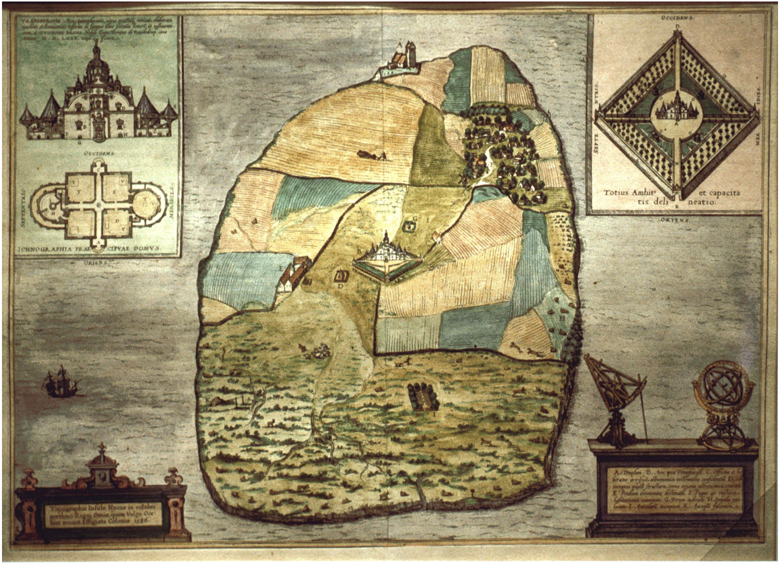
Tyge (his birth name) was born to two noble Danish houses, heir to a number of estates. He was educated in Copenhagen and Leipzig; studied at Wittenberg, Rostock, and Basel.

He accepted an offer of fife from Fredrick II to found an observatory on Hven. He lived and worked there until a falling out with Christian IV (Fredrick II's son).

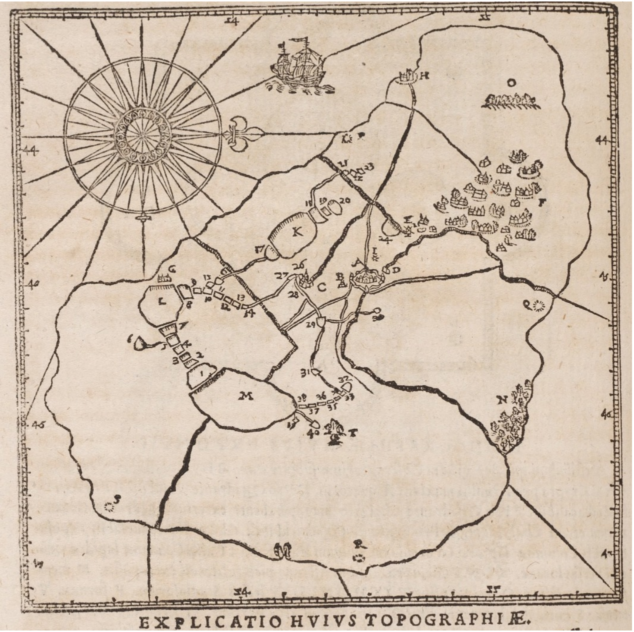
After traveling for a few years, he became imperial mathematician to Emperor Rudolph II. Died 2 years later.

Tycho's Work

- Founded and administered the first astronomical research center in Europe. His coworkers were a large group of intellectuals of various ranks, including his younger sister Sophie.
- Observed a *nova* (the explosion of a dying star) – which became an exciting topic of debate for natural philosophers all over Europe.
- Practiced and advocated a new observational basis for astronomy, by producing, with his associates, *continuous* runs of observations.
- Put forward a new system of the world.
- Works: *De Nova ... Stella* (1573), *Instruments for a Restored Astronomy* (1598), *Exercises Toward a Restored Astronomy* (1602), unpublished observations.



Upper corners: Uraniborg and grounds. North: Village and light tower.
Center: Uraniborg with Stallabord just to the Northeast.



An early triangulation map. It shows the waterworks for the mill.

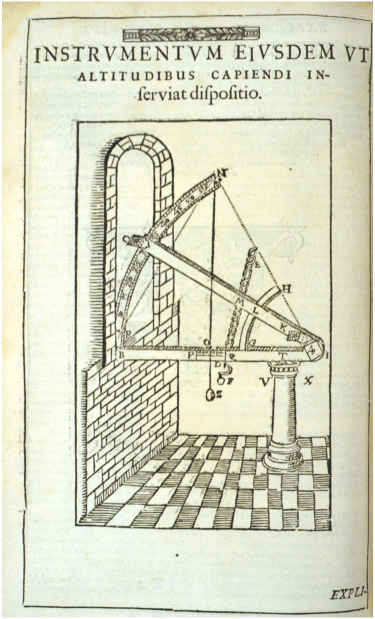
New Observations

Brahe instituted a new way of carrying out astronomical observations.

Instead of just observing significant events (transits, occultations, oppositions, etc.), he and his colleagues observed at regular intervals and noted positions in equatorial or local coordinates.

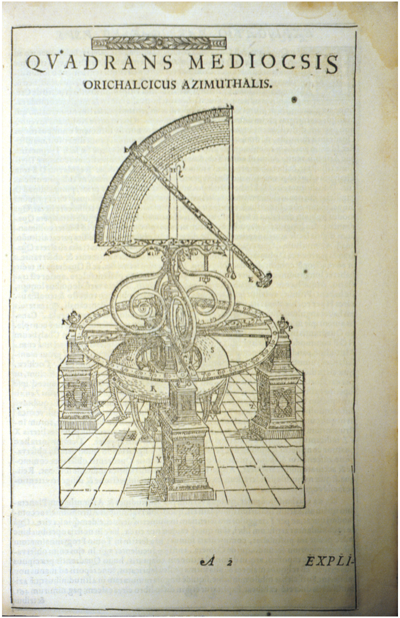
They compiled tables of observations of the planets and a new *star catalog*.

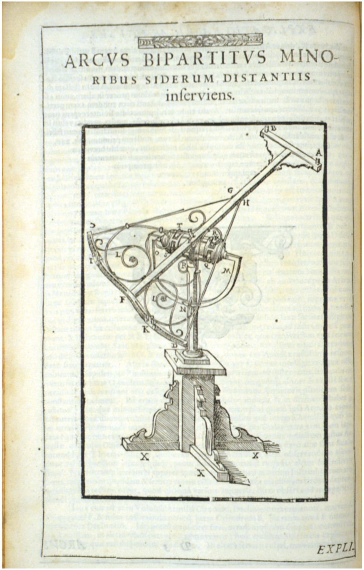
They designed and made their own instruments.



Altitude instrument.
(Local coordinates)

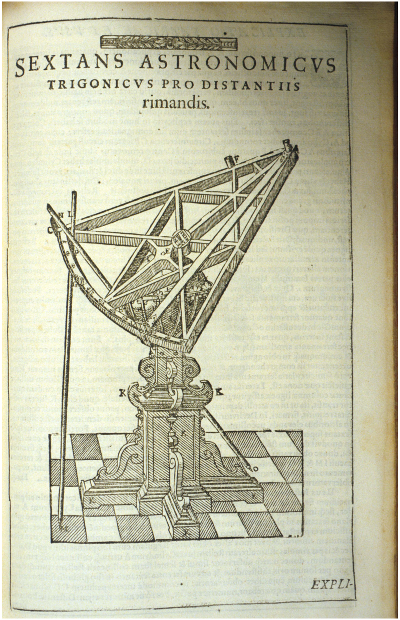
A meridian quadrant, or azimuth instrument. (Local coordinates.)





A double-arc instrument for determining angular distances.


GLOBVS MAGNVS ORICHALCICUS.
EXPLI-


SEXTANS ASTRONOMICVS
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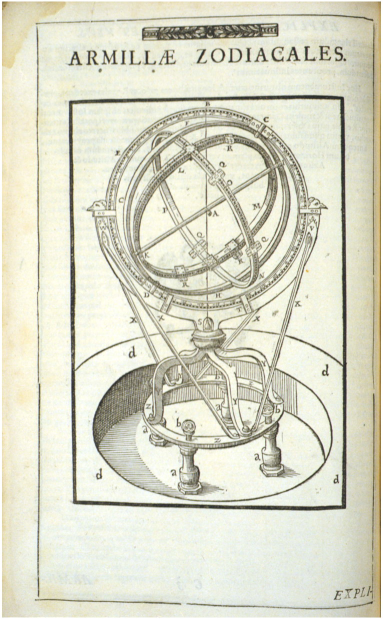
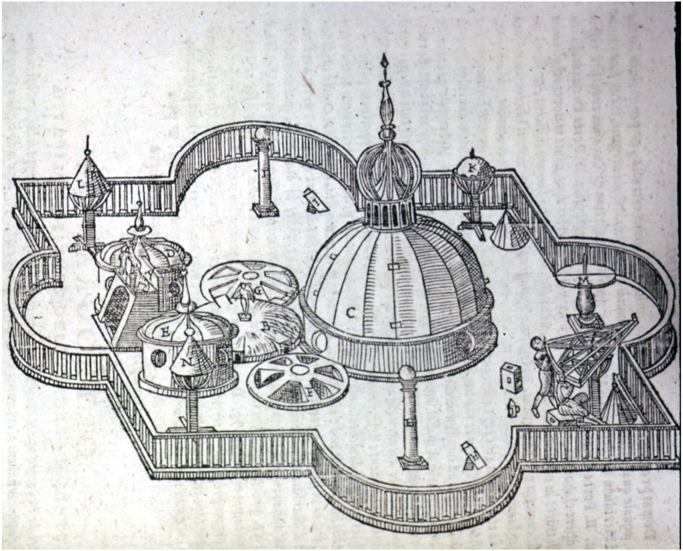
An armillary sphere
for making observations in
zodiacal coordinates.

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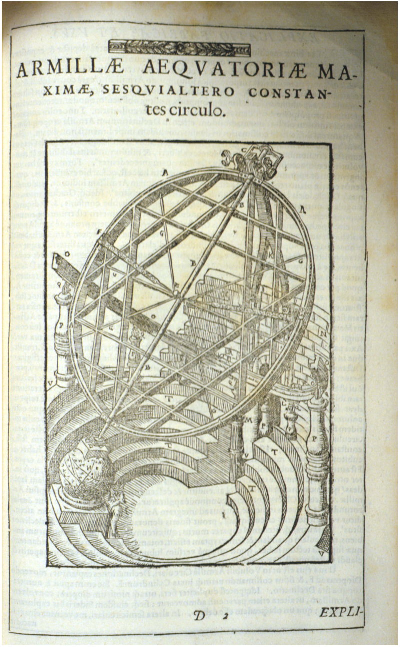
ARMILLÆ AEQVATORIÆ MA-
XIMÆ, SESQVIALTERO CONSTAN-
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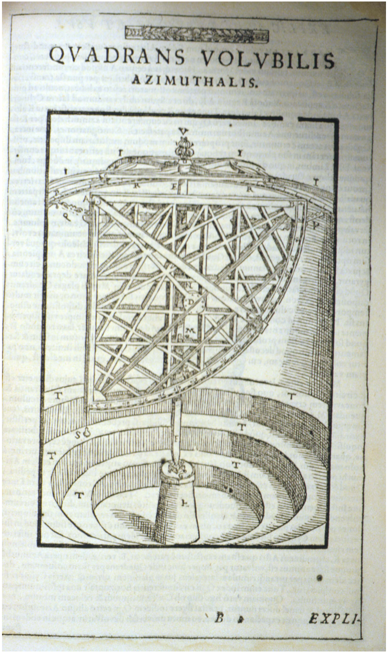
EXPLI-


QVADRANS VOLVBILIS
AZIMVTHALIS.
EXPLI-

The ruins of Stellabord (2005)

An engraving representing Tycho using the mural quadrant at the observatory on Hven

The Tychonic System

Brahe wanted to preserve the best features of the Copernican system (explanation of synodic phenomena, natural ordering and distances, and so on) and do away with the worst (the movement of the earth, vast distance of the fixed stars, lack of a physical basis, and so on).

To do this, he (1) set the earth *still at the center* of the cosmos, with the moon and the sun *orbiting the earth*.

He then (2) set all the planets orbiting the sun.

- He believed that Mars was closer than the Sun at opposition – based on parallax observations (!) and velocity.

We can describe this in terms of the Quine-Duhem thesis, insofar as Brahe sought to preserve certain hypotheses by abandoning others.

Flash Applet of Tycho's System...

Cellarius, *Harmonia Macrocosmica* (1660)

- Born to a mercantile and artisan family; raised by his grandparents.
- Studied *theology* at Tübingen. M.A. 1591. Studied mathematics with Maestlin, one of the first Copernicans.
- Taught mathematics at a seminary in Graz.
- Worked with Brahe in Prague and appointed Imperial Mathematician after Brahe died.
- After Rudolph II was deposed, he was forced to teach here and there to make ends meet.

Kepler's Work

Kepler worked in mathematics, mathematical astronomy and optics. But all of his writings are full of a kind of cosmological *mysticism*.

In all of his work he argued for scientific realism. (*Against Ursus*, in manuscript.)

His approach to the use of observations *changed* a great deal throughout the course of his career.

Works: *The Cosmographic Mystery* (1597), *Optics* (1604), *The New Astronomy* (1609), *Epitome of Copernican Astronomy* (1618), *The Harmony of the World* (1619), *Rudolphine Tables* (1626).

Mysterium Cosmographicum, 1597

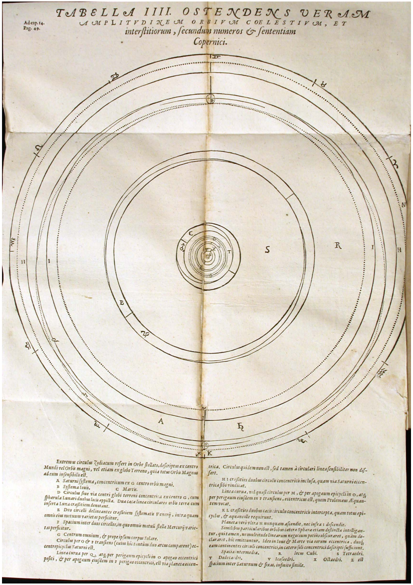
The *Mysterium* is a work of *pure theory*. (We can take it as an example of his early disinterest in observation.)

It attempts to explain the underlying mathematical structure of the Copernican cosmos, on the assumption that it is *real*.

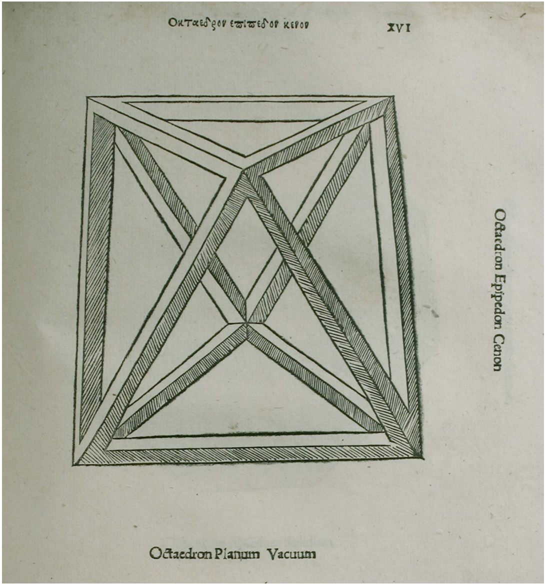
It computes the sizes of the concentric spheres and then argues that the empty space can be explained by the perfect solids.[3] In order to get this to work out, he had to fudge the numbers a bit.

The planetary orbits are determined by nesting the perfect solids: octahedron (8-sides), icosahedron (20-sides), dodecahedron (12-sides), tetrahedron (4-sides), cube (6-sides).

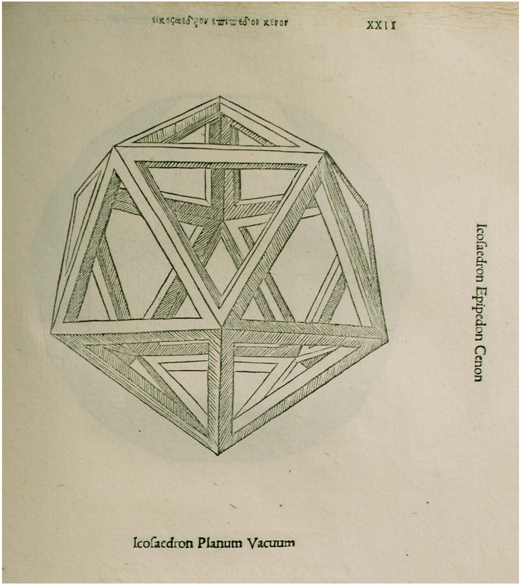
[3] The perfect solids (Platonic solids), are three dimensional figures whose sides are all equilateral two-dimensional figures. Euclid had shown that there are only five.



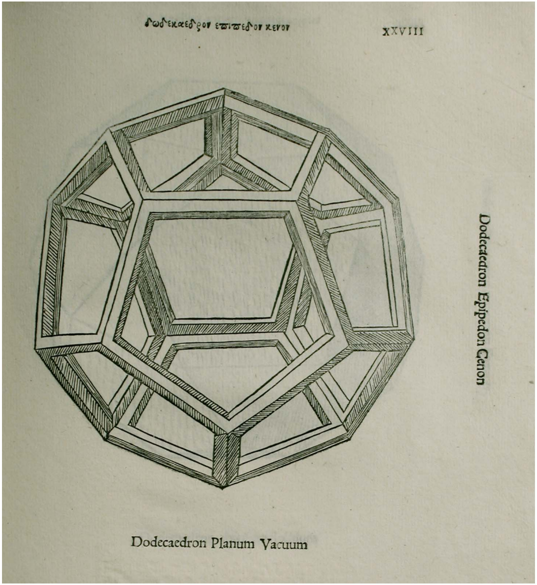
A foldout from *Mysterium Cosmigraphicum*, showing the planetary spheres and the space in between them.



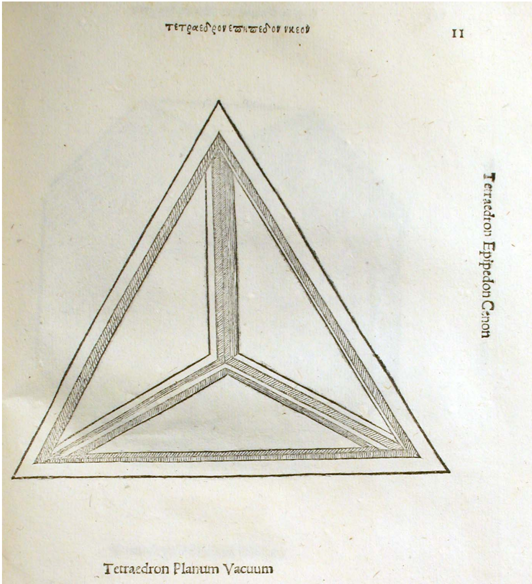
Octahedron (Pacioli, 1509). Kepler put it between Mercury and Venus.



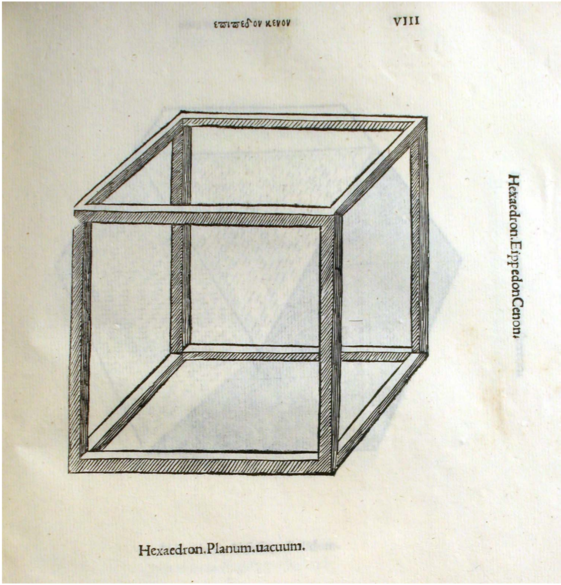
Icosahedron (Pacioli, 1509). Kepler put it between Venus and Earth.



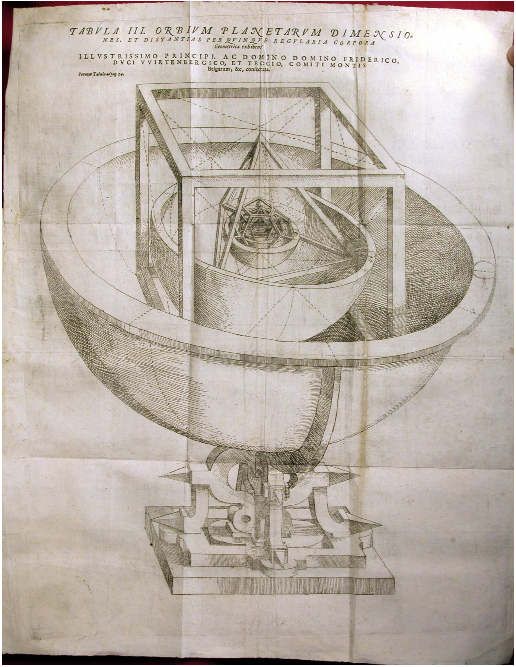
Dodecahedron (Pacioli, 1509). Kepler put it between Earth and Mars.



Tetrahedron (Pacioli, 1509). Kepler put it between Mars and Jupiter.



Cube (Pacioli, 1509). Kepler put it between Jupiter and Saturn.


TABVLA III. ORBIVM PLANETARVM DIMENSIO-
NES, ET DISTANTIAS PER QVINQVE REGVLARIA CORPORA
Geometrica exhibens
ILLVSTRISSIMO PRINCIPI, AC DOMINO DOMINO FRIDERICO,
DVCI VVIRTENBERGICO, ET TECCIO, COMITI MONTIS
Belgarum, &c, consecrata.
Ponatur Tabula ad pag. 24.

The *Astronomica Nova* is a completely different type of work. It is an almost confessional journey through Kepler's attempts to find a model for the motion of Mars that agrees with Tycho's data to a *high degree of precision*.

He was guided by the belief that the *physical cause* of the motion must lay in the solar body. (He thought it was a magnetic force.)

Astronomica Nova

"Now, the first step toward determining the physical causes consists in proving that the common point of the eccentrics is not some point or other in the vicinity of the sun, as believed by Copernicus and Tycho Brahe, but is the center of the solar body itself."

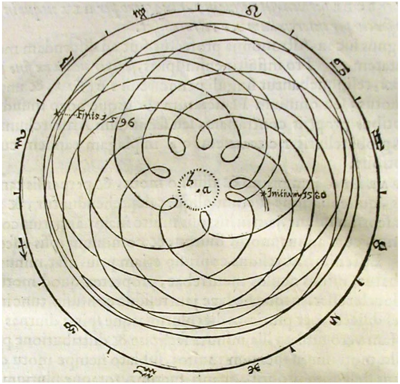
The *New Astronomy*, modeling Mars

The work itself seems to wander, but it is actually very carefully structured.

First, Kepler returns to Ptolemy's equant model and works it through, only to decide that it is not accurate enough and also physically not satisfactory. (Because it is hard to imagine a physical cause.)

Then he turns to an oval, which is also not accurate enough.

Finally, he models both the earth and mars with ellipses.



The first visual image of the complete Ptolemaic path of Mars.

Kepler's Laws

I. The planets move in ellipses with the sun at a focus. (Concerns the shape.)

II. Equal areas are swept out in equal times. (Concerns the velocity throughout the orbit.)

Flash Applet of Kepler’s Laws, I and II...

III. Periods are as the three-halves power of the distances. (Concerns the relative velocity of the planets.)

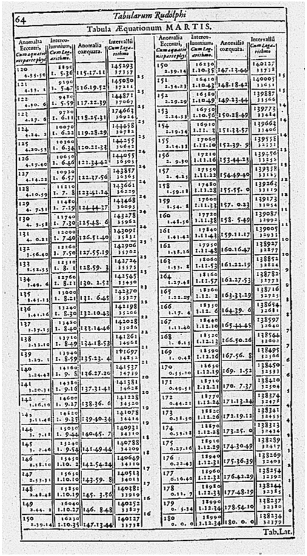
That is, the squares of the periods are as cubes of the distances, $P^2 \propto D^3$, or:

$$\frac{P_1}{P_2} = \frac{D_1^{3/2}}{D_2^{3/2}}.$$

Flash Applet of Kepler's Law, III.

The Rudolphine Tables (1627)

- This work completed the project begun by Tycho on a completely new theoretical basis.
- The tables are computed using Kepler's elliptical models, which in turn are built on Tycho's observational data.
- The set of tables was much more accurate than its predecessors, with a margin of error of $< 0;10^\circ$. (The previous margin of error was about 5°.)


64 Tabularum Rudolphi

Tabula Æquationum MARTIS.

Tab.Lat.


TABULÆ RUDOLPHI ASTRONOMICÆ
COPERNICUS.
TYCHO BRAHE.
HIPPARCHUS.
PTOLEMÆUS.
MYSTER.COSMO.
ASTR.P.OPTICA
COM.MARTIS.
EPIT.AST.COP.
INSULA. HUENNA. DANIÆ.

The Astronomical Revolution

The period we have looked at today is sometimes referred to as the astronomical revolution.

It was revolutionary in a number of different senses: (1) the order of the cosmos was changed, putting a stationary sun near the center, (2) there was a new emphasis on accurate and continuous observation and the instruments that made these possible, (3) a higher standard was introduced for the relationship between theory and observation, (4) there was a new notion of what it would mean for a theory to be realistic and a new emphasis on scientific realism.

The astronomical revolution was a revolution in technical astronomy, but it still left much work to be done in terms of cosmology and physics. Indeed, the Copernican system had no consistent physical basis, and hence many felt that it was *unrealistic*.