The Origins of Modern Astronomy:

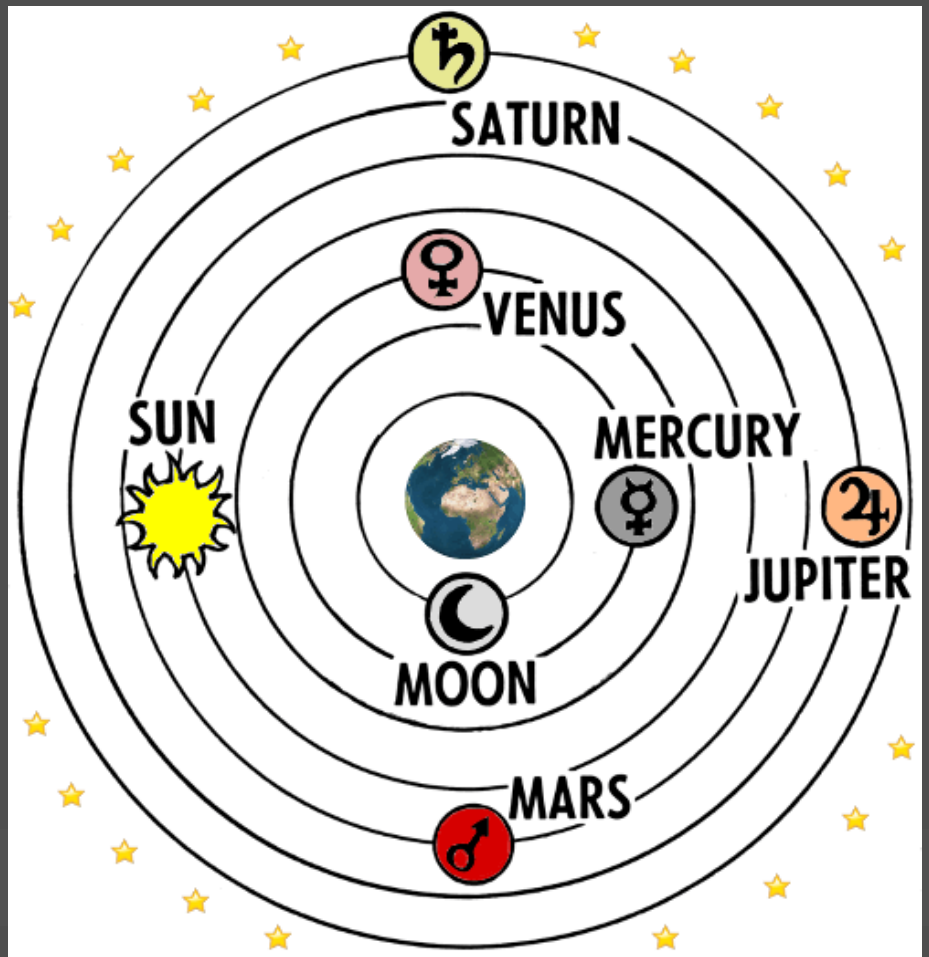
The Copernican revolution

After the fall of Constantinople (now: Istanbul) in 1453, the last remains of Roman Empire (Byzantium = Eastern Roman empire), and with them the Middle Ages formally ended. The time period of Renaissance began.

Many Byzantium scholars traveled to Western Europe, carrying with them the ancient knowledge that contributed to the birth of the Renaissance, the rebirth of western culture

The stage was set for a revolution in scientific thought

Universities in their astronomy courses were teaching the Aristotelian, geocentric structure of cosmos. All the learned mathematicians/astronomers agreed with the geocentric (at least geostatic) scheme of this kind:



But the ancient, opposing idea of heliocentrism (sun-centered system) was not completely forgotten

The original heliocentric models of the universe

*Archimedes in a book titled ''Sand-Reconer'' about Aristarchus (*Aristarchos of Samos, 310-230 BC*) writes:*

"But Aristarchus of Samos brought out a book consisting of some hypotheses, in which (...) the universe is many times greater than that now so called. His hypotheses are that the fixed stars and the sun remain unmoved, that the earth revolves about the sun in the circumference of a circle, the sun lying in the middle of the orbit, and that the sphere of fixed stars, situated about the same center as the sun, is so great that (...)"

Heliocentric model was also known to Pythagoras (who simply believed in it) and Hipparchus (who decided that geocentric model makes more sense given his observations). Thus the very idea of heliocentric system was ancient, though not popular.

Nicolaus Copernicus (1473-1543)

- Mikołaj Kopernik (*latin:* Nicolaus Copernicus) was born in Toruń, Poland
- supported by Prince-Bishop uncle (Lukas Watzenrode) Kopernik studied at University of Cracow, Poland, and later
- Univ. of Bologna and Padua in Italy
- Became the catholic church official: canon (law expert)
- Organized defense of a small city Frombork in Warmia province from the Teutonic Knights

The 2008 forensic facial reconstruction – the grave was found in 2005 after centuries, DNA-identified, & re-buried 2010.

Nicolaus Copernicus (1473-1543)

- Diplomat (signed a peace treaty)
- Physician (advised dukes)
- Economist (financial reform, quantitative theory of money, in 1517-1519 the so-called Gresham's law)
- Classical scholar and translator
- Jurist
- Polyglot (5 languages)
- Astronomer
- Mathematician

Tower he bought as home in Frombork, a town on the Baltic sea in Warmia (a province of Polish Prussia)

Nicolaus Copernicus (1473-1543)

- At the time of his birth, and throughout his life, astronomy was based on Ptolemy's (~150 CE) model of Aristotle's universe.
  - In spite of many revisions, the Ptolemaic model was still a sometimes poor predictor of planetary positions
  - Although this was causing problems for astrology,

it wasn't why Copernicus wanted to overturn geocentrism. (Being a priest he did not serve as astrologer & had no interest in astrology.)

Still, he was trolled as an "upcoming Astrologer" by the famous theologian Martin Luther ☺

Nicolaus Copernicus

- In Aristotle's philosophy, the most perfect region was in the heavens and the most imperfect region was at Earth's centre, the classical geocentric universe model
  - so, it matched the commonly held Christian view of the geometry of heaven and hell.
  - Some modern authors incorrectly claim that anyone who criticized Aristotle's model was risking a serious charge of heresy, and that the Catholic Church was forbidding the the ideas of Copernicus. This is incorrect, in general.
  - In reality, the Vatican was quite supportive of the work of Copernicus during his lifetime. It was Copernicus who hesitated and delayed publication of his works.

Copernicus's Model

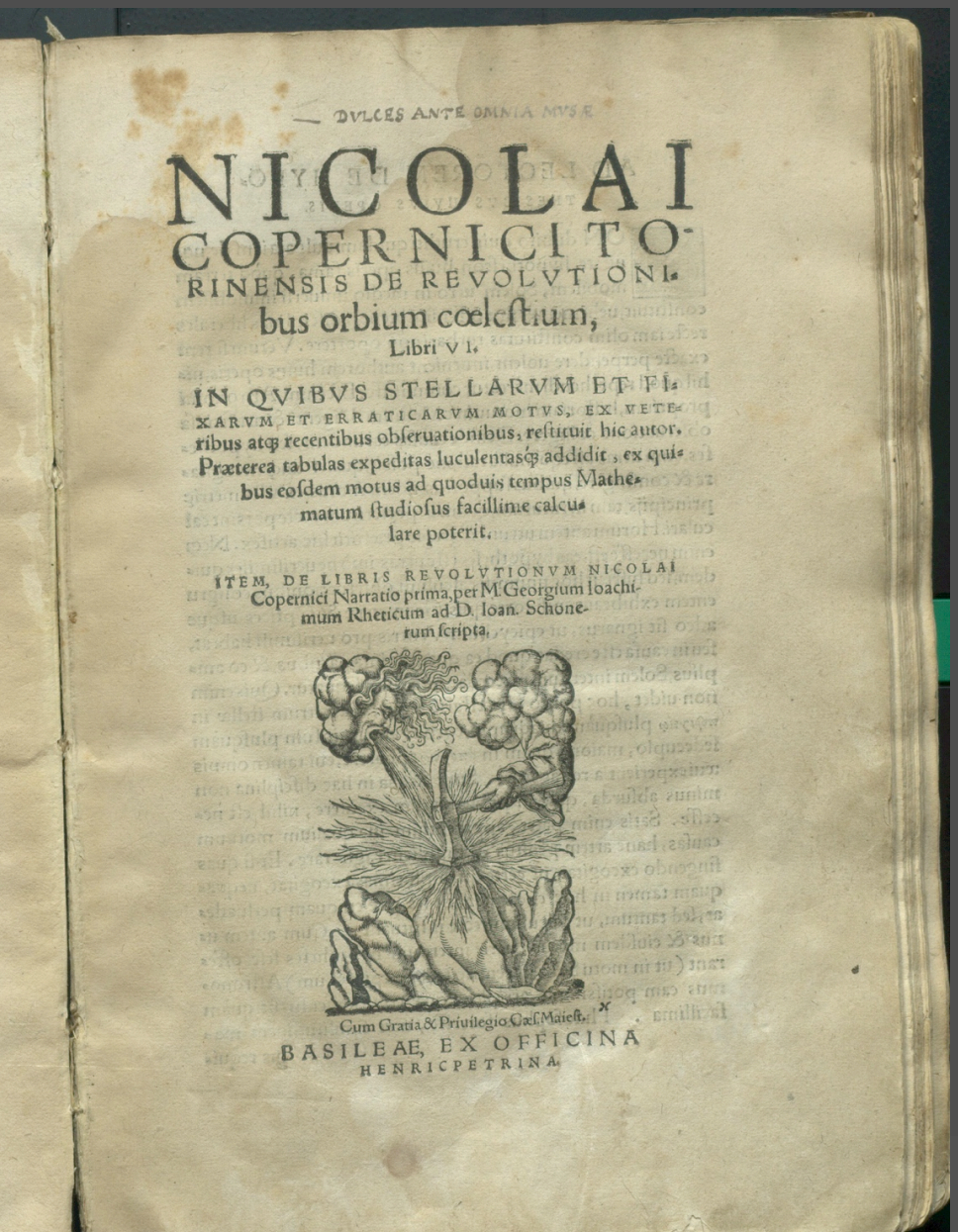
Copernicus was associated with the Roman Catholic Church throughout his life. He was a canon (doctor of church law and a minister) but was not ordained as priest.

- ~~As a result of this connection to the Church and his fear of persecution~~** ***, he hesitated to publish his revolutionary ideas that challenged the Ptolemaic model and the geometry of heaven and hell.

** - the crossed over text is a direct citation from the textbook ASTRO by Backman et al. & is incorrect. It is a part of modern myths

*** - ridicule would the correct word, ridicule not by the church but by the academia professors. Cardinals actually encouraged him to publish heliocentric model many times, even offered to pay for the publication.

De revolutionibus Orbium Coelestium (1543)



— DVLCES ANTE OMNIA MVSÆ

NICOLAI
COPERNICI TO-
RINENSIS DE REVOLVTIONI-
bus orbium cœlestium,
Libri VI.

IN QVIBVS STELLARVM ET FI-
XARVM ET ERRATICARVM MOTVS, EX VETE-
ribus atq; recentibus obseruationibus, restituit hic autor.
Præterea tabulas expeditas luculentasq; addidit, ex quí-
bus eosdem motus ad quoduis tempus Mathe-
matum studiosus facillime calcu-
lare poterit.

ITEM, DE LIBRIS REVOLVTIONVM NICOLAI
Copernici Narratio prima, per M. Georgium Ioachi-
mum Rheticum ad D. Ioan. Schone-
rum scripta.

Cum Gratia & Priuilegio Cæs. Maiest.

BASILEAE, EX OFFICINA
HENRICPETRINA.

Copernicus believed that the Sun and not Earth was the center of the universe, and that Earth rotated daily on its axis and revolved around the Sun in one year.

Copernicus Hypothesis

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

pulcherrimo 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, Sophocles 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, maximam Luna cum terra cognationẽ habet. Cõcipit interea à Sole terra, & impregnatur annuo partu. Inuenimus igitur sub hac

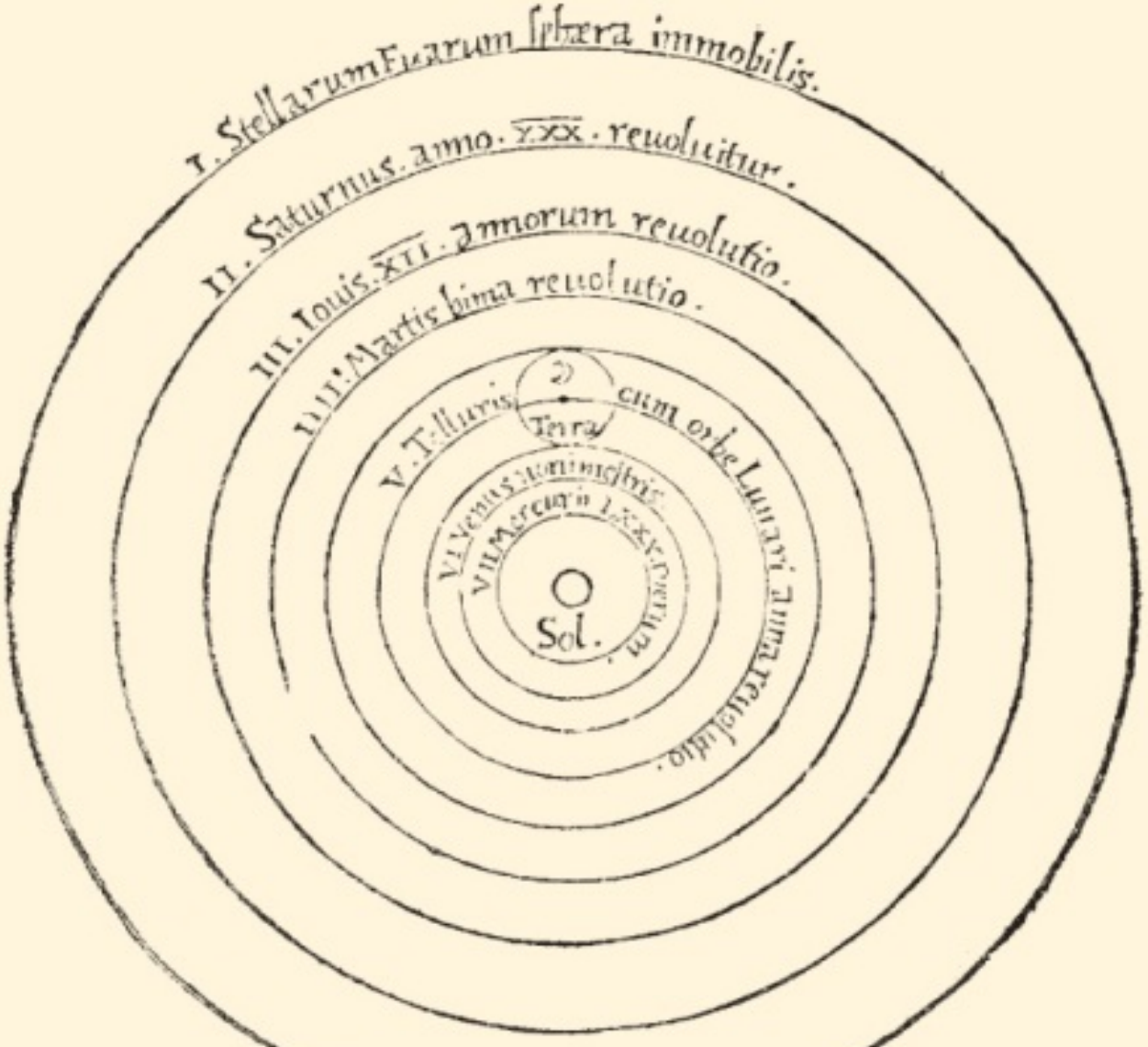
hac ordinatione admirandam mundi symmetriam, ac certũ harmoniæ nexum motus & magnitudinis orbium: qualis alio modo reperiri non potest. Hic enim licet animaduertere, non segniter contemplanti, cur maior in Ioue progressus & regressus appareat, quàm in Saturno, & minor quàm in Marte: ac rursus maior in Venere quàm in Mercurio. Quod ♃ frequentior appareat in Saturno talis reciprocatio, quàm in Ioue: rarior adhuc in Marte, & in Venere, quàm in Mercurio. Præterea quòd Saturnus, Iupiter, & Mars acronycti propinquiores sint terræ, quàm circa eorũ occultationem & apparitionem. Maxime uero Mars pernox factus magnitudine Iouem æquare uidetur, colore duntaxat rutilo discretus: illic autem uix inter secundæ magnitudinis stellas inuenitur, sedula obseruatione sectantibus cognitus. Quę omnia ex eadem causa procedũt, quæ in telluris est motu. Quod autem nihil eorum apparet in fixis, immensam illorum arguit celsitudinem, quæ faciat etiam annui motus orbem siue eius imaginem ab oculis euanescere. Quoniam omne uisibile longitudinem distantiæ habet aliquam, ultra quam non amplius spectatur, ut demonstratur in Opticis. Quòd enim à supremo errantium Saturno ad fixarum sphæram adhuc plurimum intersit, scintillantia illorum lumina demonstrant. Quo indicio maxime discernũtur à planetis, quodq; inter mota & non mota, maximam oportebat esse differentiam. Tanta nimirum est diuina hæc Opt. Max. fabrica.

De triplici motu telluris demonstratio. Cap. XI.

CVm igitur mobilitati terrenæ tot tantaq; errantium syderũ consentiant testimonia, iam ipsum motum in summa exponemus, quatenus apparentia per ipsum tanquam hypothesim demonstrentur, quem triplicem omnino oportet admittere. Primum quem diximus κυκλοφορικὸν à Græcis uocari, diei noctisq; circuitum proprium, circa axem telluris ab occasu in ortum uergentem, prout in diuersum mundus ferri putatur, æquinoctialem circulum describendo, quem nonnulli æquidialem dicunt, imitantes significationem Græcorum, apud

c ij quos

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 relidet Sol. Quis enim in hoc



Copernicus Model

- Copernicus apparently began doubting Ptolemy's geocentric model during his college days in Kraków
- At the Kraków University (founded in 1364) he took many courses in math an astronomy
- A heliocentric universe model had been discussed occasionally before Copernicus's time. As we have discussed previously, Pythagoras had a heliocentric worldview, and the sun was also at the center of the world as described by Aristarchus (Ἀρίσταρχος, *Aristarchos of Samos*, *310 BC – ca. 230 BC), as noticed by Archimedes*

- Copernicus however was the first person to produce a detailed model with substantial justifications

Copernicus's Model

- Sometime before 1514, Copernicus wrote a short pamphlet summarizing his model and distributed it in handwritten form to friends, while he worked on his major book.

- "*Commentariolus*" ("Little Commentary") is a 40-page manuscript, printed only in the 19th century, but nevertheless known to a number of top scholars & intellectuals throughout Europe in Copernicus' days

- It was copied and distributed widely by Tycho Brahe only after Copernicus died.

Copernicus's Model

Commentariolus contains some mysteriously prescient concepts and data, e.g.: the relative sizes of orbits are correct.

If the Earths orbit is 25 units, Copernicus says that Mars orbit (mean distance from the sun) is 38 units. In other words, Earth bein at 1 AU from the sun, Mars is on average 38/25 AU = 1.52 AU

- The mean radius known today is a=1.5236 AU
- Copernicus used data from Almagest (the lack of

correct frame of reference did not allow Ptolemy to realize that he had the correct sizes of orbs. (Before the telescope, parallax of any planet was unmeasurable, so this was not an observational knowledge.)

Copernicus's Model

Commentariolus contains these mean planetary distances (semi-major axis *a*) from the sun in units of AU:

planet	(Ptolemy recalc. to heliocentric)	*a*(Kopernik)	*a*(true)
Mercury	0.375	0.376	0.378
Venus	0.717	0.720	0.723
Earth	1.000	1.000	1.000
Mars	1.519	1.520	1.524
Jupiter	5.217	5.217	5.206
Saturn	9.231	9.233	9.580

Copernicus's Model

The eccentricity of the orbit of Mars & the planets was mentioned as well.

Copernicus writes that in order to produce Mars orbit, in fact all planetary orbits, one needs to place a circular epicycle on a big circular deferent, and on that epicycle to attach a second circular epicycle:

"The first [epicycle's] radius is throughout three times greater than the second [epicycle's radius]".

The two epicycles combine into a non-uniformly moving point on a nearly elliptic curve which has axial ratio 1:2 (twice as large along the orbit than in radial direction from the sun)

Copernicus's Model

This 1:2 ratio, as could be realized only in the 19th century, is the precise ratio following from the angular momentum conservation (also the empirical law later discovered by Kepler as his 2nd law).

His constructs make Copernican model exact to order $O(e^2)$, as modern astronomers would say, where *e* stands for the *eccentricity parameter* (e~0.094 for Mars, for instance). Copernicus knew the value of *e* to a high accuracy, already 30 years before his main work appeared.

It is also interesting that in 1514 he only knew the summary of Ptolemy's Almagest, which was printed in full only somewhat later, so it's not clear how he learned about it.

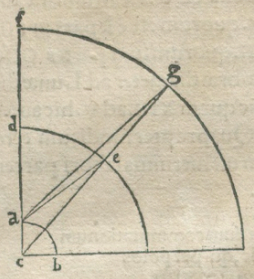
De Revolutionibus

- Copernicus' book *De Revolutionibus Orbium Coelestium Libri VI* (*On the Revolutions of Celestial Spheres, in 6 volumes*) was the main work that he was writing over many years.

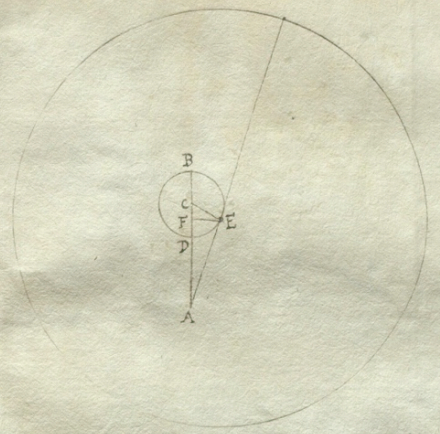
- In 1533, Johann Albrecht Widmannstetter (secretary of the Pope) delivered a series of lectures in Rome outlining Copernicus' theory.

- Joachim Rheticus (1514-1574) from Wittenberg, the only student of Copernicus, wrote *Narratio prima de libris revolutionum Copernici* (1540), the First Account of works on Revolutions by Copernicus

rum CCCLX. sunt quatuor recti, habebimus triangulum a c e, in quo duo latera a c, c e, cum angulo qui sub a c e dantur, è quibus inuenimus a e c angulum commutationis scrup. primorum XXV. secūdorū XXVIII. Et cum fuerit c e illarum partium. LXV. s. erit angulus qui sub a e c scrupu. primorum XXVI. secundorum XXXVI. Similiter tertio loco, cū fuerit c e, LV. scrup. VIII. erit angulus a e c commutationis scrup. primorum XXXI. secundorum XLII. In minima deniq; distantia dum fuerit c e partium LII. scrup. XVII. efficiet a e c angulū scrupu. primorum XXXIII. secundorum XXVII. Rursus cum de circumferentia sumatur partium LX circuli, erunt eodem ordine parallaxes, prima scrupu. primorum XLIII. secundorum LV. Secunda scrupu. XLV. secundorum LI. Tertia scrupu. LIIII. s. Quarta LVII. s. Quæ omnia conscribemus in ordinem Canonis subiecti, quem pro commodiori usu, ad instar aliorum in XXX. uersuum seriem extendemus. Sed per hexades graduum, quibus intelligatur duplicatus numerus, eorum qui à uerticē sunt horizontis ad summum nonagintasex. Ipsum uero Canonem digessimus in ordines nouem. Nanque primo & secundo erunt numeri communes circuli. Tertio ponemus Solis parallaxes. Deinde Lunares commutationes. Et quarto loco differentiæ. Quinto minimæ parallaxes, quæ in Luna diuidua ac apogæa contingunt, deficiunt, à sequentibus in plena nouaque. Sextus locus eas habebit commutationes, quas in perigæo plena uel sitiēs Luna producit. Et quæ sequuntur scrupula sunt differentiæ, quibus quæ in diuidua, ac proxima nobis existente Luna parallaxes fiunt, illas sibi uiciniores excedunt. Deinde reliqua duo spacia, quæ supersunt scrupulis proportionum seruantur. Quibus inter has quatuor limites parallaxes poterunt dinumerari, quæ etiam exponemus, & primum circa apogæum, & quæ inter priores sunt limites, hoc modo. Sit inquam circulus a b Lunę



a b Lunę epicyclus primus, cuius centrum sit c, et susceptо d centro terræ agatur recta linea d b c a, & in a apogæo facto centro describatur epicyclium secundum e f g: assumatur autem e g circumferentia partium LX. & connectantur a g, c g. Quoniam igi



AD 8600
AB 1340
Ergo BD 4740
BC 2370
AC 10970

Arcus DE grad. 60, cuius sinus FE 8660254
quarum CE 10000000, & CF sinus compl. 5000000
At quarum CE est 2370, FE est 2052 CF 1185.
AD est 8600, FD æqualis CF 1185, ergo AF 9785,
FE 2052 / Et angul. FAE gr. 11. 50. Nam

ut AF 9785, ad FE 2052, ita AF 100000, ad FE, 20970
tang. 11. 50 36

Latus AE est 9999. Nam

ut FE sinus ang. FAE 20523, ad AE 100000, ita FE 2052 ad
AE 9999.
AE est 9999
AD est 8600
Ergo Diff. 1399

Sed ut BD 4740, ad 60, ita 1399, ad 17. 42.
Scrupula proport. prioràt.

eg. duplex distan. C. a. ☉

De Revolutionibus

- However, Copernicus hesitated to publish – even though other scientists, and church officials including Pope Clement VII, concerned about reform of the calendar, knew about his work, sought his advice, and encouraged the publication

- Narratio Prima in 1540 might have been a “trial balloon” to probe the reaction to heliocentric theory

- In 1542, Copernicus finally sent Rheticus off to Nuremberg with the manuscript to be printed

- Copernicus died in 1543 before the printing run was finished, but saw the first prints on his death-bed.

De Revolutionibus

- The retrograde motion of the planets was immediately explained in a straightforward way without the epicycles and the “ugly” equant that Ptolemy used.

- A total of 34 circles (epicycles and deferents) were used by Copernicus to improve the positional fit to the data, but they were very small, <<1 AU, compared with the Ptolemy’s 24 or so epicycles, which essentially must be on the scale of 1 AU)

- It is a modern myth that Copernican model was much better because it did away with the too numerous epicycles of Apollonius and Ptolemy.

De Revolutionibus

- At the same time, the hypothesis explained correctly the brightness at conjunctions and oppositions of planets with the sun, without making the geometrical constructs needed to account for varying distances overlap in space, as was the case with Ptolemaic theory

- The issue of brightness variations is something that modern commentators miss most of the time, but it was explained in both the Commentariolus and in De Revolutionibus, and indeed is a grand unification by Copernicus

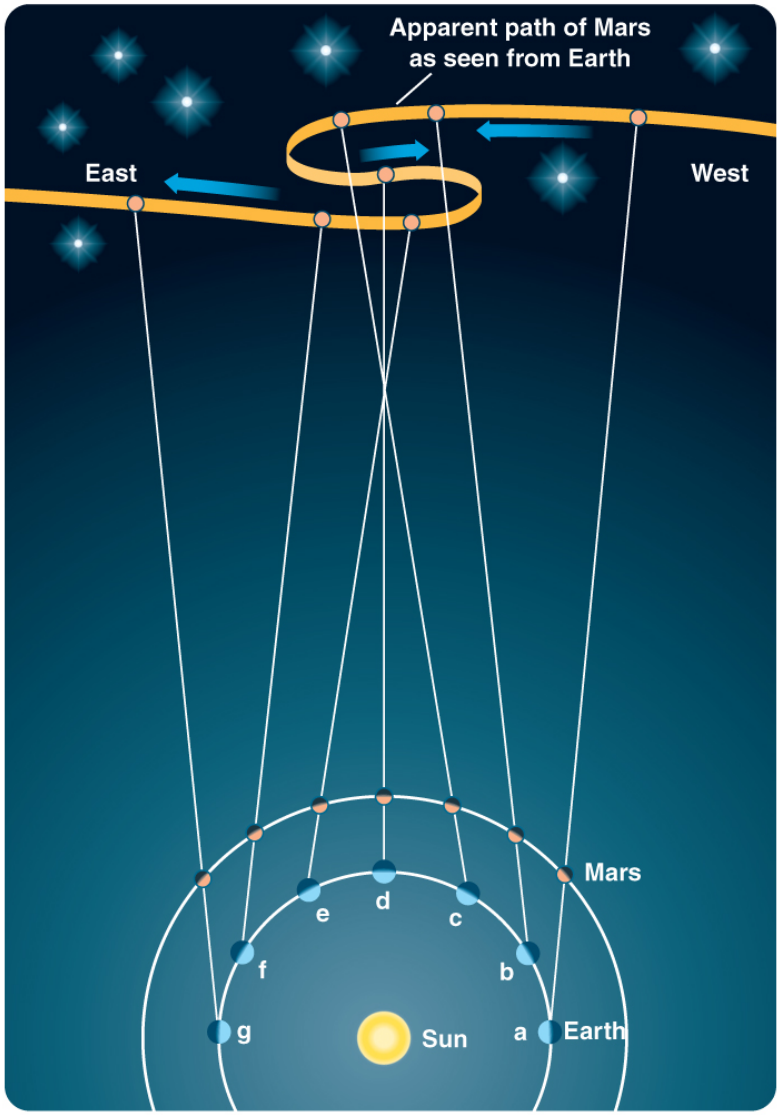
De Revolutionibus – Explanation of retrograde motion of planets

- In the Copernican model, Earth moves faster along its orbit than the planets that lie farther from the Sun.
- Consequently, it periodically overtakes and passes these planets. Imagine that you are a runner on a track moving along an inside lane.
  - Runners well ahead of you appear to be moving forward relative to background scenery.
  - As you overtake and pass slower runners in outside lanes, they fall behind – seeming to move backward for a few moments relative to the scenery.

De Revolutionibus

- The same thing happens as Earth passes a planet such as Mars.
  - Although Mars moves steadily along its orbit, as seen from Earth, it seems to slow to a stop and move westward (retrograde) relative to the background stars as Earth passes it.

Figure 3.1 Explanation of apparent retrograde (backward) motion of planets in the heliocentric model.



De Revolutionibus

- As the planets' orbits do not lie in precisely the same plane, a planet does not resume its eastward motion in precisely the same path it followed earlier.
  - Instead, it describes a loop or S-curve, depending on circumstances
  - In the multiple-exposure picture, you see the actual appearance of Mars on consecutive days, against the background of the same distant stars

De Revolutionibus

- Copernicus's basic principles were simpler than the multiple off-centre circles of the Ptolemaic model,

though we must stress that both models are in principle equivalent, since the heliocentric model can be translated into geocentric (all motion is relative, and since heliocentric model predicts positions of Earth and other bodies at different times, one can always obtain all geocentric positions by subtracting Earth's coordinates from those of other bodiesSuch a recalculation will result in geocentric coordinates of all bodies of the system, at any time. It's just cumbersome and obscures the real architecture of the planetary system.

In 16th century, accuracy of positional predictions was similar for Ptolemaic and Copernican models.

De Revolutionibus – and its old and new reception

It was felt that Copernicus ***failed to strictly disprove*** geocentrism because Copernican model could not predict the *positions* of the planets much more accurately than the Ptolemaic model.

- In the first half a century after announcement of the heliocentric hypothesis, Copernicus' main work was widely known among specialists, but only a few of then professed to believe in the heliocentrism (Georg Rheticus, Michael Maestlin, Reinhold etc). And not too many were able to understand the whole book. But those who managed to read it, were the key specialists, and that often motivated them to develop the planetary science.
- A. Kessler proposed in 1959 that De Revolutionibus was "a book nobody read". This misconception was disproved by astrophysicist & historian Owen Gingerich in a similarly titled book in 2004, summarizing his 30-year investigation.

De Revolutionibus

- Copernicus was a classically trained astronomer with great respect for the old concept of uniform circular motion
- He had neo-Pythagorean inclination
- That would explain his strong preference for heliocentrism, and his reluctance to share the knowledge with the ridiculing masses
- Would Copernicus publish his work if a young student from Germany, Georg Rheticus, had not come and press for publication of the main work at the end of his life?

De Revolutionibus

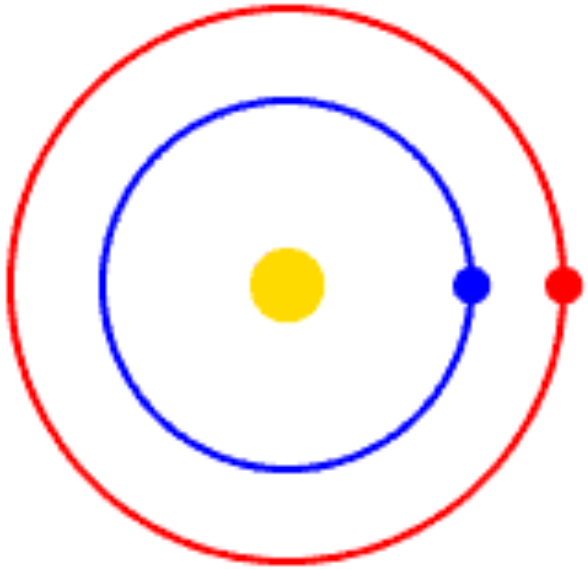
- The book was printed in Nürenburg in 1543, the year of Copernicus death. In fact, he saw the last printed part of it on his death bed (he died after a stroke).
- The printer Johannes Petraeius included the Preface by Andreas Osiander, which Petreius did not or pretended not to have noticed. The preface said the book contains hypotheses and mathematical models, not necessarily the truth.
- This enraged Copernicus' associate Georg Rheticus, who wanted his preface with a Latin verse to be published.

  Copernicus himself was probably too sick to notice the change. Petraeuis apologised to Rheticus in a letter and said he'll correct the mistake, but did not do it.
- Modern historians actually tend to excuse the printer. for half a century, the book wasn't put on the Index [of the forbidden books] thanks to the 'politically correct' Preface forged by Osiander.

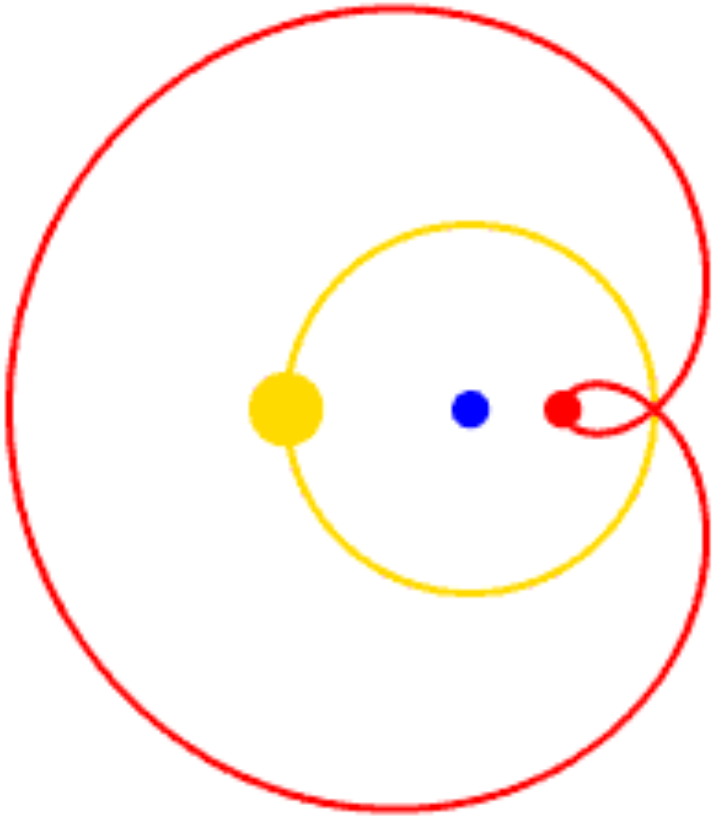
Why heliocentrism won with geocentrism

- Motion of Mars (red) and Earth (blue)

1. for an outside observer



2. relative to Earth, in the geocentric model



Why heliocentrism won with geocentrism

The Ptolemaic, geocentric model for non-uniform motion of planets (as observed in the sky) had to use

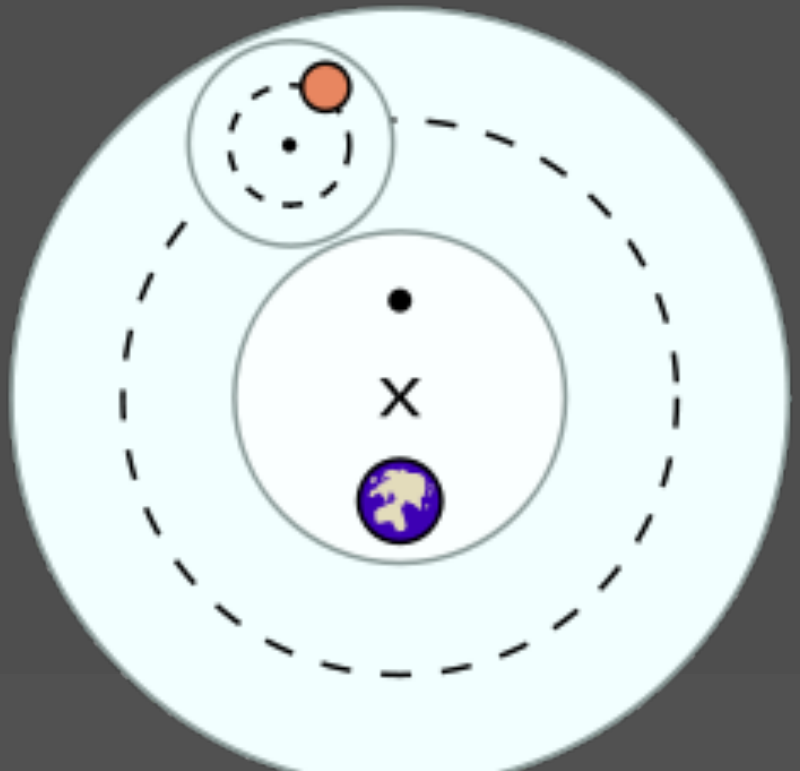
(i) ex-centric position of the Earth (blue) and

(ii) the equant point (black dot), around which the planet's epicycle (little circle) was supposed to move uniformly

Geocentric (geo-stationary) model defeats its own goal of preserving the uniform circular motion of planets, posited by ancient philosophers

E.g., Mars does not move at all uniformly on its big circle.

Copernican explanation is overall *simpler* and thus more *beautiful.*



Circles

- Like the Ancients, Copernicus held a strong but ***incorrect*** belief in uniform circular motion
- Therefore, even though his model put the Sun correctly at or near the centre of the solar system, it could not very accurately predict the positions of the planets as seen from Earth

- Copernicus had to adopt small epicycles that he called *epicyclets*, to match minor variations in the motions of the Sun, Moon, and planets. Total # = 34 (that's actually more than in the Ptolemaic system, though they were much smaller!)

    - Astronomers today recognize those variations as due to the planets' motions in elliptical orbits. That motion is non-uniform and non-circular (see L9).

De Revolutionibus

You should note the difference between the specific Copernican model and the basic heliocentric theory.

The Copernican model is unnecessarily complicated because (like its geocentric counterpart) it insists on uniform circular motions, although it dispenses with the alternative geometrical device, the equant points.

However, the Copernican hypothesis that the solar system is heliocentric is correct! It correctly identifies the Sun as a shepherd of planets.

Copernican hypothesis cleared the way for much more precise theories of the future, and gave rise to the following **Copernican Principle:**

We are not in a special place in the Universe

Later it turned out that neither is the Sun. We now know that neither the Sun nor the Galaxy are the “center of the Universe”, and that there is no such thing!

De Revolutionibus and a "gradual revolution"

- Why the heliocentric hypothesis, very *gradually (over 100 to 150 yrs)* won a wide acceptance is an interesting question that historians still debate. It wasn't more accurate back then!
- A number of reasons are cited:
  - The most important factor may be the simplicity (beauty) of the idea. In science, beautiful => true, very often
  - Unification. Through a dual motion of the Earth (spin+orbit, or rotation+revolution) many seemingly disconnected phenomena could be explained without resorting to separate explanations for each of them: rotation of the sky, loopy paths of the planets (retrogradation), phases of planets, their apparent brightness variations.
  - These are the hallmarks of a modern science, which started with *De Revolutionibus.*
  - *Science values symmetry and beauty, it explains & makes testable (falsifiable) predictions*

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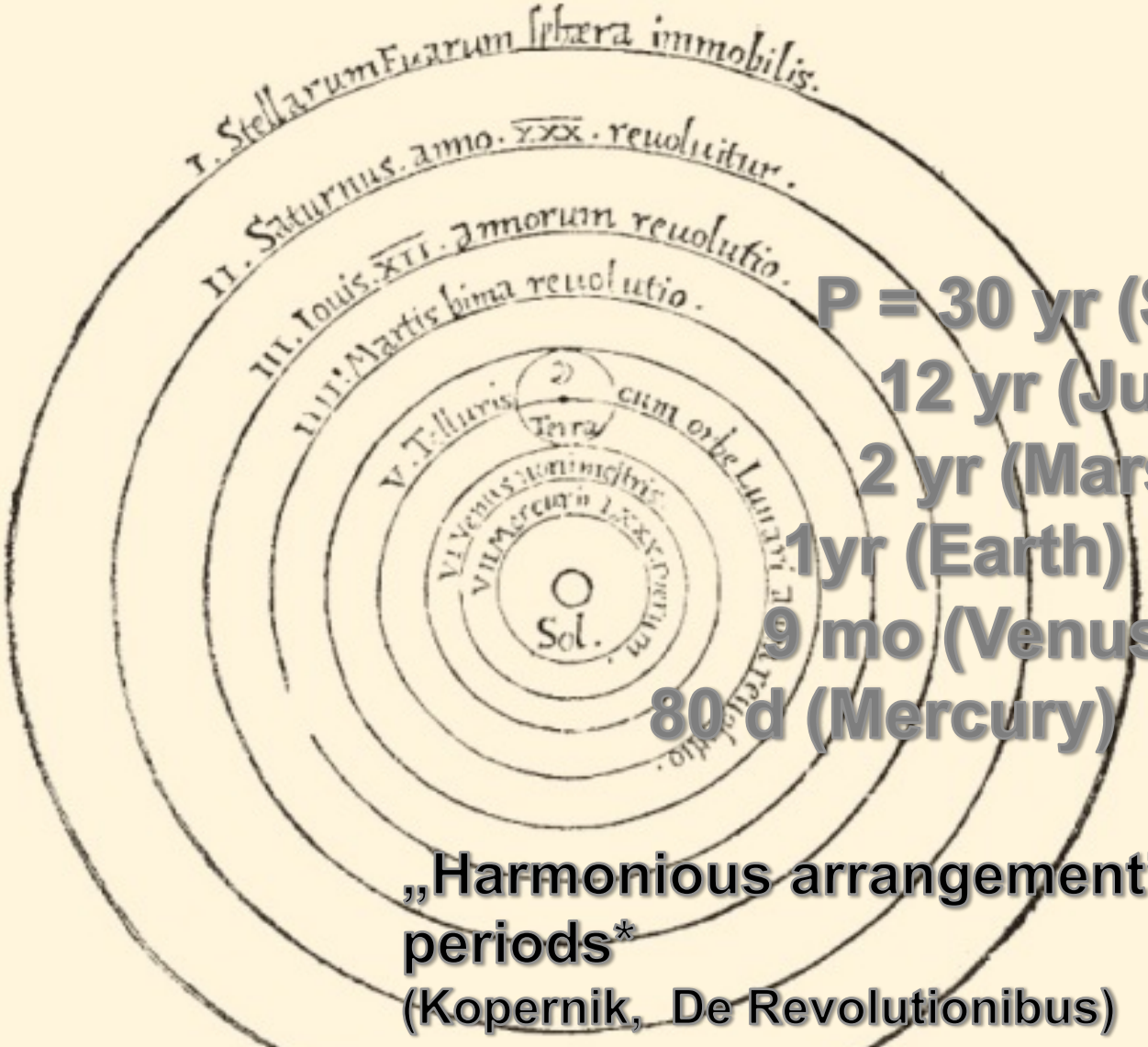
diximus. Quinto loco Venus nono mense reducitur. Sextum
denique locum Mercurius tenet, octuaginta dierum spacio circũ
currens. In medio uero omnium relidet Sol. Quis enim in hoc



P = 30 yr (Sat)
12 yr (Jup)
2 yr (Mars)
1yr (Earth)
9 mo (Venus)
80 d (Mercury)

„Harmonious arrangement" of periods*
(Kopernik, De Revolutionibus)

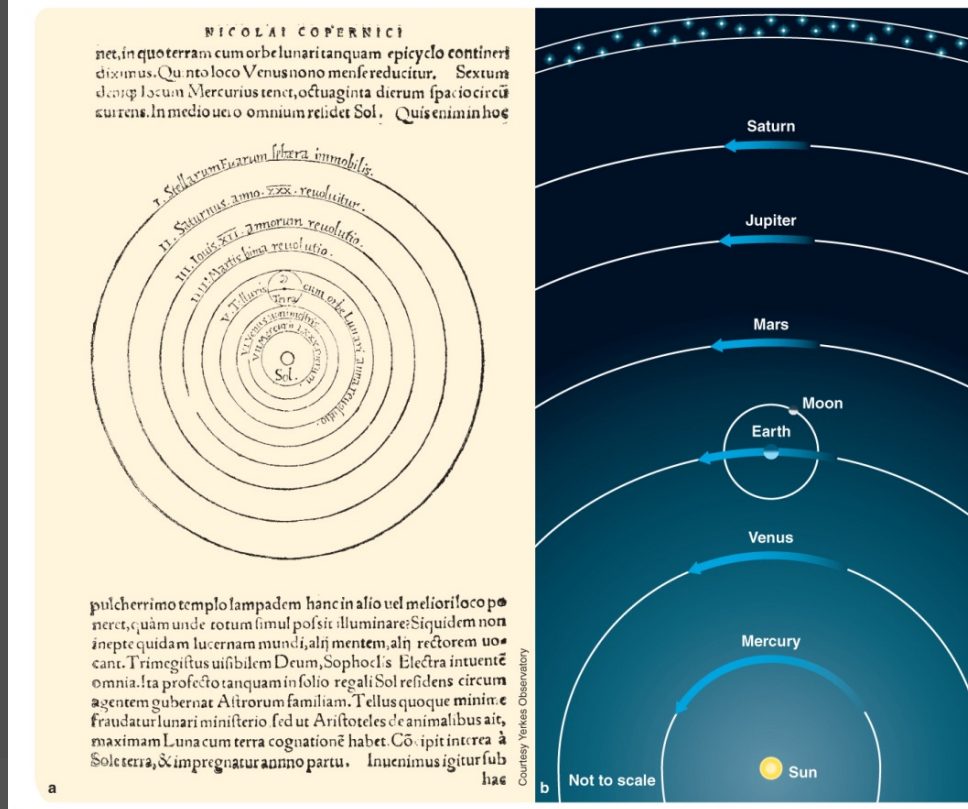
De Revolutionibus - symmetry

The sun at the centre of the universe produced a symmetry among the motions of the planets that is elegant and pleasing. It became clearer why their periods of orbital motion are as they are (i.e. gradually grow with distance in the heliocentric model)

This must be due to the Sun!

Even before modern dynamics, it intuitively felt proper for the largest body (the sun) to occupy an immovable central space & to determine those periods.

Figure 3.2



De Revolutionibus - symmetry

- In the Ptolemaic model, Mercury and Venus had to be treated differently from the rest of the planets
- These planets never deviate from the location of the sun on our sky by more than 47 degrees
- Their epicycles had to remain centered on the Earth-Sun line. Other planets inexplicably were way more independent of the sun!

- In Copernicus's model, all the planets were treated the same.
  - They all followed orbits centered on the dominant Sun

De Revolutionibus

- How the Copernican hypothesis was gradually recognized as correct has been called the *Copernican Revolution.*
  - It was not just a new result, but a total change in the way astronomers and the rest of scholars thought about the place of Earth and humanity in the bigger world or cosmos

Copernicus has made Earth a planet!

Copernican Revolution

Heliocentric hypothesis triggered a predictable controversy that would one day culminate with Galileo Gallilei facing the trial by Office of Inquisition

- This controversy over the nature of scientific and religious ideas continues even today
- To those with good knowledge of science, science and religion are not necessarily in direct conflict, unless one holds too literal a view of religious texts

- now we delve in a little bit of more detail...

Heliocentric system – how difficult to prove?

In “Early Astronomy” (1994) Hugh Thurston says:
“All motion is relative. In fact, the difference between geostatic and heliostatic systems is not of great technical astronomical importance. Its importance, if any, is theological and philosophical. Even Galileo had trouble in finding valid reasons for believing that the earth, not the sun, moved.”

Unlike Thurston and numerous other commentators of the works of Kopernik throughout the centuries, I do not think that, in Kopernik’s time, heliocentric theory was practically **in**distinguishable from geocentric theory, just because it could not provide significantly improved accuracy of the **positions** of planets on the sky as a function of time.

An idea difficult to prove?

From the Antiquity planets' positions were of paramount concern:

- where the planets were against the backdrop of constellations of "fixed" stars at any moment (for instance of a person's birth)
- when & where were they rising and setting
- when & where (in which sign of zodiac) they approached each other

All of the above was of utmost interest to **astrology**, which makes little use of the brightness of objects (that quantity was difficult to express quantitatively, at least until the magnitude scale was extended to planets). That's why we see so much emphasis on the question: can the new heliocentric system predict the *angular positions* better than the old system? And also why there was little emphasis on how these systems predict *distances to and brightness* of planets.

An idea difficult to prove? The issue of brightness

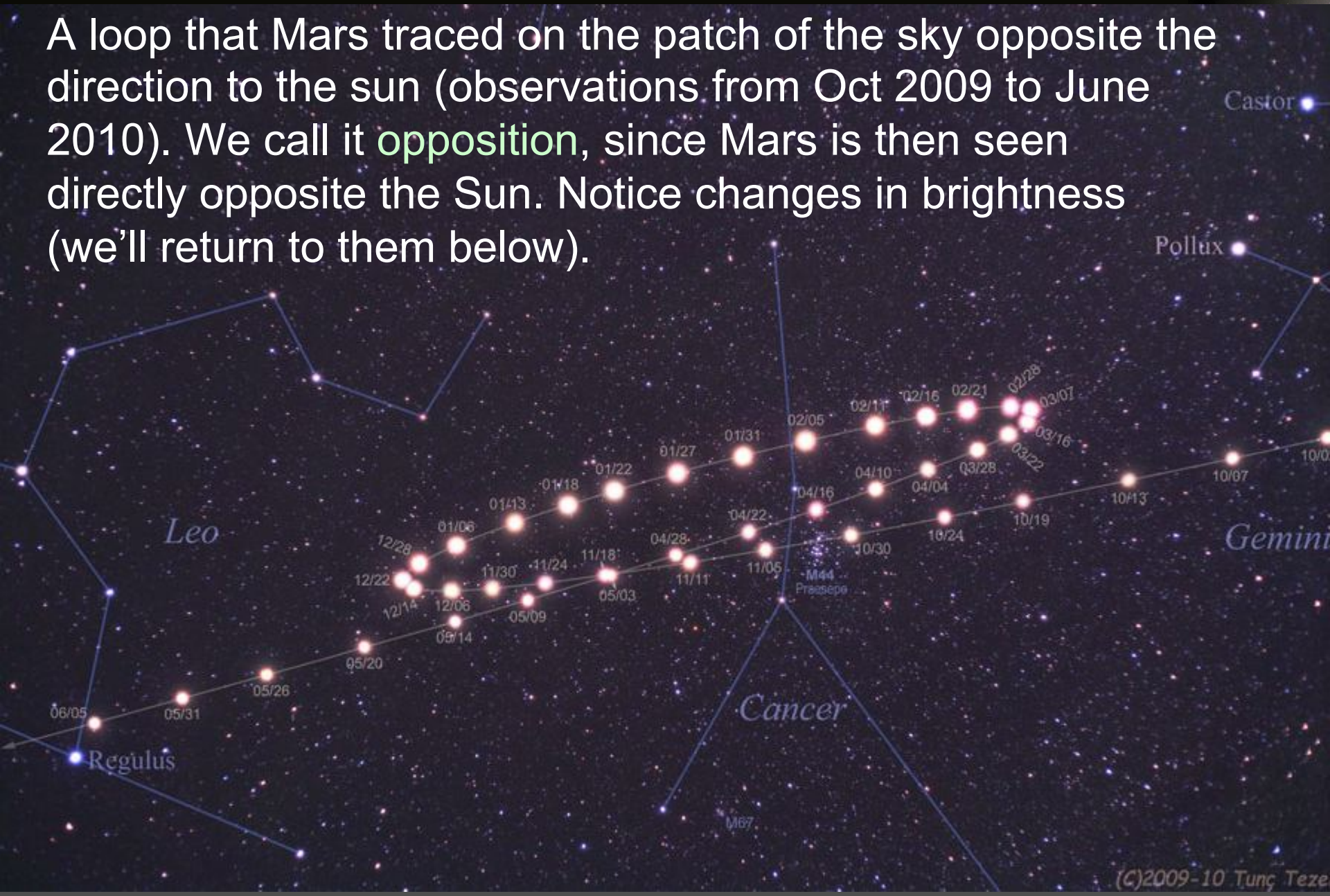
In the section titled The Ptolemaic Universe, author of "Early Astronomy" Thurston writes:
"The planetary astronomy in *Almagest* is angular. Both inputs and outputs are angles, not distances." A notable exception was that "This does not apply to the sun and moon. Ptolemy did calculate their distances."

But if distances from the sun and Earth to planets are not analyzed, then it is hard to interpret any change in the brightness of a planet. Meanwhile, planets do change their brightness as they travel through constellations, sometimes very markedly so.

This was already known to the ancient civilizations.
The planet that changes brightness most is Mars.

Mars near opposition to Sun, images every 4-6 days

A loop that Mars traced on the patch of the sky opposite the direction to the sun (observations from Oct 2009 to June 2010). We call it opposition, since Mars is then seen directly opposite the Sun. Notice changes in brightness (we'll return to them below).



Copernicanism – an idea difficult to prove?

As early as the 28th Dynasty of the New Kingdom (1570 BC to 1293 BC), Egyptians refer to Mars as “Horus the Red” and Horatkhi "Horus of the Horizon", or more literally "Horus-rising”, a sky god depicted as a human with the head of a hawk.

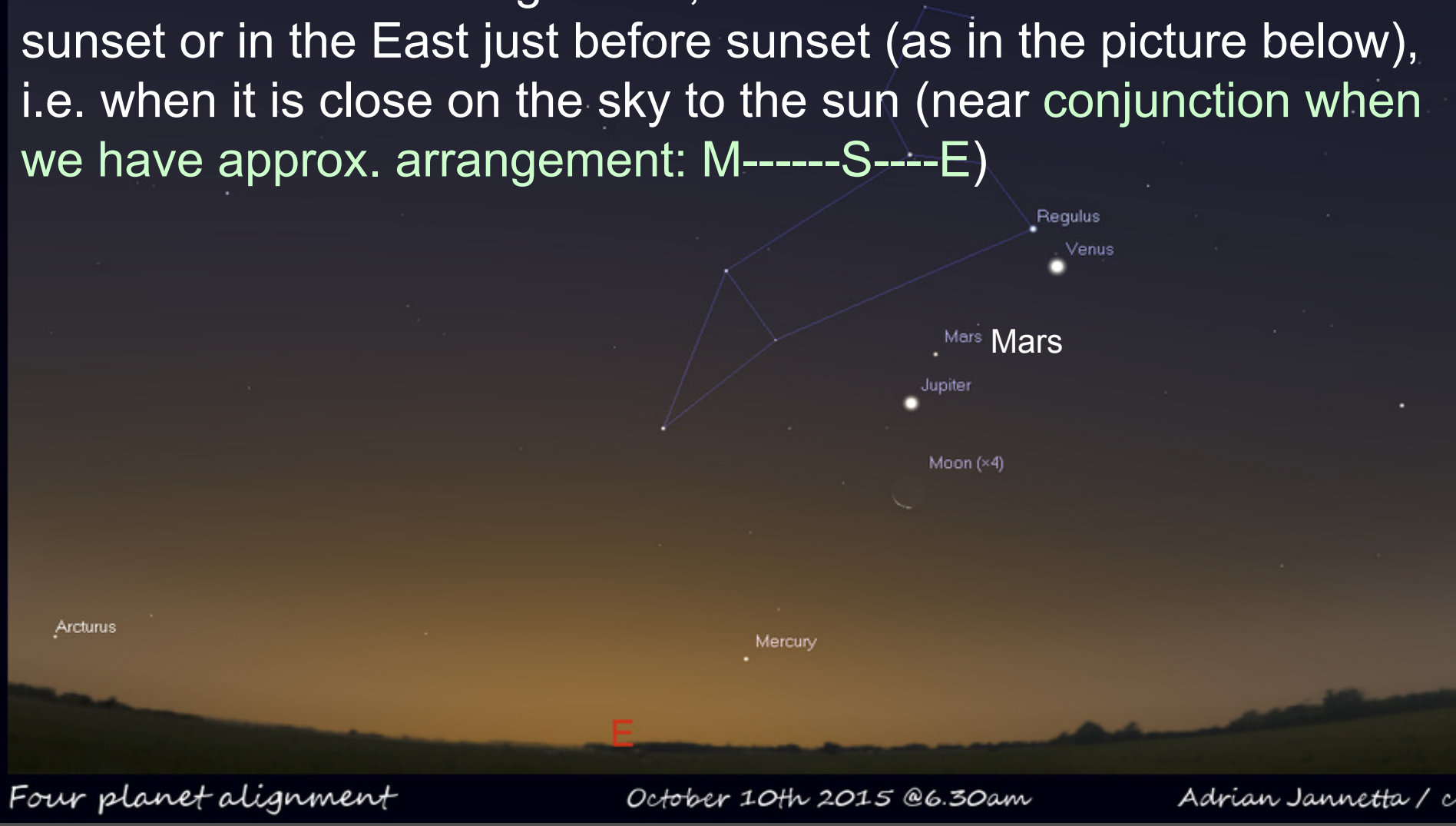
They also spoke of Mars travelling *backwards*, a clear reference to its periodic retrograde motion every 2.1 years.

In contrast, Jupiter and Saturn were described as lights illuminating the kingdom (presumably higher above the horizon).

Since the most important time of the day was either the rise or setting of the main god Ra (the Sun), the Egyptian association of Mars with the rising and high brightness probably refers to Ra rising at sundown. Mars appears very bright (as bright as Jupiter) at opposition.

Copernicanism – an idea difficult to prove?

At other times, Mars is much fainter, in fact down to only ~1/50 times the maximum brightness, when it is seen in the West after sunset or in the East just before sunset (as in the picture below), i.e. when it is close on the sky to the sun (near conjunction when we have approx. arrangement: M------S----E)



Copernicanism - an easily testable idea

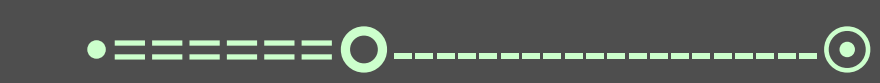
Kopernik mentioned as a fact well known to astronomers that Mars is brightest near opposition (S----E—M). That's when it does the loop in the sky (has retrograde motion). In geocentric system there was no natural explanation for the latter fact.

Incidentally, the loop sometimes looks like an S-curve (the left time-lapse image from 2014). You can see how quickly Mars becomes faint just outside the ~17^{o} wide loop. As it travels another ~170^{o} with respect to sun toward their conjunction, it becomes about 50 times fainter, as already illustrated

Copernicanism as a testable hypothesis

In Greek astronomy the simplest assumption, already adopted by Aristarchus and later by Copernicus, but not clear to Ptolemy and some others, was that planets (including the moon) are not self-luminous, but shine illuminated by the sun, by scattered light. The question arises: How are the huge variations of the brightness of Mars related to its distance from Earth and Sun?

Let's consider first the modern, heliocentric view of two configurations known as (first) opposition, and (second) conjunction. The three bodies are nearly on one line then:
(Mars & Sun in opposition, on opposite sides of the sky)



Below, Mars and Sun are in conjunction, nearby on the sky

Copernicanism as a testable hypothesis

In heliocentric system, Sun-Earth distance is close to 1 AU. Mars & Sun in opposition = 180^{o} apart on the sky, BUT close in space to Earth. For those who know the magnitude scale: magnitude up to m ≈ -2.9^{m}

Mars in conjunction with Sun, nearby on the sky, BUT far from Earth in space → Mars appears to us very faint, fainter than 100 brightest stars; magnitude down to m ≈ +2.6^{m} .

Mars is very bright in opposition, because while the distance to the sun is constant or nearly constant, the distance to Earth is up to 7 times smaller than at conjunction, resulting in up to 50 times larger apparent brightness, as observed from Earth.

Copernicanism as a testable hypothesis:

In geocentric system, Mars is placed on a large epicycle of radius >2 AU and a deferent >3 AU, to reproduce the loops on the sky. A model with such epicycle and deferent reproduces the loops but makes little sense in two respects:

(i) Mars would crash into sun's *crystal sphere* (in the ancient world planets were moving attached to crystal spheres), located 1 AU from Earth.

(ii) Secondly, as already mentioned, for unexplained reasons, geocentric model has to require Mars to always be at perigeum (closest approach to Earth) at the time of opposition with the sun, i.e. while 180^{o} apart on the sky.

(iii) E.g., right after our 2022 course ends, Mars will be closest, brightest, AND rise at sunset.

This happens every 26 months

Copernicanism is a testable idea

Here is what Mikołaj Kopernik himself had to say about the issue:

"For [Saturn, Jupiter, and Mars] are always closest to the earth, as is well known, about the time of their evening rising, that is, when they are in opposition to the sun. On the other hand, they are at their farthest from the earth at the time of their evening setting, when they become invisible in the vicinity of the sun, namely, when we have the sun between them and the earth. These facts are enough to show that their center [of orbit] belongs more to the sun, and is identical with the center around which Venus and Mercury likewise execute their motions."

[N. Copernicus, *De Revolutionibus, book I, ch. 10 'The order of heavenly spheres', 1543*]

Copernicanism vs. geocentrism

Under a watchful eye of Copernicus, his pupil Georg Joachim Rheticus wrote 3 years before the publication of the *Revolutions*:
"(…) the course of Mars is hard to trace. In addition to the other difficulties in the correction of its motion, Mars unquestionably shows a parallax sometimes greater than the sun's, and therefore it seems impossible that the earth should occupy the center of the world. (…) [?? Mars's parallax was unmeasurable!] The variation of [Mars] size is related to its distance from the earth. Whereas at its evening rising Mars seems equal to Jupiter in size; when it rises in the morning just before the sun (..) it can scarcely be distinguished from the stars of second magnitude. Consequently at its evening rising it approaches closest to the earth, while at its morning rising it is furthest away. Surely this cannot in any way occur on the theory of epicycle. Clearly then, in order to restore the motion of Mars and other planets, a different place must be assigned to the earth."

[GJ. Rheticus *De libris revolutionum Nicolai Copernici Narratio Prima, 1540*]

Heliocentrism as a verifiable hypothesis

The next-generation observer, Galileo Galilei (cf. L9), could have realized that geocentric system is incorrect, had he paid more attention to De Revolutionibus, in particular to the periodic brightening of Mars. Alas, Galileo probably never read De Revolutionibus carefully, since he did not leave any remarks (corrections of printing errors, comments) on his own copy, which was the norm among scholars. Such commentaries are now studied separately by historians of science.

Instead of following his brightness-related reasoning, Kopernik's followers and detractors got involved in arguments about positional astronomy for more than a century. Even now, most specialist claim that the destruction of the Ptolemaic world had to wait for 100+ years until better *positional* accuracy was enabled by heliocentric model. I would argue that the Copernican revolution could have been completed already by Galileo.