

The Copernican Revolution

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Outline

- the Aristotelian Universe
- Copernicus: change perspective
- Brahe: accurate measurements
- Kepler: accurate theory

Main sources

- Albert van Helden, Jan Hogendijk, 2006, Lectures in course History of Astronomy
- Arthur Koestler, *The Sleepwalkers* 1959
- Albert van Helden, *Measuring the Universe. Cosmic dimensions from Aristarchus to Halley* 1985, University of Chicago Press

The Aristotelian Universe

The universe according to Aristoteles

- finite
- spherical
- a *plenum* (=full)
- based on spaces
- two regions

Finite

- the Universe contains everything; there is nothing outside
- Christian thinkers add a Heaven where God resides

Spherical

- the Earth is spherical
- celestial objects return to the same place: placed on spheres

Apianus 1529



The Aristotelian Universe

Plenum

- there are no empty places in the Universe
- planets and stars attached to material spheres and shells that fill all space

Spaces

- Earth 'naturally' in center
- heavy objects naturally move downward
- fire moves upward
- hierarchy of elements/spaces

Two regions

sublunar (below the Moon)

- earth, water, air, fire
- changing: corrupt
- natural motion straight up or down

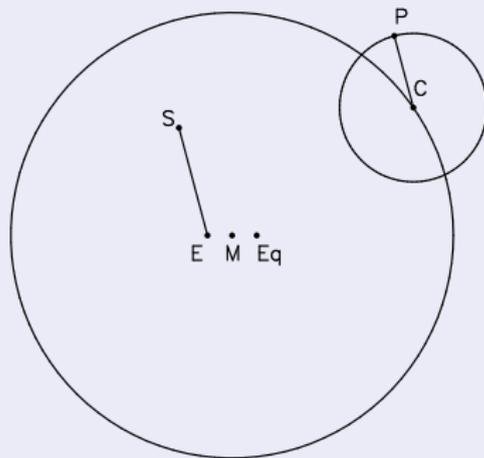
supralunar (above the Moon)

- the fifth element (quintessens, aether)
 - unchanging: perfect
 - natural movement in circles
- ⇒ the laws of nature are different in supralunar and sublunar regions

Planetary theory

- planet P on epicycle
- center C of epicycle moves on circle centered on M: 'excentric'
- motion C uniform with respect to equant Eq ('= cheating')
- direction CP parallel to direction Earth-Sun ES
- (why?)

Position of outer planet

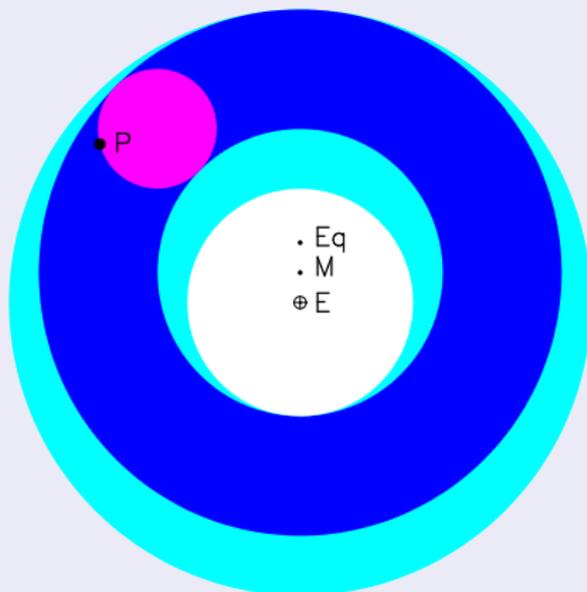


mathematics: computational rules
'algorithm'

Planetary theory

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Planetary Hypothesis



physics: filled spheres and shells

Two separate disciplines

'Physics'

- cosmology is part of philosophy of nature
- it describes the Universe in a coherent way
- based on Aristotelian physics as described above
- taught at universities
- precise position of planets less important
- usually represented in simplified manner

Fundamental to understanding of Universe

'Mathematics'

- use Ptolemaean models to compute positions of planets
- separately for each planet
- physical / philosophical background less important
- accuracy important because of astrological impact
- astrologers also outside universities
- requires revision of Ptolemaean parameters

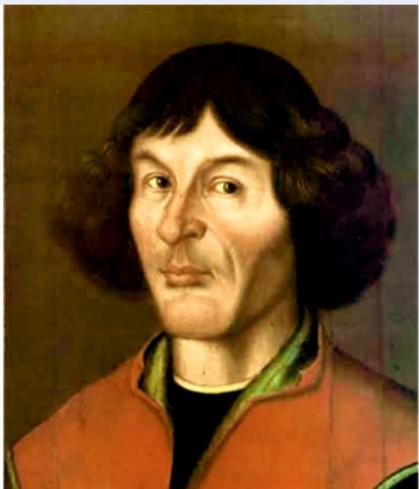
Just computational tricks to get positions right

Back to the sources: redo Ptolemaios

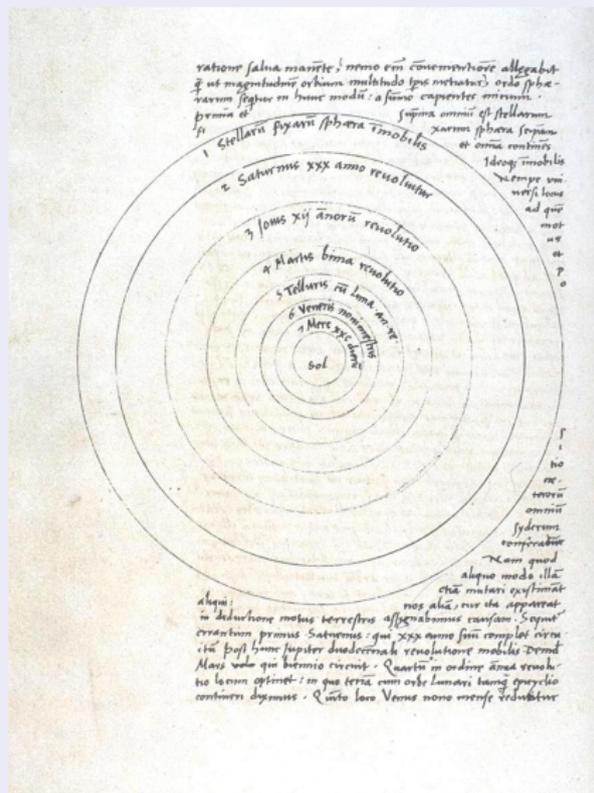
Germany in the 15th century

- Greek manuscripts available
- mathematics at required level
- Regiomontanus: Epitome in Ptolemoei Almagestum (1496)

Nicolaus Copernicus



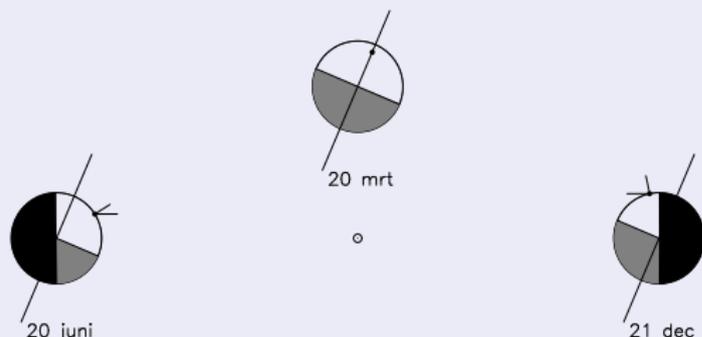
De Revolutionibus Manuscript



The Copernican revolution: Copernicus 1473-1543

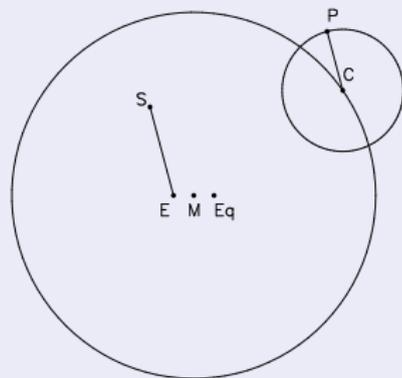
The three motions of the Earth

- 1 rotation around its own axis in 24 h
- 2 revolution around the Sun in 1 y
- 3 motion of Earth axis on cone in 1 y



the 3rd motion is necessary to keep Earth axis in fixed direction, when it is fixed on a rotating sphere

An important simplification



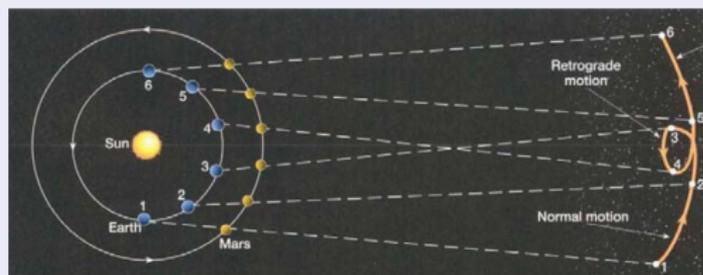
In Ptolemaios the direction Earth-Sun (ES) is required for every planet: $CP // ES$
In Copernicus the position of the planet does not depend on the position of the Earth

The Copernican revolution: major gains

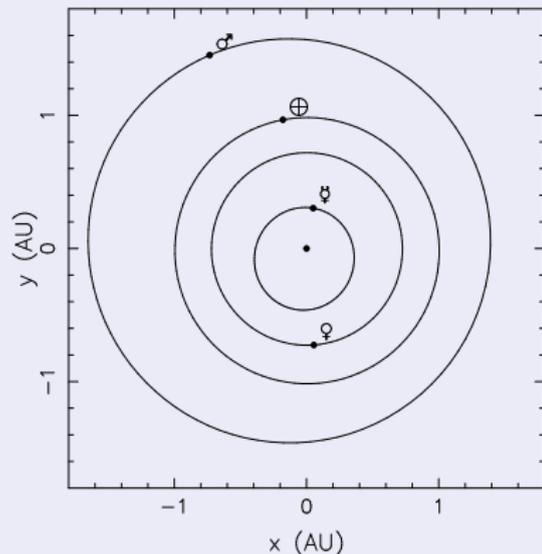
Explanation retrograde motion

As Earth overtakes outer planet, the latter appears to change the direction of its motion

Example: Mars



Angular proximity of Venus and Mercury to Sun



The Copernican revolution: other gains; problems

Other gains

- order of planets uniquely determined
- the largest object (Sun) is in the centre (argument of Aristarchos !)
- newly determined orbital parameters lead to better positions of planets

Note: (Viktor Blåsjö 2016)

Method for describing Mercury
not copied from Nasīr al-Dīn
al-Tūsī (b.1201)

Remaining problem

- large number of epicycles
(extra ones to replace equant)

Added problems

- no measureable motion of the stars
- physics of Aristotle destroyed, but no replacement with new physics
 - ▶ why don't we feel the motion(s) of the Earth?

How to judge Copernicus? Koestler vs. Gingerich

De revolutionibus orbium coelestium 1543

- posthumously
- introduction by Osiander:
'mathematics, not physics'

Arthur Koestler 1959: The sleepwalkers

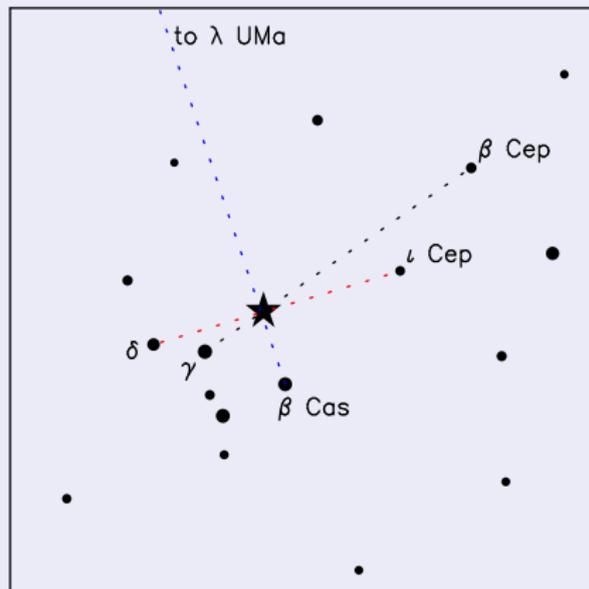
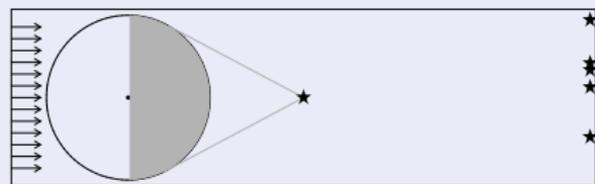
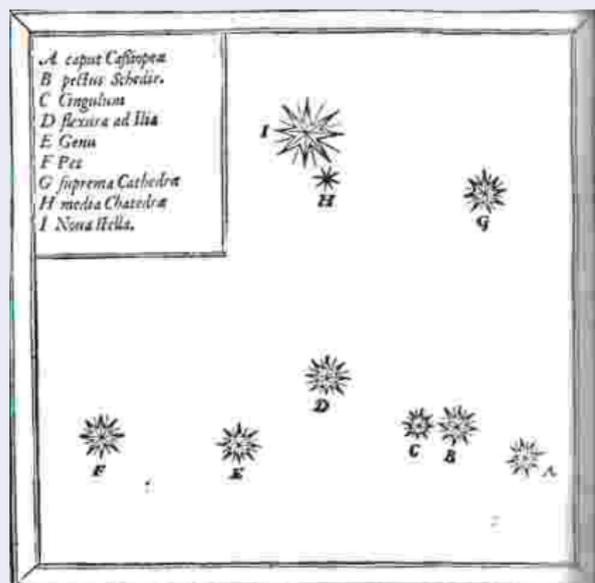
- Copernicus is conservative
- retains mishmash of
epicycles
- De revolutionibus: *The book
that nobody read*

Owen Gingerich 2004: The book that nobody read

- investigates all remaining
copies of 1st and 2nd edition
- passages forbidden by
Inquisition only deleted in
Italy (!)
- many annotations, in
technical part of book
- book widely read

FV: but *not* the chapter on
heliocentrism. . .

Exit Aristoteles: Brahe and the new star of 1572



No daily parallax: supralunar \Rightarrow
supralunar is variable

(Same conclusion for comet of 1577)

Accurate measurements: Tycho Brahe 1546-1601

Developments in Europe

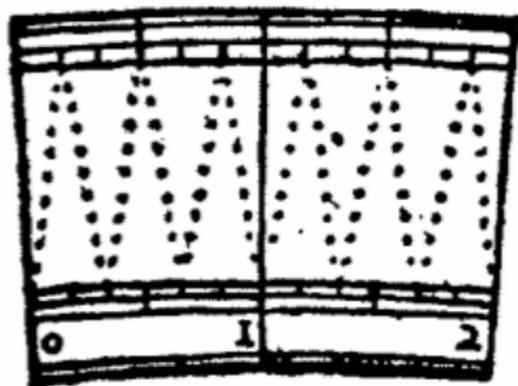
- improved metal technique
- book printing

Tycho Brahe

- astronomical Tables for planets can be wrong by a month
- problem for astrology. . .
- new, accurate measurements necessary
 - special observatory
 - special instruments
- taught by Wilhelm IV, Landgraf of Hessen (1575)



Accurate measurements: Tycho Brahe 1546-1601



- emphasis on accuracy
- own printing press
- training-centre, e.g. Joan Blaeu
- *Astronomia Instaurata* 1602

Observational material

- Brahe determined many planetary positions
- very high accuracy: 2'
- hired Kepler for mathematical analysis
- both in Prague: 1600-1601
- Brahe dies in 1601
- his heirs don't want to give Kepler the data
- so he just took the observation notebooks. . .

Accurate theory: Johannes Kepler 1571-1630

Astronomia Nova 1609

- Kepler computes the eccentric circle of the orbit of Mars from four observed oppositions
- these computations fill 900 pages folio, in small print!
- the four oppositions match computation within 2'
- the six other oppositions measured match as well
- two measurements away from opposition deviate by 8'

Astronomia Nova

'But for us, who, by divine kindness were given an accurate observer such as Tycho Brahe, for us it is fitting that we should acknowledge this divine gift and put it to use. . . If I had believed that I could ignore these 8 minutes, I would have patched up my hypothesis accordingly. But since it was not permissible to ignore them, those 8 minutes point the road to a complete reformation of astronomy.'

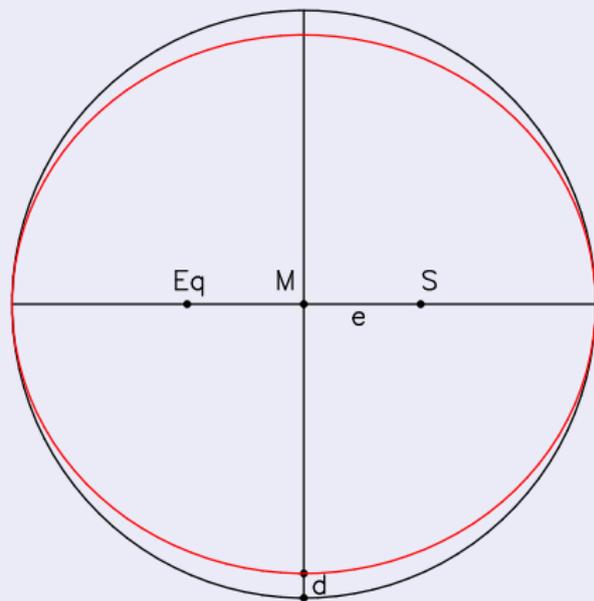
Accurate theory: Johannes Kepler

The orbit of Mars

- use observations from same location of Earth
- assume constant increase of angle from equant
- \Rightarrow orbit of Mars
- not a circle, not an oval...
- distance of Sun to center: 'ex-centricity' 0.0926
- flattening (d in figure): 0.00429
- $0.5 \times 0.0926^2 = 0.00429$

Orbit of Mars is ellipse!

Mathematics of ellipse



$$d = 1 - \sqrt{1 - e^2} \approx \frac{e^2}{2}$$

Johannes Kepler



1610

Astronomia Nova

'Ye physicists, prick your ears! for now we are going to invade your territory.'

The Sun sweeps the planets forward in their orbits with a force, that diminishes with distance. Hence the velocity diminishes with distance to the Sun.

Mathematics now united with physics.

Accurate theory: Johannes Kepler

The laws of Kepler

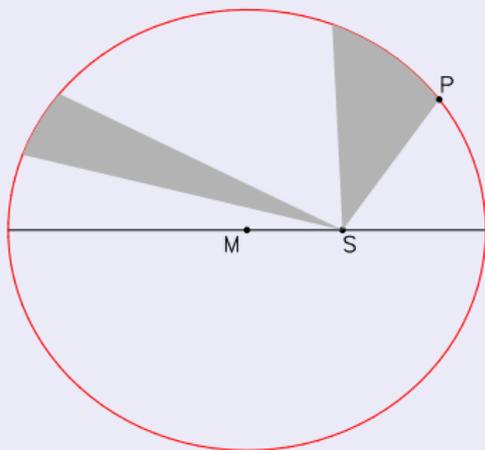
- 1 the orbit of a planet is an ellipse with the Sun in a focal point
- 2 the radius sweeps equal surfaces in equal times
- 3 the orbital period P and semi-major axis a are related

$$P^2 = \text{constant } a^3$$

The true revolution

- Kepler refuses to ignore a non-fitting observation
- he reasons physically: the force of the Sun

The law of equal areas



Conclusions, an opinion, and a book

The Copernican Revolution

The most important step
(Copernicus):

- the Earth is not the center of the Universe
- hence human beings are not central to the Universe

Important for science:

- measurements as accurate as technically possible (Brahe)
- theory as accurate as required by measurements (Kepler)

A conclusion and an opinion

Plato and Aristoteles are wholly absent from the story:

- a history of science may safely ignore them

Excellent book

Steven Weinberg (2016)

To explain the world
The discovery of modern science