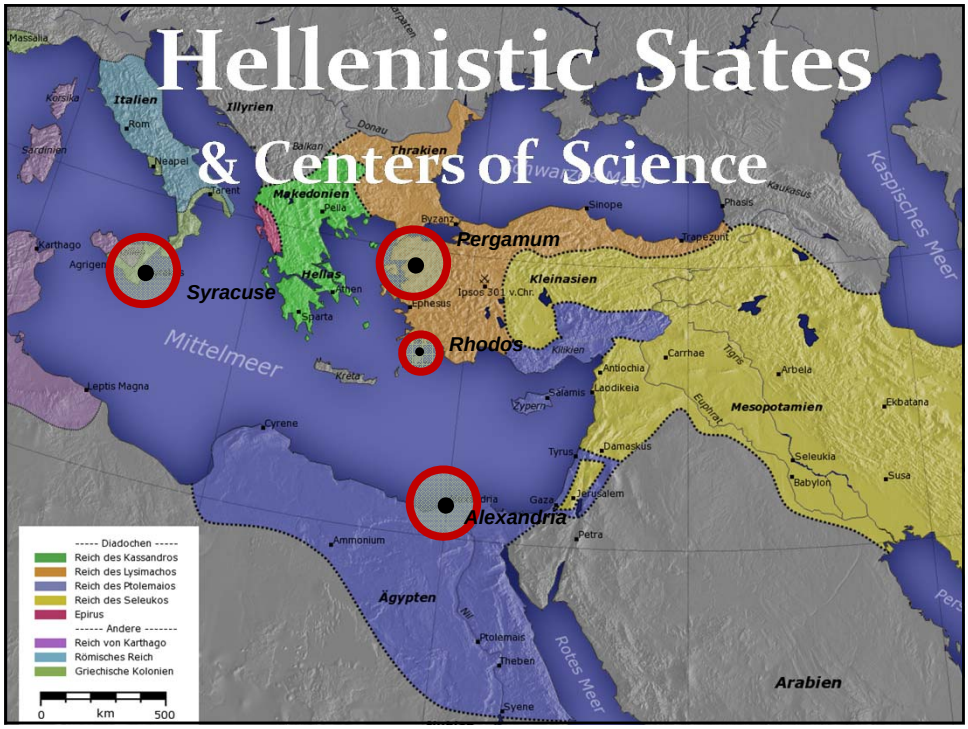

the Universe Mechanized:
Hellenistic Cosmology


the First
Scientific Revolution:
Hellenistic World
© Rien van de Weijgaert
THE EMPIRE OF ALEXANDER
334-323 B.C.
Conquest routes of Alexander
Battle
Siege
Town founded by Alexander
Settlement of existing town
Mountain pass
Greek colony
Persian royal road
Alexandria
0
500 km
Mediterranean Sea
Black Sea
Indian Ocean
ARABIA
INDIA


Hellenistic States
& Centers of Science
Syracuse
Pergamum
Rhodos
Alexandria
Mittelmeer
Ägypten
Arabien
Kleinasien
Mesopotamien
Rotes Meer
Kaspisches Meer
----- Diadochen -----
Reich des Kassandros
Reich des Lysimachos
Reich des Ptolemaios
Reich des Seleukos
Epirus
------ Andere -------
Reich von Karthago
Römisches Reich
Griechische Kolonien
0
km
500


Alexandria
Mittelmeer
Ägypten
Arabien
Rotes Meer
----- Diadochen -----
Reich des Kassandros
Reich des Lysimachos
Reich des Ptolemaios
Reich des Seleukos
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Reich von Karthago
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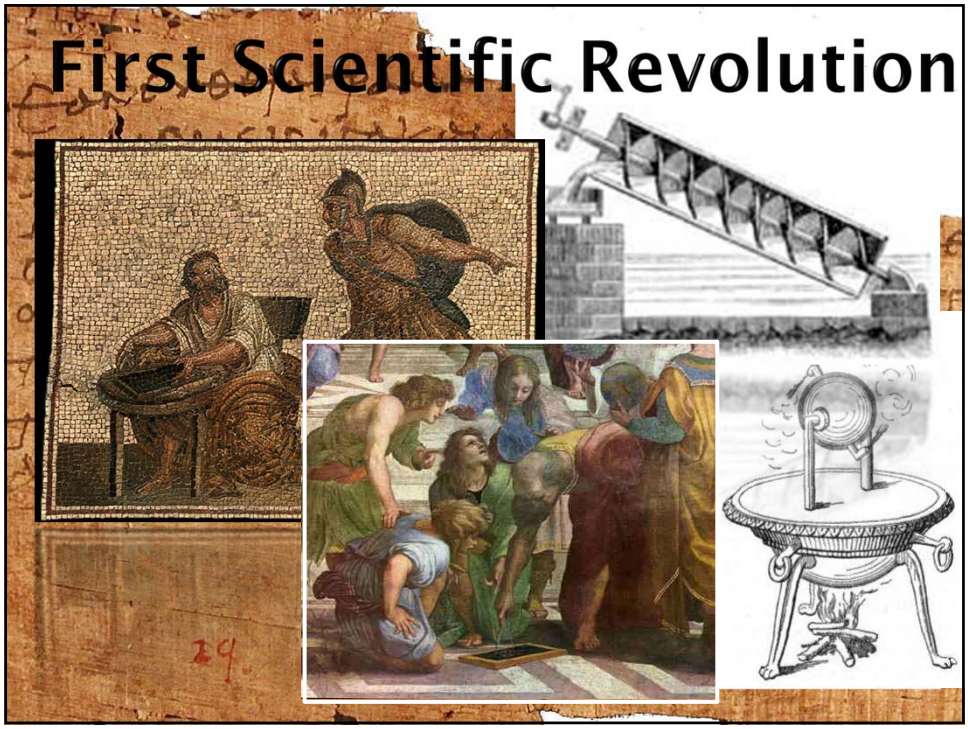
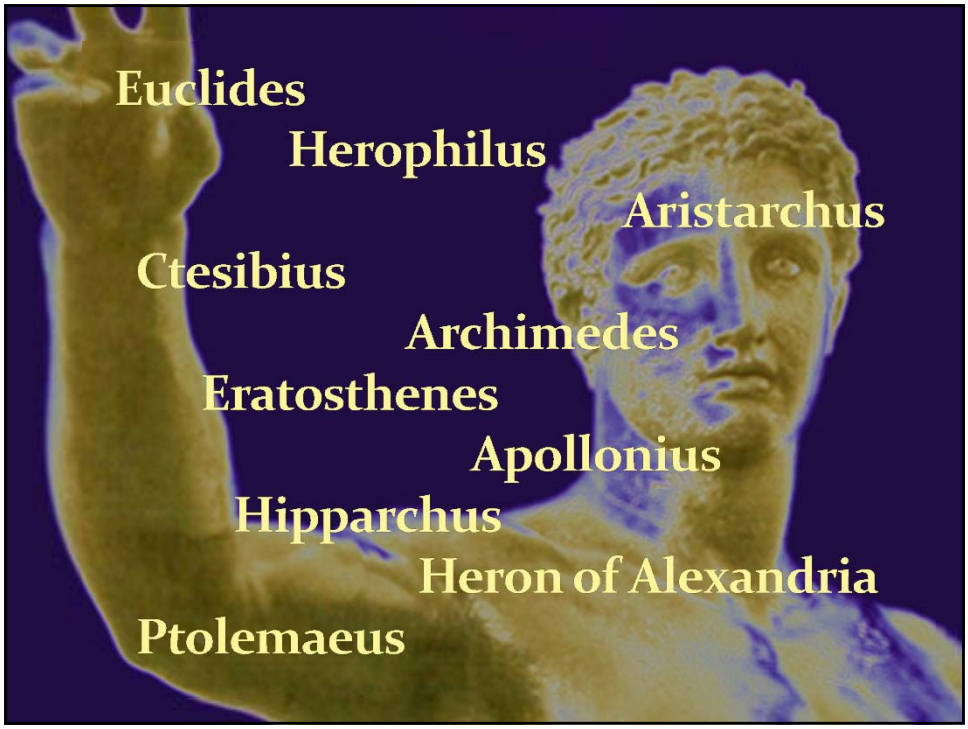
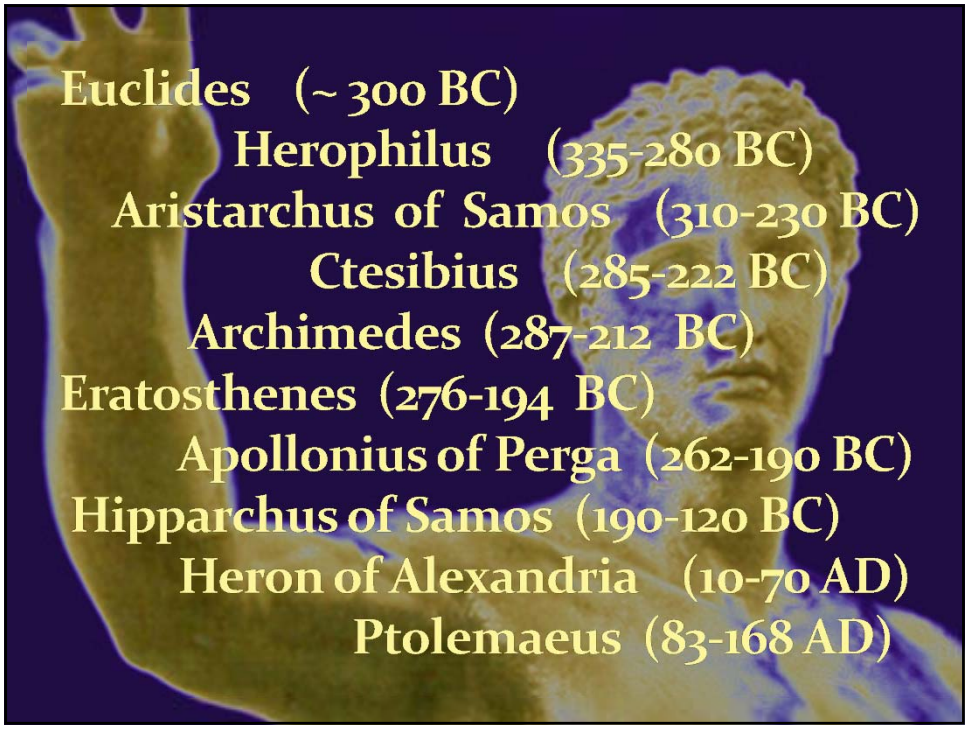
0
km
500


First Scientific Revolution


Euclides
Herophilus
Aristarchus
Ctesibius
Archimedes
Eratosthenes
Apollonius
Hipparchus
Heron of Alexandria
Ptolemaeus


Euclides
Apollonius of Perga
Hipparchus
Heron
Ptolemaeus
Eratosthenes
Archimedes
Aristarchus


Euclides (~ 300 BC)
Herophilus (335-280 BC)
Aristarchus of Samos (310-230 BC)
Ctesibius (285-222 BC)
Archimedes (287-212 BC)
Eratosthenes (276-194 BC)
Apollonius of Perga (262-190 BC)
Hipparchus of Samos (190-120 BC)
Heron of Alexandria (10-70 AD)
Ptolemaeus (83-168 AD)

Hellenistic Astronomers

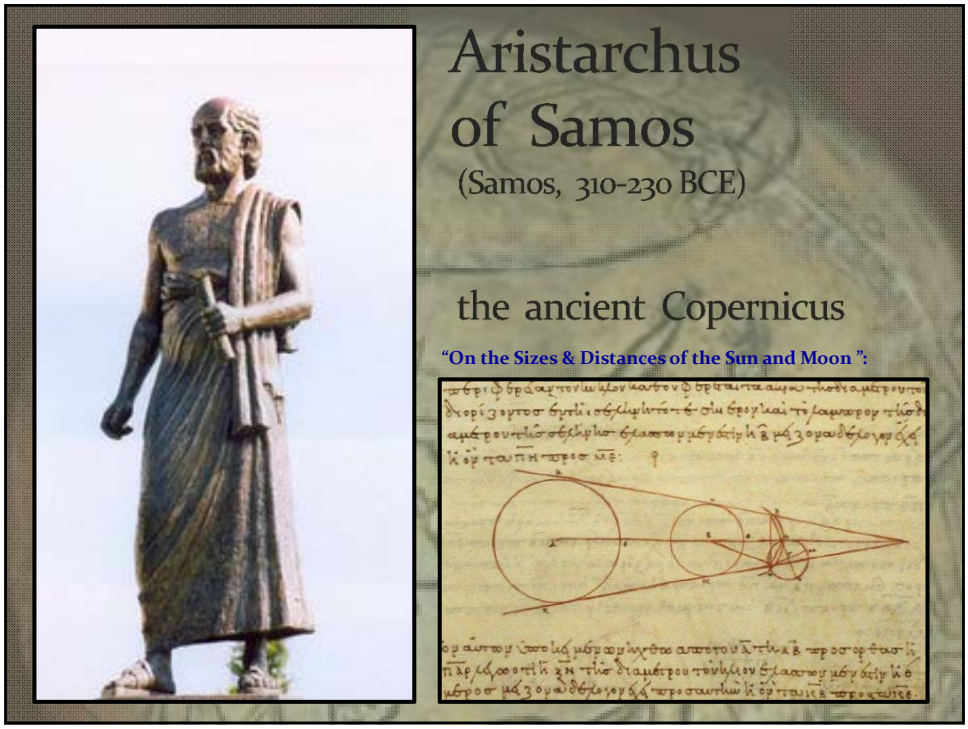
Various astronomers made significant, even amazing, contributions. Noteworthy examples:

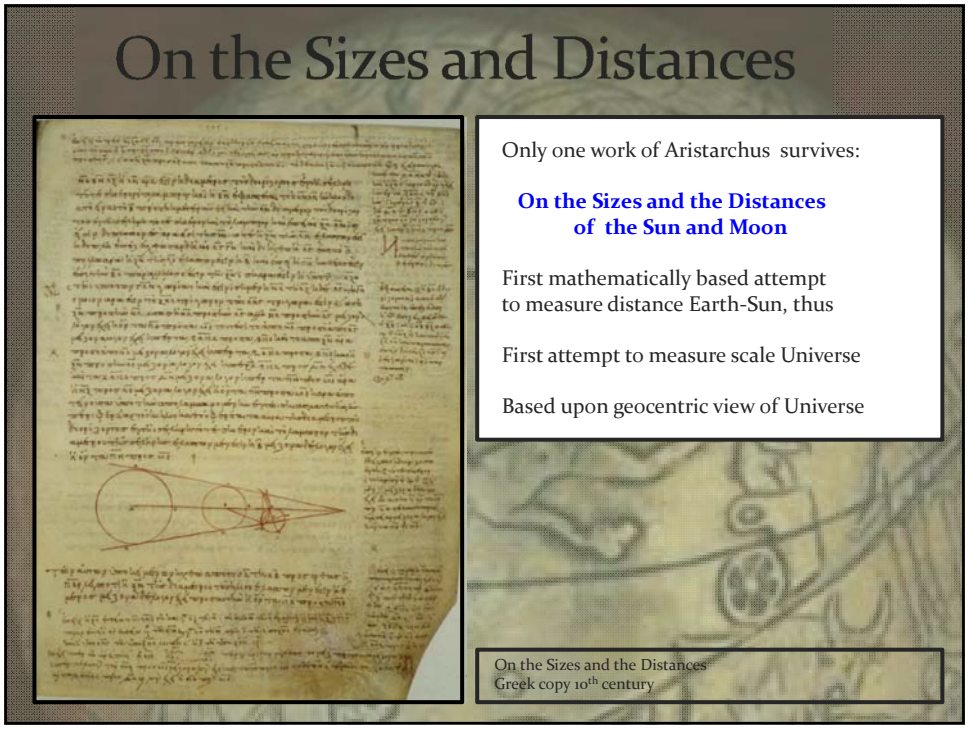
- Aristarchus of Samos - Heliocentric Universe
  - distance Moon & Sun
  - size Sun
- Archimedes - Planisphere/Planetarium ?
- Eratosthenes - Diameter Earth
- Hipparchus - multitude essential contributions

Problematic is the loss of nearly all, except for a few, of the books and works they have written …

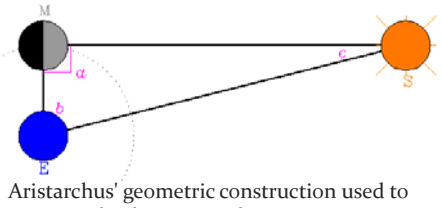
Aristarchus of Samos
Ἀρίσταρχος

310-230 BCE


Aristarchus
of Samos
(Samos, 310-230 BCE)
the ancient Copernicus
"On the Sizes & Distances of the Sun and Moon ":


On the Sizes and Distances
Only one work of Aristarchus survives:
On the Sizes and the Distances
of the Sun and Moon
First mathematically based attempt
to measure distance Earth-Sun, thus
First attempt to measure scale Universe
Based upon geocentric view of Universe
On the Sizes and the Distances
Greek copy 10th century

On the Sizes and Distances



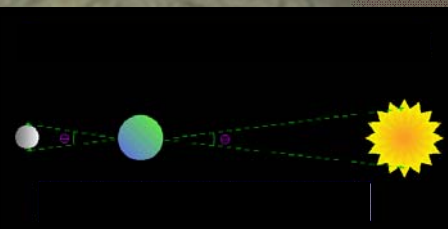
Aristarchus' geometric construction used to estimate the distance to the Sun.
Earth (E) –Sun (S)-Moon (M) triangle and sizes are not drawn to scale.

Measure angle b:
c = 90°-b EM/ES = sin(c)

Aristarchus:
b = 87° real value: b = 89°50
ES = 19 EM real value: ES = 397 EM
Numerically, very unstable procedure, reason for huge error. Nonetheless,

On the Sizes and the Distances
Greek copy 10th century

On the Sizes and Distances



Aristarchus' estimate of size Sun:

angular diameter Sun ~
angular diameter Moon

Dist. Earth-Sun = 19 Dist. Earth-Moon

→ size Sun = 19 x size Moon

→ size Sun > size Earth

On the Sizes and the Distances
Greek copy 10th century

Aristarchus: Heliocentric Universe

Archimedes, "the Sand Reckoner" (~200 BCE):

You King Gelon are aware the 'universe' is the name given by most astronomers to the sphere the center of which is the center of the Earth, while its radius is equal to the straight line between the center of the Sun and the center of the Earth. This is the common account as you have heard from astronomers.

But Aristarchus has brought out a book consisting of certain hypotheses, wherein it appears, as a consequence of the assumptions made, that the universe is many times greater than the 'universe' just mentioned.

His hypotheses are that the fixed stars and the Sun remain unmoved, that

the Earth revolves about the Sun

on 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 the circle in which he supposes the Earth to revolve bears such a proportion to the distance of the fixed stars as the center of the sphere bears to its surface.

Aristarchus: Heliocentric Universe

Aristarchus' idea of Heliocentric Universe encountered sceptical, even hostile, reactions:

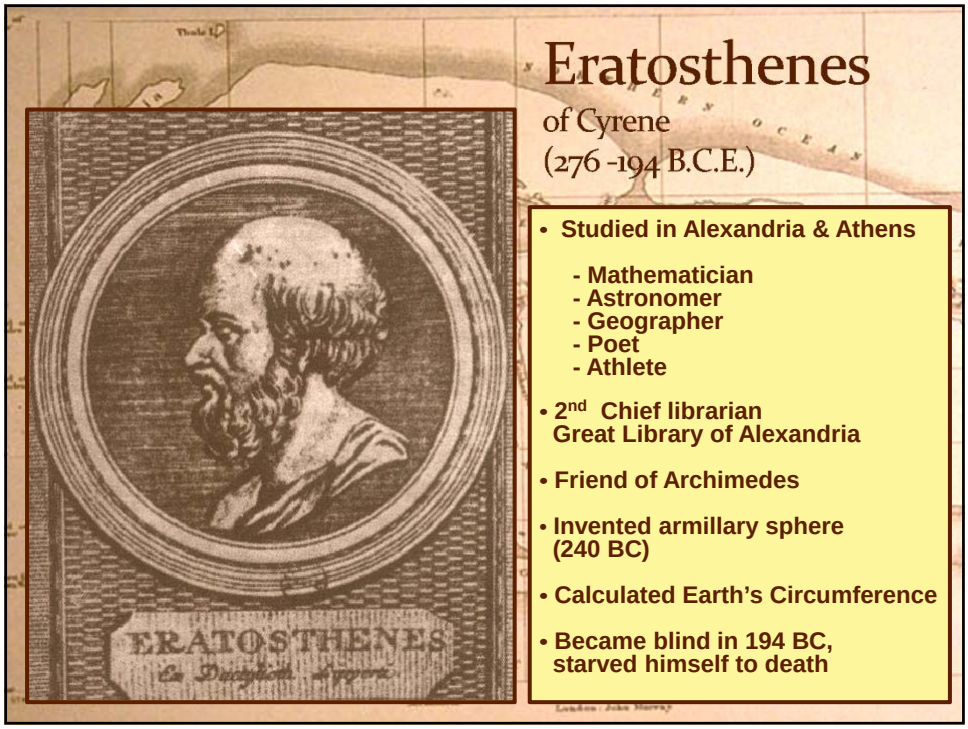
- Could not explain the absence of parallax of fixed stars (or they should be very, very far away …)
- Impiety … (even for those "rational" Greeks …)

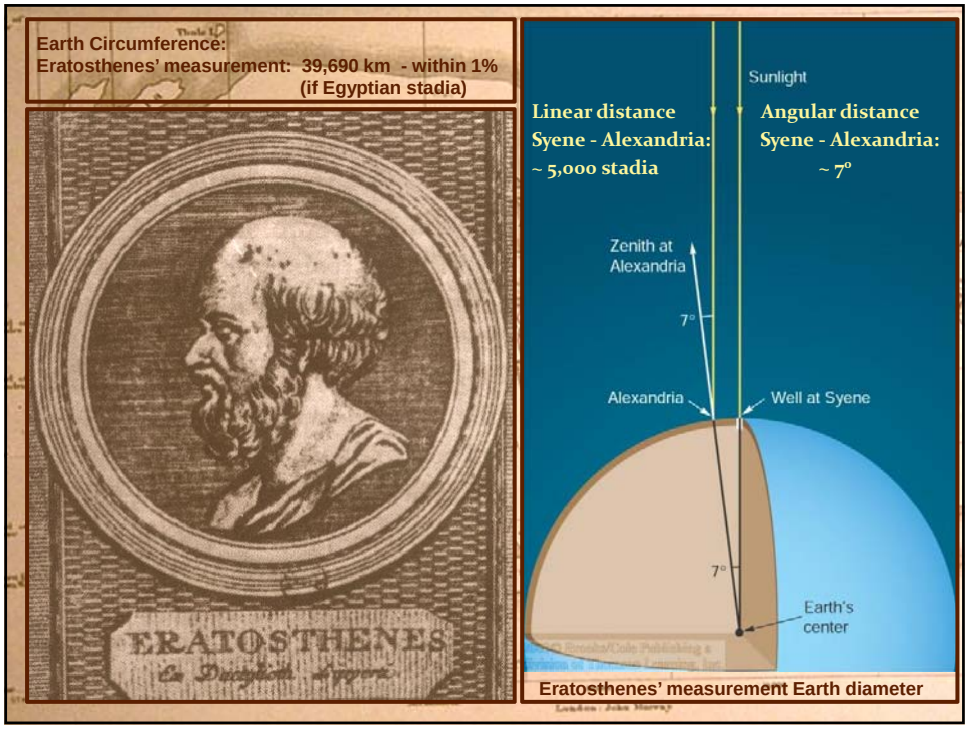
"Cleanthes thought it was the duty of the Greeks to indict Aristarchus of Samos on the charge of impiety for putting in motion the Hearth of the universe [i.e. the earth], . . . supposing the heaven to remain at rest and the earth to revolve in an oblique circle, while it rotates, at the same time, about its own axis"

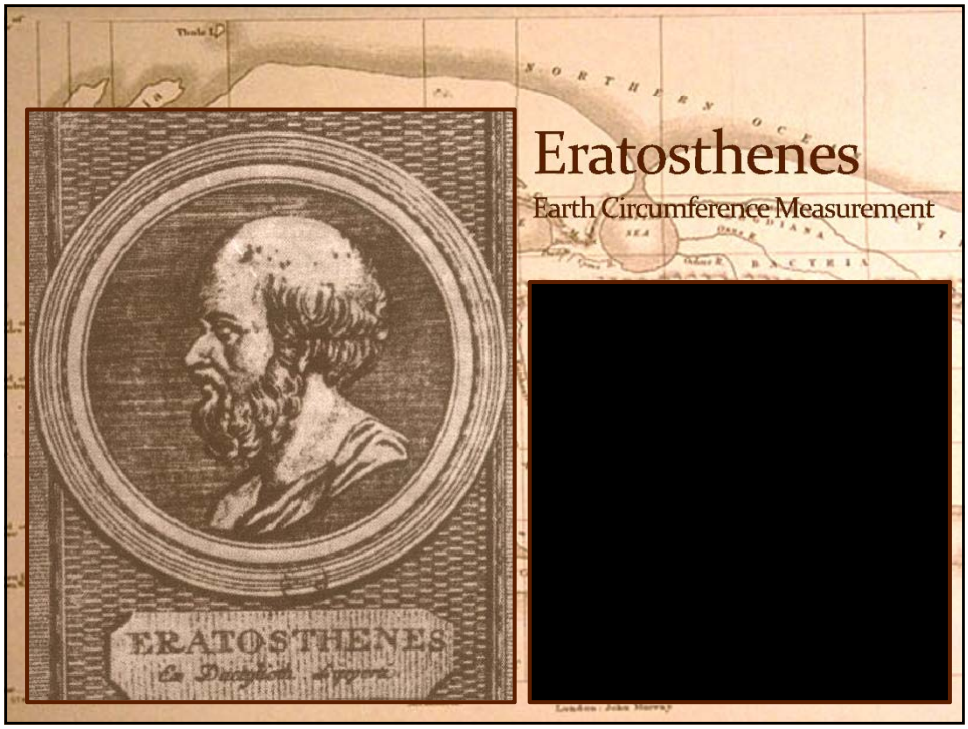
Plutarchus, "On the Apparent Face in the Orb of the Moon"

Eratosthenes of Cyrene
Ἐρατοσθένης

276 BC - 194 BC




Earth Circumference:
Eratosthenes' measurement: 39,690 km - within 1%
(if Egyptian stadia)
ERATOSTHENES
Sunlight
Linear distance
Syene - Alexandria:
~ 5,000 stadia
Angular distance
Syene - Alexandria:
~ 7°
Zenith at
Alexandria
7°
Alexandria
Well at Syene
7°
Earth's
center
Eratosthenes' measurement Earth diameter


ERATOSTHENES
Eratosthenes
Earth Circumference Measurement

Archimedes of Syracuse

Αρχιμηδης

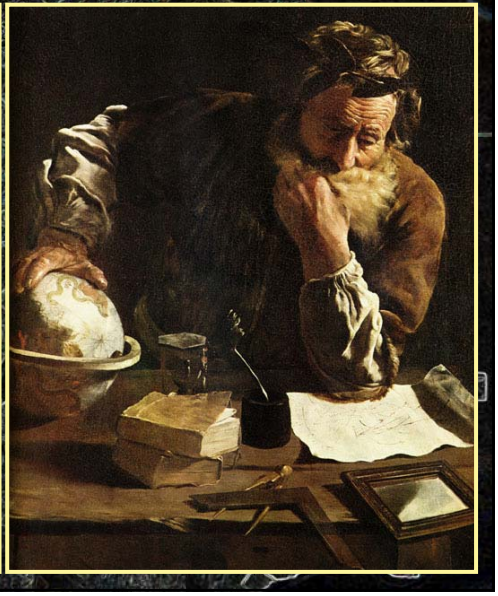
c. 287 – 212 BCE

Archimedes

Syracuse, 287-211/212 BC,
Greatest mathematician & scientist of antiquity (all time ?):

- Probably studied in Alexandria, under followers Euclides
- Killed by Roman soldier, upon Roman conquest Syracuse
- Family Hieron II, king Syracuse ?

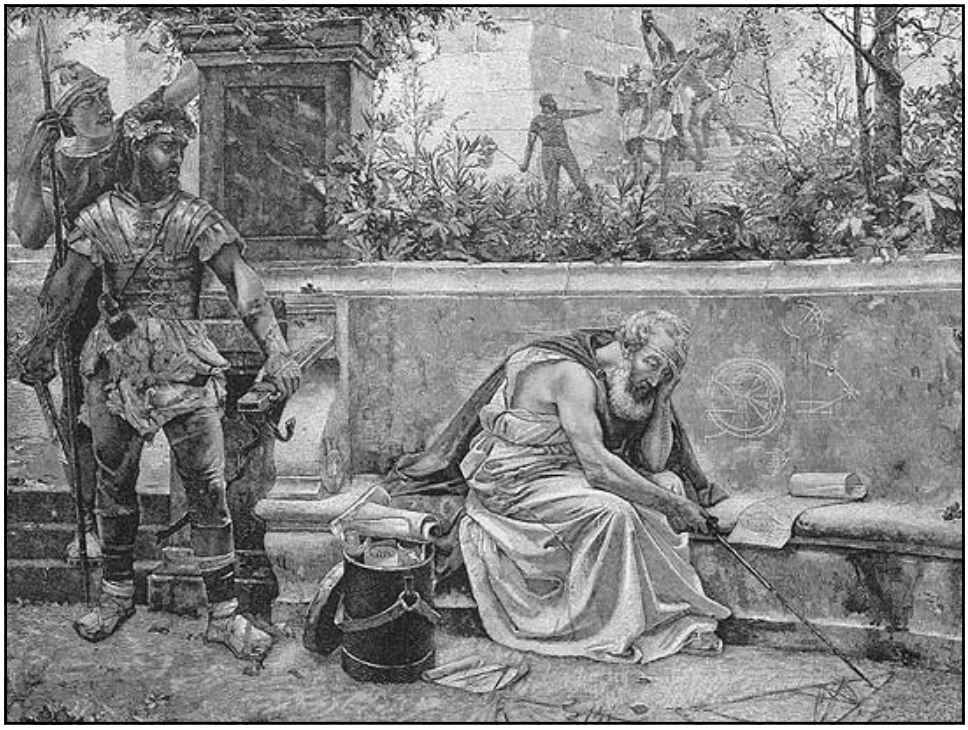
- Inventions:
  - war machines ...
  - water screw
  - water organ (?)
  - burning mirrors (???)
  - planetarium !!!!!!



Cicero mentions two planetarium like machines…

"For when Archimedes fastened on a globe the movements of moon, sun and five wandering stars, he, just like Plato's God who built the world in the "Timaeus", made one revolution of the sphere control several movements utterly unlike in slowness and speed. Now if in this world of ours phenomena cannot take place without the act of God, neither could Archimedes have reproduced the same movements upon a globe without divine genius"

Cicero, Tusculan Disputations, Book I, Section XXV



Archimedes

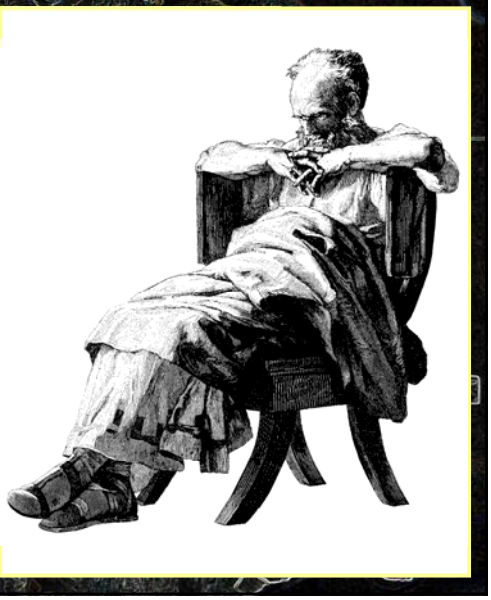
- Pappus of Alexandria: Archimedes wrote book "On Sphere-Making"

  … is this Antikythera … ?

- Compare with

  Archimedes Palimpsest: … "On the Method" …

  Fundamentals Calculus, Integral calculus …



Hipparcus

Ιπαρχος

c. 190 – 120 BCE

Hipparchus of Nicaea (190-120 BC)

Antiquities' Greatest Astronomer

Responsible for the true Revolution in Astronomy

Synthesis of
Babylonian Observational Astronomy
Greek Theoretical/Geometric Models
Astronomy as true Modern Science:
Experiment & Theory

Hipparcus

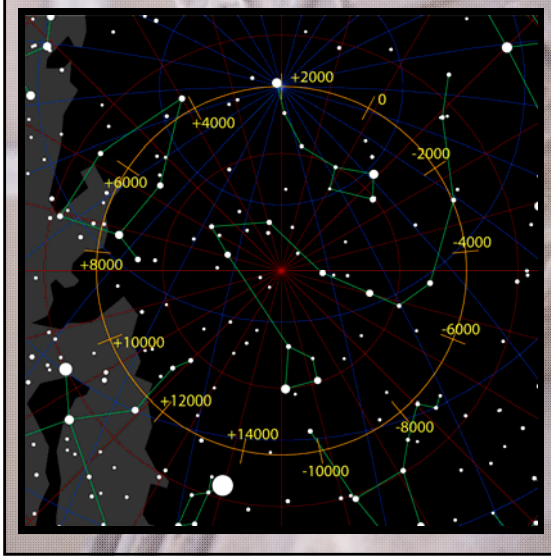
(Nicaea-Rhodos 190-120 BCE)

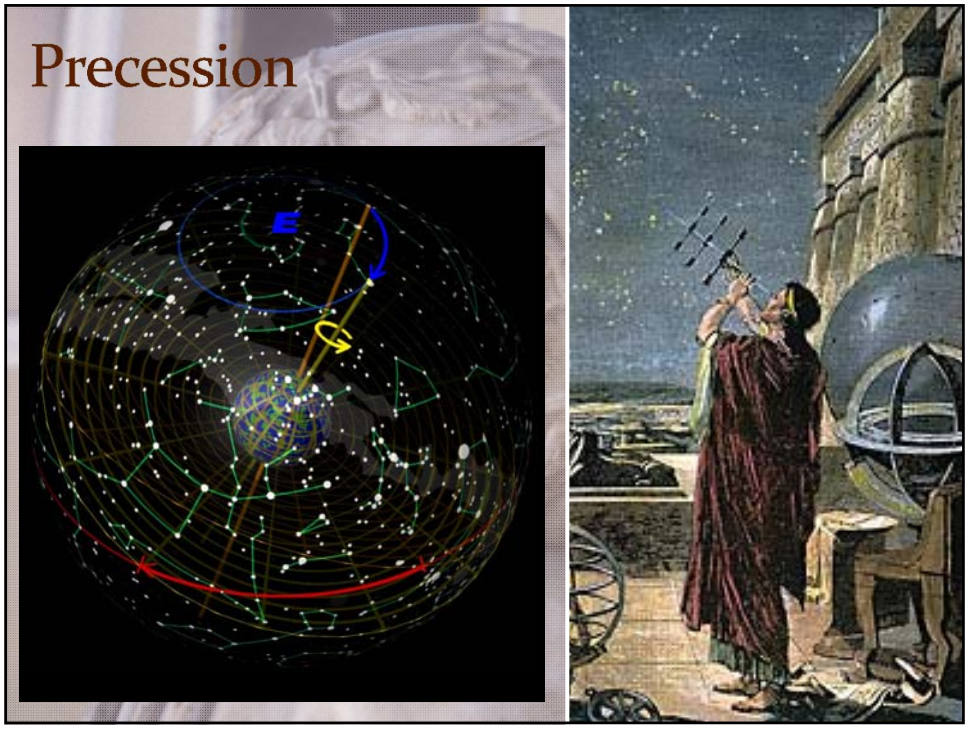
Greatest astronomer Greek antiquity

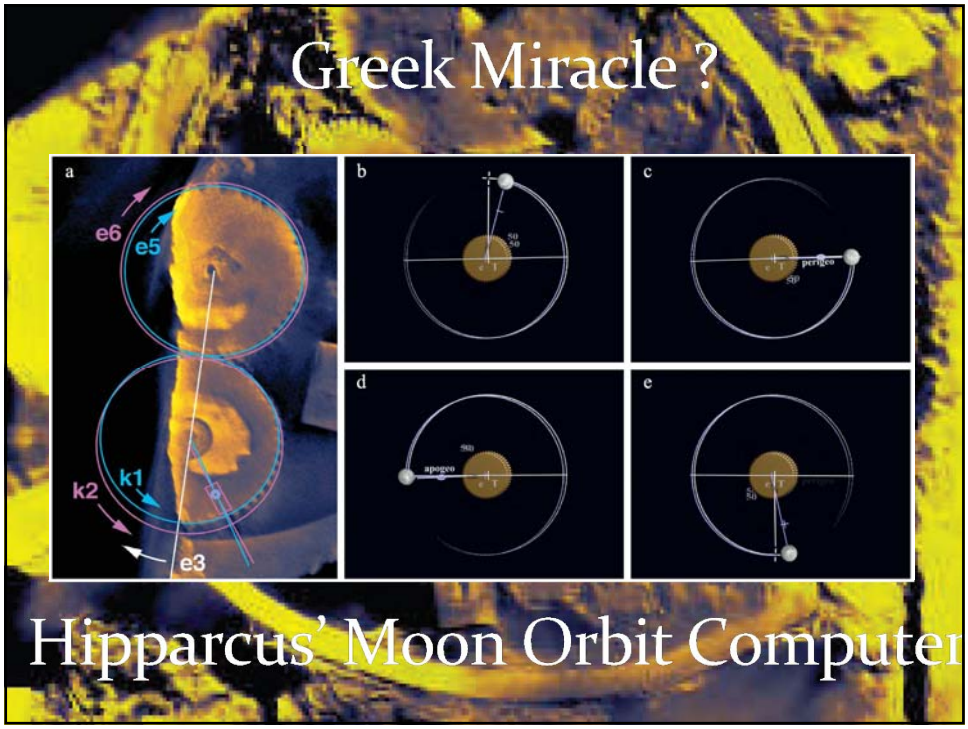
- Trigonometric Tables
- Precession of the Equinoxes
- Motion moon:
  synodic, anomalistic, ... month
- Solar & Lunar eclipses
- Orbit of the Moon:
  epicyclic theory
- Distance Moon
- Star catalogue & Celestial Globe
  Lost, yet ... Farnese Atlas ?
- Defined Magnitude Scale
- Invented the Astrolabe

Star Magnitudes

Precession




Precession


Greek Miracle ?
a
e6
e5
k2
k1
e3
b
c
d
e
Hipparcus' Moon Orbit Computer

Farnese Atlas:
Hipparchus star catalog ?

Farnese Atlas is the oldest surviving pictorial Record of Western constellations

Roman times ~ A.D. 150,
presumed to represent constellations mapped in earlier Greek work

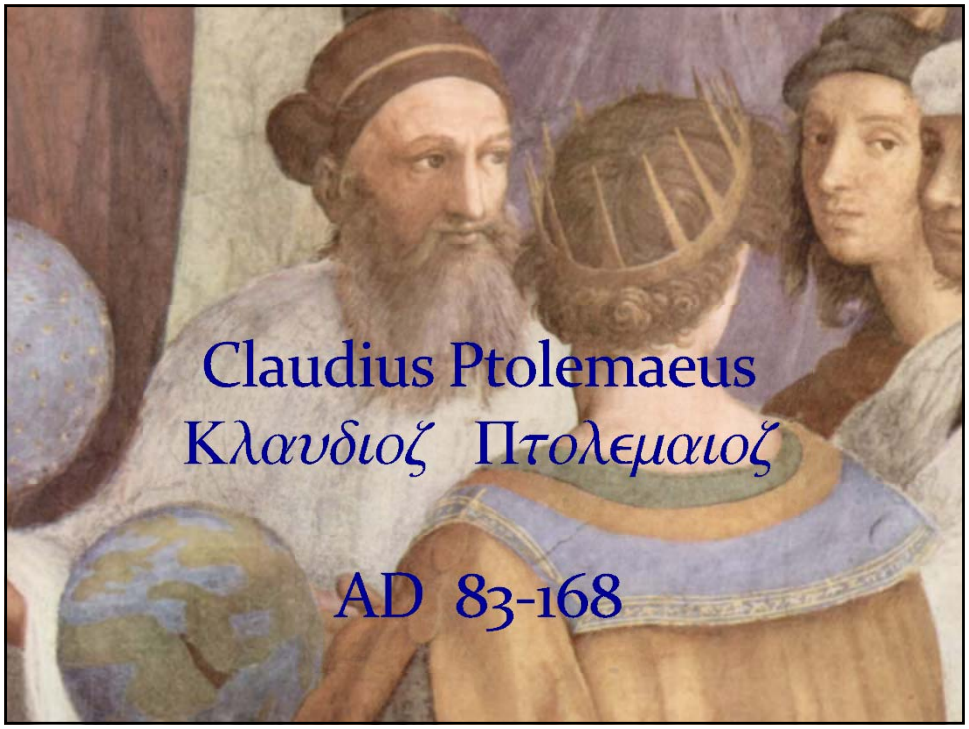
Atlas labors under the weight because he had been sentenced by Zeus to hold up the sky.

The globe shows:
- a depiction of the night sky as seen from outside the outermost celestial sphere
- low reliefs depicting 41 (42) of the 48 classical Greek constellations including:
  - Aries the ram
  - Cygnus the swan
  - Hercules

Claudius Ptolemaeus

Κλαυδιος Πτολεμαιος

AD 83-168



Claudius Ptolemaeus

Thebaid/Ptolemais Hermiou-Alexandria 83-168 A.D.

- Mathematician
- Astronomer
- Geographer
- Astrologer

additional interests in

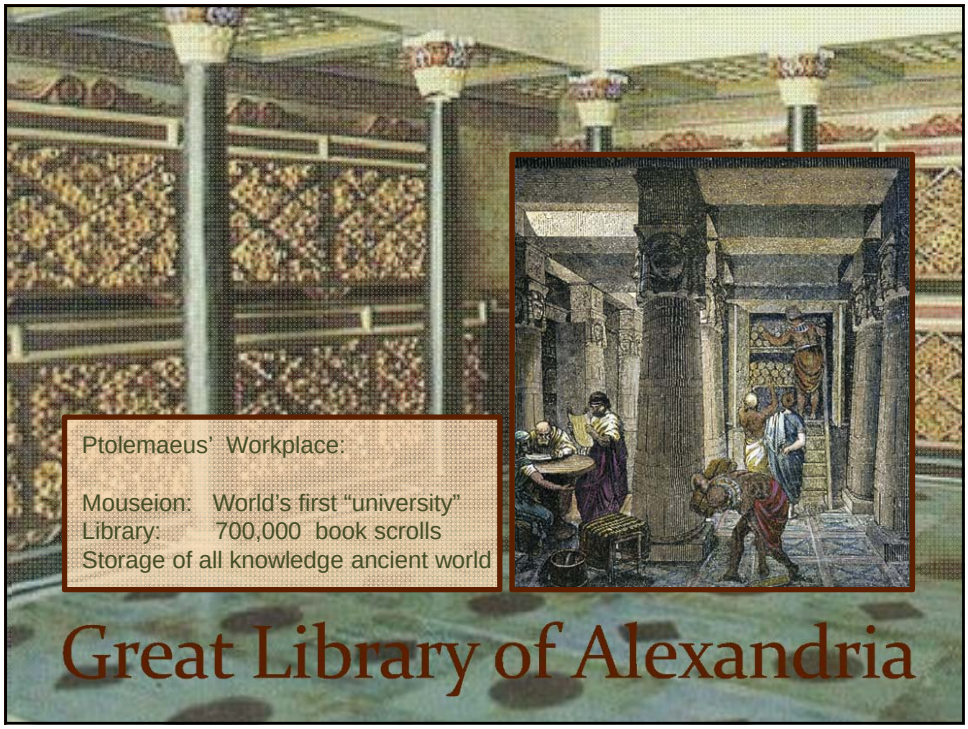
- Optics
- Music
- Philosophy

Claudius Ptolemaeus

Culmination & Synthesis
Hellenistic Astronomy
Geography in Classical World

Lasting and dominant influence,
> 1500 yrs,
European & Islamic science

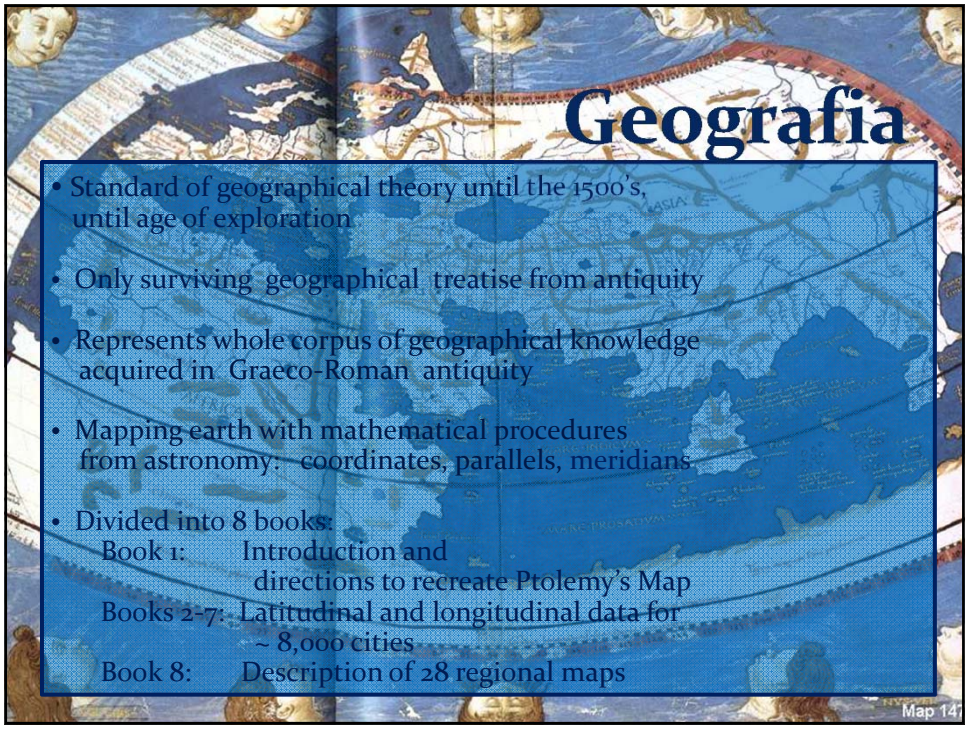

Mouseion: the Library
Alexandria:
Birthplace of the
Western Mind


Ptolemaeus' Workplace:
Mouseion: World's first "university"
Library: 700,000 book scrolls
Storage of all knowledge ancient world
Great Library of Alexandria

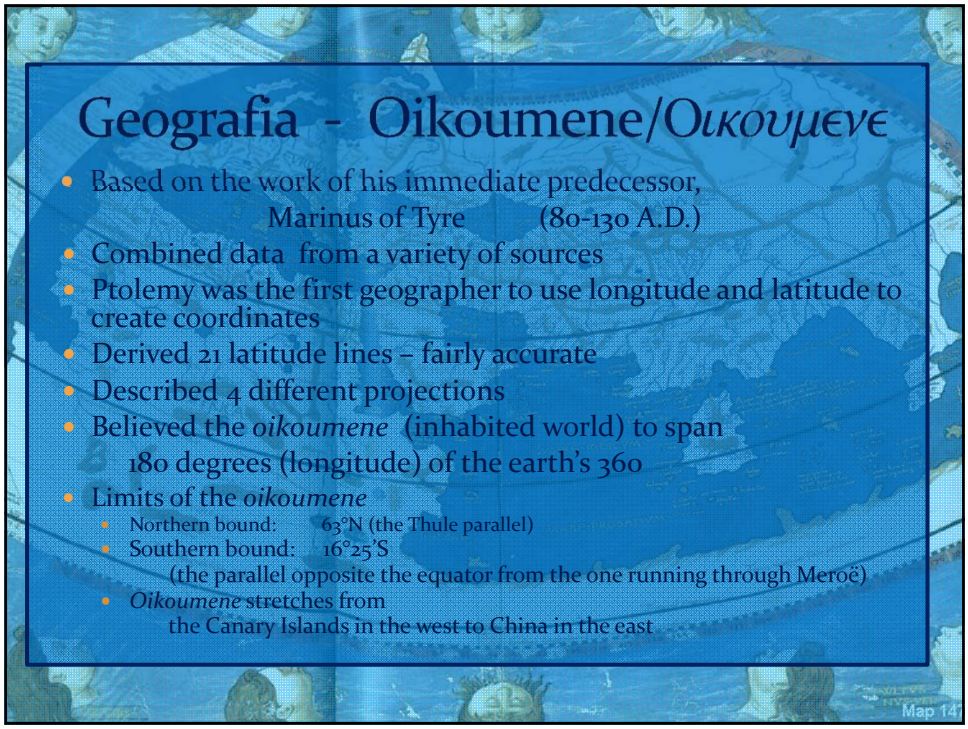
Ptolemy's Bibliography

- *Almagest* (13 books) — astronomy
- *Geography* (8 books) — geography
- *Optics* (5 books) — physics
- *Tetrabiblos* (4 books) — astrology
- *Harmonics* (3 books)
- *Planetary Hypotheses* (2 books) — astronomy
- *Analemma*
- *Canobic Inscription*
- *Planispherium* — astronomy
- Other astronomical works
- Lost works


Geografia
Map 14

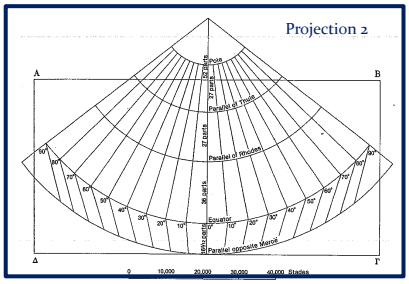

Geografia
• Standard of geographical theory until the 1500's, until age of exploration
• Only surviving geographical treatise from antiquity
• Represents whole corpus of geographical knowledge acquired in Graeco-Roman antiquity
• Mapping earth with mathematical procedures from astronomy: coordinates, parallels, meridians
• Divided into 8 books:
Book 1: Introduction and directions to recreate Ptolemy's Map
Books 2-7: Latitudinal and longitudinal data for ~ 8,000 cities
Book 8: Description of 28 regional maps
Map 14

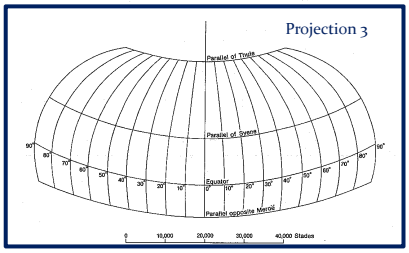

Map of Ancient India:
crucial importance for development Roman trade network with India
Geografia
DESCRIPTIO VNDECIMÆ TABV
GANGETICVS SINVS
INDICVM PELAGVS
MAGNV SINVS
SINÆ
Map 14

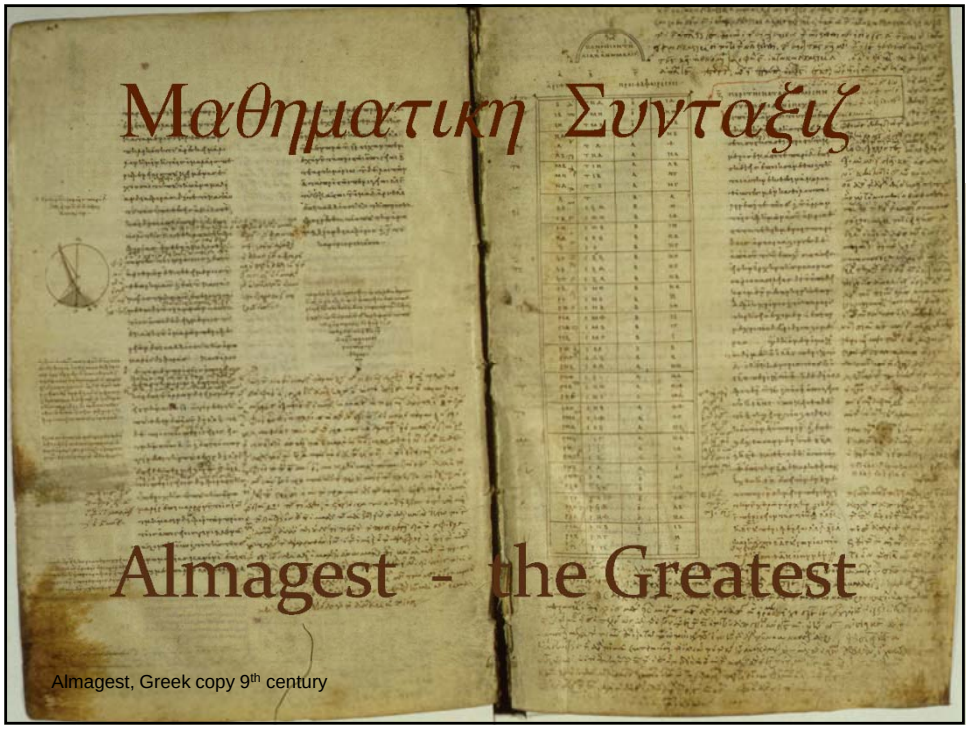

Geografia - Oikoumene/Οικουμενε
Based on the work of his immediate predecessor, Marinus of Tyre (80-130 A.D.)
Combined data from a variety of sources
Ptolemy was the first geographer to use longitude and latitude to create coordinates
Derived 21 latitude lines – fairly accurate
Described 4 different projections
Believed the oikoumene (inhabited world) to span 180 degrees (longitude) of the earth's 360
Limits of the oikoumene
Northern bound: 63°N (the Thule parallel)
Southern bound: 16°25'S (the parallel opposite the equator from the one running through Meroë)
Oikoumene stretches from the Canary Islands in the west to China in the east
Map 14

Geografia: four Map Projections

- Projection 1
  - Straight meridians & Straight parallels
  - Very similar to Marinus' map
- Projection 2
  - Straight meridians & Curved parallels
  - Preferred method of Ptolemy's successors
  - Constant scale in relation to Rhodes parallel
  - 36+1 parallel meridians, each 5 degrees apart
- Projection 3
  - Curved meridians & Straight parallels
  - made extreme parallels more accurate
- Projection 4
  - View of globe from distance
  - External rings represent latitude lines







Almagest, Greek copy 9th century

Μαθηματικη Συνταξις - Almagest


Almagest, Greek copy 13th century

"The Great Book"

Most Important & Influential Astronomical Work of Antiquity

Mathematical and Astronomical treatise proposing the complex motions of stars and planetary paths

Written in 147 / 148 A.D.:
inscription in Canopus, by Ptolemaeus

Thirteen Books

Original in Greek:
Mathematike Syntaxis - Mathematical Treatise
He Megale Syntaxis - "The Great Treatise"

Best known by its Arab name:
Almagest - "The Great Book"

Almagest the Greatest

- One of the most influential scientific works in history

  (along with Euclid's "Elements", Copernicus' "Revolutionibus", Galilei's "Dialogues" Newton's "Principia", Darwin's "Origin of Species")

- One of most influential books of all time

  (perhaps only after Bible, Qur'an, along with Euclid's "Elements", ...)


Almagest
the Greatest
Masterwork technical exposition
Brilliant synthesis
Theoretical Astronomy
Practical Handbook computation Ephemerides


Almagest
the Greatest
Systematic methodology
Observational Data
Numerical parameters planetary models
Construction tables celestial phenomena
(solar, lunar & planetary positions; solar & lunar eclipses, ...)

Almagest the Greatest

- More than any other book, demonstrated

complex phenomena of heavens

⟺

demonstratable & observable regularities

⟺

underlying mathematical description

⟺

predictions celestial events

Implication:

Secrets other aspects of our world
also understandable via underlying regularities

Geocentric Universe

Ptolemaeus' Geocentric Universe is one of the 2 world world systems under discussion in Galileo Galilei's book (1632)

Dialogue Concerning the Two Chief World System

It had to give way to the heliocentric Universe, 1500 yrs after the Almagest

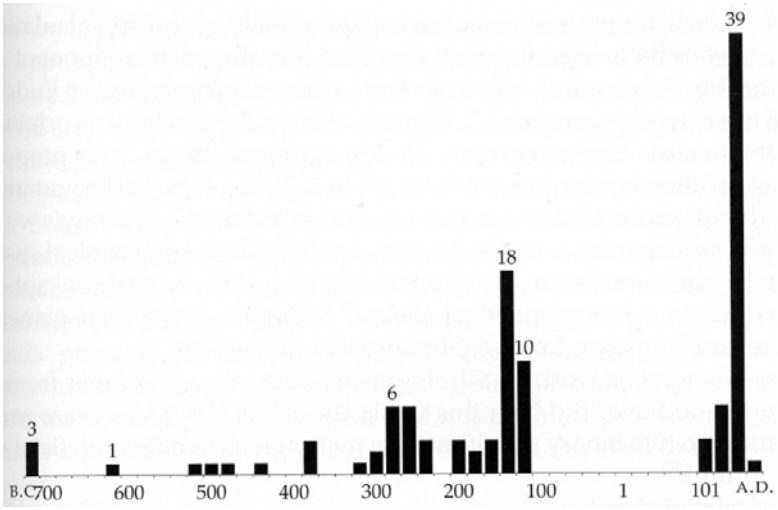
Almagest the Greatest

- Success Almagest:

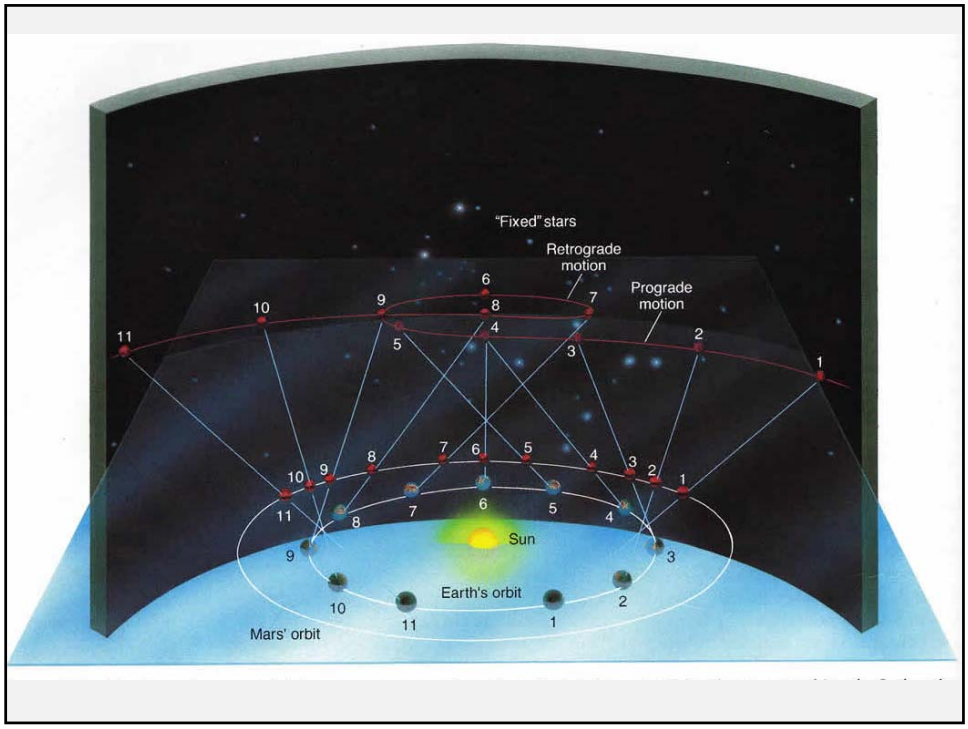
  Loss of most of work scientific predecessors: being obsolete, they ceased to be copied

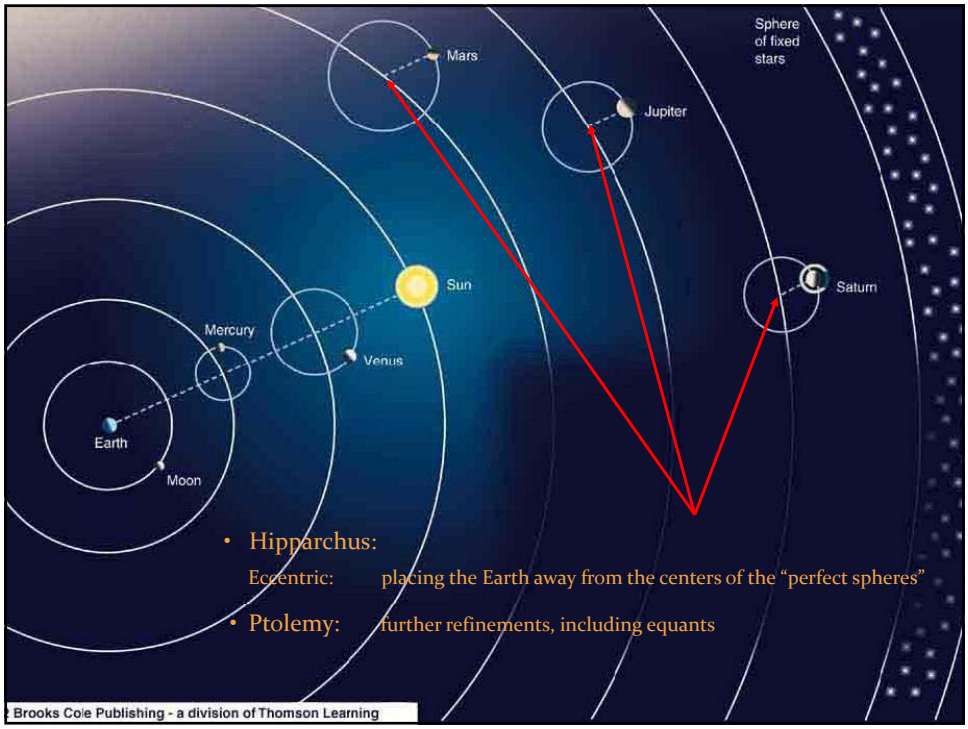
  Is this true ?

Almagest the Greatest



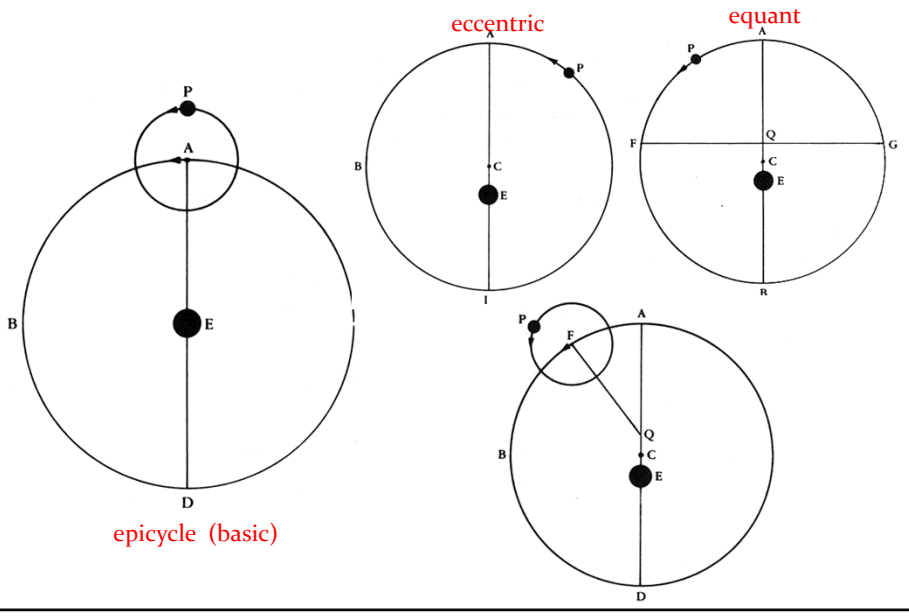
Epicyclic Theory



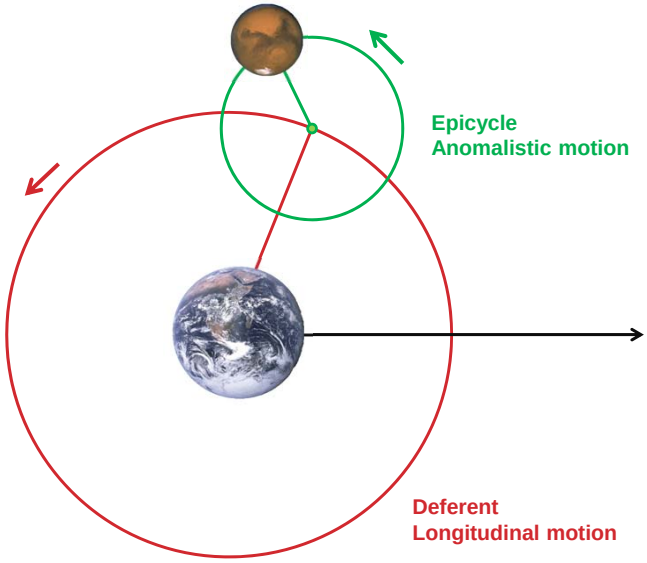


- Hipparchus:
  Eccentric: placing the Earth away from the centers of the "perfect spheres"
- Ptolemy: further refinements, including equants

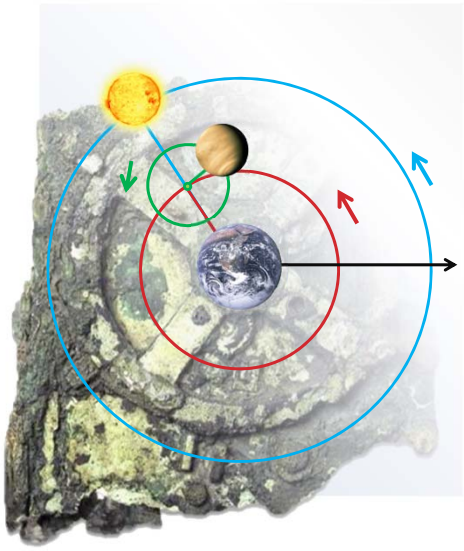
Ptolemaeus Epicycle Theory

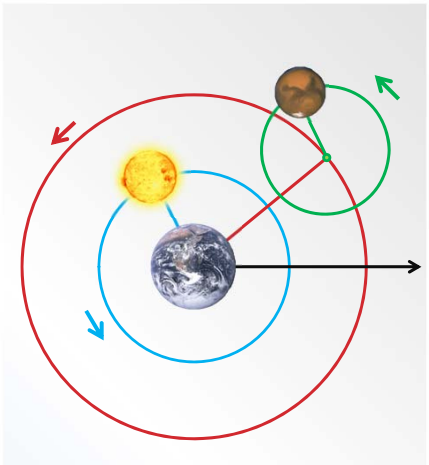


Early geometric planetary models

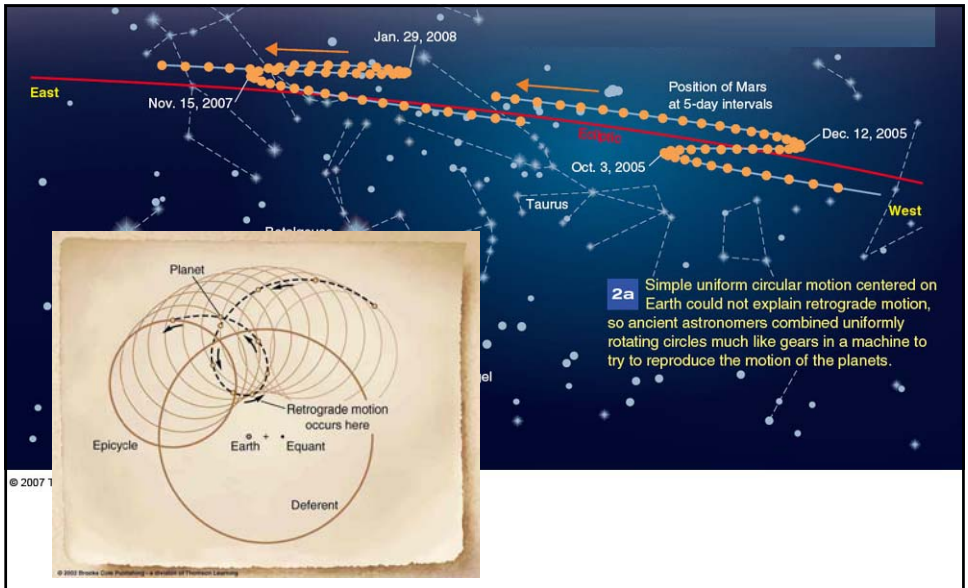


The inferior and superior planets





Period of time = Number of anomalistic periods
+ Number of longitudinal periods

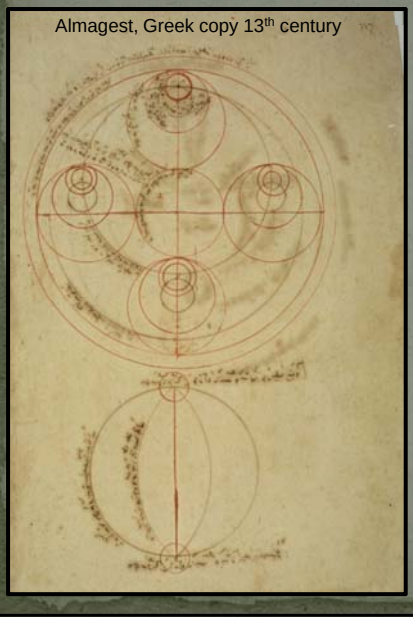


Ptolemaeus Epicycle Theory

Almagest

Η Μεγαλη Συνταξιζ
Μαθηματικη Συνταξιζ

Syntaxis - Almagest


Almagest, Greek copy 13th century

"The Great Book"

most Important & Influential Astronomical Work of Antiquity

Ptolemy first scientist to spell out inductive method:
- models framed from preliminary facts
- expand models by logical induction
- testing hypothesis against reality

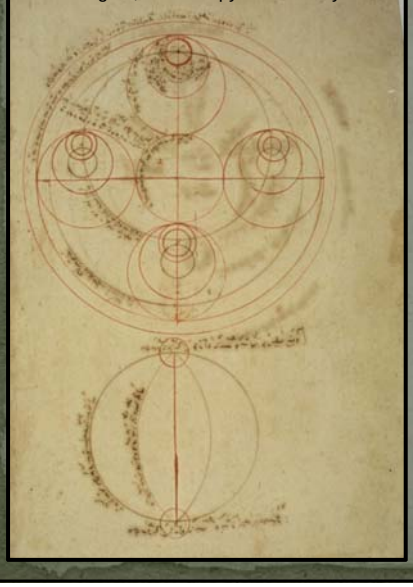
Only surviving comprehensive ancient treatise on astronomy:
- most important source of information on ancient Greek astronomy

Geocentric Model
Epicycle Theory

Dominated astronomy for > 13 centuries
- Roman (Byzantine, Western) world
- Arab world

Syntaxis - Almagest

Almagest, Greek copy 13th century



"The Great Book"

most Important & Influential Astronomical Work of Antiquity

Geometrical models based on 800 yrs observations
(Babylonians, Hipparchus, …)

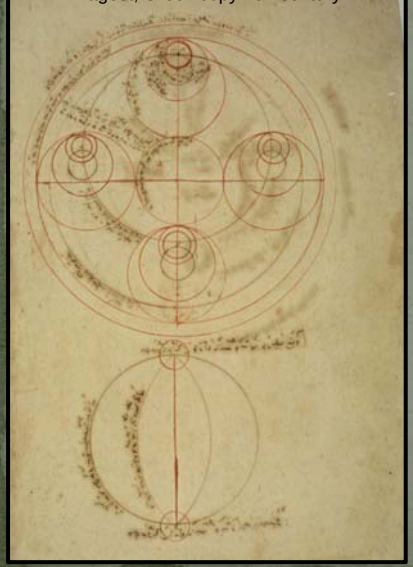
Models presented in convenient tables

Calculations fairly accurate for prediction
solar and lunar eclipses

Almagest also contains star catalogue
- appropriated version Hipparchus' catalogue
- 48 constellations: modern ones, not full sky

Syntaxis - Almagest

Almagest, Greek copy 13th century



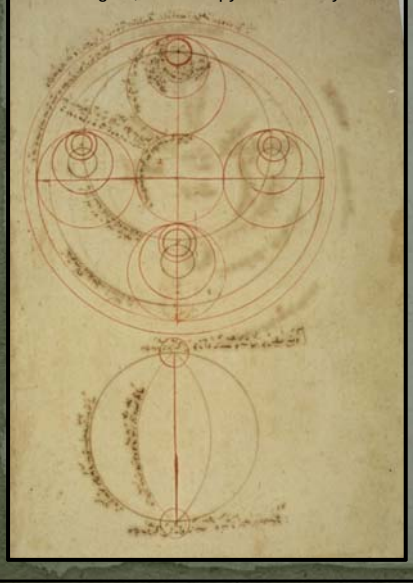
Ptolemaeus' Cosmos

The cosmology of the *Almagest:*
five main points
each subject of a chapter Book I.

- The celestial realm is spherical,
  and moves as a sphere.
- The earth is a sphere.
- The earth is at the center of the cosmos.
- The earth,
  in relation to the distance of the fixed stars,
  has no appreciable size,
  must be treated as a mathematical point
- The earth does not move.

Syntaxis - Almagest

Almagest, Greek copy 13th century



Ptolemaeus' Planetary Models

Order of planetary spheres:

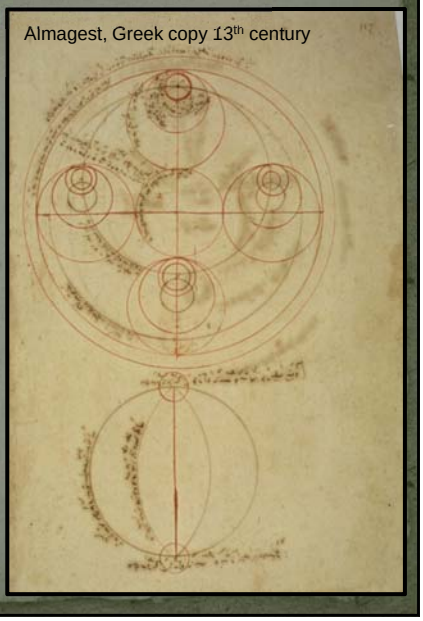
- Moon
- Mercury
- Venus
- Sun
- Mars
- Jupiter
- Saturn
- Sphere fixed stars

Syntaxis - Almagest

Almagest: 13 books

- Book I:
  outline of Aristotelian cosmology:
  - on the spherical form of the heavens,
  - the (spherical) Earth lying motionless at centre
  - the fixed stars and the various planets revolving around the earth
  - followed by explanation of chords with a set of chord tables
  - observations of the obliquity of the ecliptic
  - introduction to spherical trigonometry
- Book II:
  problems associated with the daily motion attributed to the heavens:
  - risings and settings of celestial object
  - length of daylight
  - determination of latitude
  - points at which the Sun is vertical
  - shadows of the gnomon at the equinoxes and solstices
  - other things which change with the spectator's position. There is also
  - a study of the angles made by the ecliptic with vertical, with tables.

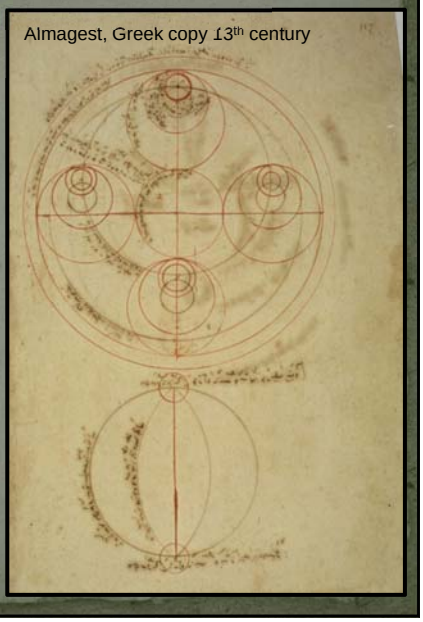
Almagest, Greek copy 13th century



Syntaxis - Almagest

Almagest: 13 books

- Book III:
  - length of the year, and the motion of the Sun
  - explains Hipparchus' discovery of the precession of the equinoxes
  - begin explanation epicycles
- Books IV & V:
  the motion of the Moon:
  - lunar parallax
  - motion of the lunar apogee
  - sizes and distances of the Sun and Moon relative to Earth
- Book VI:
  solar and lunar eclipses

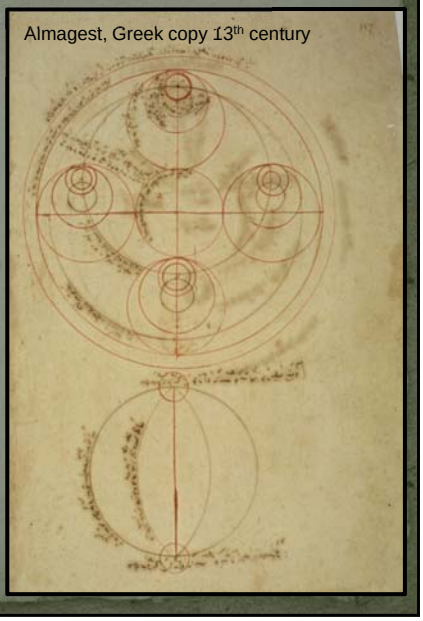


Almagest, Greek copy 13th century

Syntaxis - Almagest

Almagest: 13 books

- Books VII & VIII:
- motions of the fixed stars:
  - includes precession of the equinoxes
- star catalogue of 1022 stars:
  - described by positions in the constellations
  - magnitude scale for brightness:
    + brightness brightest stars marked of the 1st magnitude (m = 1),
    + faintest 6th magnitude (m = 6), limit human visual perception
    + each grade of magnitude considered twice the brightness of the following grade (log. scale).
    + system believed to have originated with Hipparchus
    + Stellar positions: Hipparchan origin (despite Ptolemy's claim to the contrary)
-



Almagest, Greek copy 13th century

Syntaxis - Almagest

Almagest: 13 books

- Book IX:
  - general issues associated with creating models for the five (naked eye) planets
  - motion of Mercury
- Book X:
  motions of Venus and Mars
- Book XI:
  motions of Jupiter and Saturn
- Book XII:
  stations and retrogradations,
  - occurring when planets appear to pause, then briefly reverse their motion against the background of the zodiac.
  - Ptolemy understood these terms to apply to Mercury and Venus as well as the outer planets
- Book XIII:
  motion in latitude:
  the deviation of planets from the ecliptic

Almagest, Greek copy 13th century