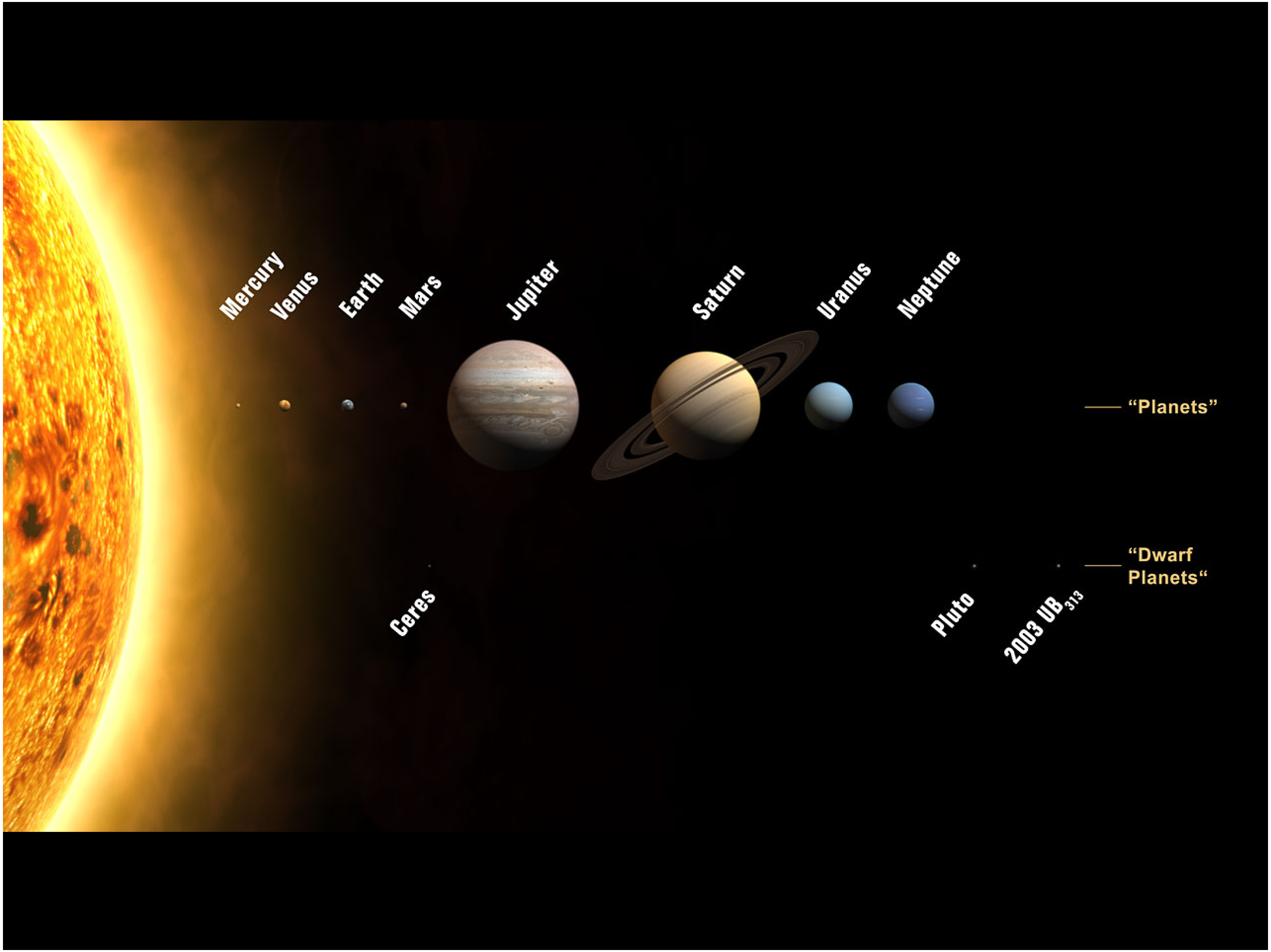
How Galileo Made the Earth Move...

Dr Martin Hendry
University of Glasgow

University of Glasgow

THE UNIVERSE
YOURS TO DISCOVER

INTERNATIONAL YEAR OF
ASTRONOMY
2009



Mercury
Venus
Earth
Mars
Jupiter
Saturn
Uranus
Neptune
"Planets"
"Dwarf Planets"
Ceres
Pluto
2003 UB313

The Scottish Solar System

http://www.scottishsolarsystem.org.uk

University of Glasgow

glasgow science centre

Early Greek Astronomy

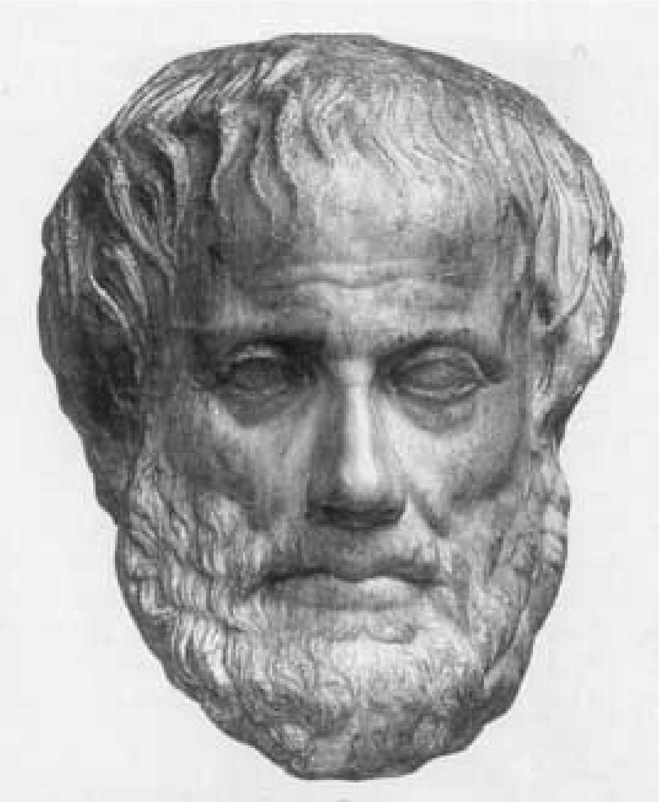
The Greeks inherited ideas from Babylonia and Egypt, but approached astronomy in a scientific way

Aristotle (384 – 322 BC):

Universe divided into two parts:

Corrupt, changeable Earth

Perfect, immutable heavens



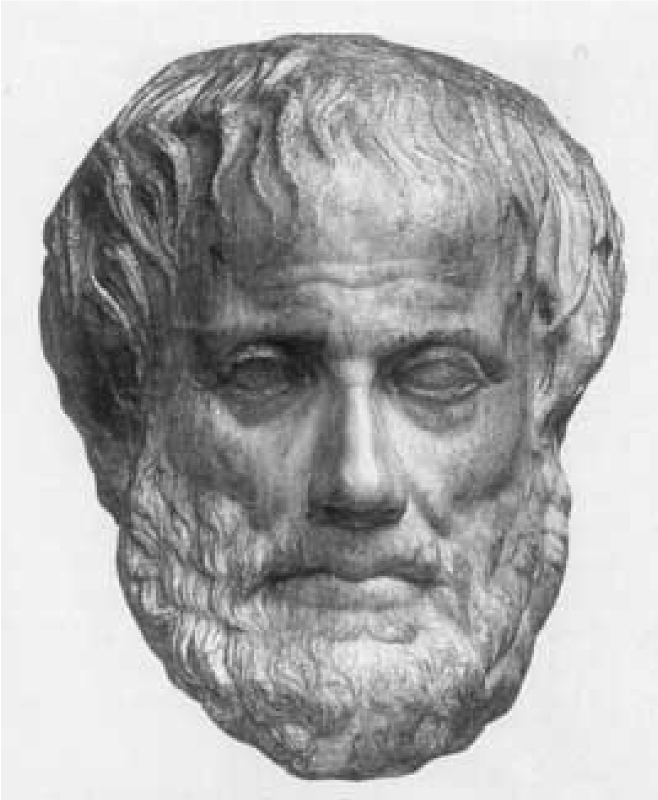
Early Greek Astronomy

The Greeks inherited ideas from Babylonia and Egypt, but approached astronomy in a scientific way

Aristotle (384 – 322 BC):

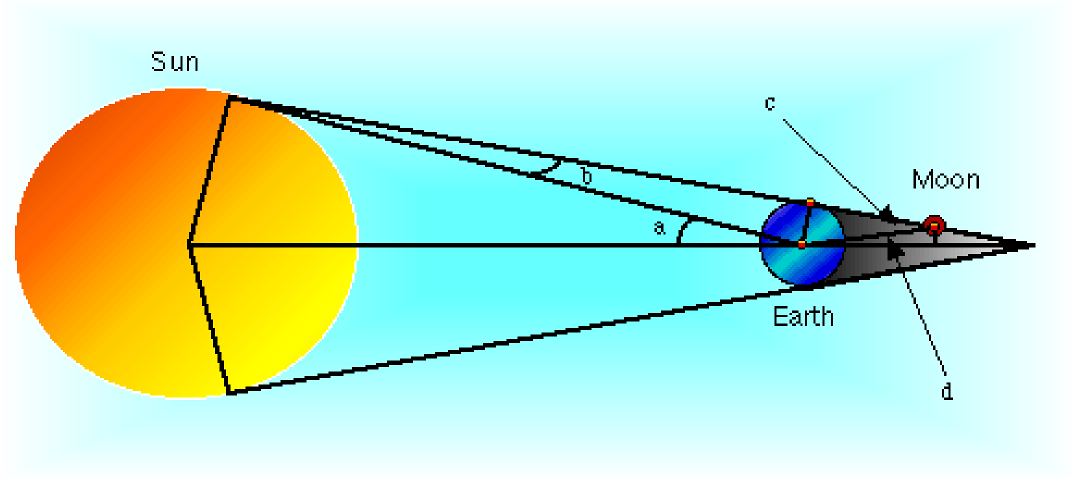
Universe **Geocentric – Earth immobile at the centre**

56 crystalline spheres: lowest sphere, the Moon, boundary between imperfection and perfection



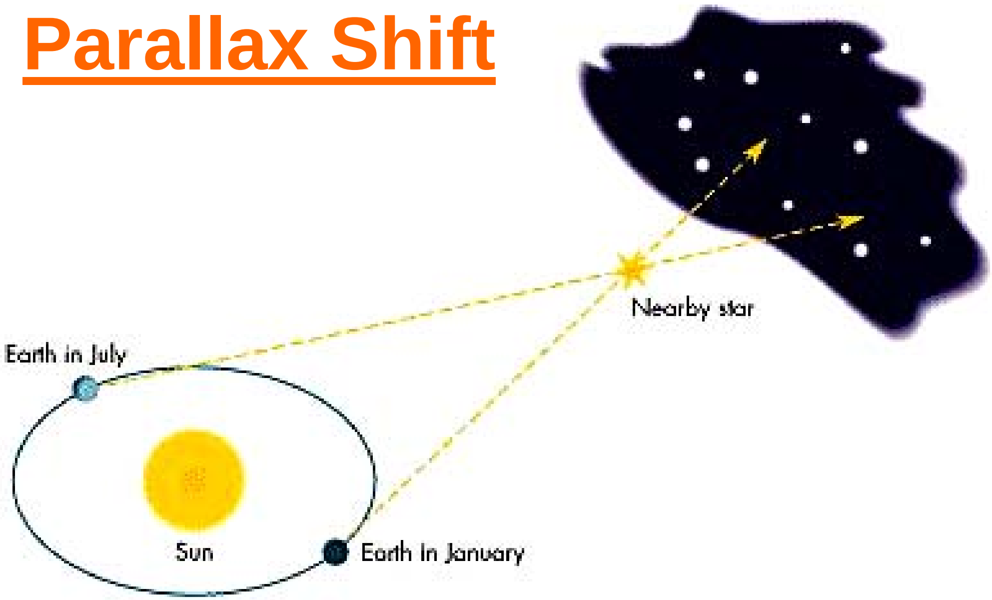
Early Greek Astronomy

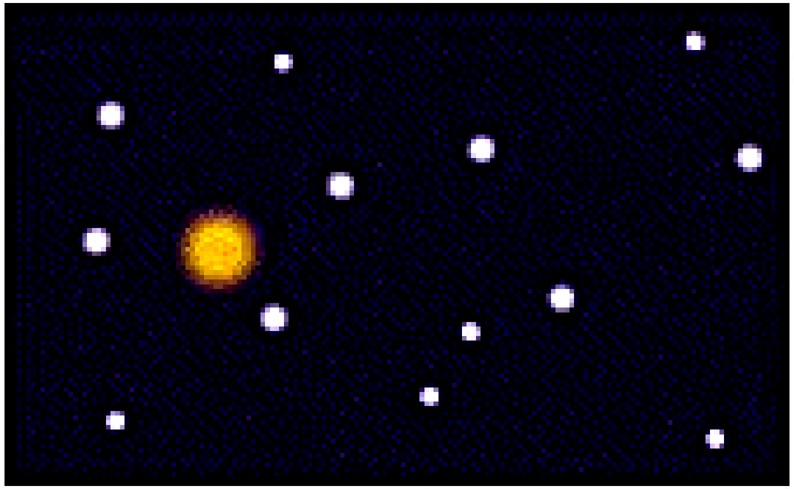
Heliocentric model of Aristarchus (310 – 230 BC):
from eclipse geometry, Sun much larger than the Earth



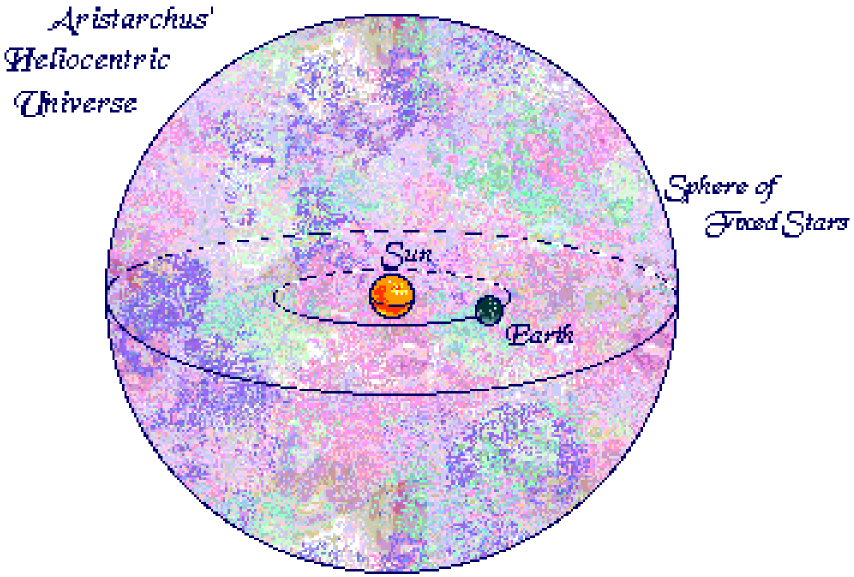
Idea not widely accepted – no stellar parallax shift

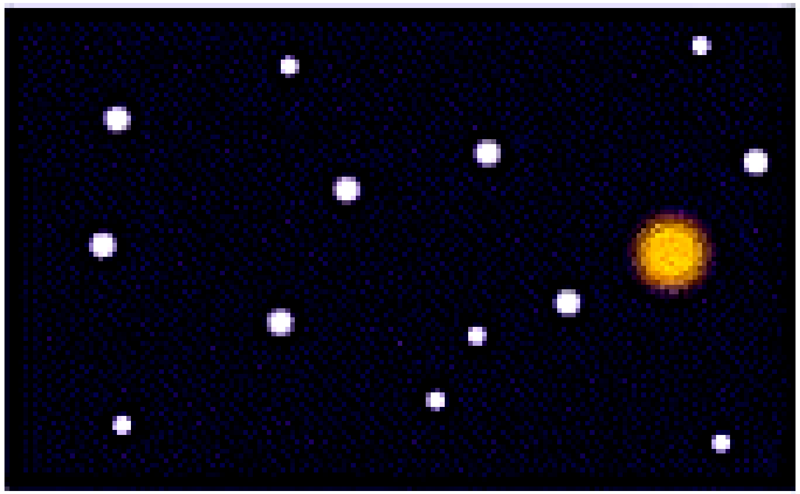
Parallax Shift





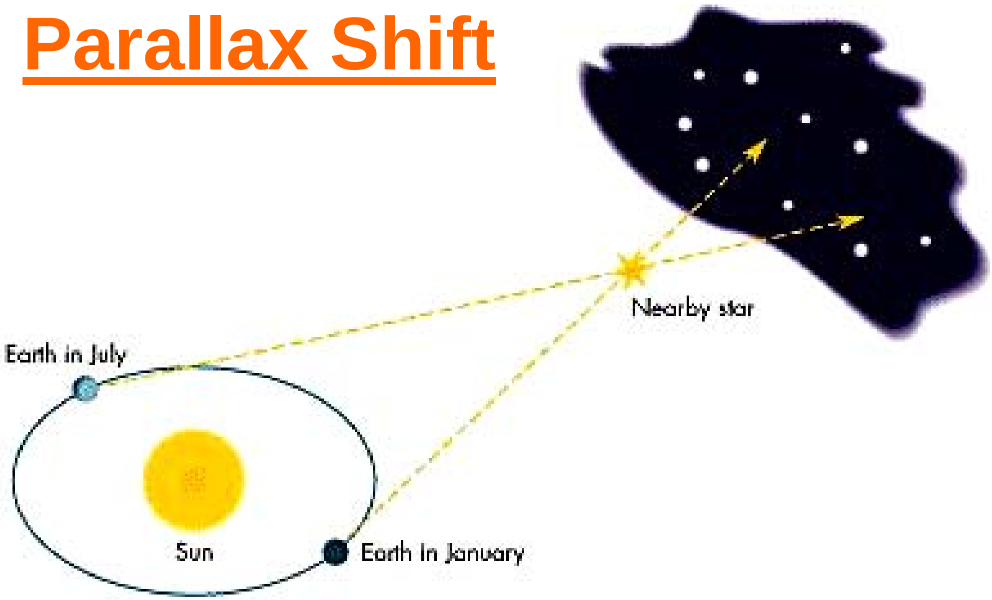
View from the Earth in January

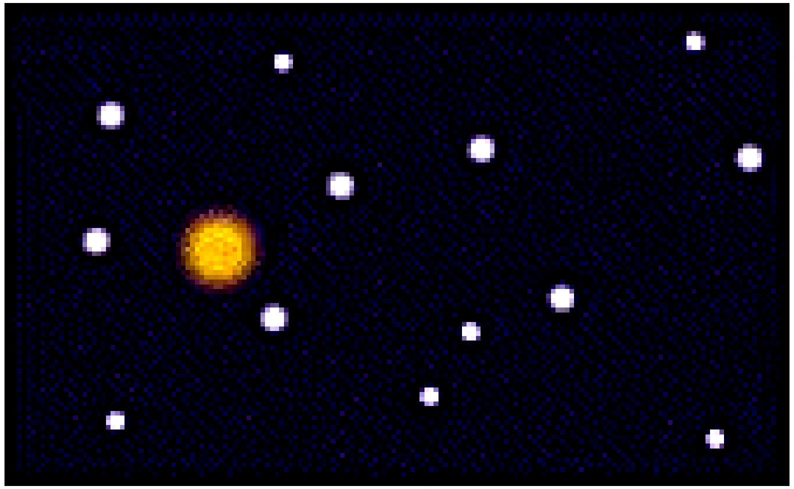




View from the Earth in July

Parallax Shift

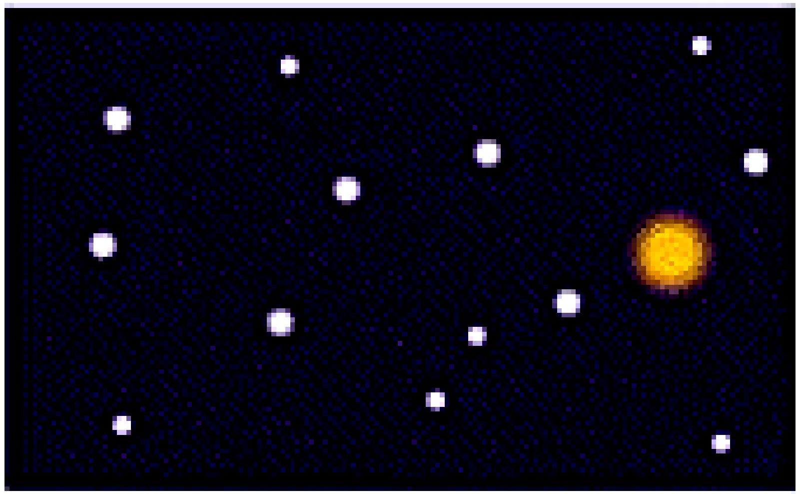




View from the Earth in January

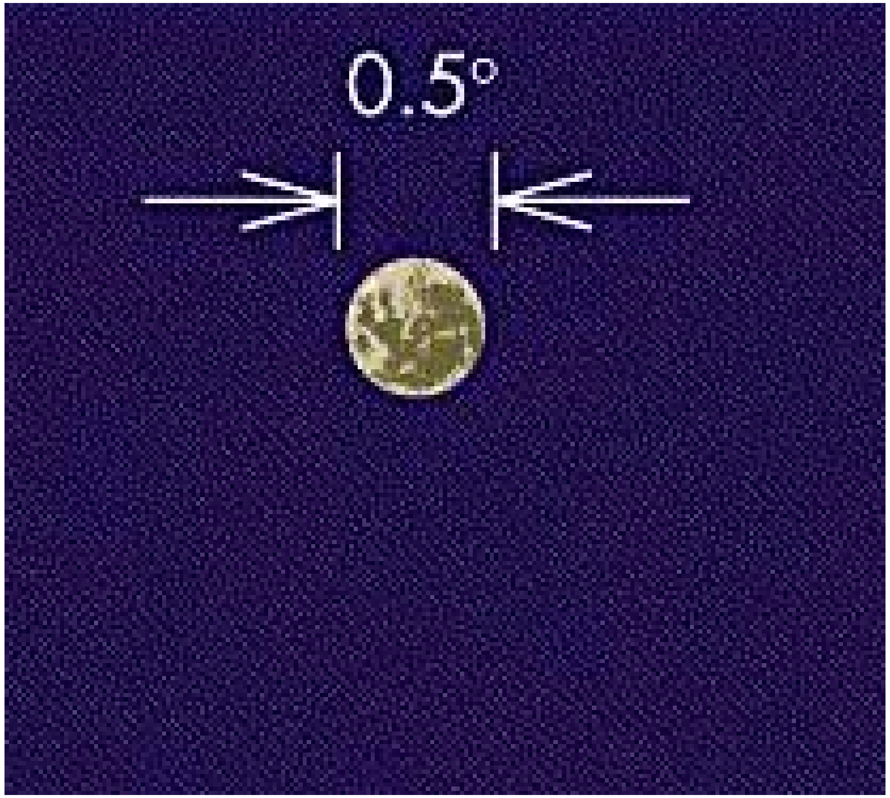
Nearby stars *do* show an annual parallax shift, but it is tiny!

First detected only in the mid 19th Century

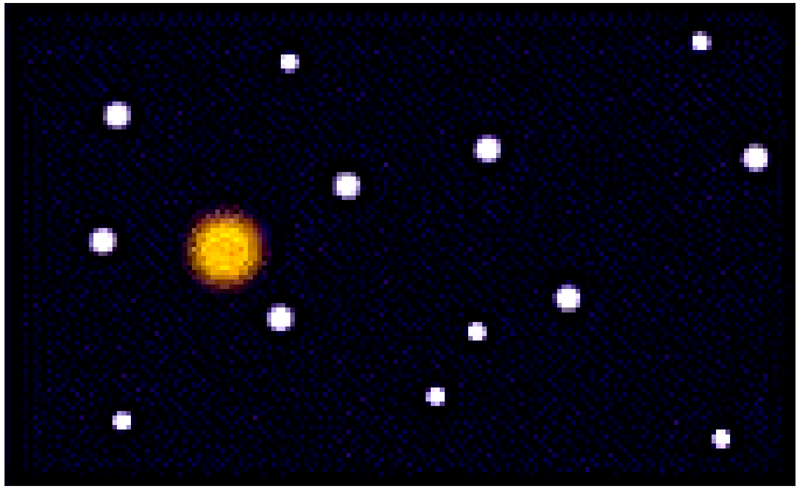


View from the Earth in July

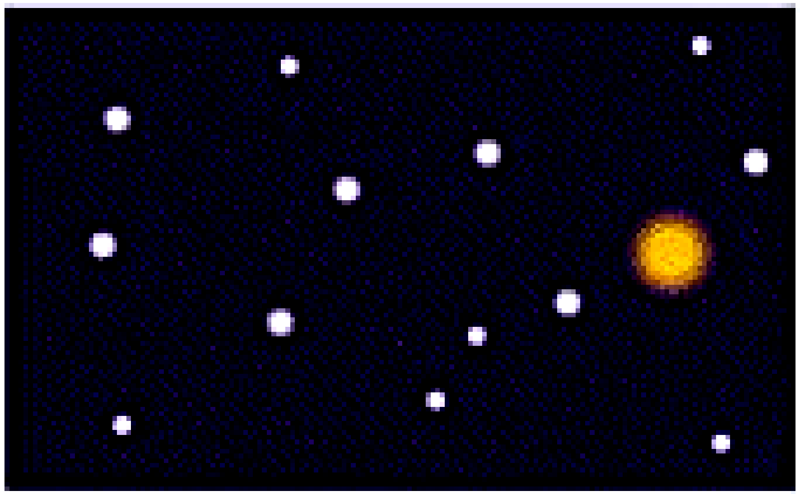
Parallax Shift



Even the nearest star shows a parallax shift of only 1/2000th the width of the full Moon



View from the Earth in January



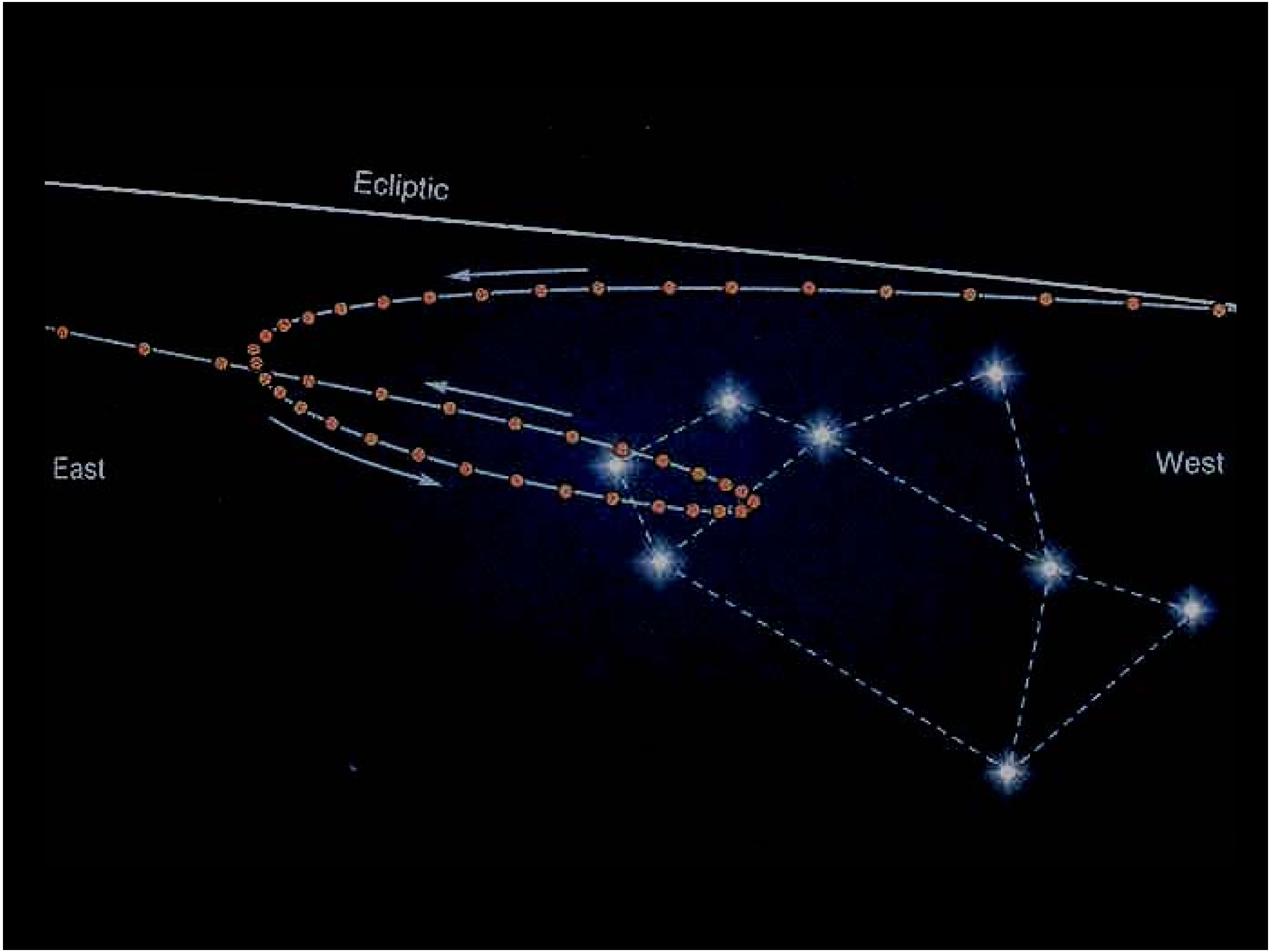
View from the Earth in July

Early Greek Astronomy

With increasingly accurate observations, Aristotle's model was found to be inaccurate

Hipparchus placed the Earth off-centre

His model still couldn't explain Retrograde motion of the planets

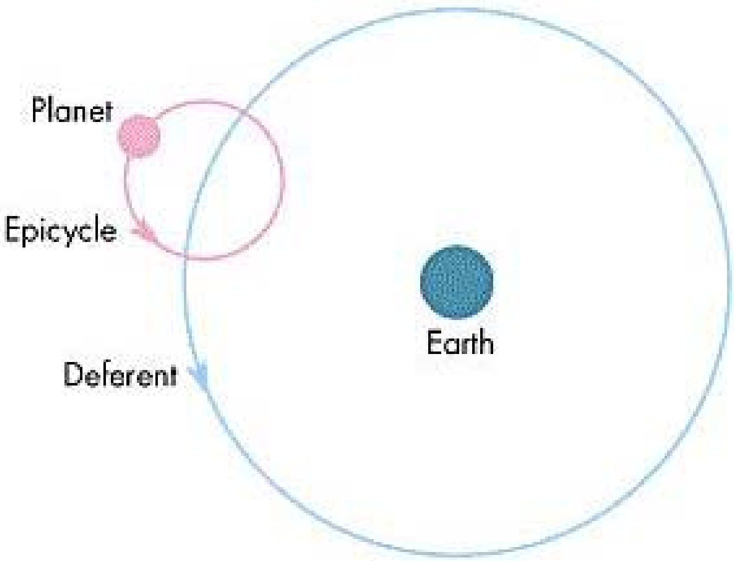

Ecliptic
East
West

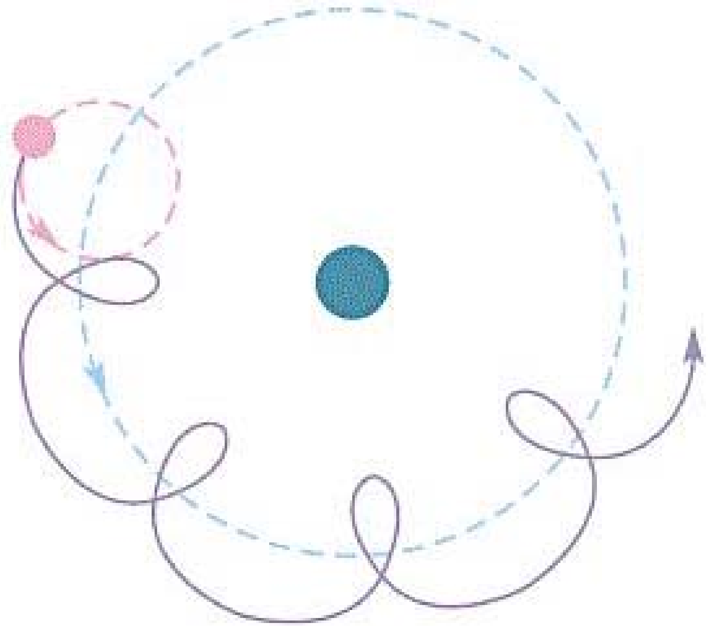
The Ptolemaic Universe

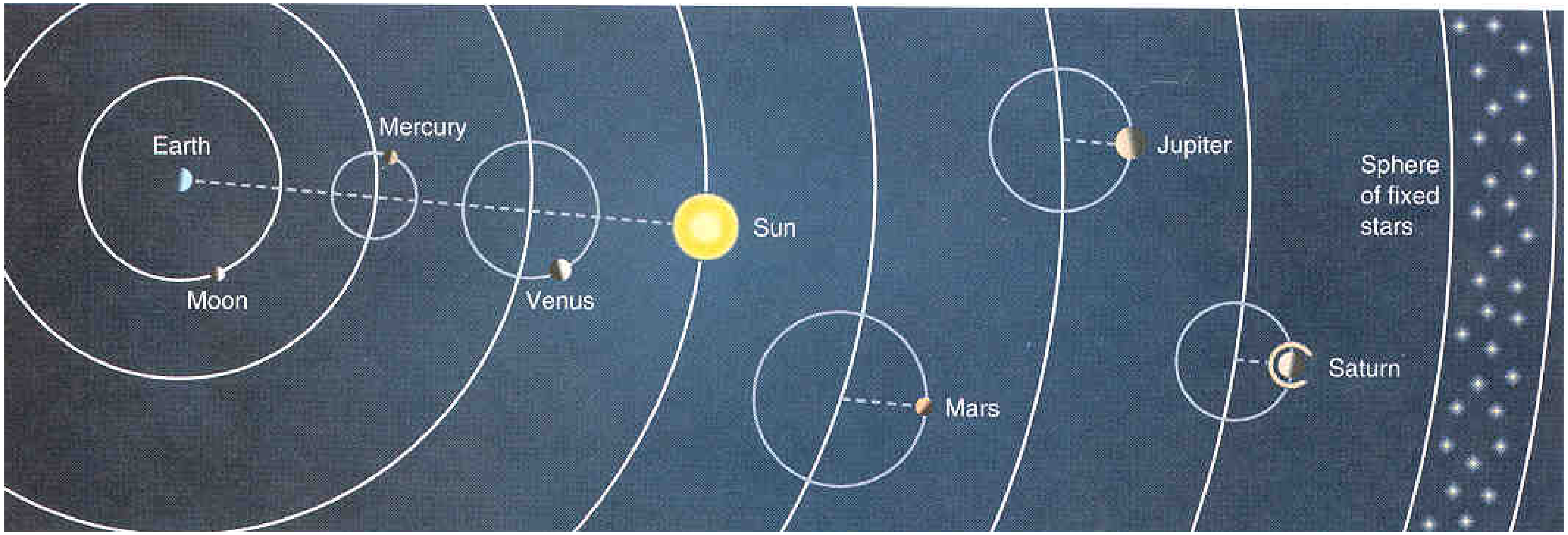
The Ptolemaic model could explain planetary motions – including retrograde loops

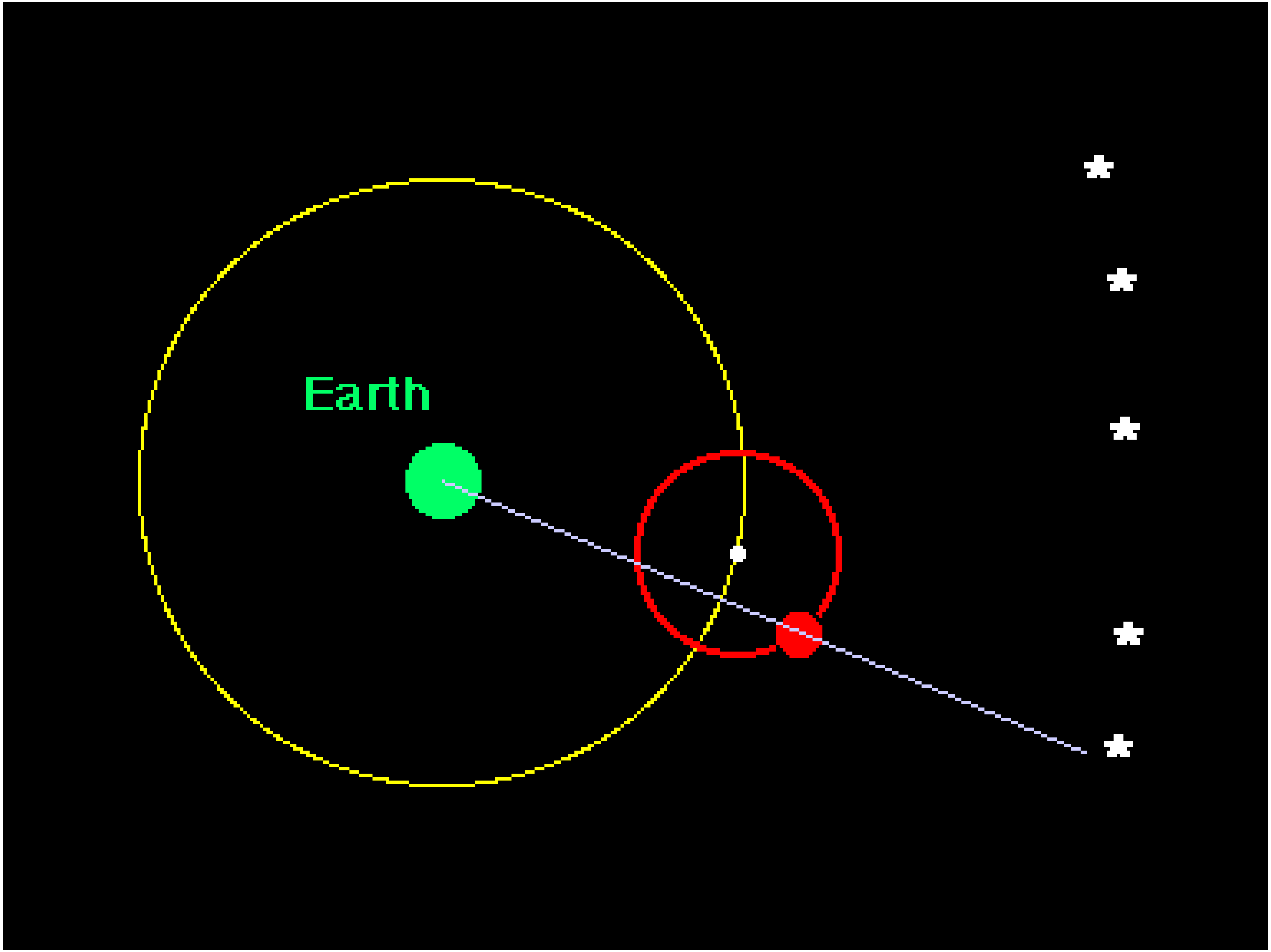
Used a system of *Epicycles*

The Ptolemaic Universe








Earth

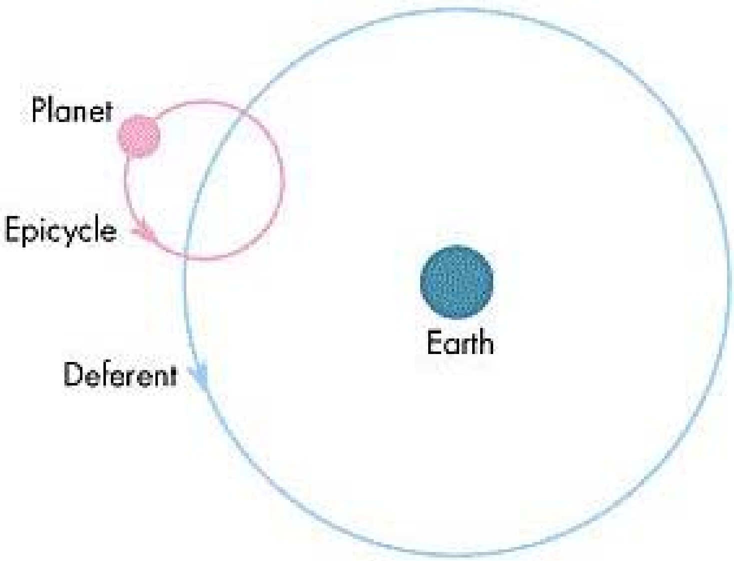
The Ptolemaic Universe

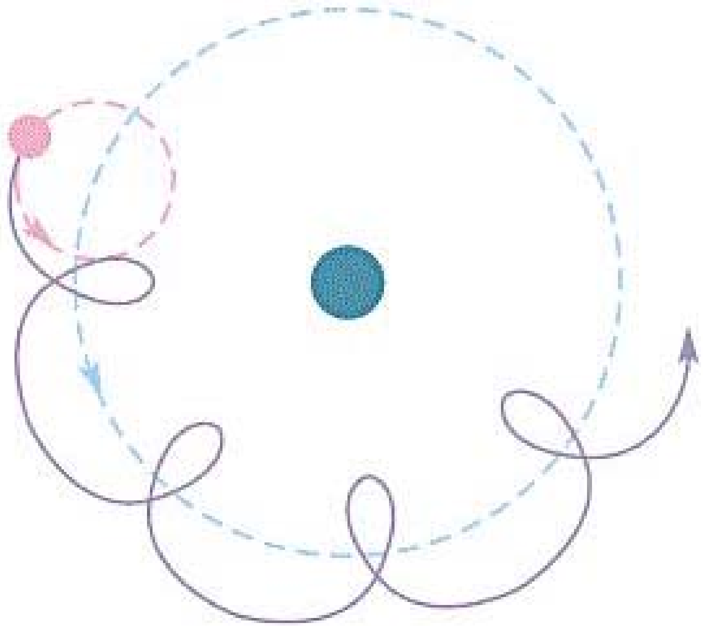
One could adjust size and speed of epicycles to match observations. (Also placed Earth slightly off centre). He published his model around 140 AD in *The Almagest*

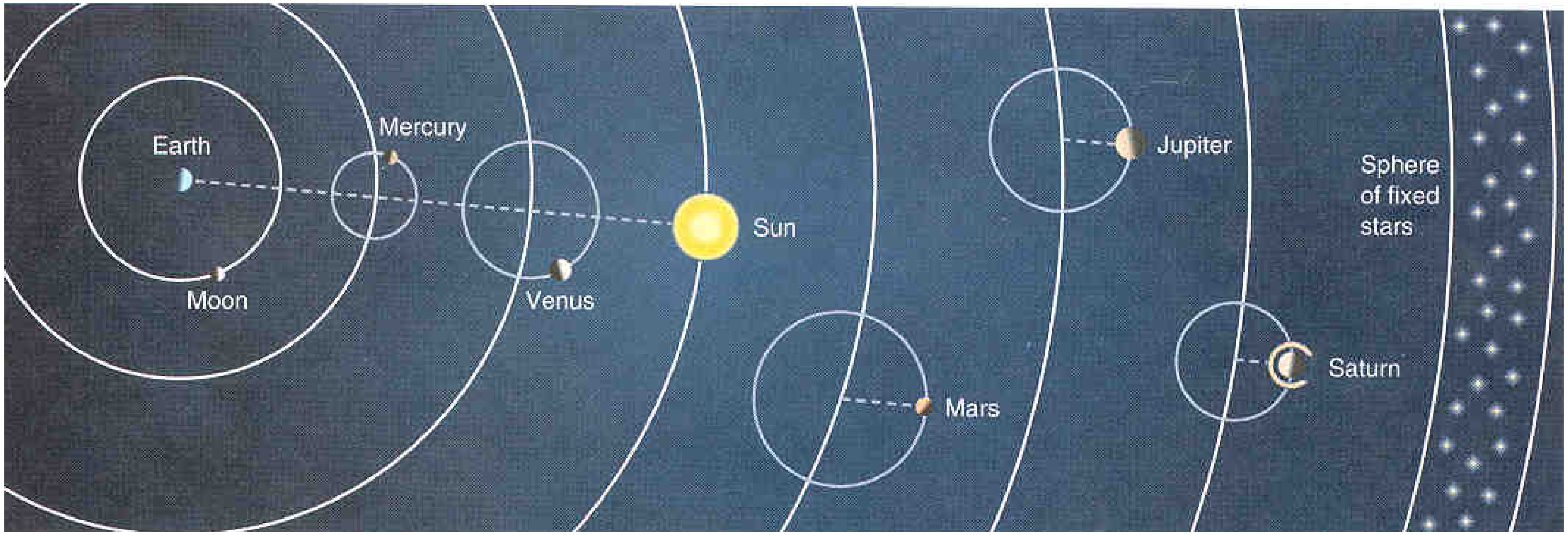
Not very elegant, but successful at predicting the positions of the Sun, Moon and planets

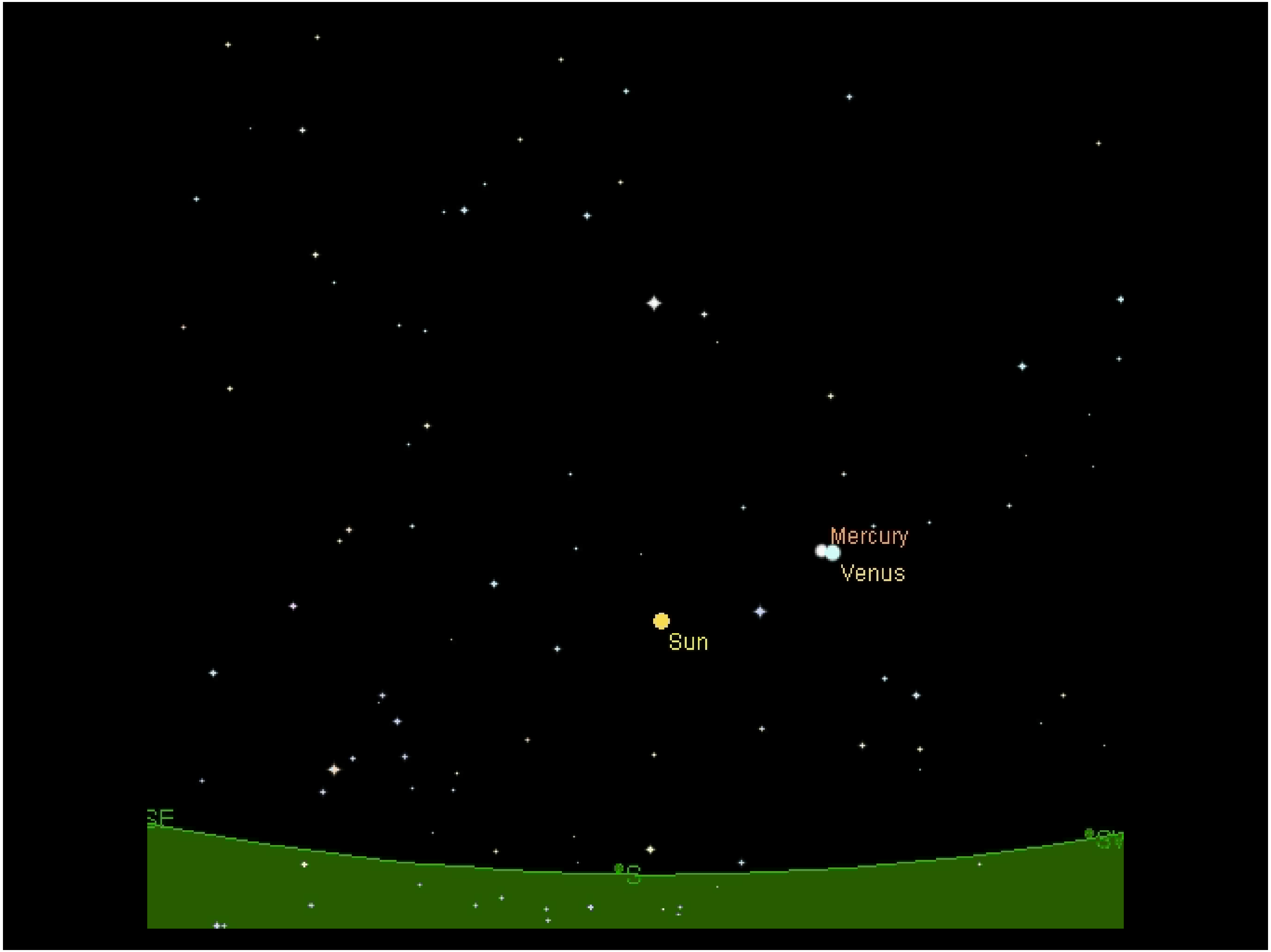

Moon
Earth

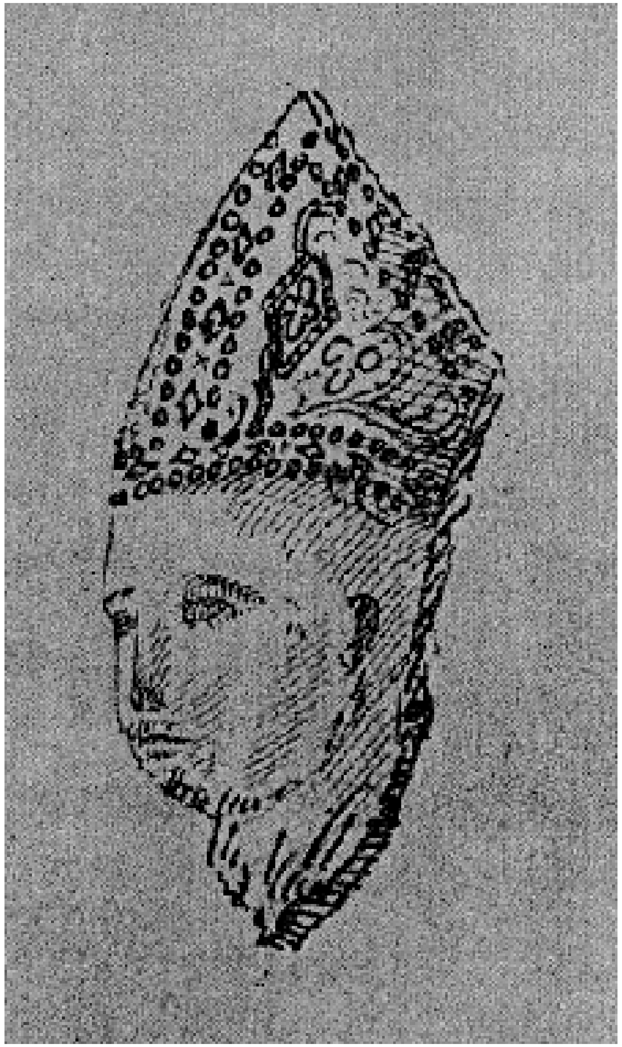
The Ptolemaic Universe



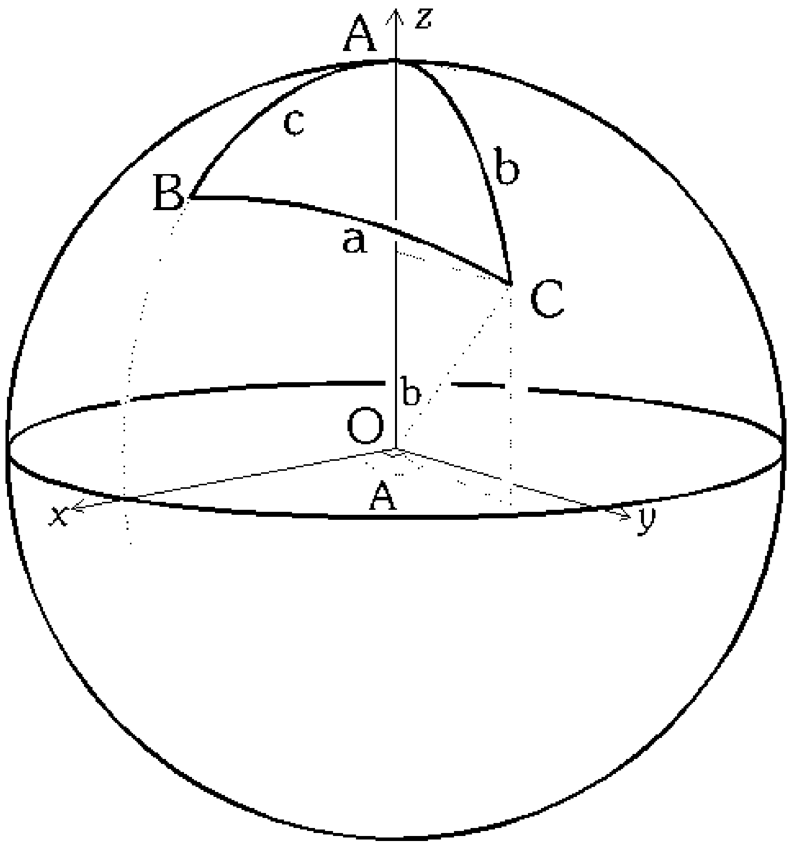





Mercury
Venus
Sun
SE
S
SW

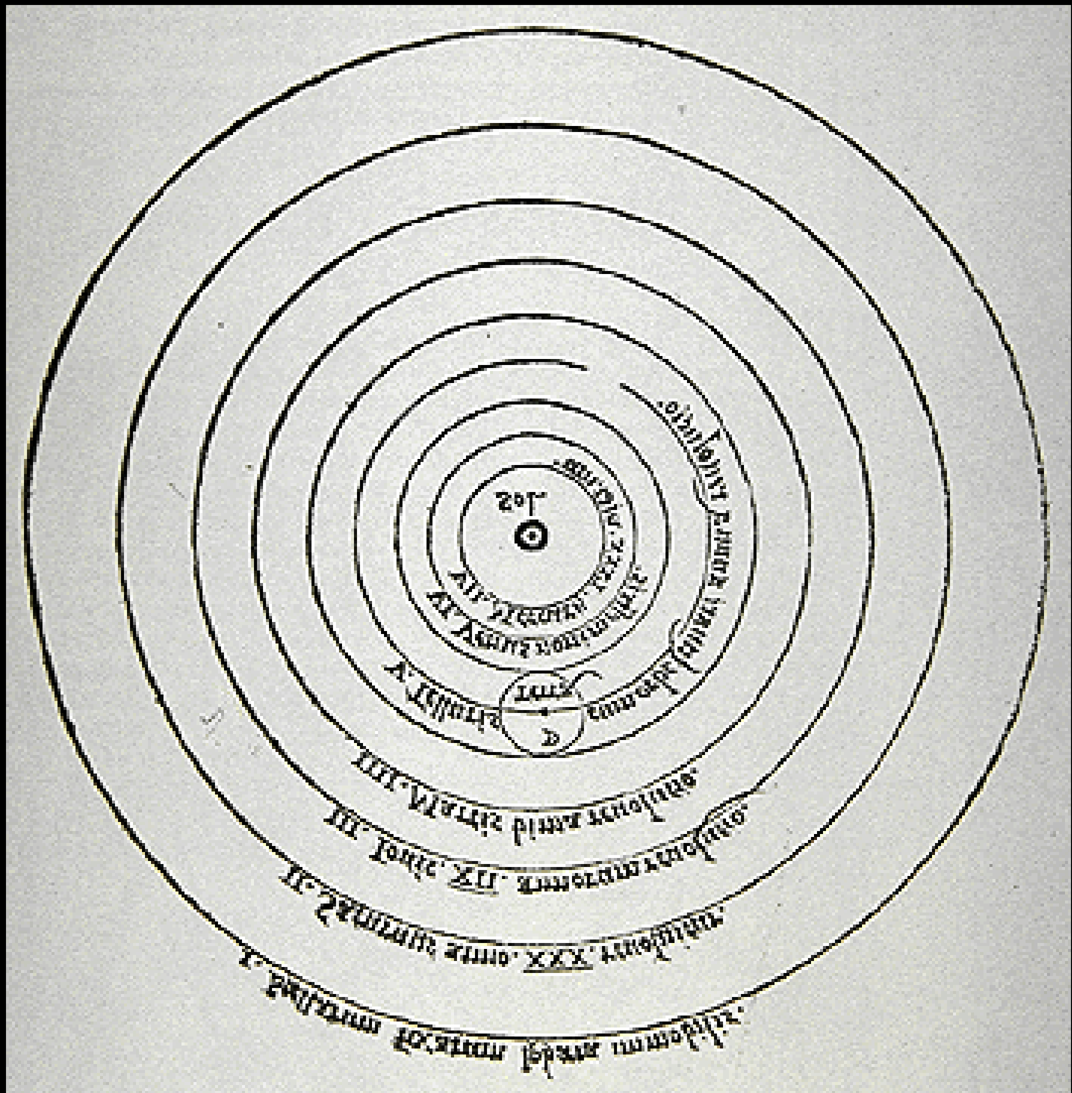


John of Holywood (c. 1200)

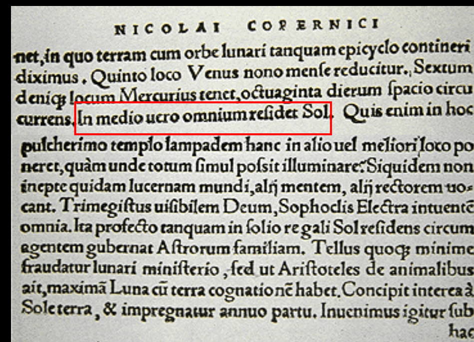


Author of ‘The Sphere’, standard textbook on spherical trigonometry

The Copernican Revolution



Nicolaus
Copernicus
1473 – 1543 AD



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 circu currens. In medio uero omnium residet Sol. Quis enim in hoc pulcherrimo templo lampadem hanc in alio uel meliori loco po neret, quàm unde totum simul possit illuminare? Siquidem non inepte quidam lucernam mundi, alij mentem, alij rectorem uo- cant. Trimegistus uisibilem Deum, Sophoclis Electra intuentē 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, maximā Luna cū terra cognationē habet. Concipit interea à Sole terra, & impregnatur annuo partu. Inuenimus igitur sub hac

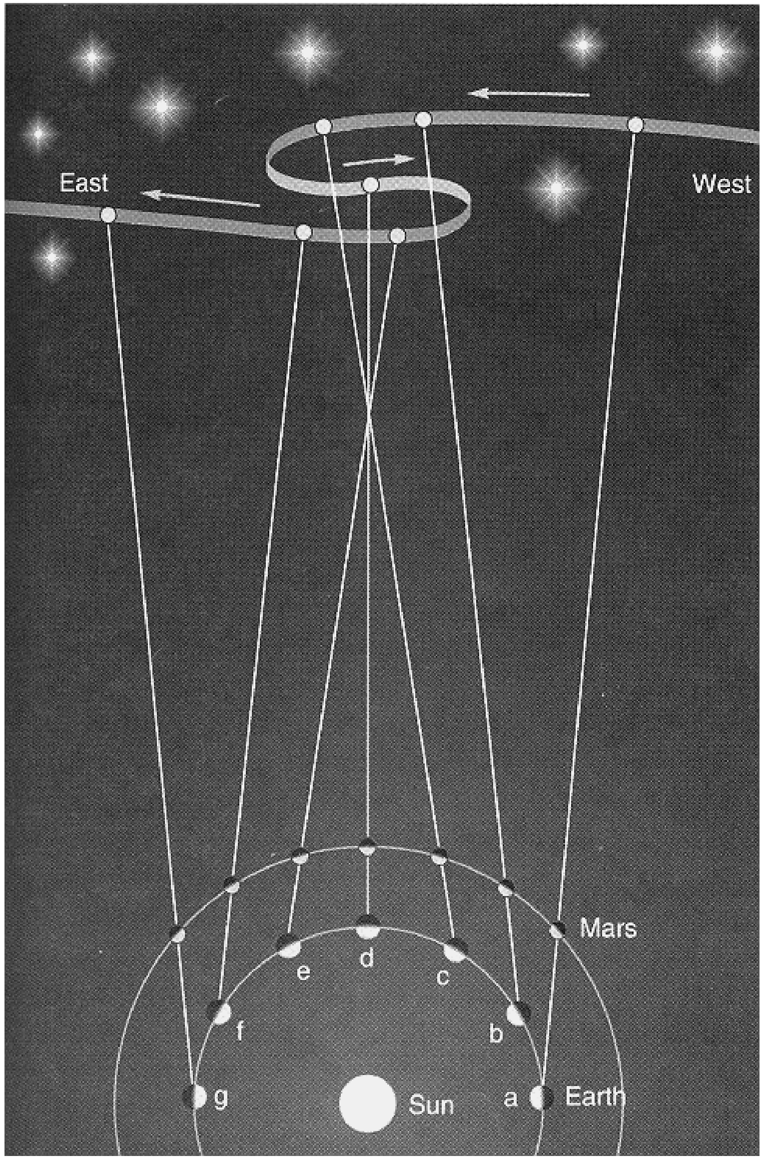
"In the true centre of everything resides the Sun"

De Revolutionibus Orbis (1543)

The Copernican Revolution

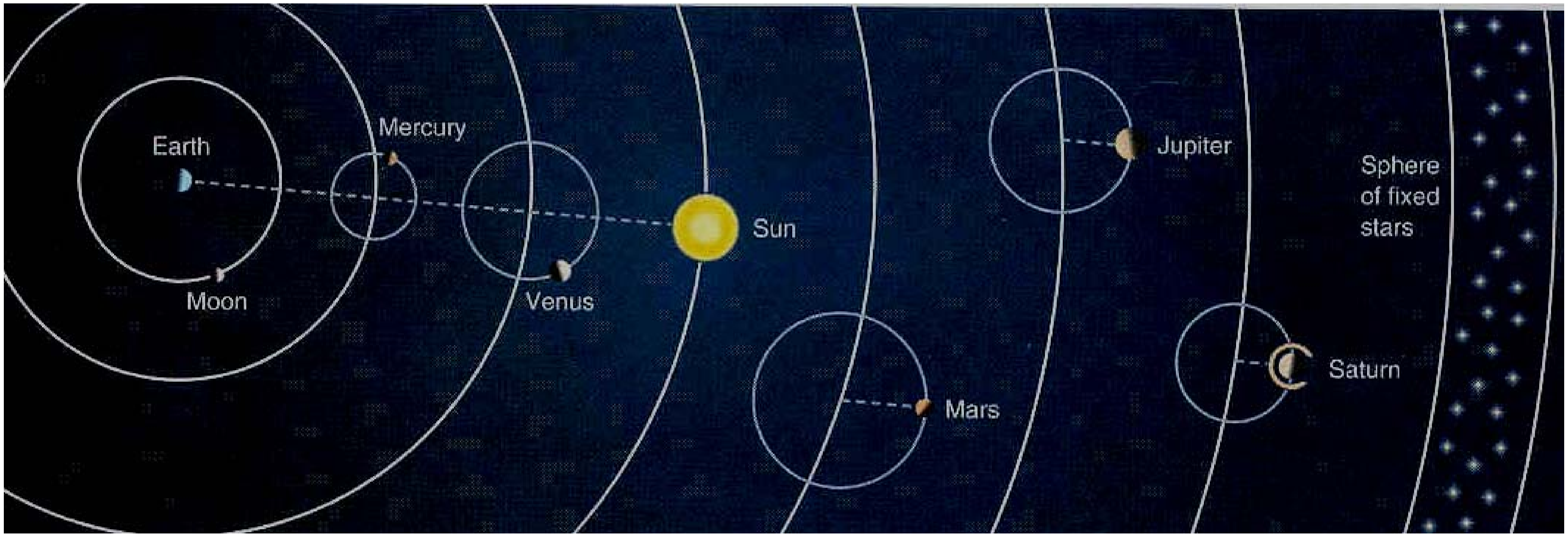
Simpler, more *elegant* explanation of retrograde motion

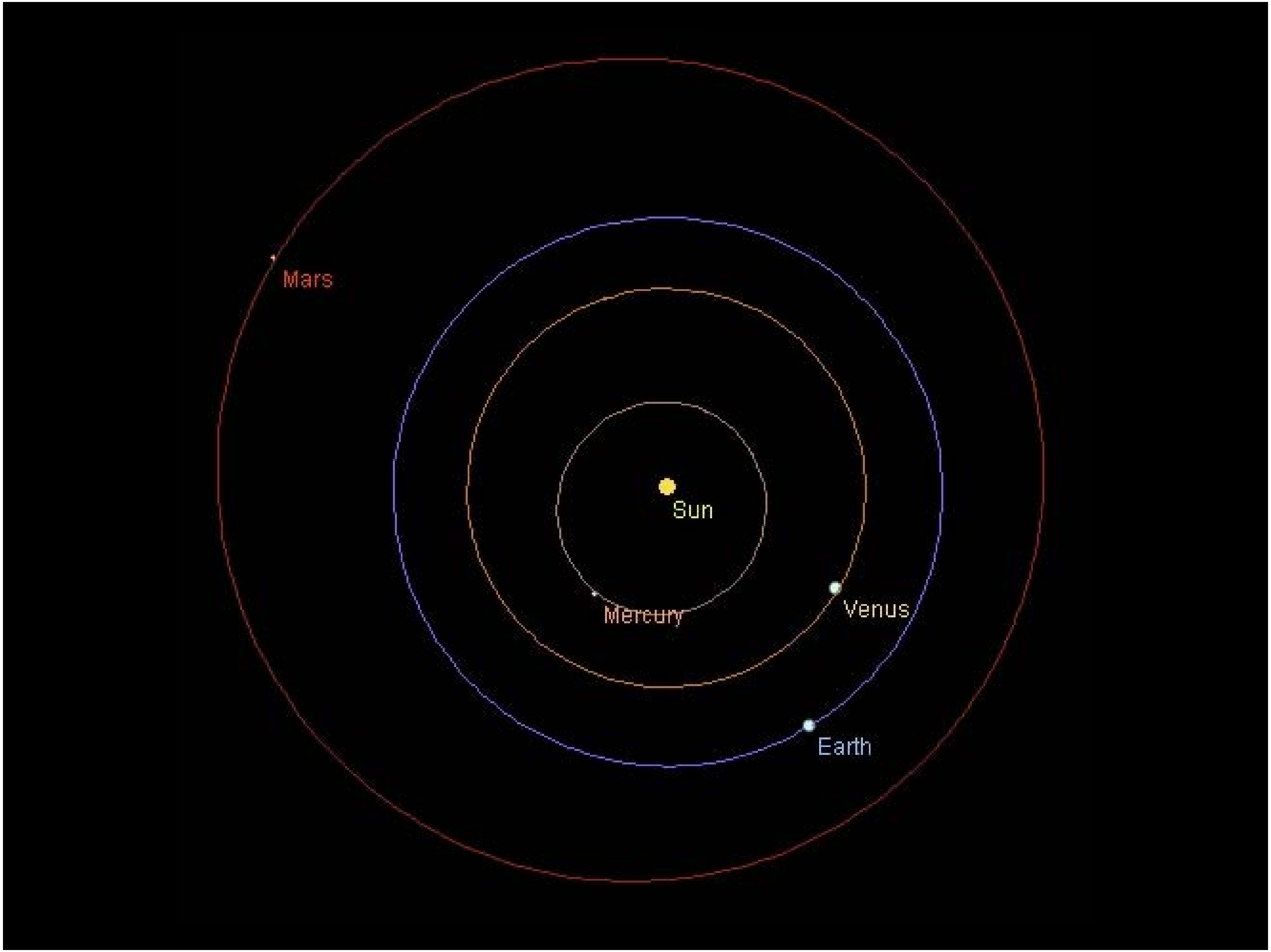
Earth 'overtakes' e.g. Mars



The Copernican Revolution

Simpler explanation why Venus and Mercury appear close to the Sun




Mars
Sun
Mercury
Venus
Earth

Tycho’s Star and Tycho’s Universe

Tycho Brahe (1546-1601)

Reknowned Danish astronomer, excellent naked-eye observer

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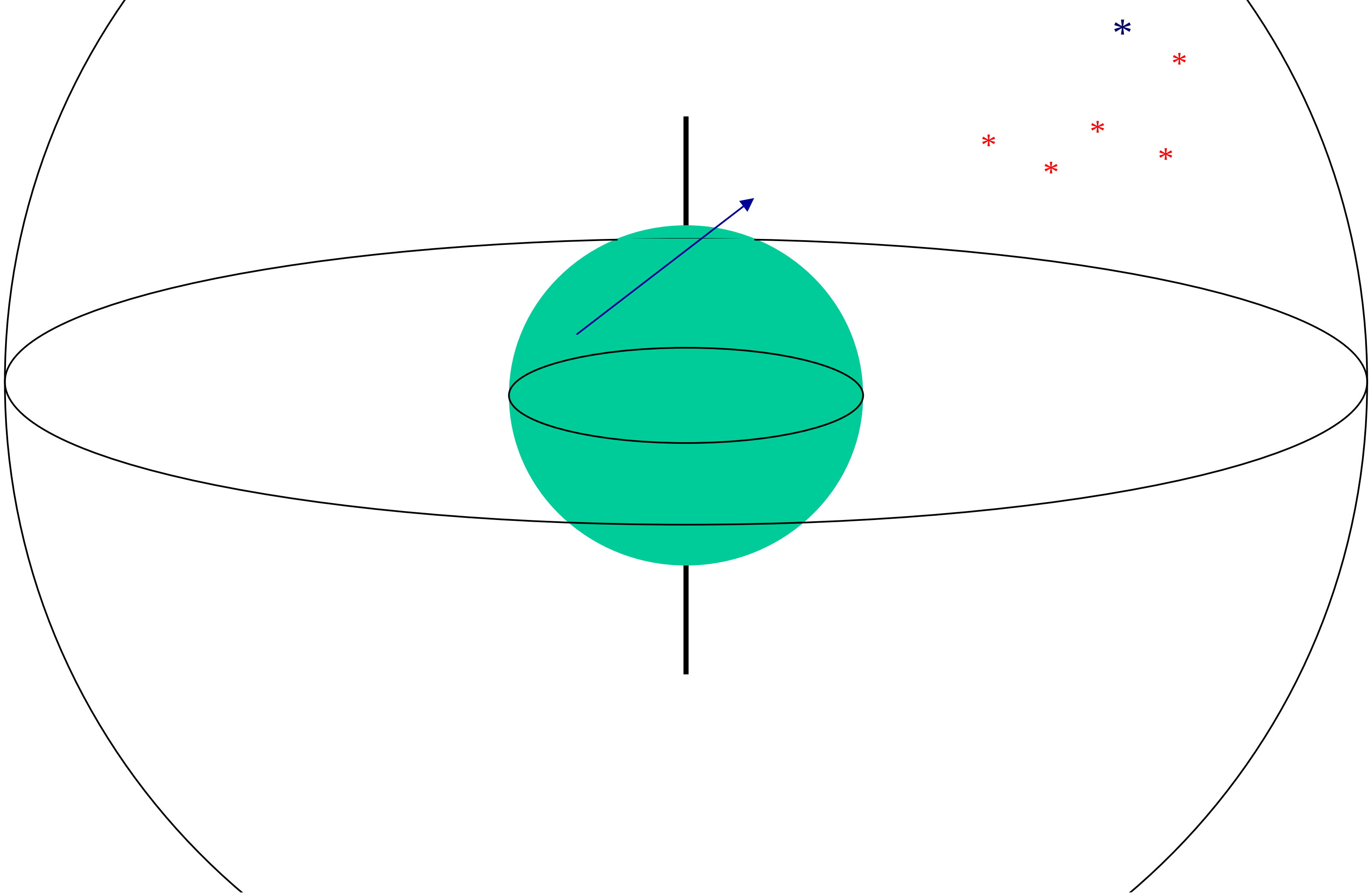
Aristotelian View:

New star closer than the Moon – part of the 'imperfect' sphere

BUT no measured parallax shift

Tycho's Star

If Tycho's star were so close, then it would appear to change position against the background of distant stars through the course of the night



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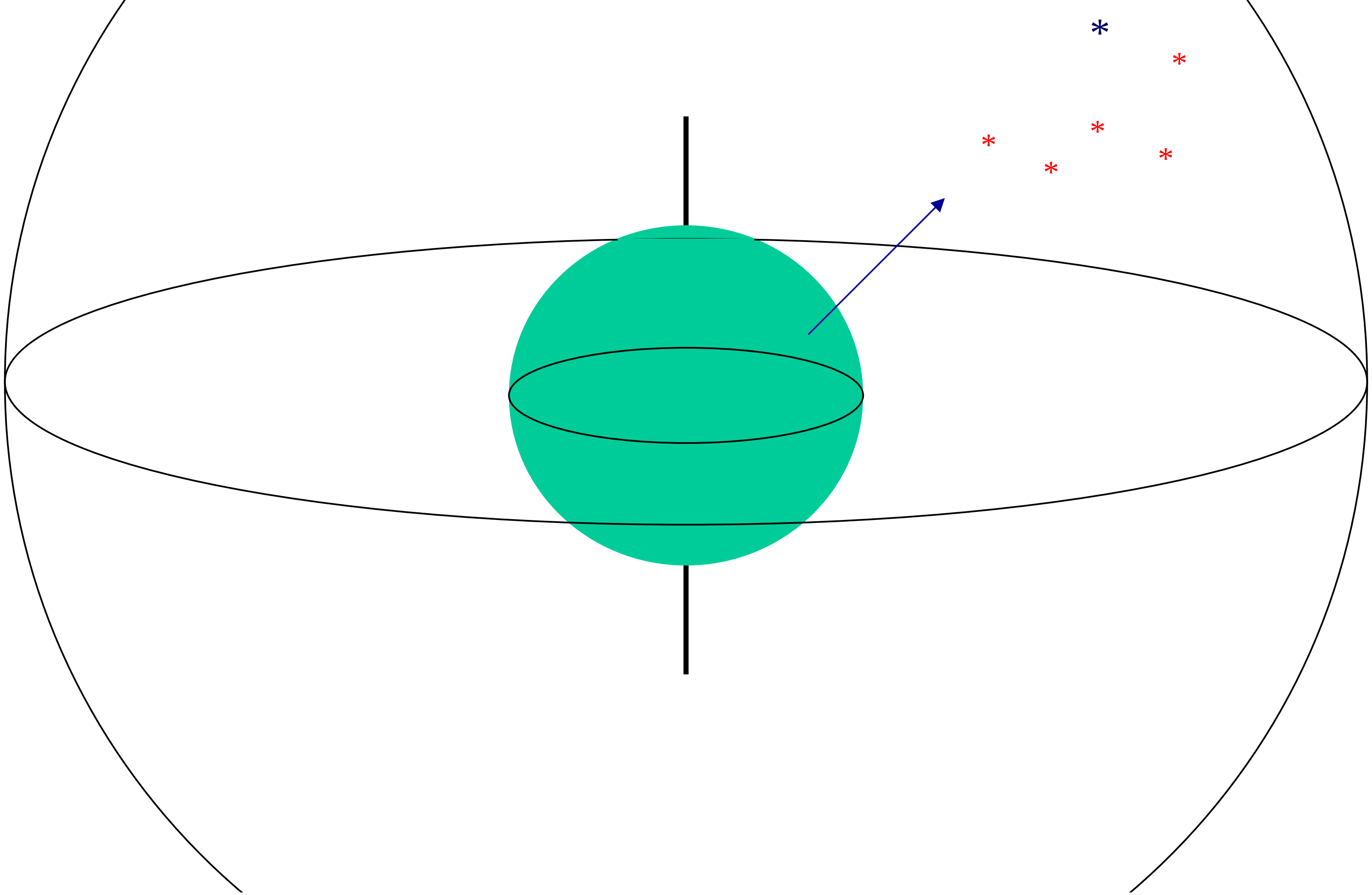

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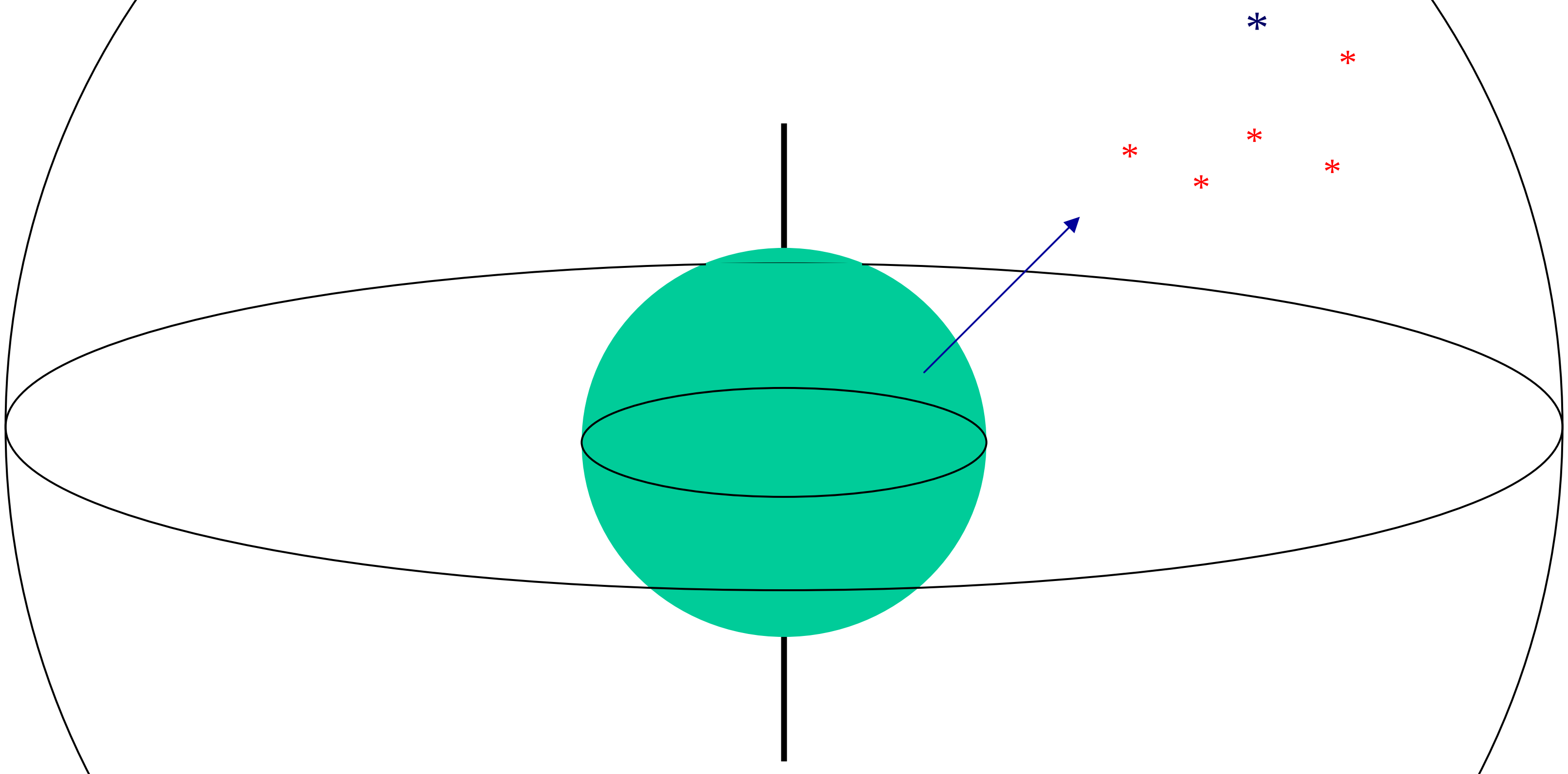


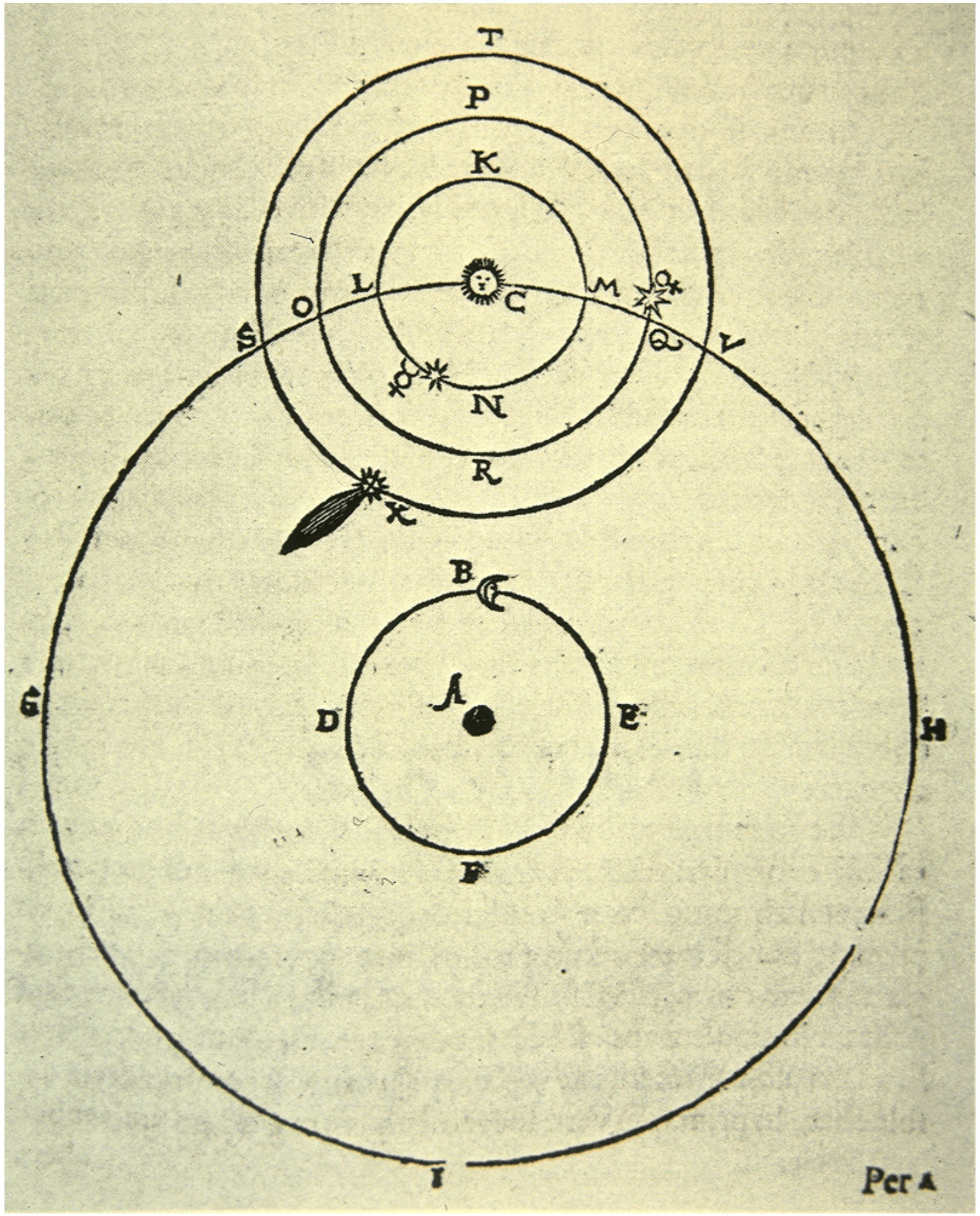
Tycho Brahe observed NO parallax shift

Tycho's Star and Tycho's Universe

Aristotelian view challenged

Tycho also realised flaws of Ptolemaic (geocentric) model – proposed a 'hybrid' (Tychonic) model:

Sun and Moon orbit the Earth; other planets orbit the Sun



Galileo Galilei

Born 15th February 1564, in Pisa

1589 appointed to the Chair of Mathematics at Pisa

1592 moved to Padova, teaching geometry, mechanics and astronomy until 1610

Kepler's Laws of Planetary Motion

Johannes Kepler (1571-1630): German mathematician and astronomer

Strong advocate of Copernican Model

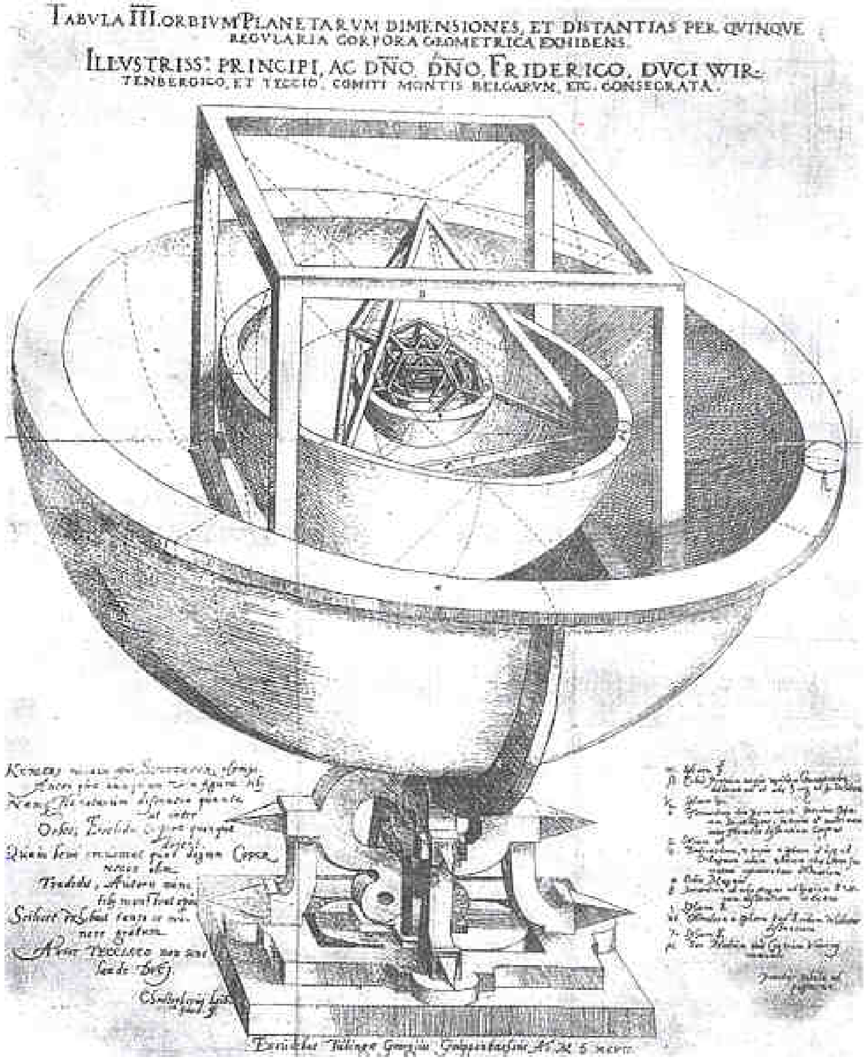
Kepler's Laws of Planetary Motion

Johannes Kepler (1571-1630): German mathematician and astronomer

Strong advocate of Copernican Model

1596: published *Mysterium Cosmographicum* – sizes of planet orbits determined by 5 regular solids of geometry?

Attempt to recapture Pythagoras' "Harmony of the Spheres"

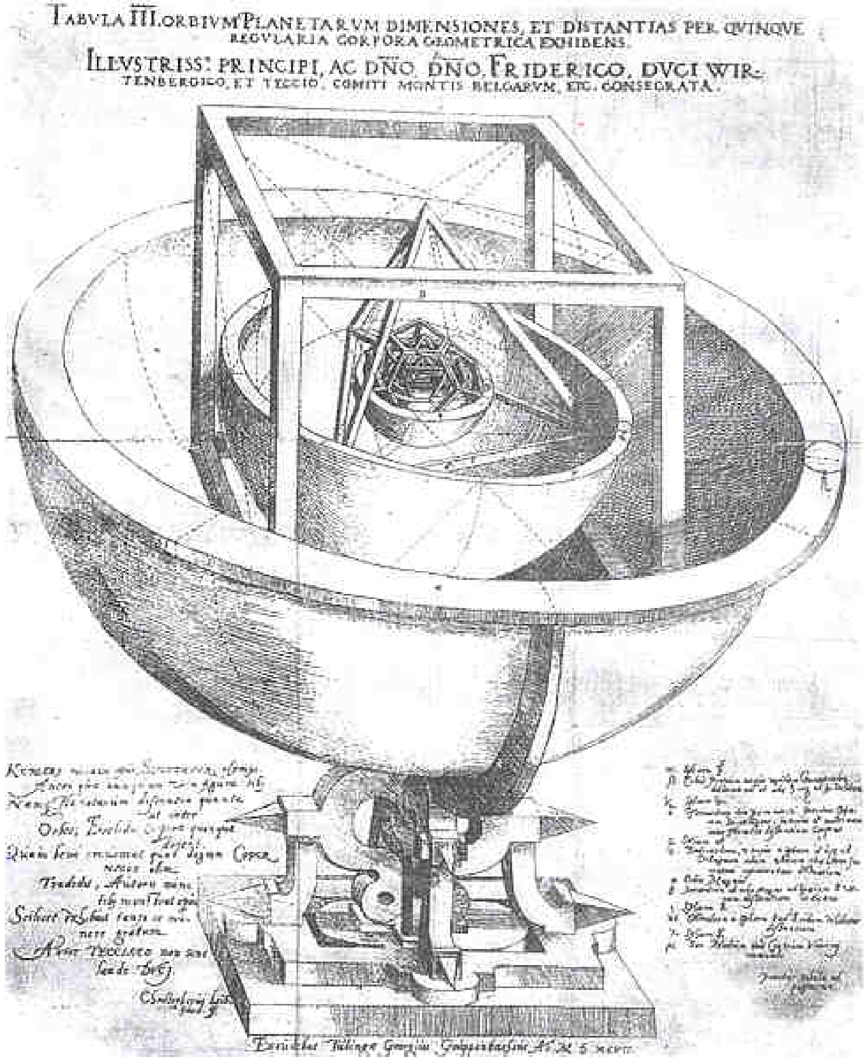


Kepler’s Laws of Planetary Motion

Johannes Kepler (1571-1630): German mathematician and astronomer

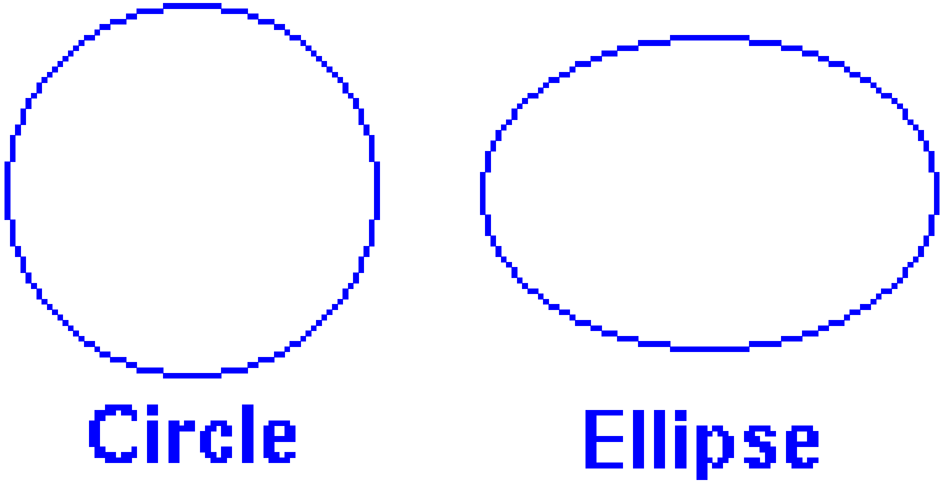
Strong advocate of Copernican Model

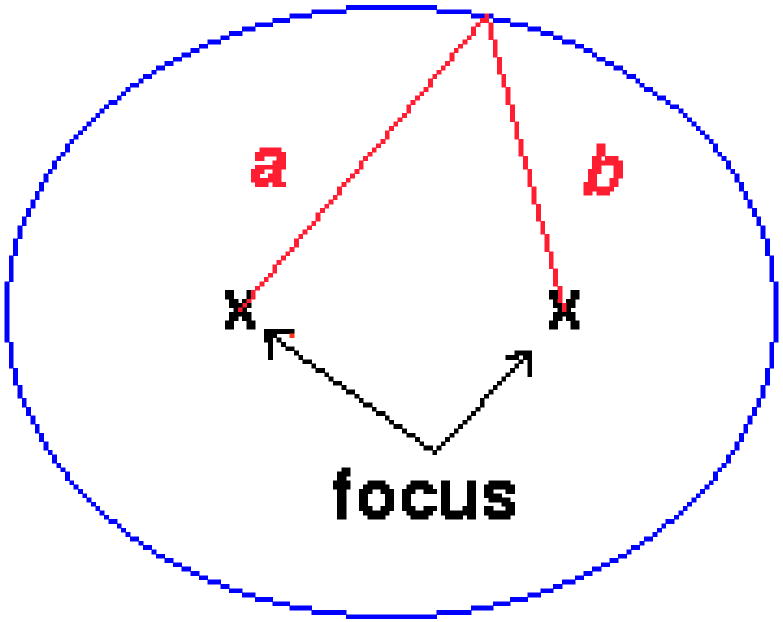
In 1601, replaced Tycho Brahe as mathematician to Emperor Rudolph II – inherited Tycho’s planetary data, but couldn’t make his model work

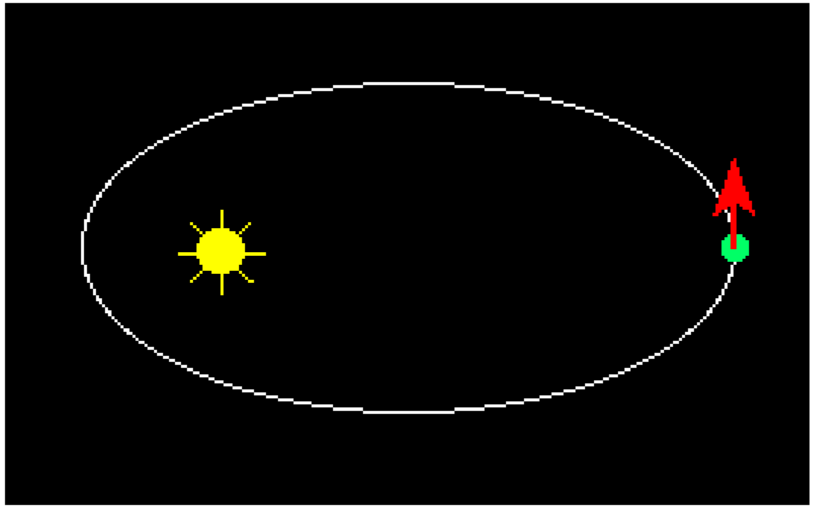


Kepler abandoned 2000-year-old belief in circular, uniform orbits

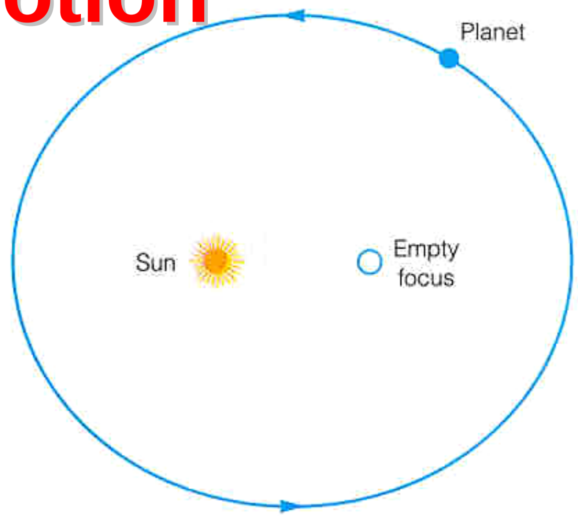
Kepler's Laws of Planetary Motion





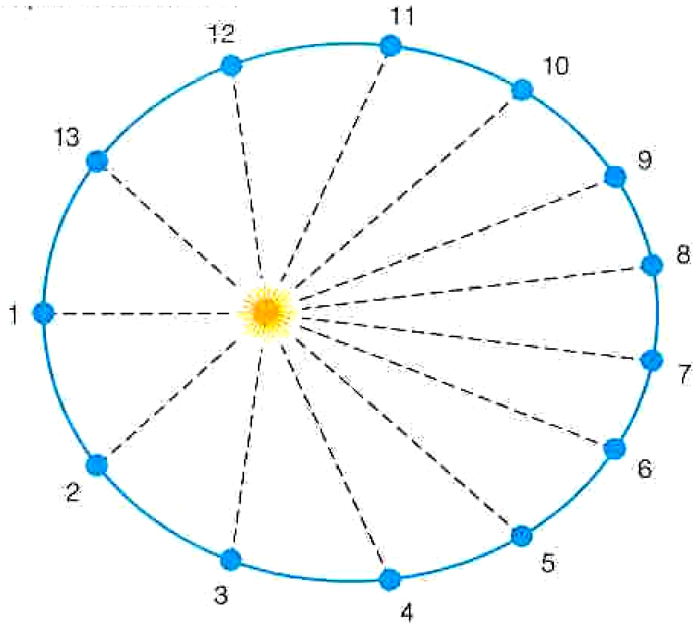


Kepler's Laws of Planetary Motion



1) Planets orbit the Sun in an ellipse with the Sun at one focus

2) During a planet's orbit around the Sun, equal areas are swept out in equal times

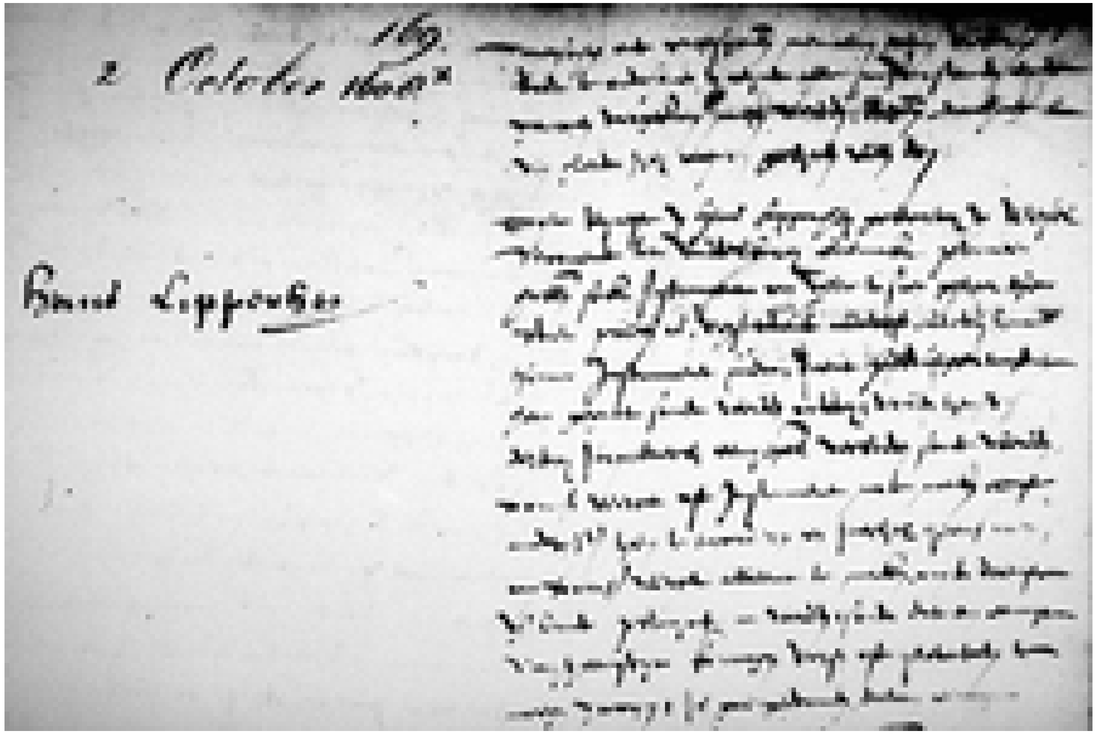


3) The square of a planet's orbital period is proportional to the cube of its mean distance from the Sun

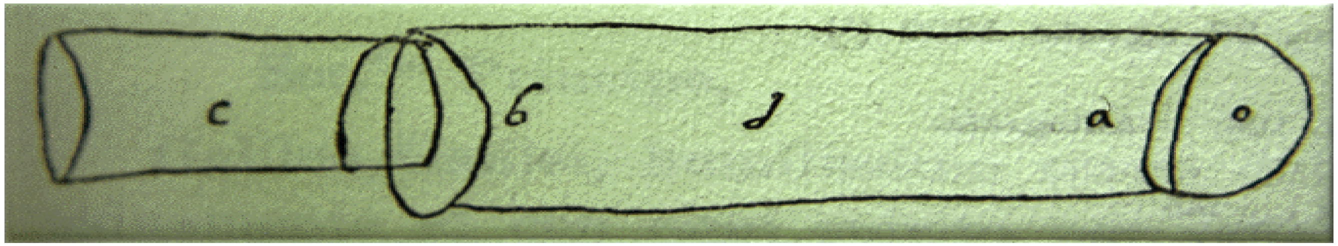
Kepler's Laws, published 1609, 1619

The Spectacle Vendor by Johannes Stradanus, 1582

Hans Lippershey's 1608 patent of a device for "seeing faraway things as though nearby."

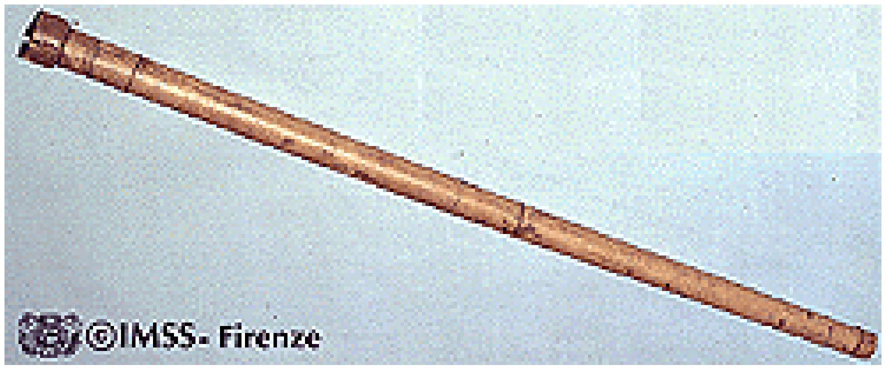


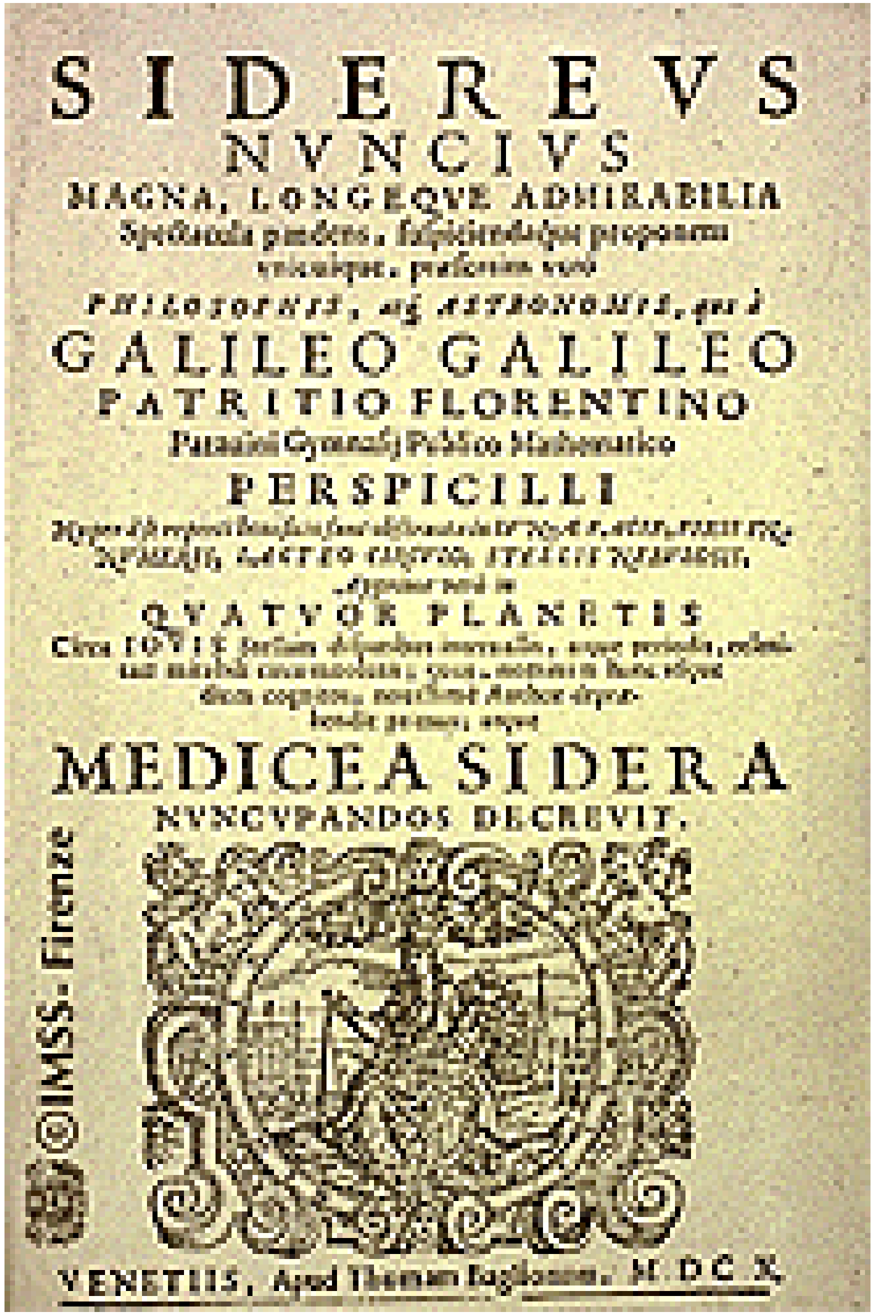
Porta's sketch of a telescope, August 1609



The Observations of Galileo

Galileo Galilei:
(1564 – 1642)

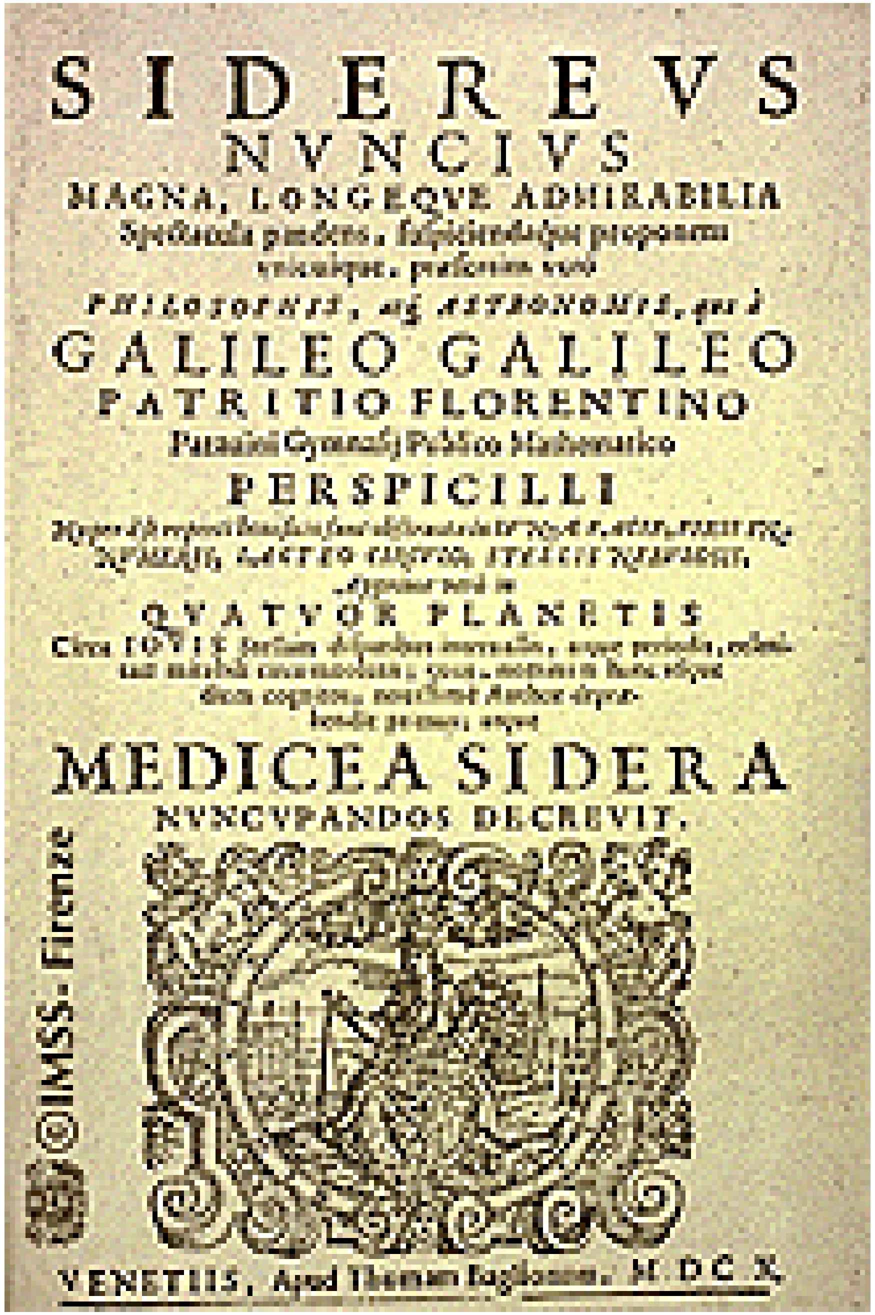




The "Starry Messenger"

Published in 1610

- Observations of the Moon
- Observations of the Milky Way
- Discovery of the Moons of Jupiter
- The nature of the planets


SIDEREVS
NVNCIVS
MAGNA, LONGEQVE ADMIRABILIA
PHILOSOPHIS, atq; ASTRONOMIS, quæ à
GALILEO GALILEO
PATRITIO FLORENTINO
Patauini Gymnasij Publico Mathematico
PERSPICILLI
QVATVOR PLANETIS
MEDICEA SIDERA
NVNCVPANDOS DECREVIT.
VENETIIS, Apud Thomam Baglionum. M DC X.

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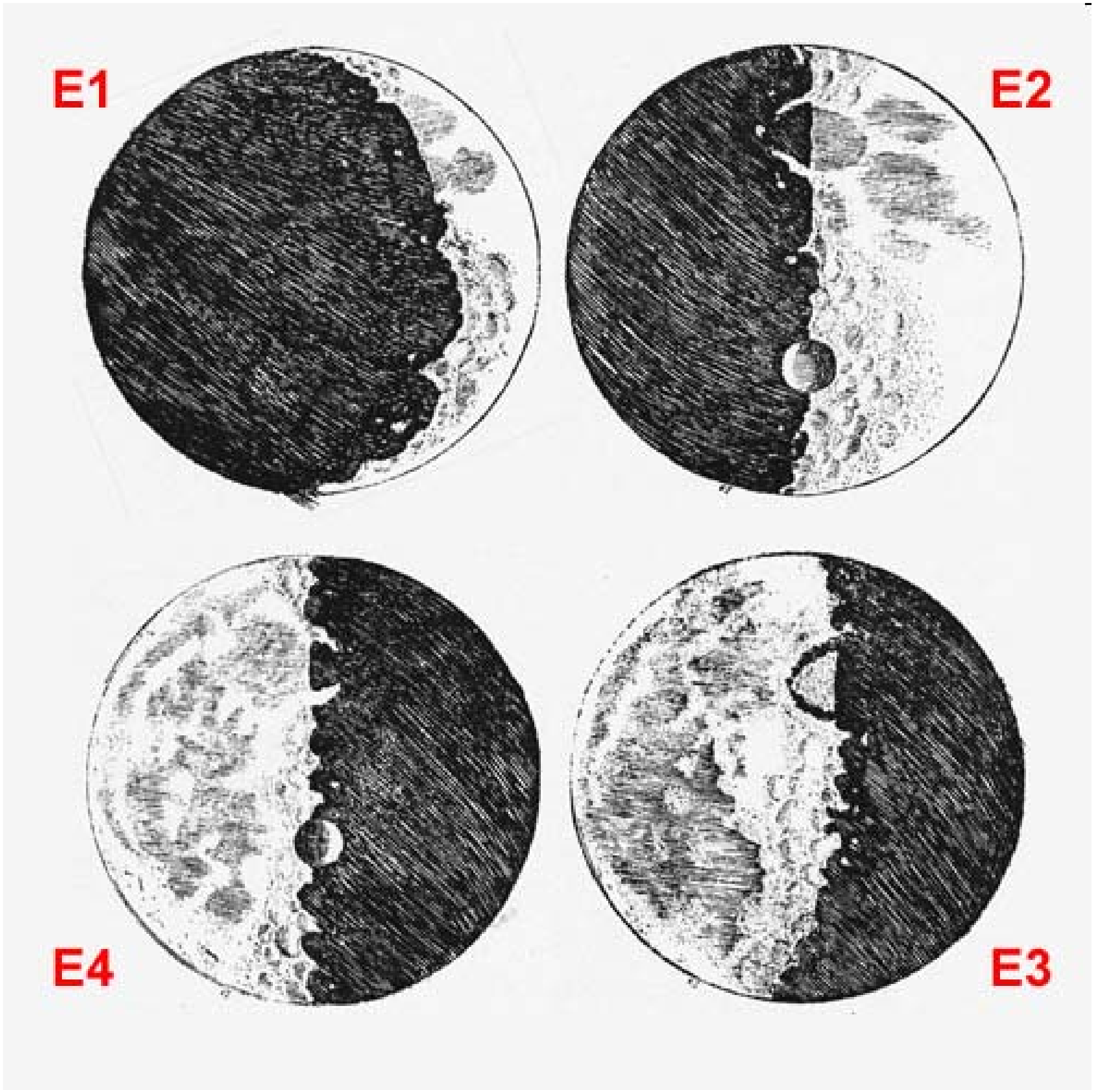

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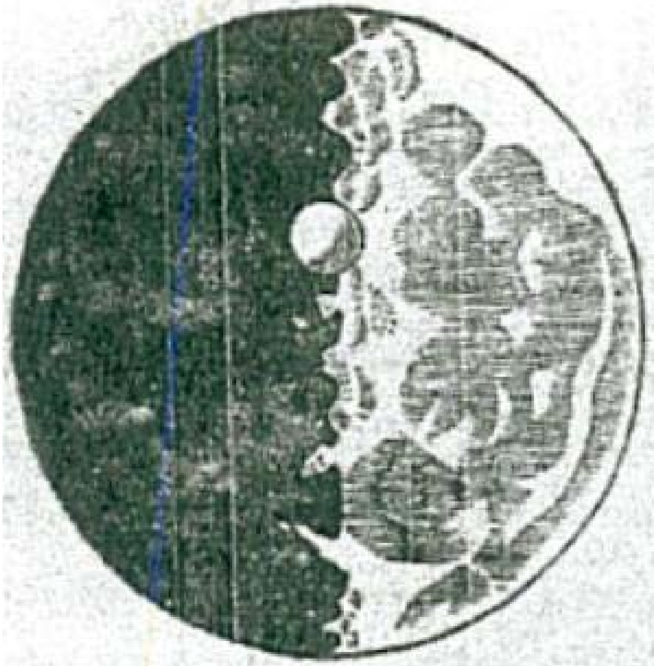
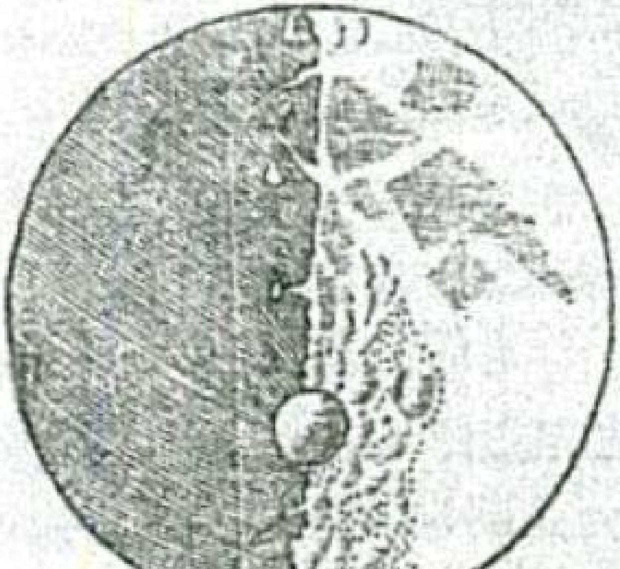
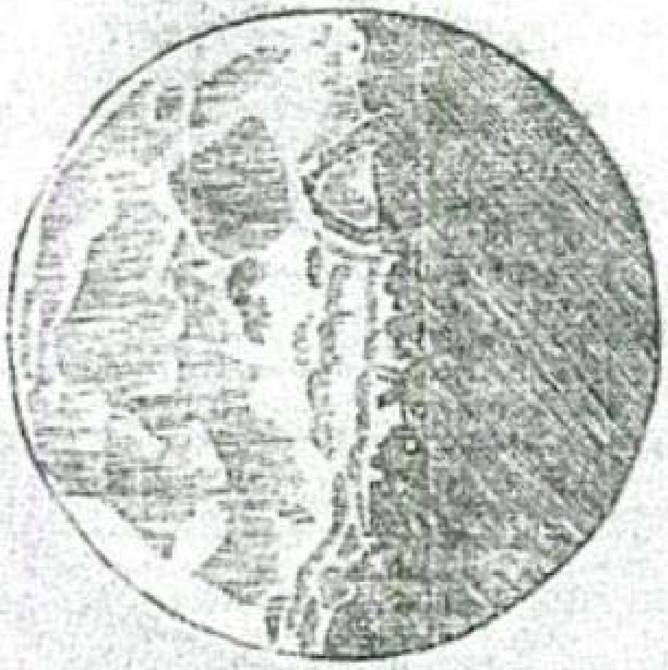
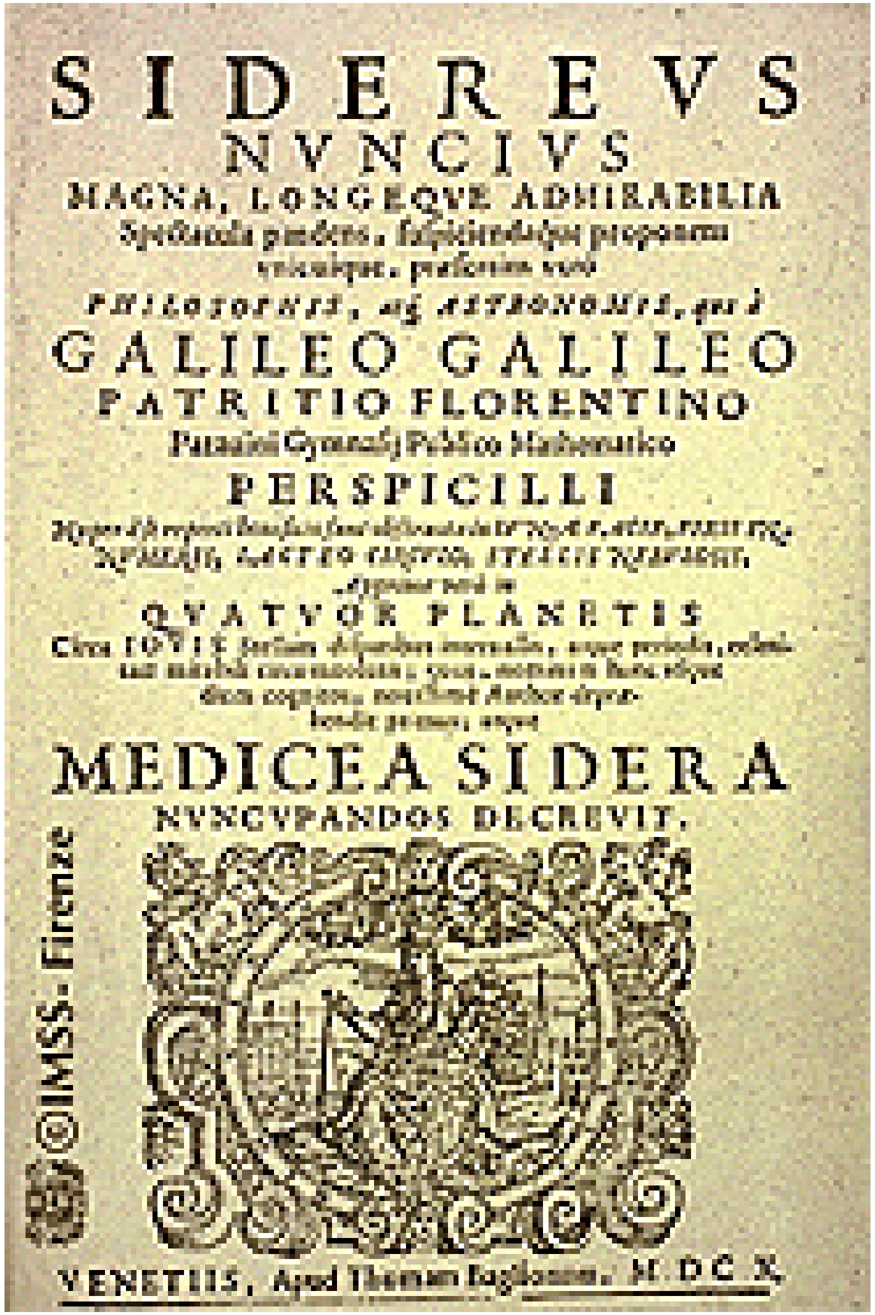
(1564 – 1642)





Hæc eadem macula ante secundam quadraturam nigri-
ribus quibusdam terminis circumvallata conspicitur, q
tanquam altissima montium iuga ex parte Soli aversa ol
scuriores apparent, quà vero Solem respiciunt, lucidior
extant, cuius oppositum in cavitatibus accidit, quarur
pars Soli aversa splendens apparet, obscura verò ac umbro
sa, quæ ex parte Solis sita est. Imminuta deinde lumino
sa superficie, cum primum tota ferme dicta macula tenebr
est obducta, clariora montium dorsa eminenter tenebra
scandunt. Hanc duplicem apparentiam sequentes figur
commonstrant.




SIDEREVS
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VENETIIS, Apud Thomam Baglionum. M DC X.
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The Pleiades


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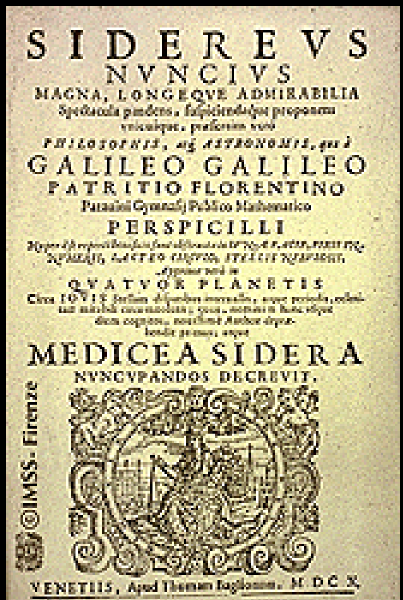

SIDEREVS
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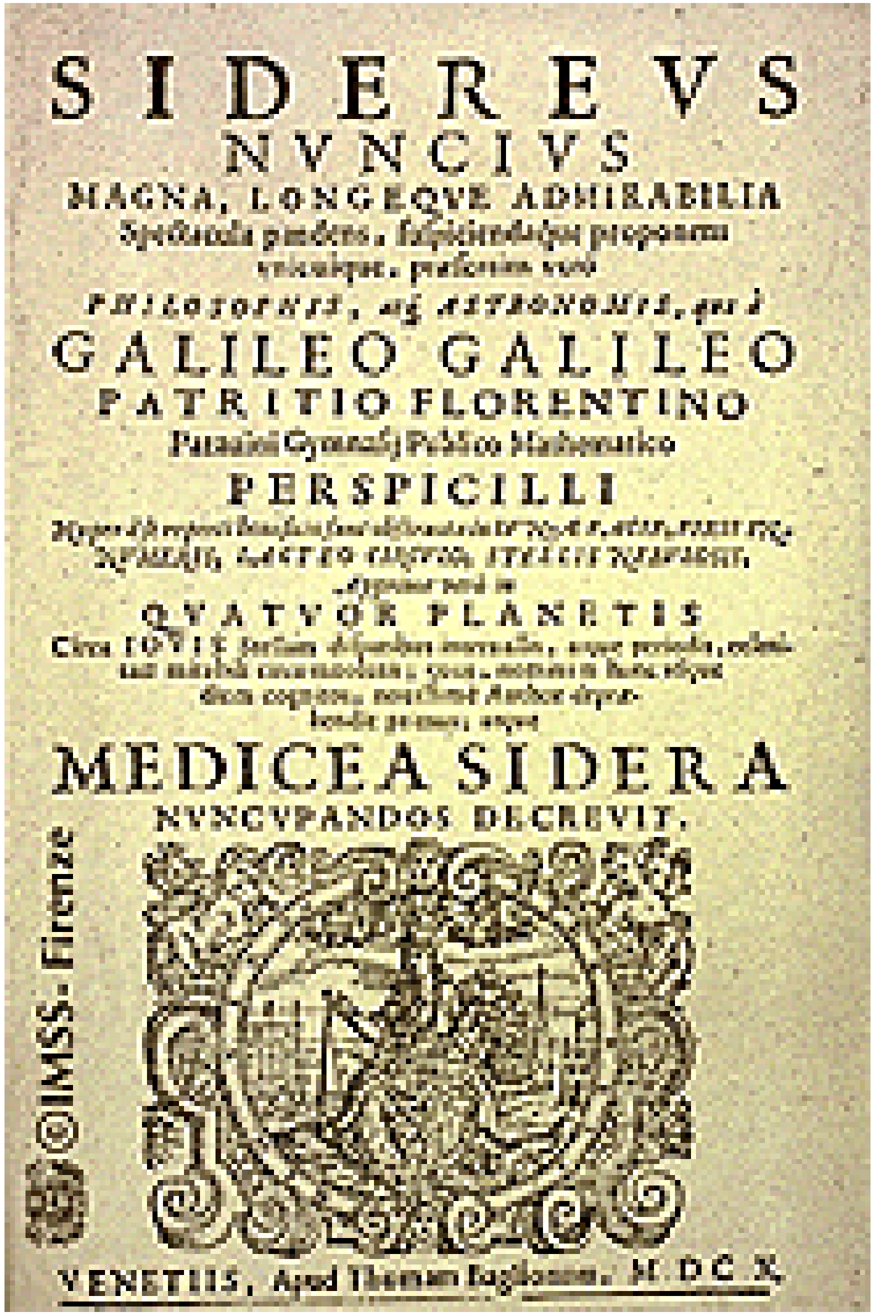
NVNCVPANDOS DECREVIT.
VENETIIS, M DC X

"I have observed the nature and the material of the Milky Way. With the aid of the telescope this has been scrutinized so directly and with such ocular certainty that all the disputes which have vexed philosophers through so many ages have been resolved, and we are at last freed from wordy debates about it.

The galaxy is, in fact, nothing but a collection of innumerable stars grouped together in clusters. Upon whatever part of it the telescope is directed, a vast crowd of stars is immediately presented to view. Many of them are rather large and quite bright, while the number of smaller ones is quite beyond calculation."

from The Starry Messenger (1610)

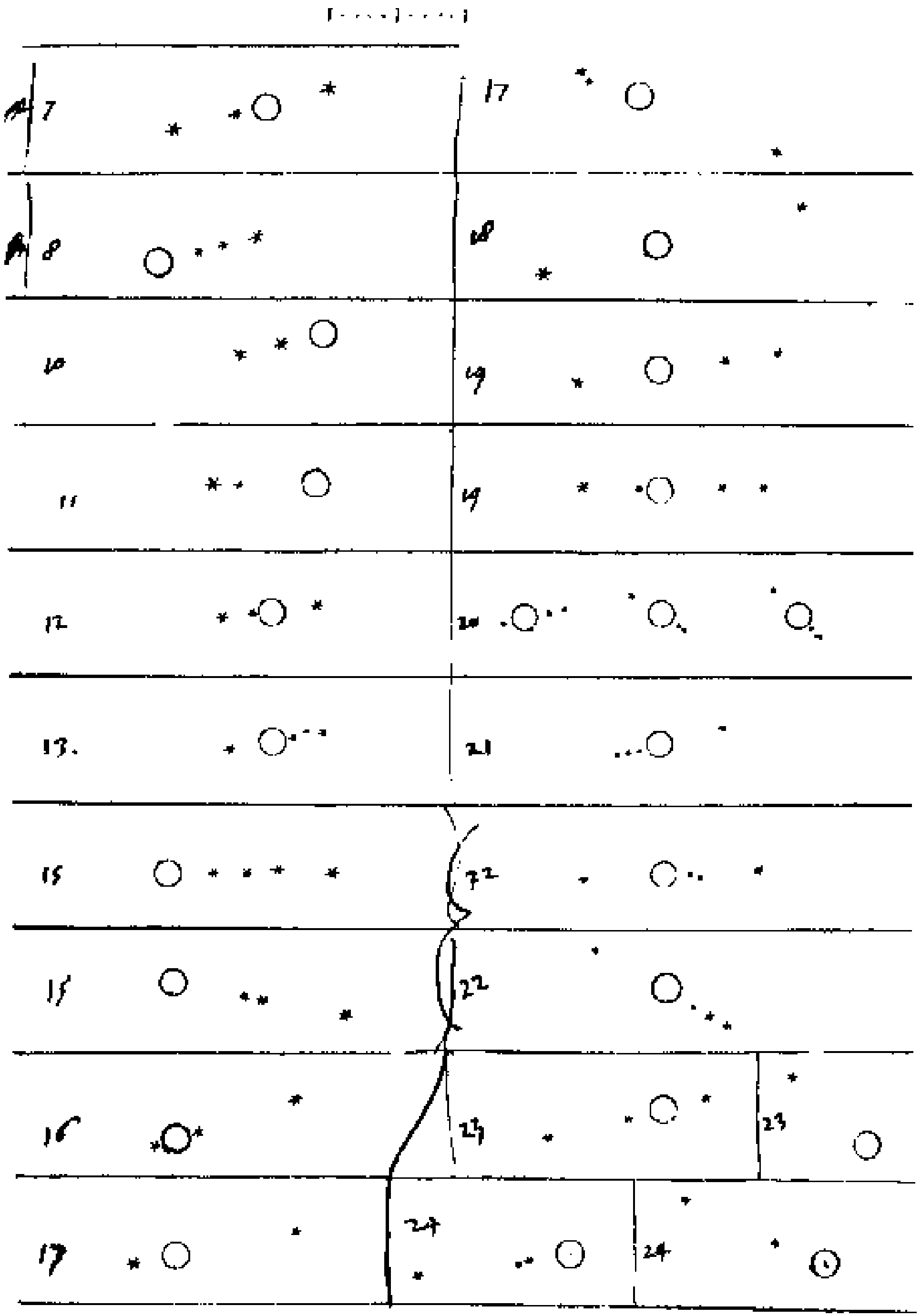


The “Starry Messenger”

Published in 1610

- Observations of the Moon
- Observations of the Milky Way
- Discovery of the Moons of Jupiter
- The nature of the planets

The moons of Jupiter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berat: Iuppiter à sequenti occidua min. 5. hæc ve-
rò à reliqua occidentaliori min. 3. erant omnes eius-

Ori. * O * * Occ.

dem proximè magnitudinis, satis conspicuæ, & in
eadem recta linea exquisitè secundum Zodiaci du-
ctum.

Die decimaseptima H. 1. duæ aderant Stellæ, orien-
talis vna à Ioue distans min. 3. occidentalis altera distas

Ori. * O * Occ.

min. 10. hæc erat aliquanto minor orientali. Sed hora
6. orientalis proximior erat Ioui distabat nempè min.
sec. 50. occidentalis verò remotior fuit, scilicet min. 12.
Fuerunt in vtraque obseruatione in eadem recta, & am-
bæ satis exiguæ, præsertim orientalis in secunda obserua
tione.

Die 18. Ho. 1. tres aderant Stellæ, quarum duæ occi-
dentales, orientalis verò vna: distabat orientalis à Ioue

Ori. * . O * * Occ.

min. 3. Occidentalis proxima m. 2. occidentalior reliqua
aberat à media m. 8. Omnes fuerunt in eadem recta ad
vnguem, & eiusdem ferè magnitudinis. At Hora 2. Stel-
læ viciniores paribus à Ioue aberant interstitijs; occidua
enim aberat ipsa quoque m. 3. Sed Hora 6. quarta Stel-
lula visa est inter orientaliorem & Iouem in tali configu
ratione. Orientalior distabat à sequenti m. 3. sequens à
Ioue

Ioue m. 1. sec. 50. Iuppiter ab occidentali sequenti m. 3.

Ori. * * O * * Occ.

hæc verò ab occidentaliori m. 7. erāt ferè æquales, orien
talis tantum Ioui proxima reliquis erat paulo minor,
eratque in eadem recta Eclypticæ parallela.

Die 19. Ho. 0. m. 40. Stellæ duæ solummodo occiduę
à Ioue conspectæ fuerunt satis magnæ, & in eadem re-

Ori. O * * Occ.

cta cum Ioue ad vnguem, ac secundum Eclypticæ ductū
dispositæ. Propinquior à Ioue distabat m. 7. hæc verò
ab occidentaliori m. 6.

Die 20. Nubilosum fuit cœlum.

Die 21. Ho. 1. m. 30. Stellulæ tres satis exiguæ cerne-
bantur in hac constitutione. Orientalis aberat à Ioue

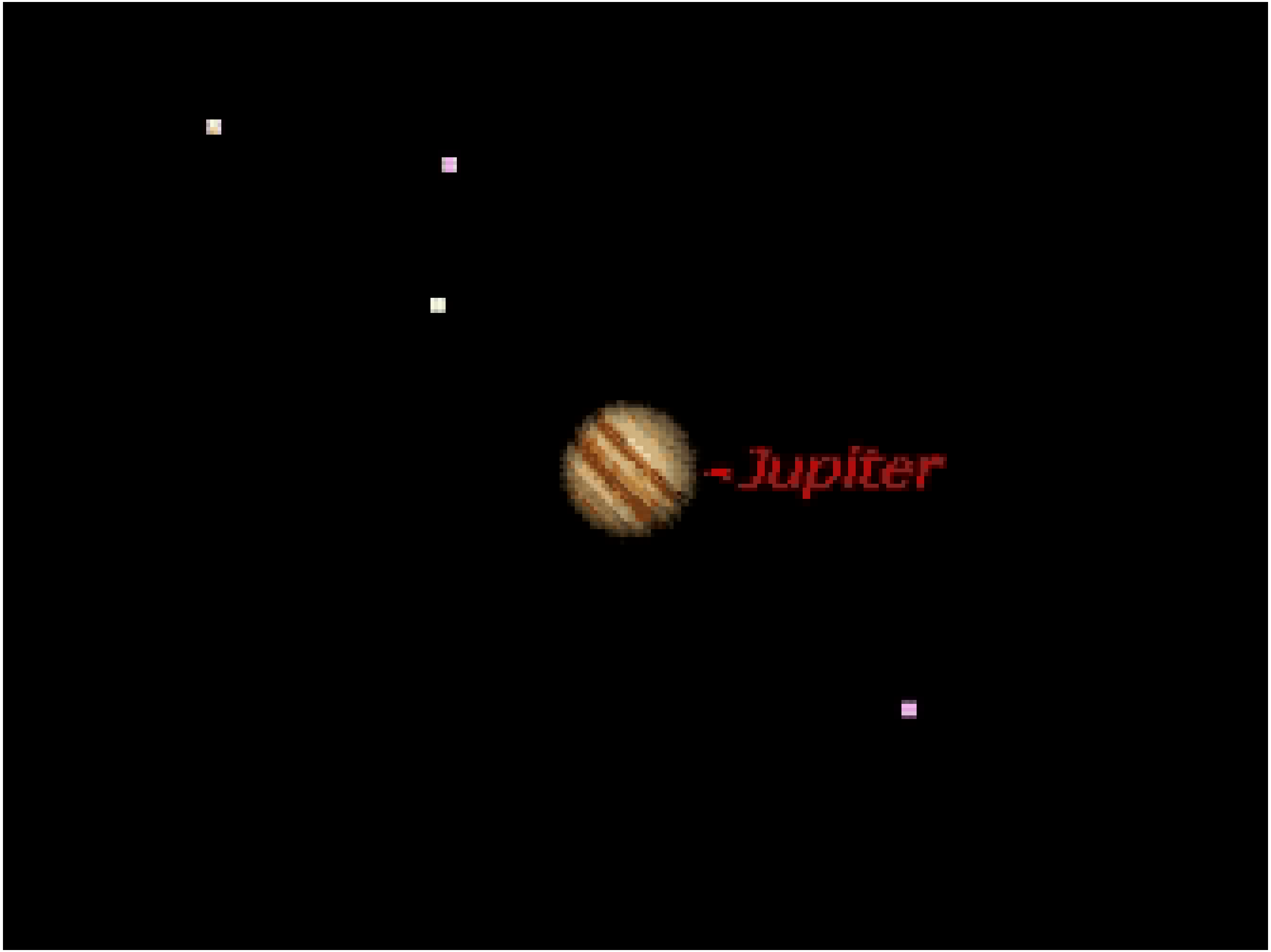
Ori. * O * * Occ.

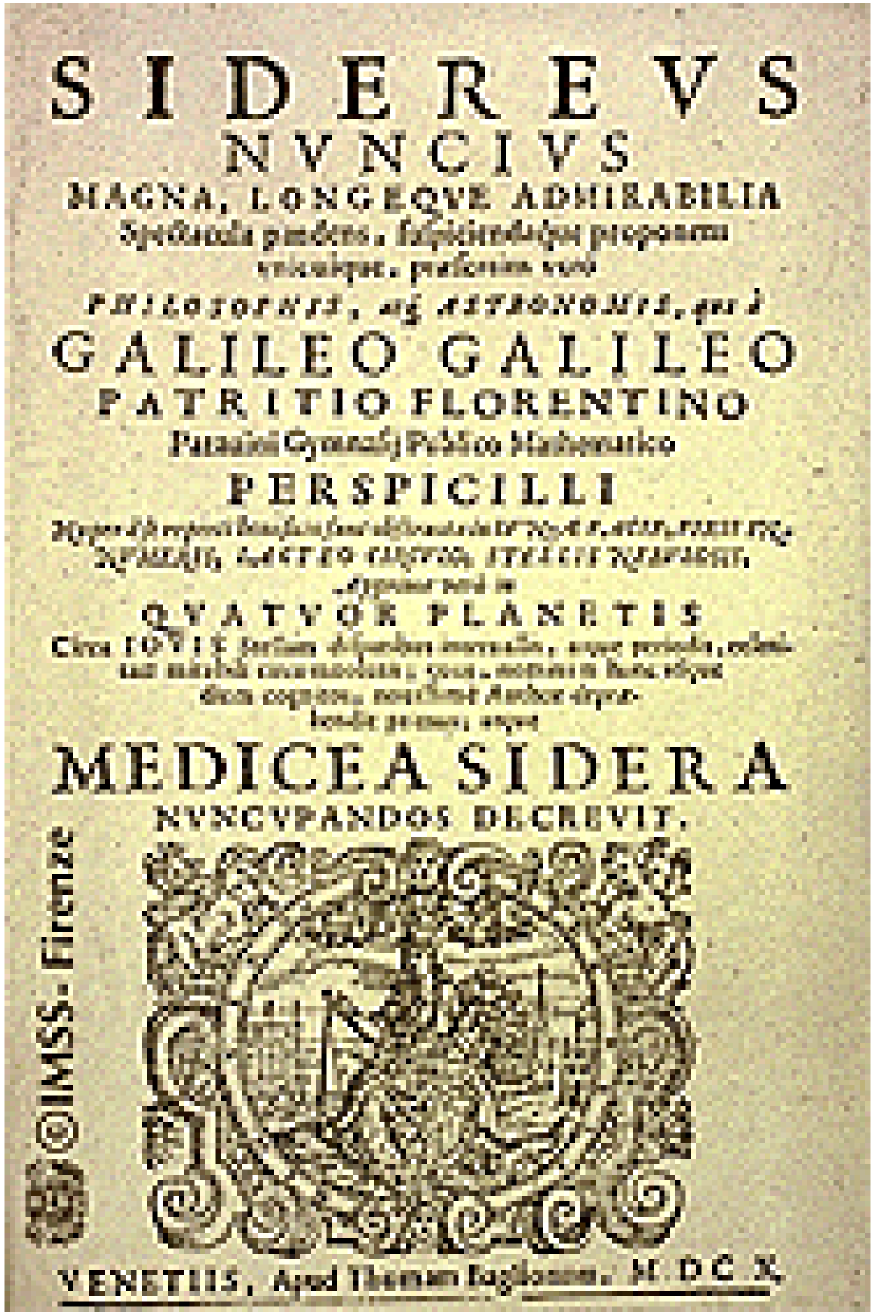
m. 2. Iuppiter ab occidentali sequente m. 3. hæc verò ab
occidentaliori m. 7. erant ad vnguē in eadem recta Ecly-
pticæ parallela.

Die 25. Ho. 1. m. 30. (nam superioribus tribus nocti-
bus cœlū fuit nubibus obductum) tres apparuerūt Stel

Ori. * * O * Occ.

læ. Orientales duæ, quarum distantiæ inter se, & à Ioue


Jupiter



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Measuring stellar brightnesses

Hipparchus (160-127 BC) introduced a system of Magnitudes – scale of six classes:

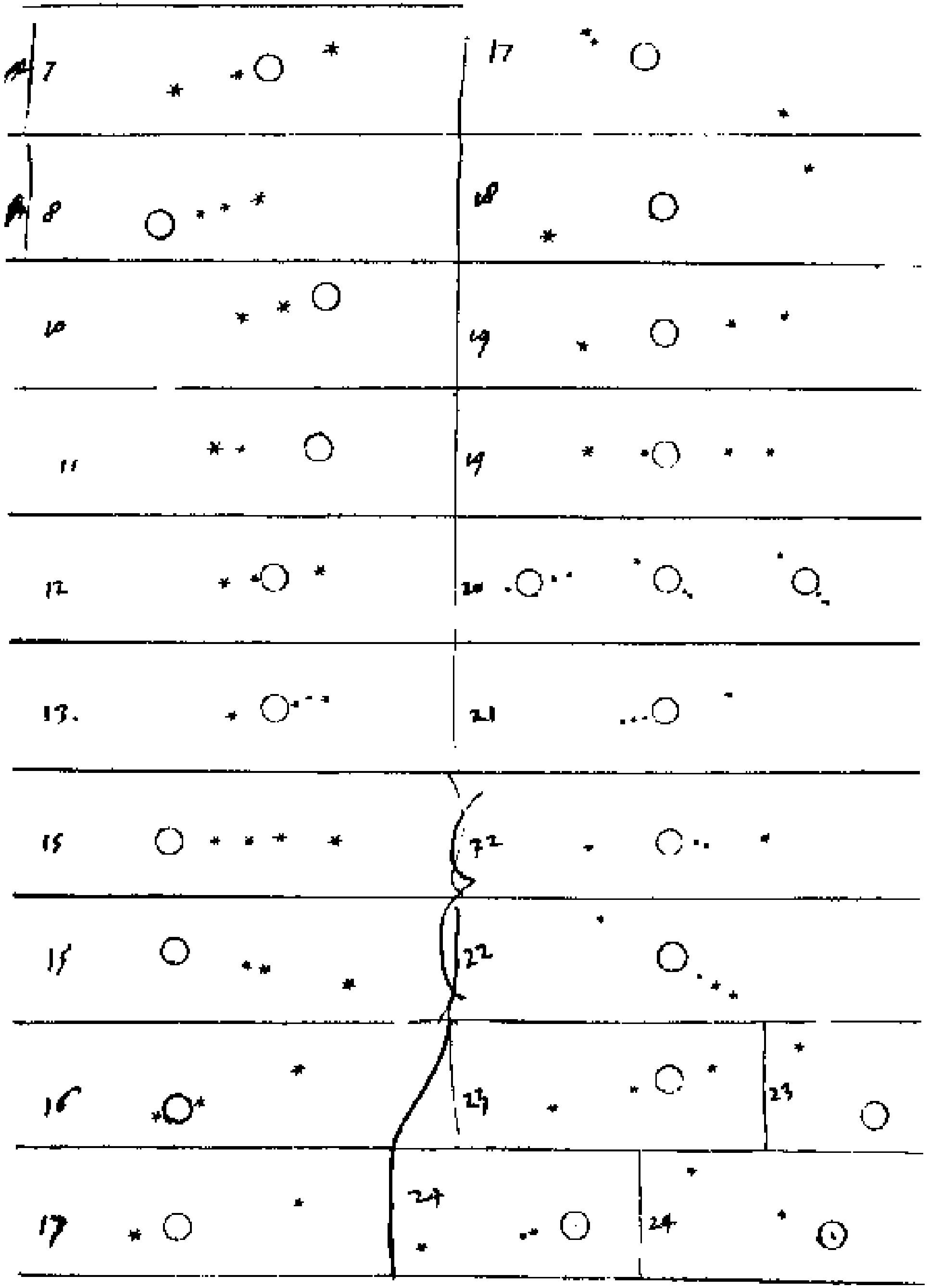
Brightest stars = 1st Magnitude

↓

Faintest stars = 6th Magnitude

(same as golf handicaps!)

Since Hipparchus' day,
magnitude system extended and refined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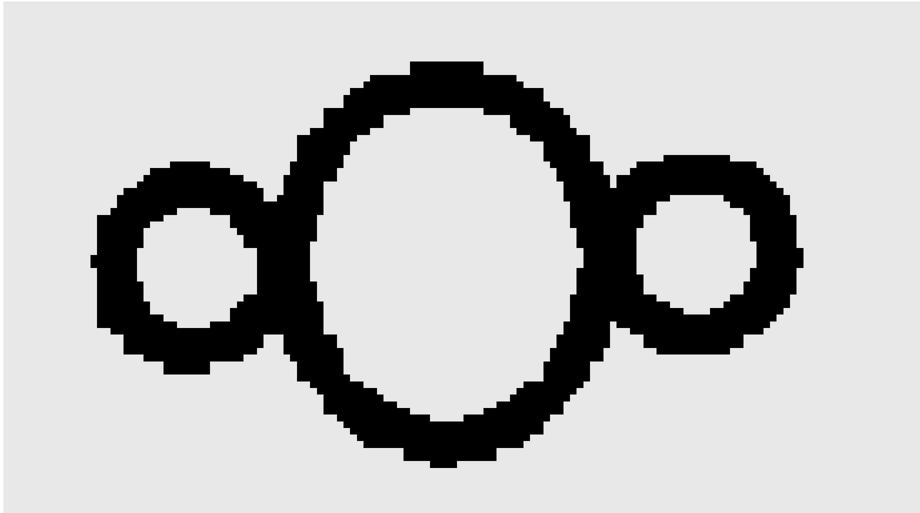
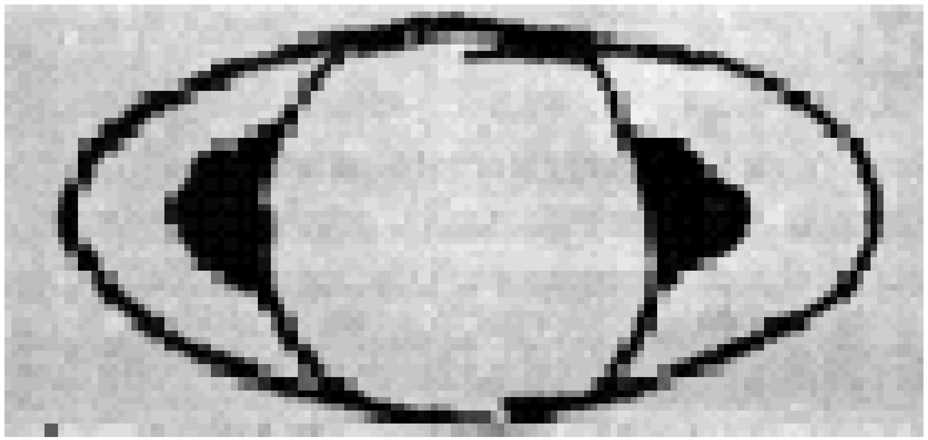
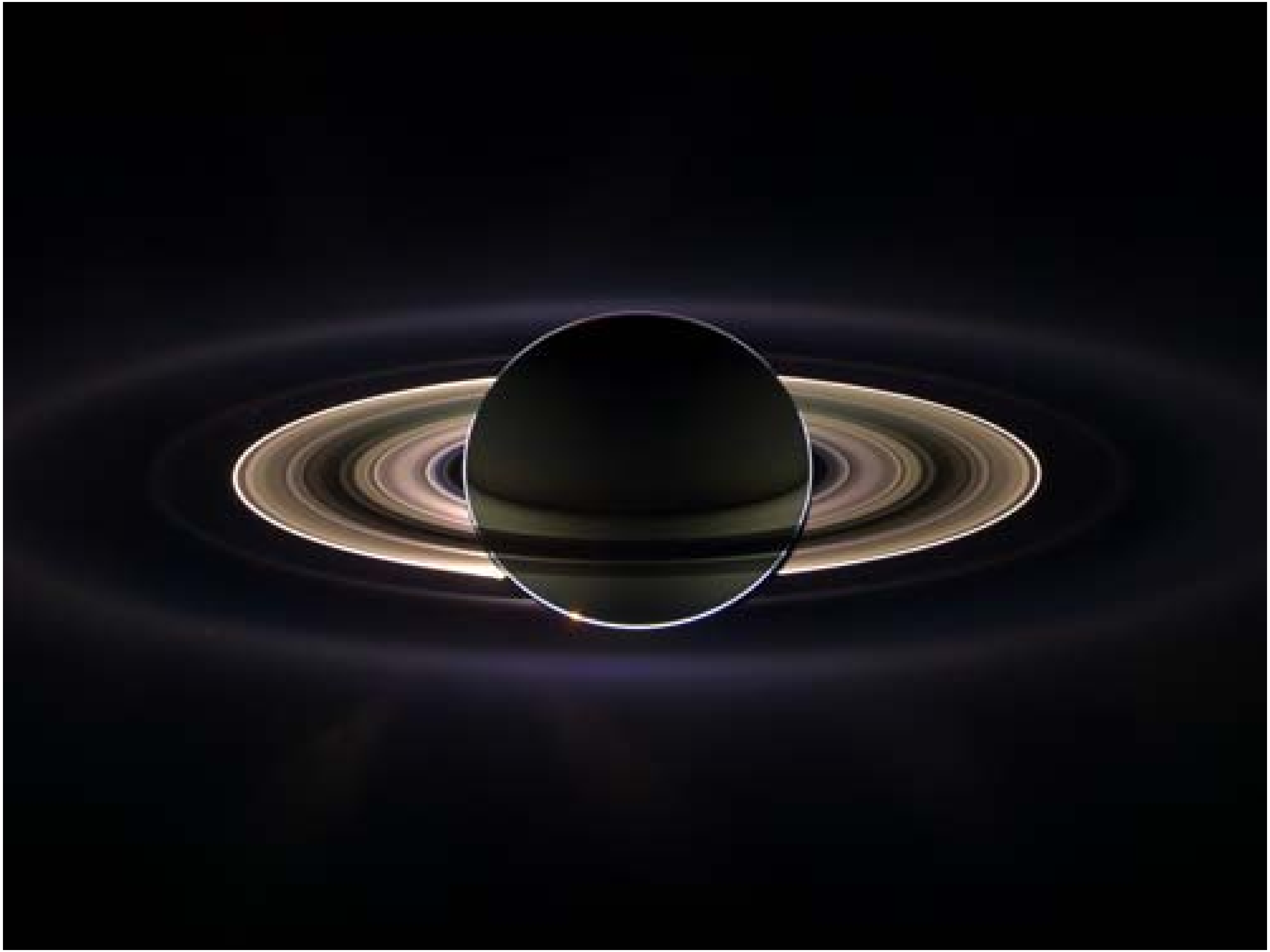
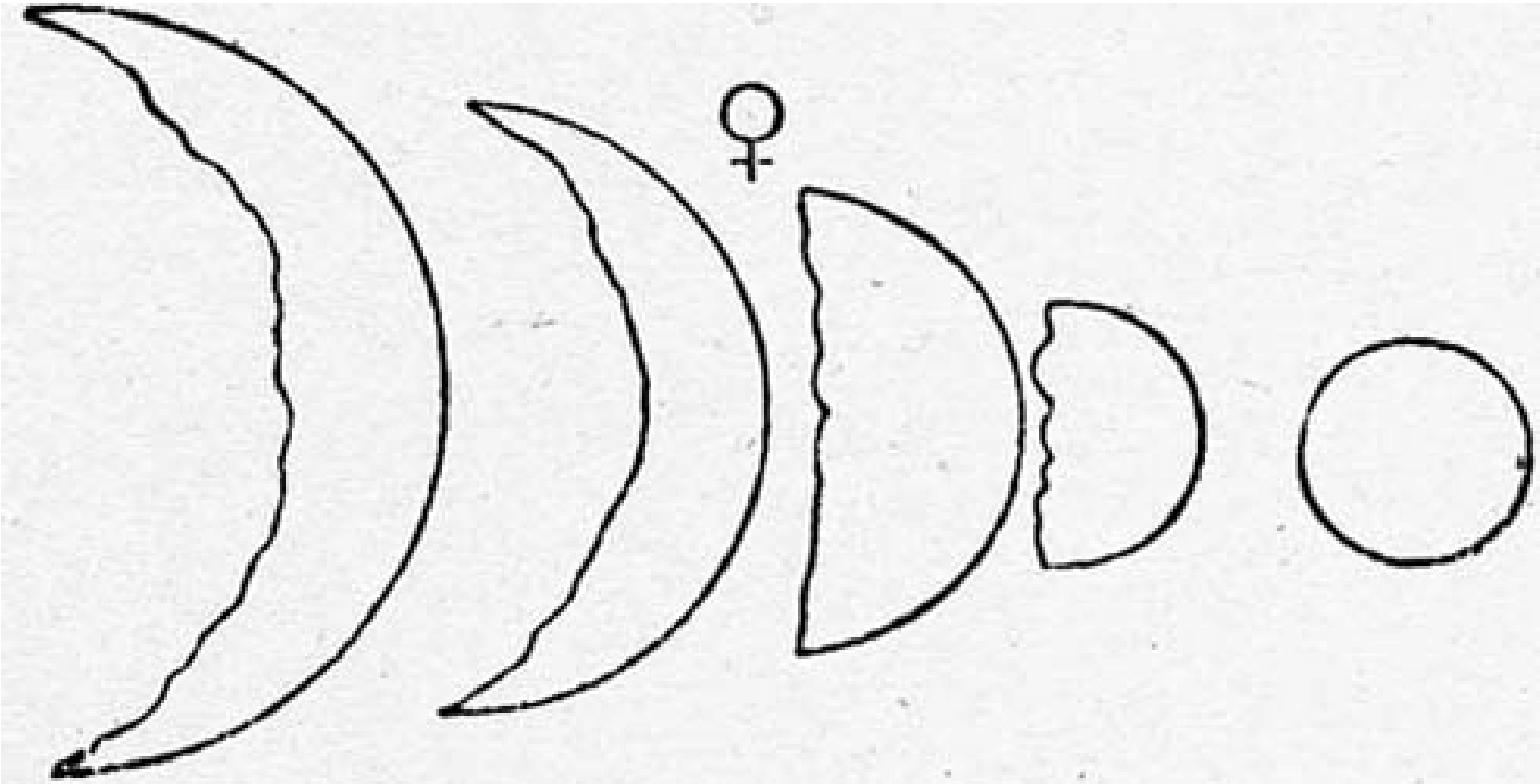






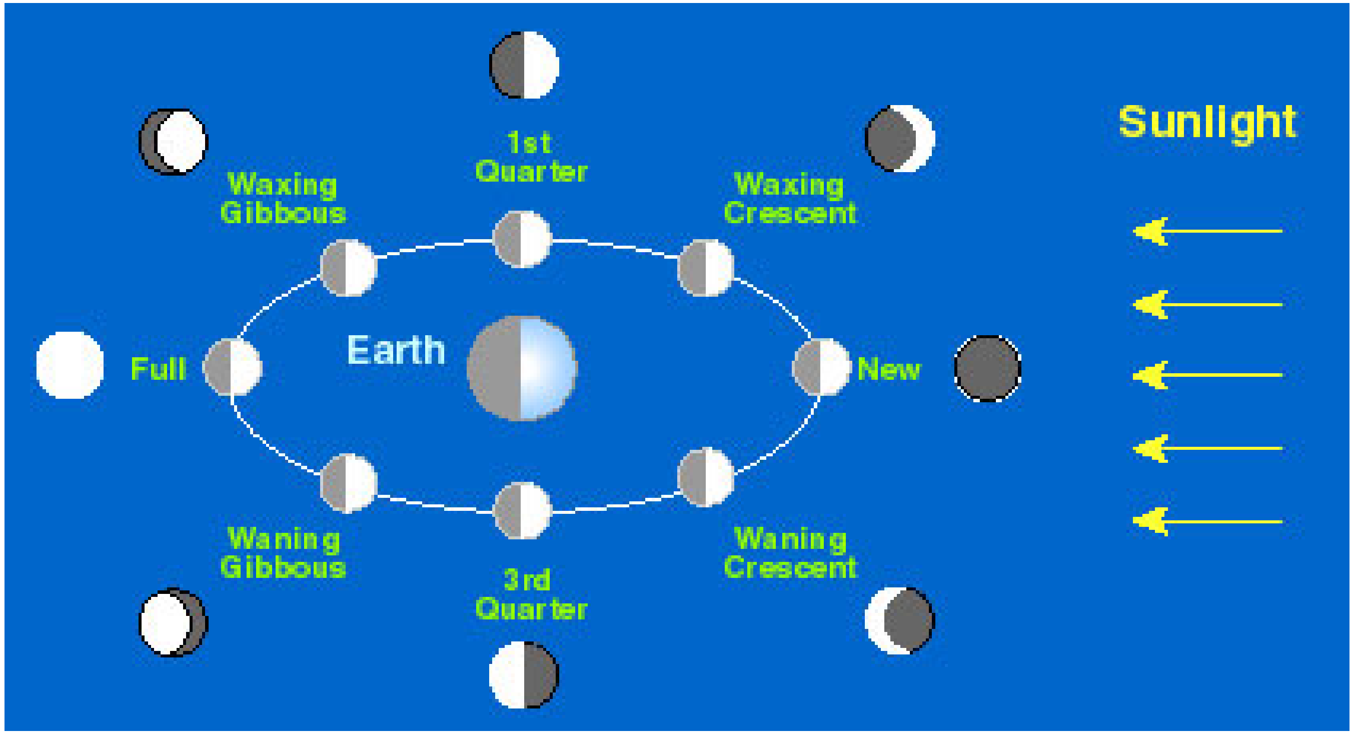
The Phases of Venus



Phases of the Moon

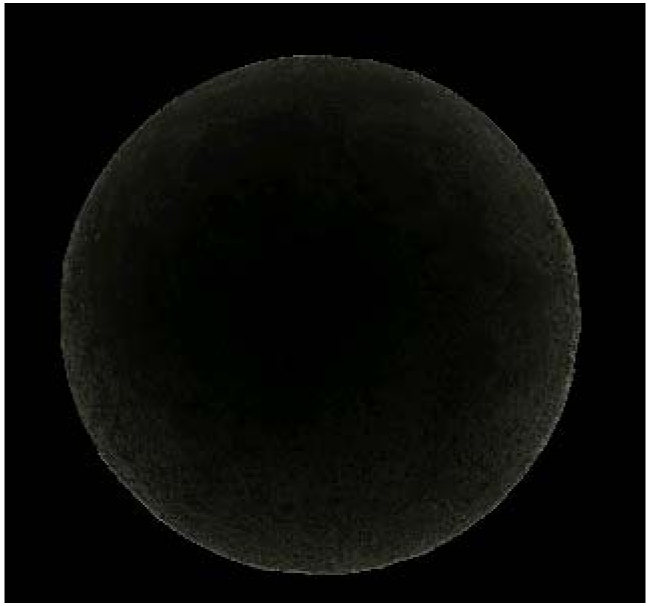
The Moon orbits the Earth once per <u>month</u>.

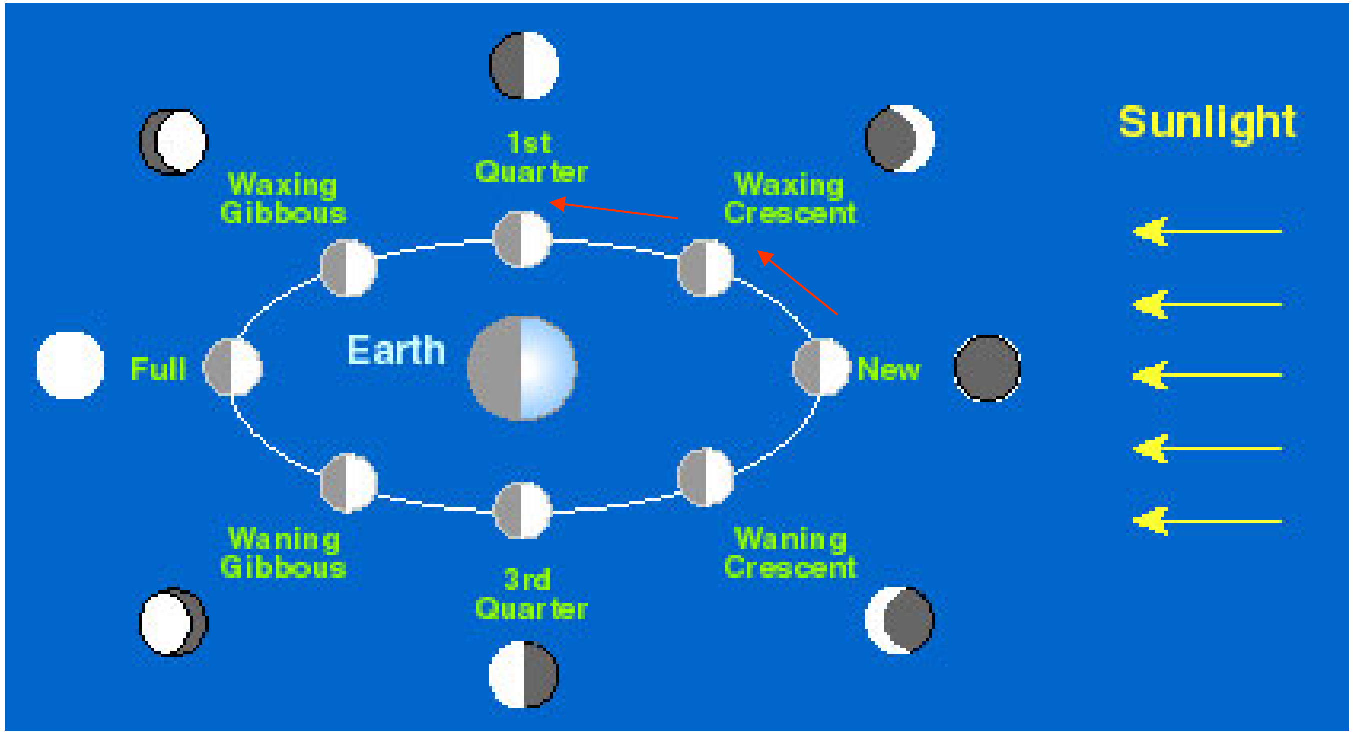
It doesn't shine itself, but reflects light from the Sun. This is why the Moon shows Phases



Phases of the Moon:

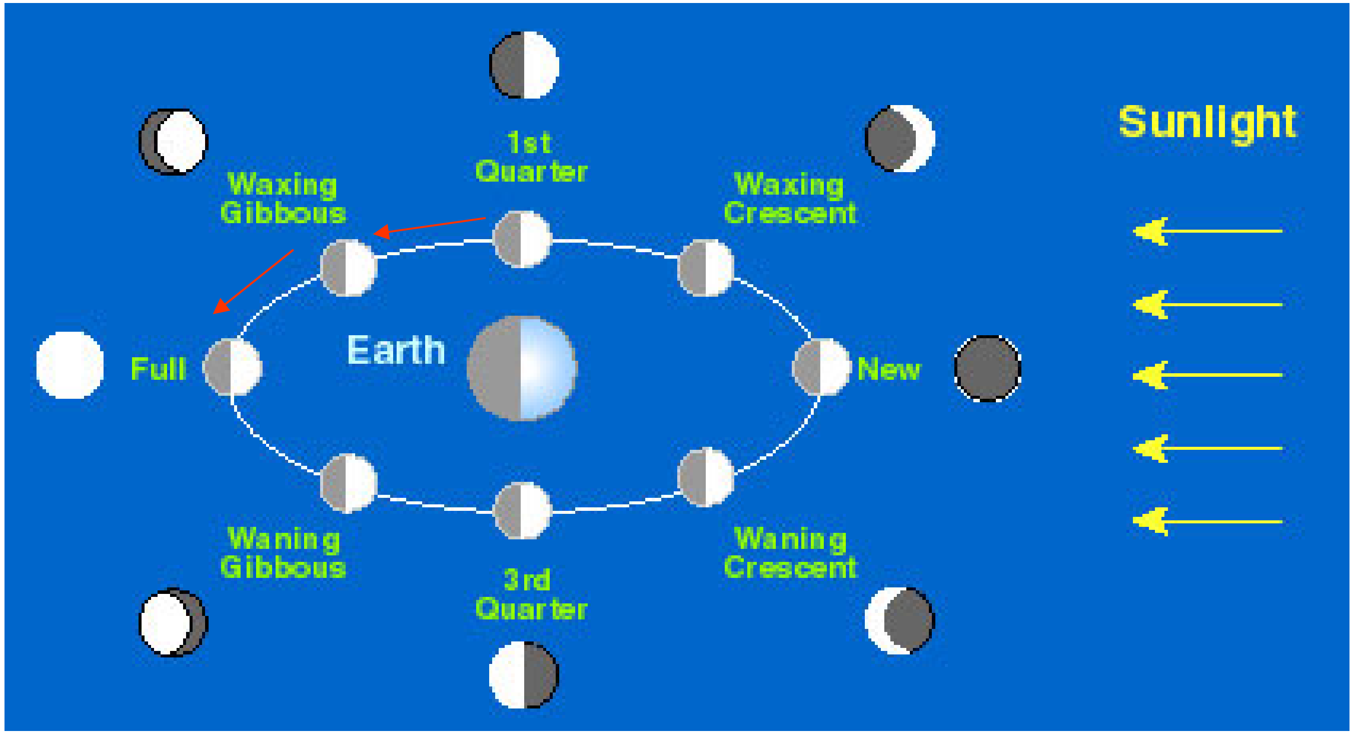
New Moon, through Waxing Crescent, to First Quarter





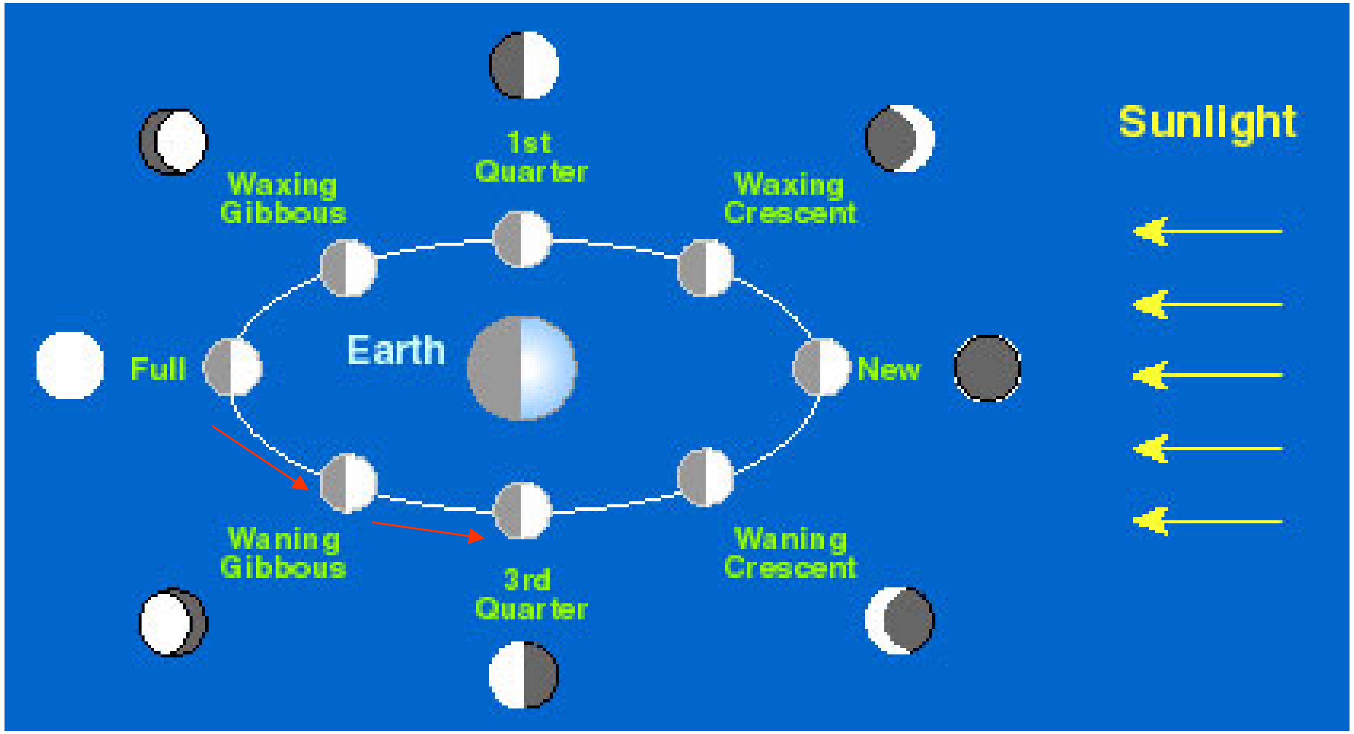
Phases of the Moon:

First Quarter, through Waxing Gibbous, to Full Moon



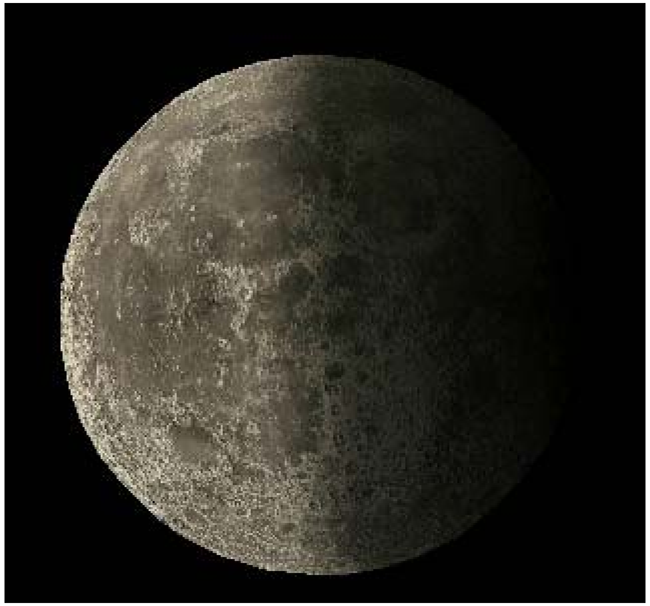
Phases of the Moon:

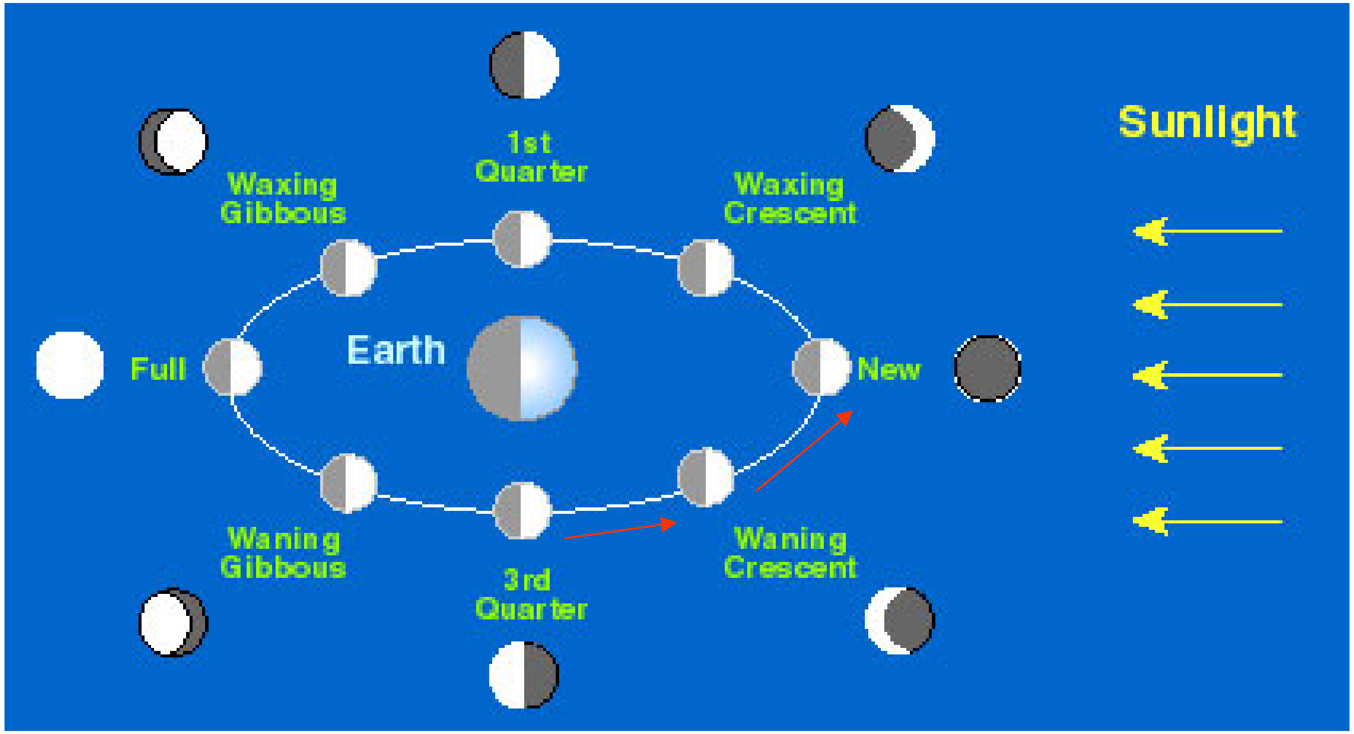
Full Moon, through Waning Gibbous, to Third Quarter



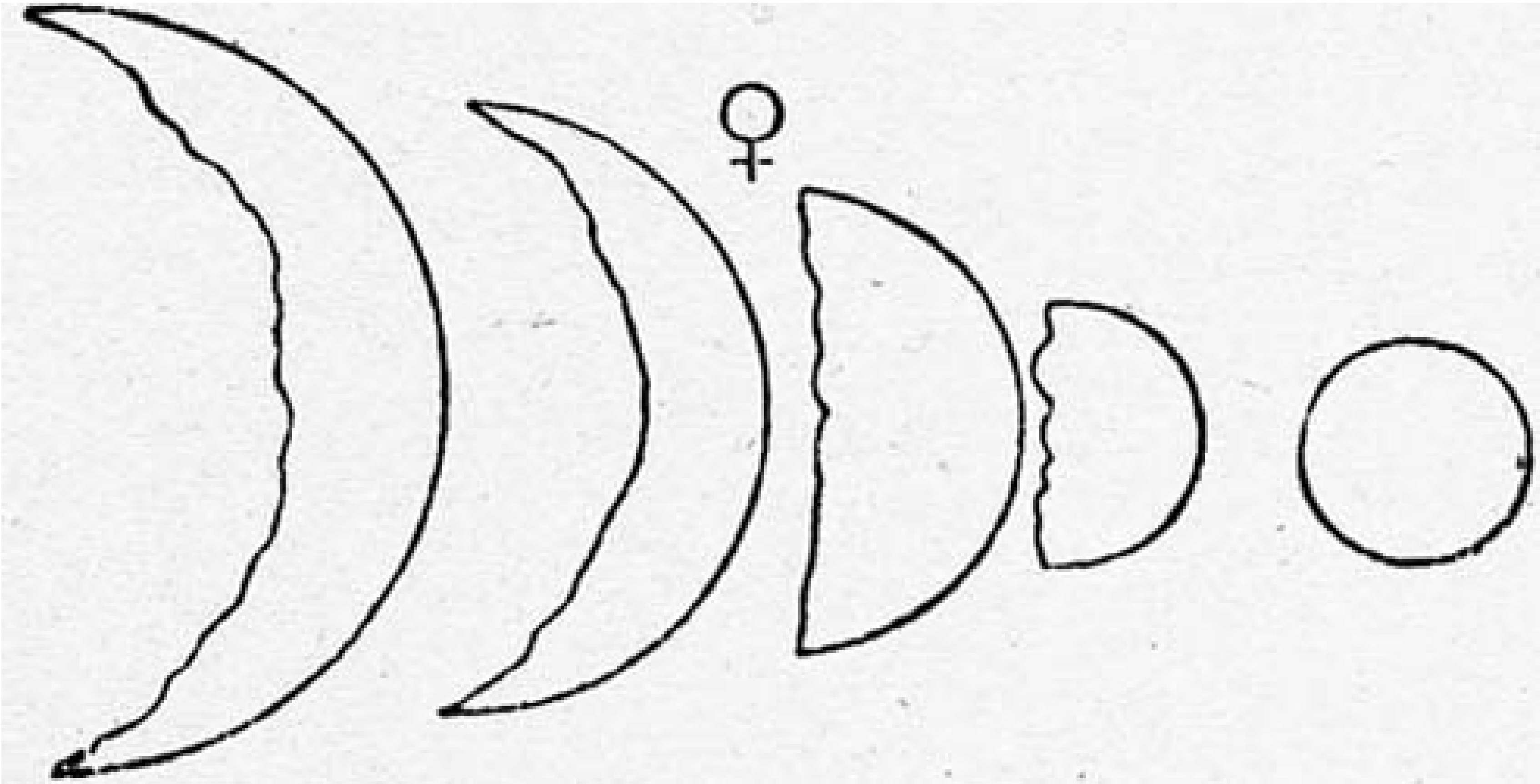
Phases of the Moon:

Third Quarter, through Waning Crescent to New Moon



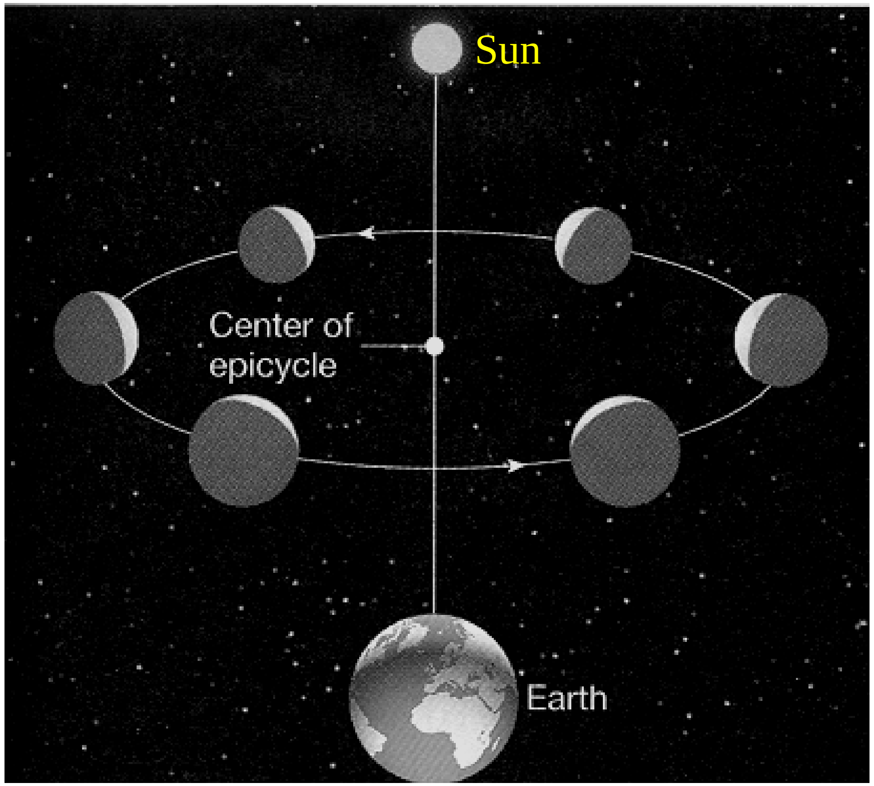


The Phases of Venus

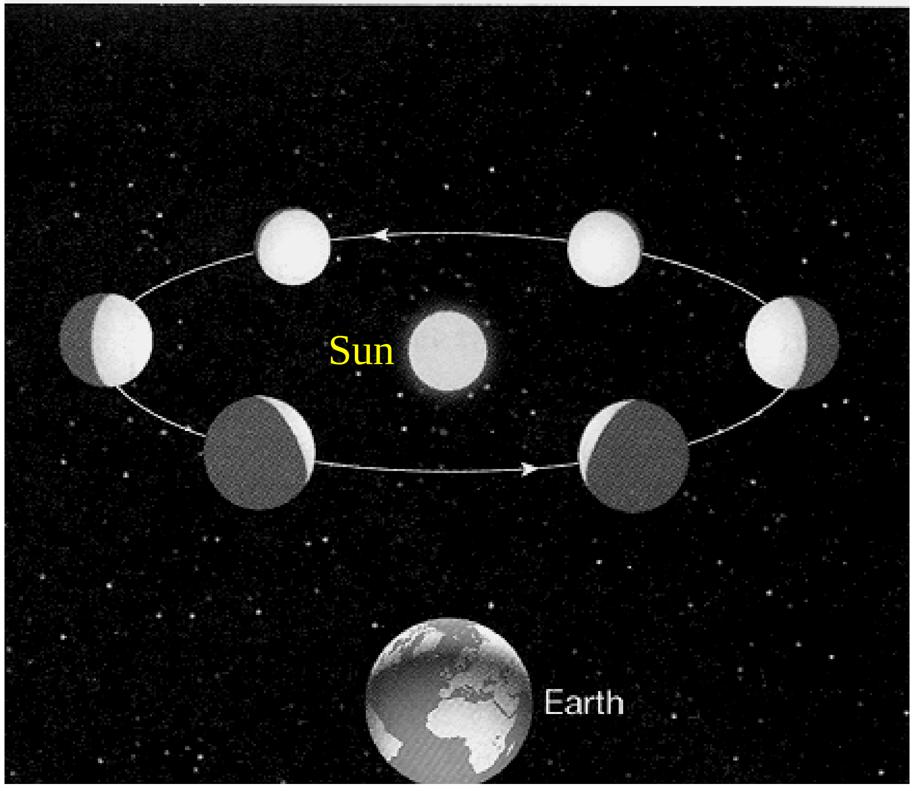


Galileo also observed the phases of Venus

Earth-centred



Sun-centred



The Observations of Galileo

Clear evidence that the Earth went round the Sun, and not the other way round

DIALOGO
DI
GALILEO GALILEI LINCEO

MATEMATICO SOPRAORDINARIO

DELLO STVDIO DI PISA.

E Filosofo, e Matematico primario del

SERENISSIMO

GR. DVCA DI TOSCANA.

Doue ne i congressi di quattro giornate si discorre
sopra i due

MASSIMI SISTEMI DEL MONDO
TOLEMAICO, E COPERNICANO;

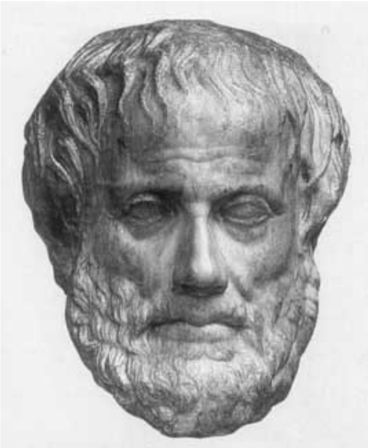
Proponendo indeterminatamente le ragioni Filosofiche, e Naturali tanto per l'vna, quanto per l'altra parte.

CON PRIVILEGI.

IN FIORENZA, Per Gio: Batista Landini MDCXXXII.

CON LICENZA DE' SVPERIORI.

How do things move?….



V

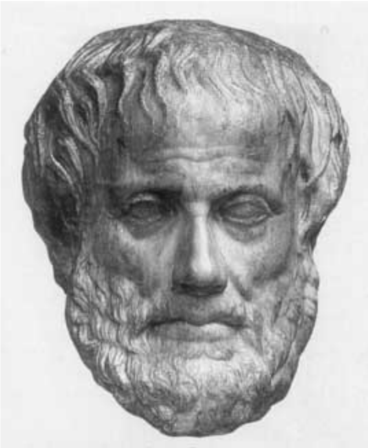
Aristotle's Theory:

1. *Objects move only as long as we apply a force to them*
2. *Falling bodies fall at a constant rate*
3. *Heavy bodies fall faster than light ones*

Galileo's Experiment:

1. *Objects keep moving after we stop applying a force (if no friction)*
2. *Falling bodies accelerate as they fall*
3. *Heavy bodies fall at the same rate as light ones*

How do things move?….



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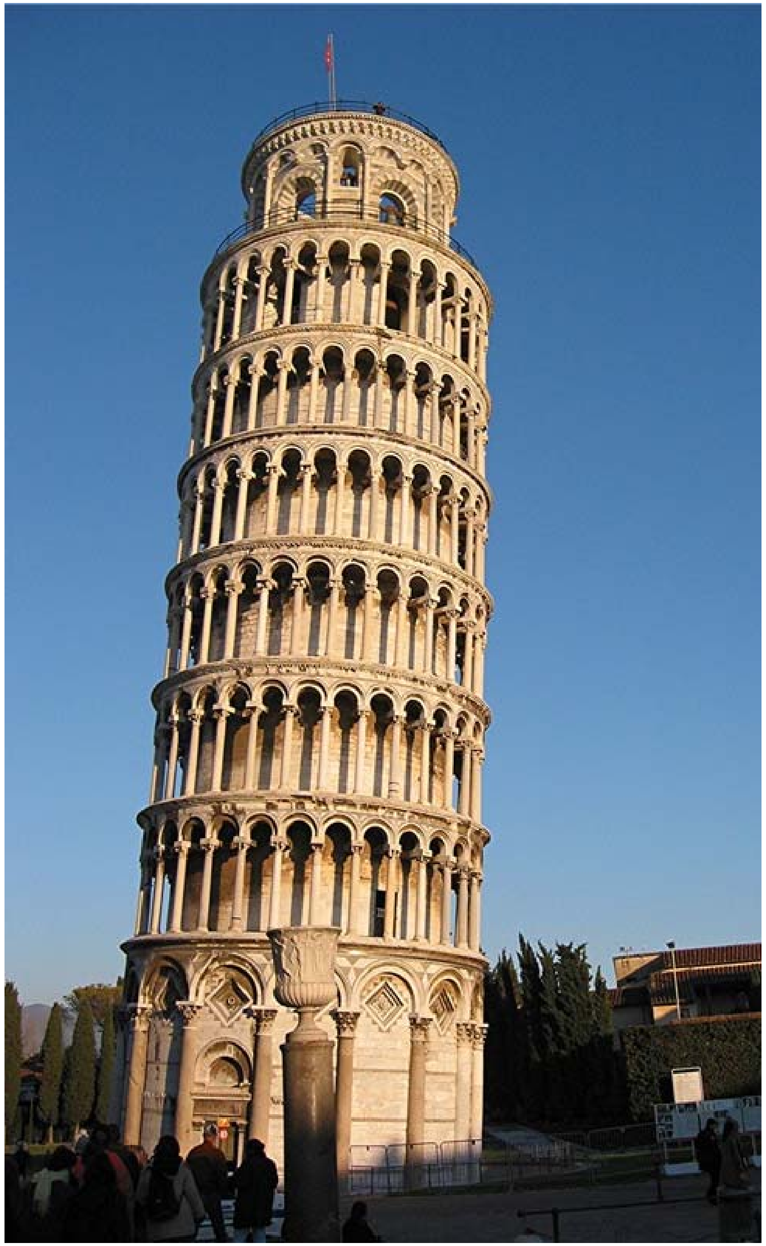

GINGIN OBSERVATORY
THE SPACE PLACE

Gravity Discovery Centre

http://www.gdc.asn.au

Apollo 15 astronaut David Scott

THE UNIVERSE
YOURS TO DISCOVER

INTERNATIONAL YEAR OF
ASTRONOMY
2009