THE COPERNICAN REVOLUTION

Actually, due as much to Kepler and Galileo, but it "started" with Copernicus, so…..

Nicolas Copernicus (1473-1543)

Came to know of the model of Aristarchus while studying in Italy. In many ways, he was a conservative who believed in the Platonic concept of *uniform circular motion*. BUT:

- He felt that Ptolemy's *equant* violated this concept

- He knew that the planetary tables based on Ptolemy (the Alfonsine Tables) were seriously in error (one Jupiter/Saturn conjunction was off by 10 days; many positions were 5 degrees off)

Copernicus realized that the system could be simplified by making the Sun, not the Earth, the center of the universe.

1529 - *Commentariolis* circulated

1. The heavenly bodies do not all move about the same center

2. The Earth is not the center of the universe, only of the Moon's orbit and terrestrial gravity

3. The Sun is at the center of the planetary system and hence the universe

4. The stars are much farther from the Sun than the Earth is

5. Daily motion is due to the rotation of the Earth on its axis

6. Annual motion of the Sun is due to the Earth's motion around it (and the other planets orbit in the same fashion)

7. The apparent motion of the planets are due to the combined motions of the Earth and planets around the Sun

Note: Final version of the model not published until 1543!

Methods of Copernicus

Determination of Sidereal Periods of planets

Example: Inferior Planet

Let E = Sidereal Period of Earth; P = Sidereal Period of Planet
S = Synodic period of Earth/Planet

- Earth travels 360°/E deg/day

- Planet travels 360°/P deg/day
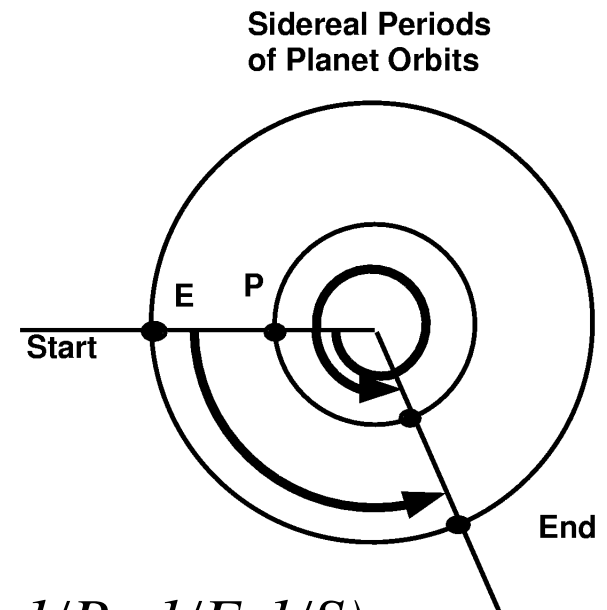
After a time equal to S days:

- Earth has gone S(360°/E) degrees

- Planet has gone S(360°/P) degrees

But here planet has traveled an additional 360° : S(360°/E)+360°=S(360°/P)

$\therefore$ ***1/P = 1/E + 1/S***

**Sidereal Periods
of Planet Orbits**

E   P

Start

End

(Superior Planet: 1/P=1/E-1/S)

Worked example:

The sidereal period of the Earth is 365.25 days

The observed synodic period of Venus with respect to Earth is 583.80 days.

What is the sidereal period of Venus?
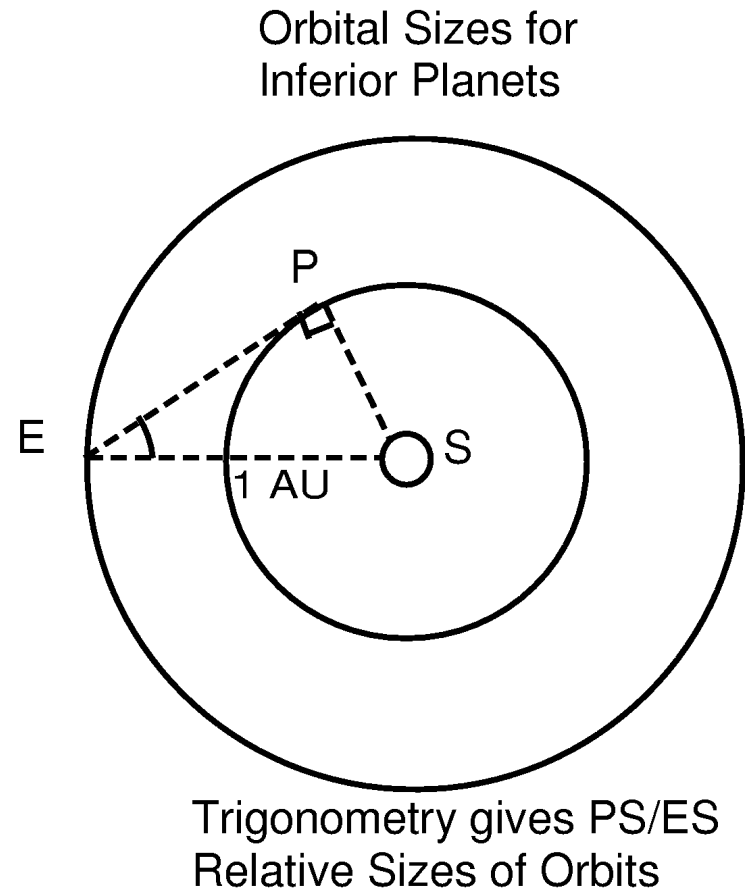
$1/P = 1/E + 1/S = (S+E)/(SE)$ so $P = (SE)/(S+E)$

$E = 365.25$ days

$S = 583.80$ days

$P = (583.80d \, x365.25d)/(583.80d \, x365.25d) = 224.68 days$

Sizes of Orbits

Example: Inferior Planet

Orbital Sizes for
Inferior Planets

P

E

S

1 AU

Trigonometry gives PS/ES
Relative Sizes of Orbits
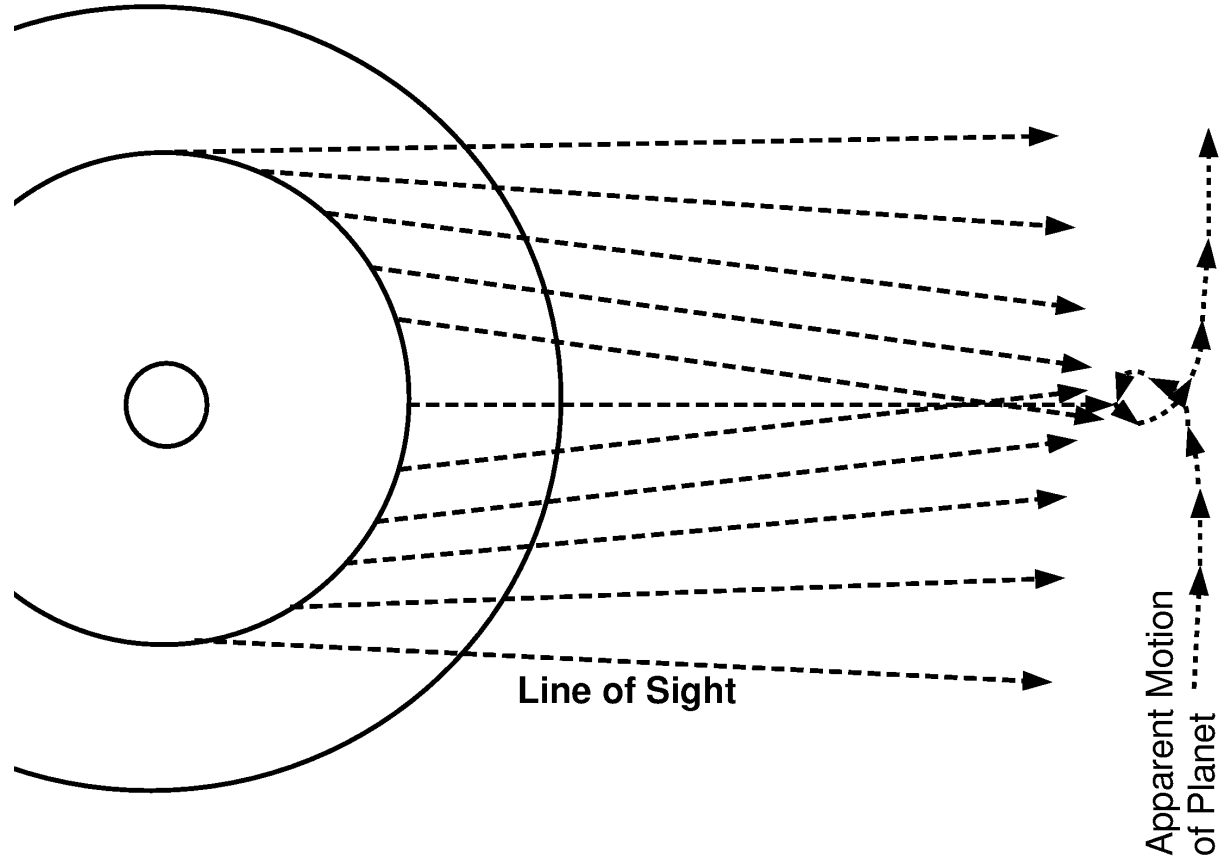
(For superior planets, a similar, but more complicated method can be used.)

Retrograde Motion

Superior Planet

Line of Sight

Apparent Motion of Planet

More History

1538 - Cardinal Schoenberg urges Copernicus to publish model & G.J. Rheticus learns of model

1539 - GJR visits Copernicus and gets permission to publish an "account" of the work, as long as Copernicus is not mentioned by name. *Narratio Prima* published.

1541 - GJR begins copying ***De Revolutionibus Orbium Coelestium*** for publication.

1542 - Typesetting begins, along with "anonymous preface" by Andreas Osiander, suggesting the model need not be true.

1543 - De Revolutionibus Orbium Coelestium published

- An all-time "worst-seller"
- 1st edition never sold out
- Only 4 editions in 330 years, with the first English translation in 1952
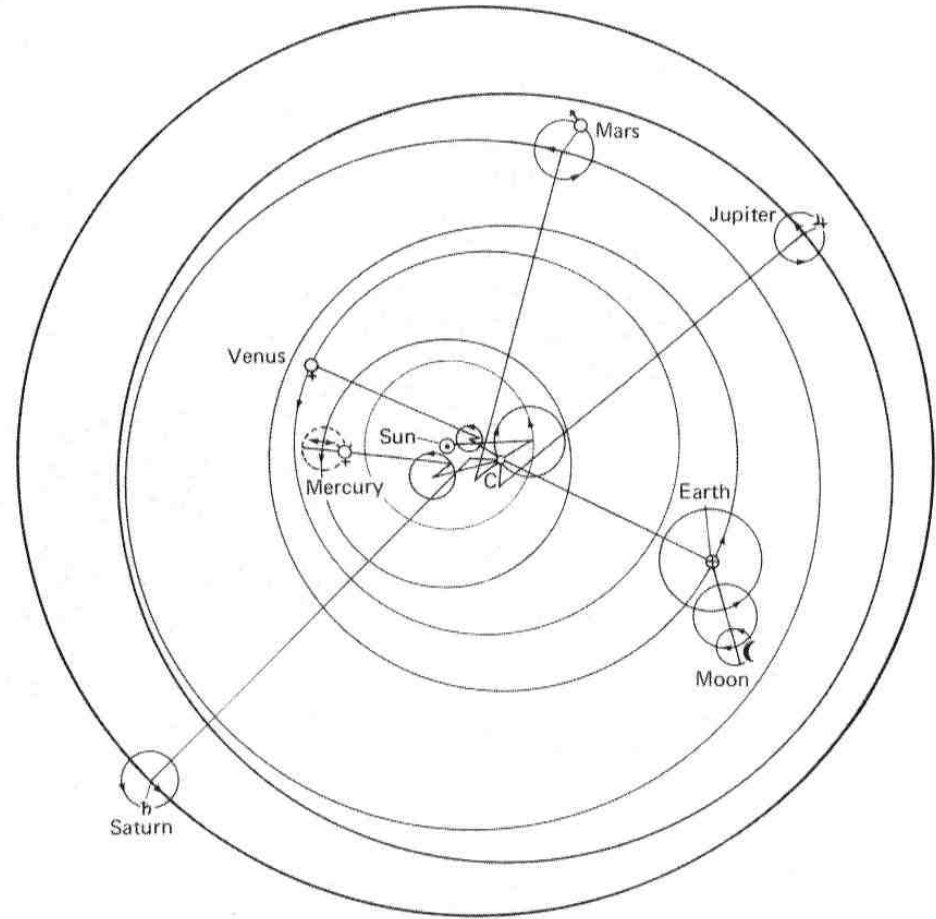- IT WAS UNREADABLE
        Other problems:
- Centers of orbits *near* Sun, but each planet had a *different* center!
- Eventually needed 48 circles (including epicycles). More accurate than Ptolemy, but just as complex.

Compare Models!
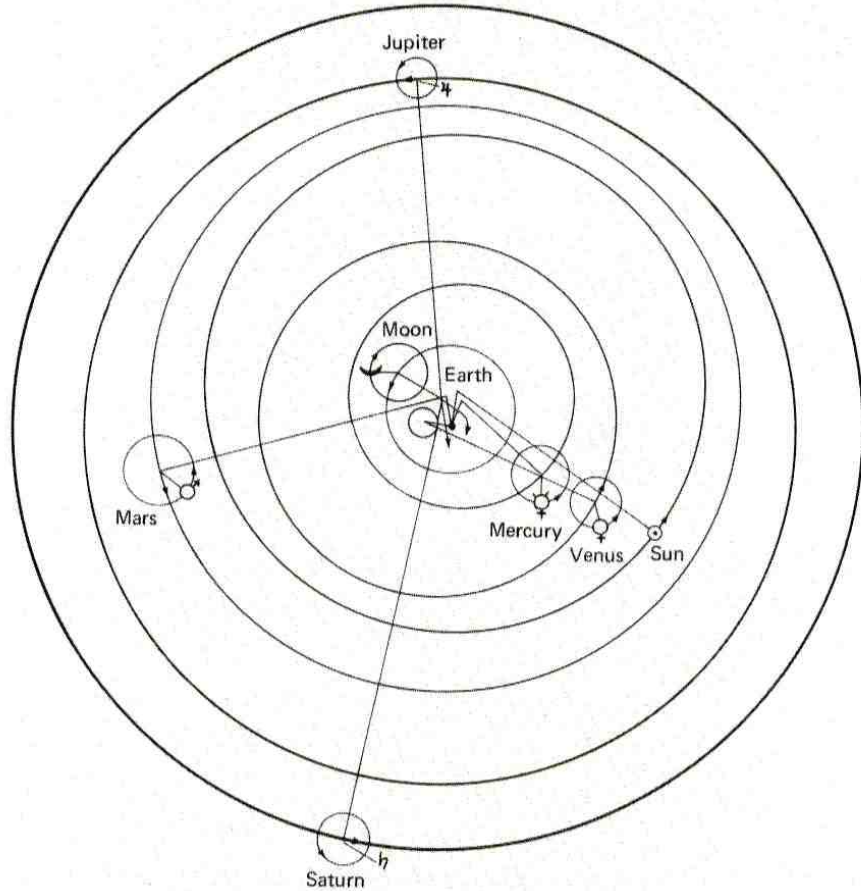
Ptolemy   Copernicus

Summary

Copernicus, having learned of Sun-centered cosmologies while in Italy, spent his life trying to fit a moving Earth into a medieval framework of Aristotelian Physics and Ptolemaic Wheels.

Why did it have such a profound effect?

- A moving Earth requires a REALLY BIG universe to avoid the *stellar parallax* problem.

- Other planets behave like Earth and might be made of similar stuff.

- Earth is no longer a "special" place. The hierarchical order of heaven" up there" and Earth (and "man") "down here" is broken. *Where, then, is the physical location of heaven?*

Johannes Kepler (1751-1630)

Asks WHY there were only 6 planets, WHY their orbits had a certain size, and WHY they traveled at different speeds.

Noticed the orbits of Jupiter & Saturn could be "spaced" by an equilateral triangle
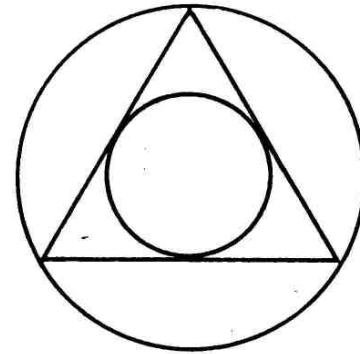
Tries to fit spacings of all the planets with equal-sided triangles, squares, pentagons, hexagons, etc. *Didn't work.*
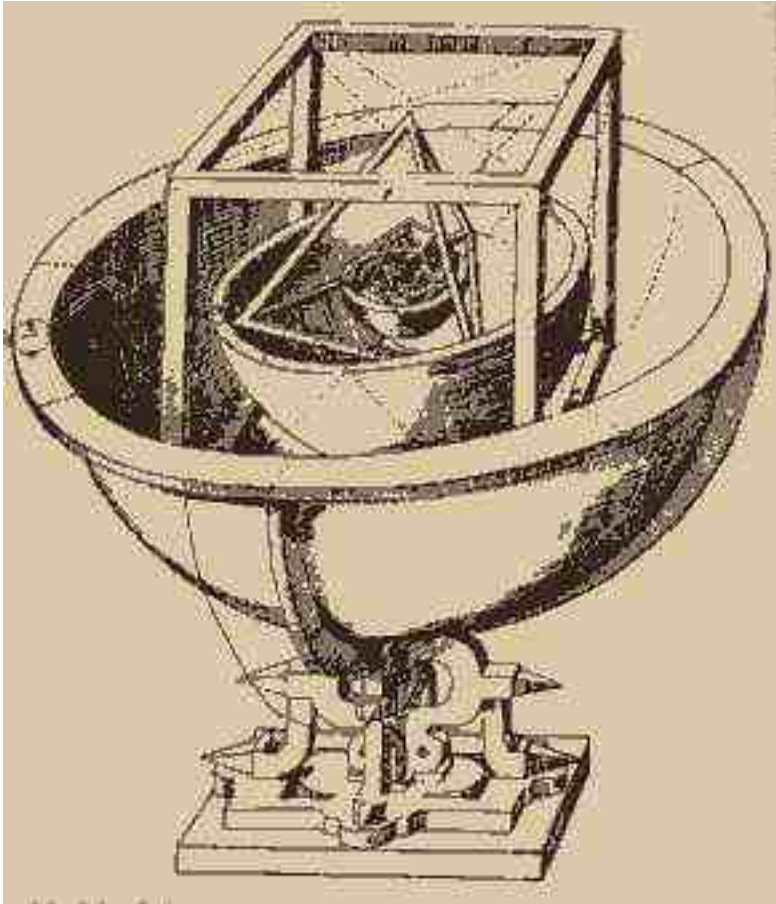
"And now I pressed forward again. Why look for two-dimensional forms to fit orbits in space? One has to look for three-dimensional forms - and, behold dear reader, now you have my discovery in your hands!….." - *J. Kepler*
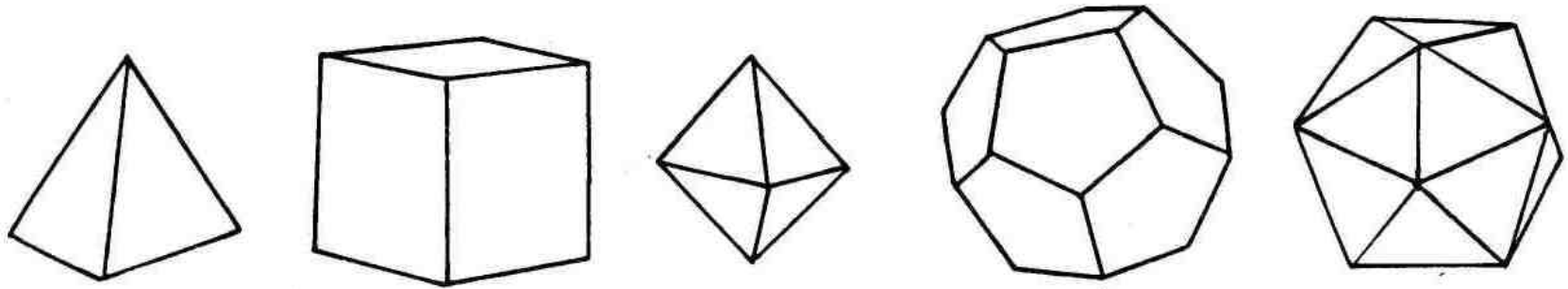
Tetrahedron   Cube   Octahedron Dodecahedron Icosahedron

The "perfect" solids (also called *Pythagorean* or *Platonic* solids)

1597 - *Mysterium Cosmographicum*

Kepler fits the orbital spacings with the "perfect" solids. Seems to *almost* work.

Most of *MC* was bunk, but….

- Along the way, thought more about why planets farther from the Sun moved more slowly

- Deduced that *there must be a force emanating from the Sun* that drives the planets, and that this *force diminishes in strength with distance from the Sun.*

- FOR THE FIRST TIME SINCE ANTIQUITY, AN ATTEMPT WAS MADE TO NOT ONLY DESCRIBE THE HEAVENLY MOTIONS, BUT TO ASSIGN THEM A PHYSICAL CAUSE.

In order to "get the details right", Kepler knew he needed better data, so he set out to meet the pre-eminent observer of the day, Tycho de Brahe, on Jan. 1, 1600.

Tycho de Brahe (1546-1601)

- 1563 - Discouraged by available predictions of planetary positions, sets out to make the most precise and continuous set of astronomical observations ever made.

- 1572 - Brahe & others observe a *nova* ("new star"). Data (esp. Brahe's) showed **it did not move.**

- 1573 - *Die Stella Nova* published - Permanence and immutability of the stellar sphere (*quintessence*, etc.) was shattered. (Later showed that comets were distant objects, not in the Earth's atmosphere.)

More on Tycho

- King Frederick II of Denmark gives island to Brahe, money to build an observatory, and an annual stipend to run it.

- "Uraniborg" built. Brahe spends next 20 years making observations with the best instruments of the pre-telescopic era.

- Forced to leave Denmark & settles in Prague. Made *Imperial Matematician* by Emperor Rudolph II. Given Benatek Castle.

Kepler & Brahe

Brahe develops own geocentric model (*he saw no stellar parallax*), but needs help of brilliant mathematician. Sends for Kepler.
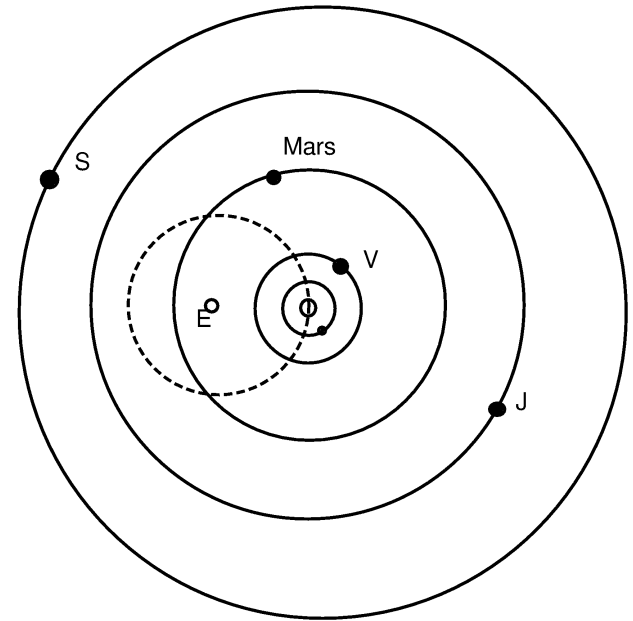
Kepler arrives, but given data (on Mars) piecemeal by Brahe

Brahe dies (of a burst bladder?) 18 mo. Later, in 1601

Kepler fights with Brahe's heirs over control of Brahe's data, eventually wins out (steals the data?).

1609 - *Astronomia Nova*

Contains THE FIRST NATURAL LAWS in the modern sense - PRECISE, VERIFIABLE STATEMENTS ABOUT PHENOMENA, EXPRESSED IN MATHEMATICAL STATEMENTS.

First Attempts

- Measure distances from Sun (that force….)
- Shows that the plane of orbit of Mars intersects Sun
- Keeps circular motion but REJECTS UNIFORM SPEED, going back to using *equant* (undoing what Copernicus did)
- FITS 10 OPPOSITIONS OF MARS RECORDED BY BRAHE!

Oppositions of Mars
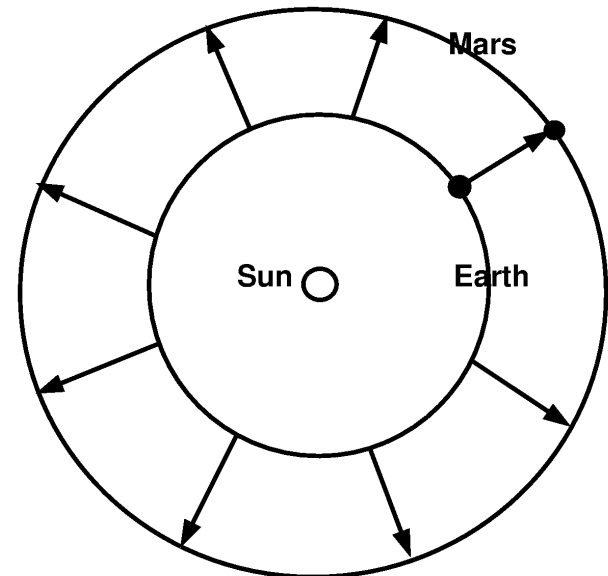
But upon comparing model to 2 other observations of Brahe, gets an error of 8 arcmin…

- He knew the observations were correct
- He believed in the physical causality of planetary motions
- Hence, adding more "wheels" was UNPHYSICAL
- Decided he must ***DISCARD SOME OR ALL OF HIS MODEL BECAUSE IT DID NOT WORK***!- the essence of the scientific method.

Probably, circular motion must go as well. But what, then IS the shape of Mars' orbit? Need to know Earth's motion first……

Kepler's *Second* Law
of Planetary Motion

Discovers that the Earth
and Mars (and by
implication the other
planets) move faster when
closer to the sun according
to a specific prescription:
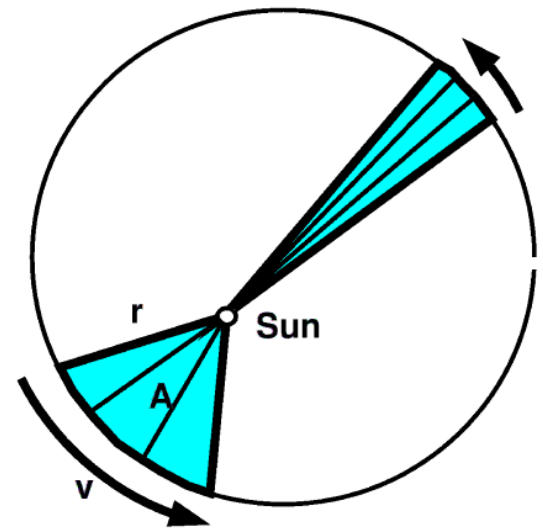
*THE LINE BETWEEN THE SUN AND A
PLANET SWEEPS OUT EQUAL AREAS IN
EQUAL INTERVALS OF TIME*

This is the first "natural law" ever discovered by anyone!

- Up to now, he had junked uniform speeds
- NOW he does away with circular orbits, **because they did not fit the data**
- Tries various orbital shapes, without success
- Finally tries *ellipses* (first studied by *"Ferris Wheel Universe" Apollonius*) and finds that they FIT!
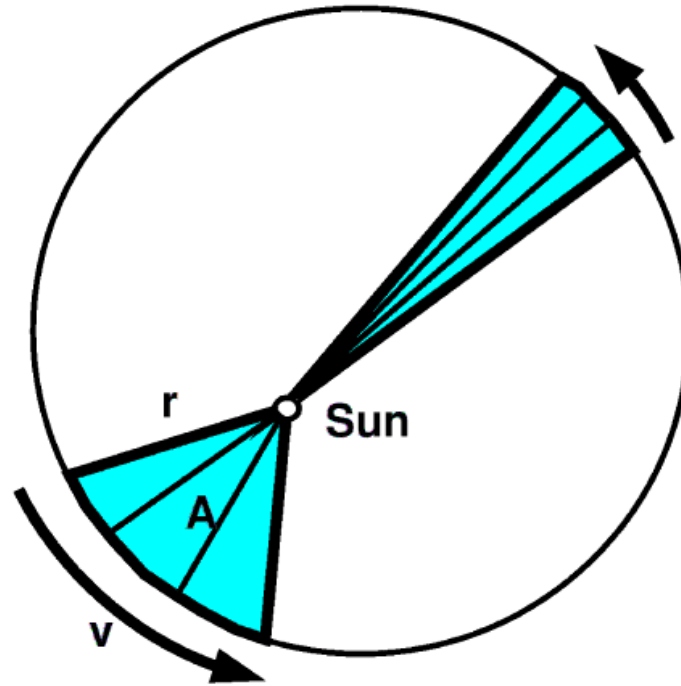
Kepler's *First* Law of Planetary Motion
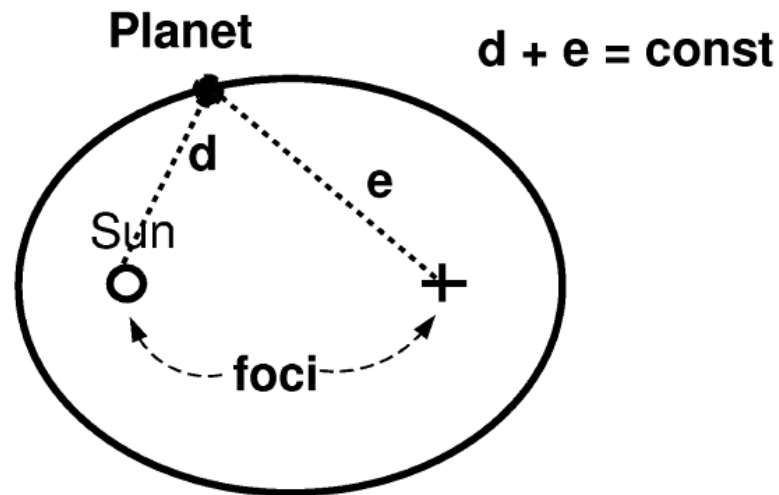
THE ORBIT OF A PLANET IS AN ELLIPSE WITH THE SUN AT ONE FOCUS

Kepler's *Second* Law of Planetary Motion

A LINE BETWEEN THE SUN AND A PLANET SWEEPS OUT EQUAL AREAS IN EQUAL INTERVALS OF TIME

Result:

- No more epicycles, deferents, and equants
- No more uniform circular motion
- Vastly simpler - one figure for each planet - an ellipse
- Replaces old system with entirely new one
- Beginning to put Physics & Astronomy back together (that force….)
- Not just an idea ripe for its time, but the work of one mind BECAUSE only he thought that the orbits must obey physical causality, and were due to a FORCE. *This frees astronomy from all the decrees of Plato, Aristotle, and Ptolemy.*

1610 - Kepler Hears of Galileo's discovery of the moons of Jupiter

Galileo - Part 1

- Discovers Pendulum Law as a student
- 1597 Galileo read *MC* but generally ignores Kepler. Secretly professes to be a *"Copernican"*
- 1609 Galileo hears of the Telescope, makes his own & presents it to the Venetian Senate
- Turns telescope on the SKY
- 1610 Published *The Starry Messenger* in Italian, and with a new terse & factual style of writing

The Starry Messenger

- THE MOON IS NOT SMOOTH
- THERE ARE MANY STARS TOO FAINT TO SEE WITH THE UNAIDED EYE
- JUPITER HAS MOONS ORBITING IT

Initially met with skepticism, these discoveries were later confirmed, including Clavius, the leading Jesuit astronomer in Rome.

Later, Galileo leaves Venice for Tuscany.

Later Discoveries

- "MOONS OF SATURN" (actually the RINGS!)

- *GIBBOUS PHASES OF VENUS!* This is totally incompatible with the model of Ptolemy, although not inconsistent with Herakleides and Brahe
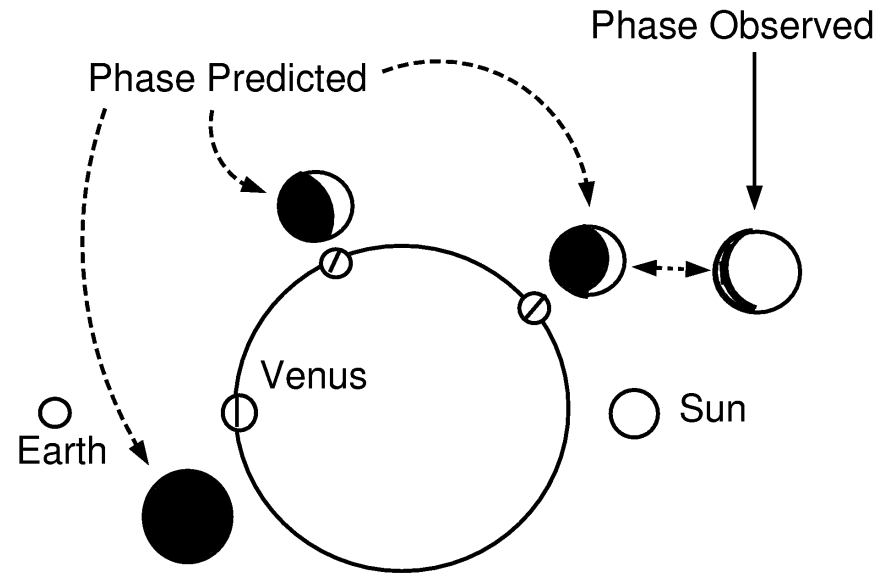
Gets a telescope, confirms existence of moons of Jupiter, coins the term *"satellite"* to describe these objects

1610 - Publishes *Dioptrics*

- Inverse-Square Law of Light
- How the Camera Obscura Works
- How Eyeglasses Work
- How the Lens in the Human Eye Works
- How a Telescope Works

1618 - *Harmony of the Worlds*

(he's back to mystical drivel, BUT includes:)

Kepler's *Third* Law of Planetary Motion

P = sidereal period of the planet

a = semi-major axis of the elliptical orbit

$$P^2 \propto a^3$$

Specifically, for P measures in years and a measured in Astronomical Units (1 AU = semi-major axis of the Earth's orbit) then

$$P^2 = a^3$$

Kepler had *finally* found the law that described the sizes of orbits, and prescribed exactly how fast each planet should go.

Kepler was the one to discover this because HE WAS THE FIRST TO BELIEVE THAT SUCH A RELATION *OUGHT* TO EXIST (that force from the Sun again…...)

AS LONG AS COSMOLOGY WAS SEPARATE FROM *PHYSICAL CAUSALITY*, THE RIGHT QUESTION TO ASK NEVER OCCURRED TO ANYONE!

Kepler didn't realize that his 3 Laws were the **Key** to discovering the existence of ***Universal Gravity***

- Too obsessed with all the other mystical garbage, such as the Pythagorean Solids
- Did not have the mathematical tools (specifically, needed *calculus*)

1618, 1620, 1621 - *Epitome Astronomiea Copernicanae*

- Actually a textbook on the Keplerian (not Copernican) system
- Extends his 3 Laws to all the planets, the Moon, the satellites of Jupiter

1627 - *Rudolphine Tables*

- Tables & Rules for predicting Planetary Positions

- Catalog of 1005 Star Positions

- Refraction Tables to correct for the bending of light through Earth's atmosphere

- (First use of Logarithm Tables in astronomy)

Amidst war, Kepler begins wandering Europe in search of a new home….

Begins writing *Somnium* - "The Dream"

- Describes effects of *Acceleration* on Space Travelers
- Describes Regions of *Zero Gravity*
- Almost gets *Newton's 1st law of Mechanics*
- Describes Lunar Astronomy, *adaptation of lunar creatures to their environment*, etc.

Dies penniless in Ratisbon 15 November 1630

Galileo - Part 2
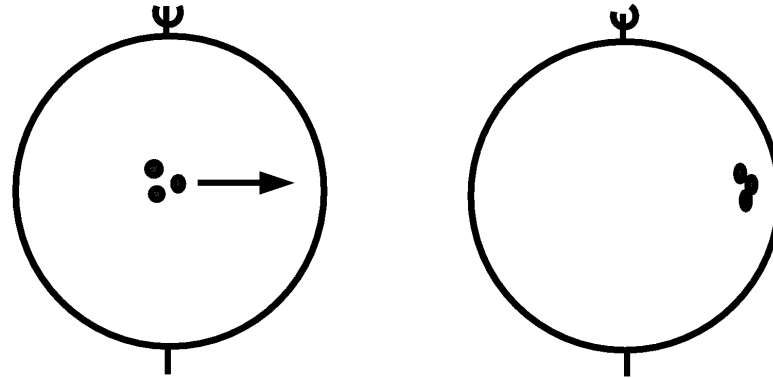
- Comes into conflict with Aristotelian academics concerning his study of HYDRODYNAMICS
- Comes into conflict with Church (and Aristotelians) over discovery of Sunspots
- First tentative formulation of *Principle of Inertia* (Newton's 1st Law of Mechanics, actually discovered by Galileo)
- First written support of the Copernican System

1630-1632 *Dialog on the Great Word Systems*

- Refutation of Aristotelian Cosmos
- Refutation of Arguments against a Moving Earth by Terrestrial Physics
- Arguments For & Against Copernican Model
- "Proof" of the Earth's Motion

Dialog banned and Galileo summoned
before the Inquisition

1633 - Galileo Charged with Disobedience for:

- Deviating from the hypothetical treatment of the Copernican Model (found Not Guilty, although he actually was……)

- Holding as true the motion of the Earth, which was *heresy* (found Guilty, although this idea was never declared *heretical*, but merely *reckless*)

- Teaching the Copernican Model in any way (found Guilty, but the document upon which this charge is based may be a forgery)

After being "shown the instruments of torture", Galileo recants his beliefs, and placed under house arrest for the remainder of his life.

1636 - *Dialogs Concerning Two New Sciences smuggled to Leiden* - Contains the first scientific discussion of *DYNAMICS*

1642 - Galileo dies and Newton is born

BUT problems remain:

•STILL HAVE NOT PROVED THE CORRECTNESS OF THE HELIOCENTRIC MODEL

•STILL HAVE NOT COMBINED CELESTIAL AND TERRESTRIAL PHENOMENA

ACTUALLY - THESE ARE THE SAME PROBLEM!