Themes for today

- Why did the Earth-centered Ptolemaic system last so long?

  Why wasn't the heliocentric theory popular before 1543?

- What problem was Copernicus trying to solve?
- What makes a "good" theory?

  What criteria are used to test a theory?

Let's try to see astronomy from a viewpoint of ~1600 A.D.

Keep in mind:

- Observational data available then, including
  - direct astronomical observations
  - other physical observations on how things move
- The general organization of the world view, including metaphysical assumptions.

Aristotle:

Dialectical: understand the world by thinking hard
Natural: generalize experience of the world

Development of Astronomy. Why?

Early experiment consists of direct observation and measurement of length of shadows (the sun and moon) and angles.

How did they measure the length of the day? What was their **operational definition**?

Solar Measurements (i.e. sundials or gnomen)

1. Define noon as the time when the sun's shadow is the shortest. We can quantitatively measure the change of seasons.
2. Define the summer and winter solstices as the days on which the minimum and maximum shadows occur.
3. But measurements depend on location
   - North-south movements change lengths
   - East-west movements change times (what does that mean? how could they know?)

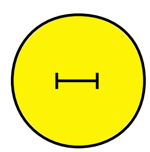
Why is the earth a sphere and not flat?

- Ships disappear over the horizon
- The angle of the north star depends on latitude
- The time of an eclipse depends on the longitude
- The shadow of the earth on the moon is circular
- Spheres are simple (metaphysics)

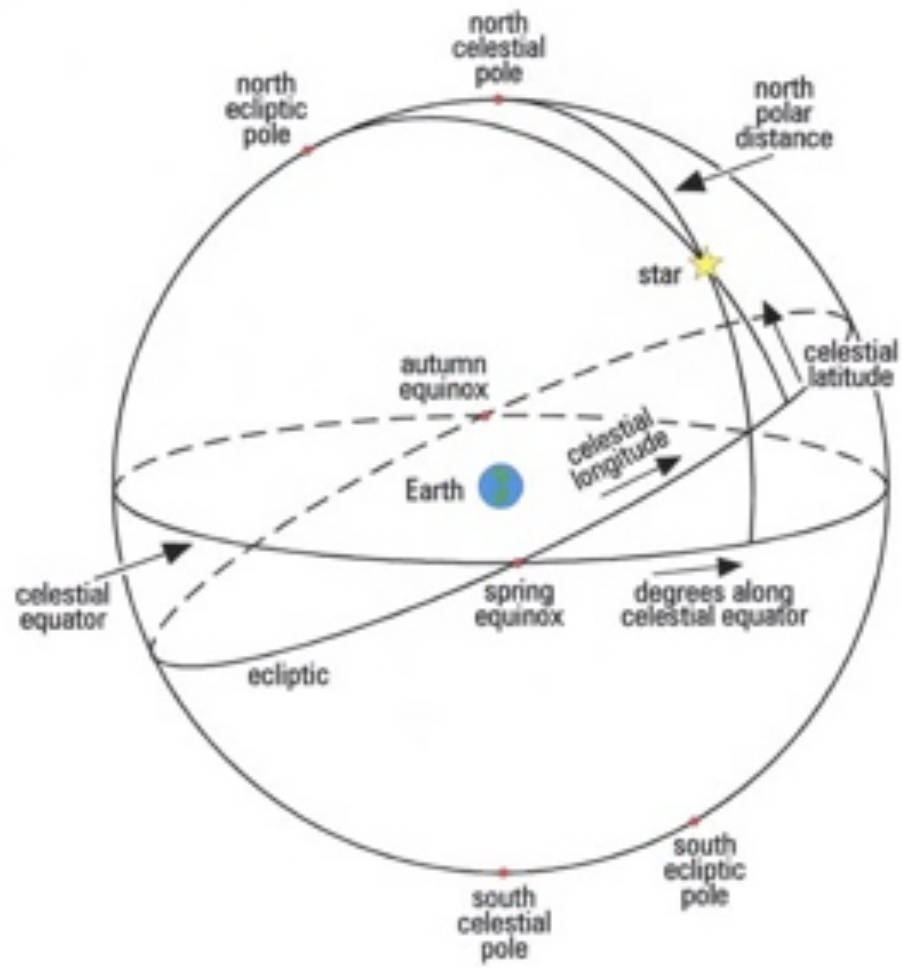
The astronomical data

(remember, no telescopes until after 1600)

- The positions of all celestial objects (day or night) rotate about the north pole approximately once per day.
- The stars move in lock-step (*e.g.*, constellations don't change shape).
- The Sun loses one rotation per year with respect to the "fixed" stars.
  - The entire disk of the Sun is lit.
- The Moon loses one rotation per month w.r.t. the stars.
  - Only that part of the Moon which faces the Sun is lit. During a solar eclipse it is between the sun and the earth.
- The motion of the planets is complicated (more on this later).
- A comment about the data:
  - The data available in the time of Copernicus was mostly old and unreliable. Some had clearly been fudged to fit predictions of the Ptolemaic model (see below). Even the best data was accurate only to 10 minutes of arc (1/3 the visual size of the moon):



2 sphere model



The intuitive picture (Aristotle)

On Earth

- The Earth doesn’t seem to be moving. It doesn't feel like you're moving.
- Objects don't keep moving with respect to the earth, but come to rest on the earth.

- Matter resists displacement and tries to regain its natural place:

  AIR> FIRE >WATER>EARTH

- Explains a spherical earth, with water and air in certain places.
- Nature abhors a vacuum. Hence the space between Earth and the stars is filled with aether.
- The only motions that are natural are linear and circular.

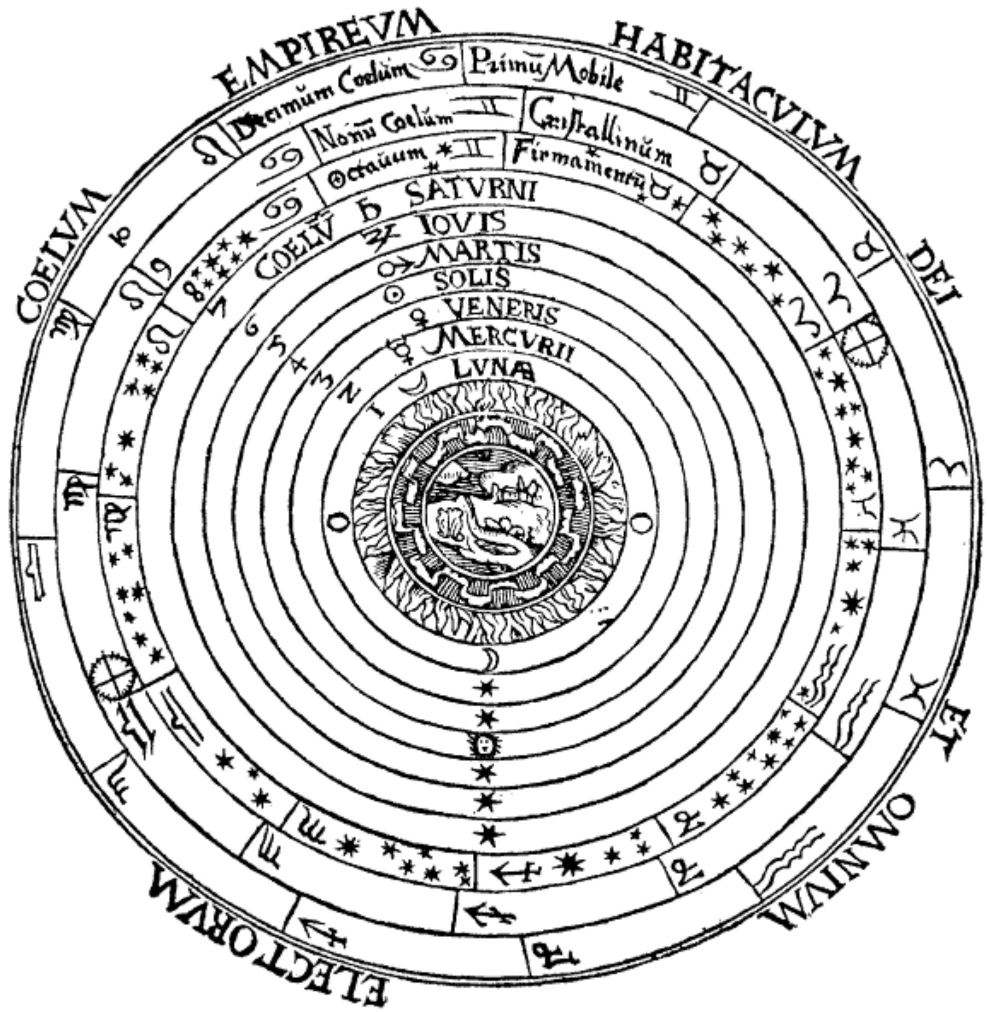
In the sky (thanks to Aristarchus, about 250 BC) via geometry, using lunar eclipses and half-moons.

- the Moon is about 1/3 the diameter of the Earth.
- the Sun is much larger than the Earth.

Two sphere model

- One sphere (the inner one) is the Earth, the other (the outer one) is the stars. The Earth is stationary; the stars rotate once per day. The positions of the orbits of the Sun, Moon, and planets are intermediate, size determined by orbital period.
- The figure is oversimplified. The theory must explain some complications, starting with:
  - The seasons:
    The circle the Sun follows moves north and south. (The motion of its sphere w.r.t. the outer sphere is still circular, but with an axis at a tilt compared to the axis of the star-sphere rotation.)

Schema huius præmissæ diuisionis Sphærarum.



Peter Apian's *Cosmographia* (Antwerp, 1539)

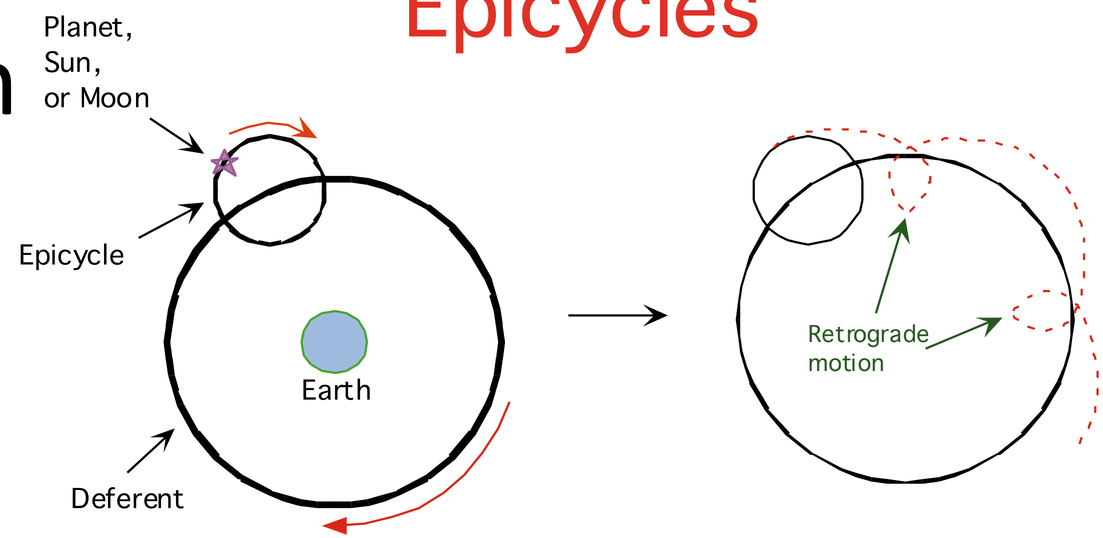
Further complications

- The slightly non-uniform motion of the Sun and Moon. Their speed increases and decreases around the circle.
- The complicated motion of the planets. Sometimes, they move backwards with respect to the stars (*i.e.*, westward, instead of slipping slowly eastward).

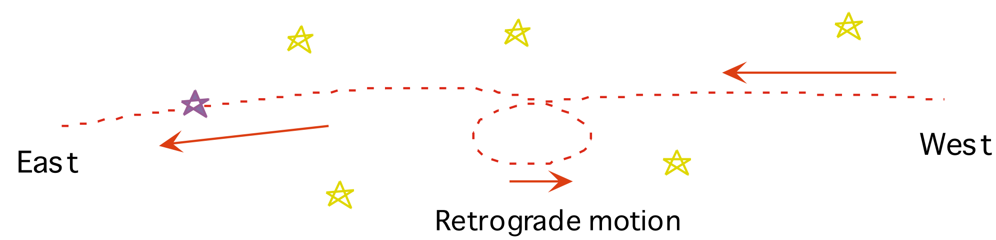
Planetary Motion

- The Ptolemaic solution to the planetary problem makes the actual theory quite complicated. It uses epicycles, eccentrics, and equants. (see figure)
- Ptolemaic system was loosely based on an Earth-centered cosmology, but the *ad hoc* devices violated this.

Epicycles



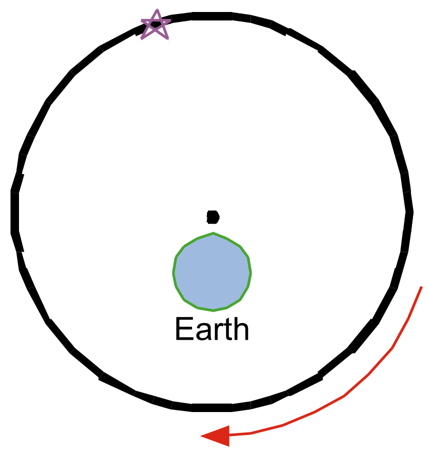
What an earthbound astronomer sees in the sky. This is the motion with respect to the fixed stars:



Only planets actually move backwards. Sun and Moon merely speed up and slow down.

Eccentrics and Equants

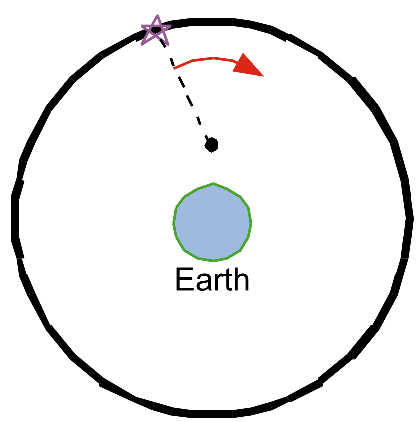
Eccentric :



Center of uniform circular motion is not the Earth.

Both devices cause the apparent speed of the motion across the sky to vary.

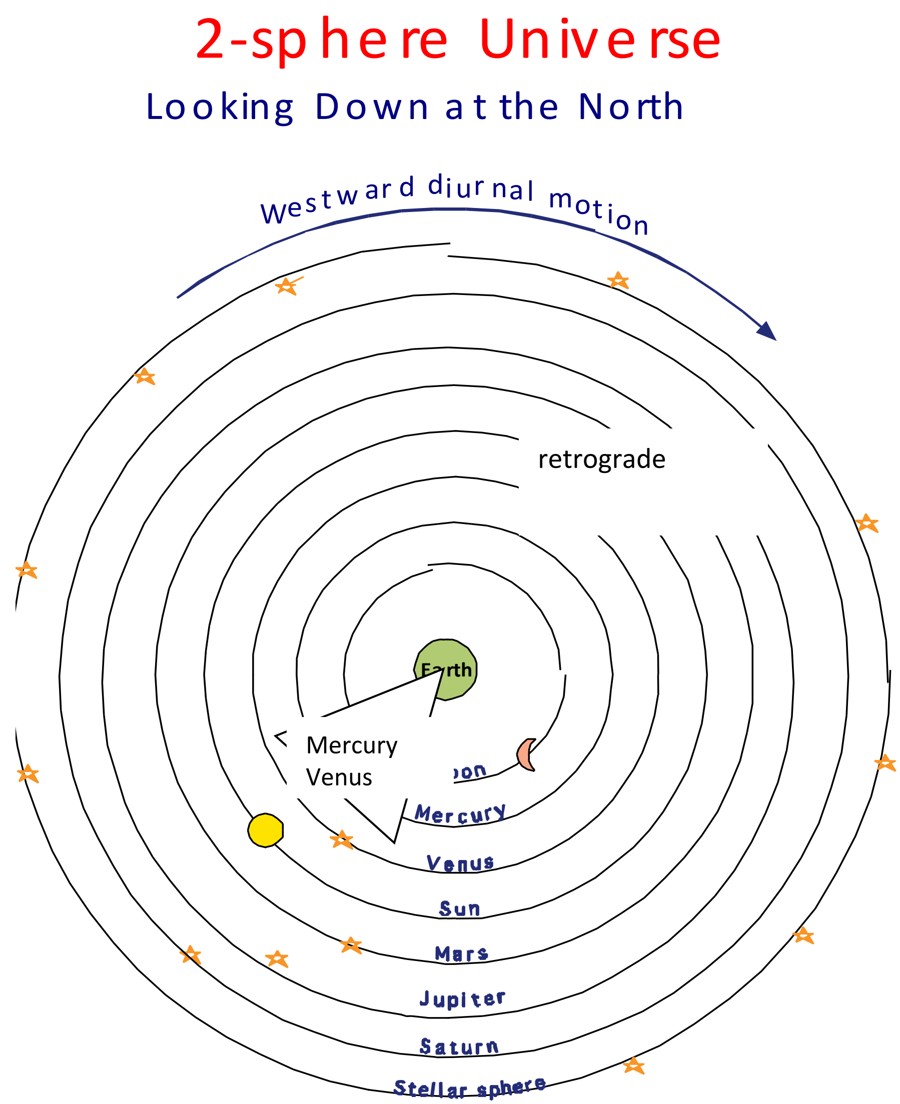
Equant :



Center is the Earth. Angular motion is uniform about another center

Other Issues

- Although particular versions of the system were not especially accurate, that could always be fixed by adding epicycles, etc.
- There were more qualitative problems.
  - Why are Venus and Mercury always close to the Sun?
  - Why does retrograde motion always occur when a planet is in opposition to the Sun? (opposite in the sky)
  - How can the mechanical picture of "crystal spheres" be reconciled with the epicycles, etc.?



Selling points of two-sphere picture

- Conceptual economy. It ties together many facts in a simple geometical model still used today.
- It "preserves the phenomena", i.e. describes basic astronomical observations of days, seasons, eclipses ...
- The universe is finite. (infinity is a difficult concept)
- The Earth stands still.
- The Earth is the center of everything
  - (intuitive, and in accord with most theologies).
- Motion increase systematically with distance from the Earth.
- Heavy ("earthlike") objects are at the center.
  "Firelike" objects are at the outside.
  - (heavy objects fall and fire rises... so the pattern connects with terrestrial dynamics)

Philosophical background

- Renewed interest in Platonic and Pythagorean philosophy (vs. Aristotle's) increased value placed on mathematical simplicity. Copernicus disliked equants particularly.
- So, there was an important shift in the answers to two questions:
  - Is it legitimate to use any point of reference in astronomy other than the Earth?
    - The Aristotelian/Ptolemaic answer was no.
      The Pythagorean answer was yes.
    - In fact, the followers of Pythagoras, most notably Aristarchus, had invented heliocentric cosmology in the fifth to third centuries BC.
  - Is the universe as a whole, including our Earth, fundamentally mathematical in its structure?
    - Aristotle implicitly assumed yes, (hence the perfect circles), but didn't follow up the implications.
    - The Pythagoreans also tended to assume yes, but left the question of the particular mathematical form open.
- Question: What justification is there for the assumption of mathematical simplicity? Occam's razor?

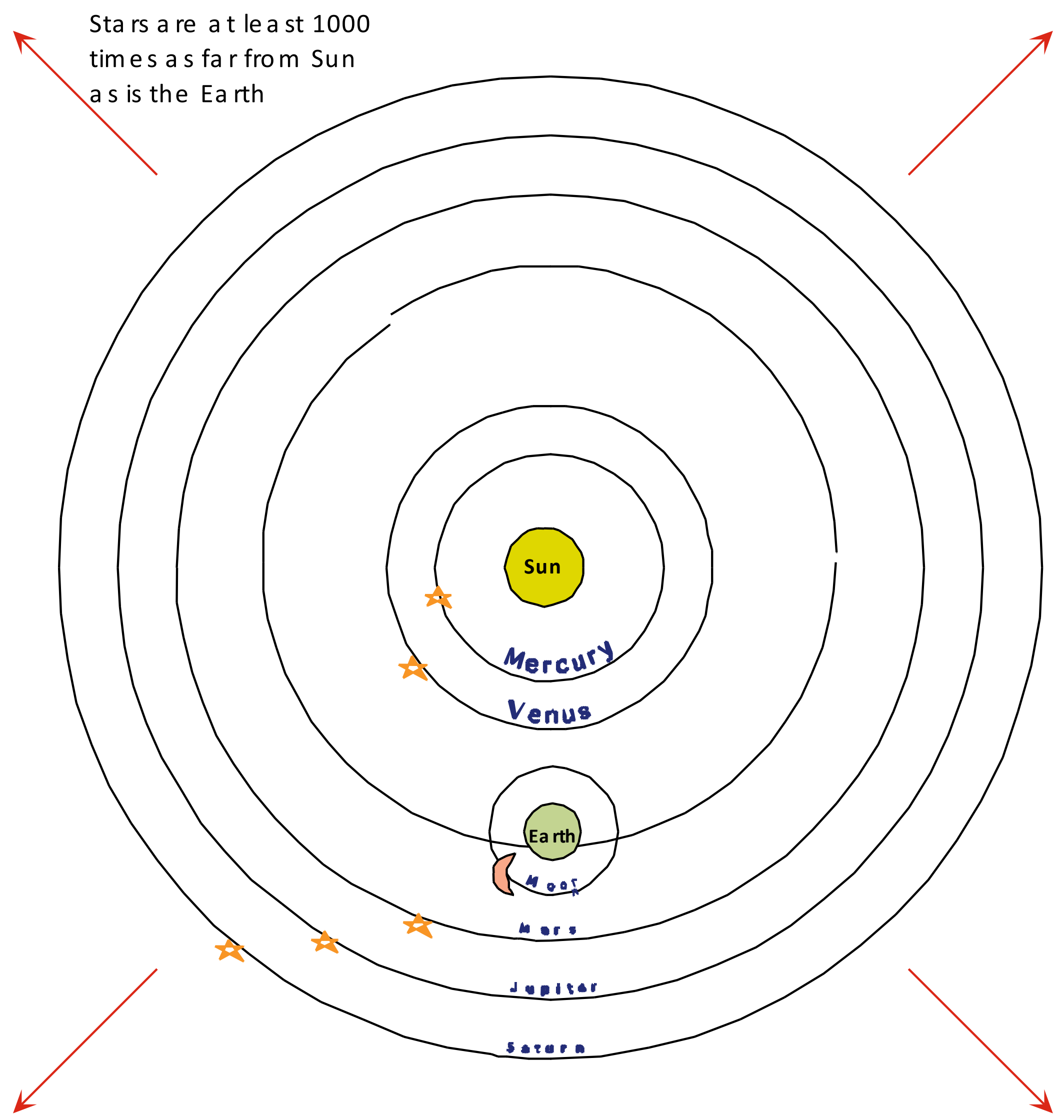
Copernicus
(& Aristarchus)

- Made the *Earth* rotate once every 23 hours 56 minutes.
- Made the *Sun stationary*, at the center.
- Made the stellar sphere stationary (and very large).
- Put the Earth in a circular orbit around the Sun.
- Put the planets in circular orbits around the Sun.
- Kept the Moon in a circular orbit around the Earth.
- Why have most objects (including the Earth!) orbit the sun, but to have the Moon alone orbit the Earth?

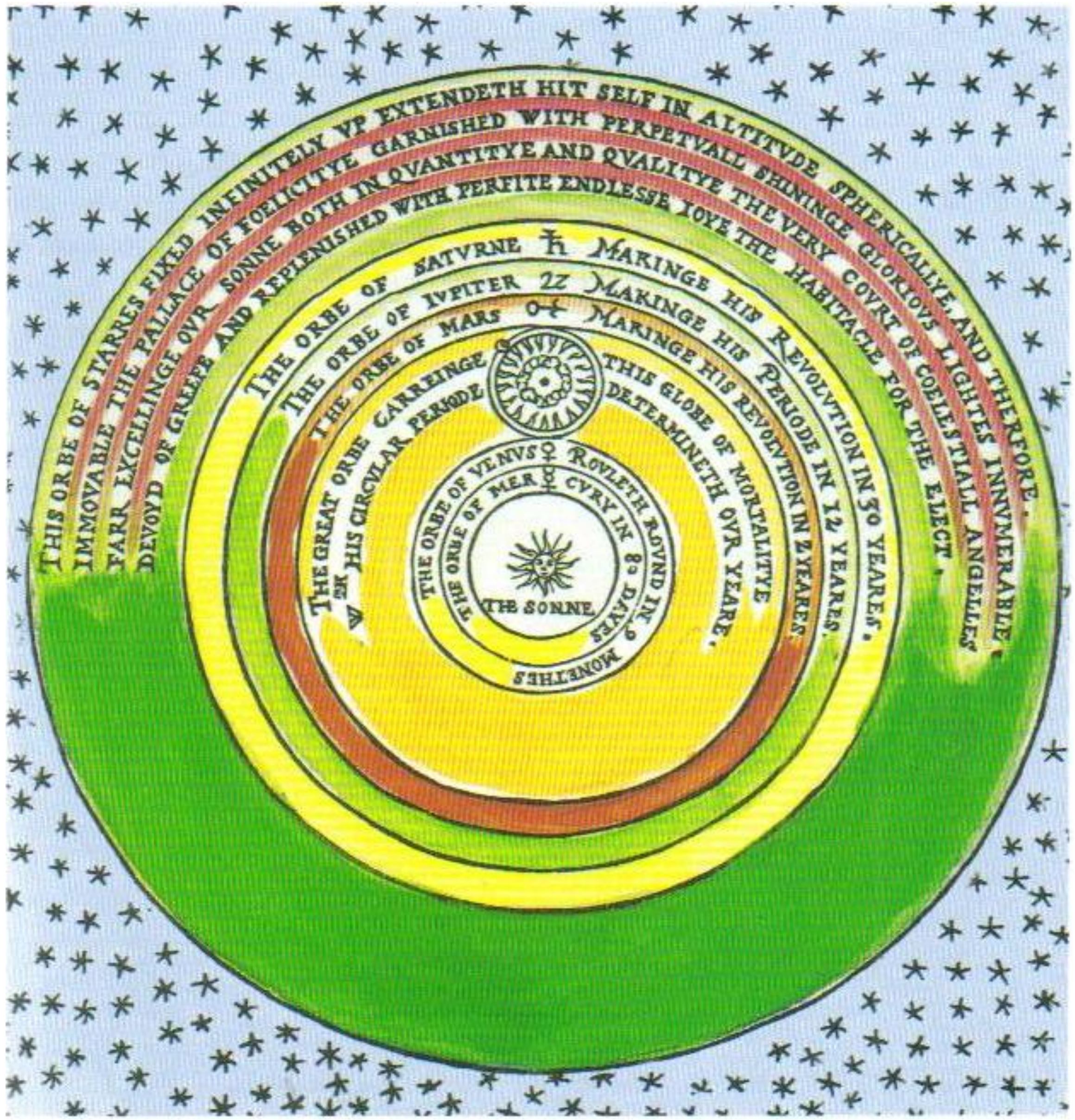
Copernicus' universe

Looking Down at the North Pole

(not to scale)



Thomas Digges' 1576 Copernican heliocentric model of the celestial orbs



Copernicus' accomplishments

- There's a pattern to which object moves:
  - the smaller object always orbits the bigger one. (if either orbits the other)
- *One* motion (Earth's rotation) explains the major motion of *all* astronomical objects (the diurnal motion).
- Retrograde motion
  - Eliminates the major epicycles.
  - Naturally gives REGULARITIES of the retrograde motion with fewer arbitrary parameters. It happens when superior planets (farther out than Earth) are opposite to the Sun and when inferior planets are between Earth and Sun.
- Venus and Mercury appear close to the Sun in the sky, have same net motion as Sun on the average--because they *are* close to it.
- Fixes relative sizes of planetary orbits without requiring any additional assumptions (*i.e.*, no appeal to other principles such as natural motion).

What Copernicus did *not* accomplish:

- Any significant improvement in accuracy of predictions.
- Elimination of most Ptolemaic devices (minor eccentrics, *etc*.). Only the biggest features were replaced by the Earth's motion.

Why are we called Copernicans, not Aristarchans?
What was going on for those 1800 years?

Drawbacks of Copernicus' theory

- The "second and third motions" of the Earth (see Kuhn p. 165)
  - The earth is supposed to be carried around the Sun by a crystal sphere. That would make the Earth's axis (which isn't parallel to the rotation axis) also rotate yearly. But the apparent motions are described by keeping the Earth's axis fixed. So Copernicus adds another wobble to the Earth, which has the odd effect of just canceling the effect of the crystal sphere on the Earth's axis.
  - Notice that we've used *two* hypotheses (crystal sphere and extra wobble) to explain *zero* effects (Earth's axis doesn't wobble.) It seems there should be a simpler way. But then we would need some other way (not attachment to a rigid sphere) to explain why the Earth orbits the Sun.
  - A simpler solution of this problem requires a new dynamics.
- The Earth moves!
  - Doesn't fit with Aristotelian physics, which is strongly based on intuition.
  - throw a rock up! A falling body would be left behind
  - the atmosphere would be left behind—a huge wind (Aristotle)
  - the earth itself would fly apart owing to force of rotation.
  - Copernicus does not dispute—his hypothesis is simply to make predictions.
- One systematic pattern- the relation between the apparent *type* of object and its cosmic place- is lost. The earth is just one of several planets—it is not unique.
- Stars are far away because parallax is not observed. Why did the creator waste all that space?
- Copernicus explicitly used the same criteria for evaluating a scientific explanation that we typically use today: "We find then in this arrangement an admirable harmony of the world, and a dependable, harmonious interconnection of the motion and the size of the paths, such as cannot otherwise be discovered ... And all this results from the same cause, namely the motion of the Earth. "

Scorecard

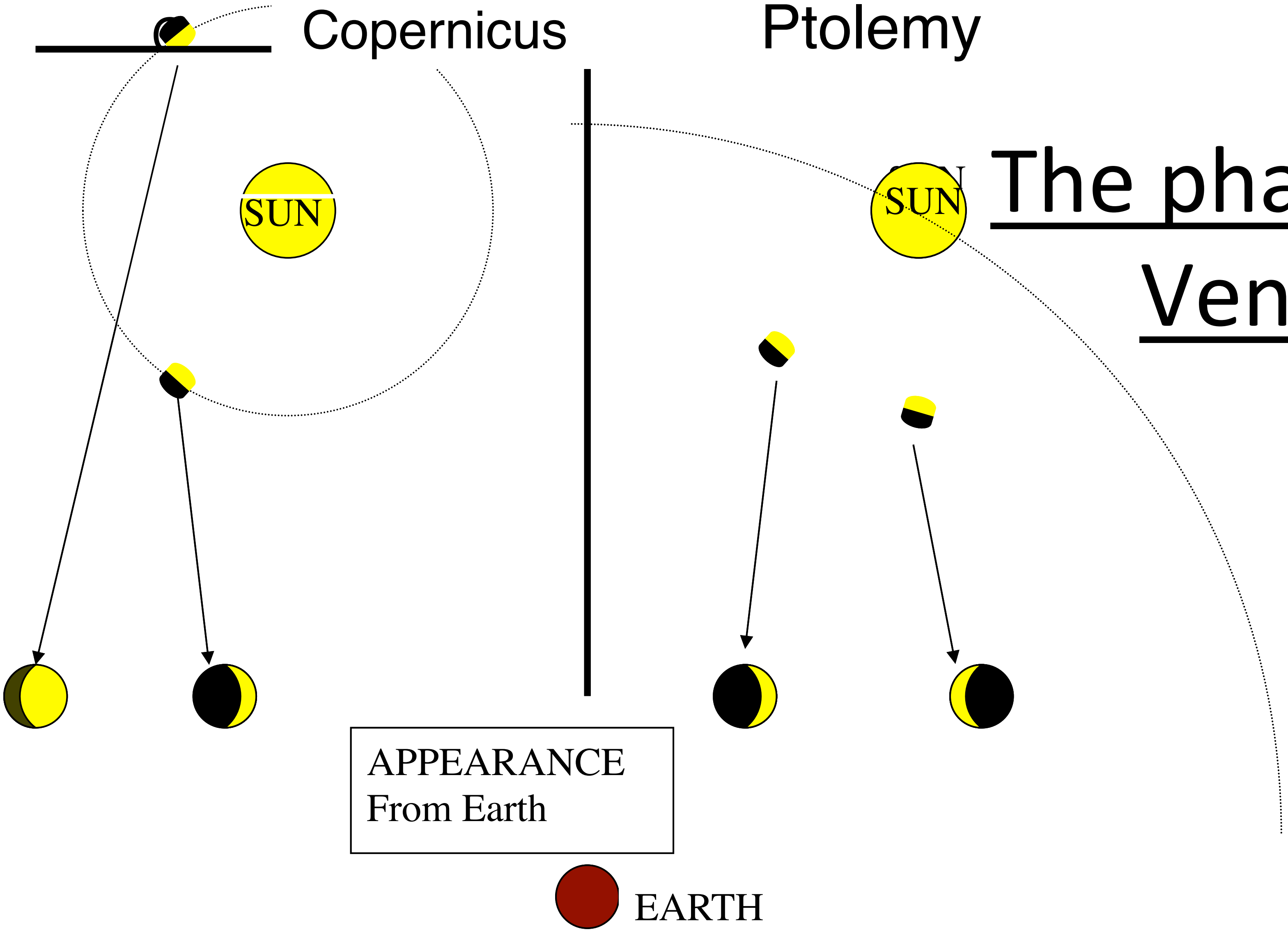
Copernicus	Ptolemy
Approximate mathematical simplicity	Agrees with ordinary physical intuition

Ptolemaic cosmology held on for about 60 years after 1543.

- Is there some crucial observation to settle who's right or wrong?
- If we can eliminate one of these theories, will we then know whether the earth goes around the sun?

The two cosmologies made different predictions,
but they were ~unobservable until the invention of the telescope.
In 1609, Galileo looked at the heavens with a telescope and observed for himself new “facts” supporting Copernicus. (see Kuhn, pp. 219-225)

The phases of Venus



Proves that Venus orbits the Sun, and shows that Venus is spherical

So Ptolemic model is completely ruled out

Other telescopic evidence:

- The moons of Jupiter
  - Shows another center of orbital motion.
    So why should the Earth be the center of the universe?
- The stars have smaller angular size than was thought.
  - Weakens one argument against their great distance- they might not have to be much larger than the other known source of light, the Sun

First homework is due at noon tomorrow (Friday Jan 23rd) on Compass.