Cosmological Models

How do we know?

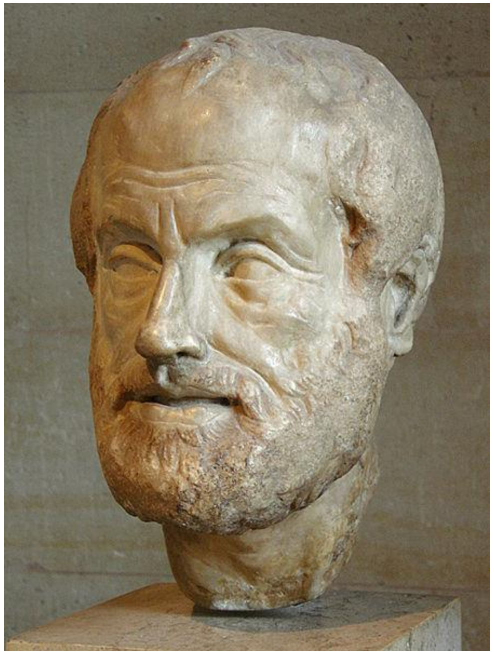
Cosmological Models

I. Planetary Motion
II. Aristotle and Ptolemy
III. Copernicus
IV. Galileo
V. Kepler's Laws
VI. Newton's Laws
VII. Einstein

	The student will be able to:	HW:
1	Describe and illustrate the apparent motion of each of the eight planets as seen from Earth bringing special attention to the similarities and differences. ✓	1 – 5
2	Define, illustrate, and apply the following concepts: direct or prograde motion, retrograde motion, conjunction, opposition, and elongation. ✓	
3	Explain and illustrate aspects of ancient geocentric models of the universe including the concepts of deferents, epicycles, and the works of Ptolemy.	6 – 8
4	Explain and illustrate the heliocentric model of the universe proposed by Copernicus including its seven main points and its own inconsistencies.	9 – 11
5	Explain and illustrate how Galileo was able to provide evidence for the validity of the heliocentric model.	12
6	Desribe Tycho Brahe's contribution to the formation of Kepler's Laws.	13 – 14
7	Define and apply the characteristics of ellipses: focus, semi-major axis, semi-minor axis, and eccentricity.	15 – 16
8	Define, illustrate, and apply the concepts of aphelion and perihelion.	
9	Explain, illustrate, and apply Kepler's three laws of planetary motion and properties of ellipses to solve problems involving orbits.	17 – 21
10	Explain, illustrate, and apply methods for determining the absolute and relative scale of the solar system.	22 – 25
11	Explain, illustrate, and apply Newton's Laws of Motion and Universal Gravitation.	26 – 29
12	Compare and contrast Newton's Laws with Kepler's Laws.	30 – 32

Understanding What We See

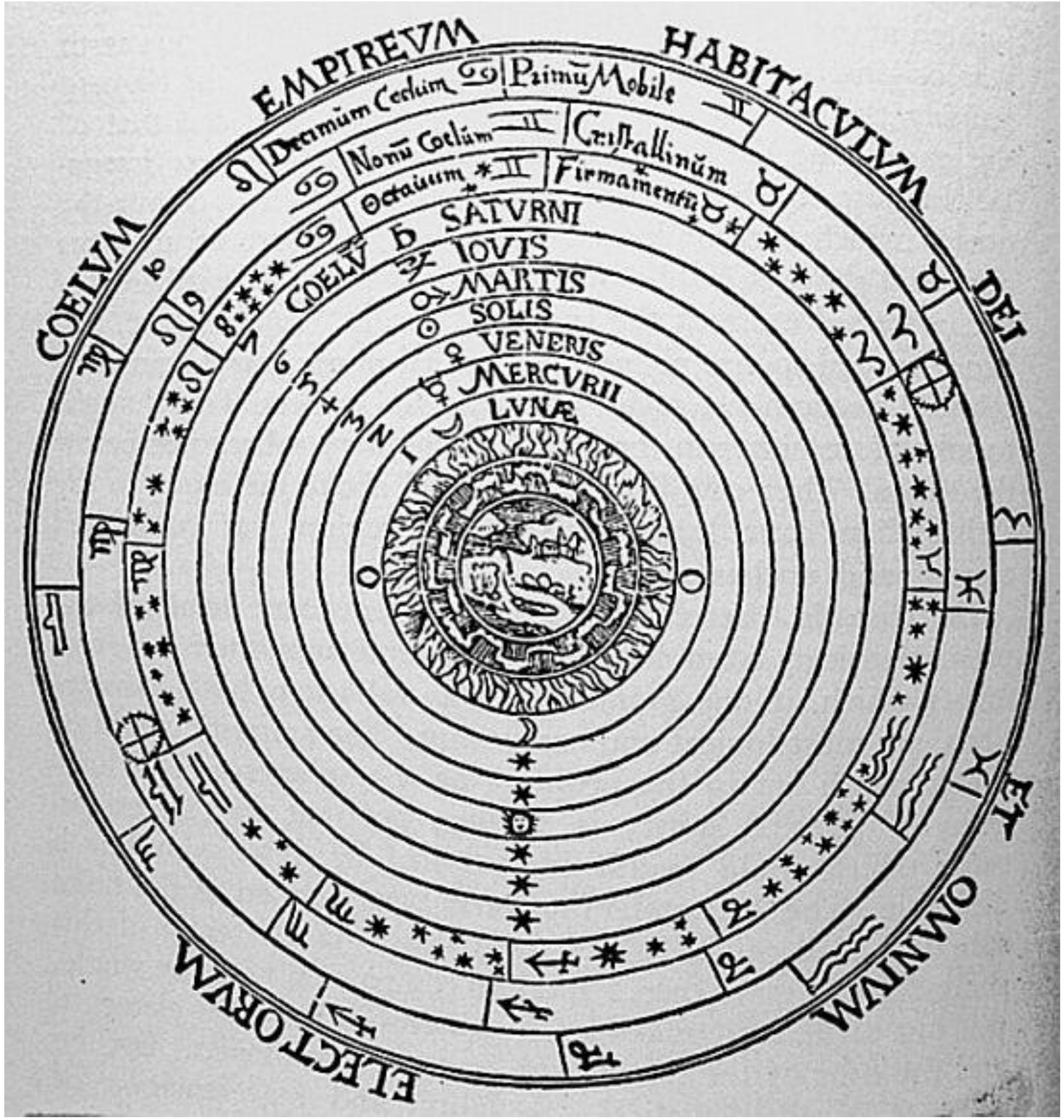
- There are various apparent motions of the stars, the Sun, the Moon, and the planets.
- A cosmological model is an attempt to make sense out of these appearances.
- It can be argued that mankind's attempts to understand the motion of the planets led to our enlightenment and the development of science and mathematics.



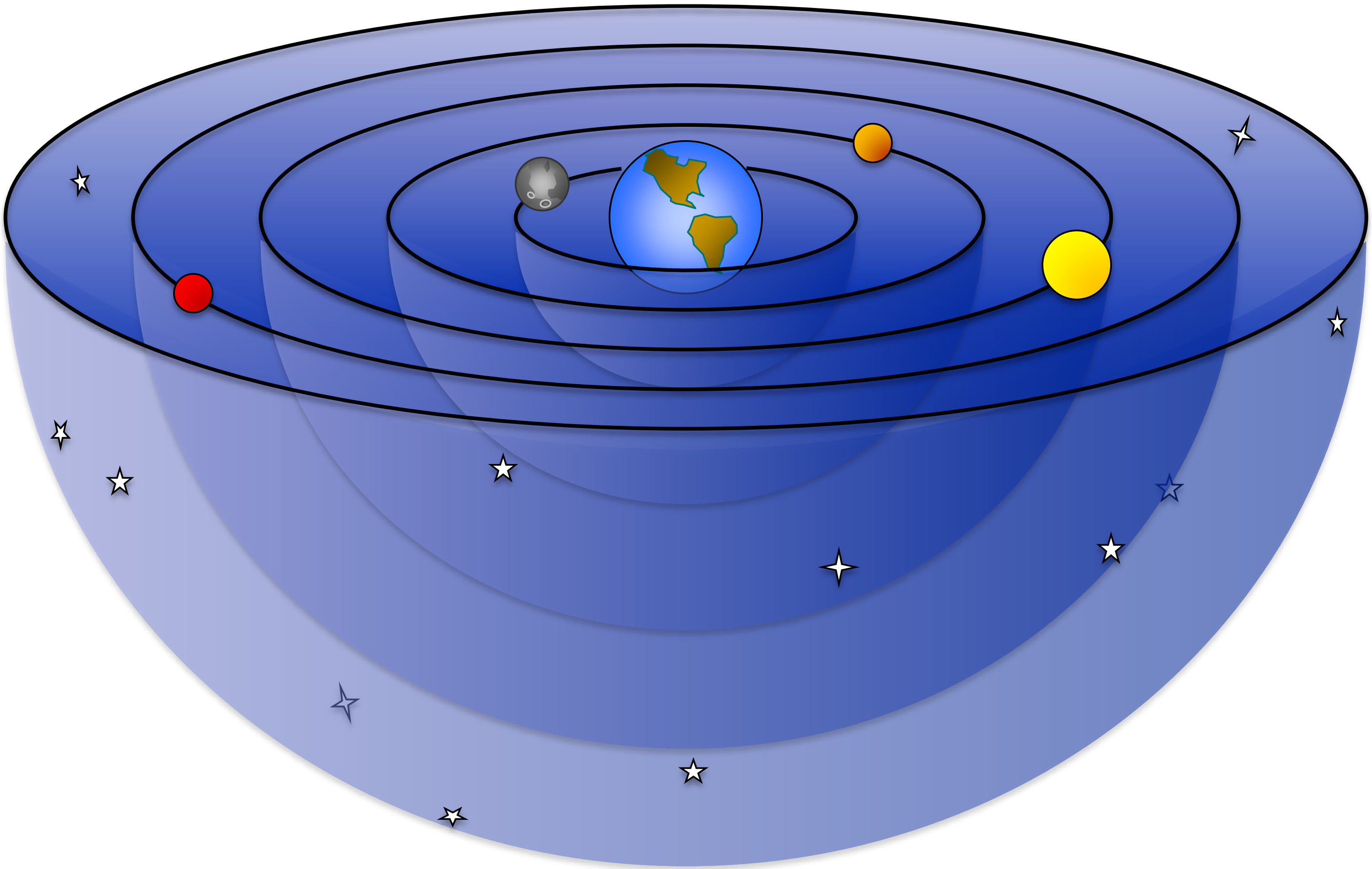
Aristotle
384 – 322 BC

Aristotle thought there were 5 elements: Fire, Earth, Air, Water, and Aether. He also believed there were only two types of natural motion: linear and circular.

Based on these principles he thought that the Earth was the center of the universe and that all heavenly bodies moved in perfect spheres.

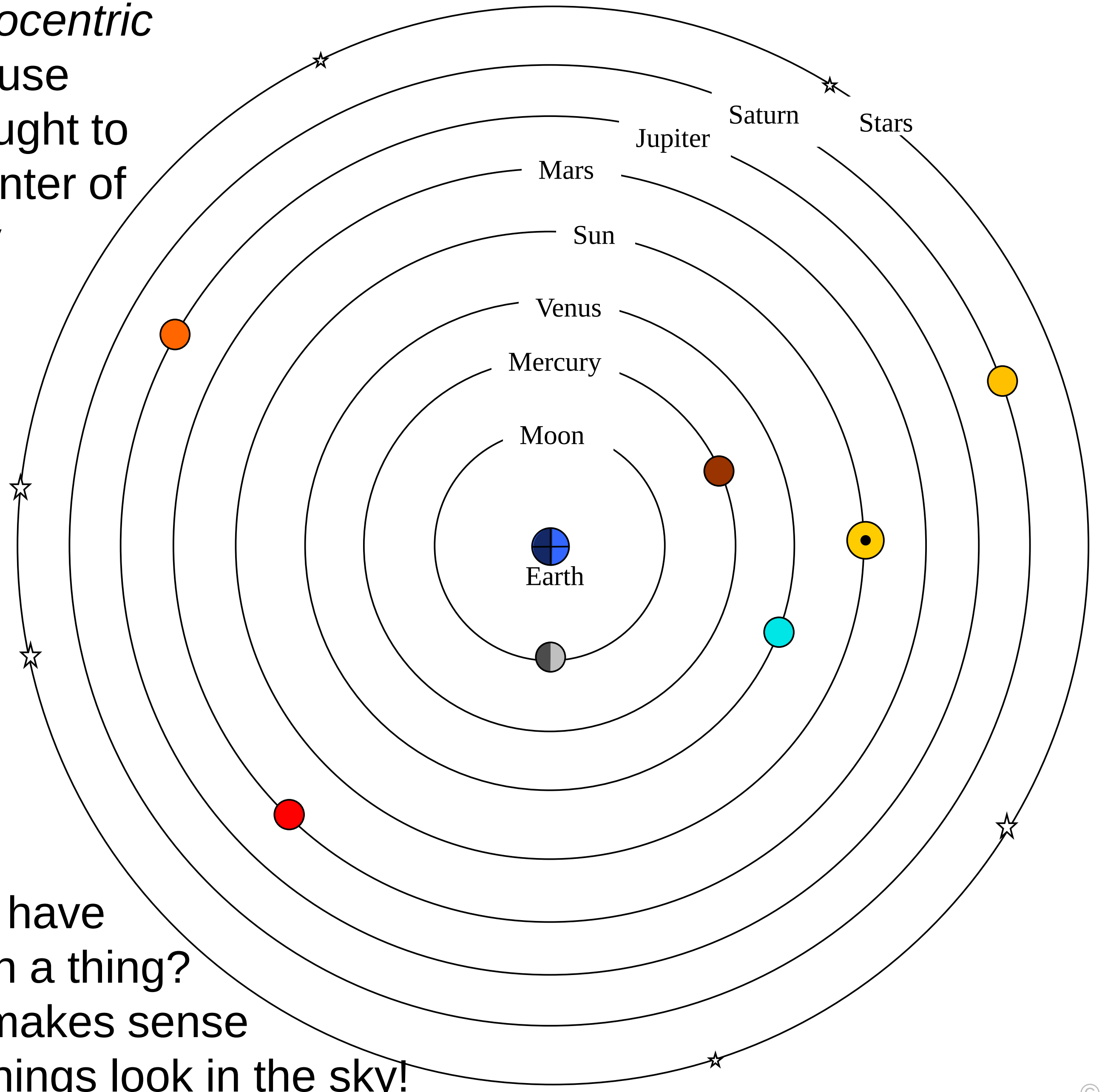

COELVM EMPIREVM HABITACVLVM DEI ET OMNIVM ELECTORVM
Decimum Coelum
Primū Mobile
Nonū Coelum
Cristallinū
Octauum
Firmamentū
COELV SATVRNI
IOVIS
MARTIS
SOLIS
VENERIS
MERCVRII
LVNÆ

Aristotlean Geocentric Spheres:



Aristotlean Geocentric Spheres:

This is a *geocentric* model because Earth is thought to be at the center of all heavenly bodies.



Why would people ever have thought such a thing? Because it makes sense of the way things look in the sky!

How do *you* know the Earth is *not* the center of the universe?

Problems with Aristotle's Ideas

- Retrograde motion does not make sense if planets move in perfect circles.
- The brightness of the planets changes and the apparent sizes of the Sun and the Moon change as well. These things do not make sense if the "orbits" are perfect circles centered on Earth.

Aristarchus
310 – 230 BC

Aristarchus believed that the Sun was the center of the universe. He thought that the Earth and the stars moved in circles about the Sun.

This is called a *heliocentric* model because Sun is at the center.

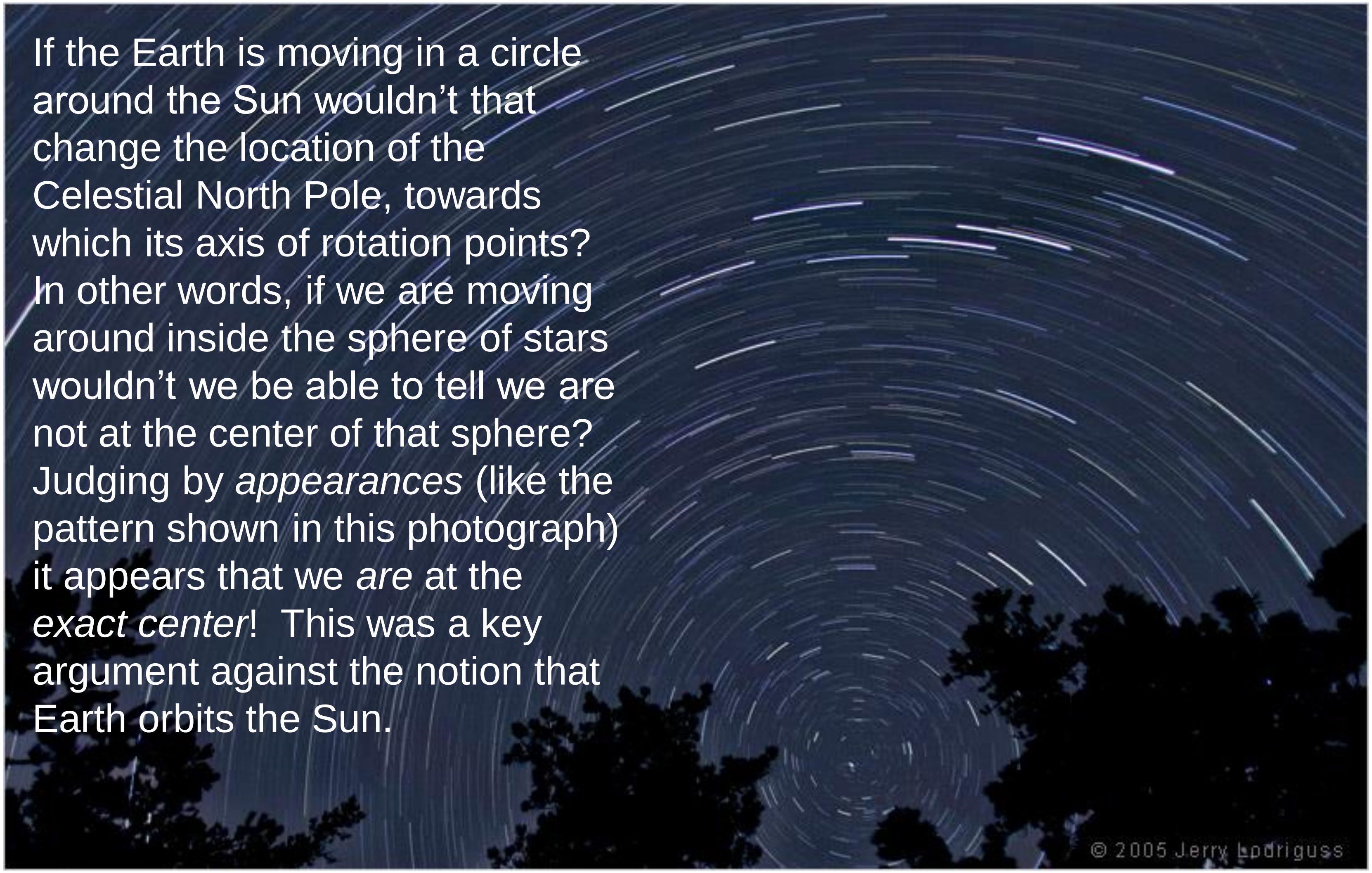
Aristarchus' ideas were rejected in favor of Aristotles'.

Aristarchus
310 – 230 BC

The primary objection to a heliocentric model was that the appearance and relative position of the stars would change if the Earth was in motion.

The celestial sphere of stars *appears* unchanging and the stars *appear* to move in perfect circles about the celestial poles.

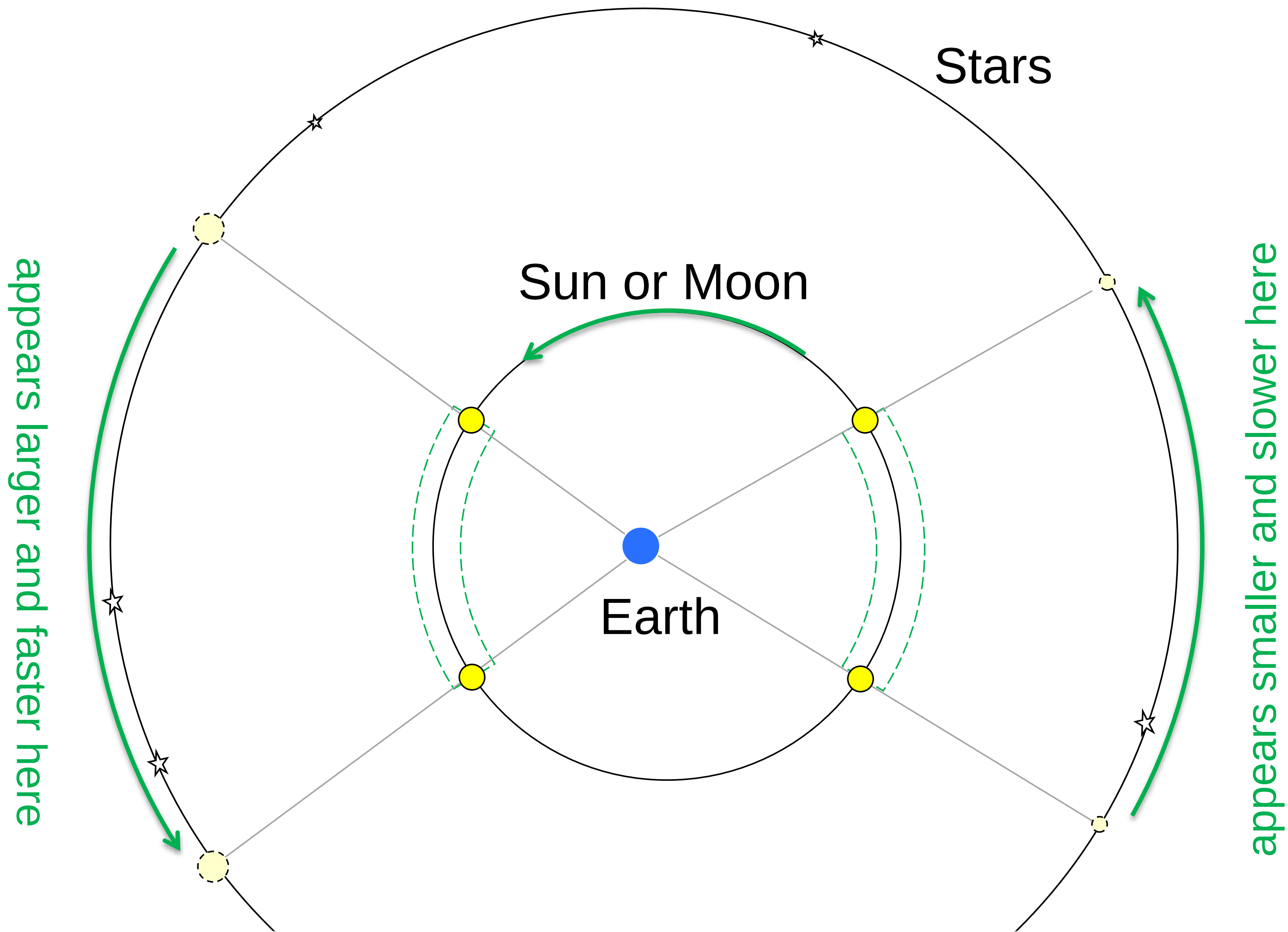
If the Earth is moving in a circle around the Sun wouldn't that change the location of the Celestial North Pole, towards which its axis of rotation points? In other words, if we are moving around inside the sphere of stars wouldn't we be able to tell we are not at the center of that sphere? Judging by *appearances* (like the pattern shown in this photograph) it appears that we *are* at the *exact center*! This was a key argument against the notion that Earth orbits the Sun.



Hipparchus
190 – 120 BC

Hipparchus applied mathematics and geometry to the geocentric concept. In order to explain the changes in appearance of Sun and Moon he calculated that their spheres were not *exactly* centered on the Earth.

He mapped and cataloged the stars and discovered the precession of the equinoxes and its rate of progression.



Hipparchus thought that the Sun and the Moon moved at constant speed in perfect circles about Earth. *But* he imagined these circles were *not exactly centered* on Earth and this explained the variation in the observed speed and size of these two objects.

What aspect(s) of planetary motion are not satisfactorily explained by the geocentric views of Aristotle and Hipparchus?

Many aspects of the appearance of the Sun, Moon, planets, and stars actually *can* be explained by the geocentric views of Aristotle and Hipparchus. However, one of the key things that is *not* well explained is the peculiar retrograde path that occurs for each planet at particular points in time under particular circumstances.

Ptolemy
85 – 165 AD

Ptolemy developed the most complete and detailed geocentric model of the heavens.

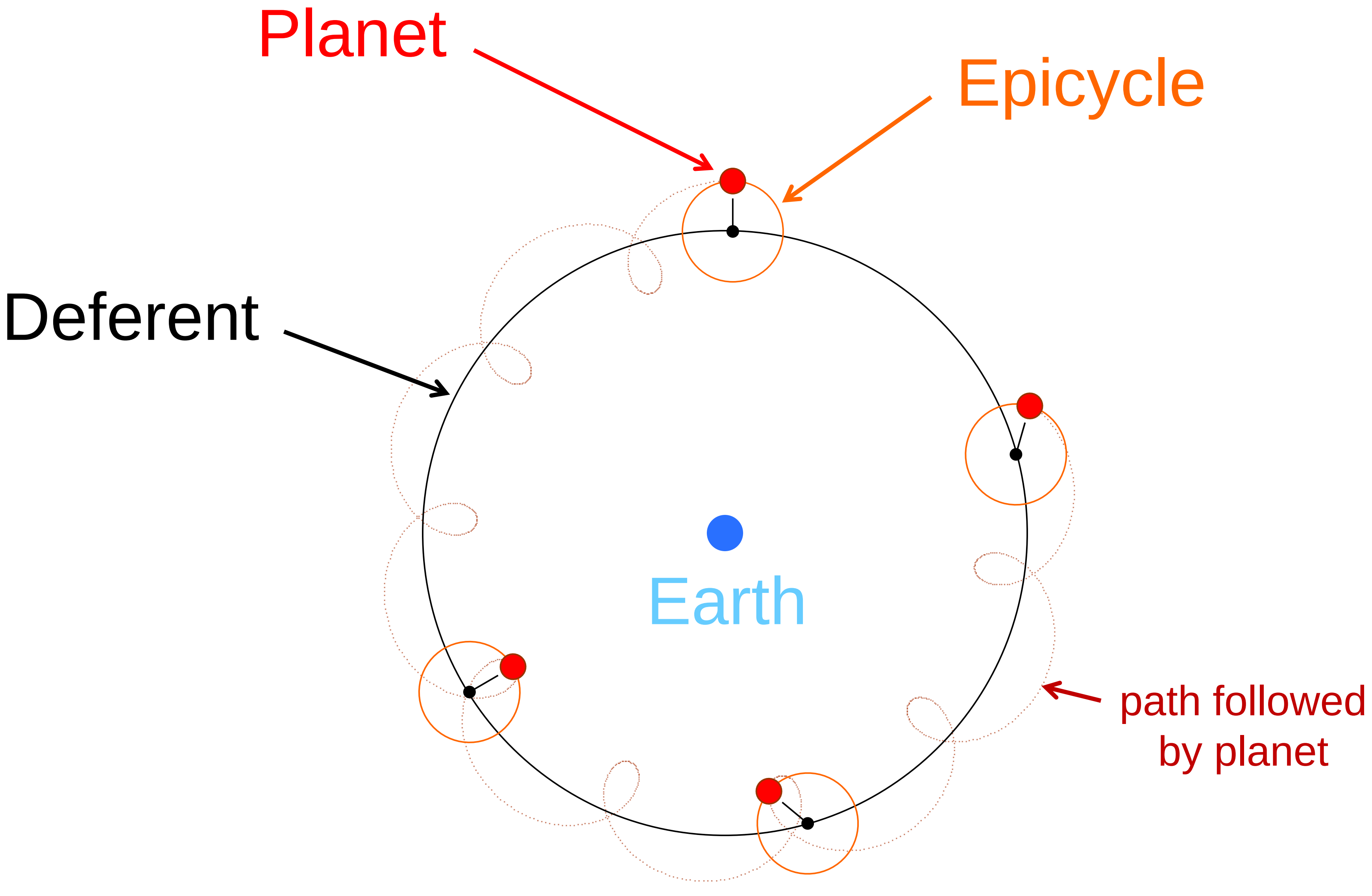
In order to explain the retrograde motion of planets he developed the concept of the deferent and epicycle.

His model was *very accurate* and could be used to predict future positions of the planets, Moon, Sun, etc. to within one degree!

Ptolemy
85 – 165 AD

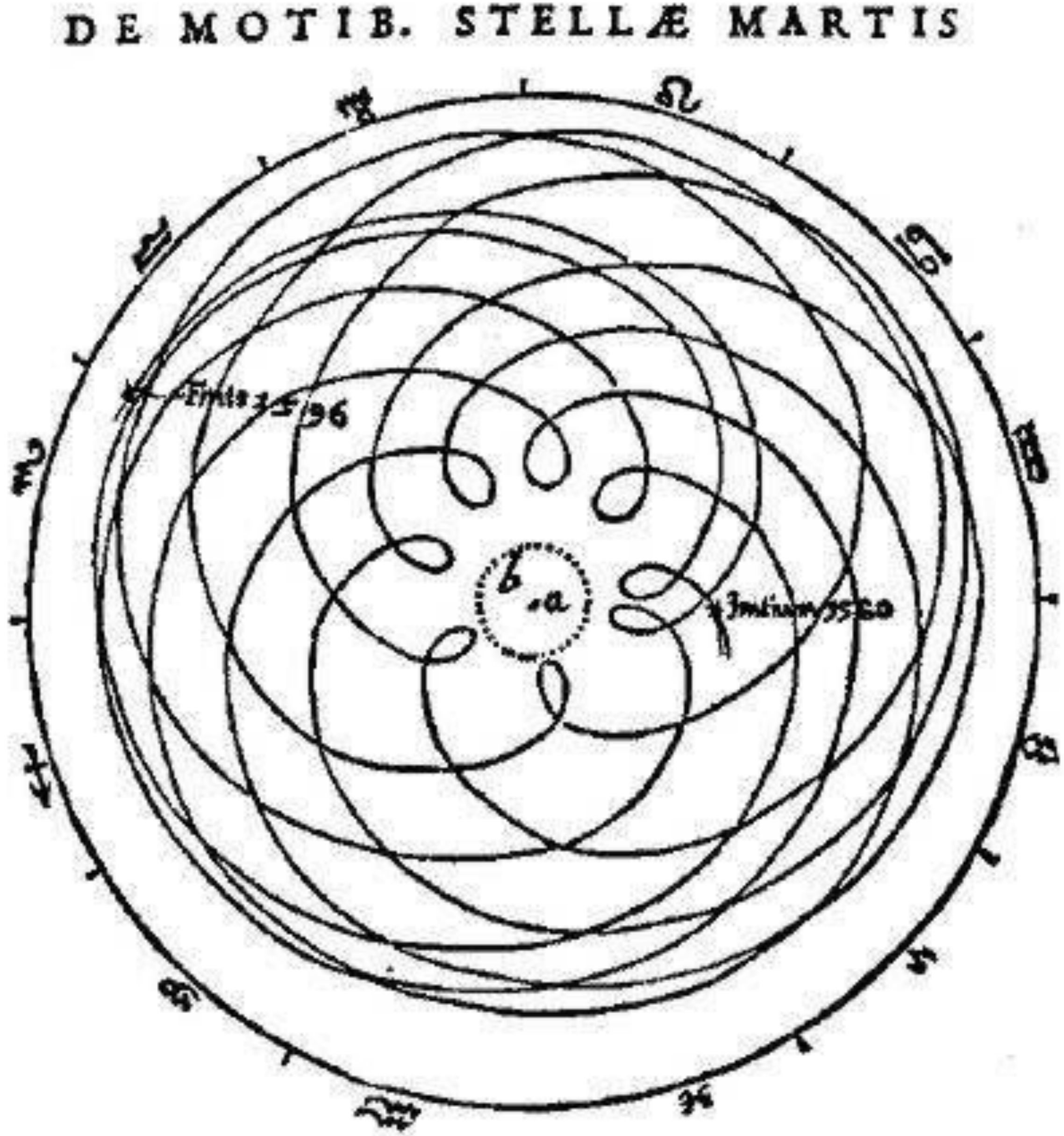
Ptolemy's system is called the *Almagest*, which translates as "the greatest"!

The *Almagest* was used for nearly 1500 years!

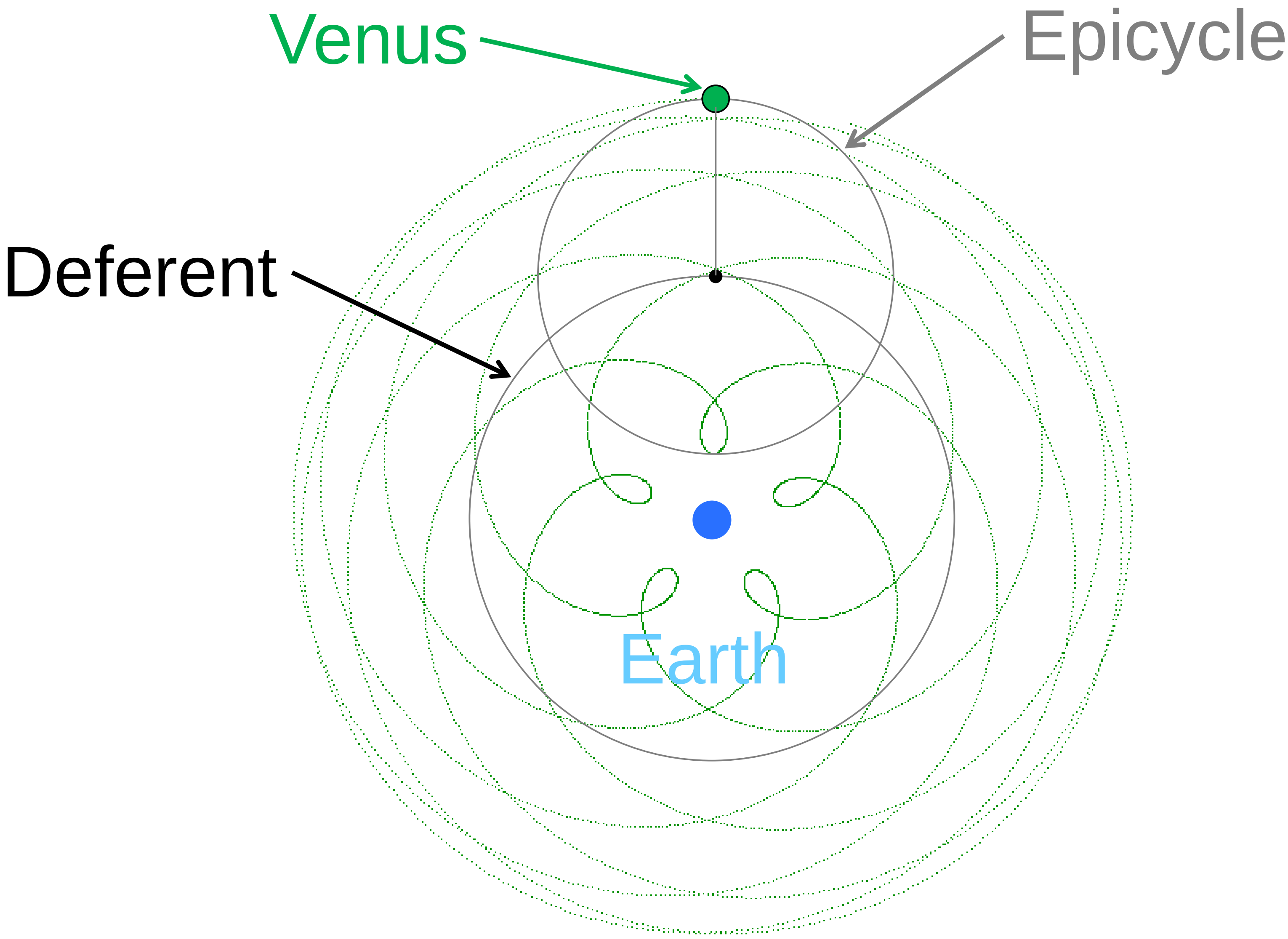

Planet
Epicycle
Deferent
Earth
path followed
by planet

Ptolemy's Genius

- Without breaking from the idea of "perfect circles" and geocentricism, Ptolemy was able to "explain" the motion of the planets.
- The deferent and epicycle combined to produce periodic retrograde motion.
- Changes in apparent brightness of the planets could be explained as could changes in apparent angular size of Moon and Sun.

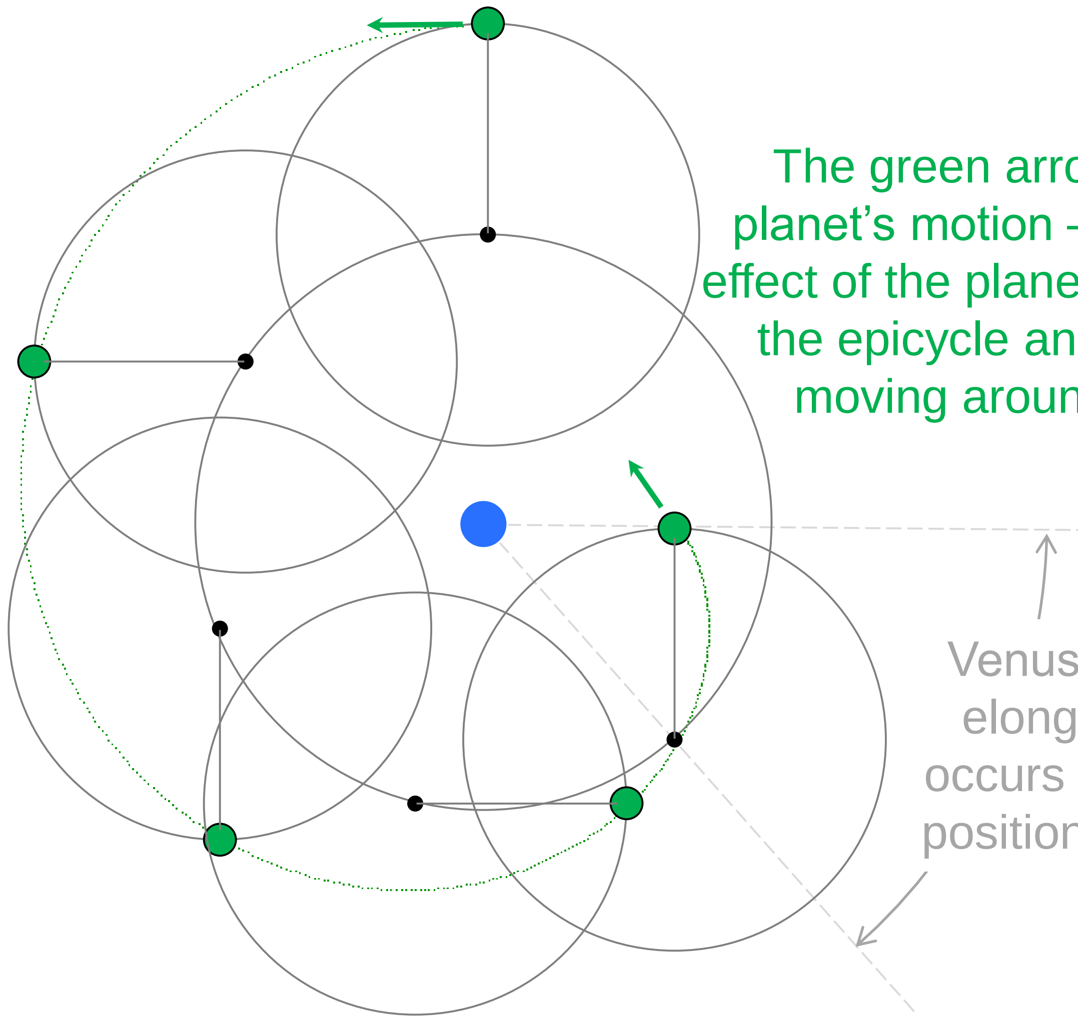


The path of Mars based on Ptolemy’s system of deferent and epicycle.



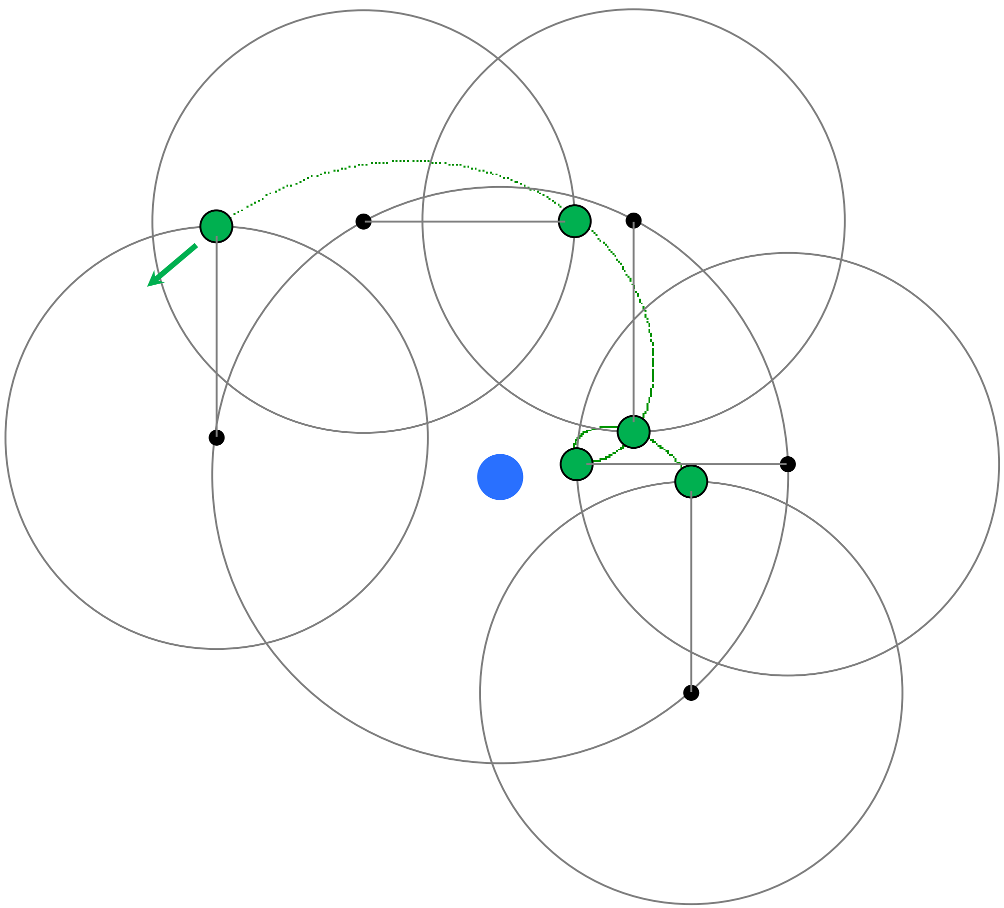
The path of Venus based on Ptolemy’s system of deferent and epicycle.

Here Venus is shown making one trip around its epicycle while the epicycle travels a little more than half way around the deferent that is centered on Earth. The small green dots show the path travelled by Venus in this time.



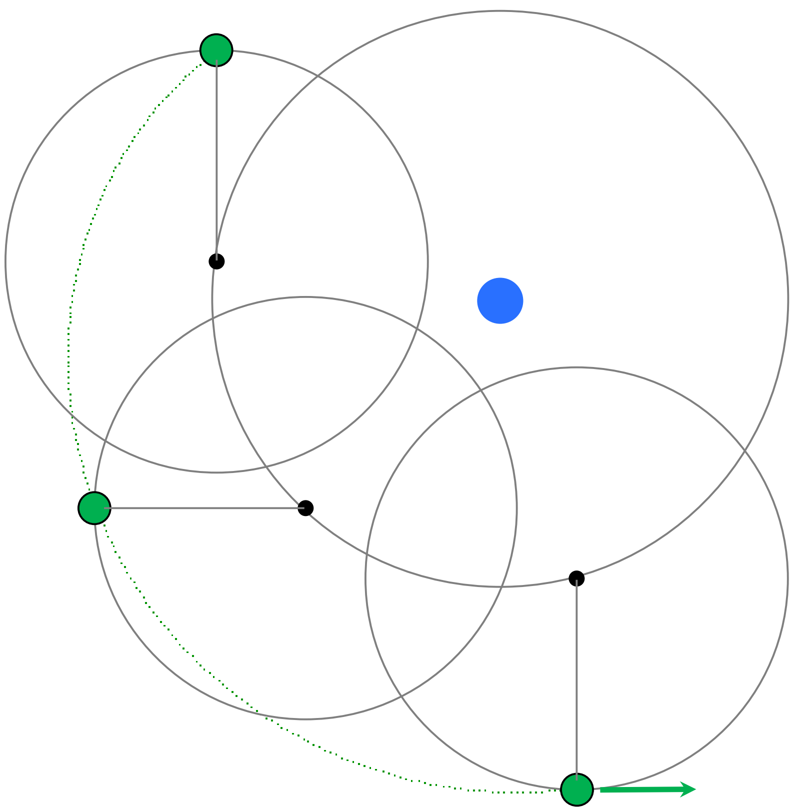
The path of Venus based on Ptolemy's system of deferent and epicycle.

Here Venus is shown making one trip around its epicycle while the epicycle travels a little more than half way around the deferent that is centered on Earth. The small green dots show the path travelled by Venus in this time.



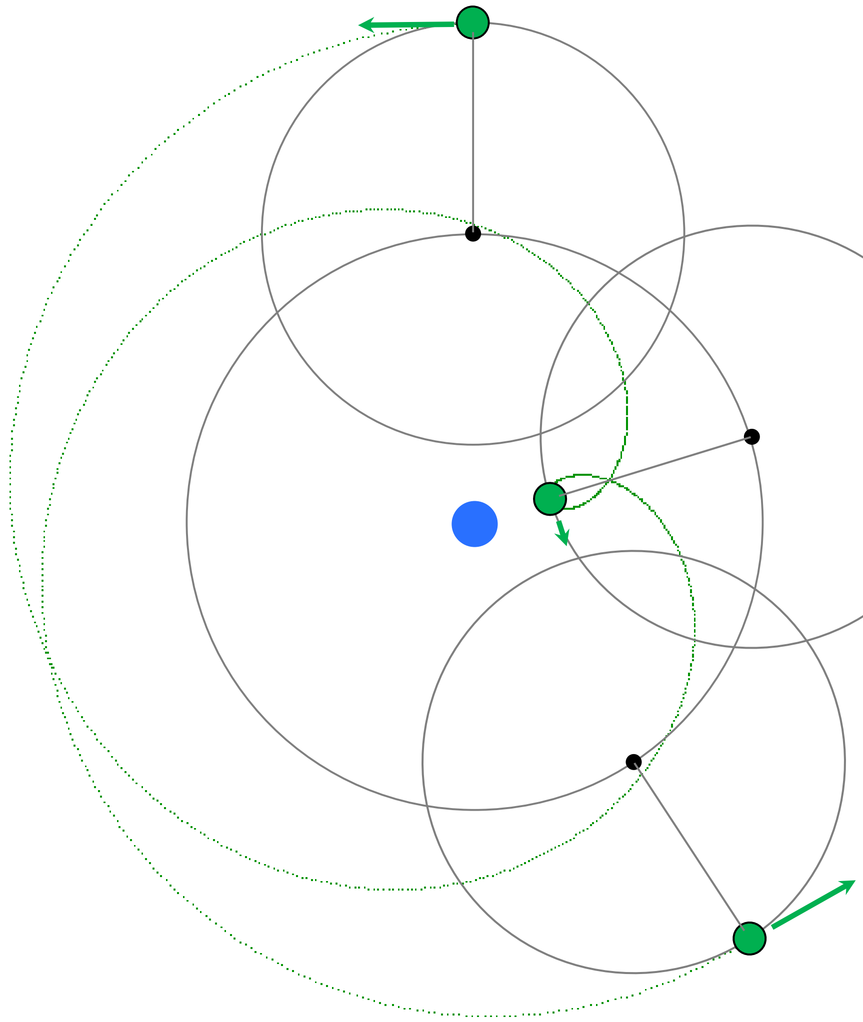
The path of Venus based on Ptolemy's system of deferent and epicycle.

Here Venus is shown making a half trip around its epicycle while the epicycle travels a little more than quarter way around the deferent that is centered on Earth. The small green dots show the path travelled by Venus in this time.



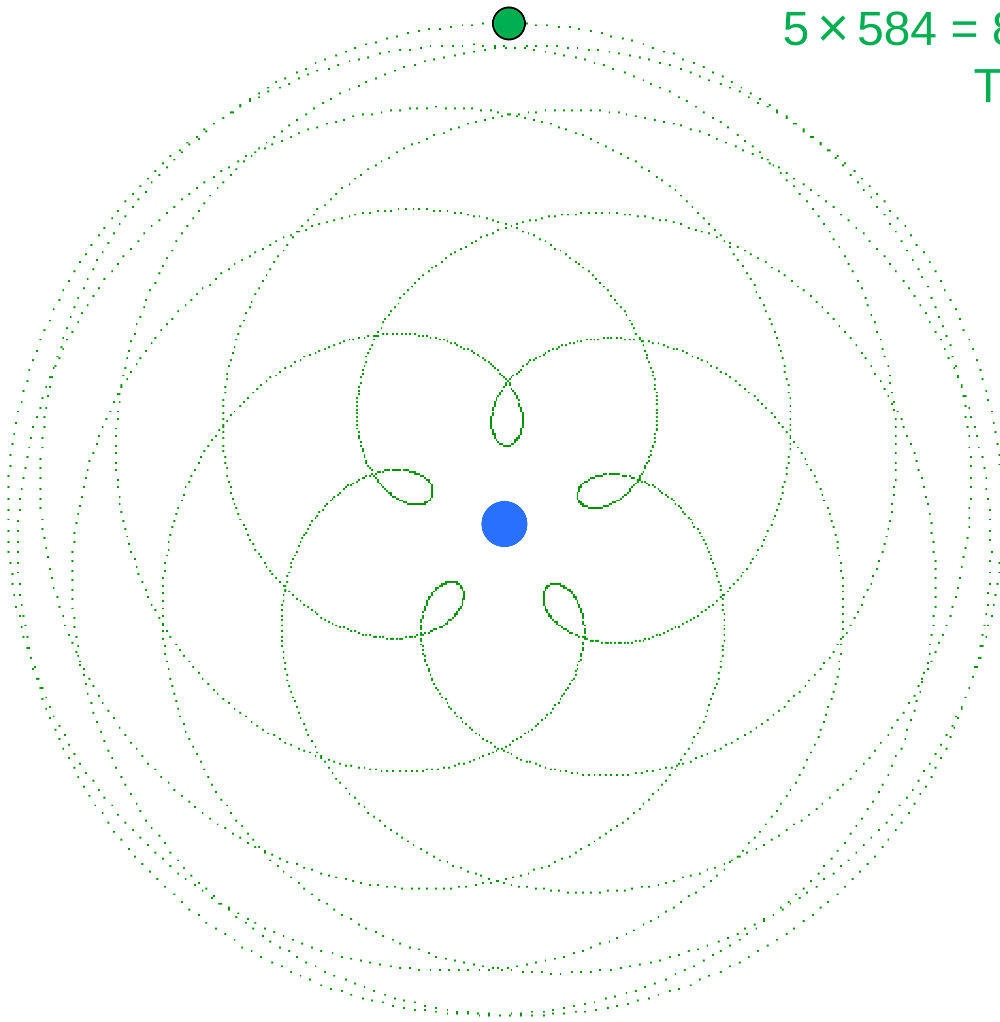
The path of Venus based on Ptolemy's system of deferent and epicycle.

This diagram shows a complete synodic period of 584 days, starting and ending with a conjunction with maximum prograde motion. Midway through the cycle is a conjunction with maximum retrograde motion.



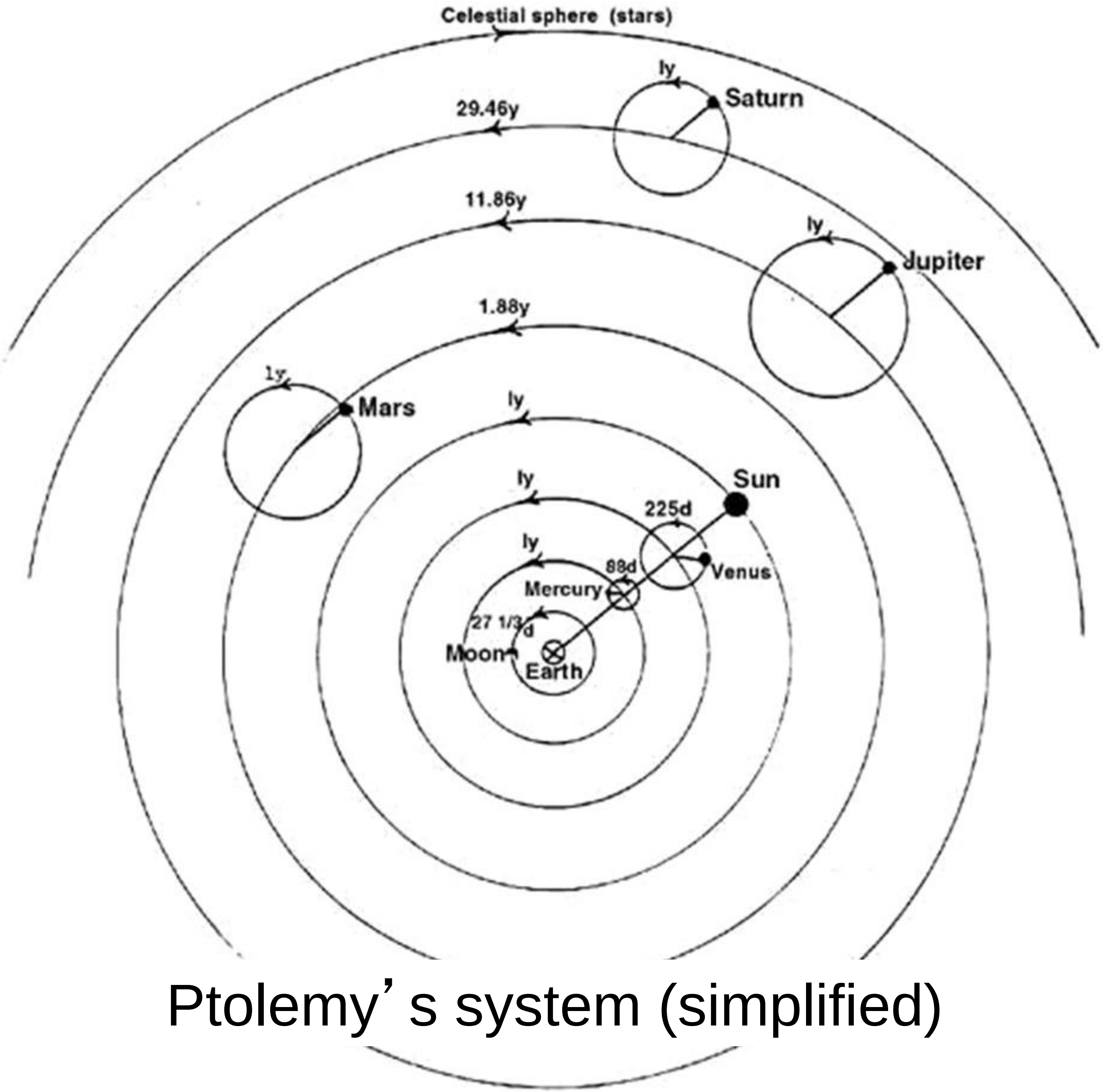
The path of Venus based on Ptolemy's system of deferent and epicycle.

The small green dots are shown at one day intervals. Five synodic periods happens to be very nearly eight years, causing Venus to produce this pattern.



5 × 584 = 8 × 365 = 2920 days
This is the number of dots in the figure!

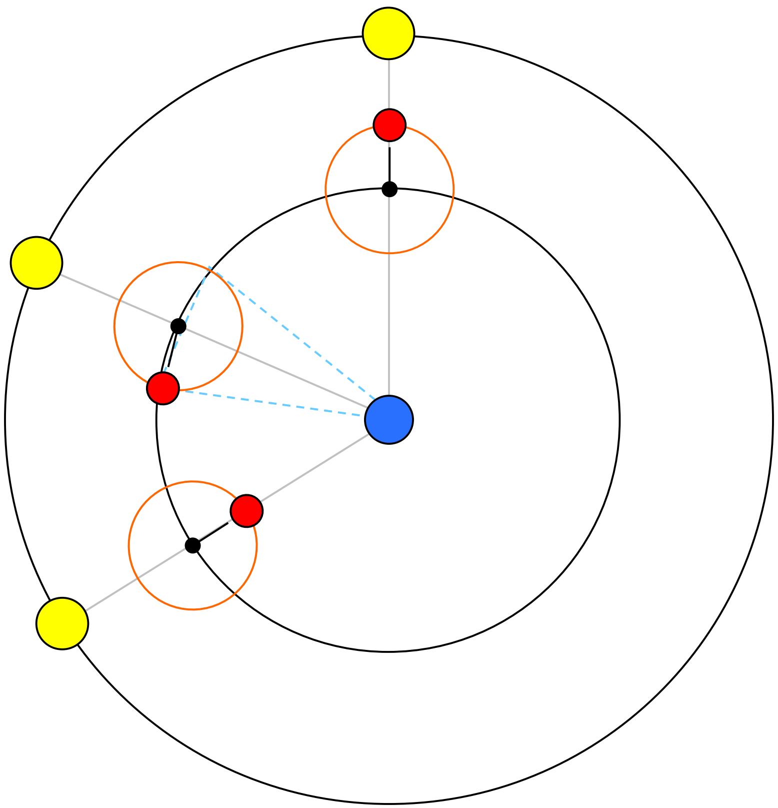
The path of Venus based on Ptolemy's system of deferent and epicycle.



Ptolemy’s system (simplified)

Motion of an “inner planet” (Mercury or Venus)

At all times the center of the epicycle is aligned with the Sun and the Earth.

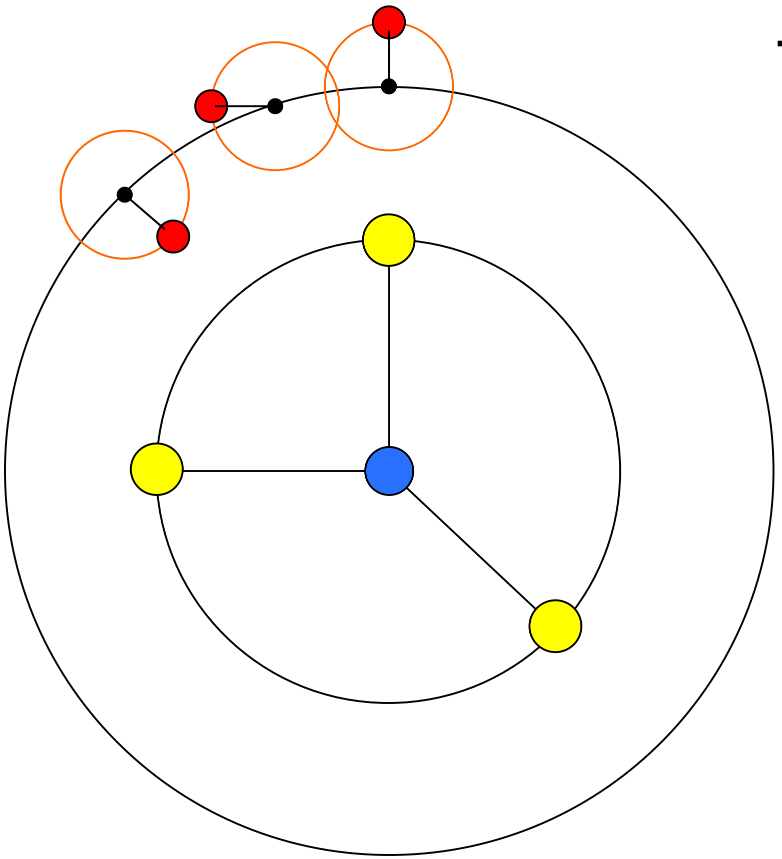


The size of the epicycle is determined by the planet’s maximum elongation.

Note that retrograde occurs around the time of conjunction, as expected!

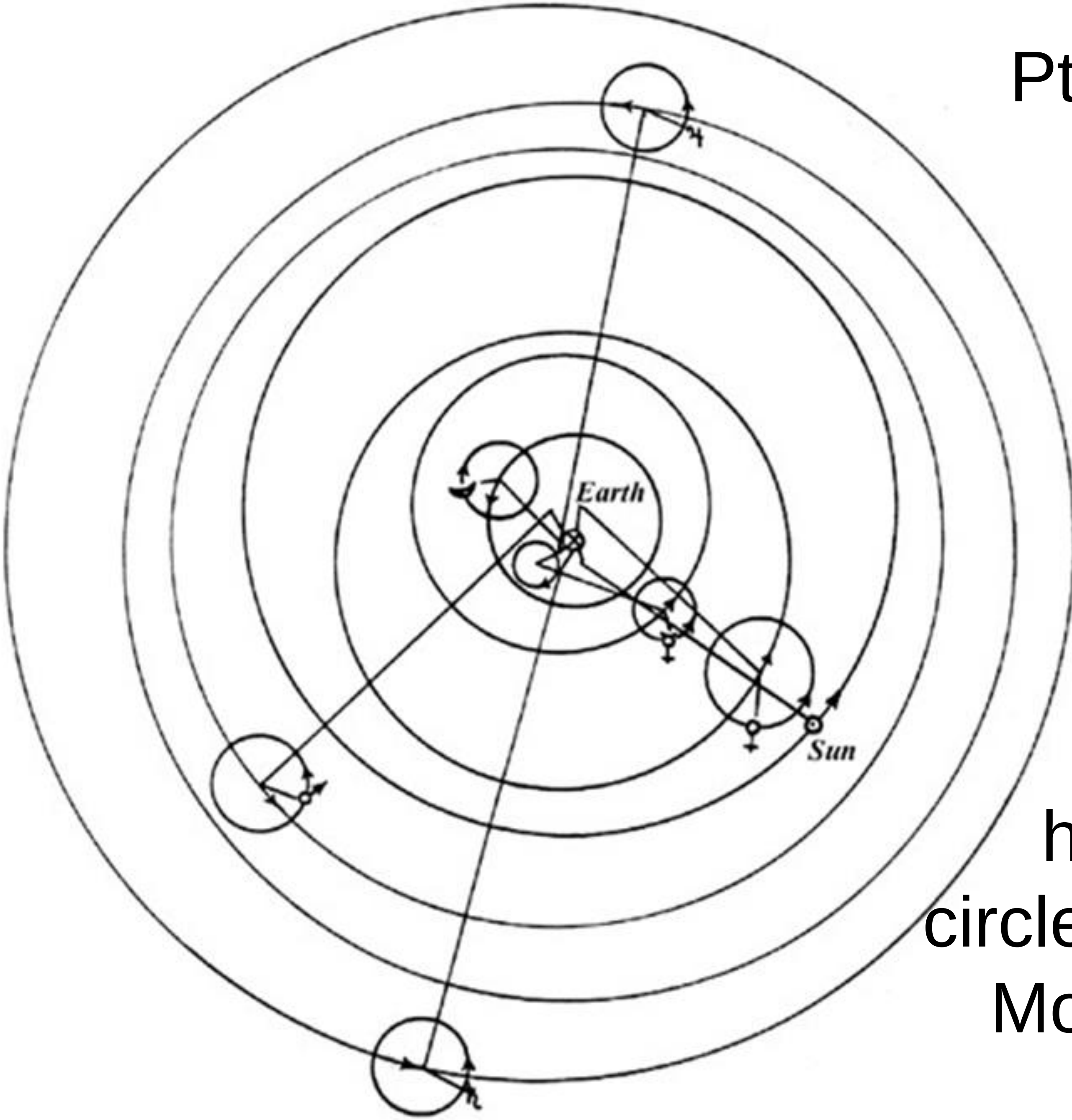
Motion of an “outer planet” (Mars, Jupiter, Saturn)

The line from the planet to the epicycle’s center is always parallel to the line from Sun to Earth.



The size of the epicycle is determined by the planet’s observed retrograde loop.

Note that retrograde and maximum brightness occur around the time of opposition, as expected!



Ptolemy's model also employed eccentrics and equants!

The Almagest had a total of 80 circles modeling the Moon, Sun, and 5 known planets.

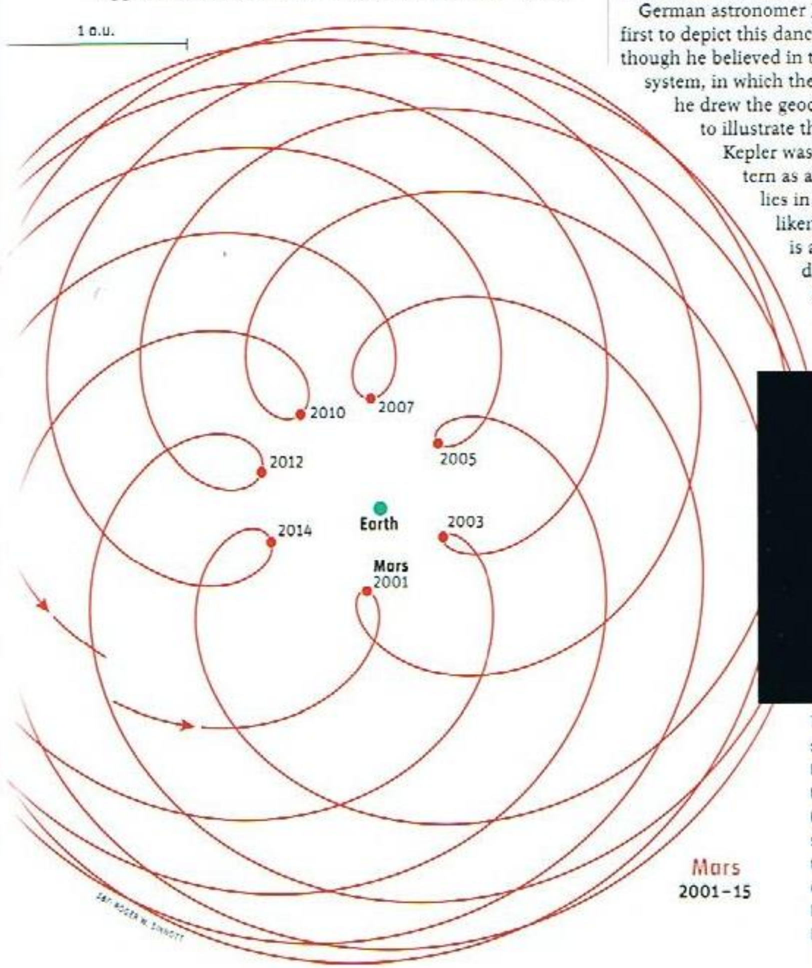
What fault is there in Ptolemy’s model?

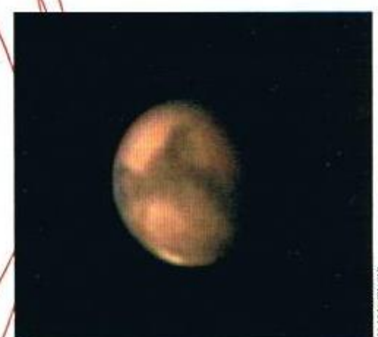
Planetary Pretzels Three diagrams show the inner workings of the orbits of Mercury, Venus, and Mars. By Owen Gingerich and Richard Conn Henry

IN AUGUST 2003 the Red Planet made an unusually close approach to Earth. As noted in that year's June issue of *Sky & Telescope* (page 94), Mars had not come this close to our home planet in recorded history, nor would it again be as close for nearly three centuries. How did astronomers know this? Did they calculate the distance of Mars for every single day between now and August 28, 2287?

The answer is that the calculation can be much easier than that. Mars makes a close approach whenever it's near opposition to the Sun in our sky, and this happens every 2.135 years (on average), including the one this November. And the closest of these comes every 15 or 17 years, when the opposition takes place in July, August, or September. This is because Mars's orbit is not concentric with the Sun. It's slightly off center, and the closest possible approach to Earth comes when the Red Planet reaches *perihelion*, its closest point to the Sun, in late August when Earth is also close to the Mars–Sun perihelion line. Therefore, it's necessary to check Mars's position only for a couple of days every 15 or 17 years.

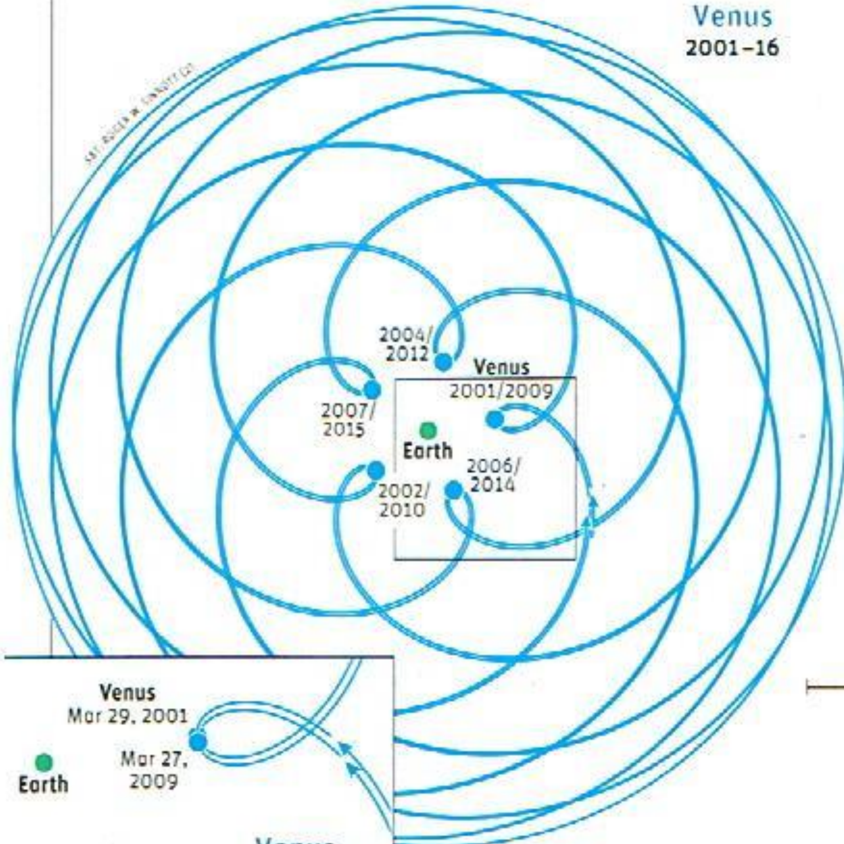
German astronomer Johannes Kepler (1571–1630) was the first to depict this dance of Mars with respect to Earth. Although he believed in the Copernican model of the solar system, in which the Sun was the center of the universe, he drew the geocentric (Earth-centered) path of Mars to illustrate the planet's apparent motion. At first, Kepler was tempted to describe the orbital pattern as a ball of yarn, but since the pattern lies in a flat plane, he reconsidered and likened it instead to a pretzel. To the left is a modern version of Kepler's pretzel diagram, and it shows how the 2003 opposition of Mars brought it a little closer to us than the one this November and how the 2007 opposi-

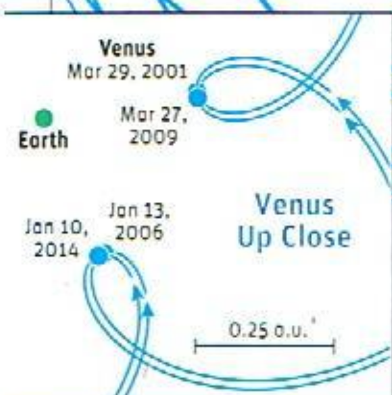


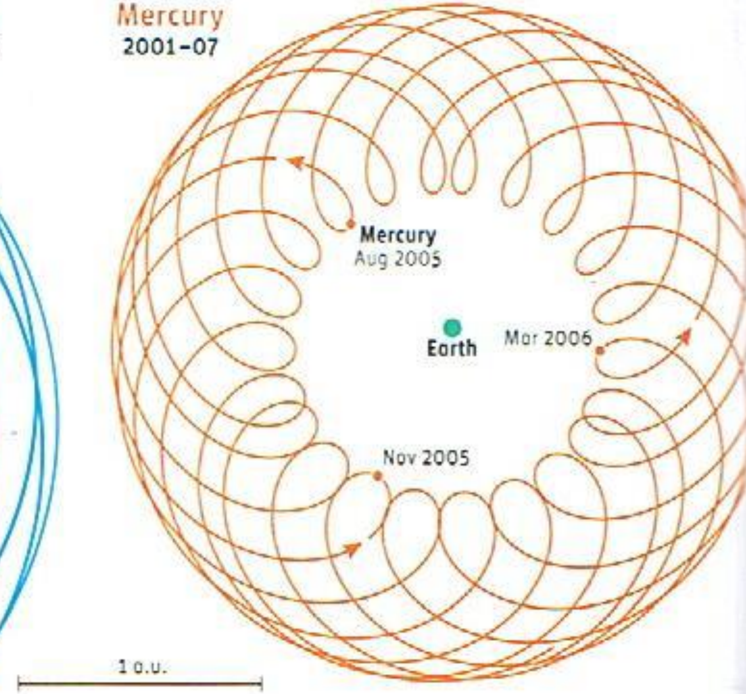


This diagram and the two on the next page show each planet's motion with respect to Earth, beginning January 1, 2001. All are plotted at the same scale; 1 astronomical unit (a.u.) is the mean Earth–Sun distance. Mars shows a greater variation in close approaches than either Mercury or Venus. But the current one is only slightly less favorable than the historic close approach of 2003. *Inset:* Mars last August 22nd, when it was 13" wide.

Think geocentricism is dead? Check out this November 2003 Sky & Telescope article!







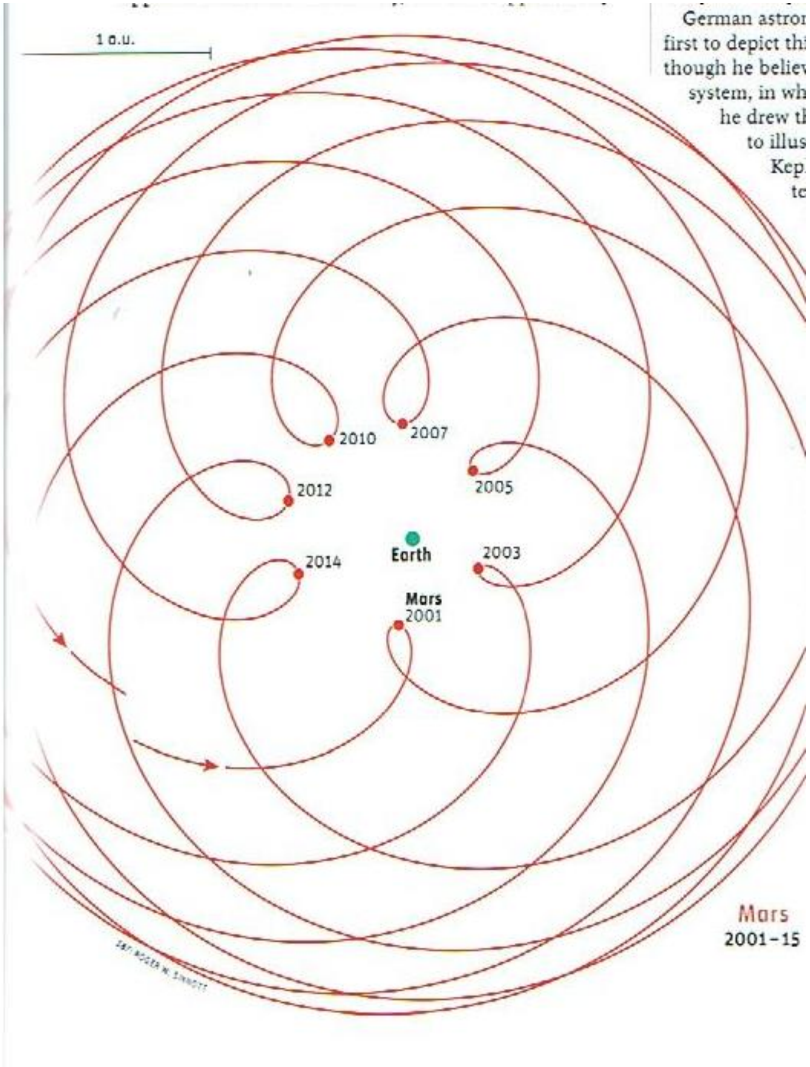
Above: Mercury makes a close approach to Earth in late November 2005, but the planet comes a little closer next March. *Left:* Two 8-year cycles of Venus are superposed to show how closely they repeat. The inset at far left shows the dates when Venus is closest to Earth. These dates fall within a day of Venus's inferior conjunction with the Sun.

tion will keep the Red Planet still farther away.

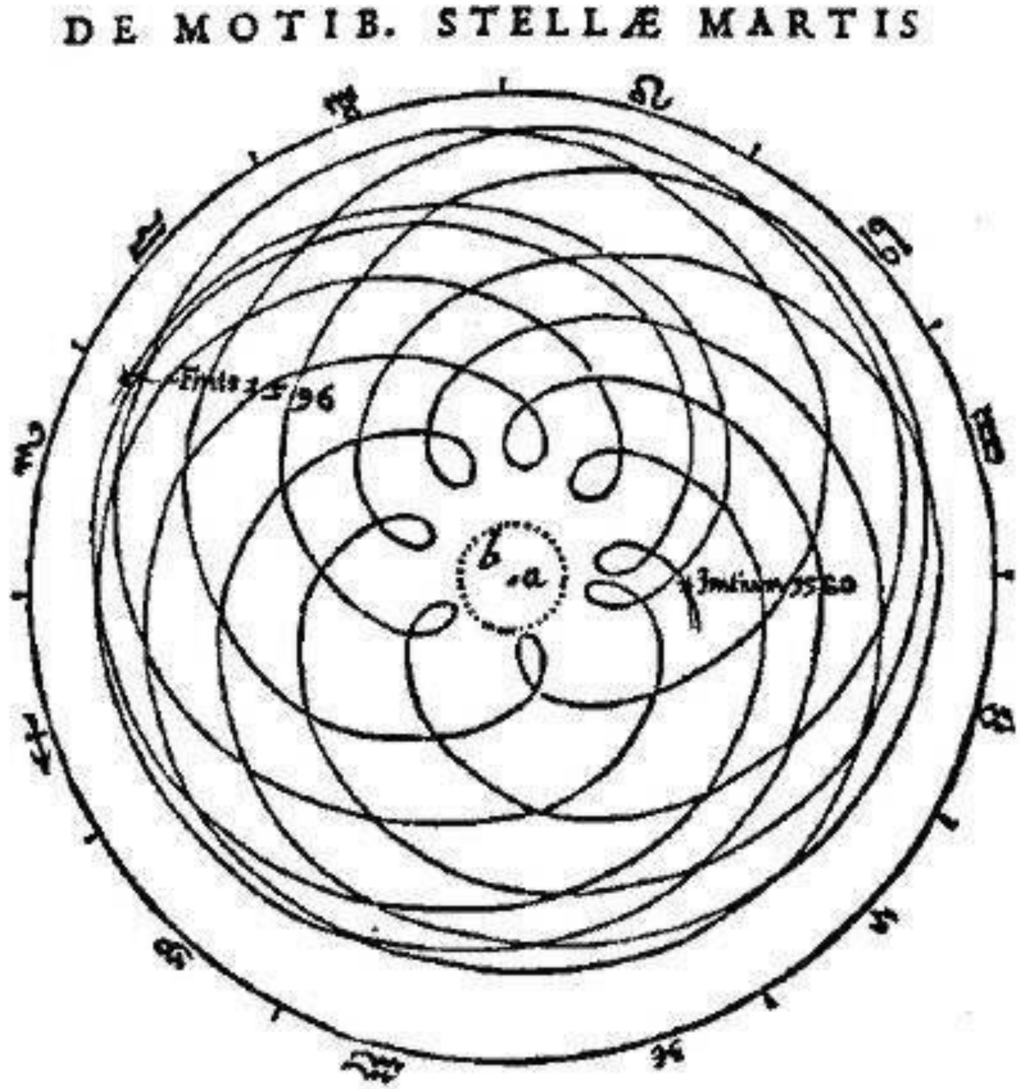
The same kind of pretzel diagram for swift Mercury shows more frequent loops — roughly three a year — and an approximate repeat of the entire wickerwork pattern every 21 years. Because Mercury is an inner planet, with its orbit lying between the Sun and Earth, it will come closest to us when it's at *aphelion,* or farthest from the Sun (see the upper part of the diagram above, right). At this time, Mercury moves most slowly (according to Kepler's law of equal areas in equal times), and the retrograde loops are narrowest. Note that Mercury never comes as close as Mars.

The most extraordinary diagram of this sort is for the planet Venus. Notice that it repeats almost identically every eight years. Both the Babylonians and the Maya discovered this cycle, and it became an important feature in the Maya calendar. It's tempting to suppose that somehow the period of Venus is gravitationally locked with Earth's, but their orbits are too nearly circular for this to be a strong effect. It seems this is just a wonderful coincidence!

Owen Gingerich *is a professor emeritus of astronomy and of the history of science at Harvard University and a senior astronomer emeritus at the Smithsonian Astrophysical Observatory, while* Richard Conn Henry *is a professor of astronomy at Johns Hopkins University in Baltimore and director of the Maryland Space Grant Consortium.*

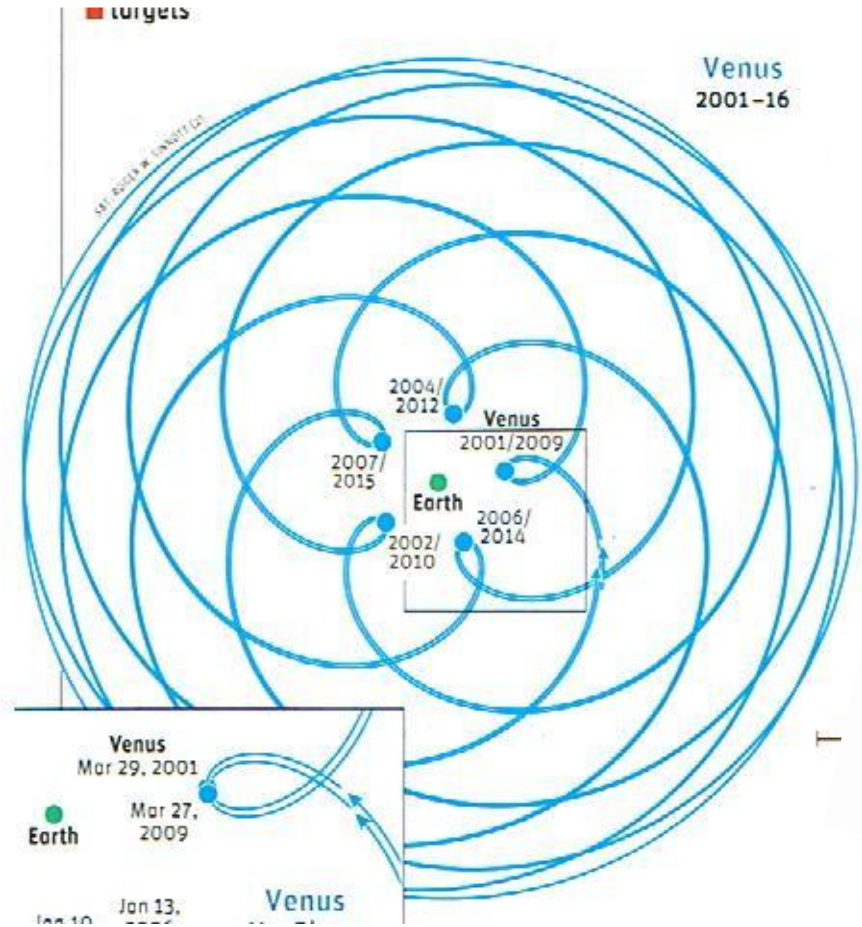


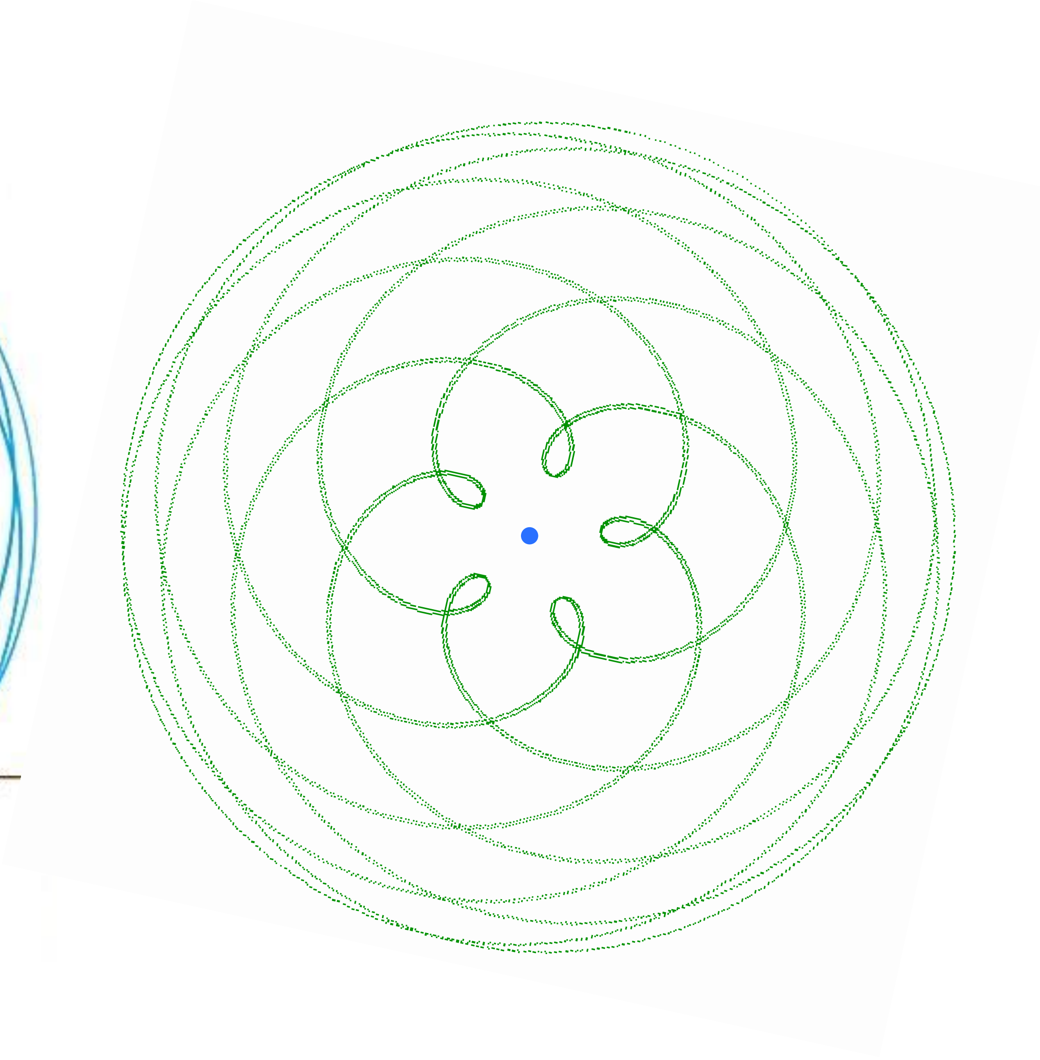
Relative path of Mars calculated by computer based on actual orbits.



Path of Mars determined by Ptolemy's ancient system of epicycles & deferents.

Notice any similarities?!





Relative path of Venus calculated by computer based on actual orbits.

Path of Venus determined by Ptolemy's ancient system of epicycles & deferents.

Notice any similarities?!

There basically is no “fault” in Ptolemy’s <u>model</u> in the sense that it correctly represents <u>all</u> aspects of celestial motion visible to the naked eye. It truly is an impressive and *great* achievement!

However, it lacks any sort of theory that explains <u>*why*</u> the planets should do such things.