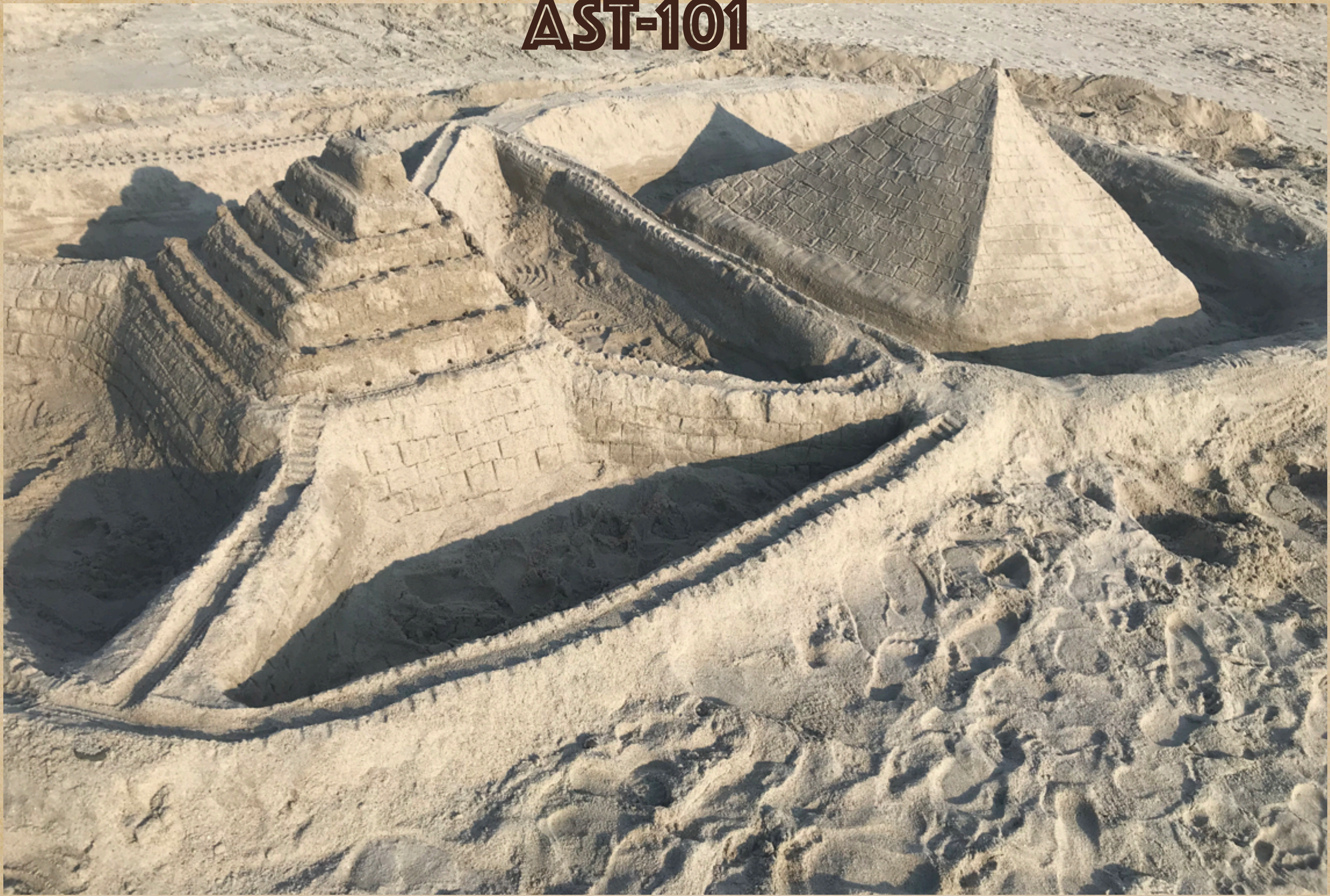
AST-101



Copernicus, Kepler, and Galileo

Luis Anchordoqui

What is Science

Science has a two-fold definition

- A body knowledge
- A process of learning about nature

Mathematics is a tool for science

- Analyze, test and quantify theories

Scientific theory

Begins with a hypothesis

- ➢ Tries to describe and predict the natural world
- ➢ Explain observations/experiments
- Possibly contributing to or encompassing physical laws

But theories may break down

- ➢ May not be able to explain new observations/ experiments
- ➢ A new hypothesis is then proposed to modify or replace current explanations
- Must also be under observational/experimental scrutiny

Occam's Razor

- When there exist two competing theories that make exactly same prediction, the simpler one is the better

- A scientific theory should be
  - ✓ simple
  - ✓ without fewest unproven assumptions
  - ✓ verificable

An Early Scientific Question

Is the Sun or the Earth at the center of our universe?

- ➢ The answer is neither
  - but which view best explains the motions of the stars, planets, and Sun in our sky?
- ➢ How this question was tackled over the years gives insight as to how science is performed
  - also gives a historical context to astronomy

Early Astronomy and Planetary Motion

Aristotle

- Earth is a sphere that is positioned at center of theuniverse
- Geocentric cosmology

Aristarchus

- Sun is at center of the universe
- Sun and stars are stationary
- Earth and planets revolve around the sun

In contemporary Greece, Aristotle was far more influential than Aristarchus

- the Earth-centered universe became the accepted norm

Observational evidence:

- Earth is not felt to move beneath ones feet, so it must be stationary
- Stars, planets, and Sun seem to revolve around the Earth

Claudius Ptolemy
90 AD-168 AD

Ptolemaic Model

Claudius Ptolemaeus

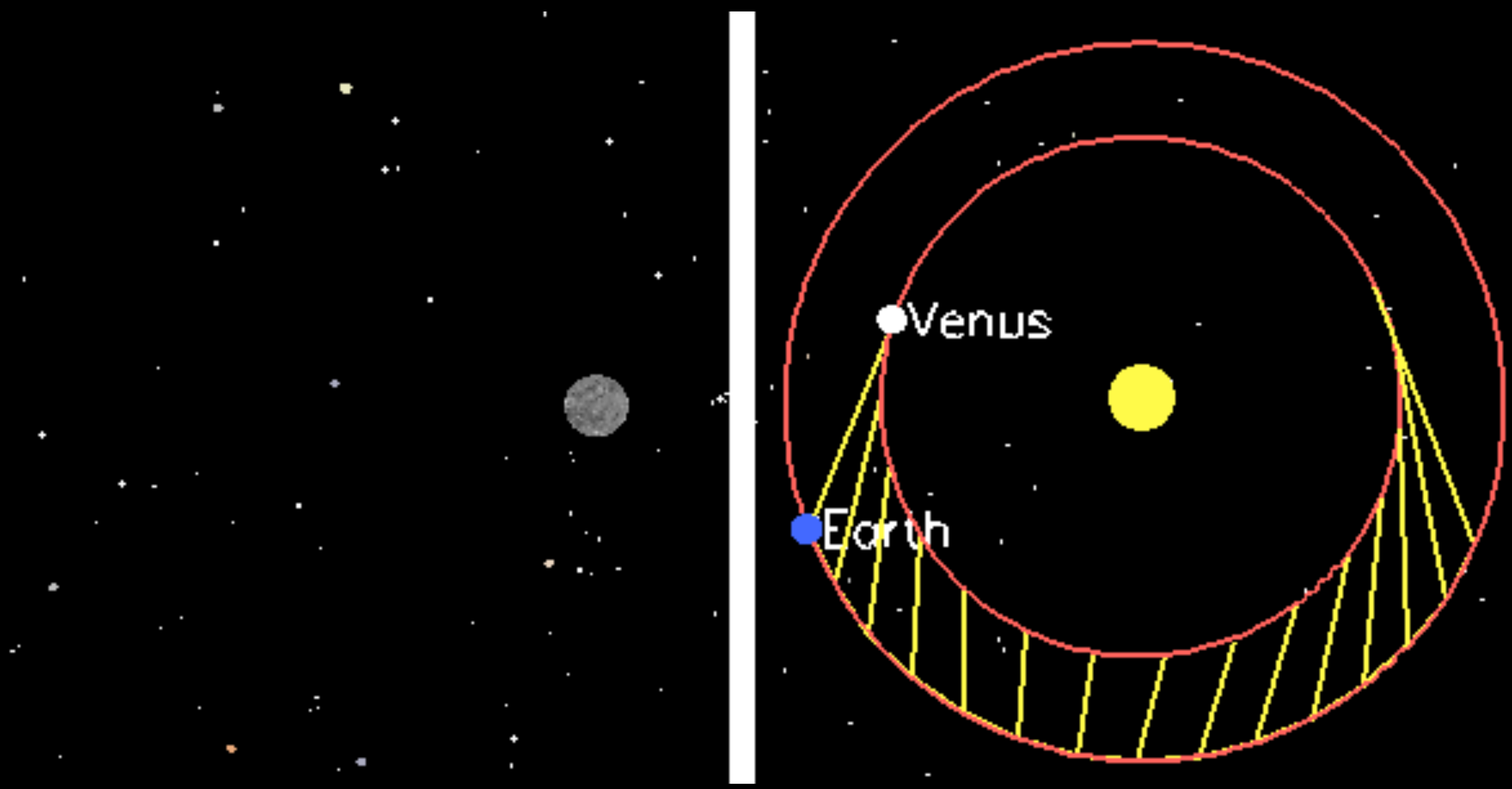
Devised a Geocentric model to describe motion of heavenly bodies

Based on teachings of Aristotle and other Greek scholars

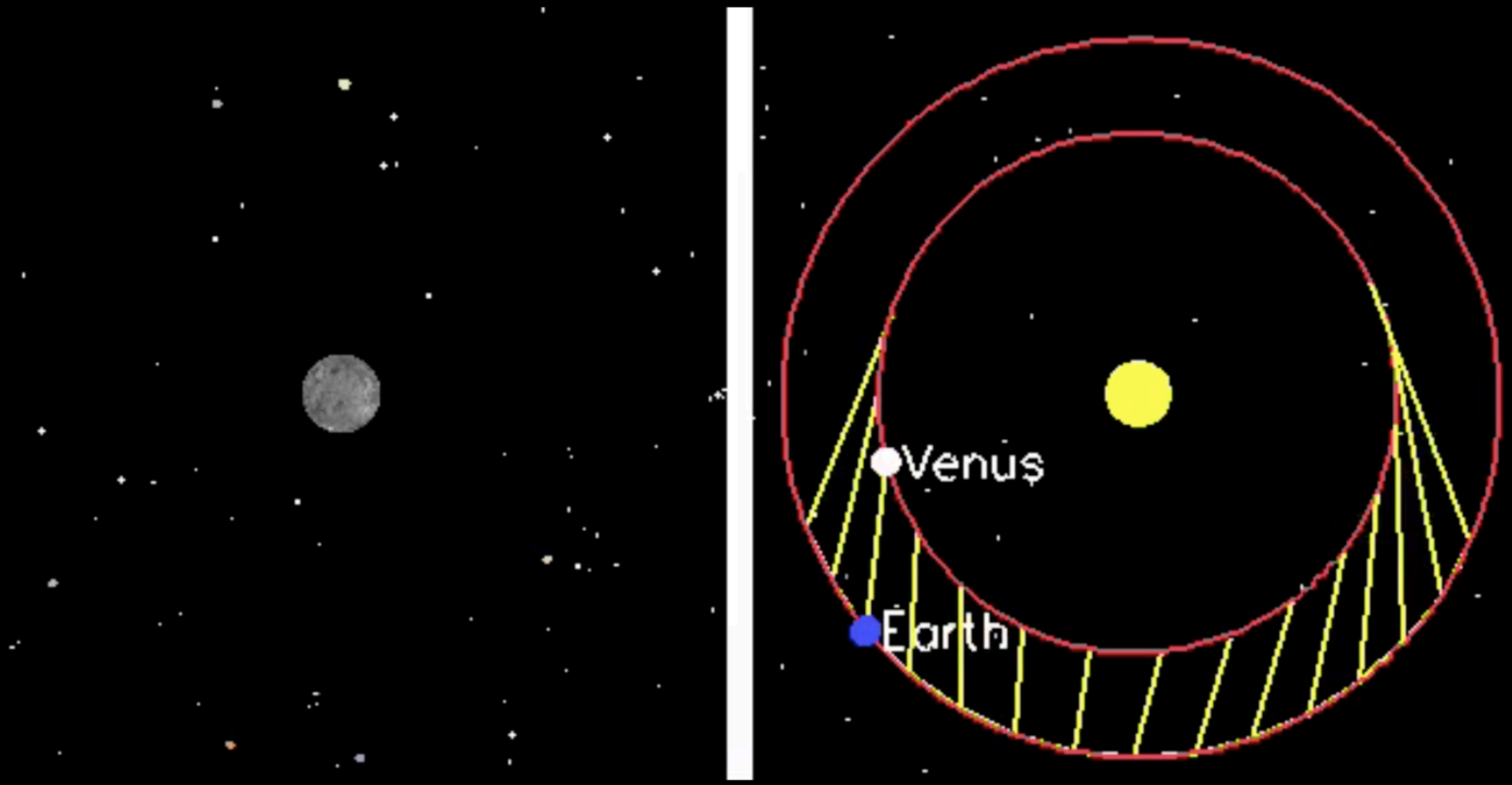
Motion of celestial objects must have perfect uniform circular motion

Explained observed retrograde motion of the planets

Retrograde motion



Retrograde motion



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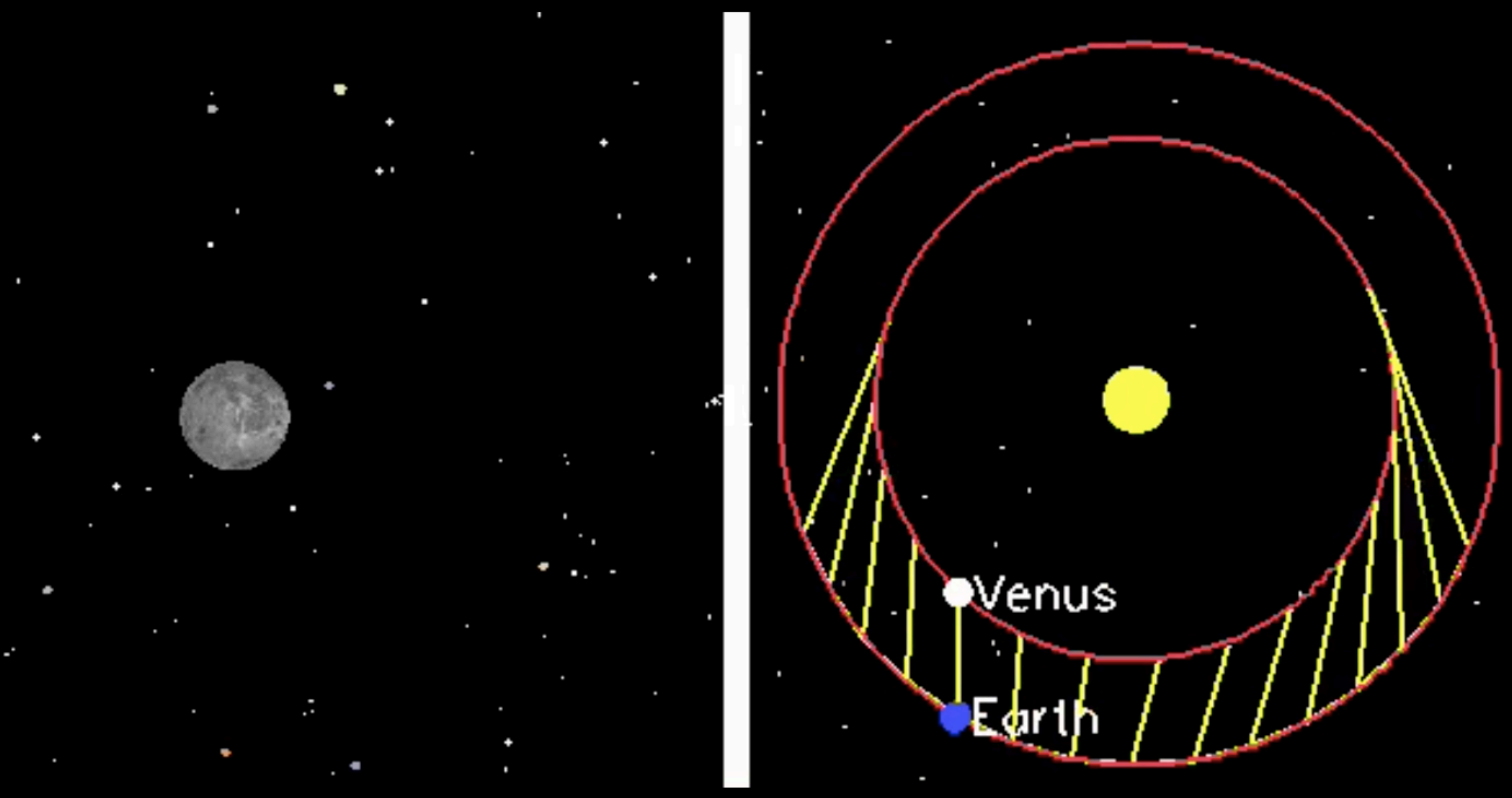

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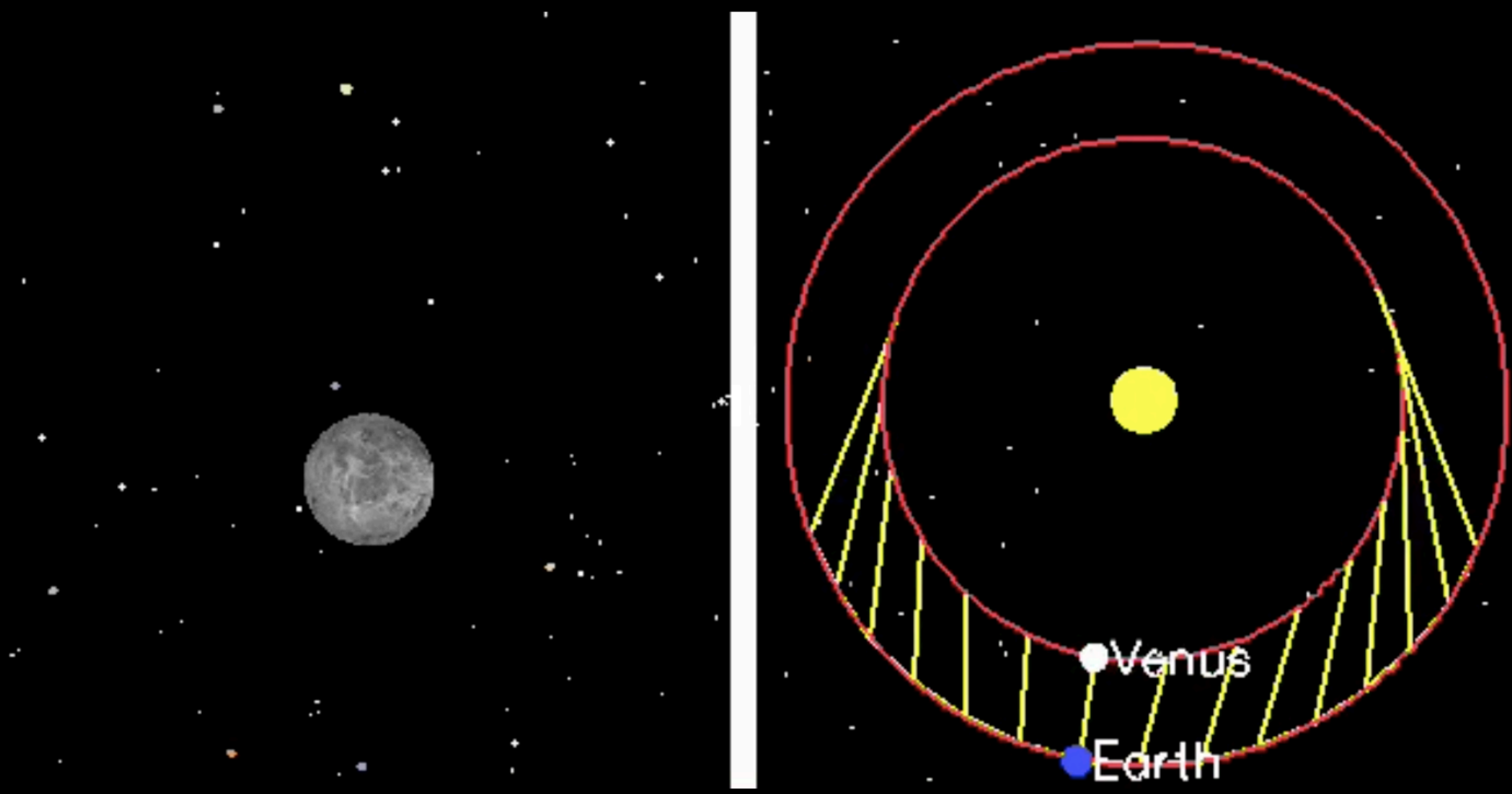

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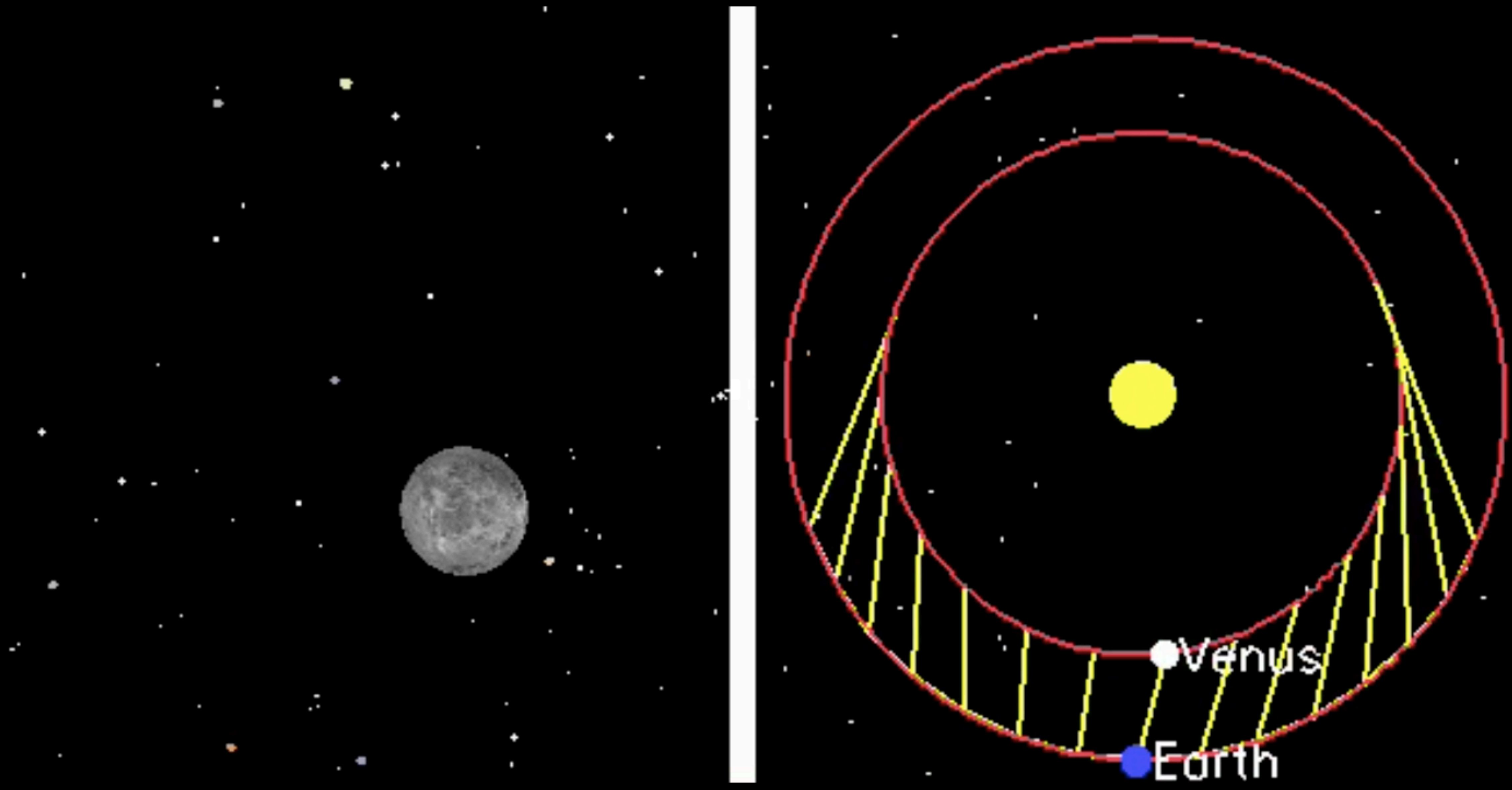

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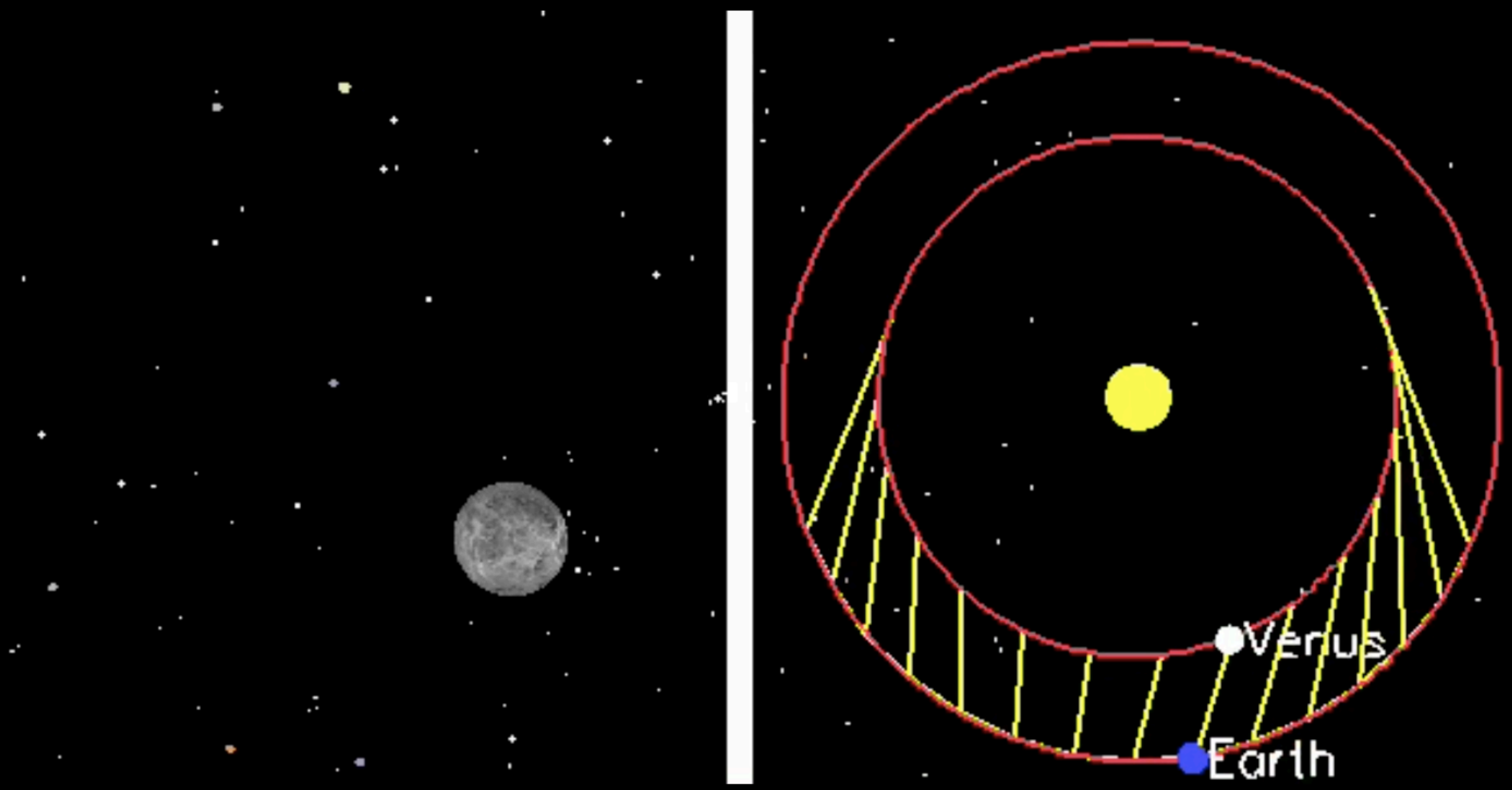

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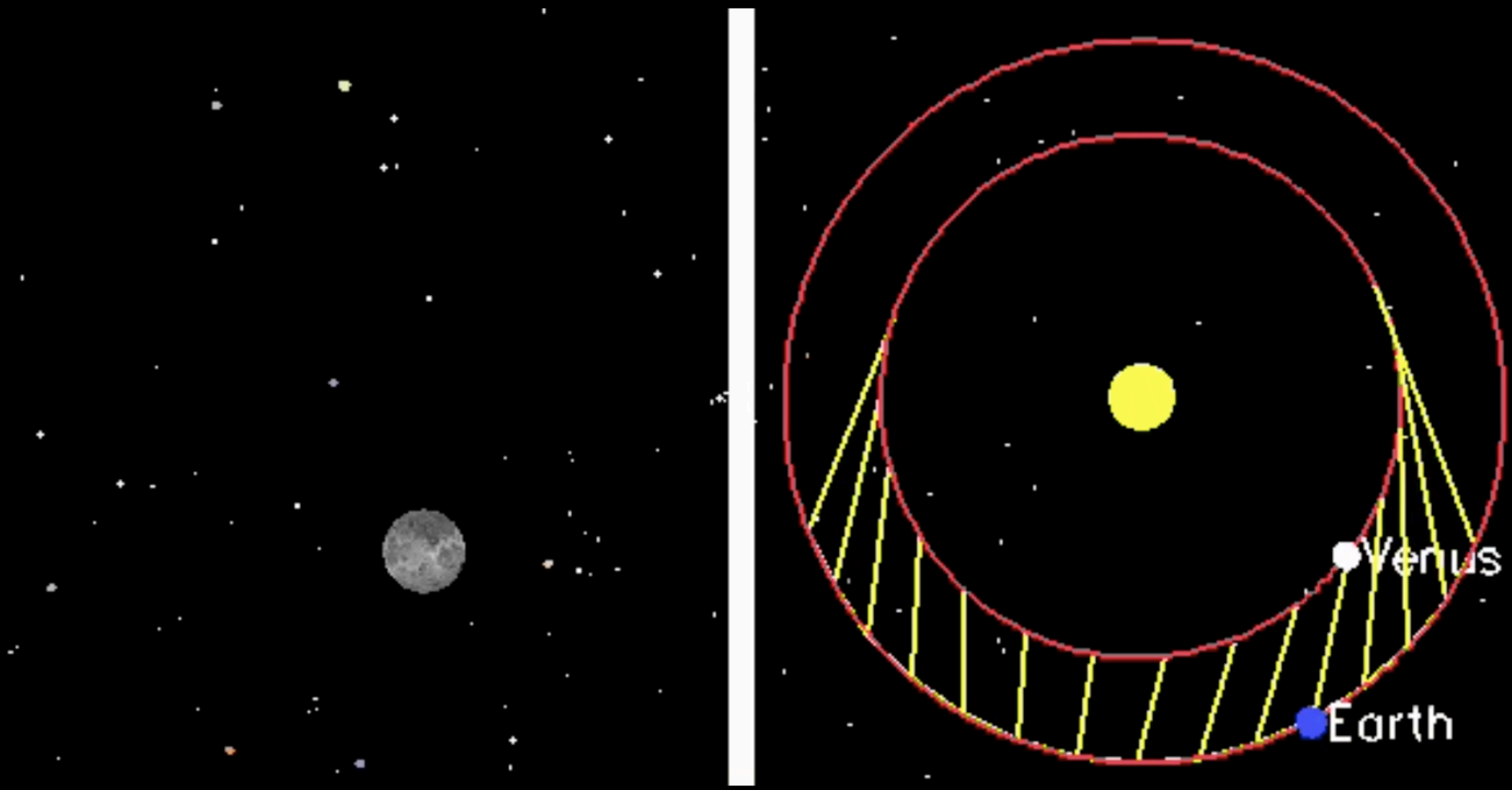

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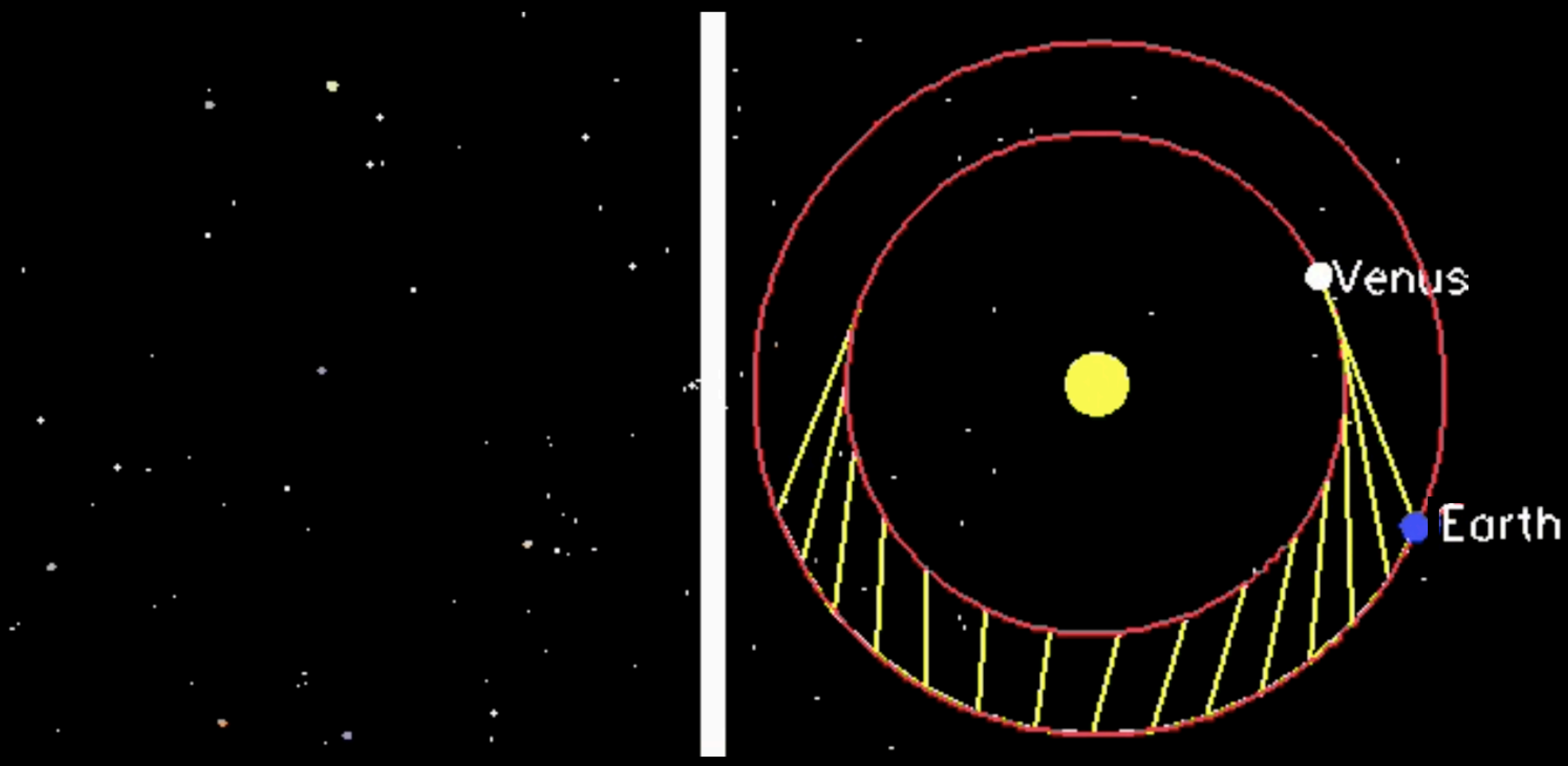
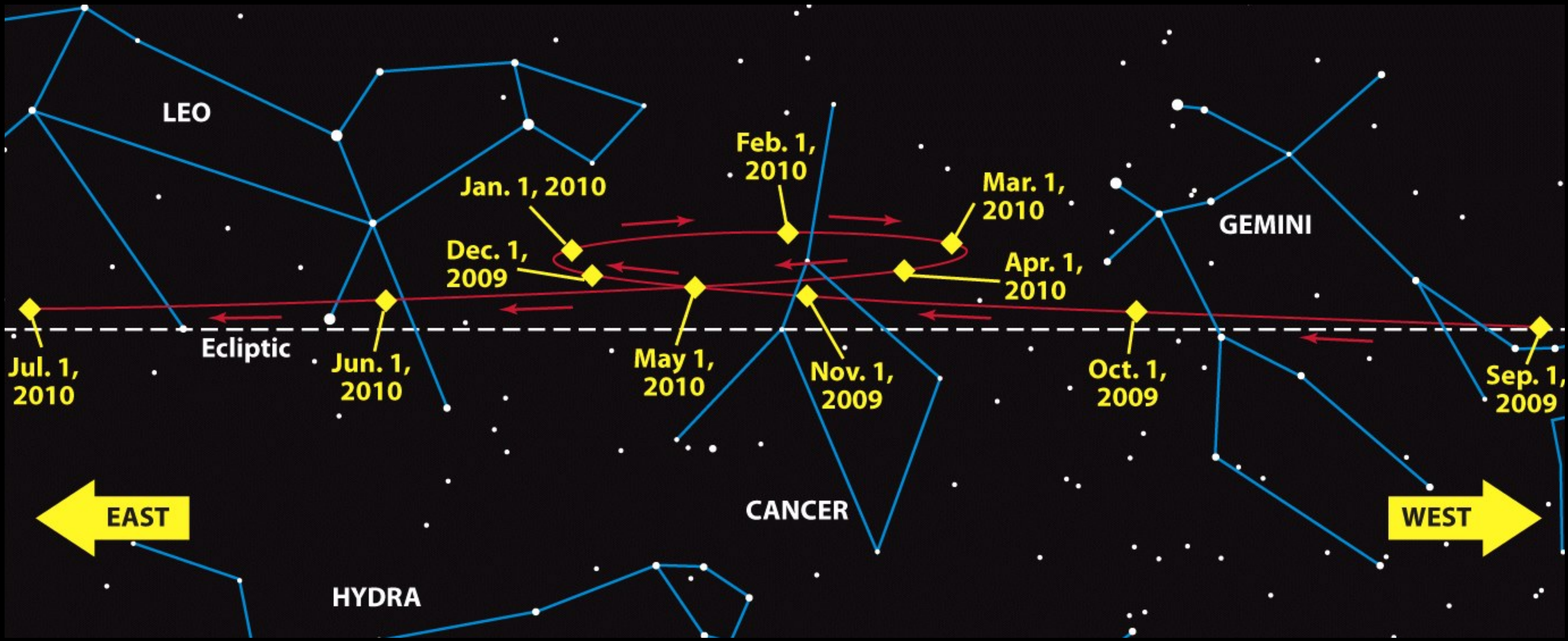


Retrograde motion of Mars

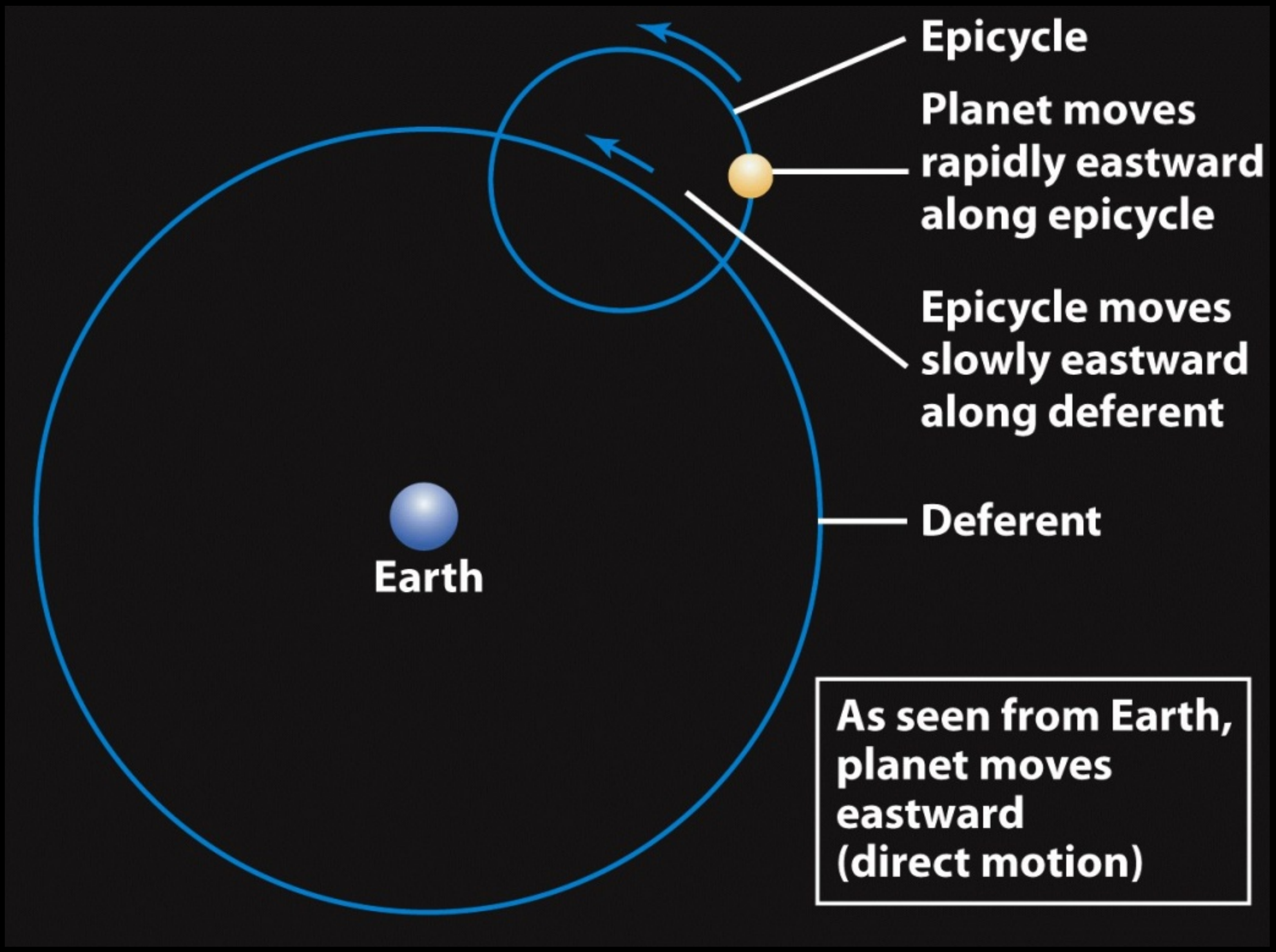


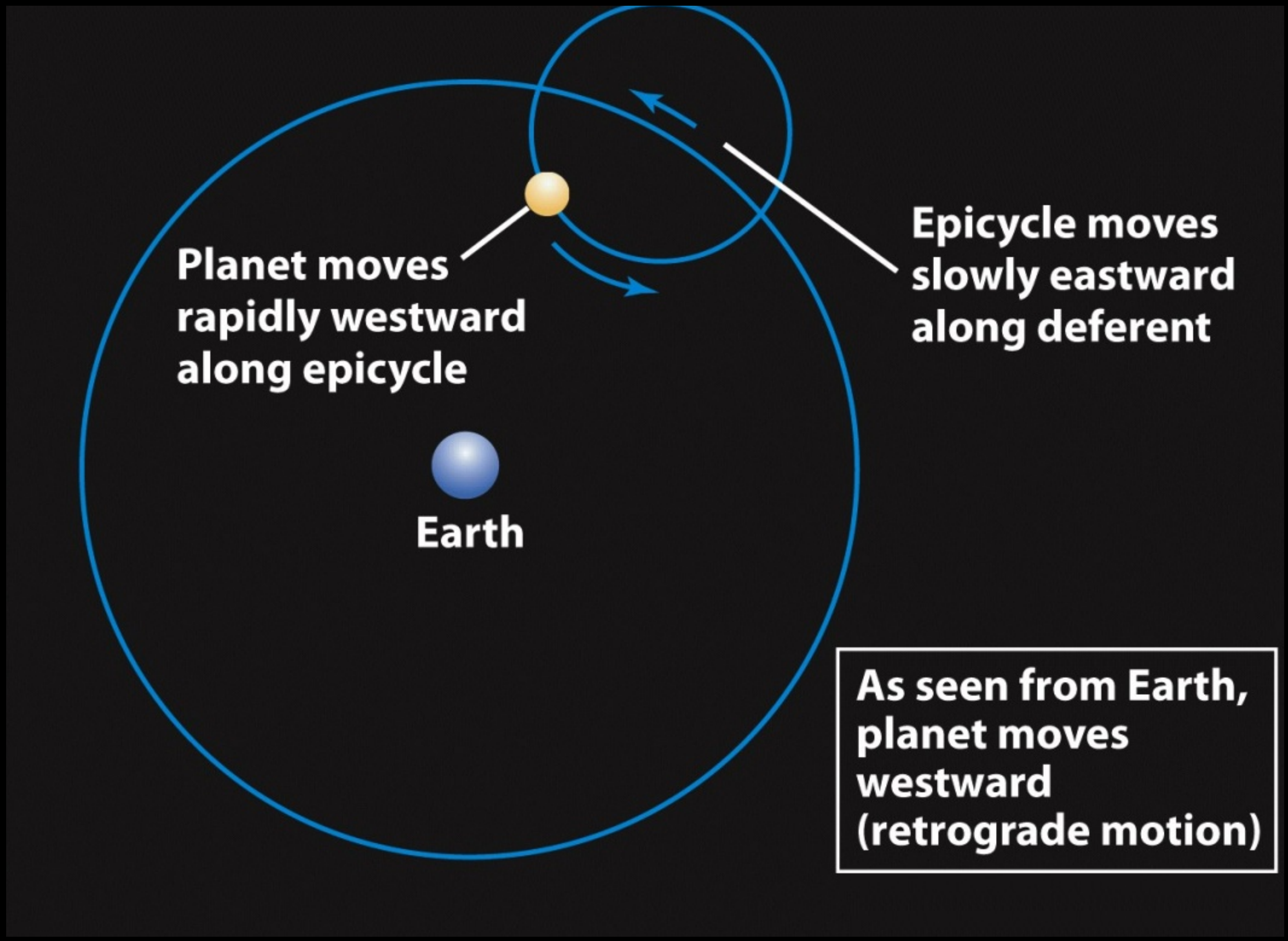
Object seems to reverse its general direction with respect to background stars

Example ☛ Path of Mars

Retrograde motion

A Geocentric Explanation

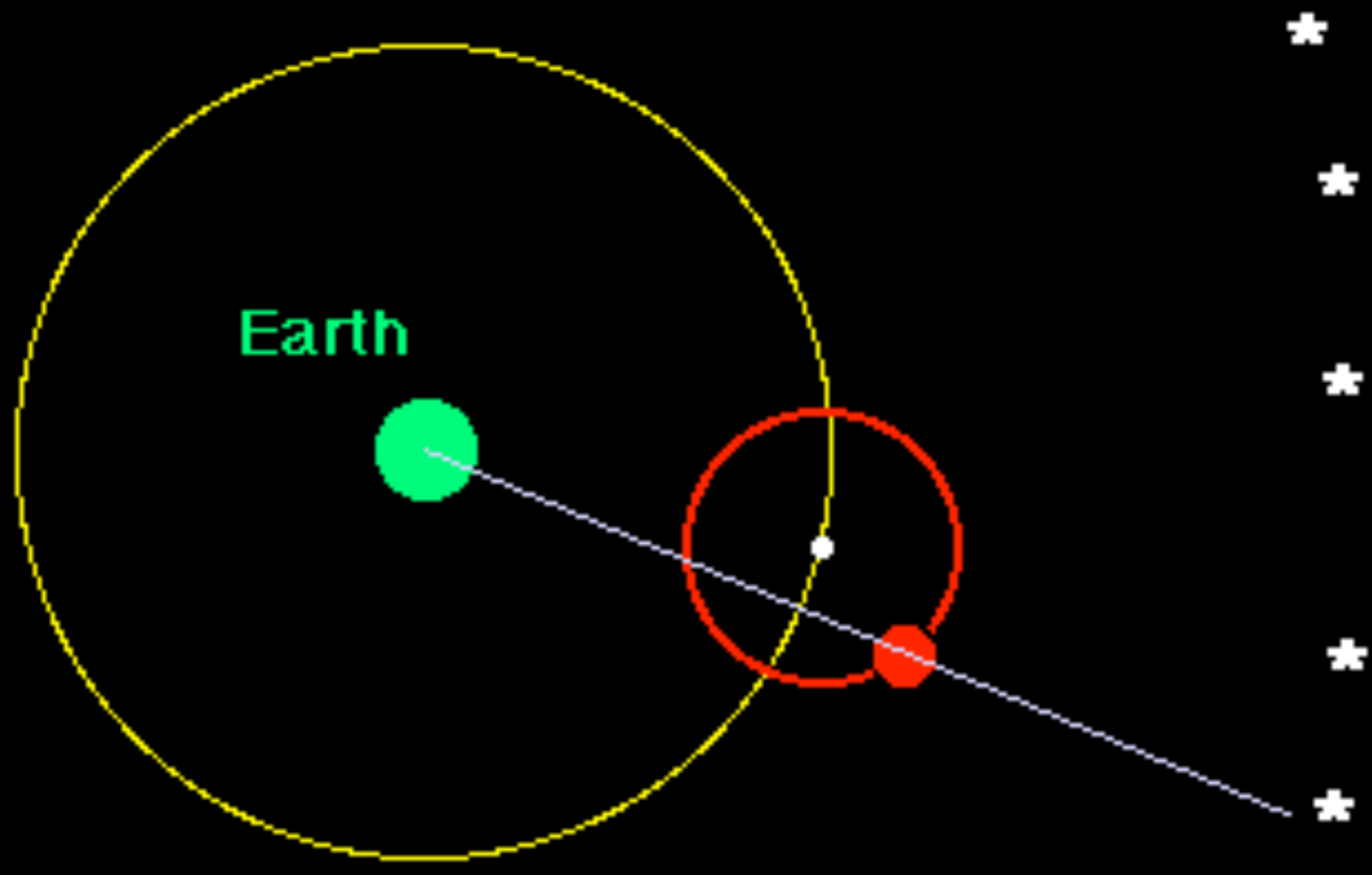




- In order to account for retrograde motion Ptolemaic model incorporates epicycles
  - Epicycle orbits on a circle called the deferent
  - Planet moves along epicycle

Retrograde motion

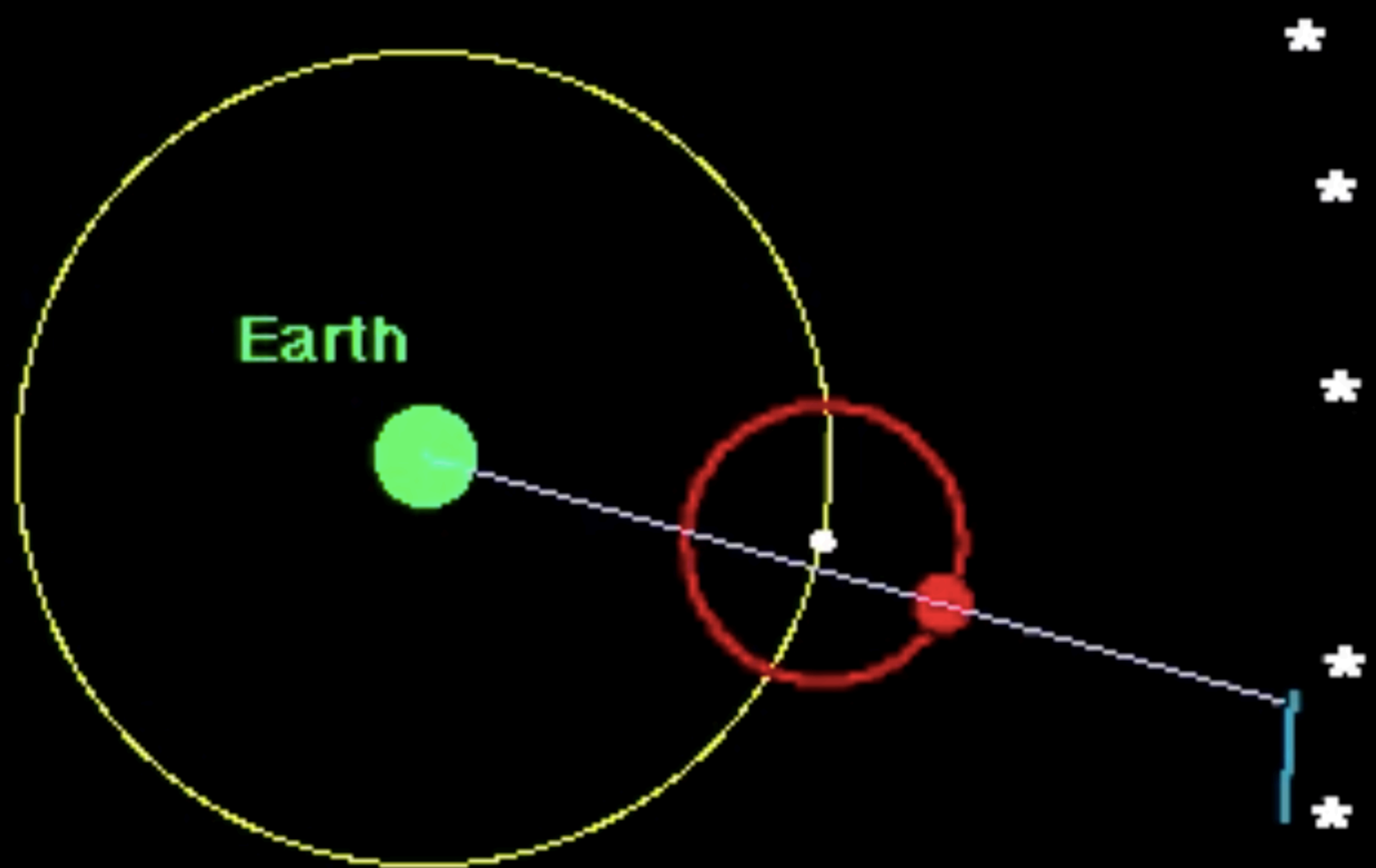
A Geocentric Explanation



- Ptolemaic model reasonably explains retrograde motion
- Further predictions of planetary positions using Ptolemaic model did not match observations

Retrograde motion

A Geocentric Explanation



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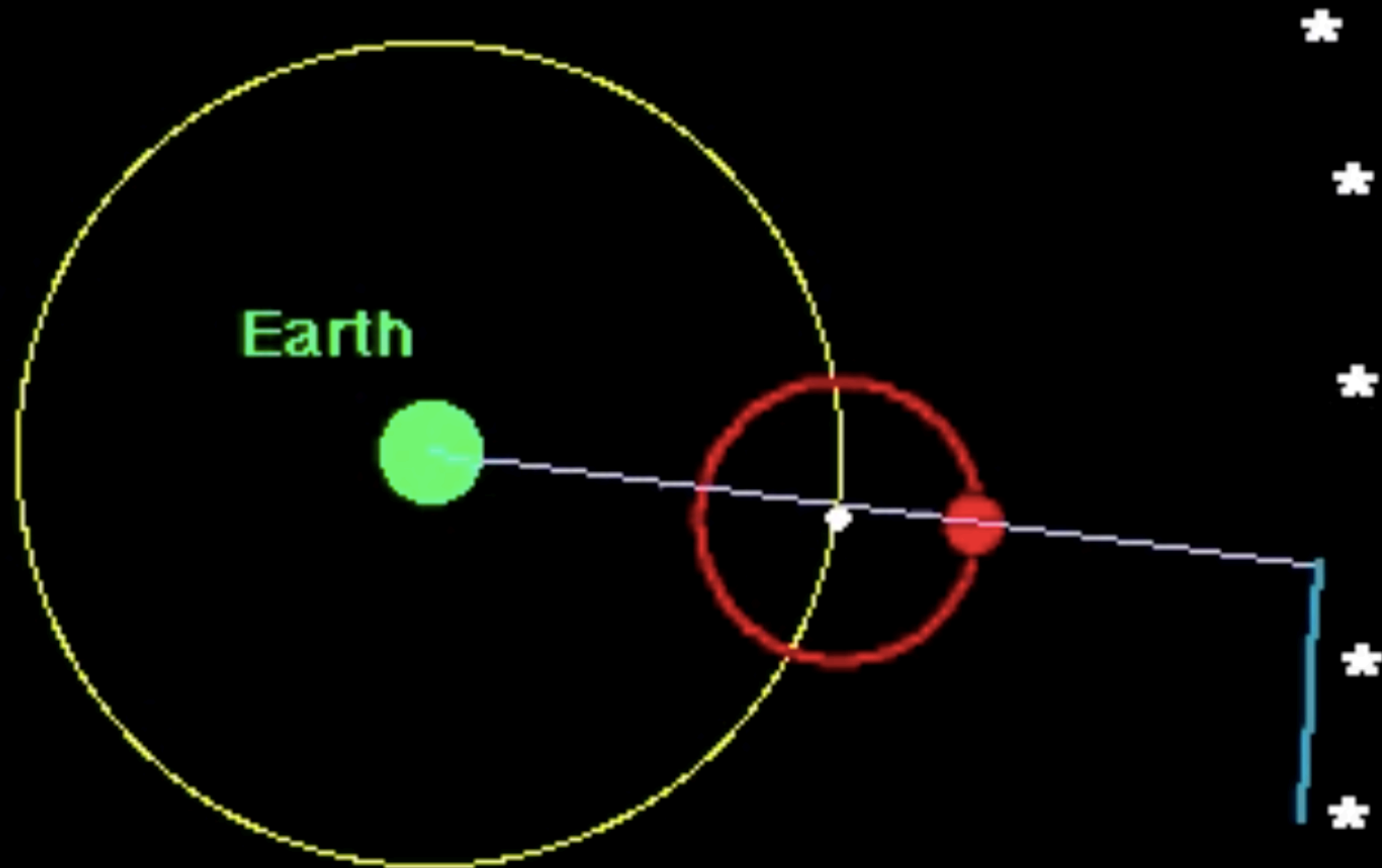

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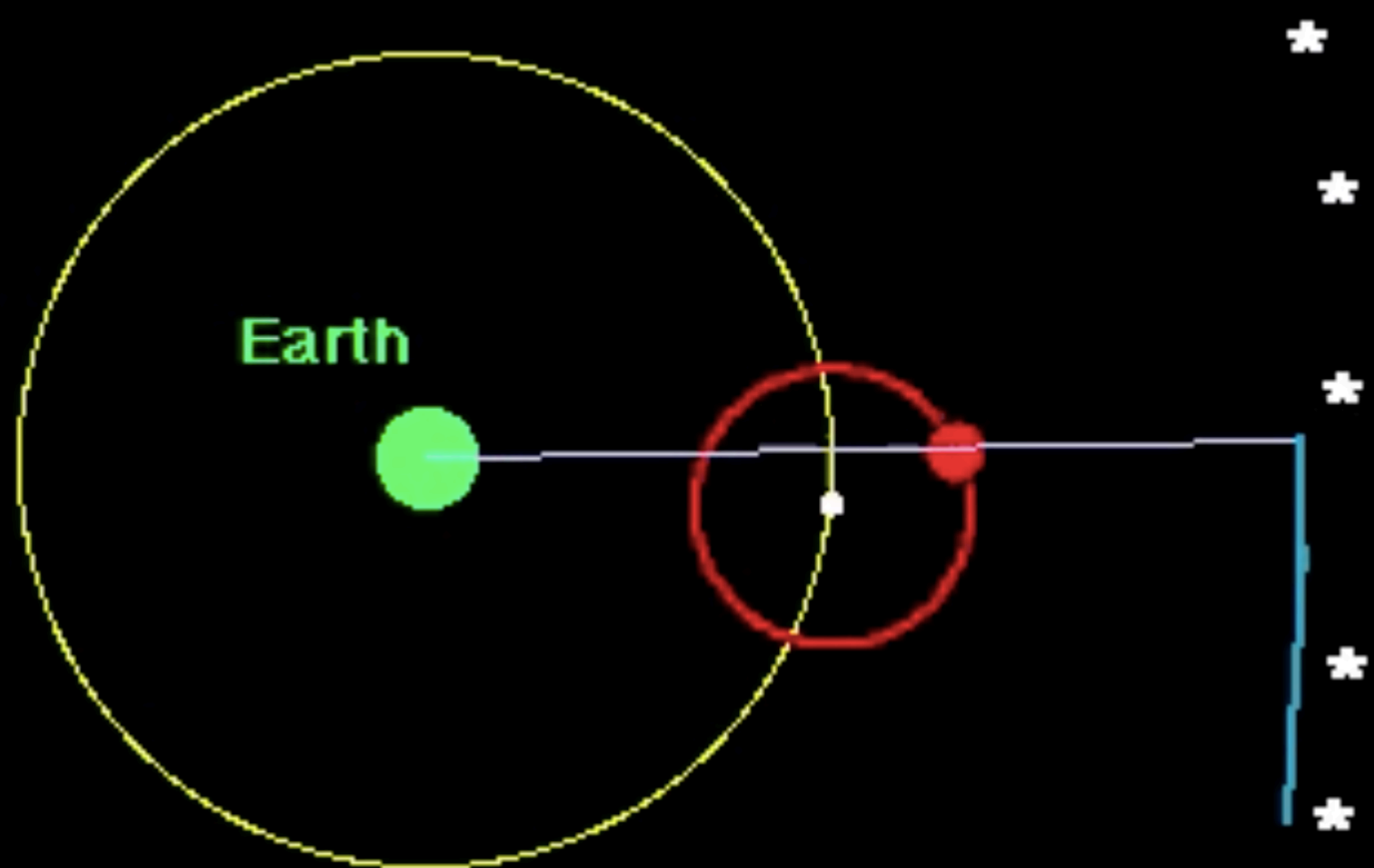

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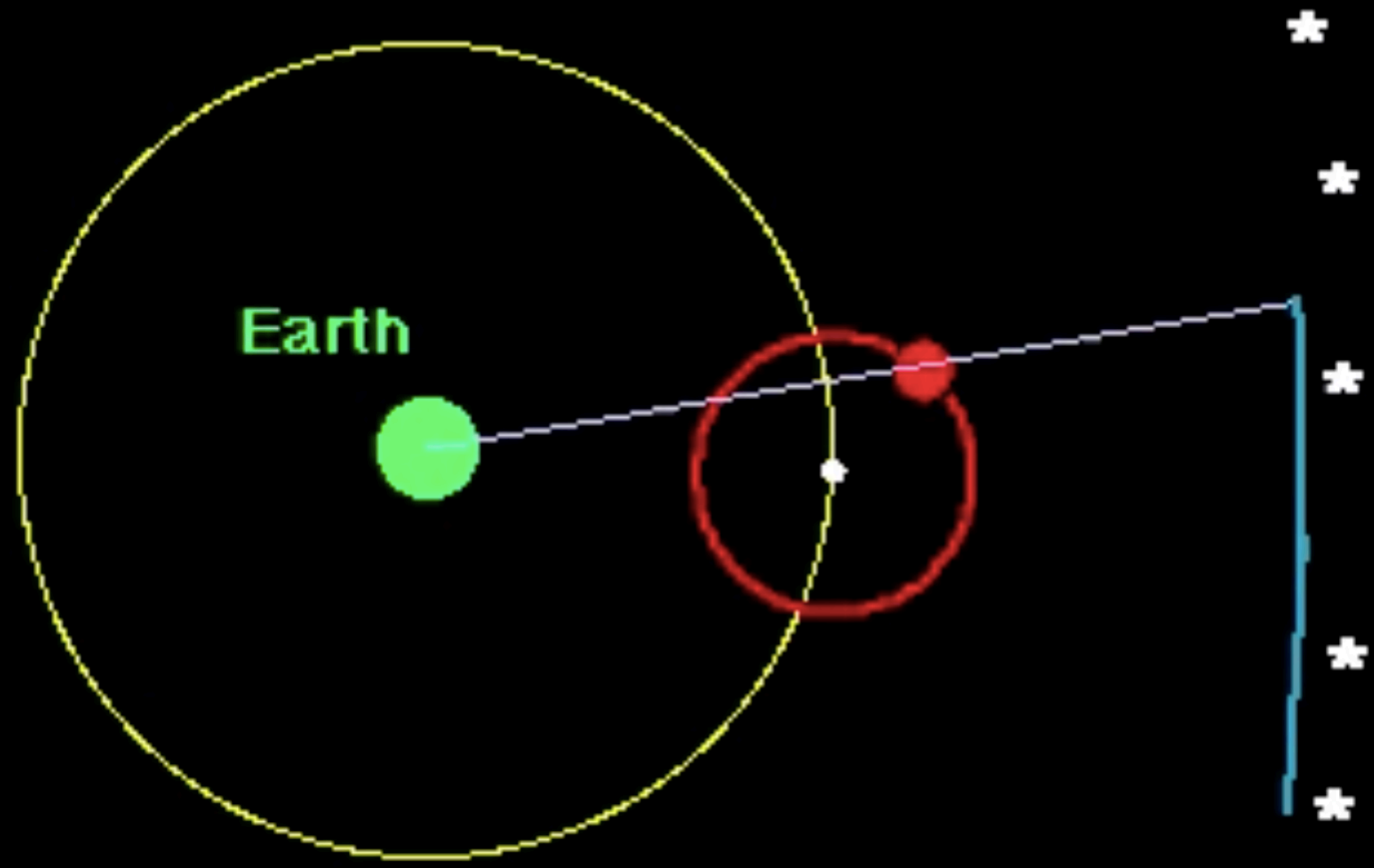

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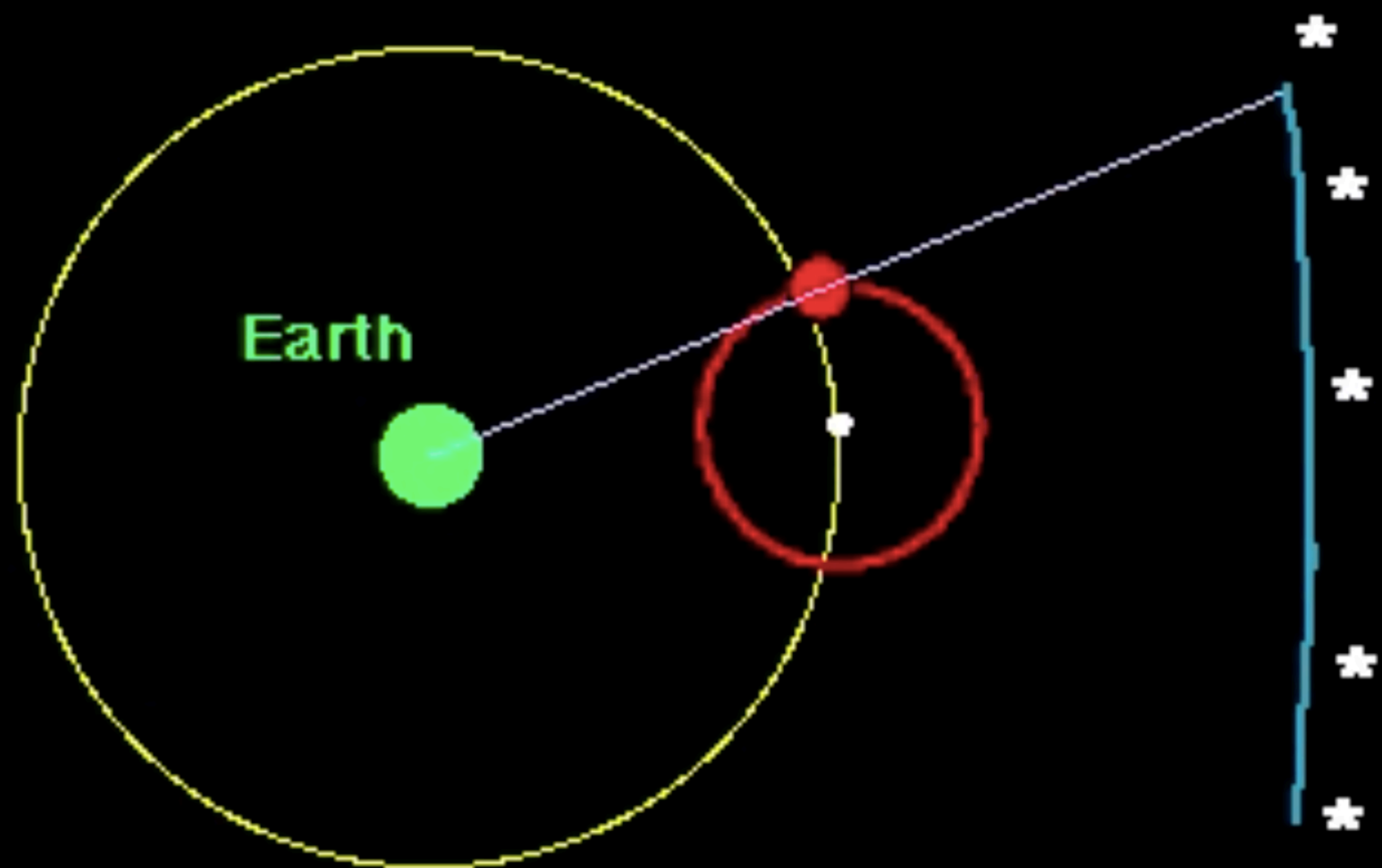

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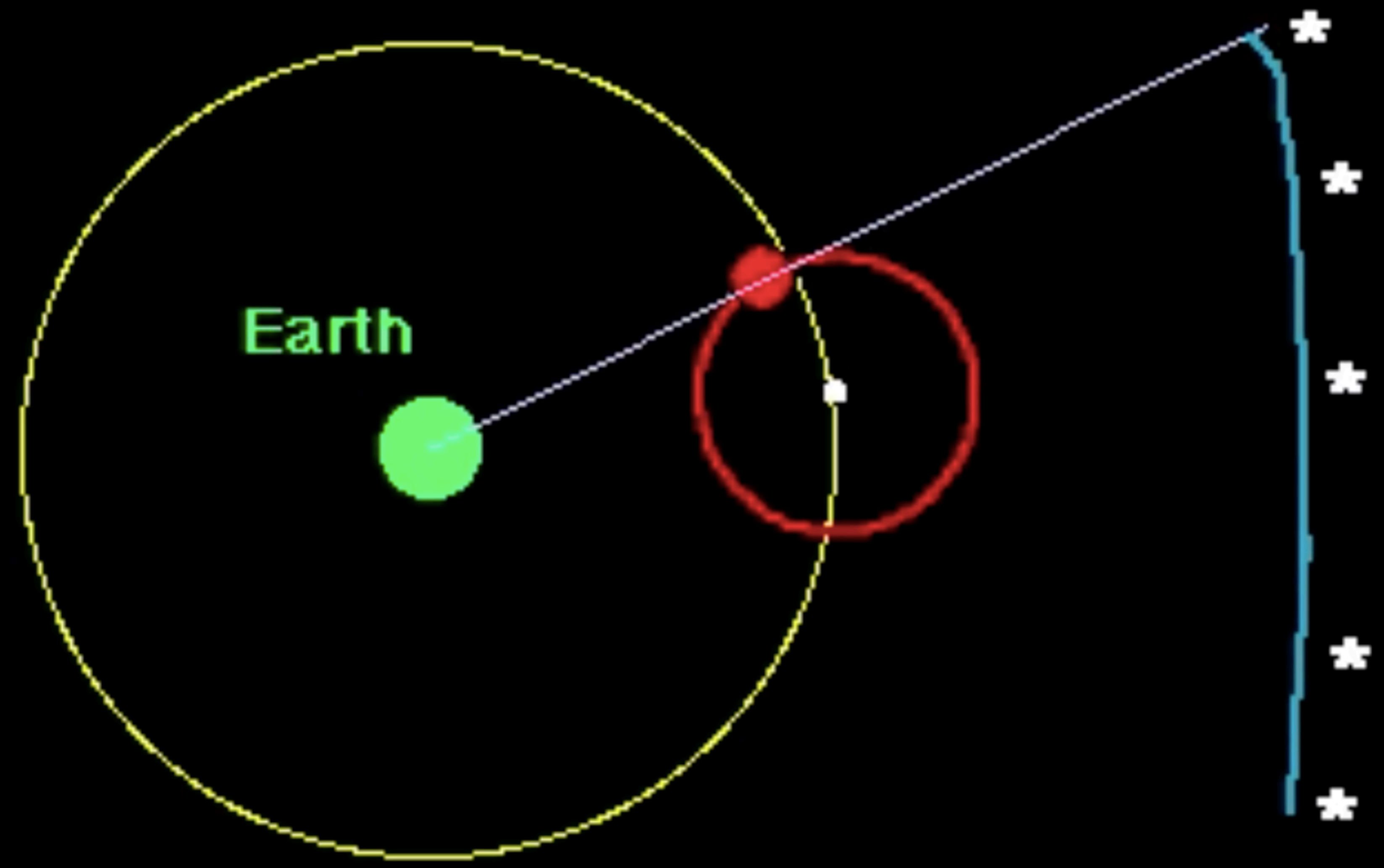

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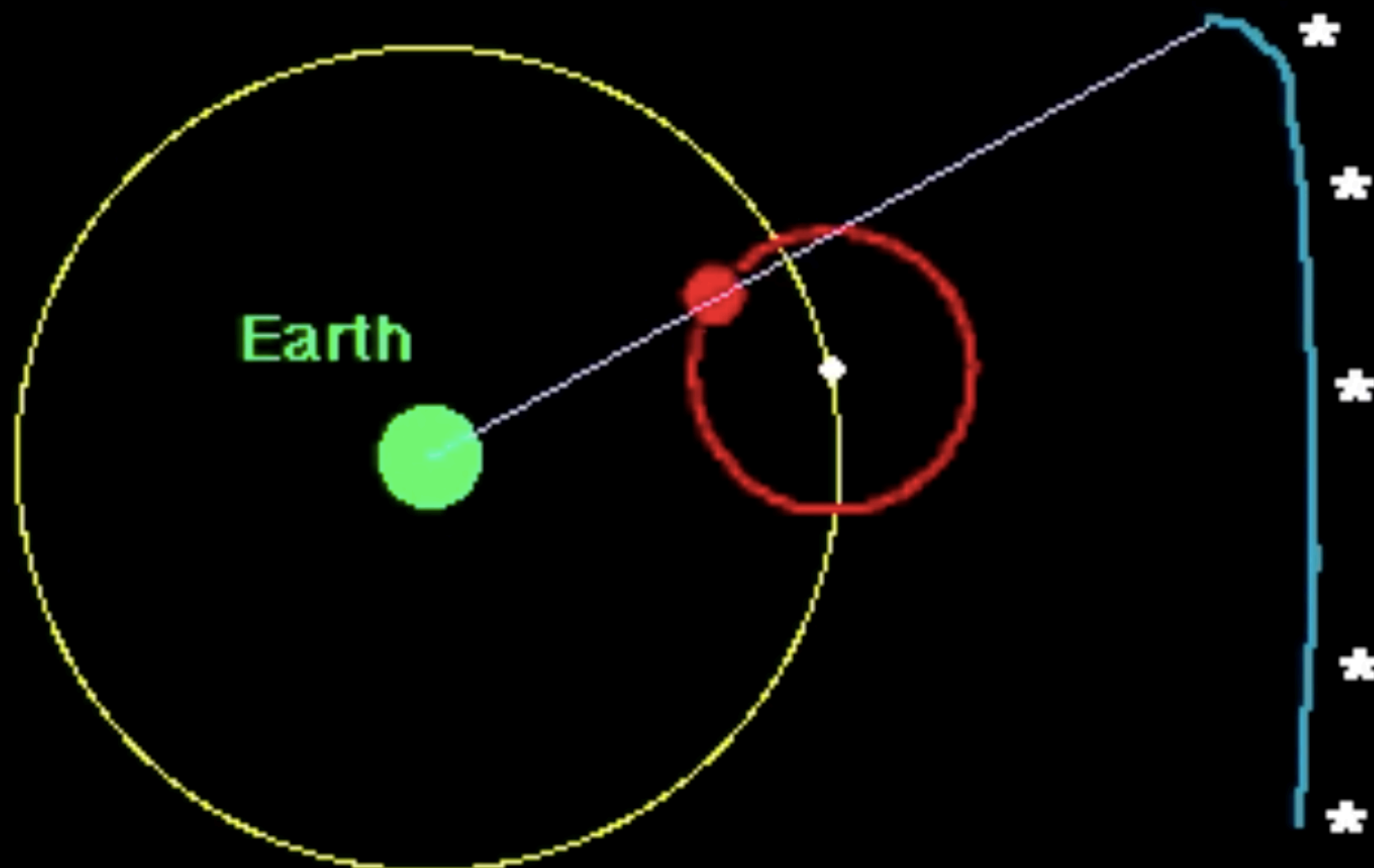

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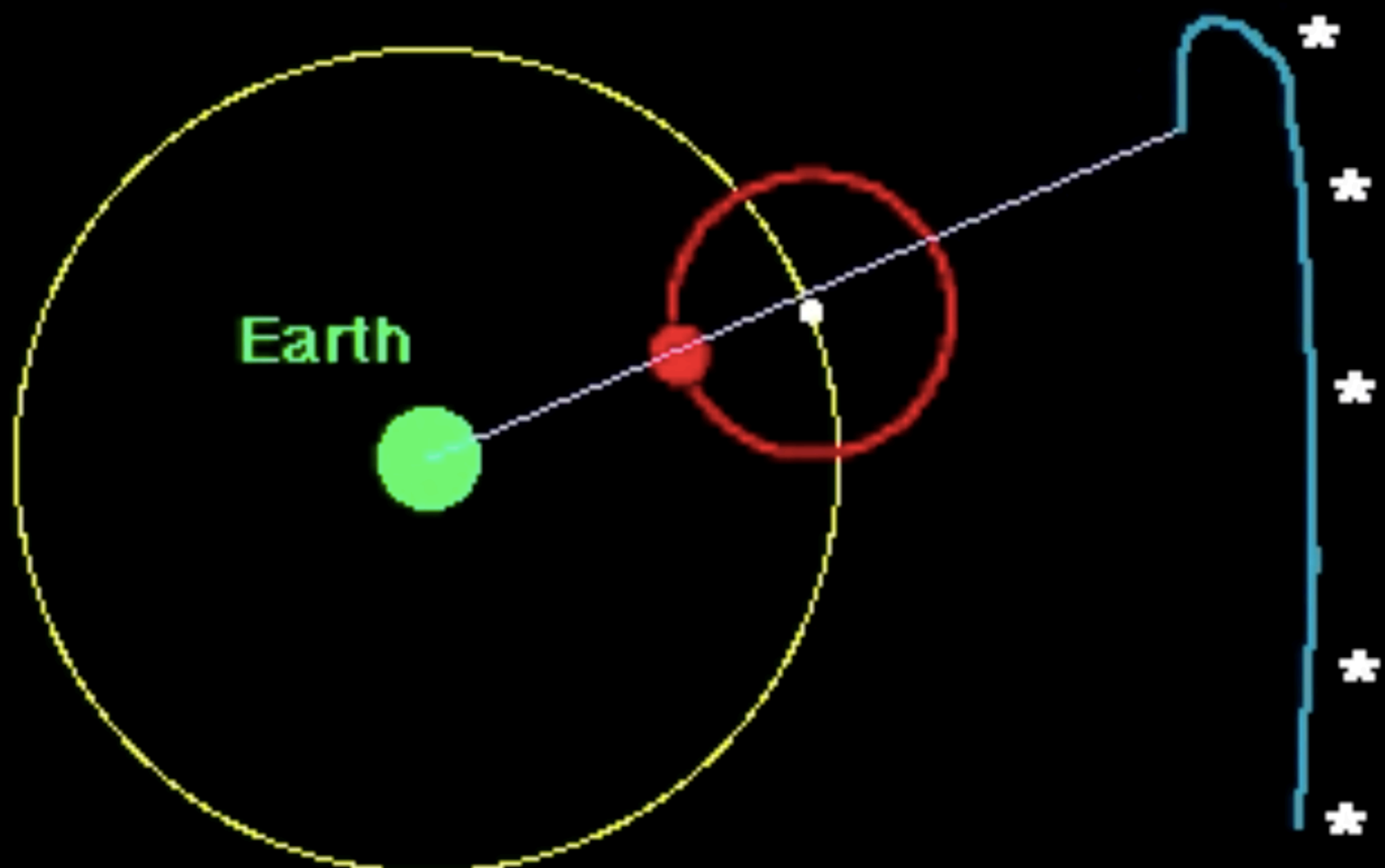

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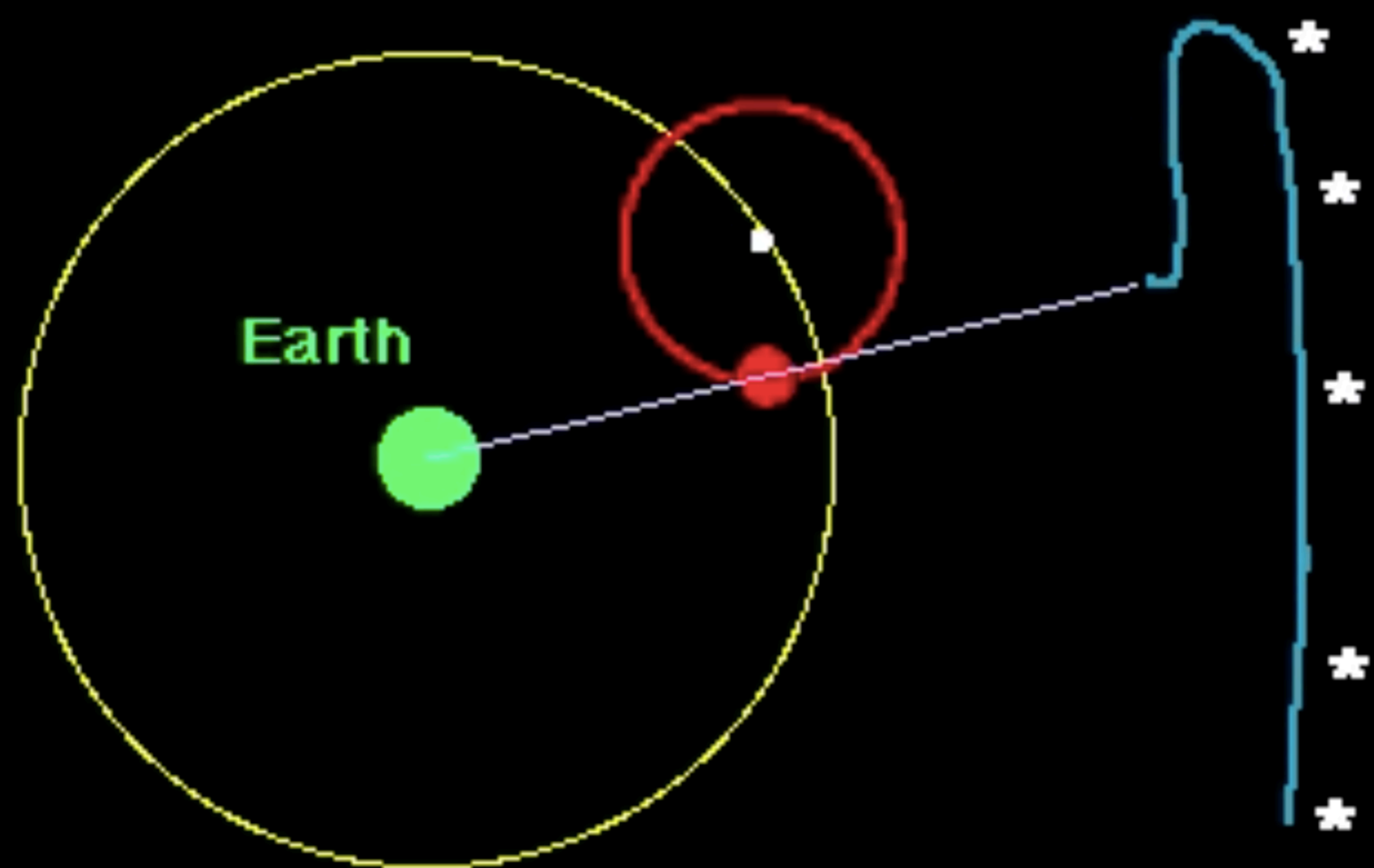

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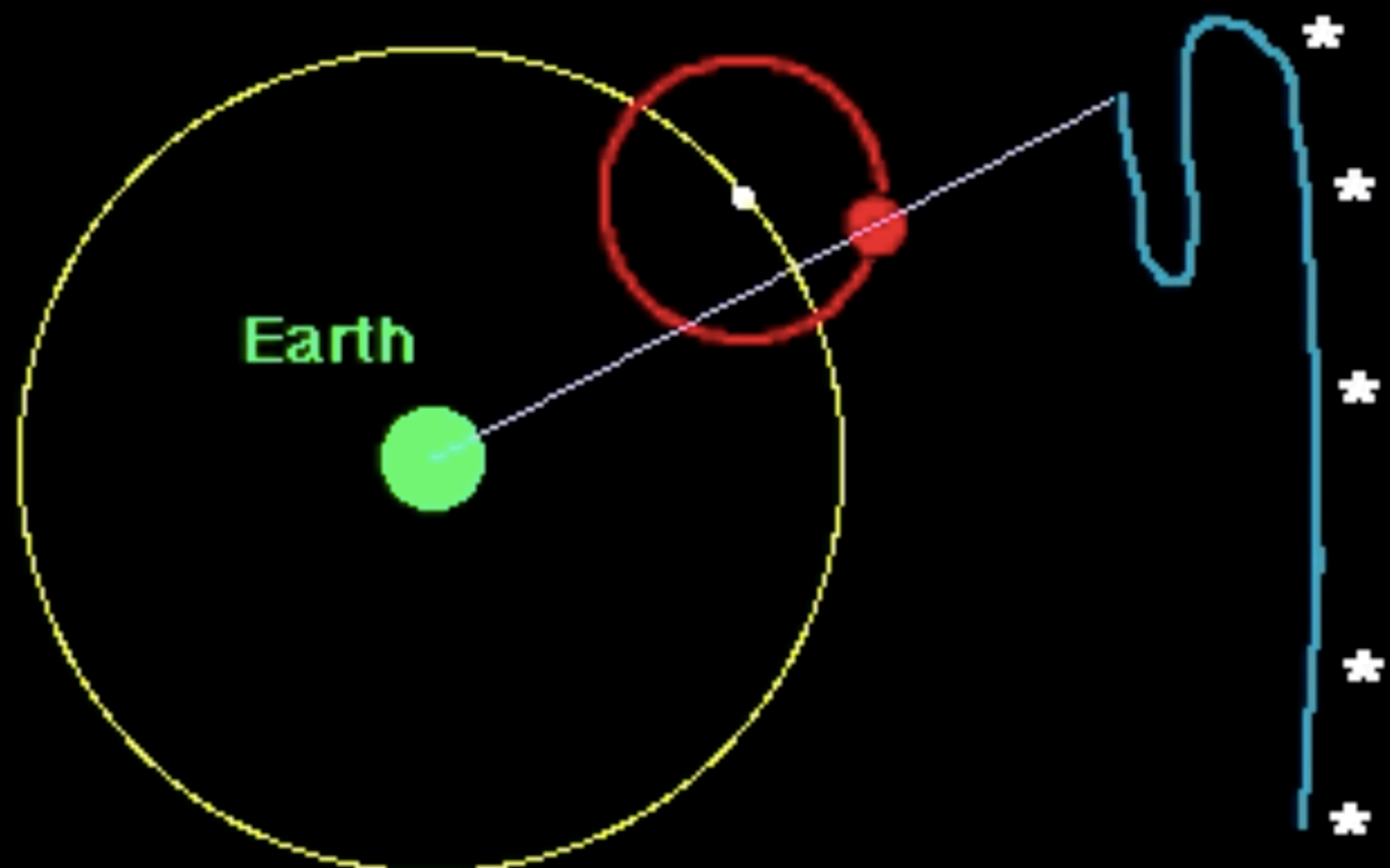

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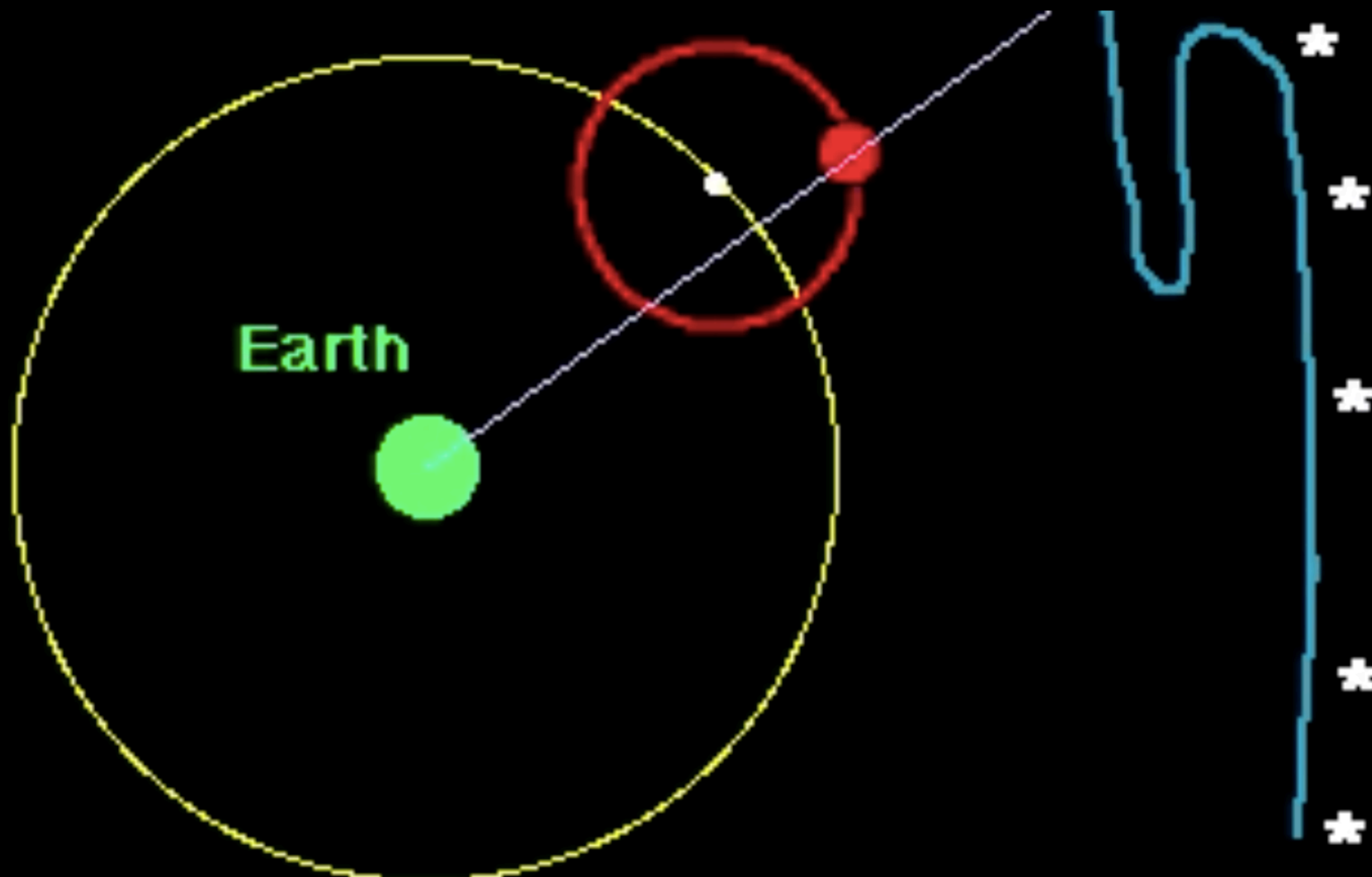

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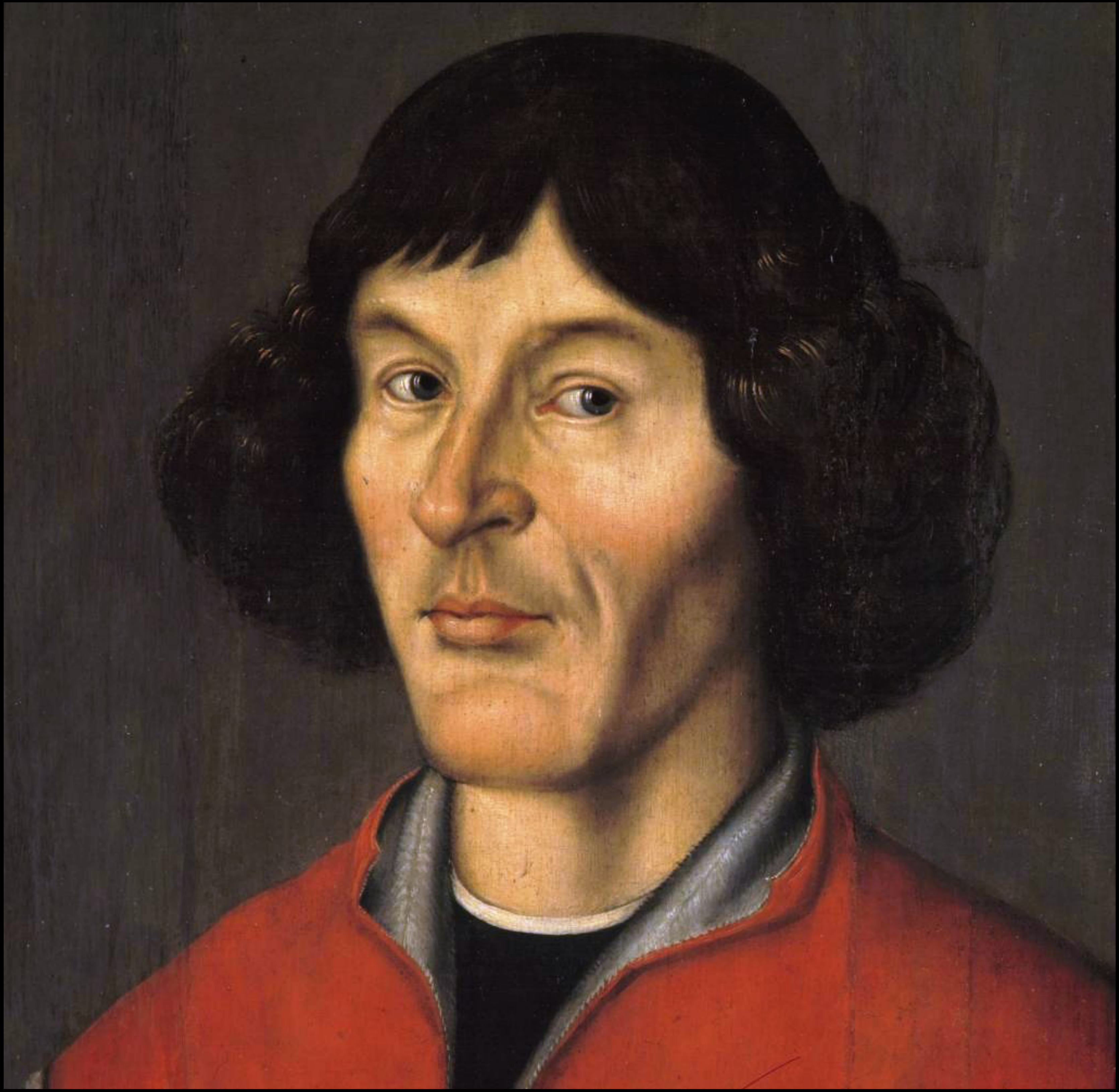
Niocolaus Copernicus (1473 - 1543)



Placing the Sun at the Center

Ideas of Aristarchus were revived

- ✓ heliocentric cosmology

Planets, including Earth, orbit the Sun

Easily explains complex motions of the planets

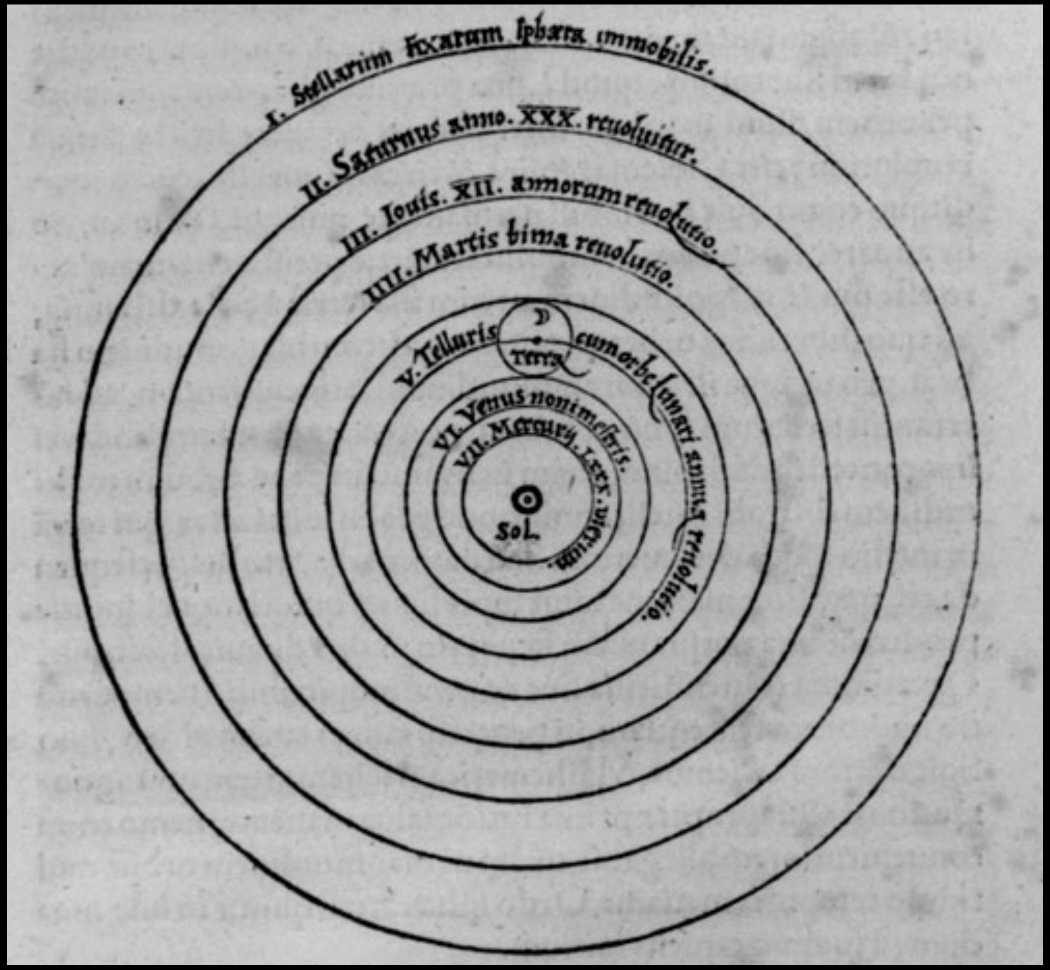
Copernican Model

- Devised a heliocentric model of universe
- Sun is the center, and planets revolved around it in perfect circles
- Correctly placed the position of the known planets of the time

  Mercury, Venus, Earth, Mars, Jupiter, Saturn

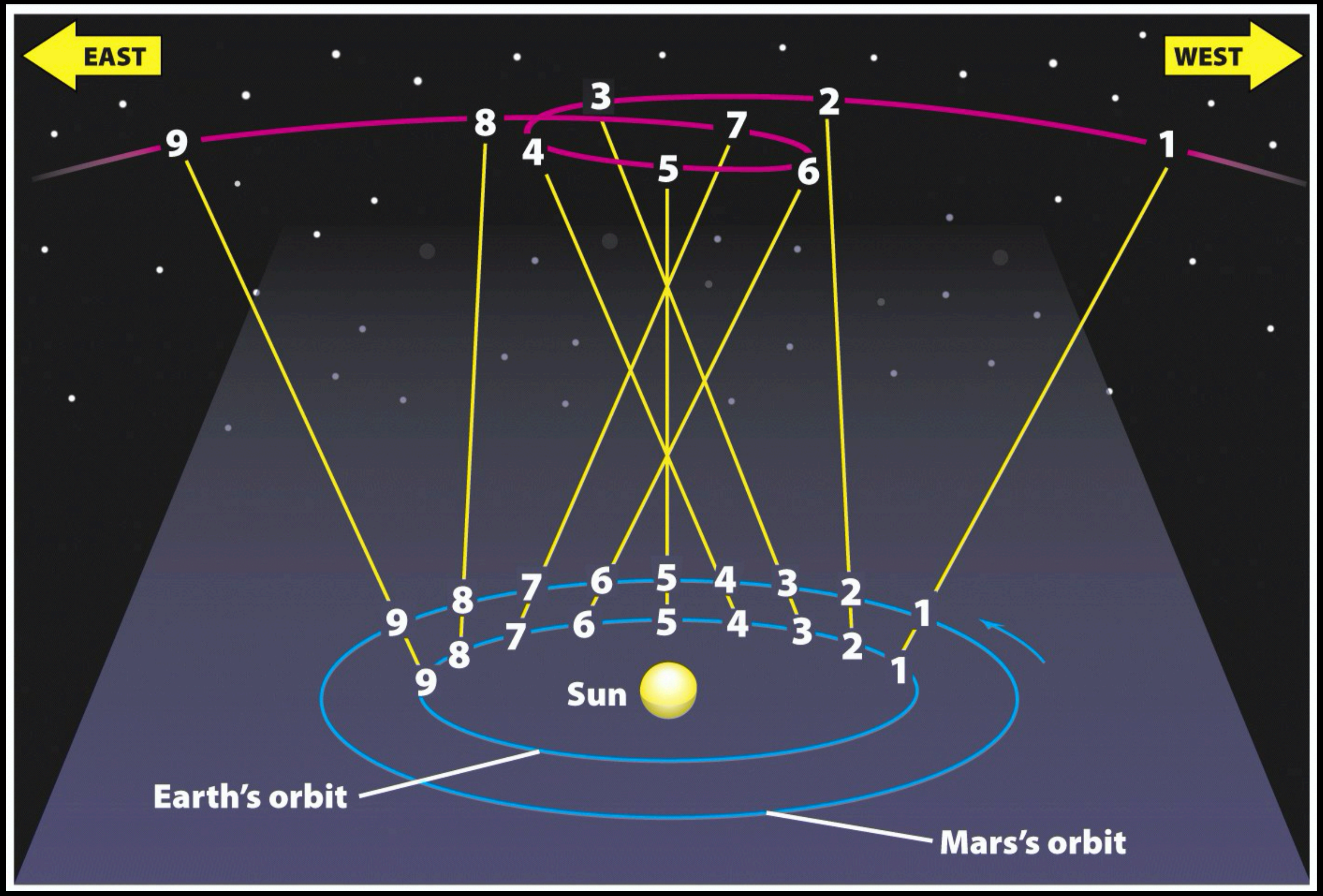
- The Moon orbits the Earth
- Stars are fixed
- Elegantly describes retrograde motion
- Error is introduced due to assumption

  that orbits are perfect circles



Retrograde motion

A Heliocentric Explanation



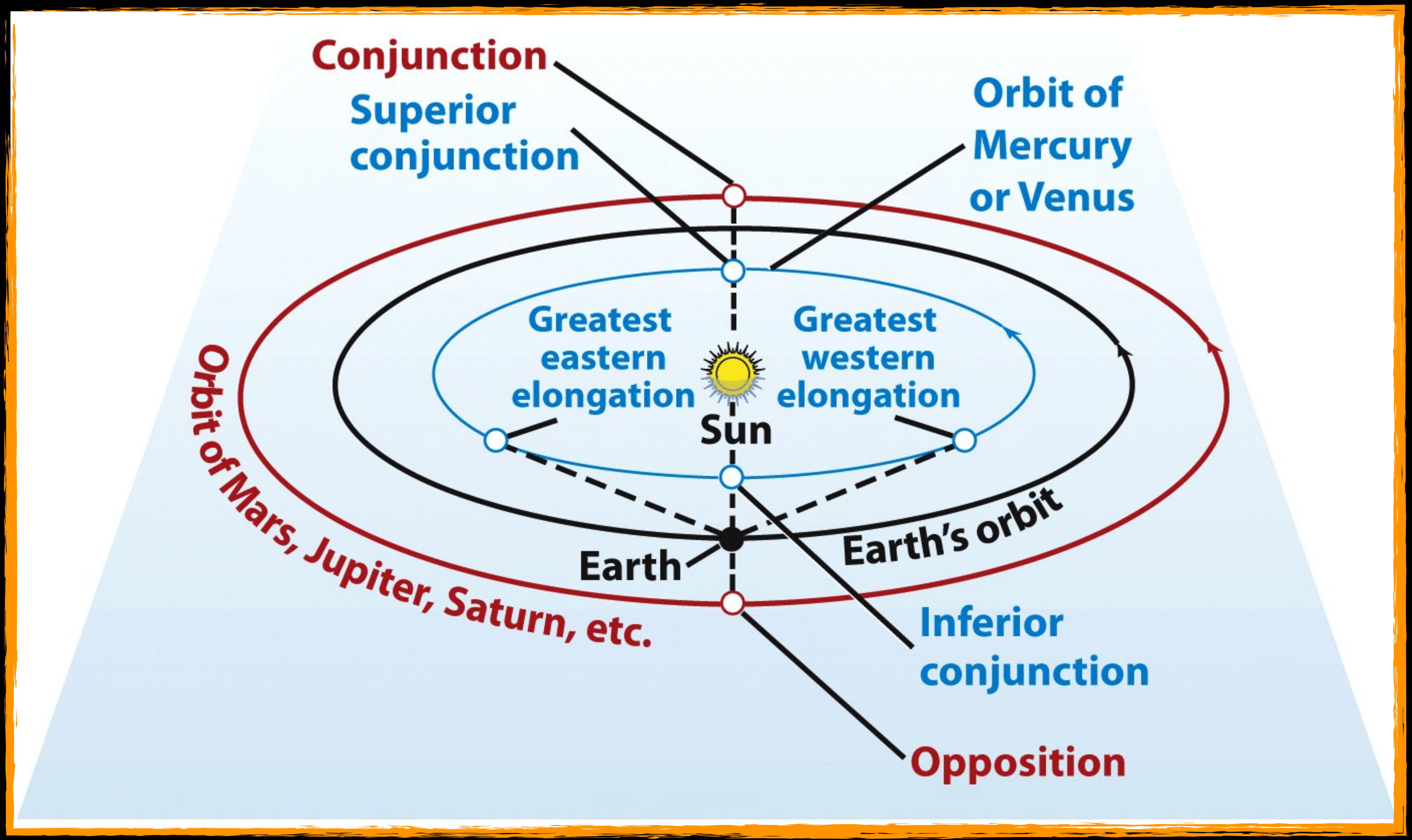
Explained due to Earth being closer to Sun than Mars and orbiting more rapidly

1-4 ☛ Mars appears to move eastward with respect to background stars

4-6 ☛ Earth passes Mars–Mars seems to reverse direction

6-9 ☛ Earth passed Mars–Mars resumes eastward motion

Planetary Configurations



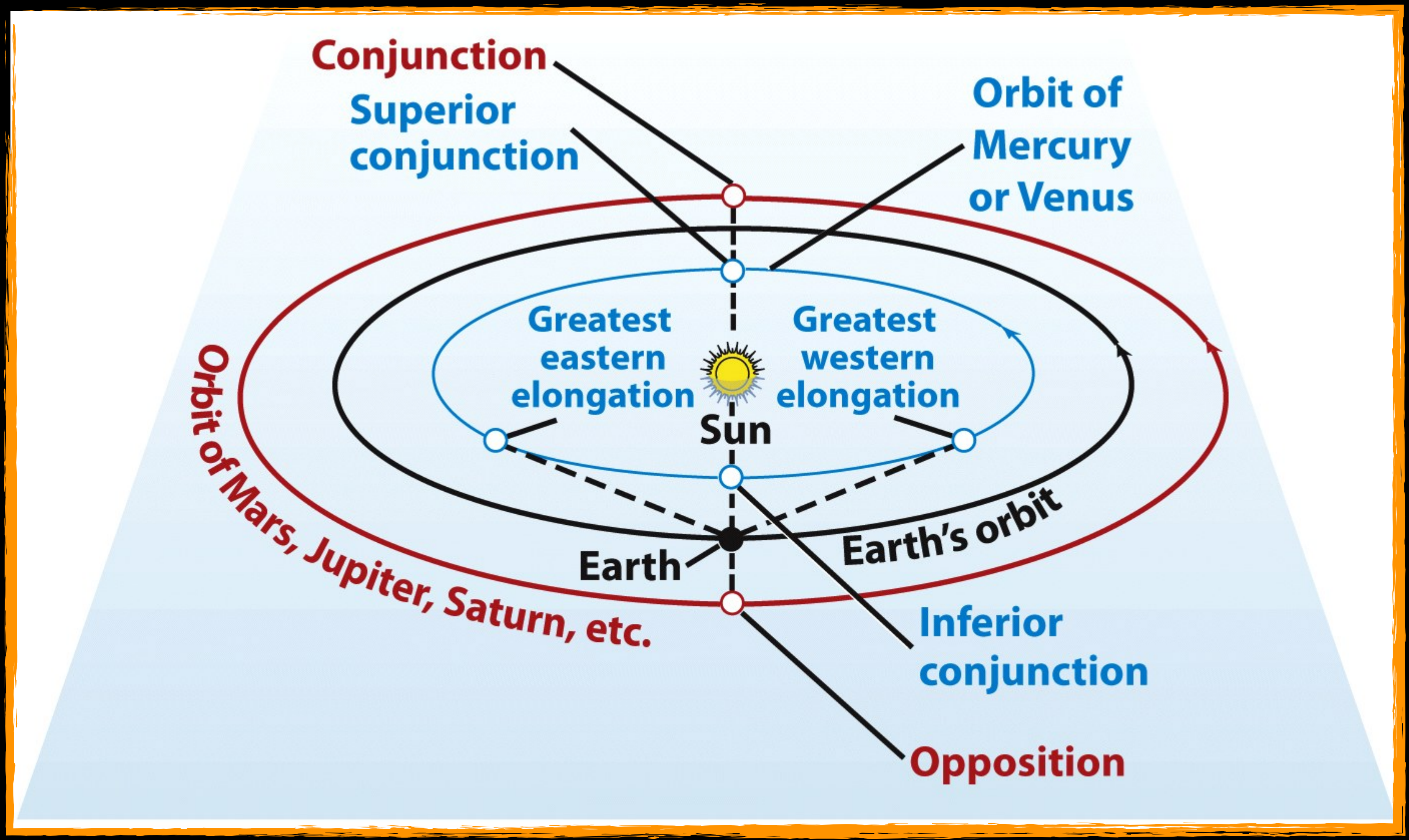
Inferior planets (Mercury, Venus)

Inferior conjunction: Planet in line with Sun & Earth on same side of Sun as Earth

Superior conjunction: Planet in line with Sun & Earth on opposite side of Sun to Earth

Elongation: Planet makes 90 degree angle between Sun and Earth

Planetary Configurations



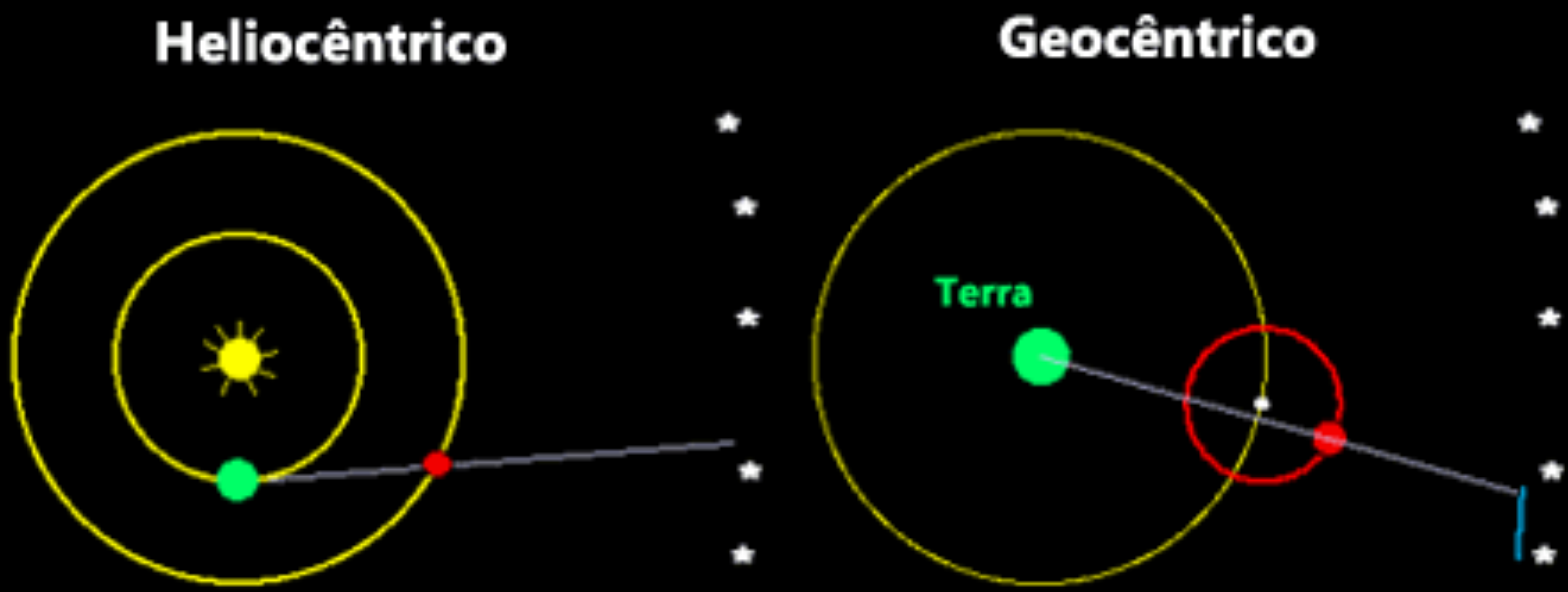
Superior planets (Mars, Jupiter, Saturn, Uranus, Neptune)

Conjunction: Planet in line with Sun & Earth on opposite side of Sun to Earth

Opposition: Planet in line with Sun & Earth on same side of Sun as Earth

Early Astronomy and Planetary Motion

Early Astronomy and Planetary Motion



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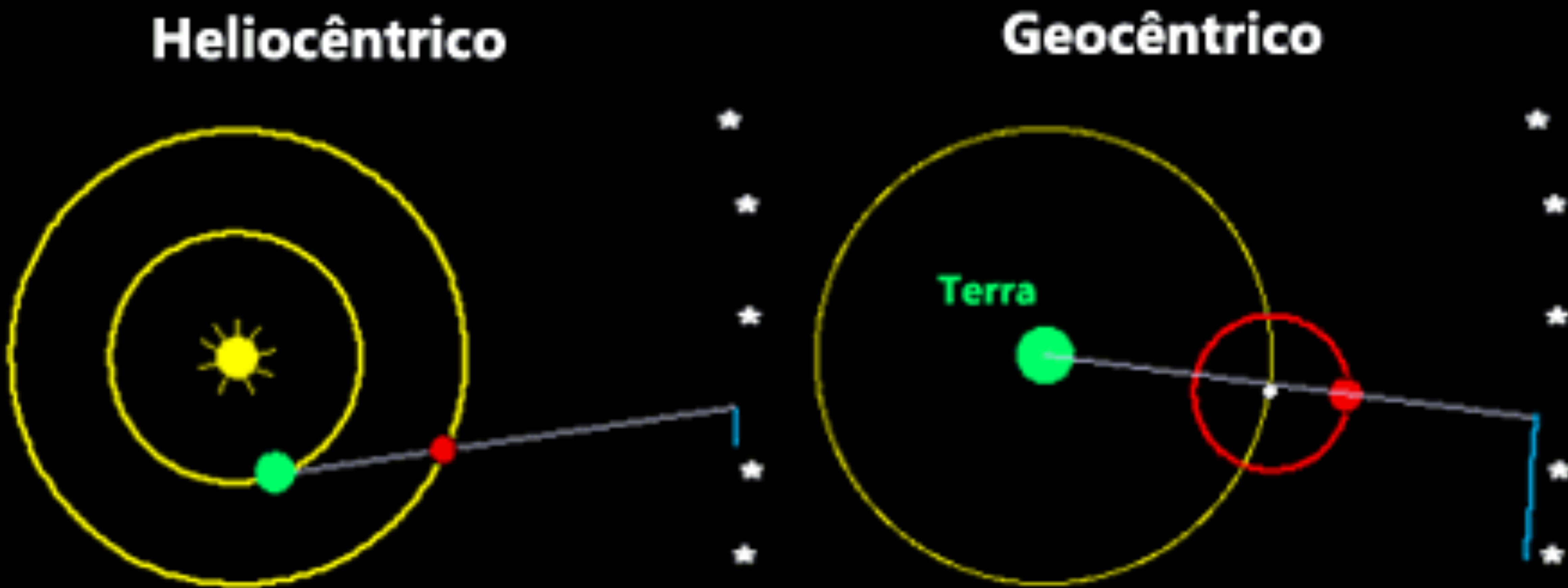

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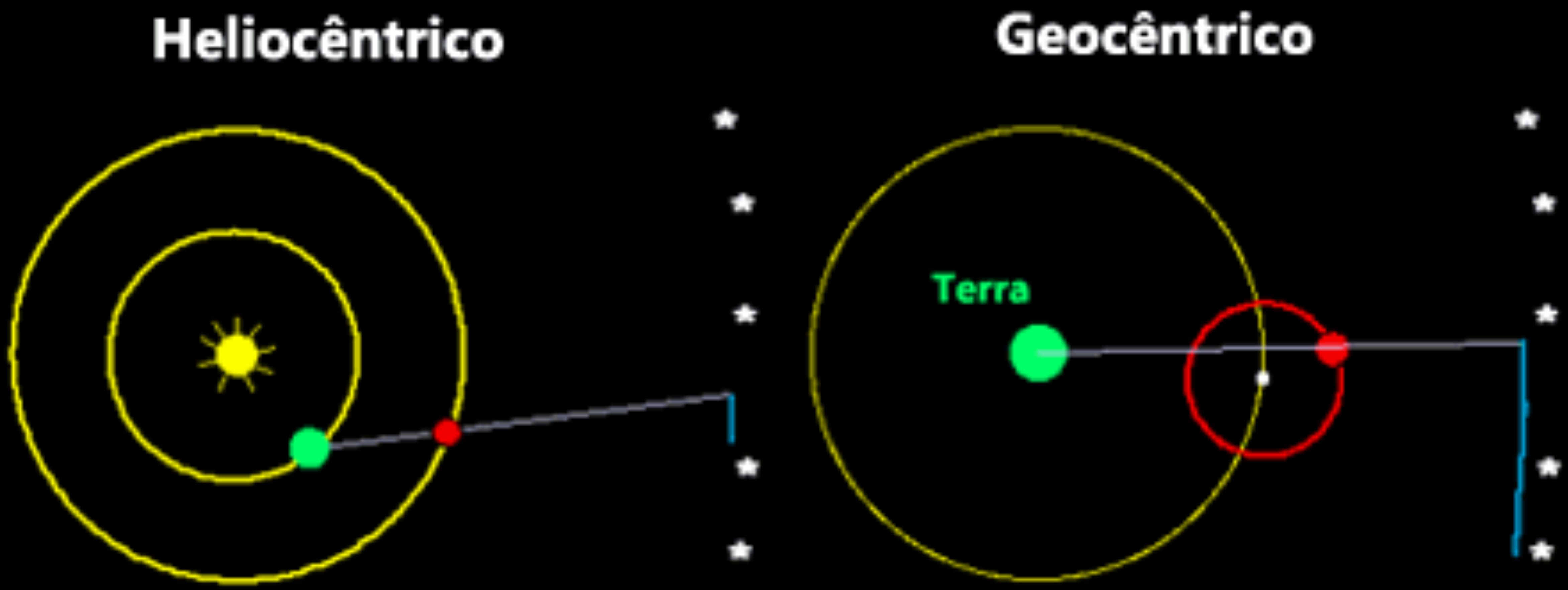

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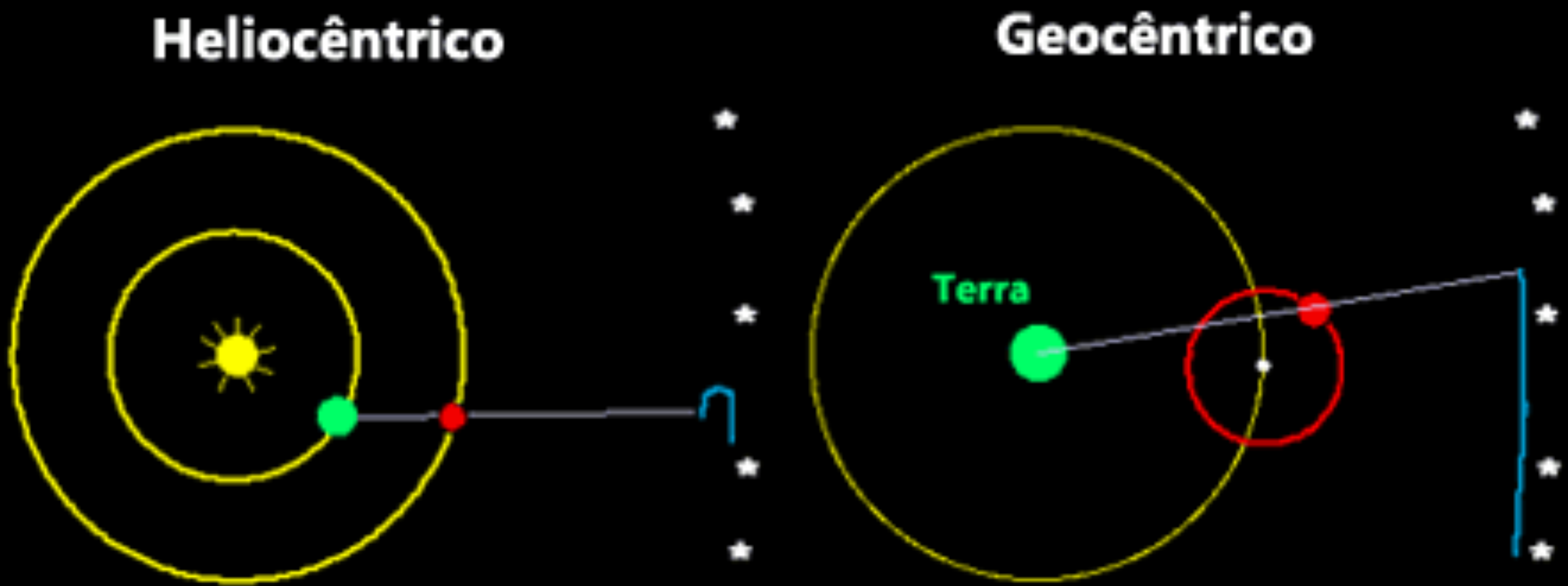

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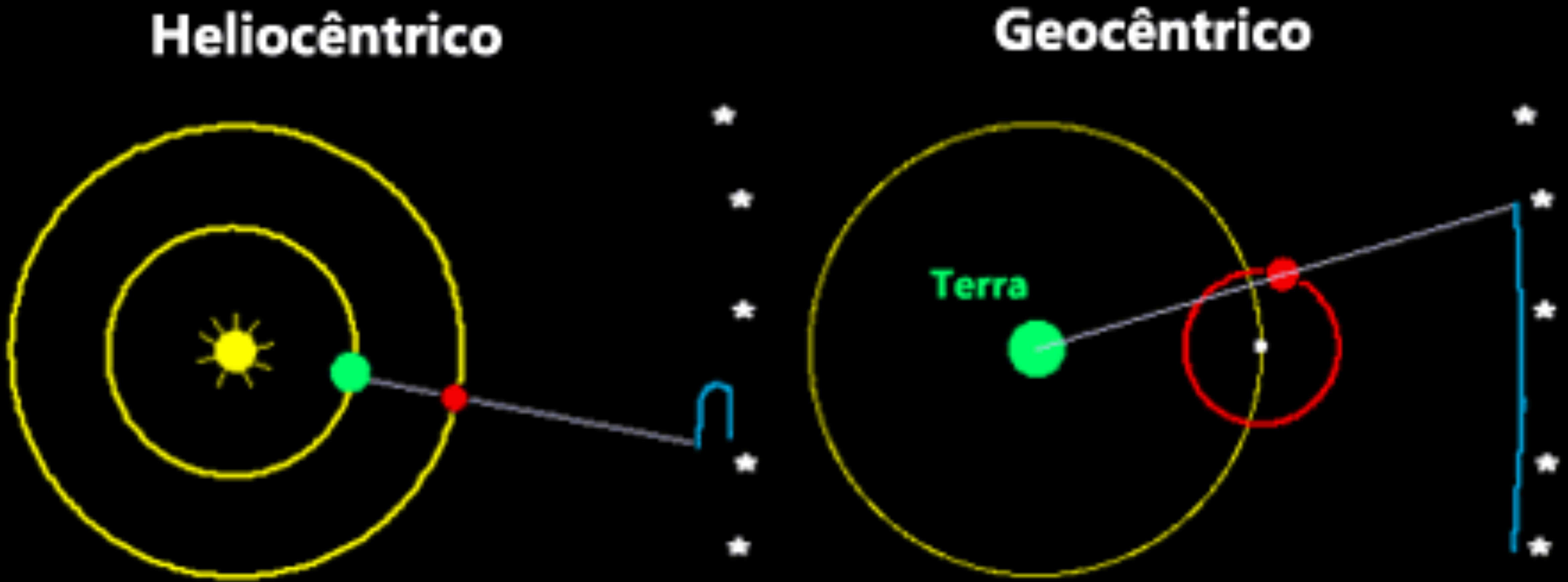

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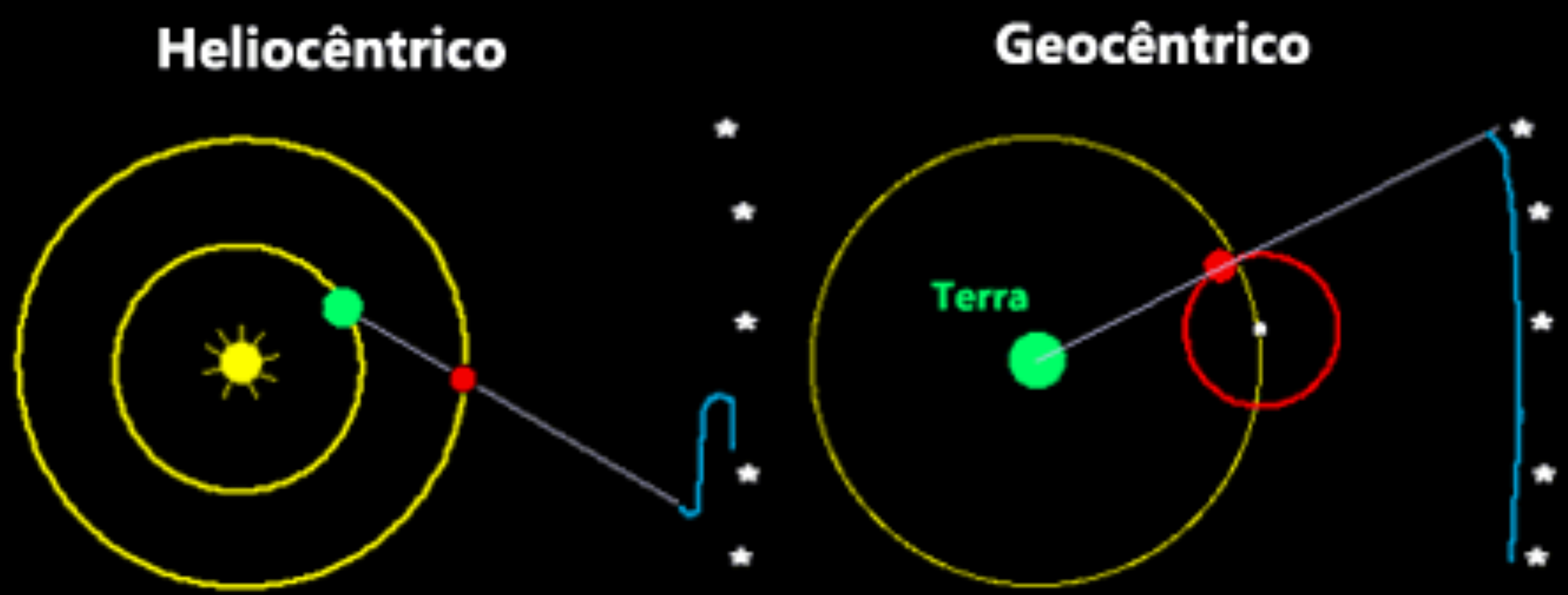

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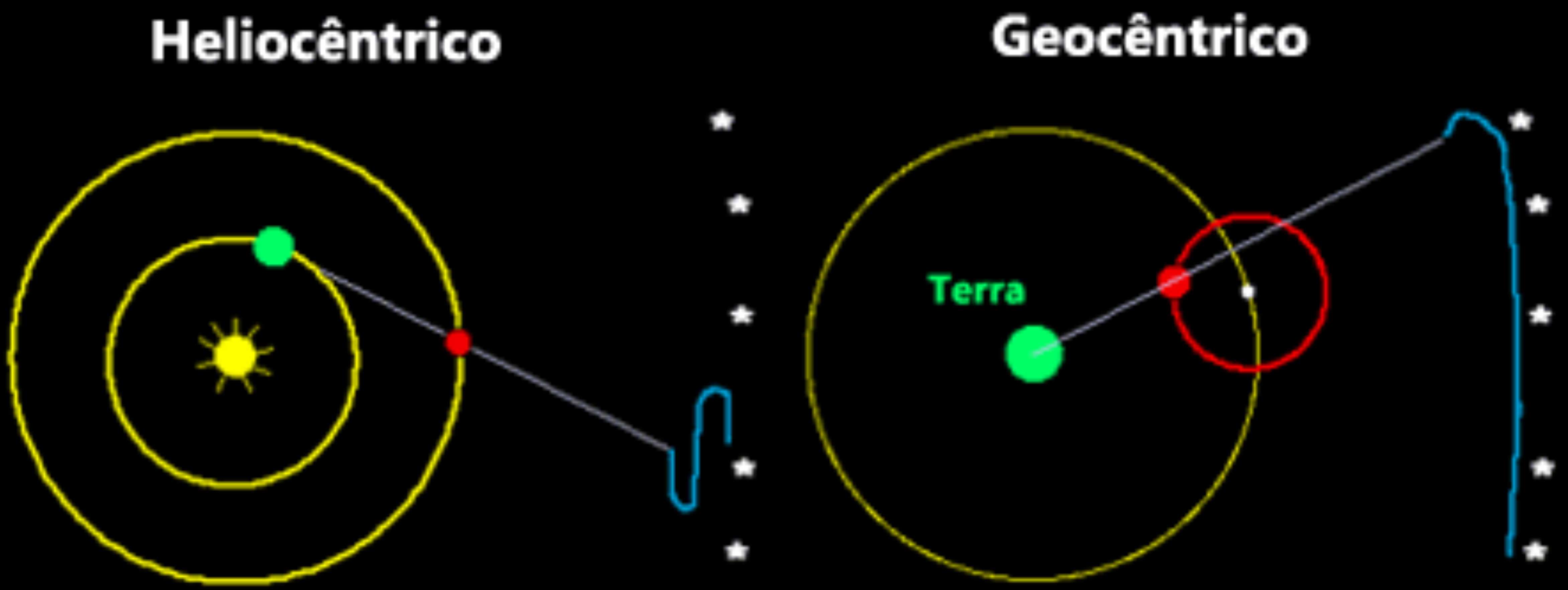

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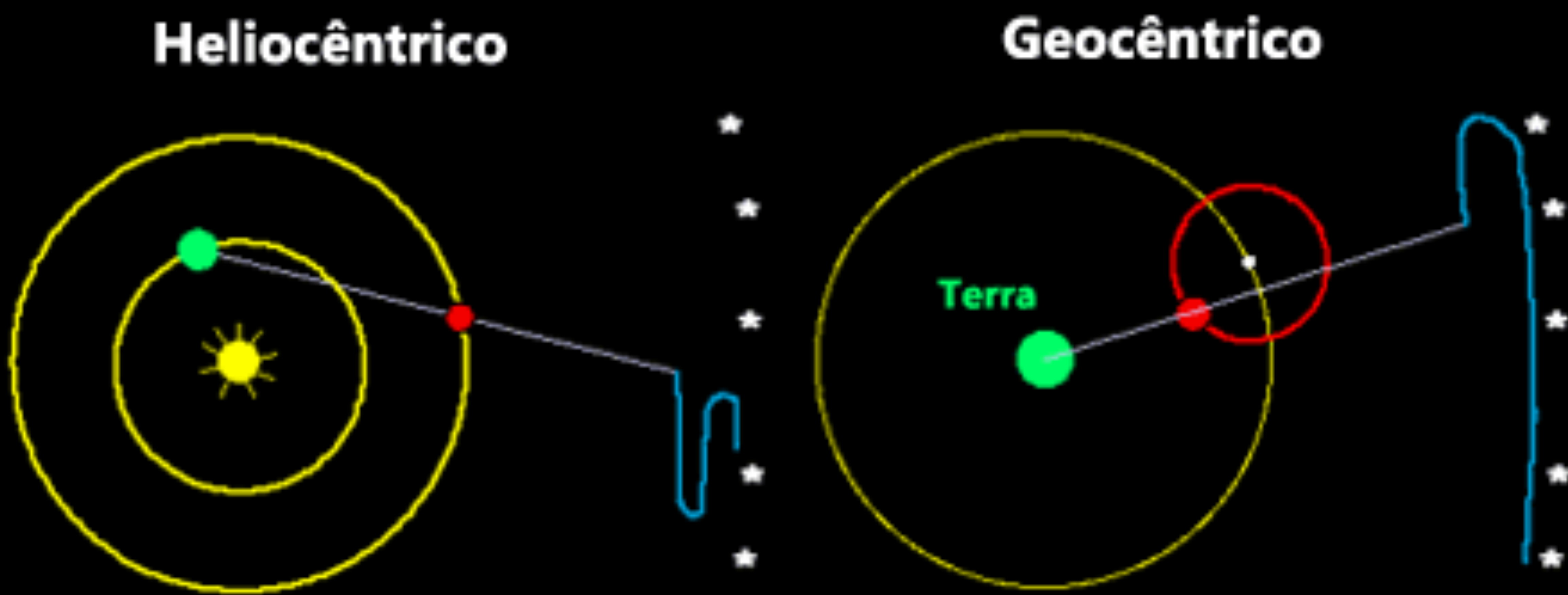

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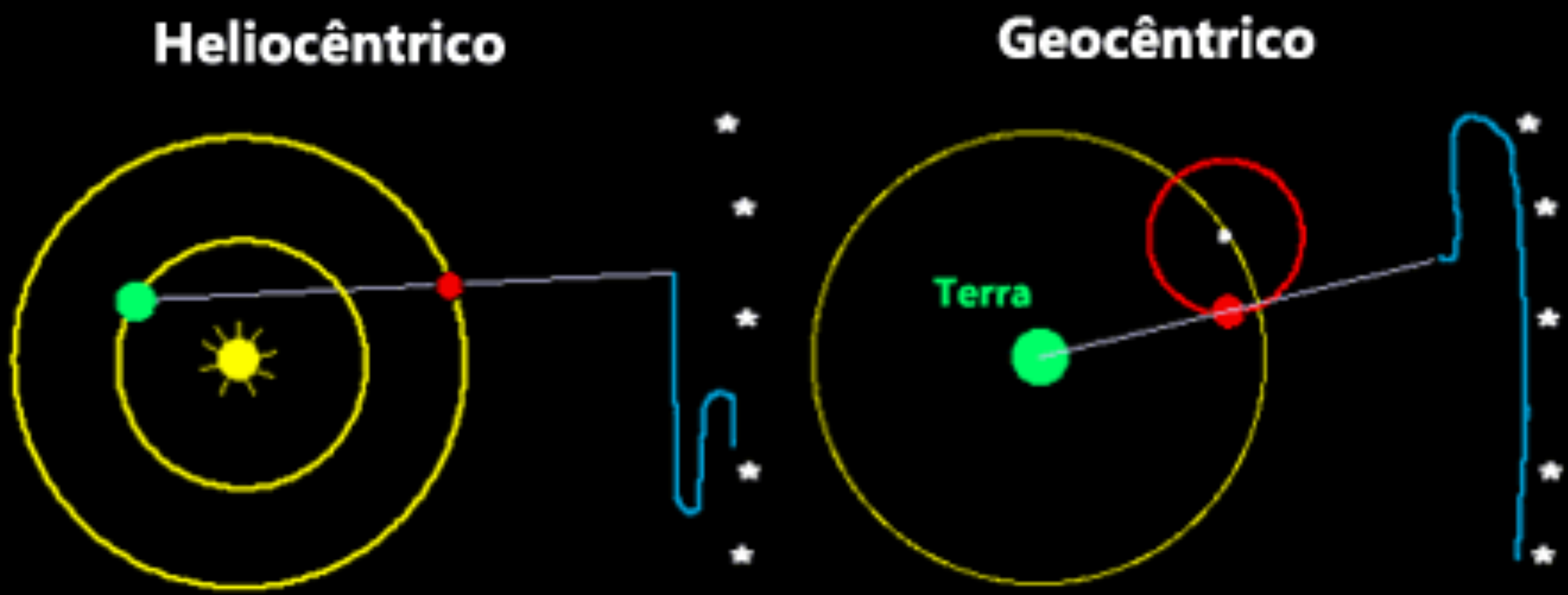

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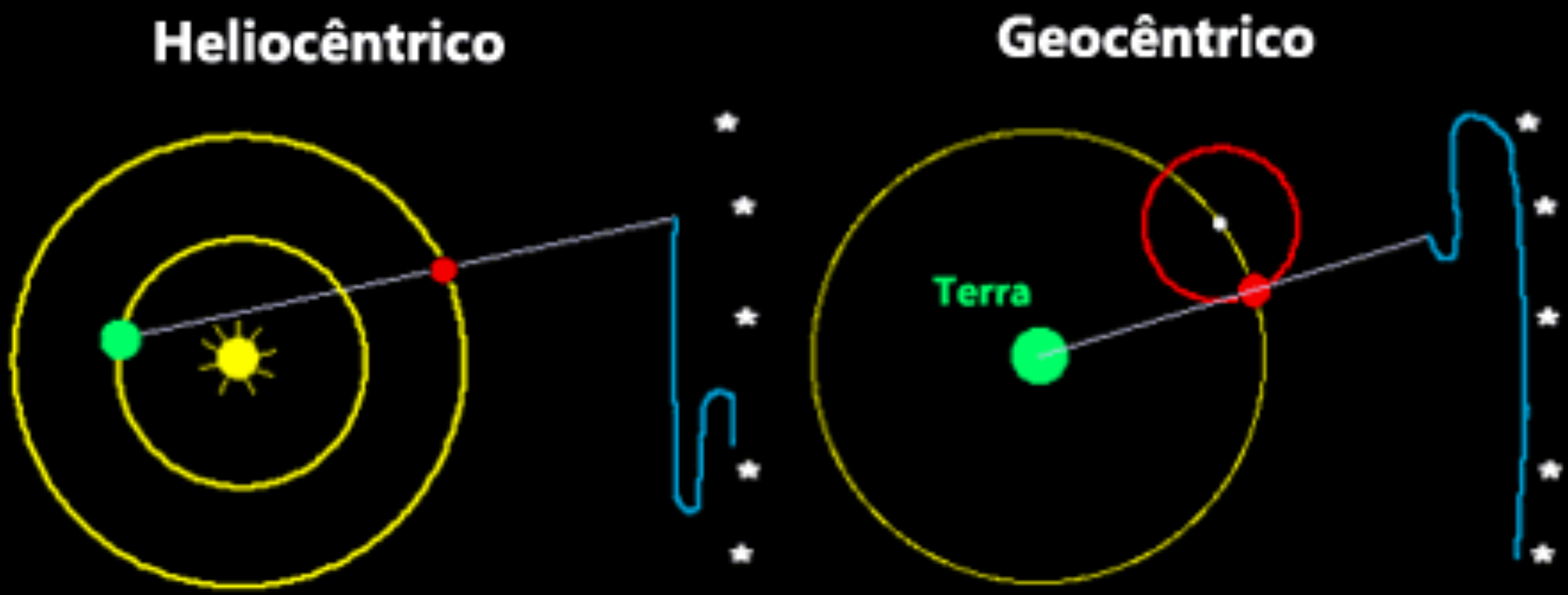

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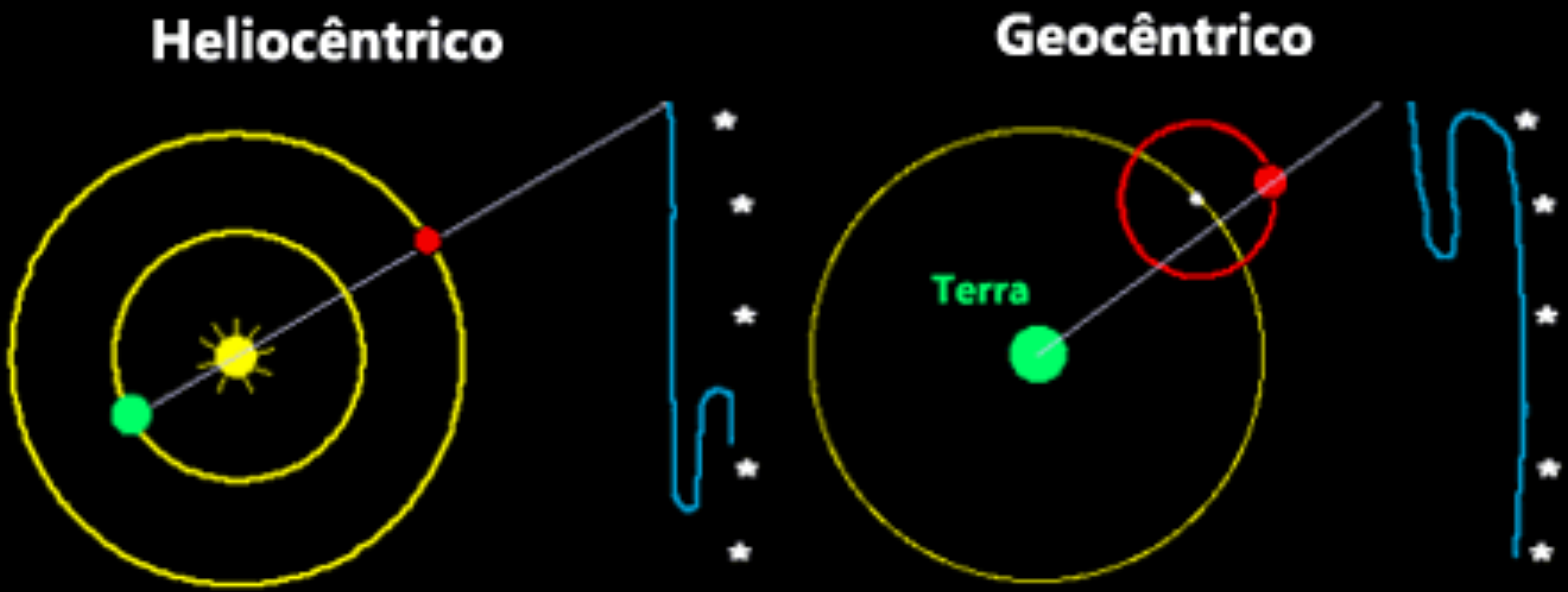
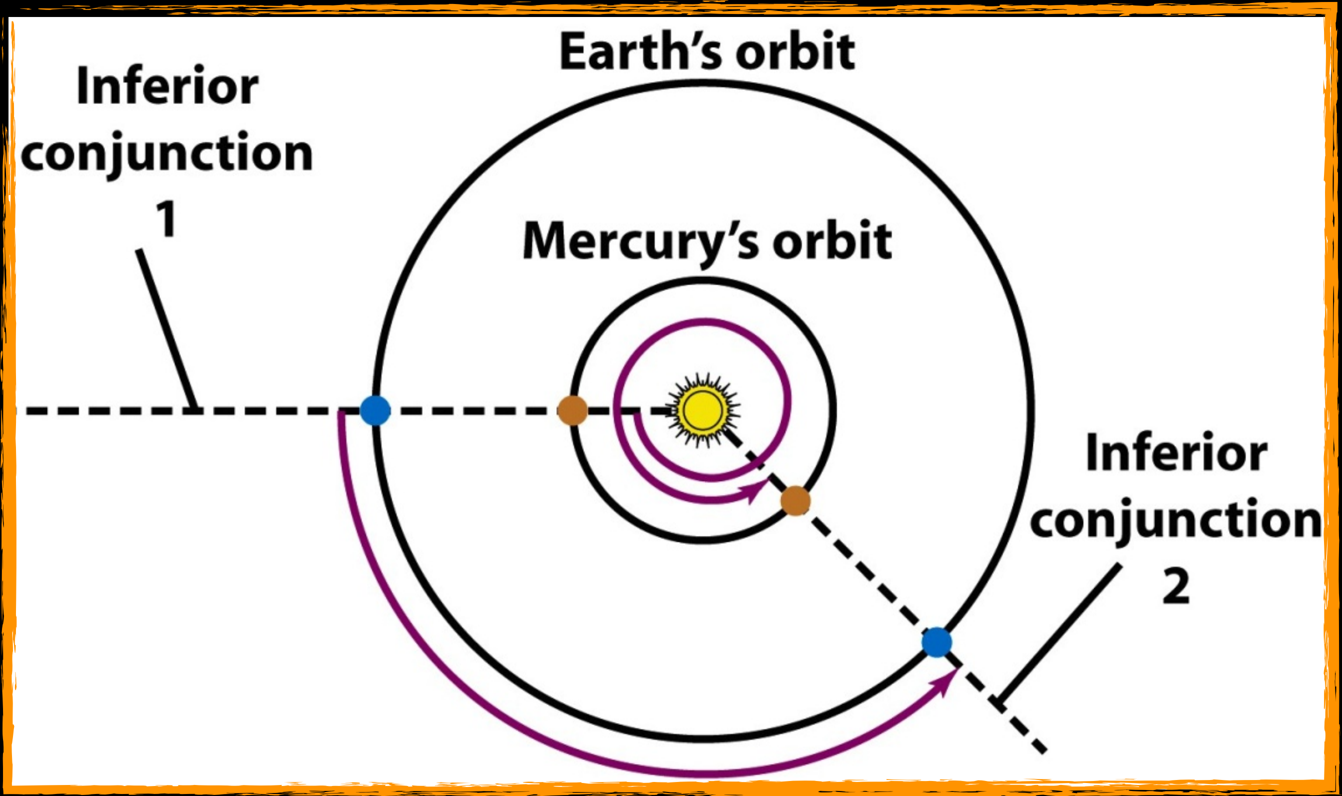


Synodic and sidereal periods



	Synodic (year)	Sidereal (year)
Mercury	0.318	0.241
Venus	1.599	0.616
Earth	—	1.0
Mars	2.136	1.9
Jupiter	1.092	11.9
Saturn	1.035	29.5
Uranus	1.013	84.0
Neptune	1.008	164.8

SynodicYear

☛ time between consecutive conjunctions of planet with Earth

Sidereal Year

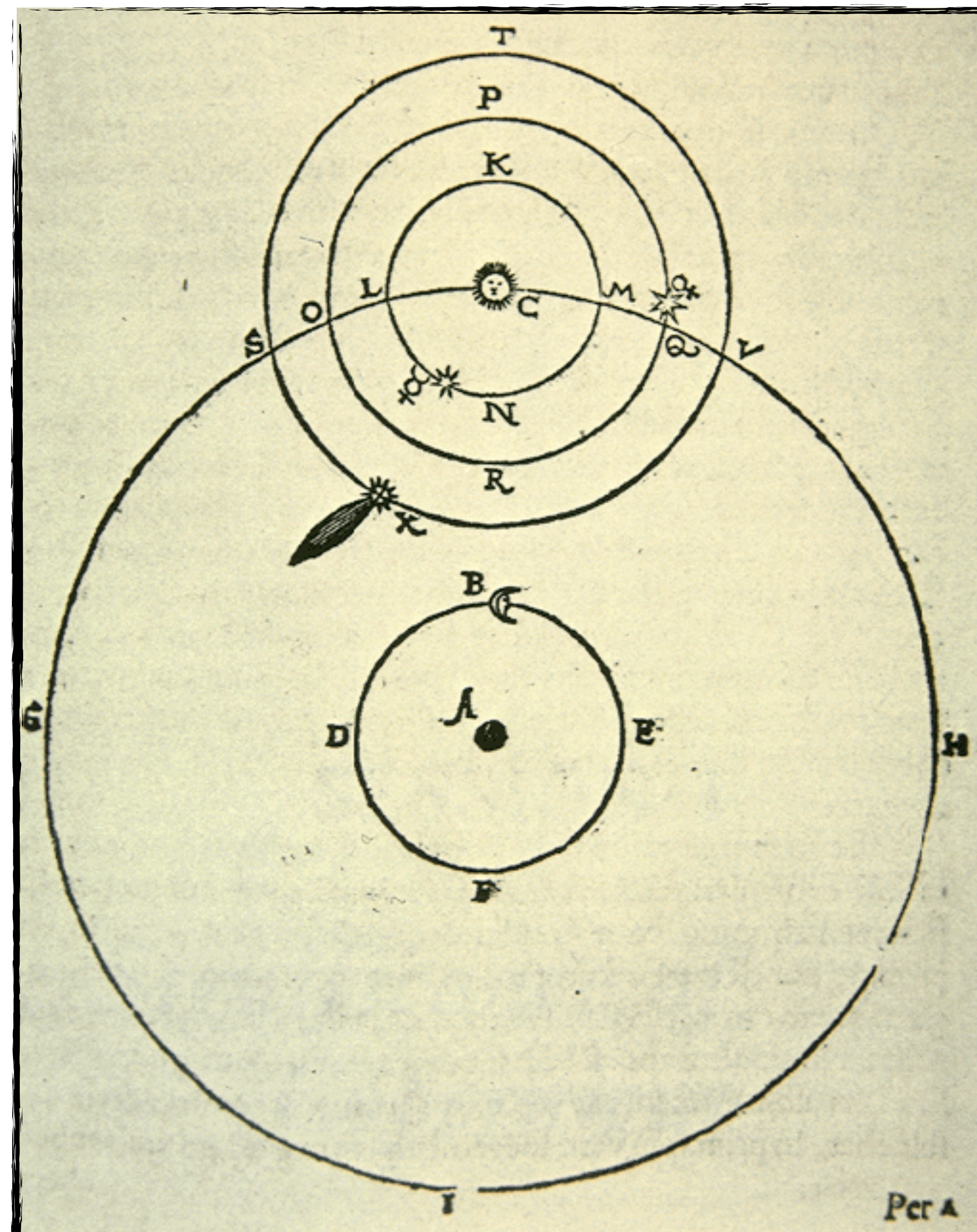
☛ time for that planet to make one full rotation around Sun with respect to background stars

Tycho Brahe (1546-1601)

Tycho's cosmos

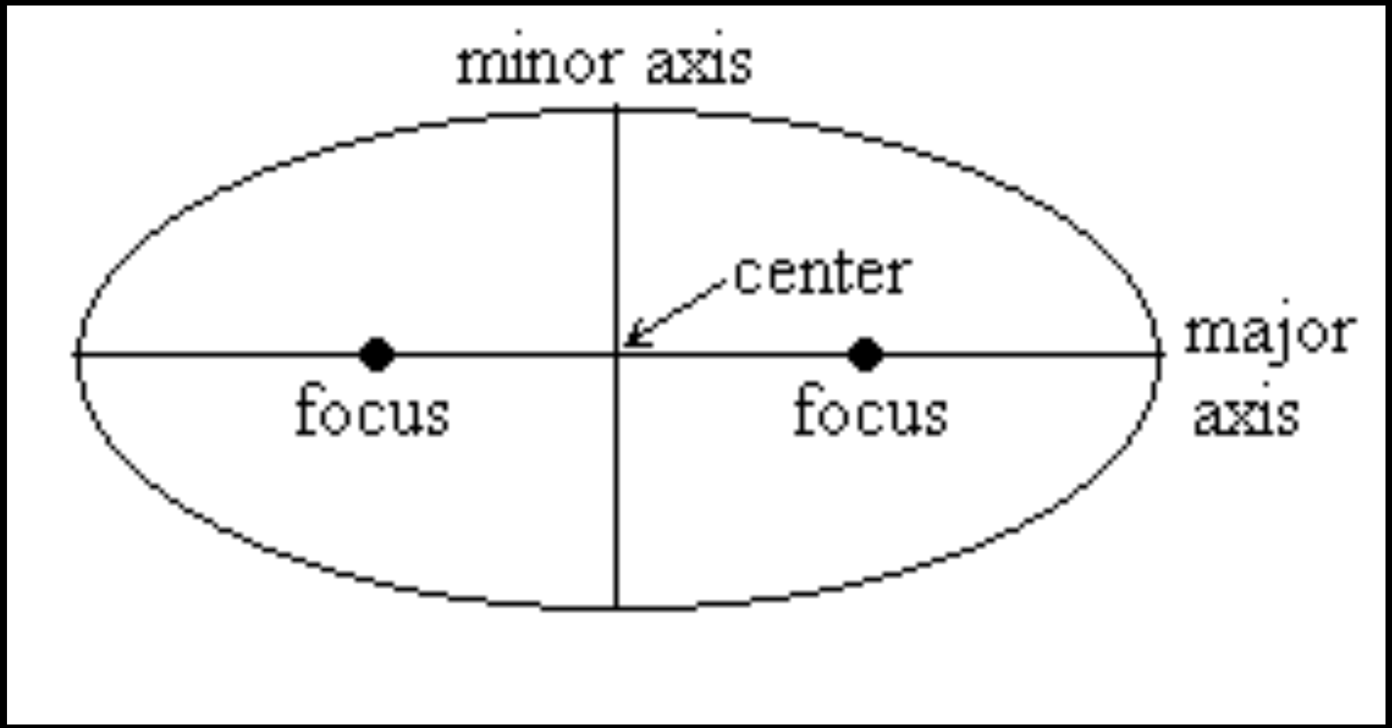
Tycho had made most accurate observations obtained at that time on planets

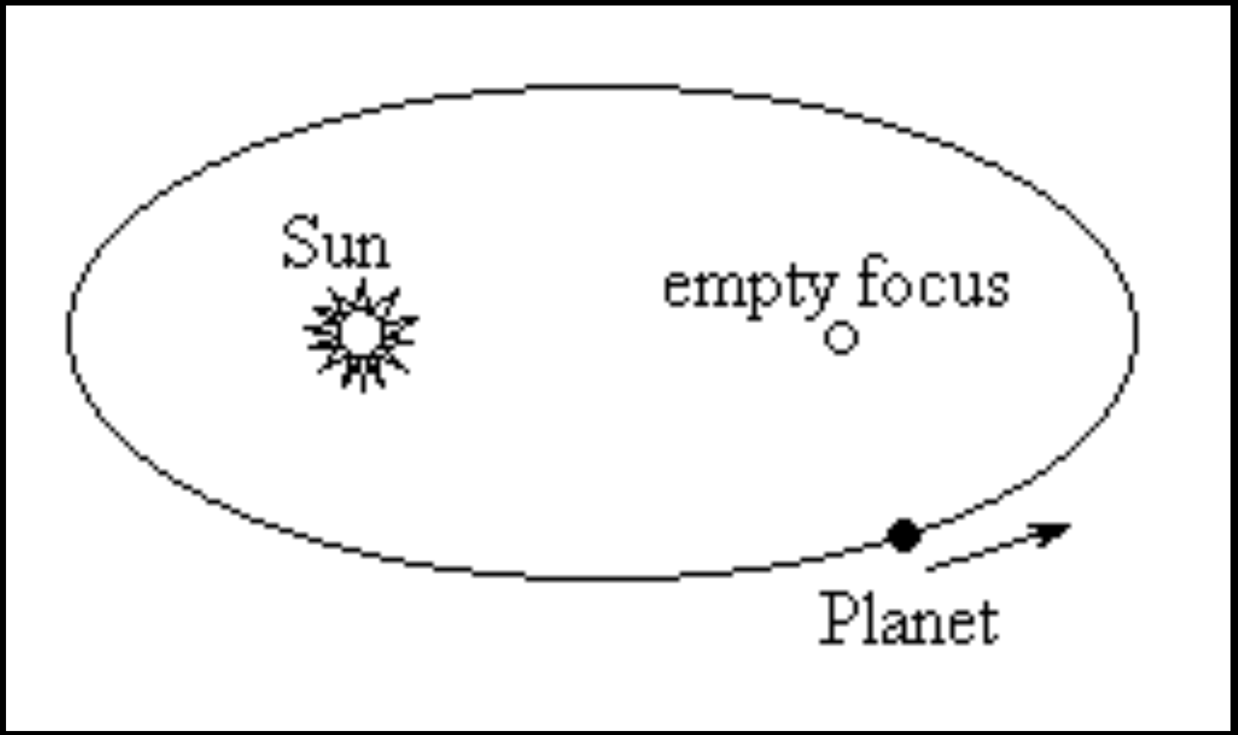
Tycho's model of heavens had planets orbiting around Sun and Sun orbiting around Earth at center of the Universe



Johannes Kepler (1571-1630)

Kepler's Laws





Defined by Johannes Kepler

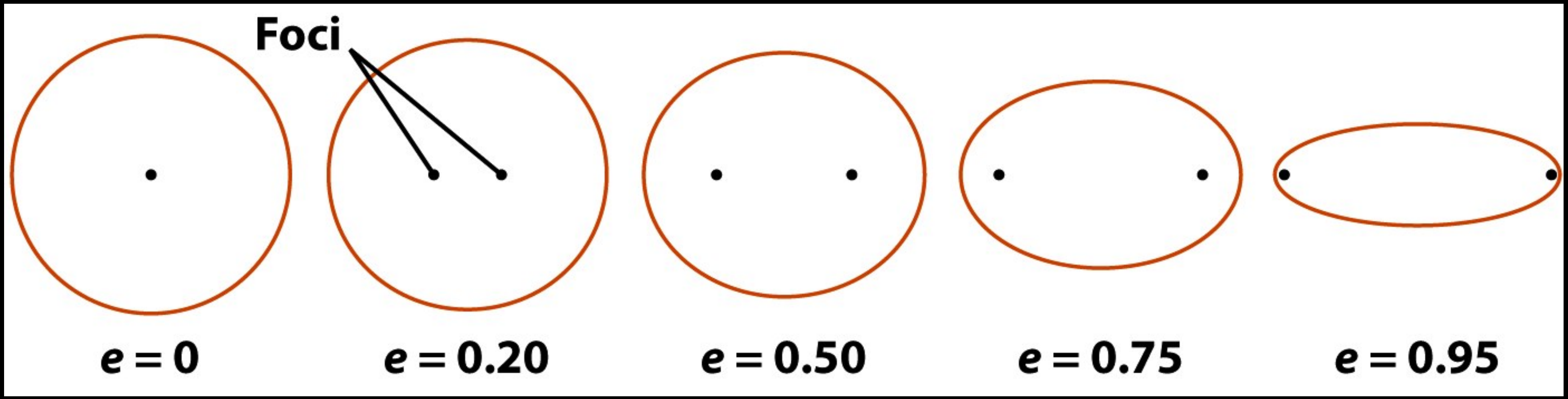
– Using Tycho's observations

Assumption planetary orbits are circular introduces errors when making predictions

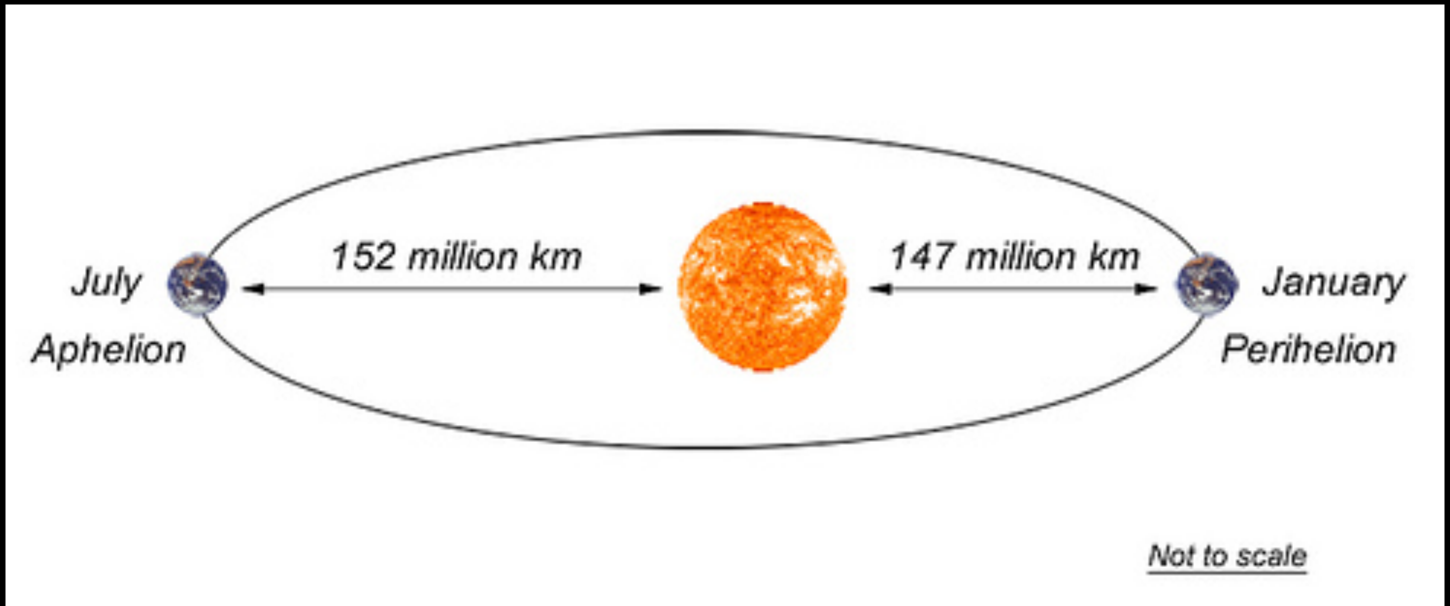
Invoking elliptical orbits provides a far better description

Geometric Aside

Elliptical Eccentricity

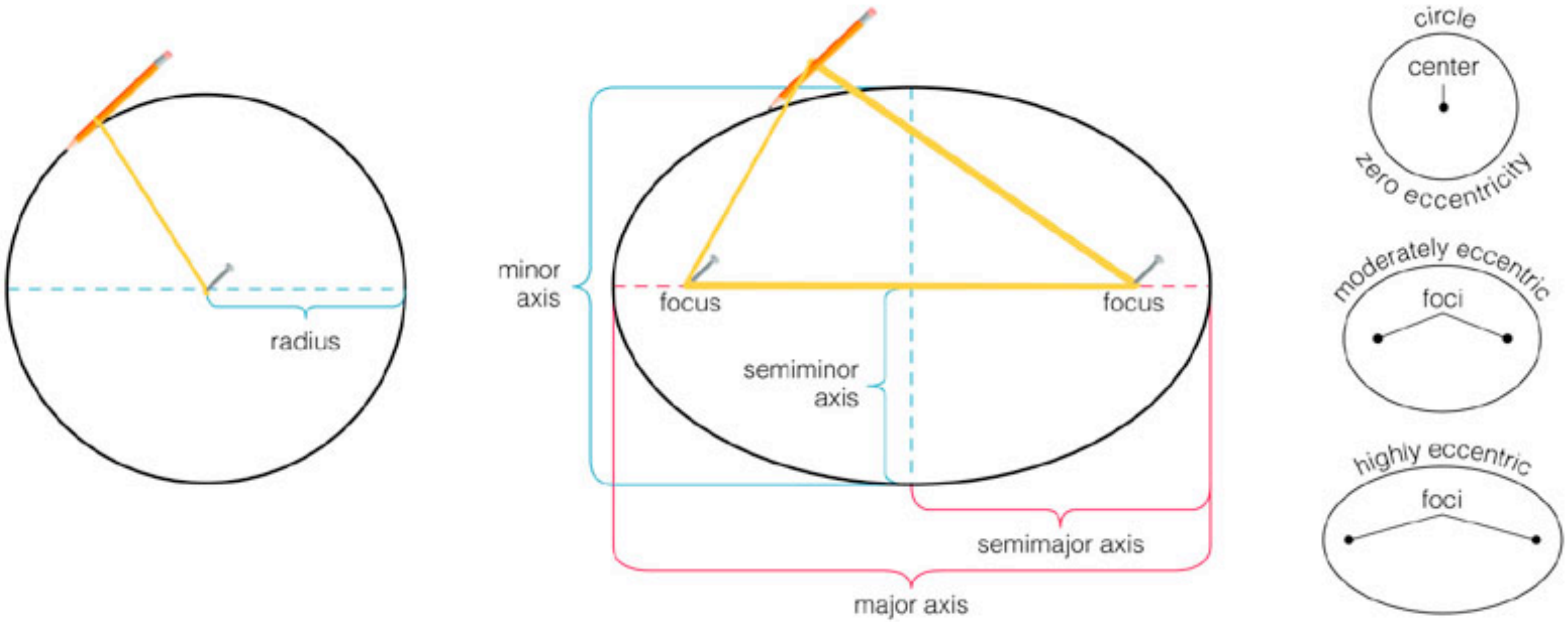


- ➢ Eccentricity measures the deviation of a circle
- ➢ As eccentricity e increases the shape elongates

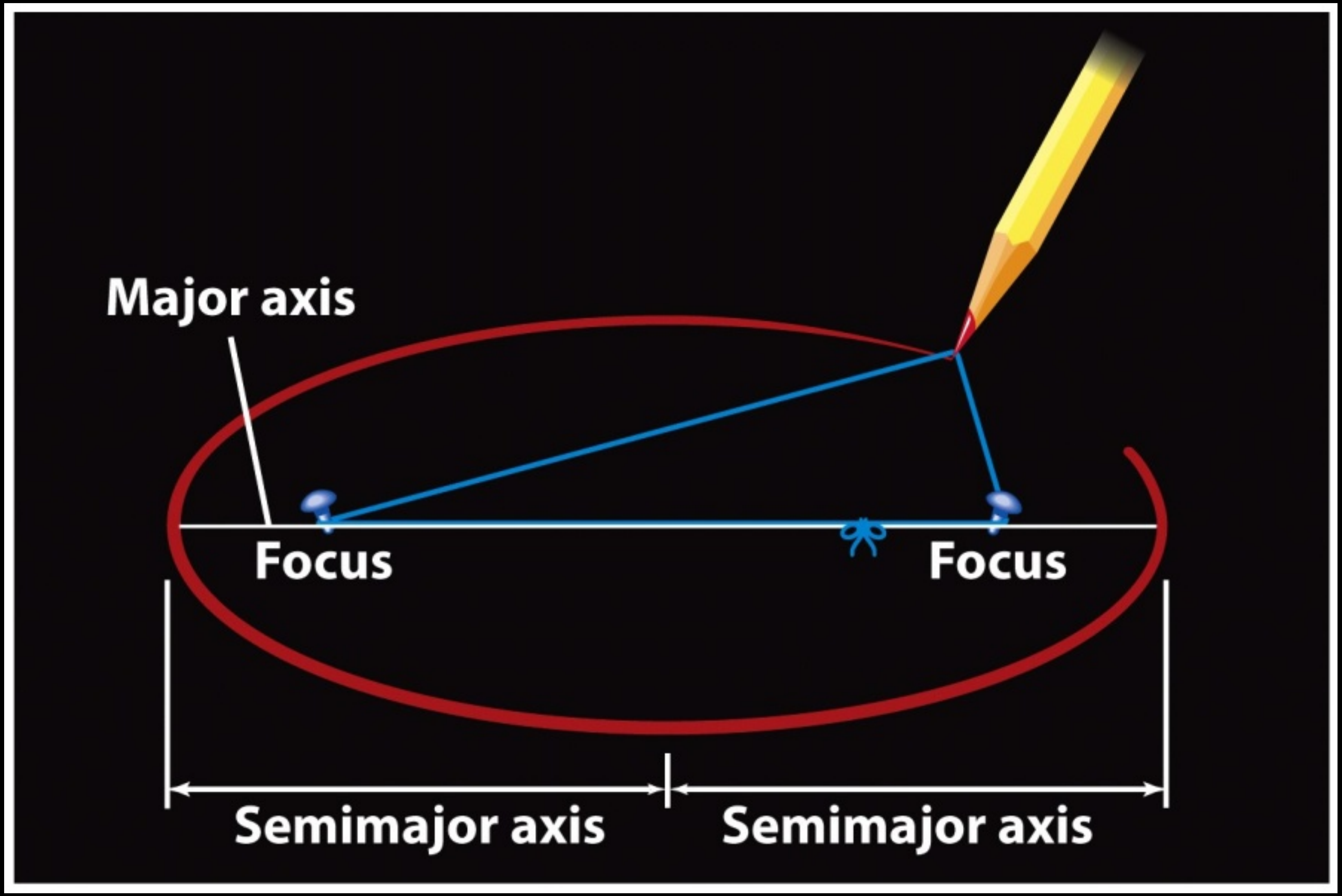


- ➢ aphelion distance - distance farthest from Sun
- ➢ perihelion distance - distance closest to Sun

Geometry of ellipses

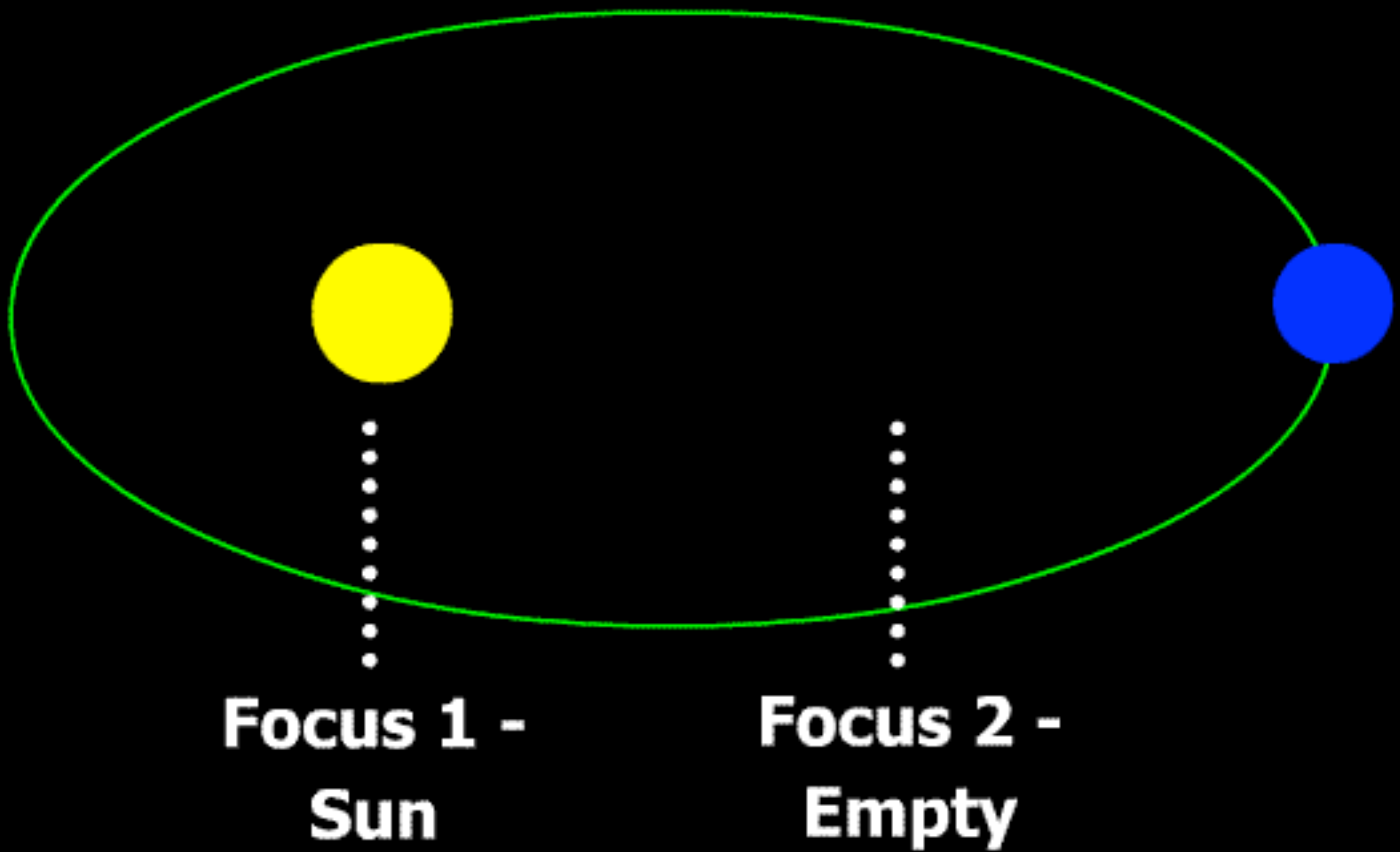


Kepler's First Law



The orbit of a planet around the Sun is an ellipse, with the Sun at one focus

Kepler's First Law



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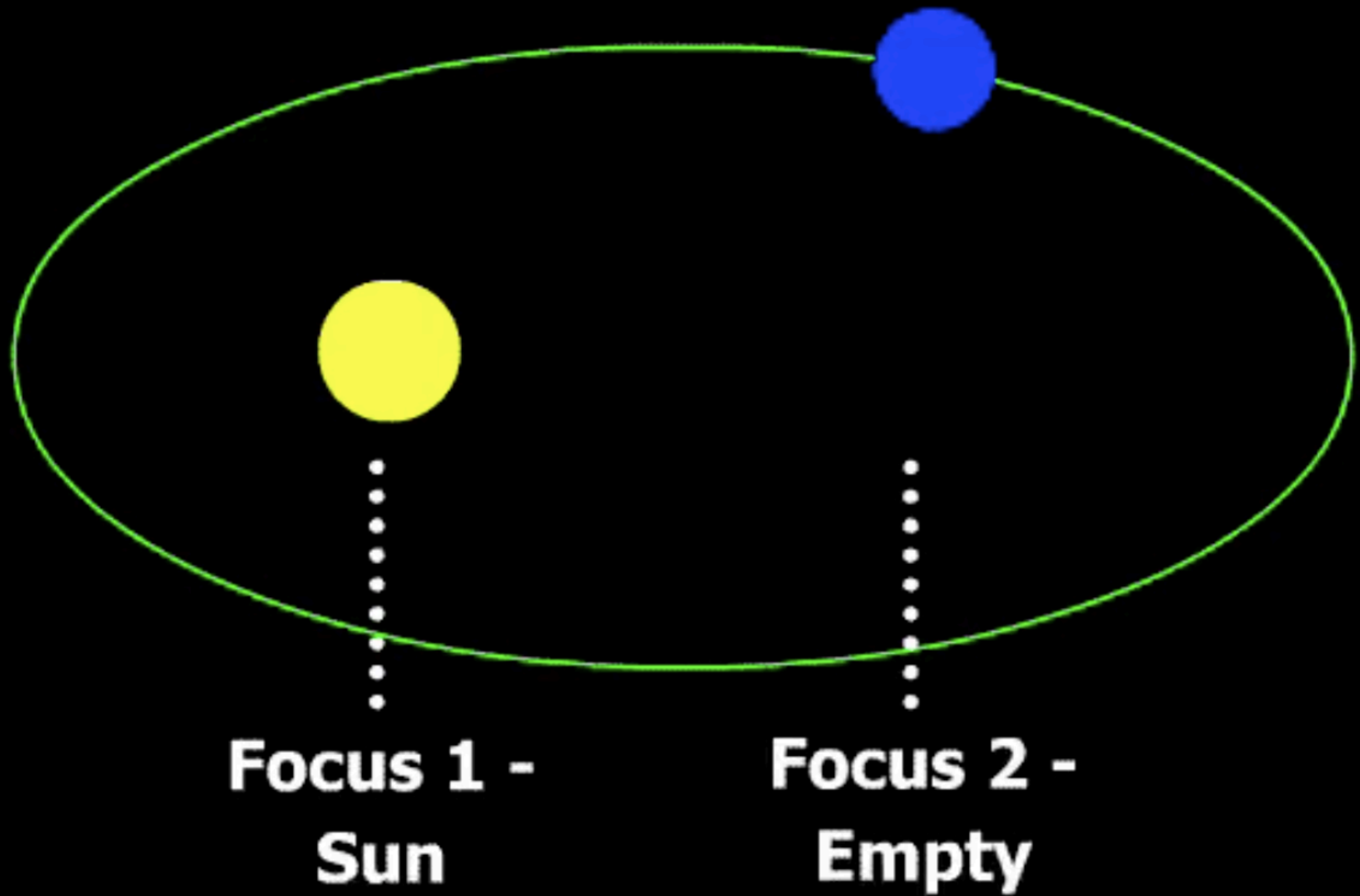

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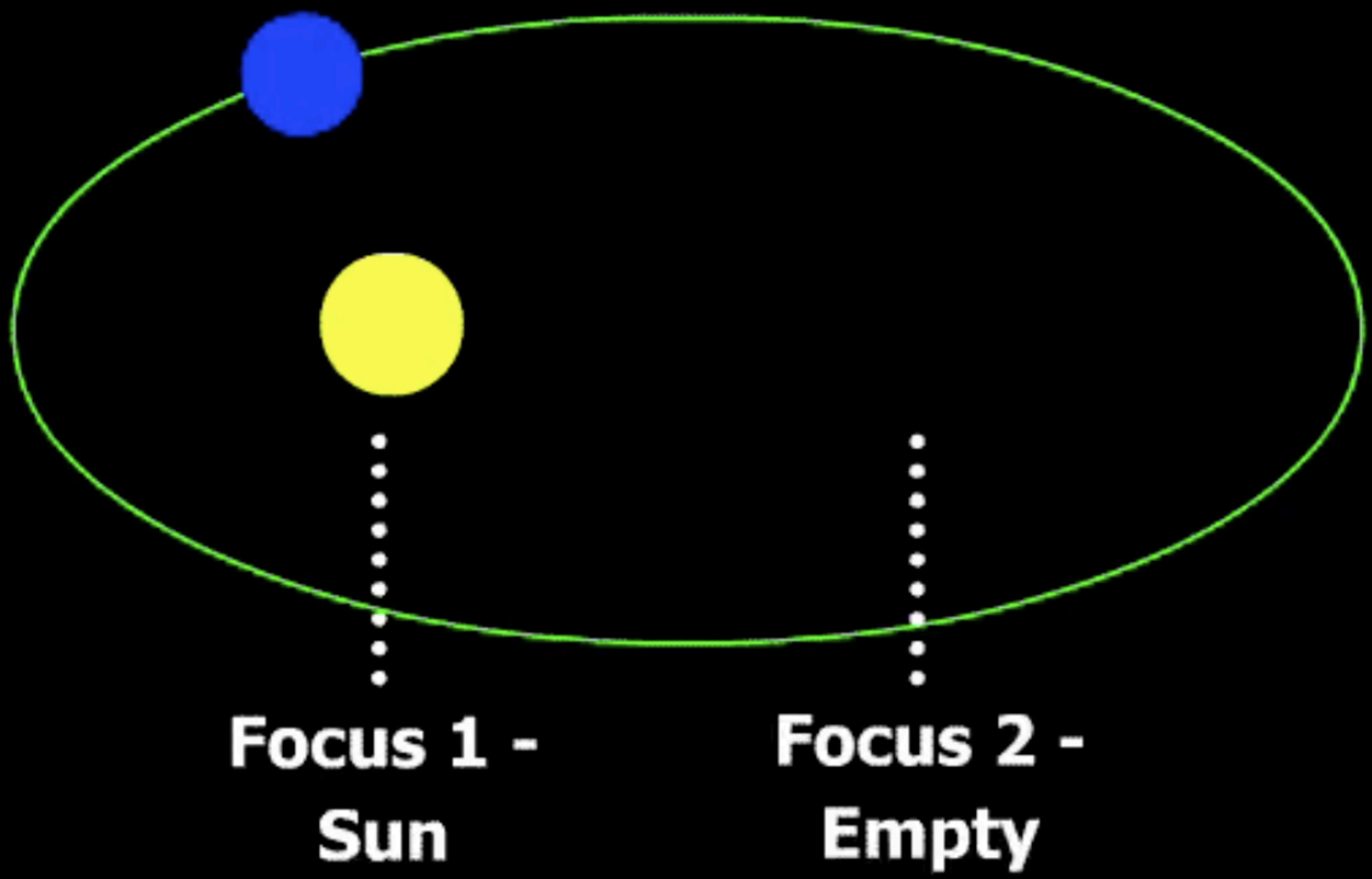

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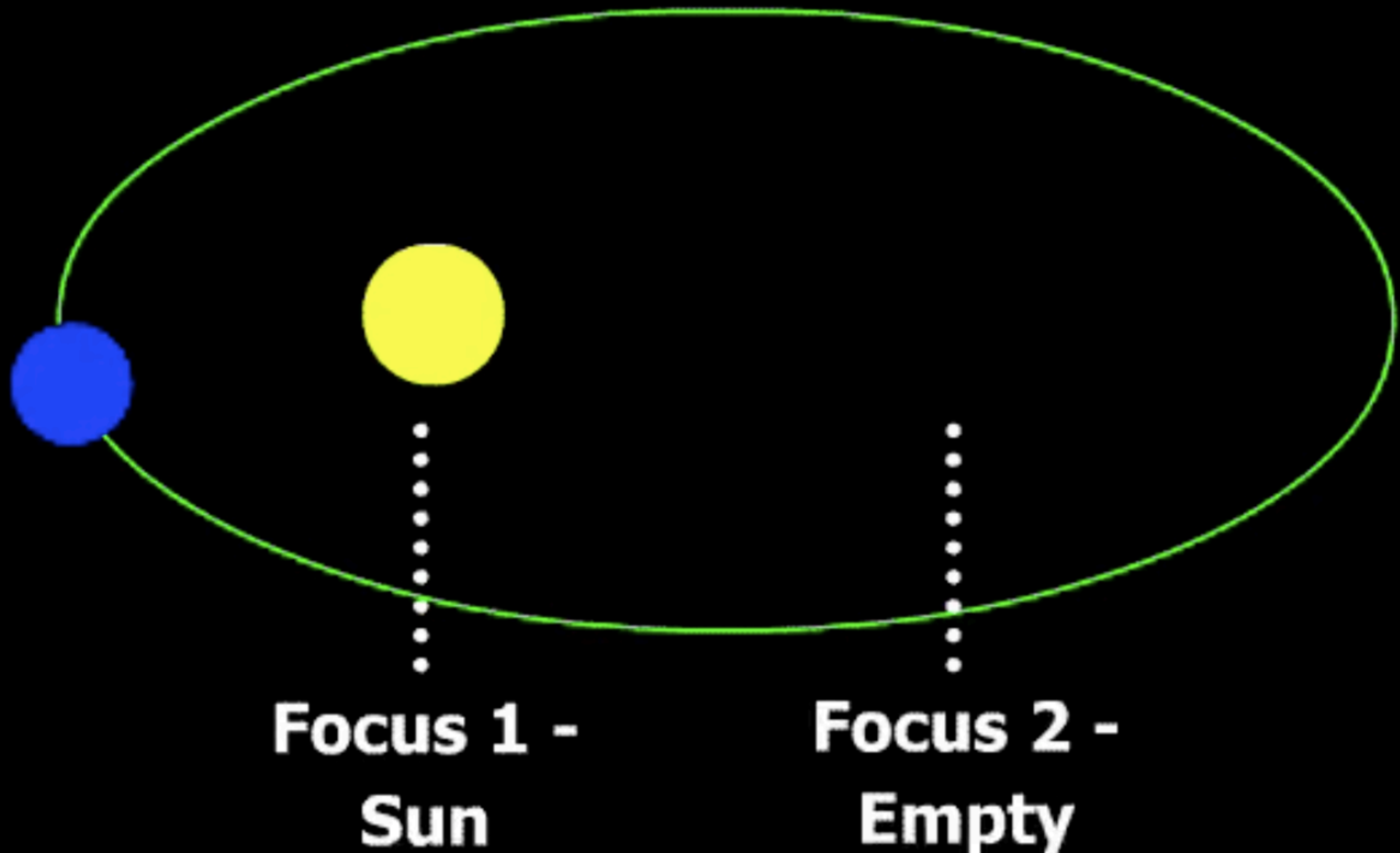

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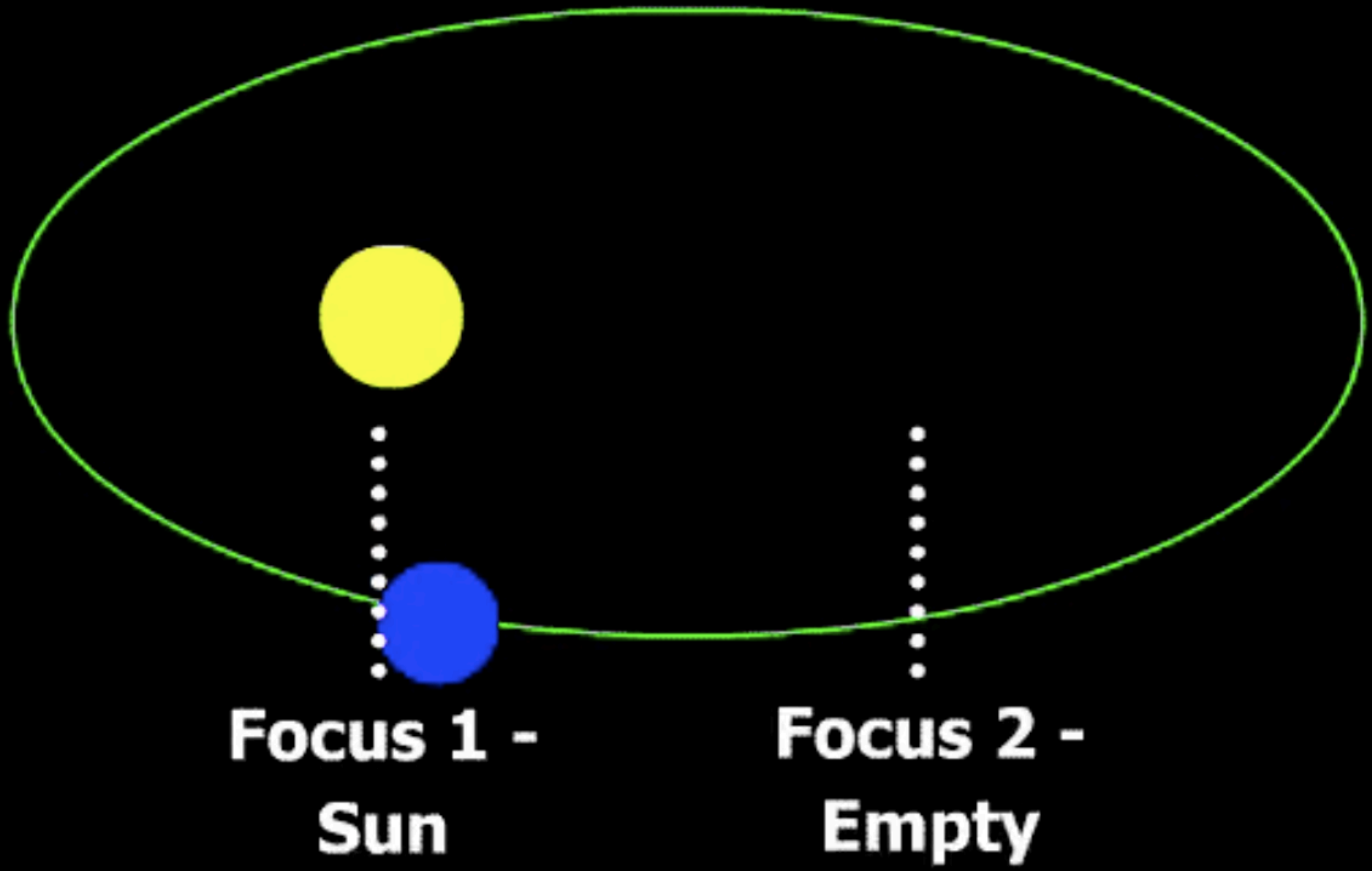

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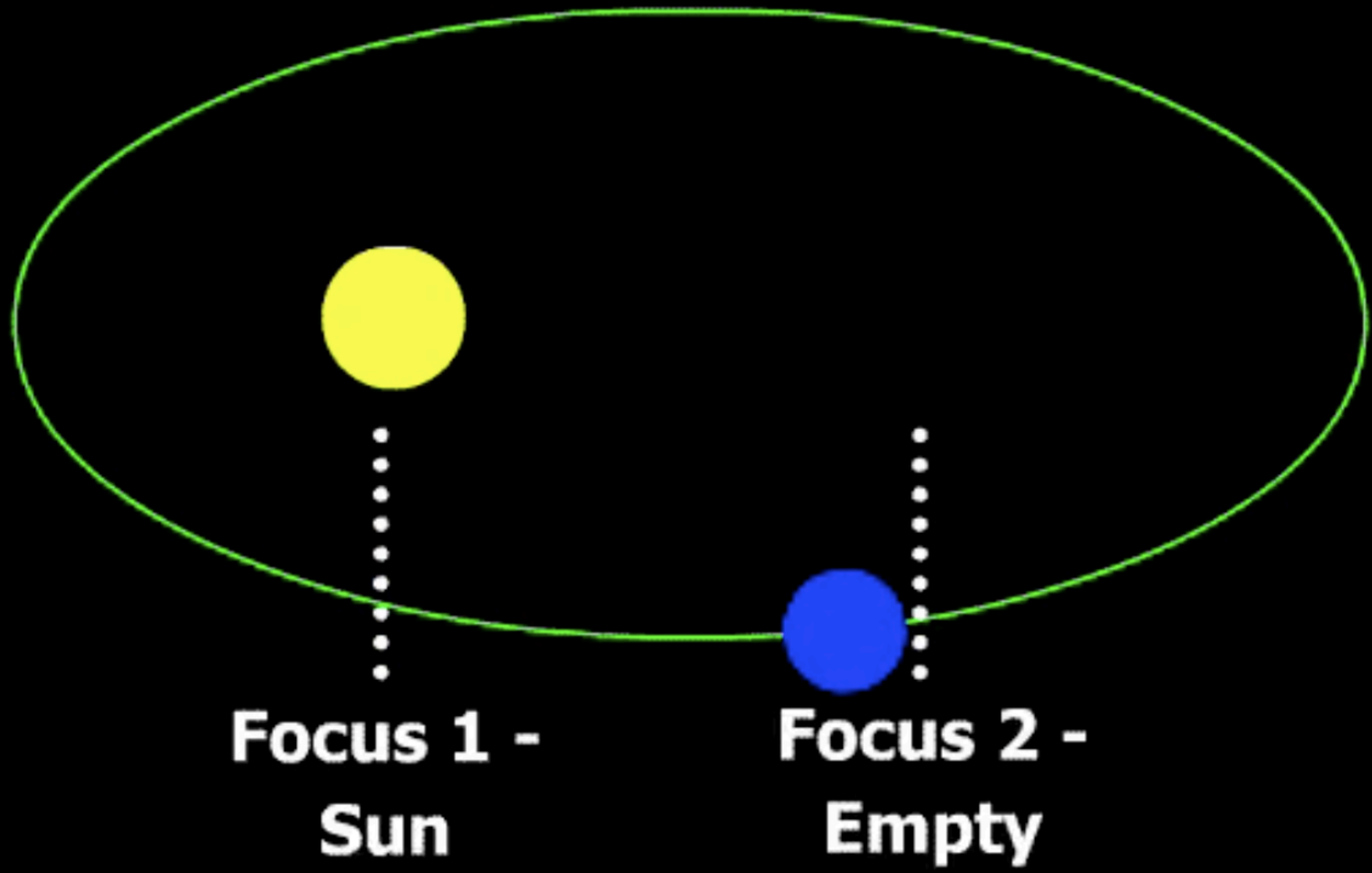

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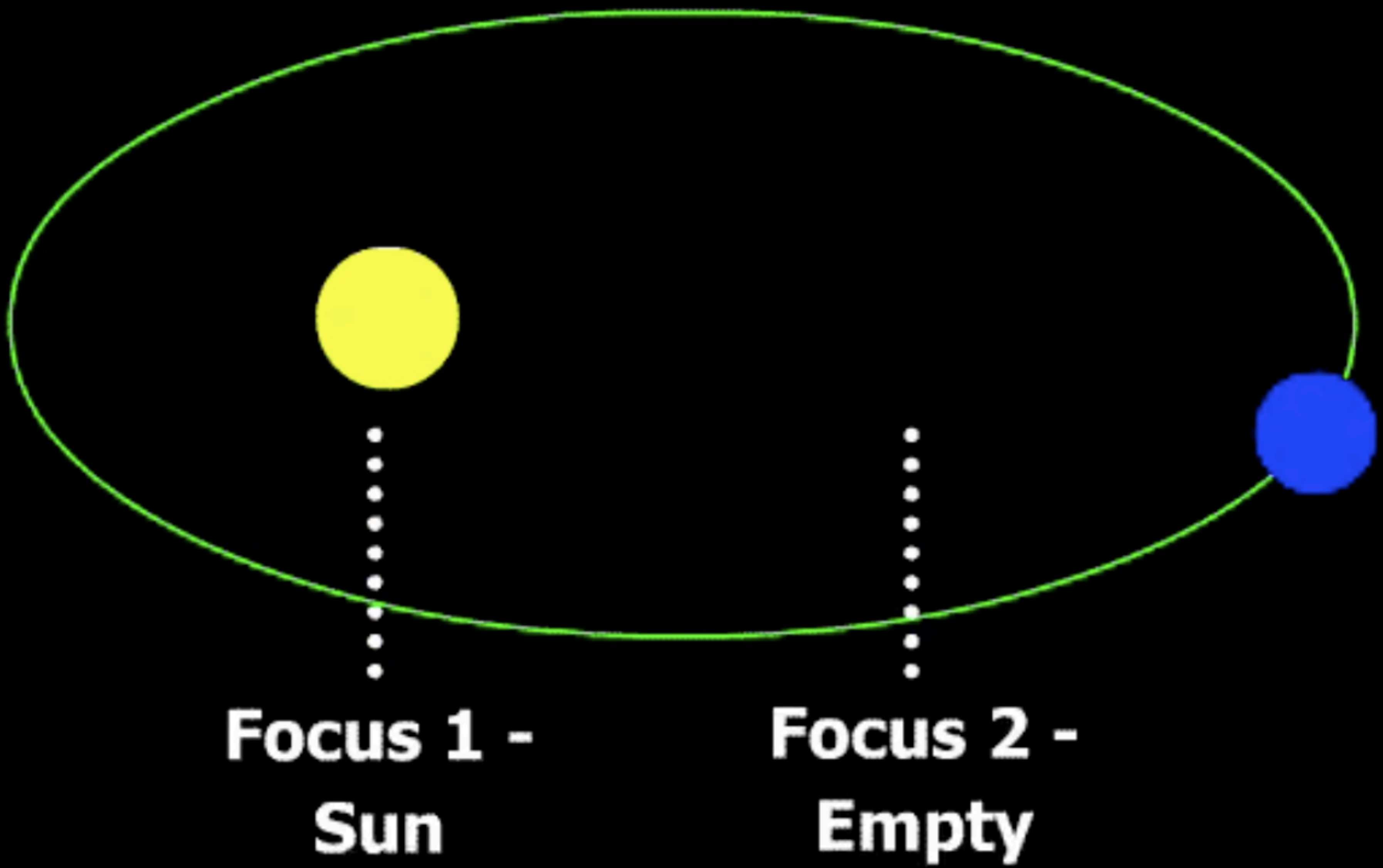
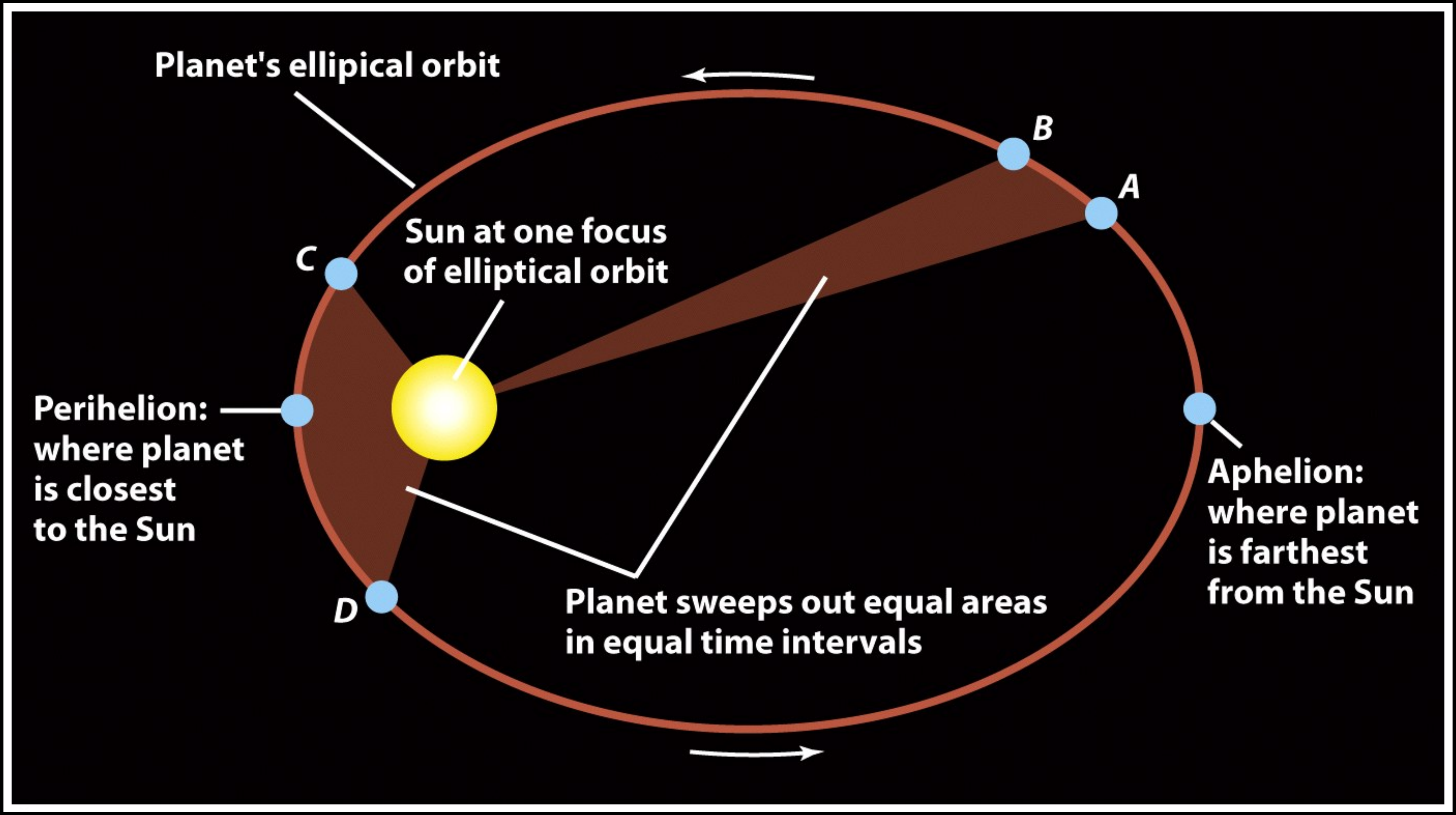
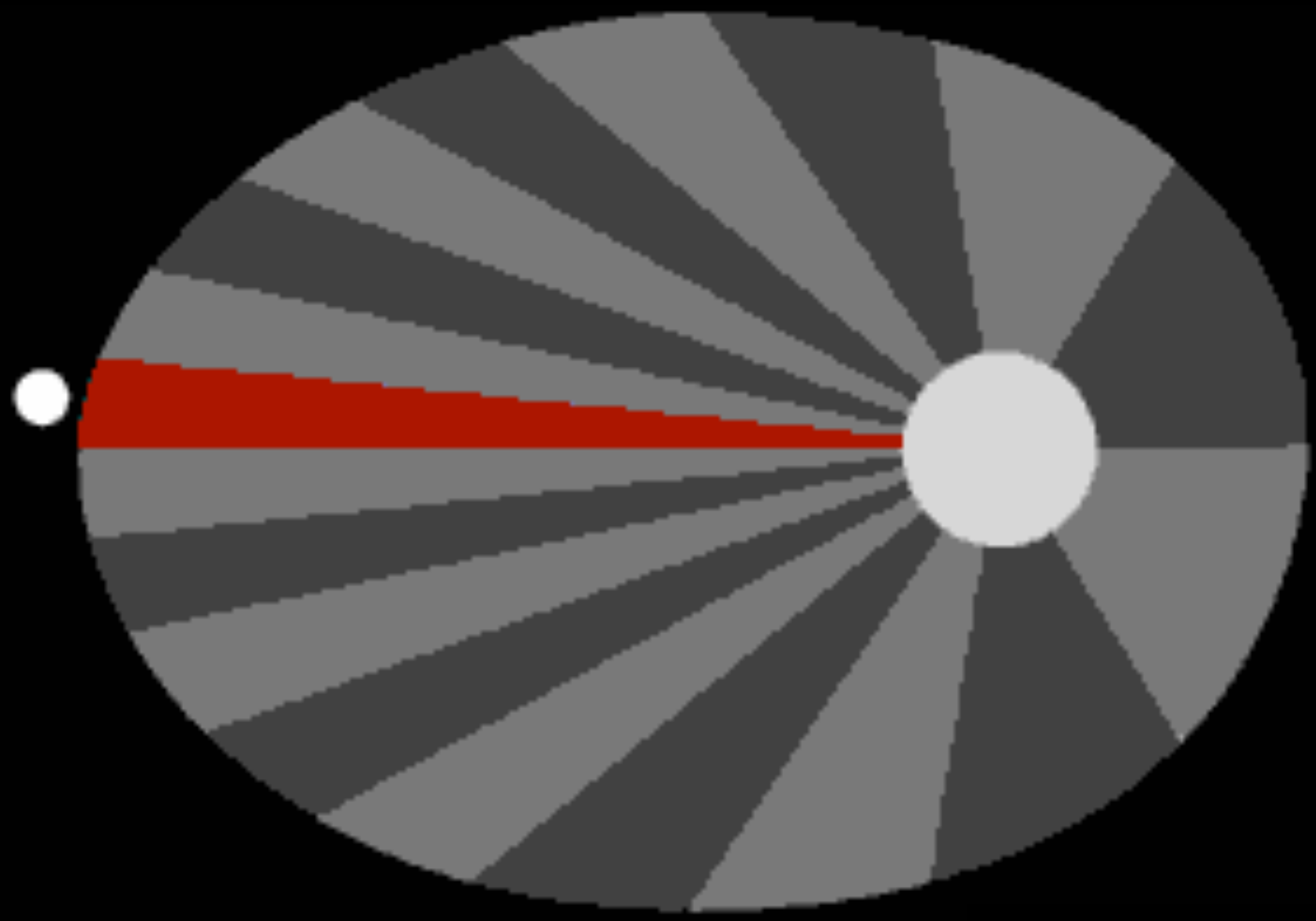


Kepler's Second Law

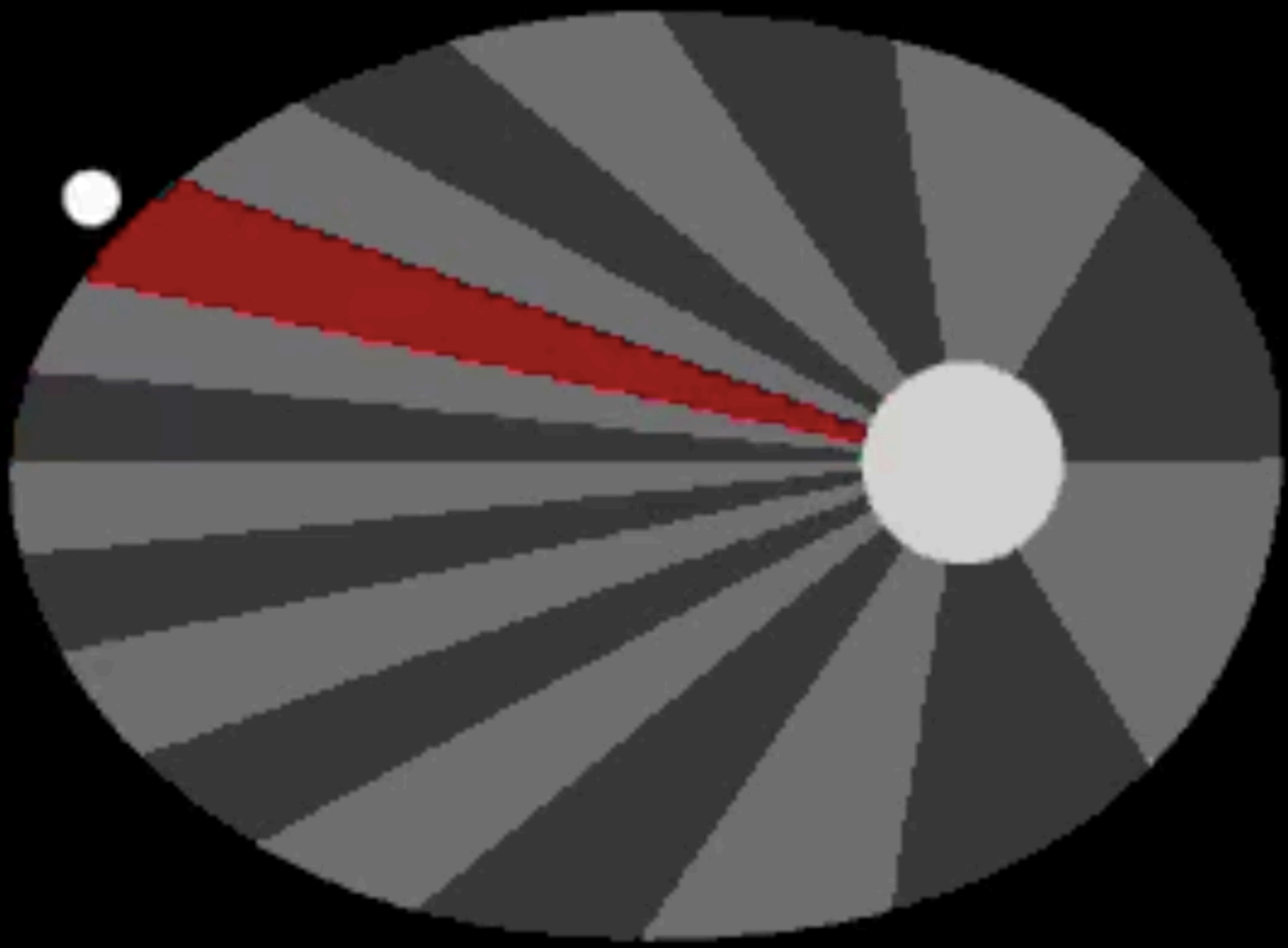


A line joining a planet and Sun sweeps out equal areas in equal intervals of time

Kepler's Second Law



Kepler's Second Law



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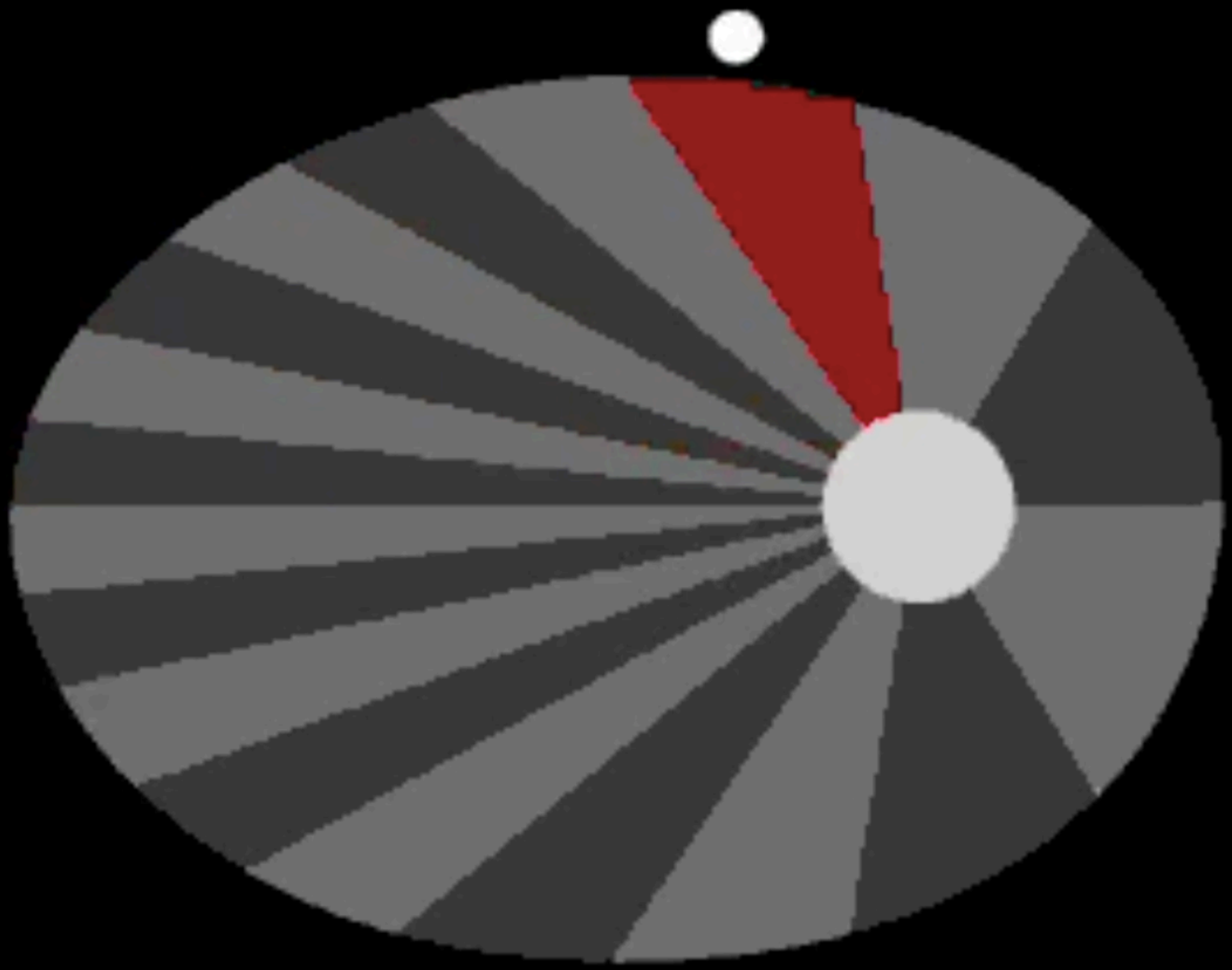

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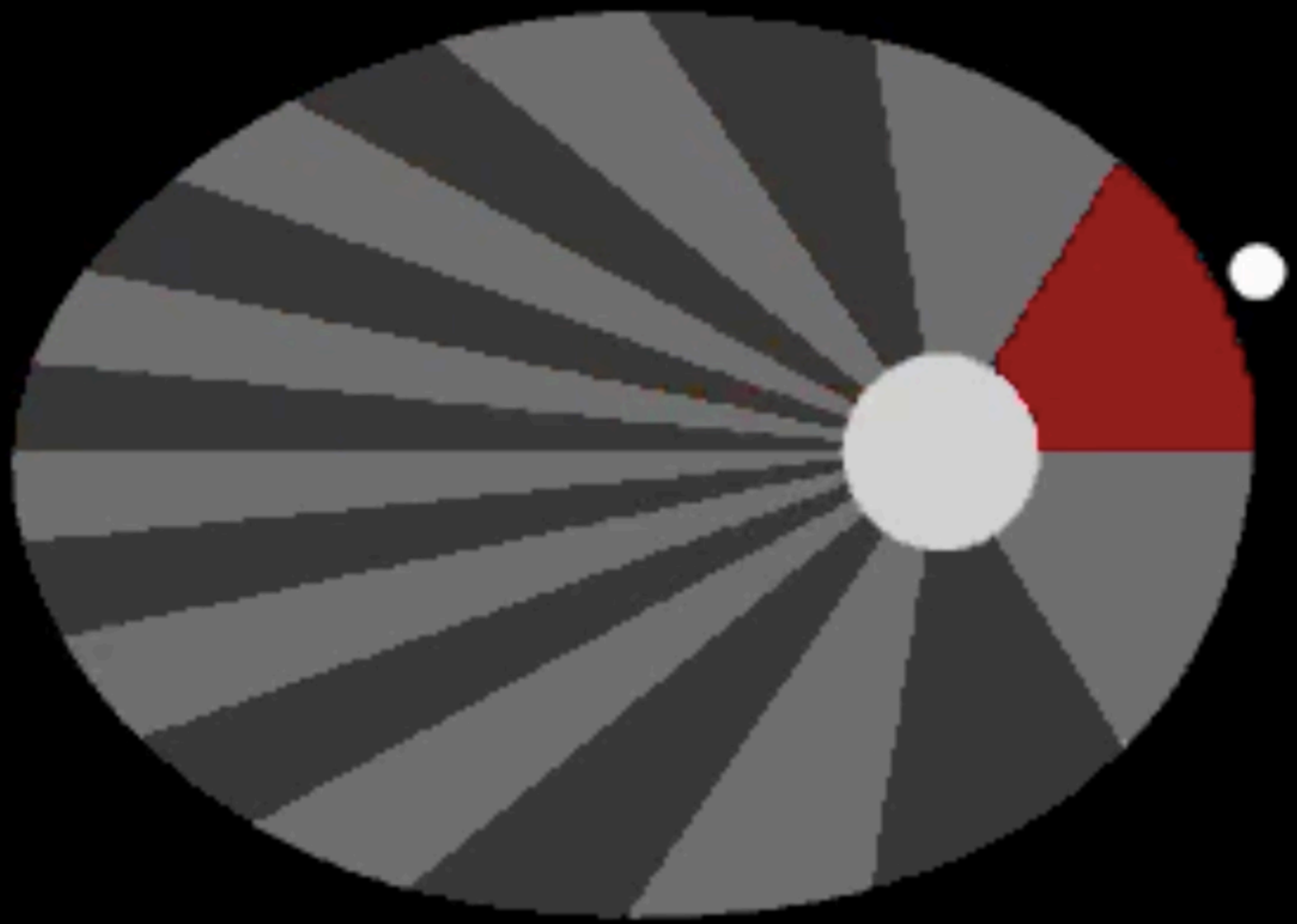

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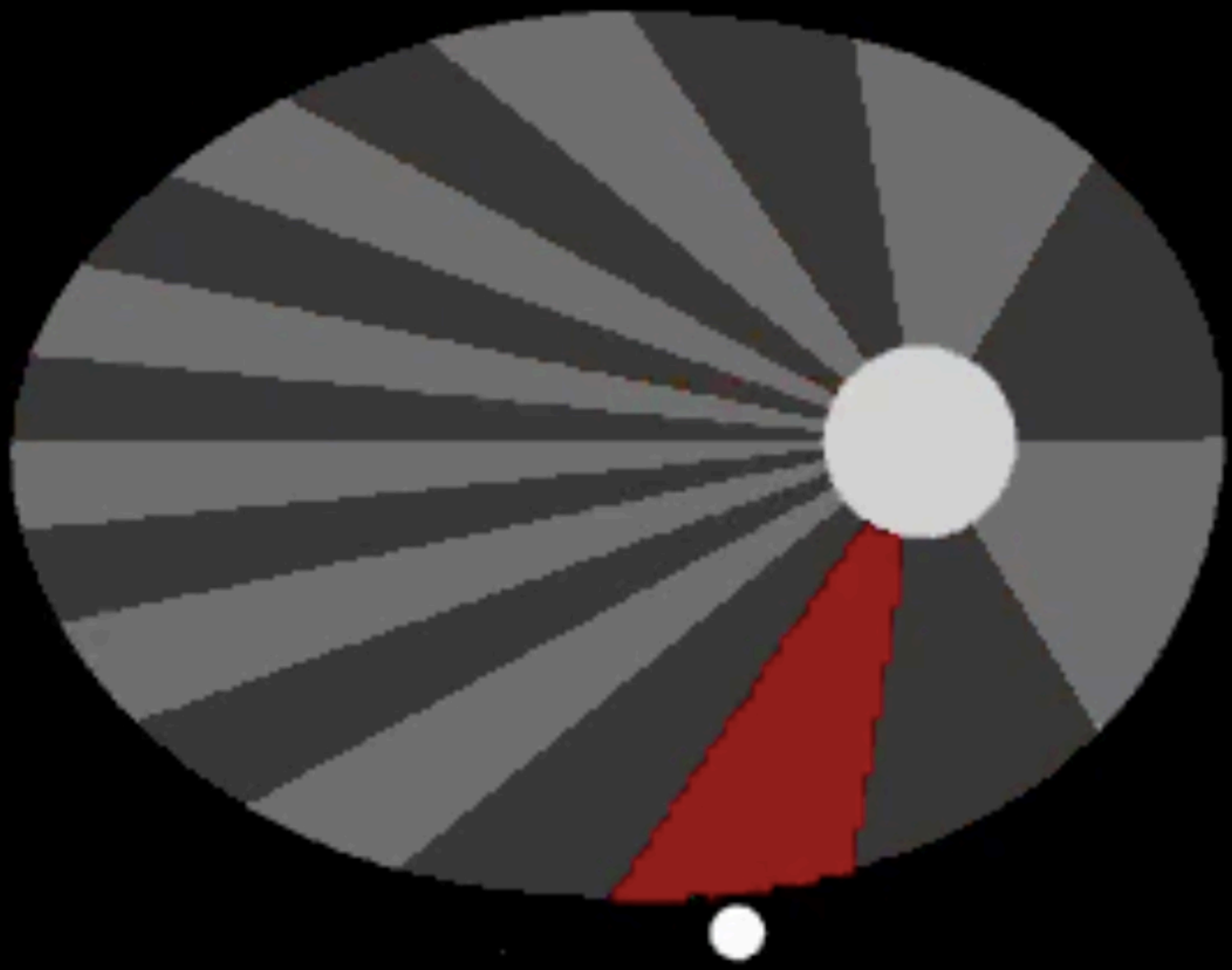

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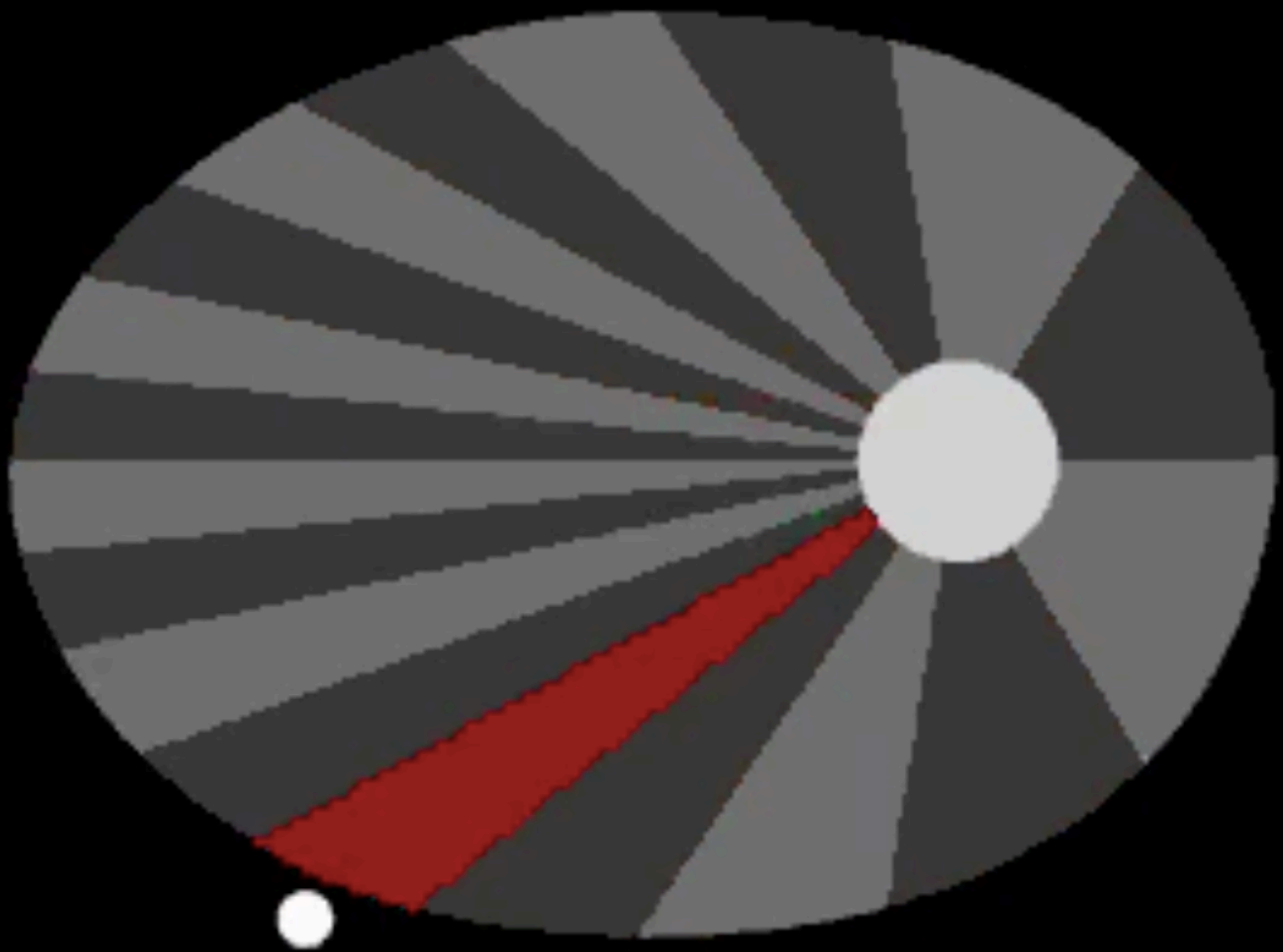
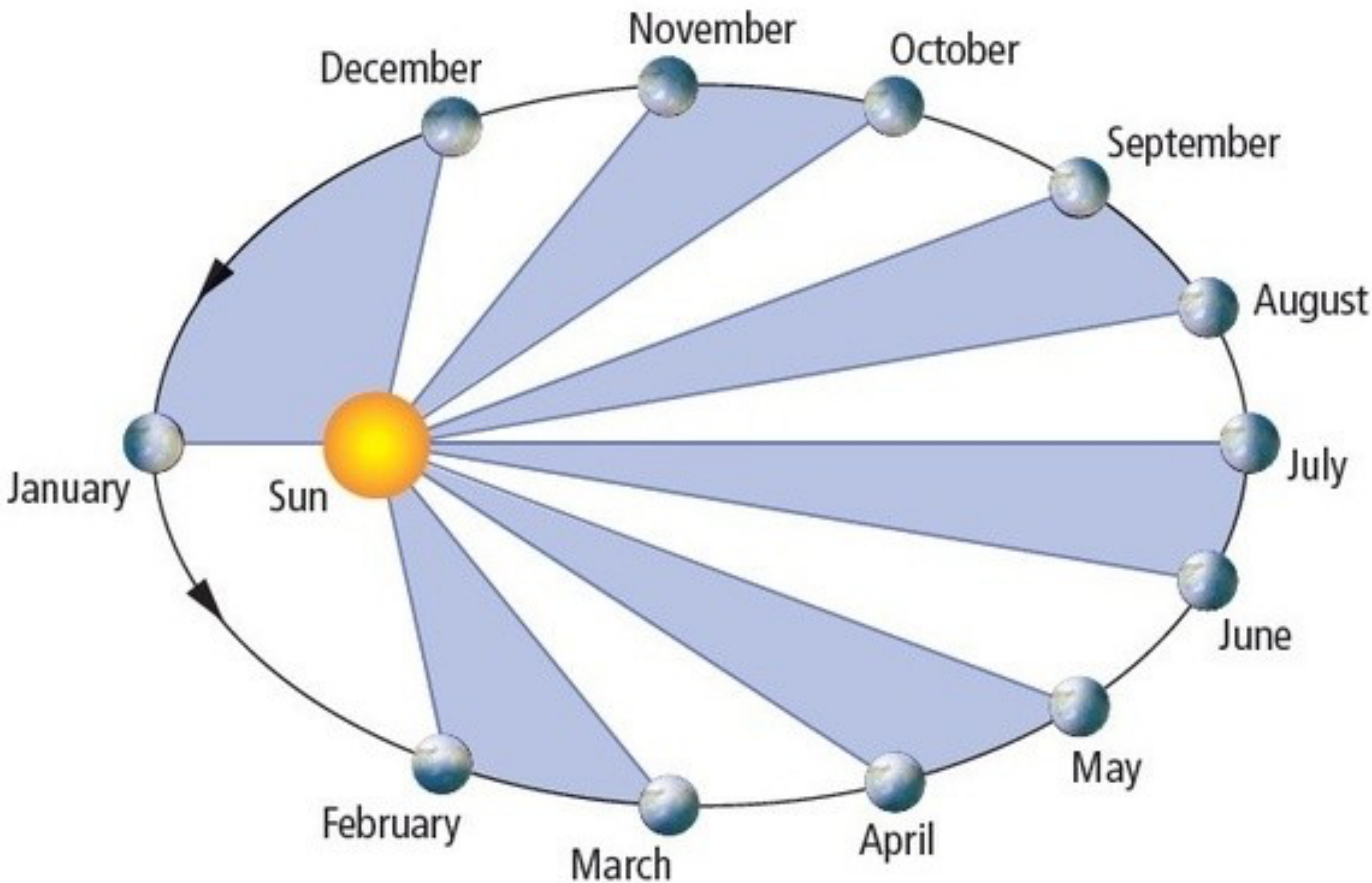
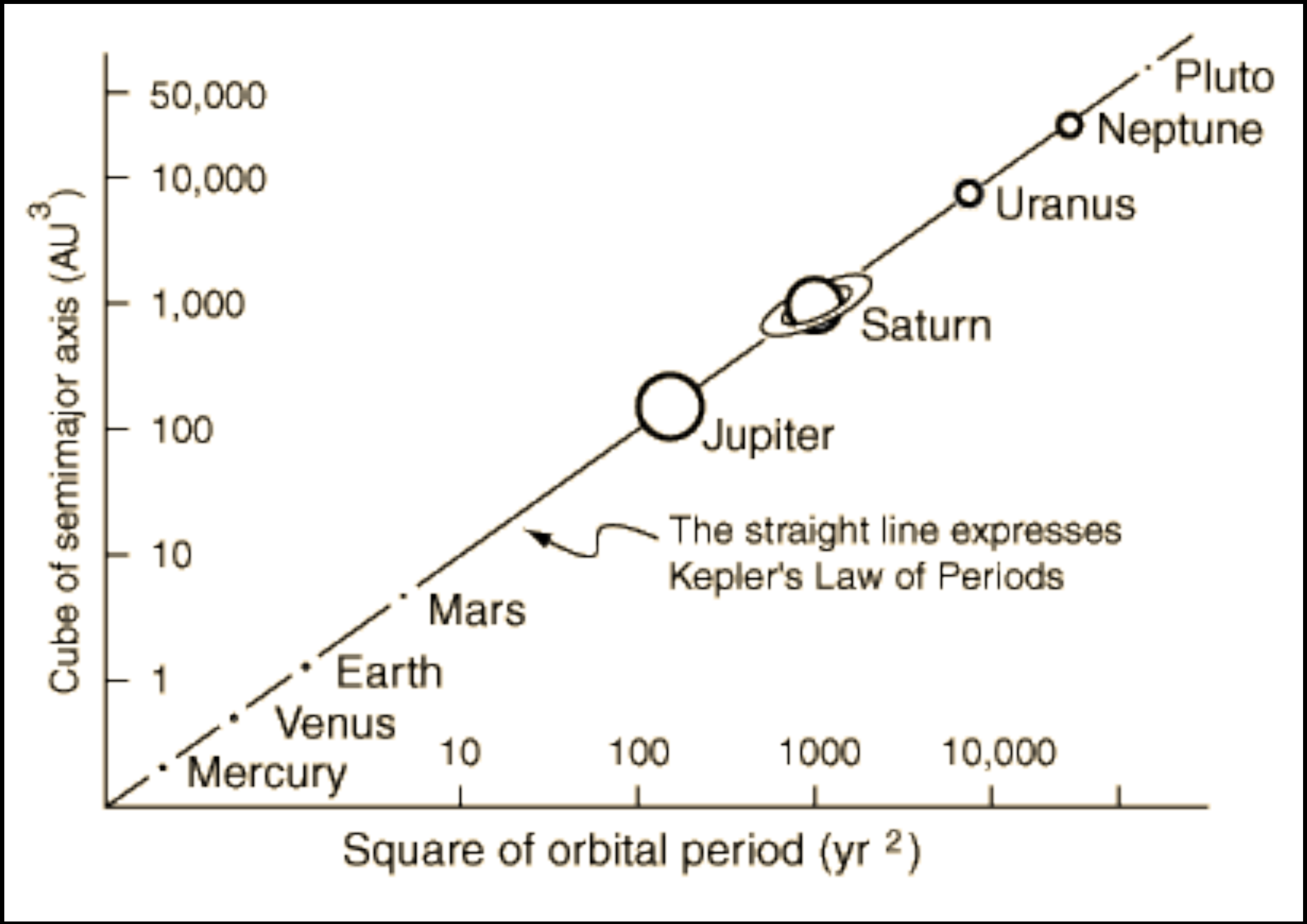



November
October
December
September
August
July
January
Sun
June
May
February
April
March

Kepler's Third Law



The square of a planet's sidereal period around the Sun is directly proportional to the cube of the length of its orbit's semimajor axis

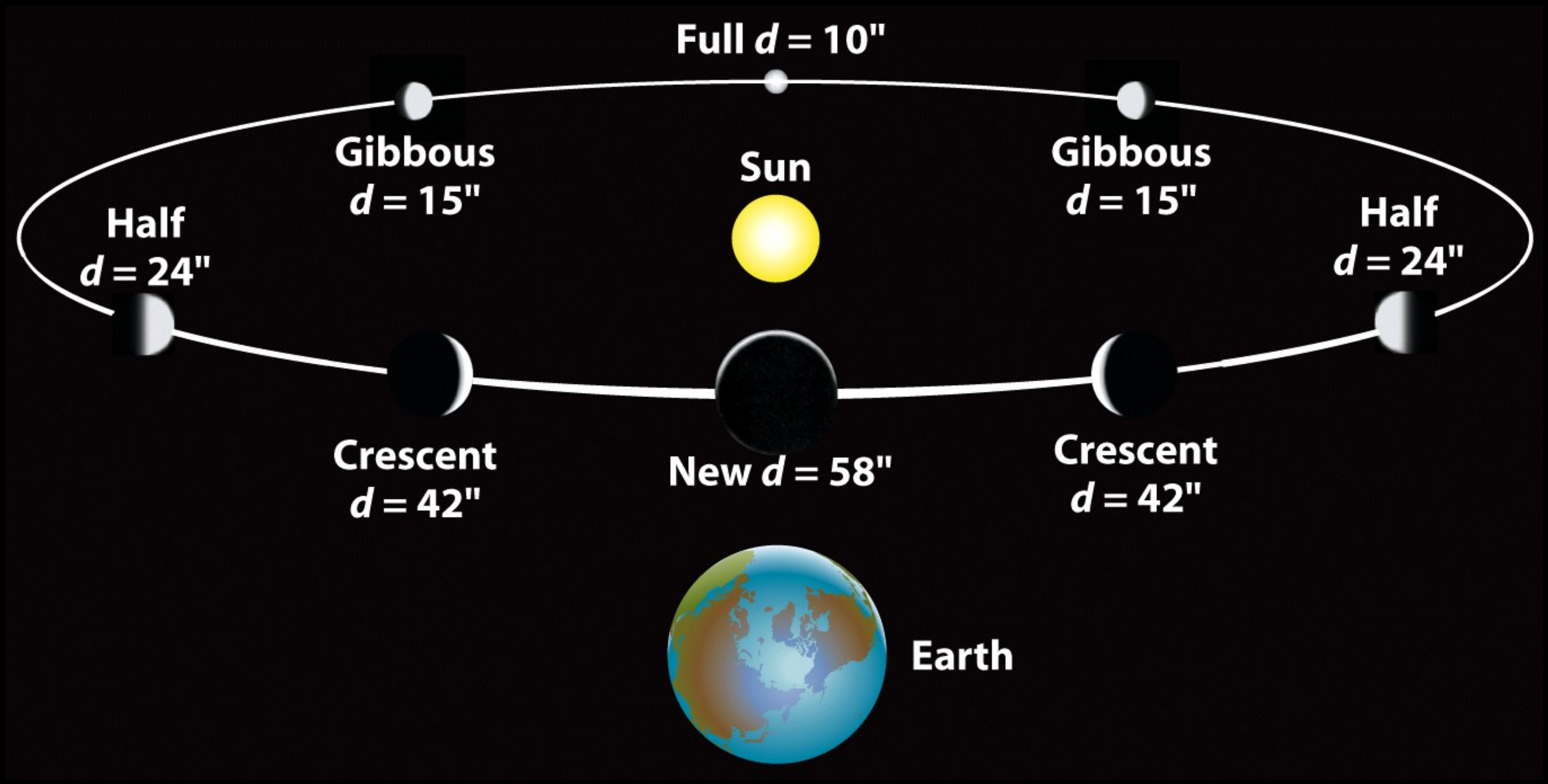
$$(T^2 \propto R^3)$$

Galileo Galilei (1564-1642)

Galileo Galilei

- Made many discoveries that supported heliocentric view and Kepler's laws
- Was the first to make use of and published results using a telescope
- Discovered moons of Jupiter
- Discovered that Venus has phases

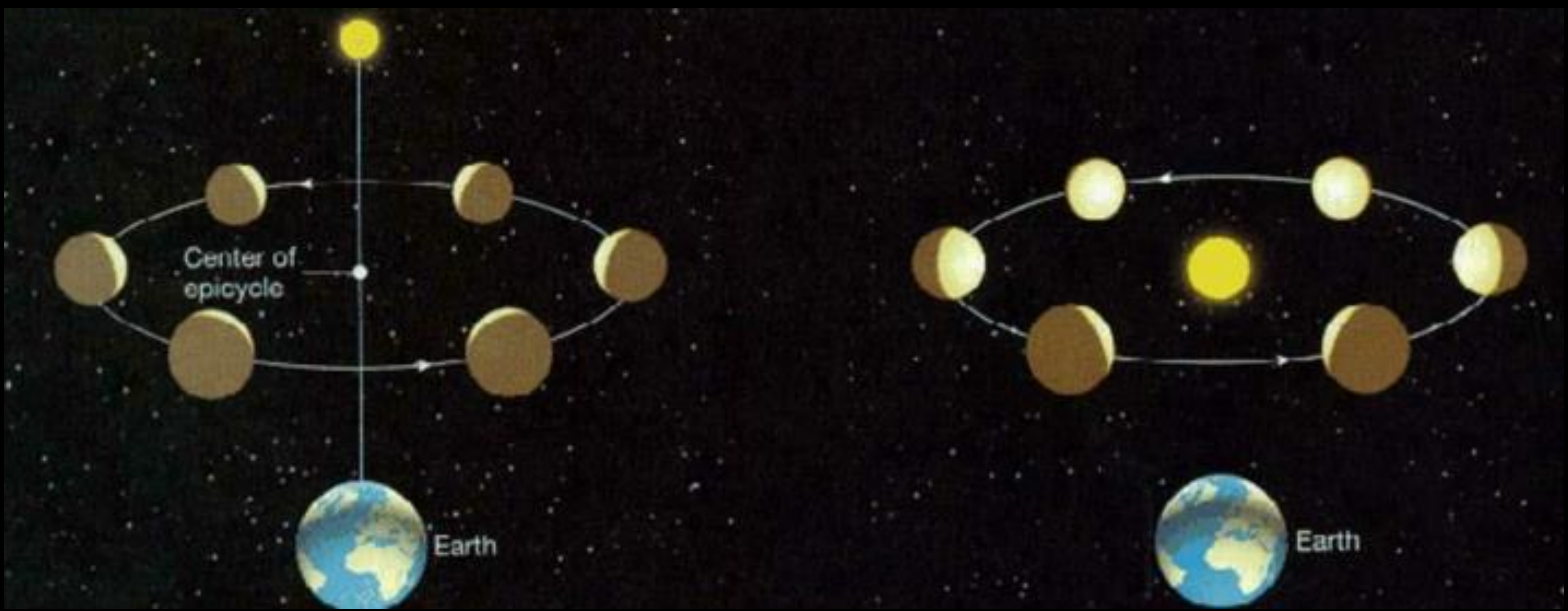
Galileo Observations of Venus



- Venus appears small at gibbous phase and large at crescent phase
  - Note: Ptolemaic model does not predict Gibbous nor Full phases
- d is diameter in units of arcsec
  - the farther an object is the smaller its angular size

Phases of Venus

- In the Ptolemaic system (left), Venus always lies between the Sun and the Earth and it would always show a crescent phase
- The Copernican system (right) predicts a full range of phases for Venus as it passes from between the Sun and the Earth to being on the opposite side of the Sun from the Earth



- Because of orbital mechanics, a planet with a superior orbit (one that orbits the Sun further away than Earth) will not go through phases, as we see it, because the planet won't cast a shadow from our perspective
- Earth will go through phases from the point of view of any planet that has an orbit superior to earth
- This extends to the relative position of any planet
- Somebody on Jupiter would see phases on Mars, but not on Saturn
- Somebody on Neptune could see phases on all seven of the other planets

- Mars is a partial exception to the superior orbit rule
- You will not see phases on Mars from Mars' shadow of sunlight, but Mars is close enough to Earth that Earth's shadow can cause some partial phasing

- This can make Mars appear irregular (or gibbous) because of Earth's interference with the light from the sun
- Planets further out into the solar system are too distant for Earth to interfere in this way

May 6, 2018

Galilean Moons of Jupiter

- Discovered that Jupiter has moons
- Confirmed orbits of moons obey Kepler's laws $(T^2 \propto R^3)$

What is the motion called when a planet seems to be moving westward in the sky?

A. retrogade

B. parallax

C. reverse parallax

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A. elipse

B. parabola

C. circle

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On what planet does a “year” last only 88 days?

A. Mars

B. Mercury

C. Jupiter

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In what year did Galileo first use an optical telescope to study the moon?

A. 250 BCE

B. 1611

C. 1945

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Galileo discovered something about Venus with his telescope that shook the old theories.

Which of the following was Galileo's discovery?

A. Venus surface is similar to Earth

B. Venus has phases like the moon

C. Venus has rings

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Heliocentric means around:

A. Sun

B. Earth

C. Moon

D. Jupiter

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The greatest distance of a planet from the sun is called what? Is it the planet's:

A. aphelion

B. perihelion

C. helix

D. eccentricity

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According to Kepler's Laws, the cube of the mean distance of a planet from the sun is proportional to the:

A. area that is swept out

B. cube of the period

C. square of the period

D. fourth power of the mean

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According to Kepler's Laws, all orbits of the planets are:

A. ellipses

B. parabolas

C. hyperbolas

D. squares

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With a telescope here on Earth, would we ever see Venus in a crescent phase?

A. Yes

B. No

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A. Yes

B. No

With a telescope here on Earth, would we ever see Jupiter in a crescent phase?

A. Yes

B. No

With a telescope here on Earth, would we ever see Jupiter in a crescent phase?

A. Yes

B. No

QUERY 3

(*i*) Mars is 1.5 AU away from the Sun. What is its orbital period?

(*ii*) Jupiter's mean orbital radius is 5.2 AU. What is the period of Jupiter's orbit around the Sun?

[AU is the abbreviation for astronomical units, where 1 AU = 1.5×10^{11} m is the mean Earth-Sun distance]

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Kepler's constant

Kepler's law ☛ $R^3 = KT^2$

Since Earth is at 1 AU and it takes 1 year to go around the Sun ☛ $K = \frac{\mathrm{AU}^3}{\mathrm{yr}^2}$

(i) Period of Mars is ☛ $T = \sqrt{R^3/K} = 1.84 \text{ yr}$

(ii) Period of Jupiter is ☛ $T = \sqrt{R^3/K} = 11.85 \text{ yr}$

QUERY 4

Earth has an orbital period of 365 days and its mean distance from the Sun is 1.495×10^{8} km. The Pluto's mean distance from the Sun is 5.896×10^{9} km. Using Kepler's third law, calculate Pluto's orbital period in Earth days

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What we know ☛ $T_E = 365$ days $\quad r_E = 1.495 \times 10^8$ km $\quad r_P = 5.896 \times 10^9$ km

$T_P = ?$

$$\left(\frac{T_E}{T_P}\right)^2 = \left(\frac{r_E}{r_P}\right)^3$$

$$\left(\frac{365\ days}{T_P}\right)^2 = \left(\frac{1.495x10^8\ km}{5.896x10^9\ km}\right)^3$$

$$\left(\frac{365\ days}{T_P}\right)^2 = (2.54x10^{-2})^3$$

$$\left(\frac{1.32x10^5\ days^2}{{T_P}^2}\right) = 1.63x10^{-5}$$

$$T_P = \sqrt{\frac{1.32x10^5\ days^2}{1.63x10^{-5}}}$$

$$\boxed{T_P = 9.00 \times 10^4 \text{ days}}$$