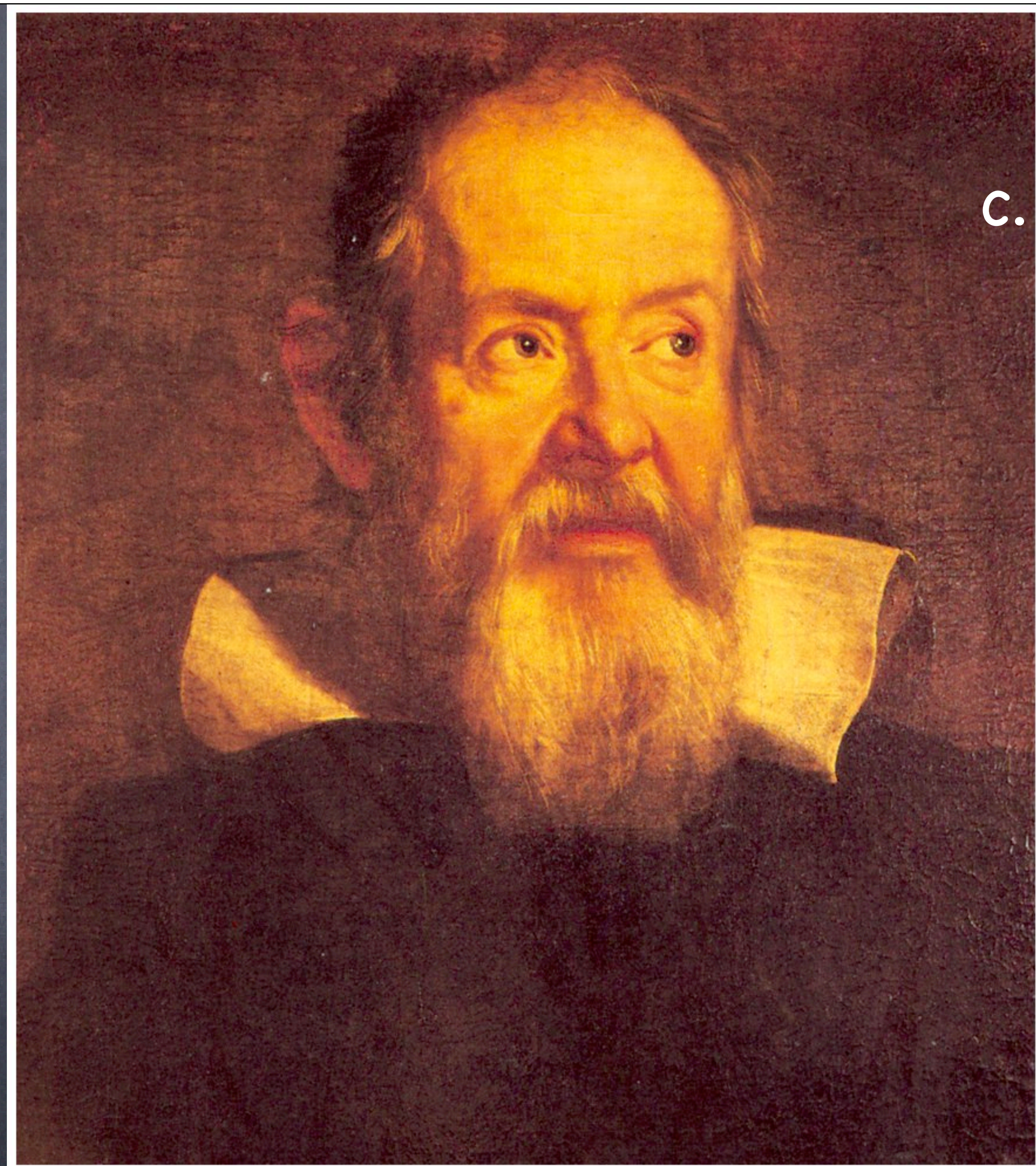
Today

- Galileo
- Planetary Motion
  - Tycho Brahe's Observations
  - Kepler's Laws

Galileo

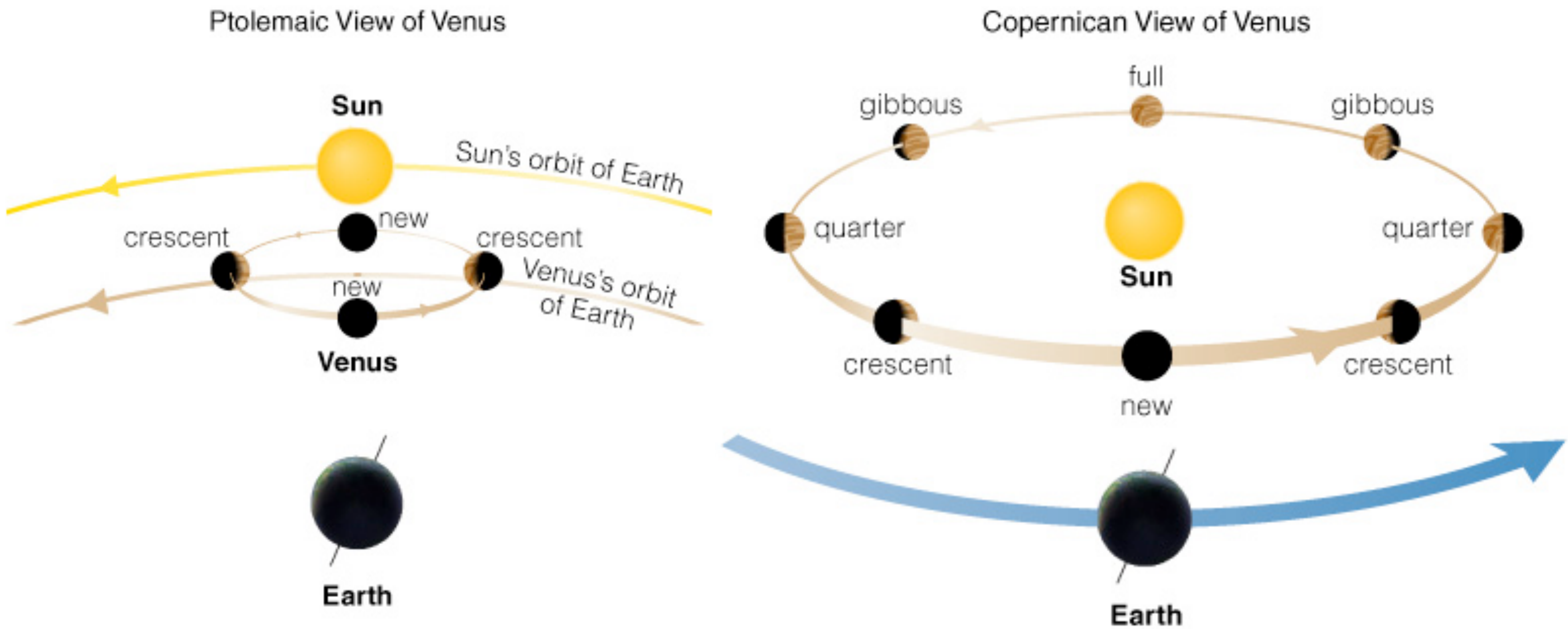
c. 1564-1642



First telescopic astronomical observations

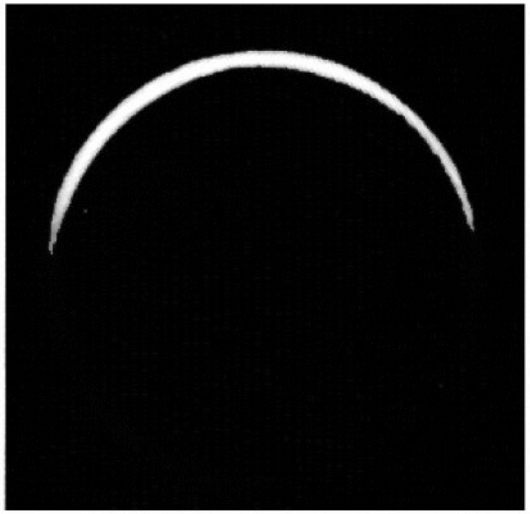
- First use of telescope for astronomy in 1609
- 400 years ago!

THE UNIVERSE
YOURS TO DISCOVER
INTERNATIONAL YEAR OF
ASTRONOMY
2009

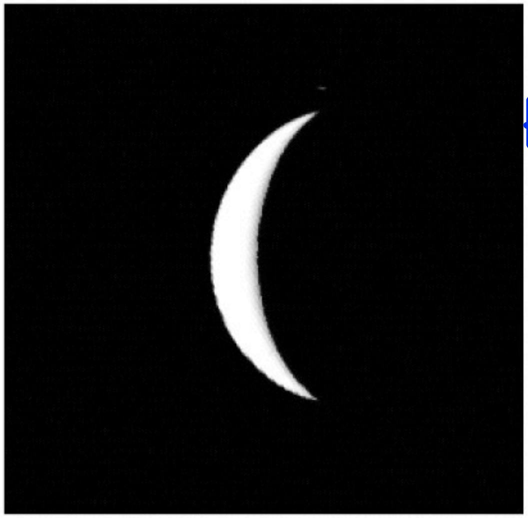


Galileo's observations of phases of Venus proved that it orbits the Sun and not Earth.

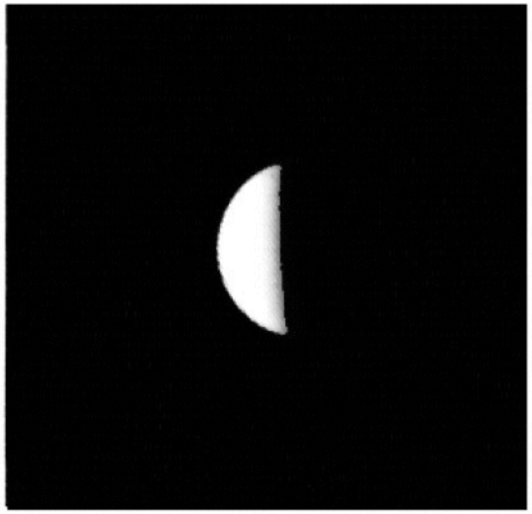
Phase and angular size of Venus depend on elongation



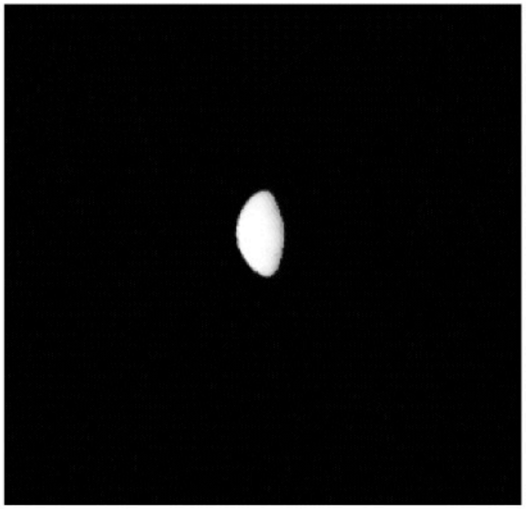
$\alpha = 58^\circ$



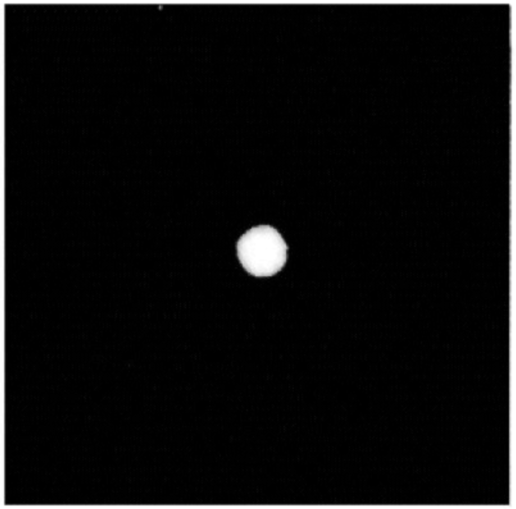
$\alpha = 42^\circ$



$\alpha = 24^\circ$



$\alpha = 15^\circ$



$\alpha = 10^\circ$

Competing Cosmologies

Geocentric	**Heliocentric**
Ptolemaic	Copernican
Earth at center	Sun at center

The sun is the source of light in both models

Explains

- **Motion of Sun**
- **Motion of Moon**
- **Solar and Lunar Eclipses**
- **Phases of Moon**

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Retrograde Motion

Geocentric	Heliocentric
Needs epicycles	Consequence of Lapping **nicer**

Inferiority of Mercury & Venus

Geocentric	Heliocentric
Must tie to sun	Interior to Earth's Orbit **nicer**

Predicts

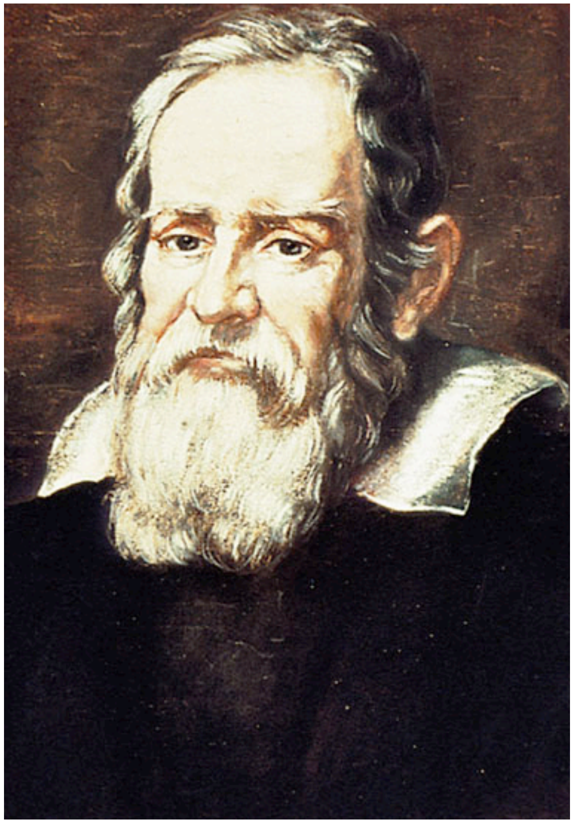
- No parallax ✓
- Venus: crescent phase only X

- Parallax X
- Venus: all phases ✓

Heliocentric Cosmology

- Provides better explanation for
  - Retrograde motion
  - proximity of Mercury and Venus to the Sun
- Provides only explanation for
  - Phases of Venus
  - Angular size variation of Venus
- What about parallax?

How did Galileo solidify the Copernican revolution?



Galileo (1564–1642) overcame major objections to the Copernican view. Three key objections rooted in the Aristotelian view were:

1. Earth could not be moving because objects in air would be left behind.
2. Noncircular orbits are not "perfect" as heavens should be.
3. If Earth were really orbiting Sun, we'd detect stellar parallax.

Overcoming the first objection (nature of motion):

Galileo’s experiments showed that objects in air would stay with a moving Earth.

- Aristotle thought that all objects naturally come to rest.
- Galileo showed that objects will stay in motion unless a force acts to slow them down (law of inertia).

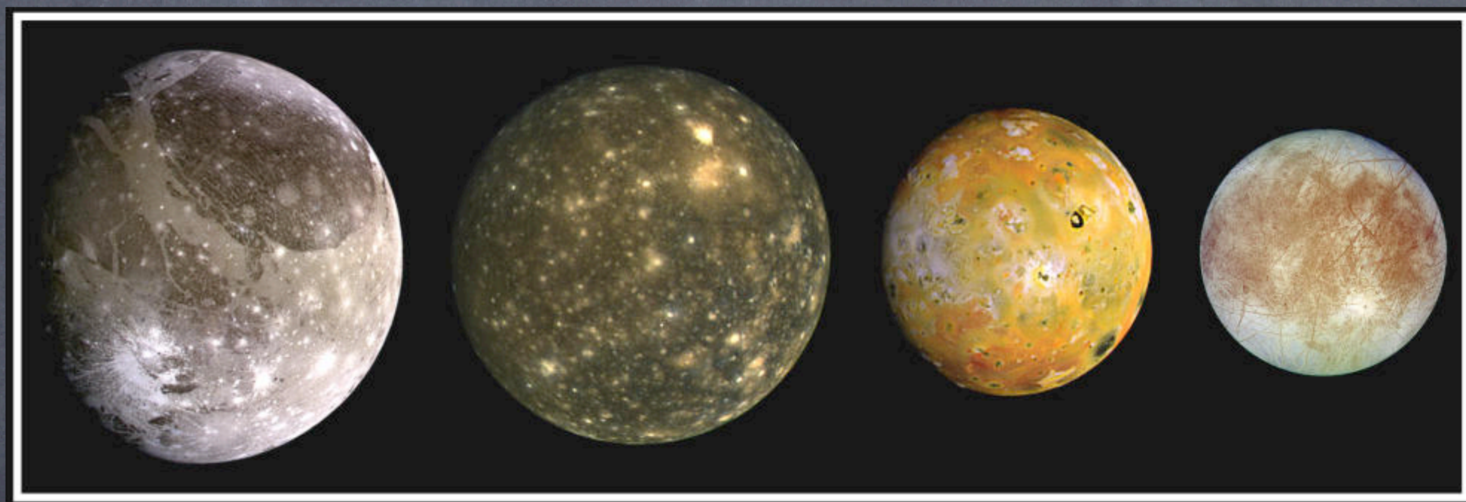
Galileo's telescopic discoveries

- Stars in the Milky Way
- Mountains on the Moon
- Sun spots (celestial spheres NOT perfect)
- Rings of Saturn (barely resolved)
- Moons of Jupiter ("Medicean stars")
  - Earth NOT center of all revolution
- Phases of Venus
  - Good test of geocentric hypothesis

Jupiter and moons

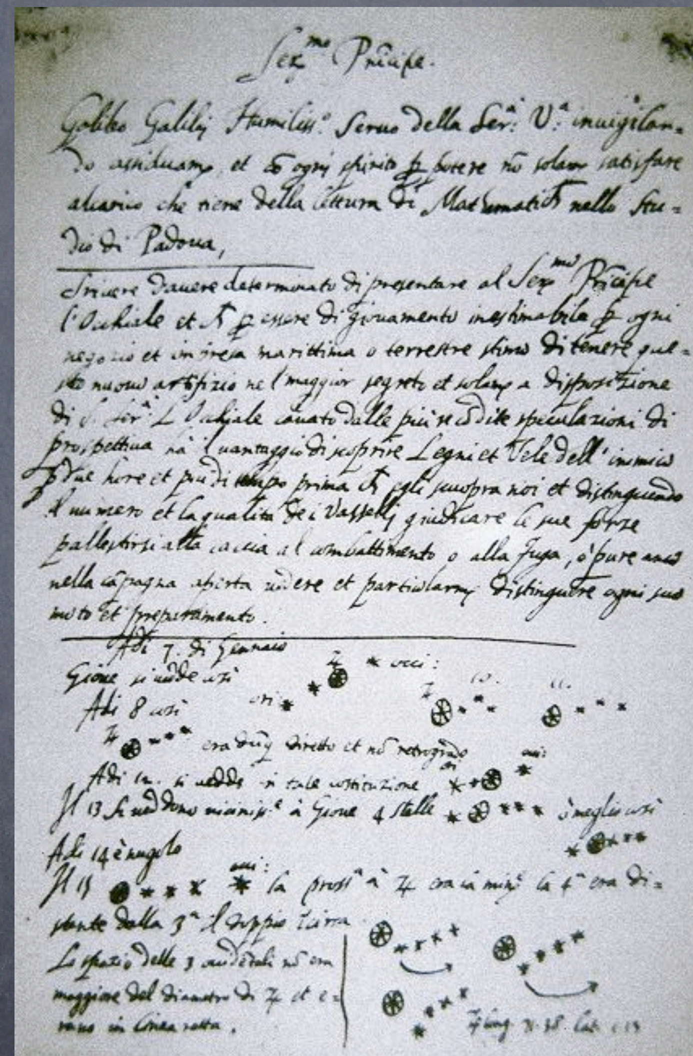
Fig. 4.16

Galilean moons (from Galileo spacecraft!)



NASA

Letter from Galileo to Prince of Venice reporting the discovery of Jupiter's moons…



Ser.mo Principe.

Galileo Galilei Humiliss.o Servo della Ser.tà V.a invigilan-do assiduam.te et con ogni spirito per potere non solam.te satisfare al carico che tiene della lettura di Matematica nello Stu-dio di Padova,

Invero havere determinato di presentare al Ser.mo Principe l'Occhiale et per essere di giovamento inestimabile per ogni negotio et impresa marittima o terrestre stima di tenere questo nuovo artifitio nel maggior segreto et solam.te a dispositione di S. Ser.tà L'Occhiale cavato dalle più recondite speculazioni di prospettiva ha il vantaggio di scoprire Legni et Vele dell'inimico due hore et più di tempo prima che egli scuopra noi et distinguendo il numero et la qualità dei Vasselli giudicare le sue forze allestirsi alla caccia al combattimento o alla fuga, o pure ancora nella campagna aperta vedere et particolarm.te distinguere ogni suo moto et preparamento.

Adi 7. di Gennaio Giove si vedeva così

Adi 8 così

Adi 12. si vedde in tale costituzione

Adi 13 si veddono vicinissime a Giove 4 stelle o meglio così

Adi 14 è nugolo

Adi 15 la prossima a ♃ era la minore la 4a era distante dalla 3a il doppio in circa

Lo spatio delle 3 occidentali non era maggiore del diametro di ♃ et erano in linea retta.

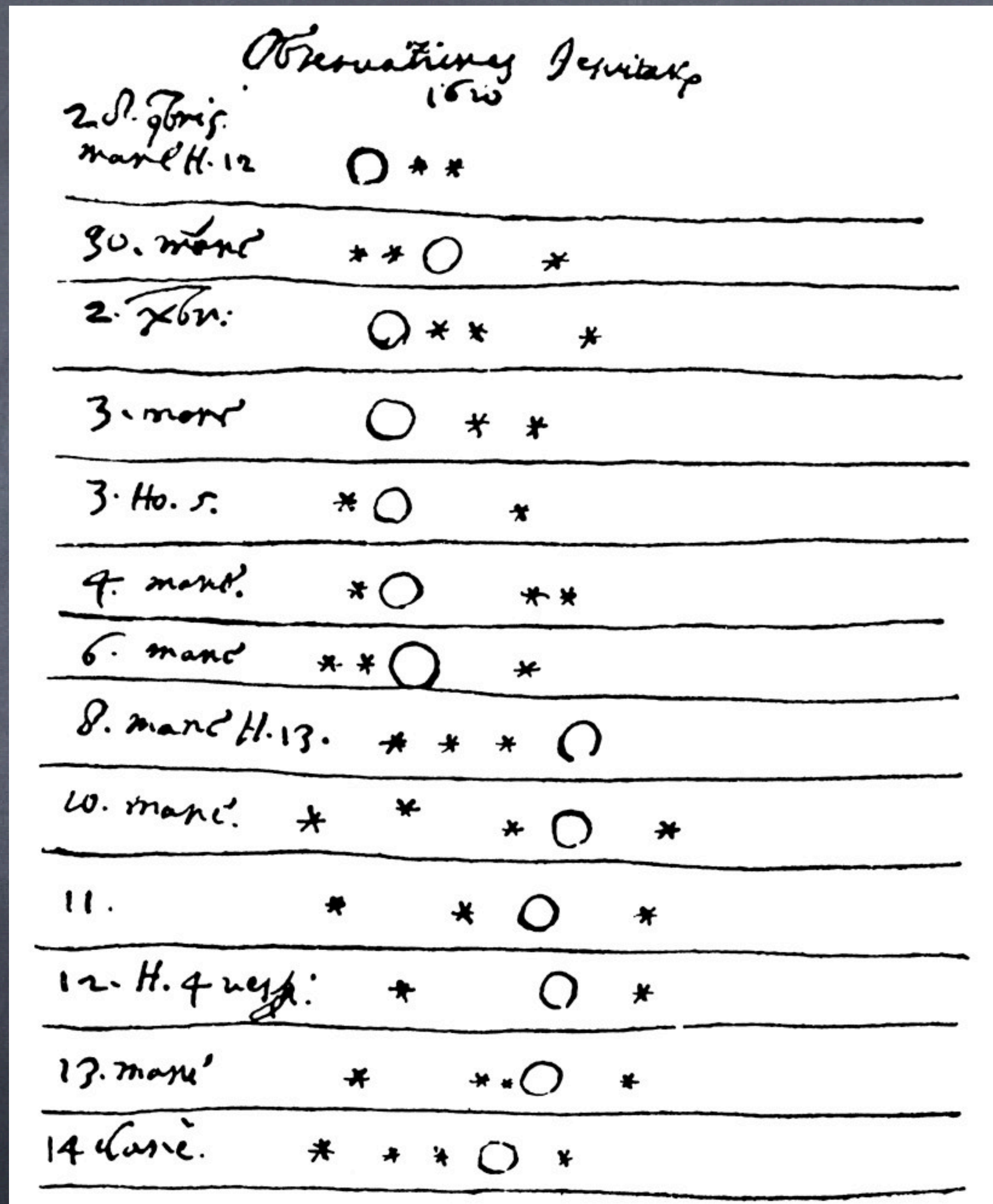


Fig. 4.17

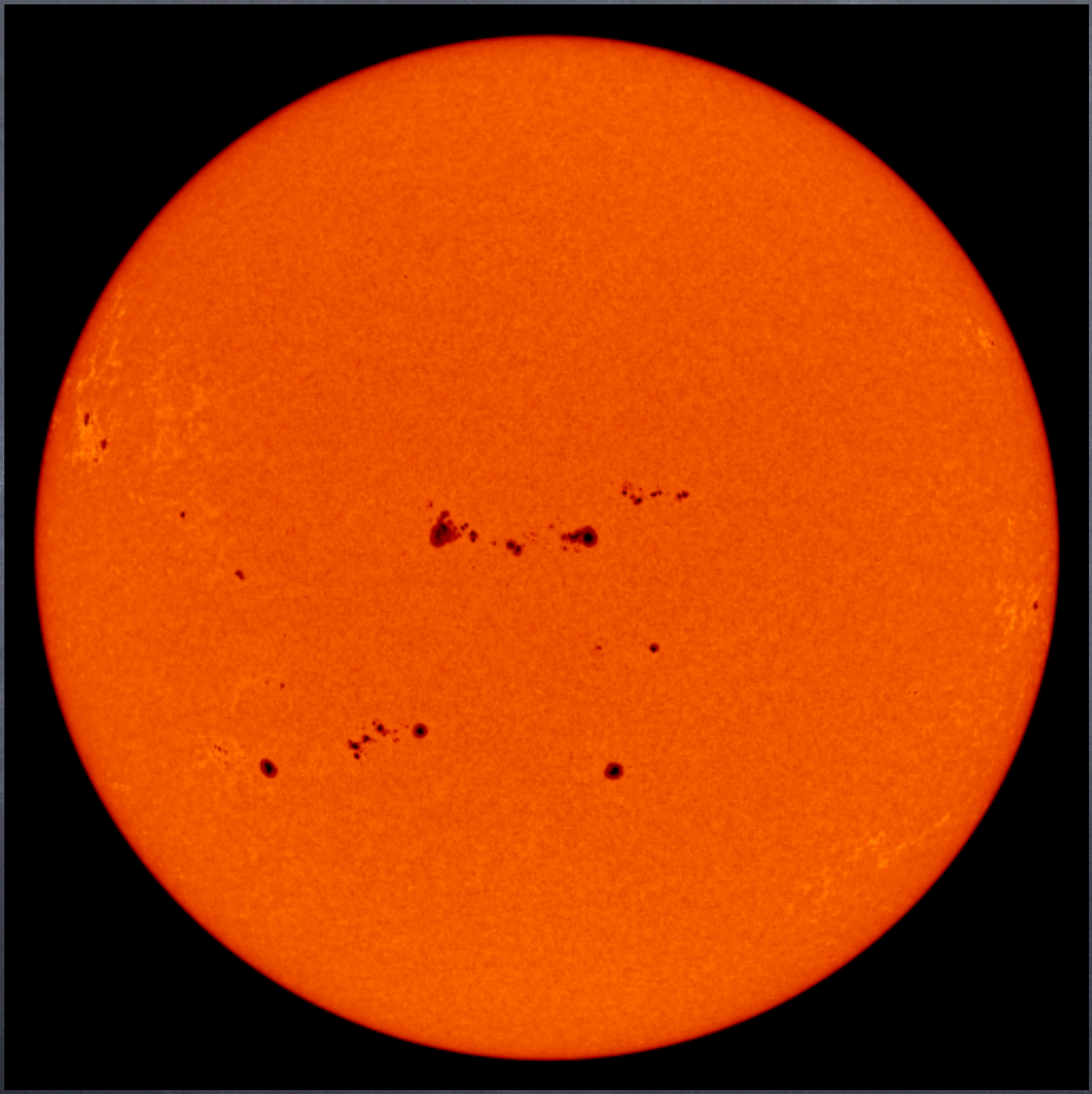
“Medician stars”

Overcoming the second objection (heavenly perfection):

- Tycho's observations of comet and supernova already challenged this idea.
- Using his telescope, Galileo saw:
  - — Sunspots on Sun ("imperfections")
  - — Mountains and valleys on the Moon (proving it is not a perfect sphere)

Heavenly spheres NOT perfect

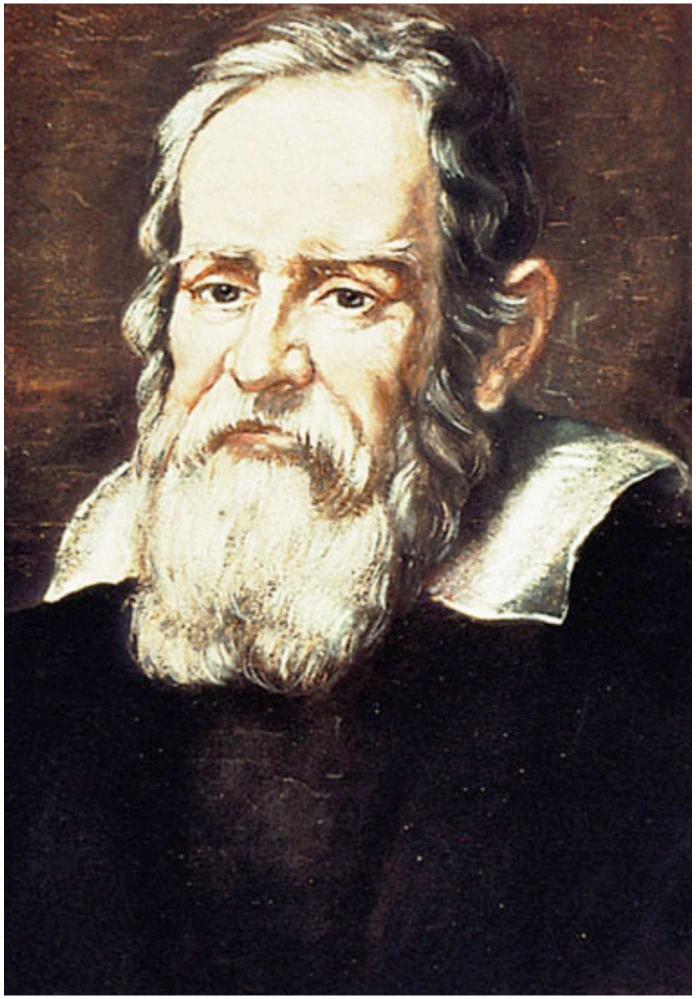
Even the sun has spots!



Overcoming the third objection (parallax):

- Tycho *thought* he had measured stellar distances, so lack of parallax seemed to rule out an orbiting Earth.
- Galileo showed stars must be much farther than Tycho thought—in part by using his telescope to see that the Milky Way is countless individual stars.

✓ If stars were much farther away, then lack of detectable parallax was no longer so troubling.



Galileo Galilei

In 1633 the Catholic Church ordered Galileo to recant his claim that Earth orbits the Sun.

His book on the subject was removed from the Church's index of banned books in 1824.

Galileo was formally vindicated by the Church in 1992.

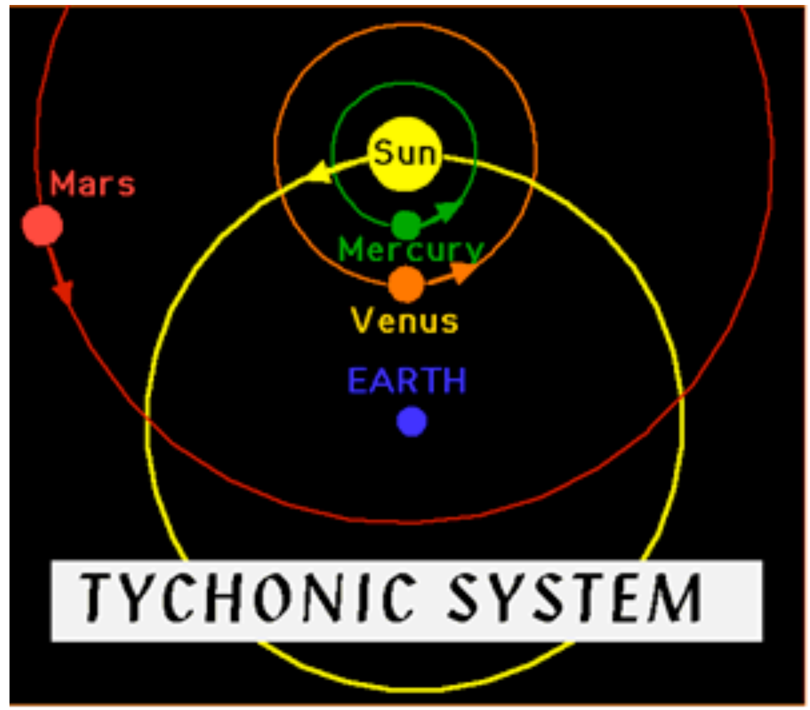
Tycho Brahe

the last great naked-eye observer

1546-1601

Tycho Brahe

- Brahe compiled the most accurate (one arcminute) naked eye measurements ever made of planetary positions.
- He still could not detect stellar parallax, and thus still thought Earth must be at the center of the solar system (but recognized that other planets go around Sun).



publishing as Addison Wesley.

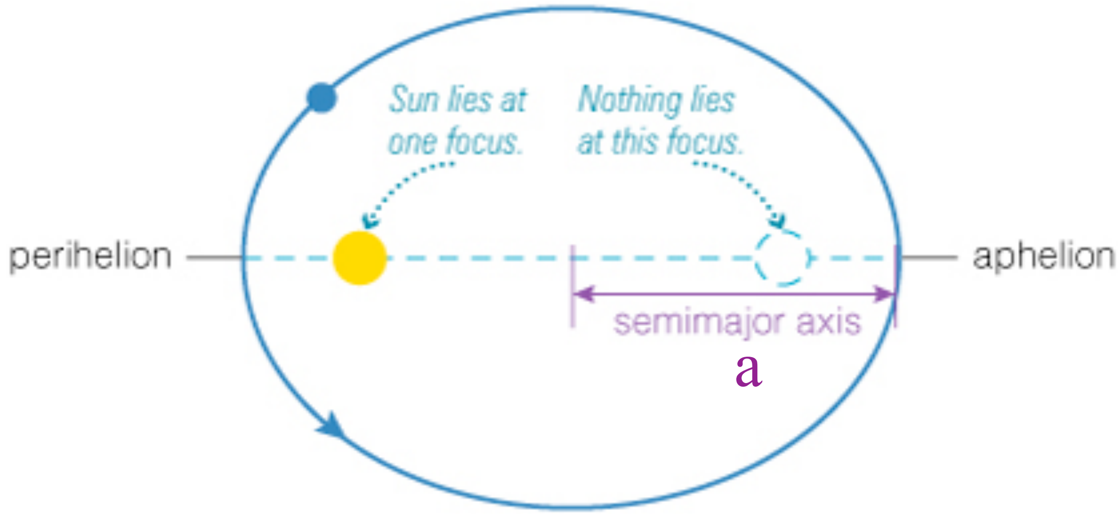
Johannes Kepler
(1571–1630)

- Kepler analyzed Brahe’s data
- Kepler first tried to match Tycho’s observations with circular orbits.
- But an 8-arcminute discrepancy led him eventually to ellipses.

“If I had believed that we could ignore these eight minutes [of arc], I would have patched up my hypothesis accordingly. But, since it was not permissible to ignore, those eight minutes pointed the road to a complete reformation in astronomy.”

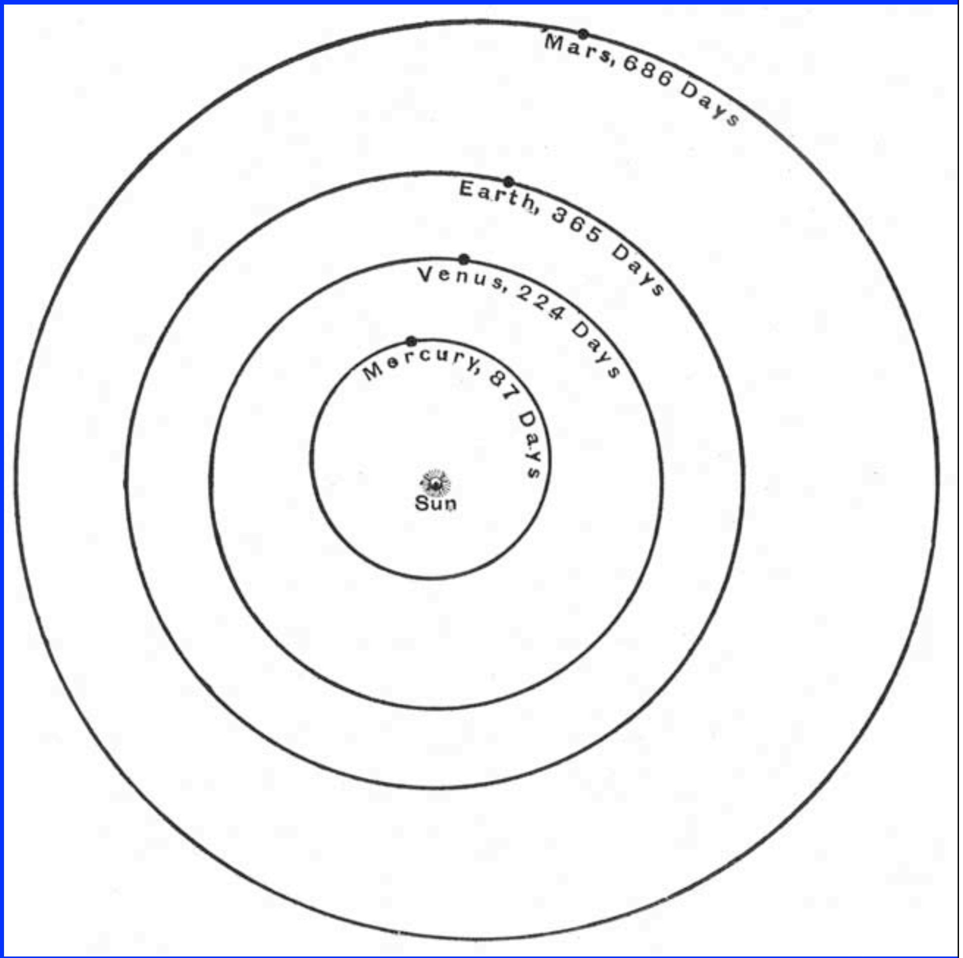
Kepler's Laws of planetary motion

Kepler's First Law: The orbit of each planet around the Sun is an ***ellipse*** with the Sun at one focus.



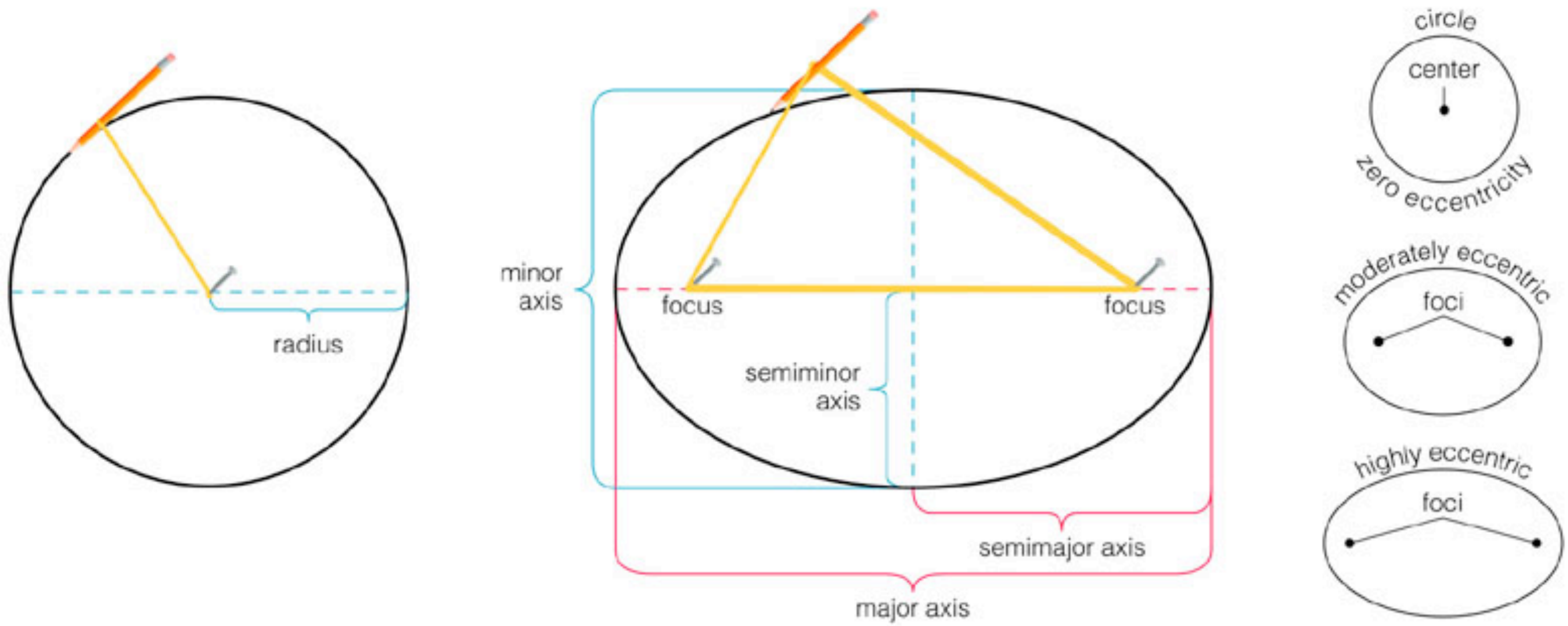
Not very elliptical!

- As in the previous slide, orbits are often shown as very elliptical so that you get the idea
- But in reality, the orbits of the planets are quite close to circular!
- Can you tell that the orbits at the right are not circles?



http://www.gutenberg.org/files/28853/28853-h/images/i-078.jpg

An ellipse is the shape that is equidistant from two **foci**. The **eccentricity** of an ellipse depends on the ratio of the long and short axes. Half of the long axis is the **semimajor axis**, **a**.



An ellipse looks like an elongated circle. Indeed, a circle is a special case of an ellipse where the two foci overlap.

Objections to Kepler

Which of the following might have been an objection to Kepler's first law?

A. What's at the other focus?

B. The law doesn't fit observations

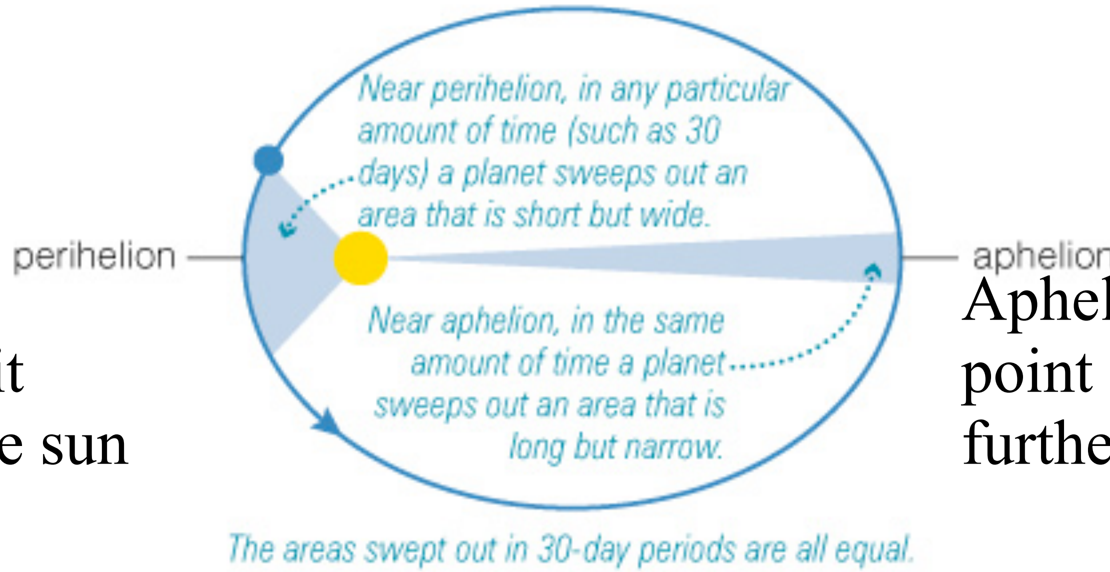
C. Ptolemy rules, Kepler drools!

D. The law of gravity predicts circles

E. I don't know

Kepler's Second Law: As a planet moves around its orbit, it sweeps out equal areas in equal times.

Perihelion:
point in orbit
closest to the sun



Aphelion:
point in orbit
furthest from the sun

This means that a planet travels faster when it is nearer to the Sun and slower when it is farther from the Sun.

Kepler's Third Law

More distant planets orbit the Sun at slower average speeds, obeying the relationship

$$P^2 = a^3$$

P = orbital period in years
a = distance from Sun in AU
(semi-major axis of orbit's ellipse)

Earth: **P** = 1 year, **a** = 1 AU

Kepler's Third Law

- A simple example: Imagine an asteroid orbiting the Sun with a semimajor axis of 4 AU

$$P^2=a^3$$
$$P^2=4^3$$
$$P^2=64$$
$$P=64^{1/2}$$
$$P=8 \text{ yr}$$

Kepler's Third Law

- What about the other way around? Suppose that we see an object orbiting the Sun with a period of 1/8 yr

$$P^2=a^3$$

$$(1/8)^2=a^3$$

$$1/64=a^3$$

$$a=(1/64)^{1/3}$$

$$a=(1/4)\ \mathrm{AU}$$

Kepler's Third Law

- Now your turn: Mercury orbits the Sun with a period $P = 0.24$ year. What is its semimajor axis in AU?

Kepler's Third Law

- Mercury: P = 0.24 year

$$P^2 = a^3$$

$$a = P^{2/3}$$

$$a = (0.24)^{2/3}$$

$$a = 0.39 \text{ AU}$$

Kepler's Third Law

- Another example: Jupiter orbits the Sun with a semimajor axis a = 5.2 AU. What is its orbital period in years?

Kepler's Third Law

- A worked example: Jupiter: a = 5.2 AU

$$P^2 = a^3$$

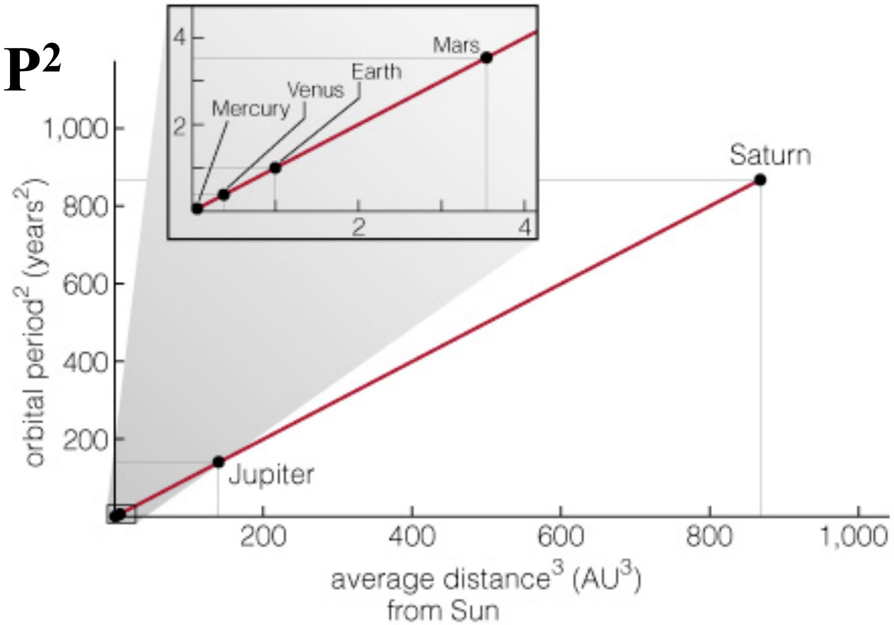
$$P = a^{3/2}$$

$$P = \sqrt{(5.2)^3}$$

$$P = 11.9 \text{ years}$$

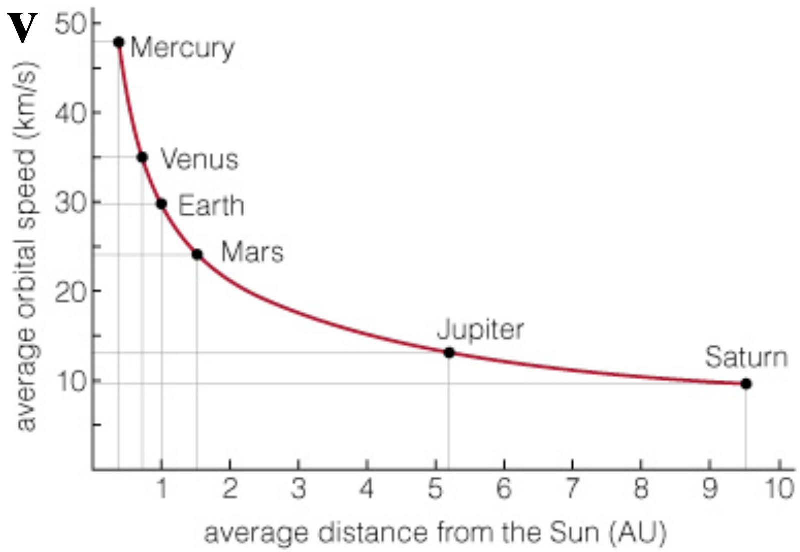
Graphical version of Kepler’s Third Law

P^2



a^3

v



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- Kepler's Laws:
    1. The orbit of each planet is an ellipse with the Sun at one focus.
    2. As a planet moves around its orbit it sweeps out equal areas in equal times.
    3. More distant planets orbit the Sun at slower average speeds: $p^2 = a^3$.