Observational Astronomy - Lecture 4
Orbits, Motions, Kepler's and Newton's Laws

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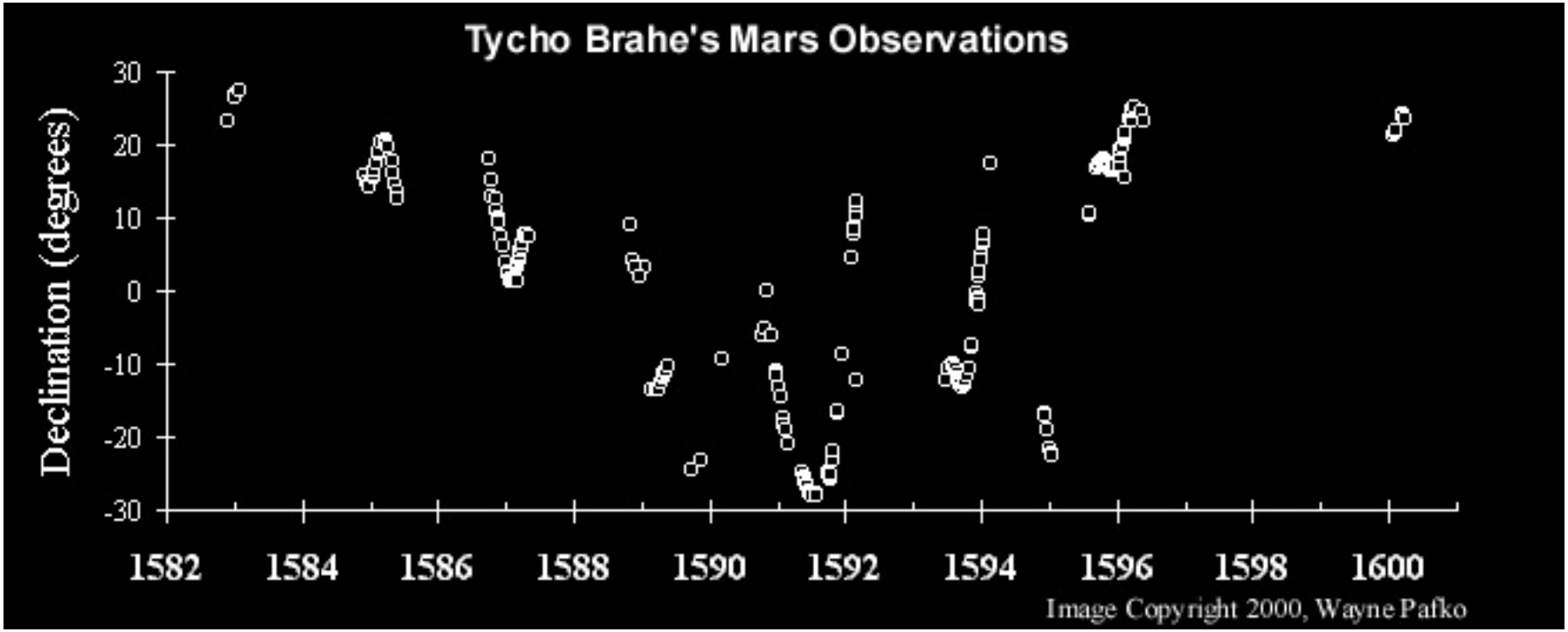
Tycho Brahe's Equatorial Armillary

Tycho Brahe ca. 1580

Tycho's Armillary: ≈3 m across.

"I've studied all available charts of the planets and stars and none of them match the others. There are just as many measurements and methods as there are astronomers and all of them disagree. What's needed is a long term project with the aim of mapping the heavens conducted from a single location over a period of several years." -Tycho Brahe, 1563 (age 17).

Tycho's Observations of Mars



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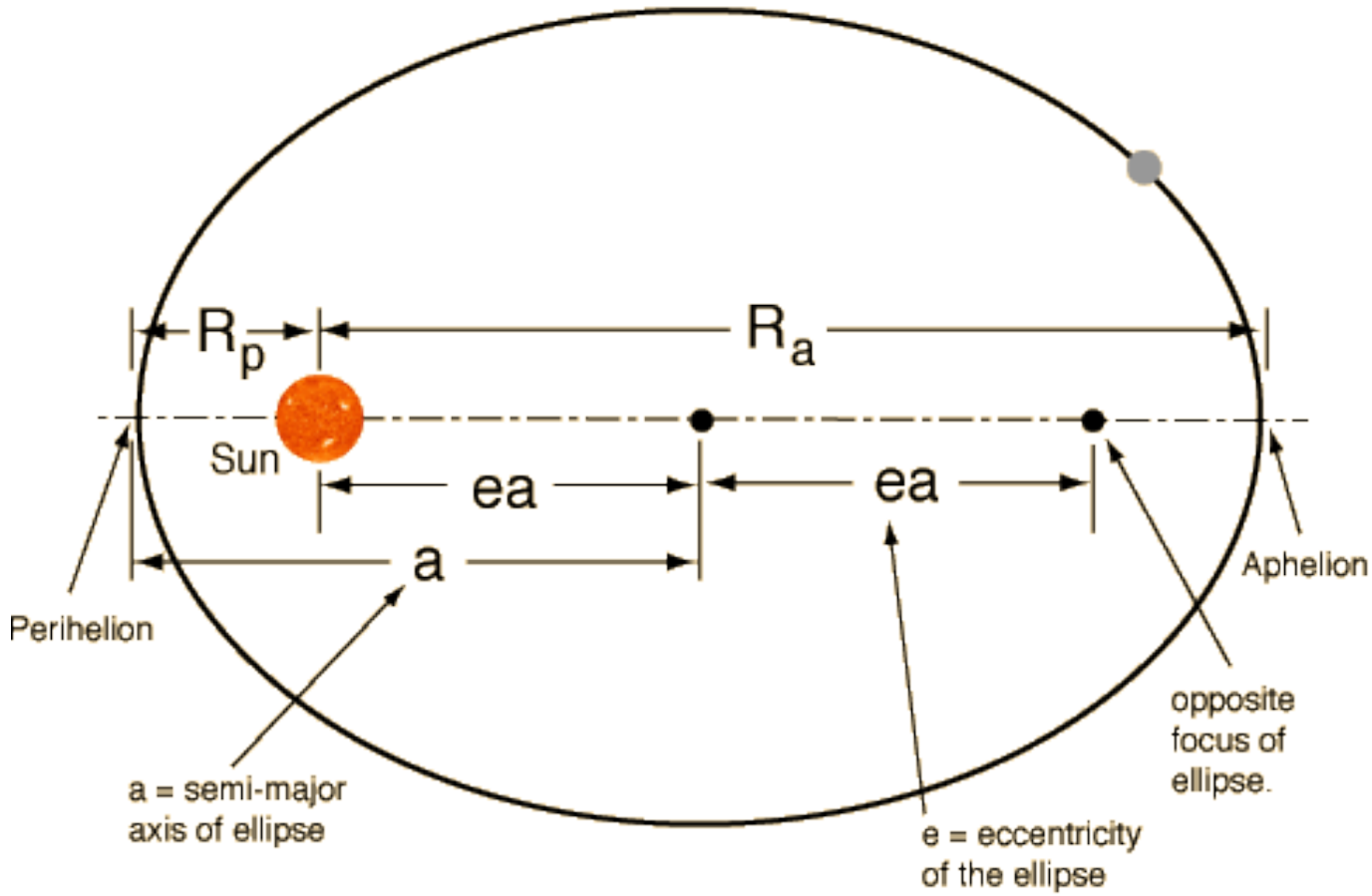
Tycho made measurements of unprecedented accuracy $\approx 2'$. The human eye has a resolving power of $\approx 1'$, so since this was done before telescopes, he could not have done much better.

Kepler's Laws of Planetary Motion

Johannes Kepler ca. 1610

1. The orbit of every planet is an ellipse with the Sun at one of the two foci.
2. A line joining a planet and the Sun sweeps out equal areas during equal intervals of time.
3. The square of the orbital period of a planet is proportional to the cube of the semi-major axis of its orbit.

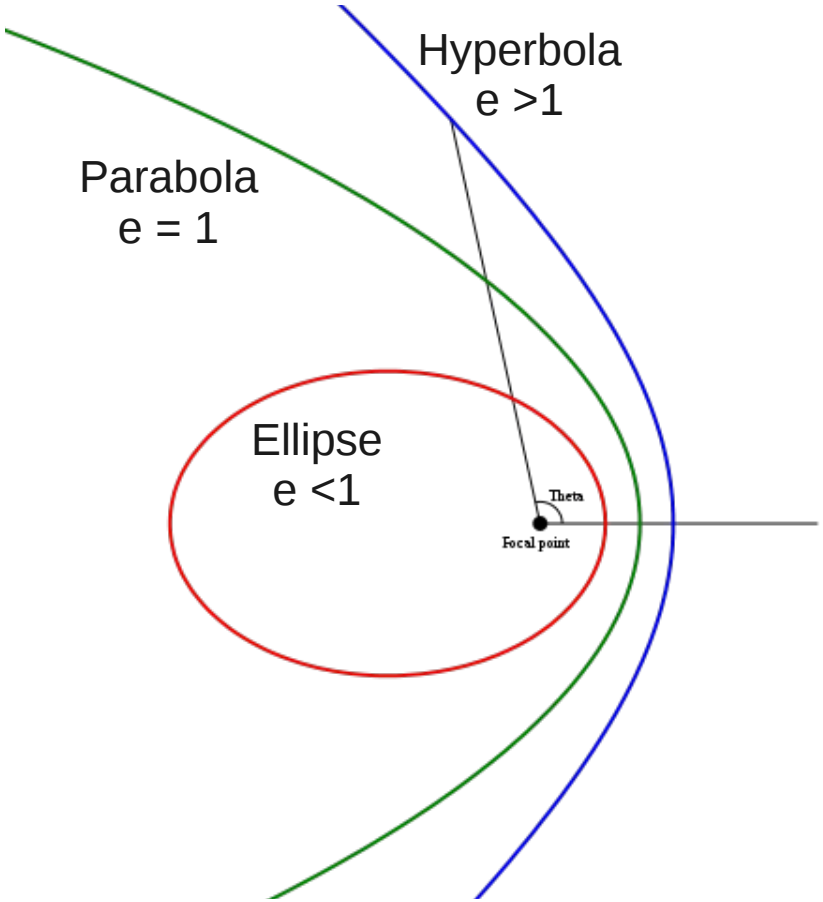
Kepler's First Law - Elliptical Orbits

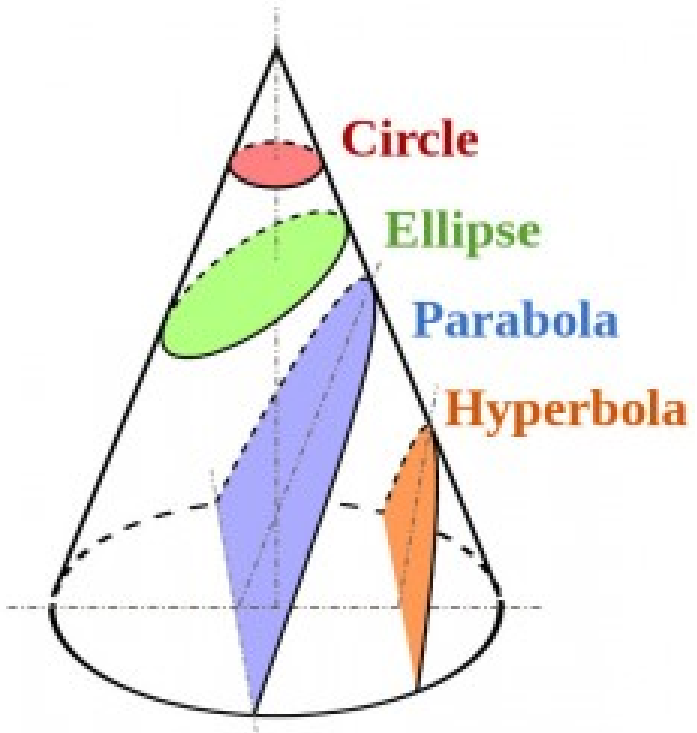


$R_a = a(1+e)$ $R_p = a(1- e)$

Circle: e = 0. As e gets larger the orbit gets more elliptical.

Shapes of Orbits





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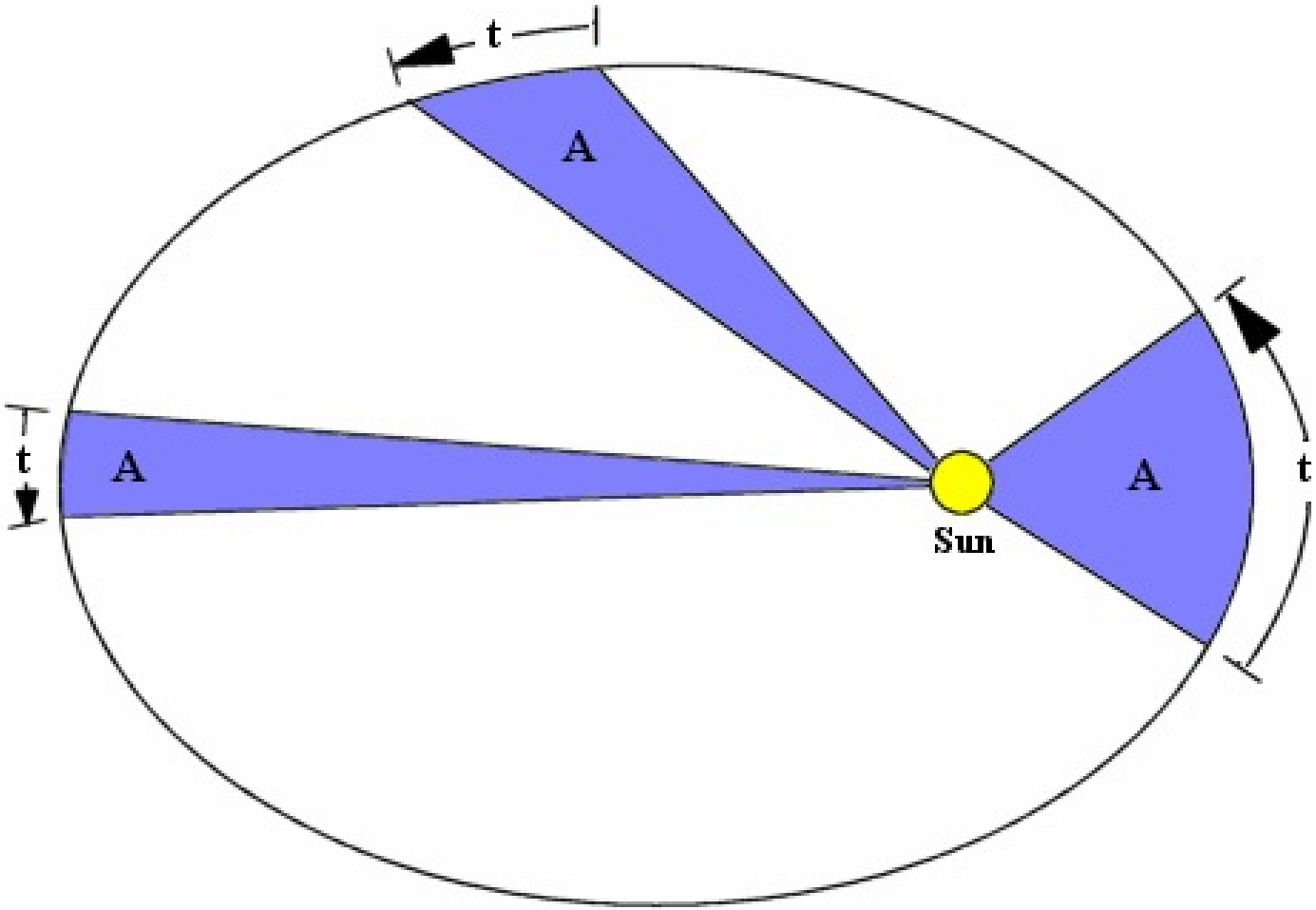
Orbit shapes are always conic sections

Kepler's Second Law



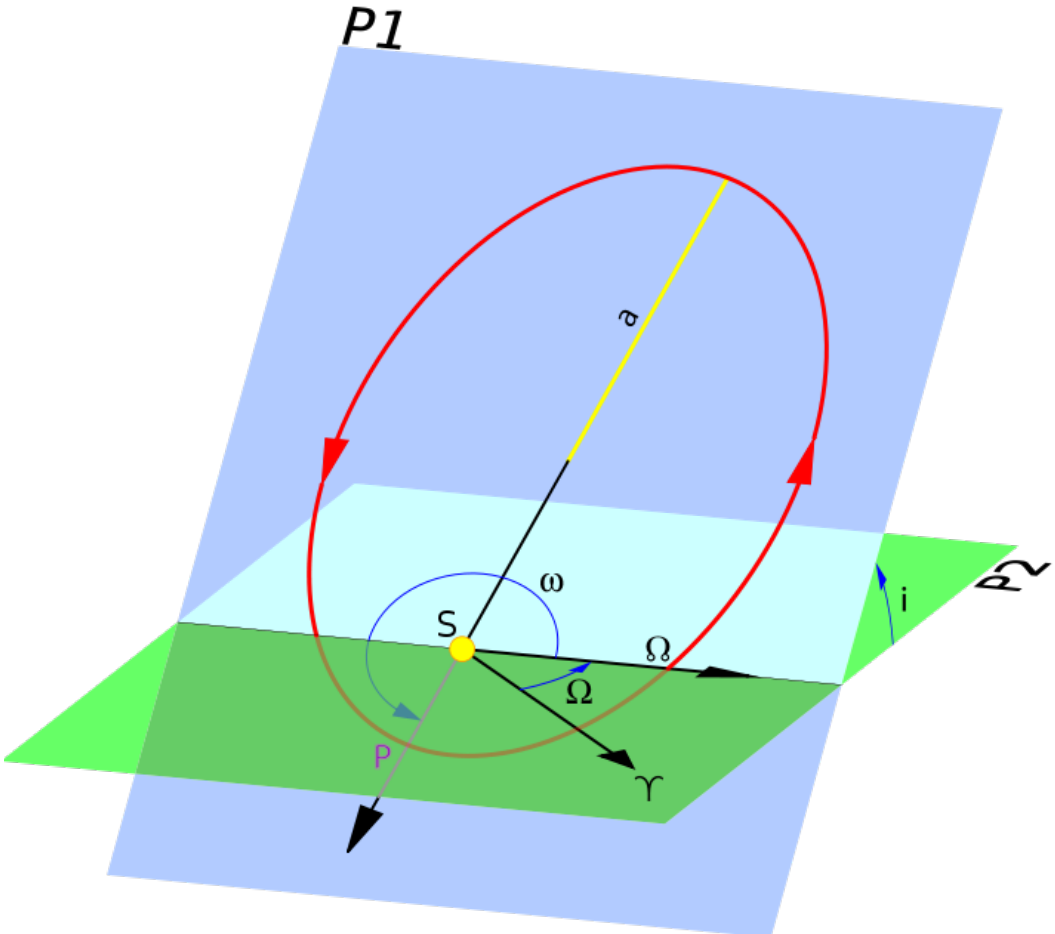
The planet goes faster when it is closest to the sun.

Kepler's Third Law in our Solar System

Planet	a(AU)	T(Yr)	a^3/T^2
Mercury	0.387	0.241	0.998
Venus	0.723	0.615	0.999
Earth	1.000	1.000	1.000
Mars	1.523	1.881	0.998
Ceres	2.767	4.600	1.001
Jupiter	5.204	11.862	1.002
Saturn	9.582	29.457	1.014

- An astronomical unit (AU) is defined to be equal to the semi-major axis (a) of the Earth's orbit. It is about 1.5×10^8 km, or about 150 million km.
- Kepler's third law, $\mathrm{a}^3 \propto \mathrm{T}^2$, works extremely well!

An Orbit is described by 6 Orbital Elements



- a: Semimajor Axis
- e: Eccentricity
- i: inclination
- ω: Argument of the perihelion
- Ω: Longitude of the ascending node
- M_0: True anomaly

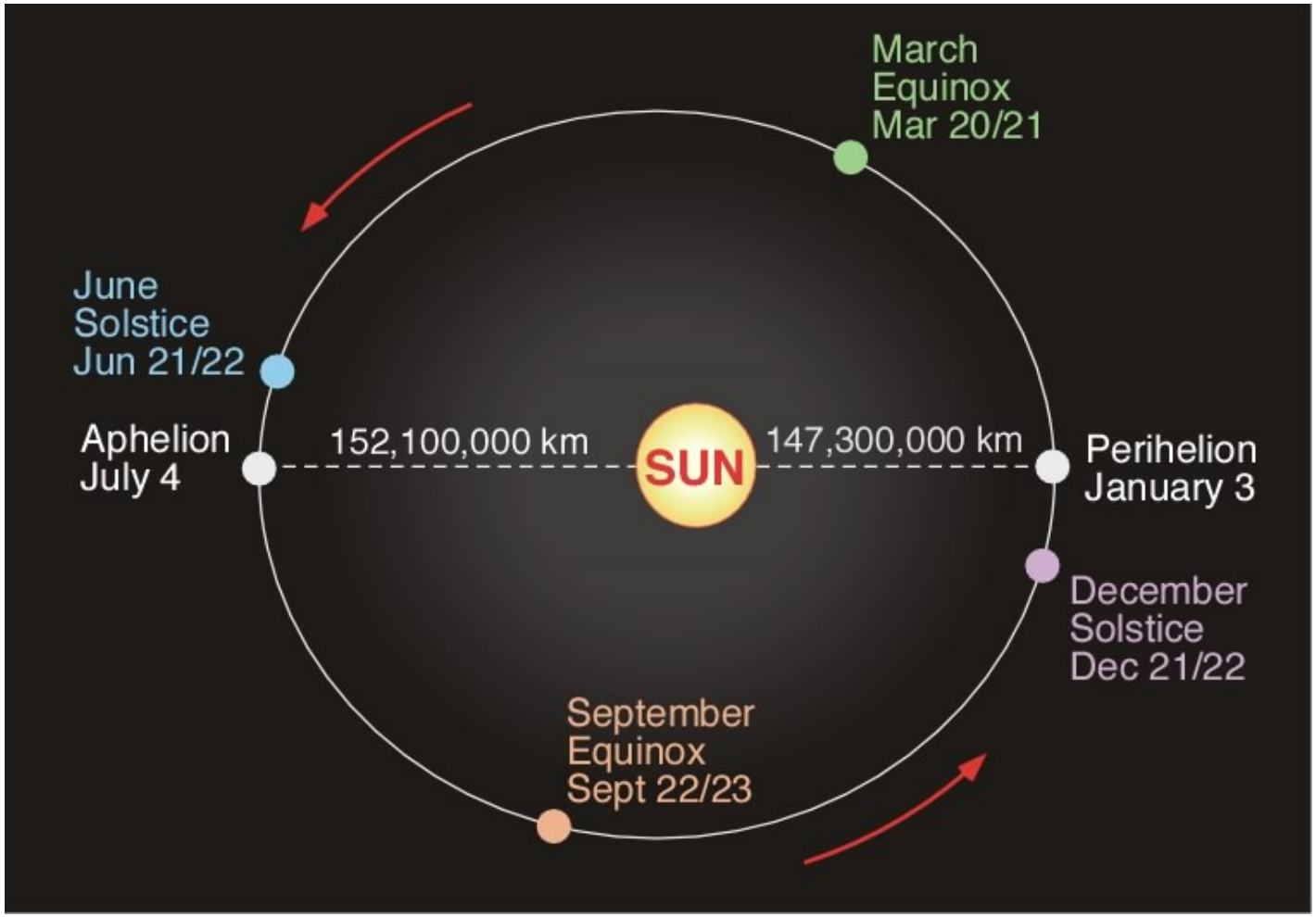
Size: a; Shape:e; Orientation: $\mathrm{i}, \omega, \Omega$;
Planet Location in the Orbit:M_0

Elements of our Planetary Orbits

	a(AU)	e	I (degrees)	Ω (Degrees)	ω (Degrees)	M (Degrees) (1/1/2000)
Mercury	0.387	0.206	7.005	48.331	125.789	174.793
Venus	0.723	0.007	3.395	76.680	208.282	50.377
Earth/Moon	1.000	0.017	0.000	0.000	102.938	-2.473
Mars	1.524	0.093	1.850	49.560	25.616	19.390
Jupiter	5.203	0.048	1.304	100.474	115.202	19.668
Saturn	9.537	0.054	2.486	113.662	206.261	-42.645
Uranus	19.189	0.047	0.773	74.017	244.971	142.284
Neptune	30.070	0.009	1.770	131.784	176.749	-100.085
Pluto	39.482	0.249	17.140	110.304	334.373	14.860
	Size	Shape	Orientation			Position in orbit

- With this table of numbers we can predict the positions of the planets far into the future or past.

Earth's orbit



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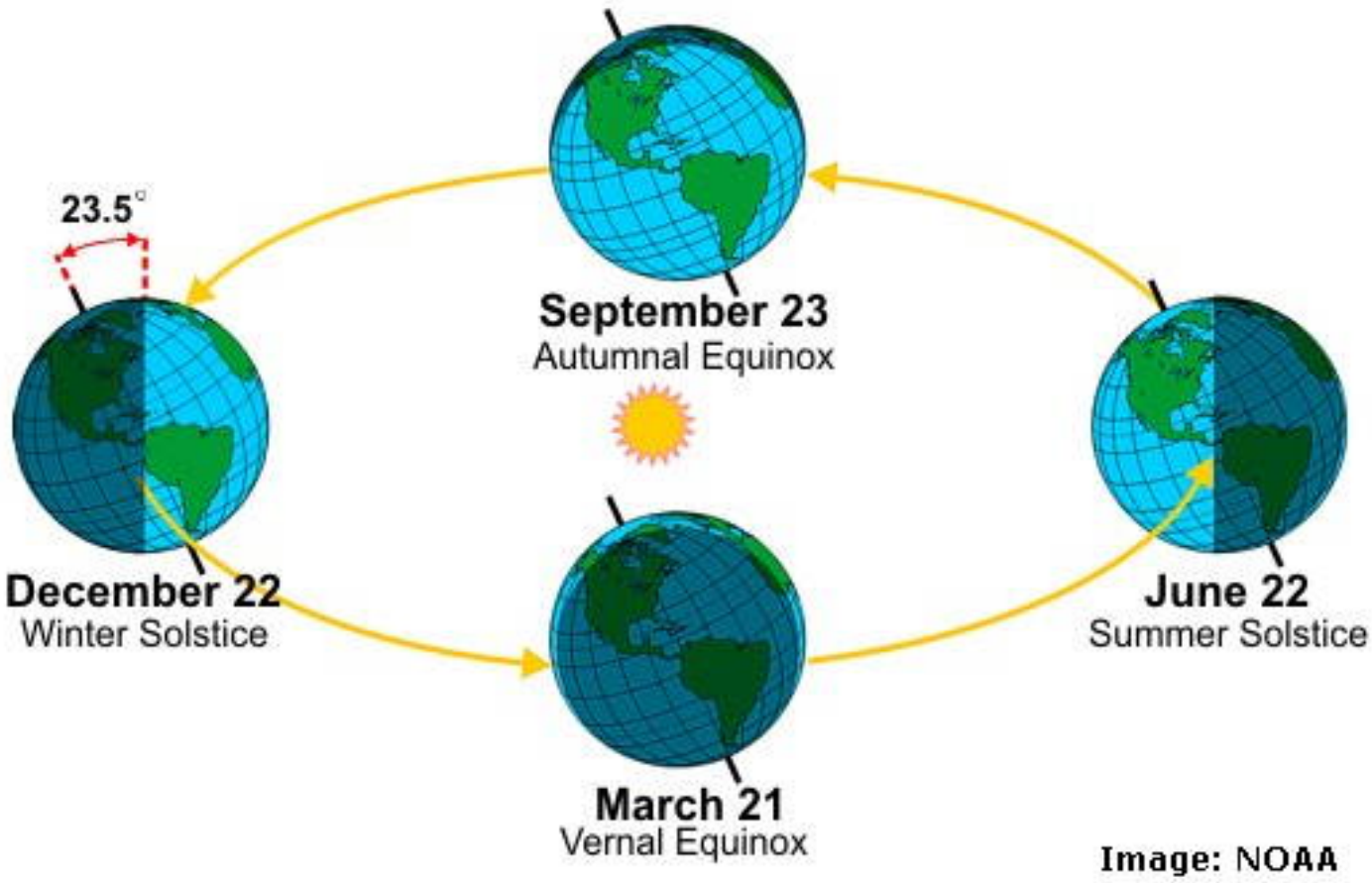
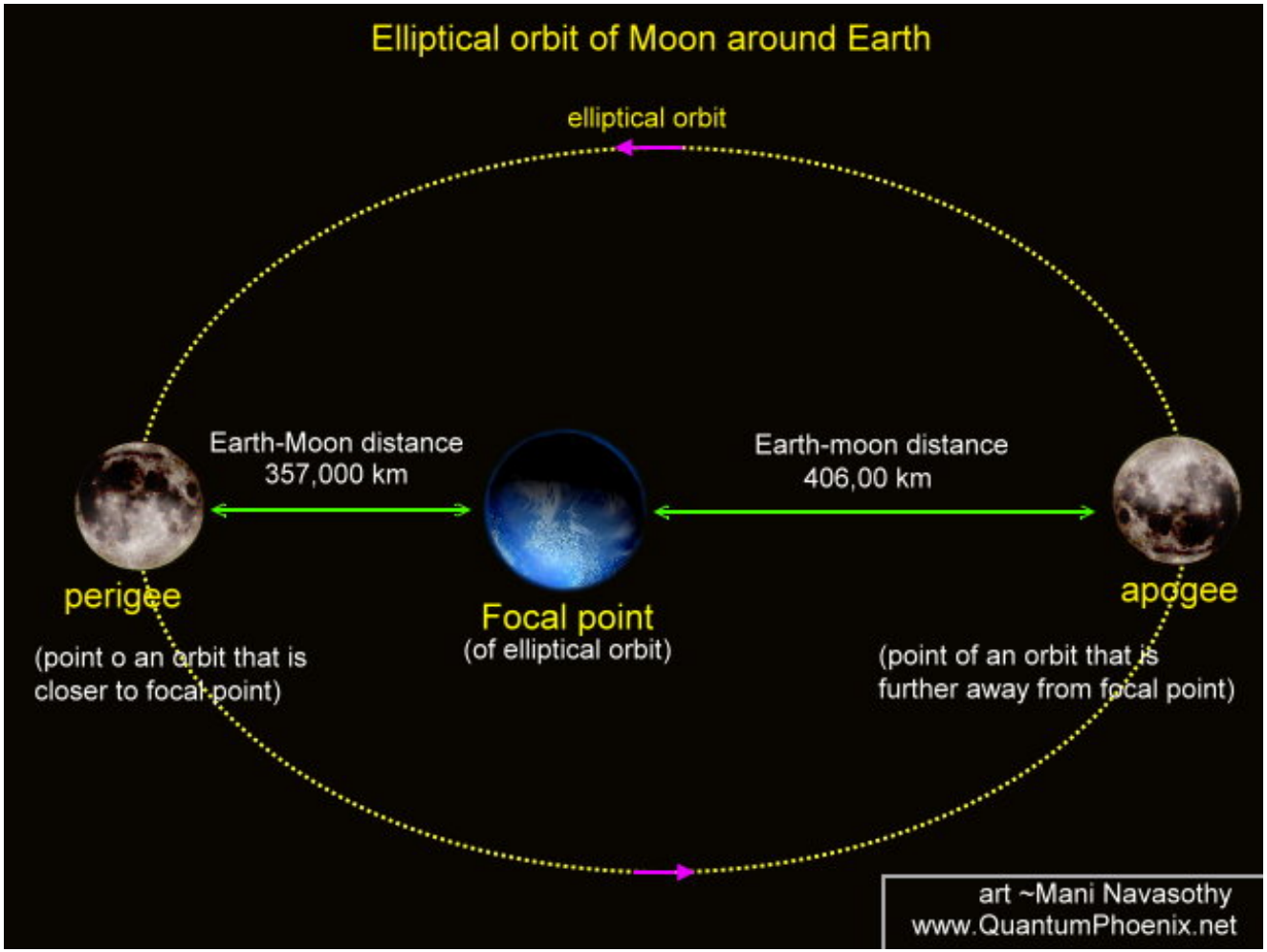
The Earth's orbit is not quite circular.

Earth's orbit and the Seasons



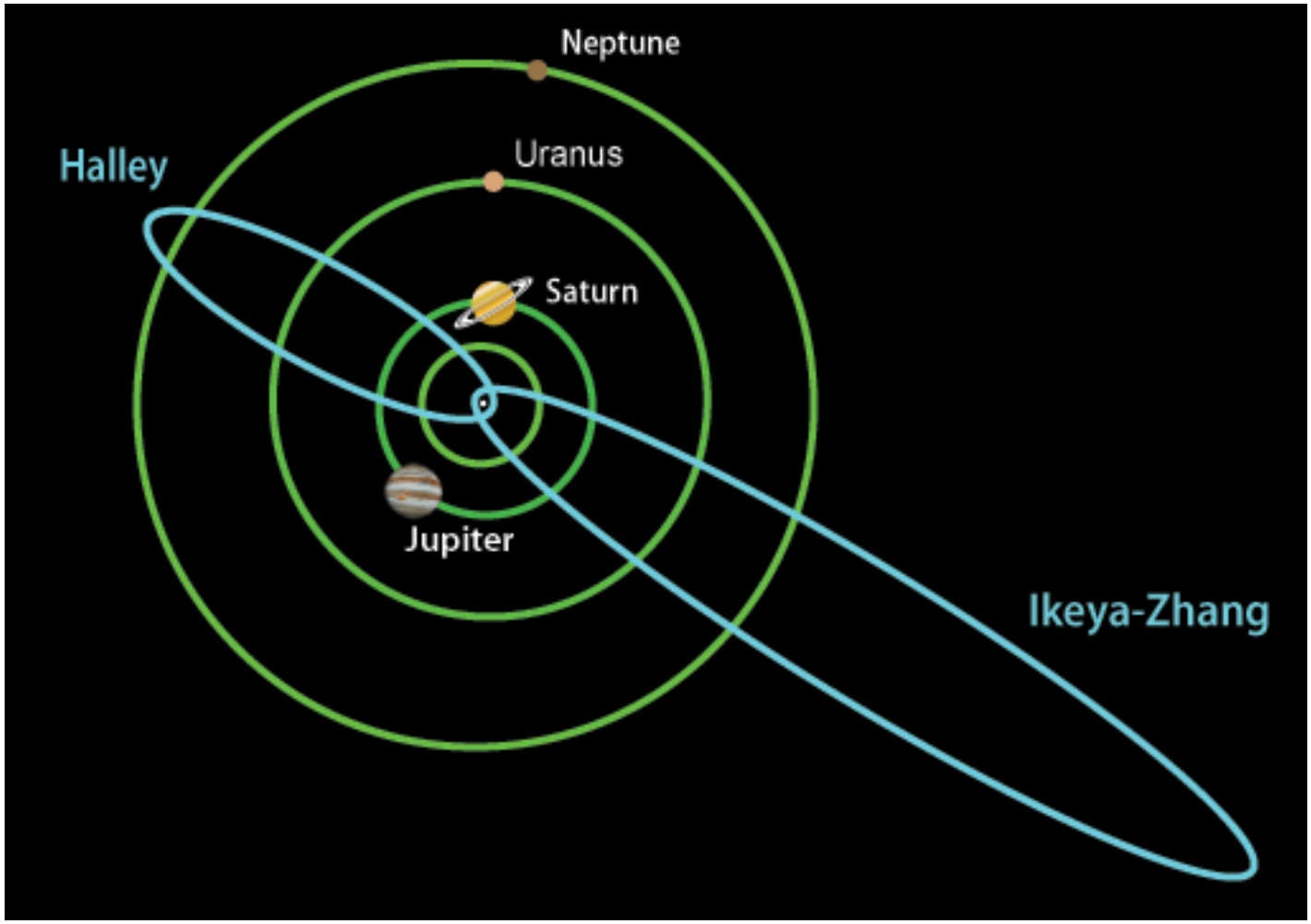
The seasons are caused by the tilt of the Earth's axis, *not* by the non-circularity of the Earth's orbit.

Moon's orbit



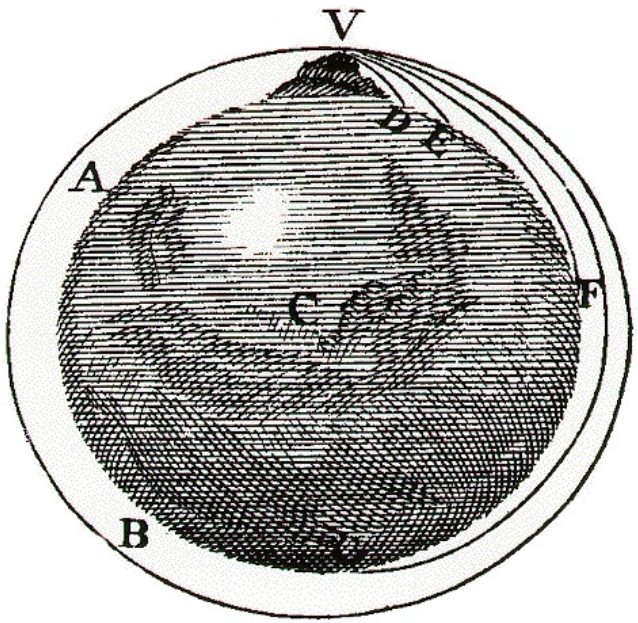
When referring to orbits around the Earth, we use the terms perigee and apogee instead of perihelion and aphelion.

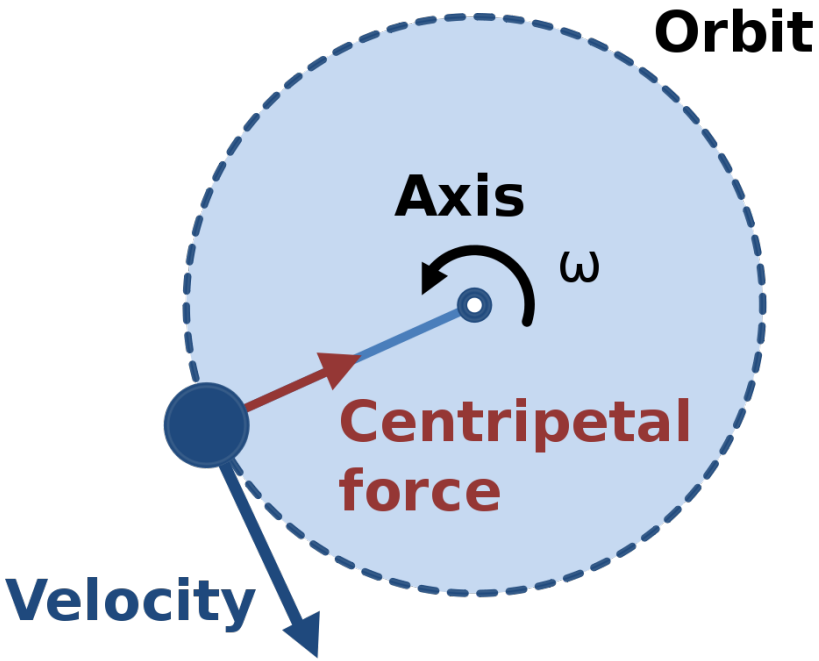
Typical Comet Orbits



Most comets follow highly elliptical orbits

Newton's Mountaintop Thought Experiment and Centripetal Force

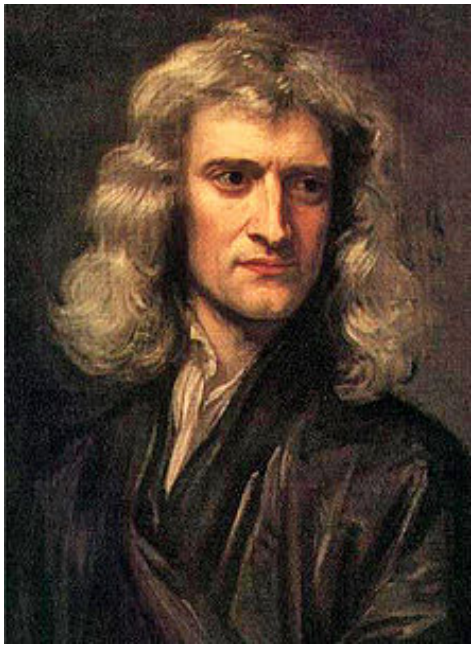




Centripetal Force

$$F = \frac{mv^2}{R}$$

Newton's Laws of Motion



Isaac Newton - 1689

1. An object at rest will remain at rest unless acted on by an unbalanced force. An object in motion continues in motion with the same speed and in the same direction unless acted upon by an unbalanced force.

2. Acceleration is produced when a force acts on a mass. The greater the mass of the object being accelerated, the greater the amount of force needed to accelerate the object.

$$\mathrm{F} = \mathrm{ma}$$

3. For every action there is an equal and opposite reaction.

Why $A^3 \propto T^2$?

- Newton's law of Universal Gravitation:
- Every mass in the universe attracts every other mass with a force:

$$F = \frac{Gm_1m_2}{R^2}$$

- Gravity provides the centripetal force, so:

$$F = \frac{m_p v^2}{R} = \frac{Gm_pm_s}{R^2}$$

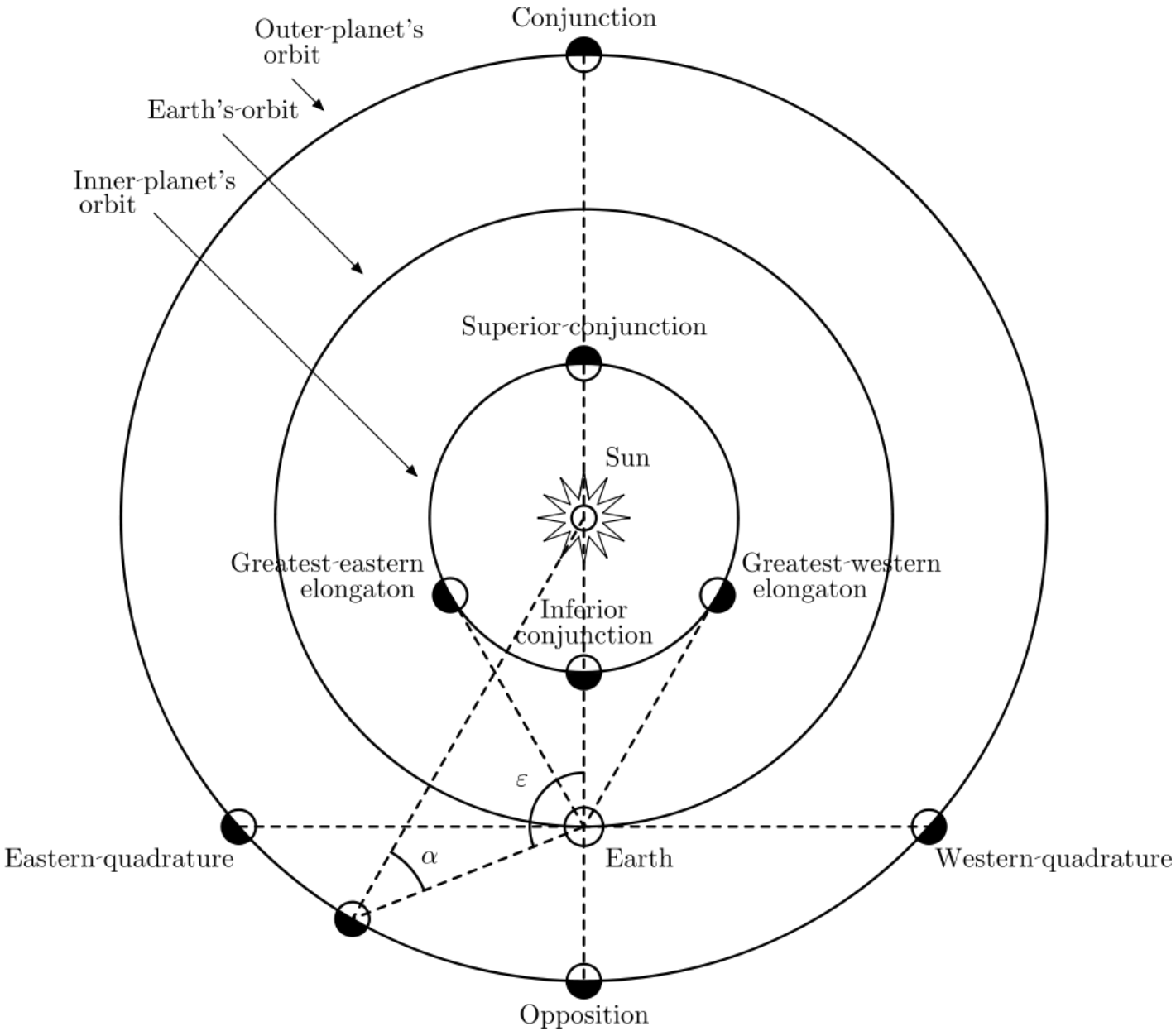
- Velocity is distance divided by time, so:

$$v = \frac{2\pi R}{T}$$

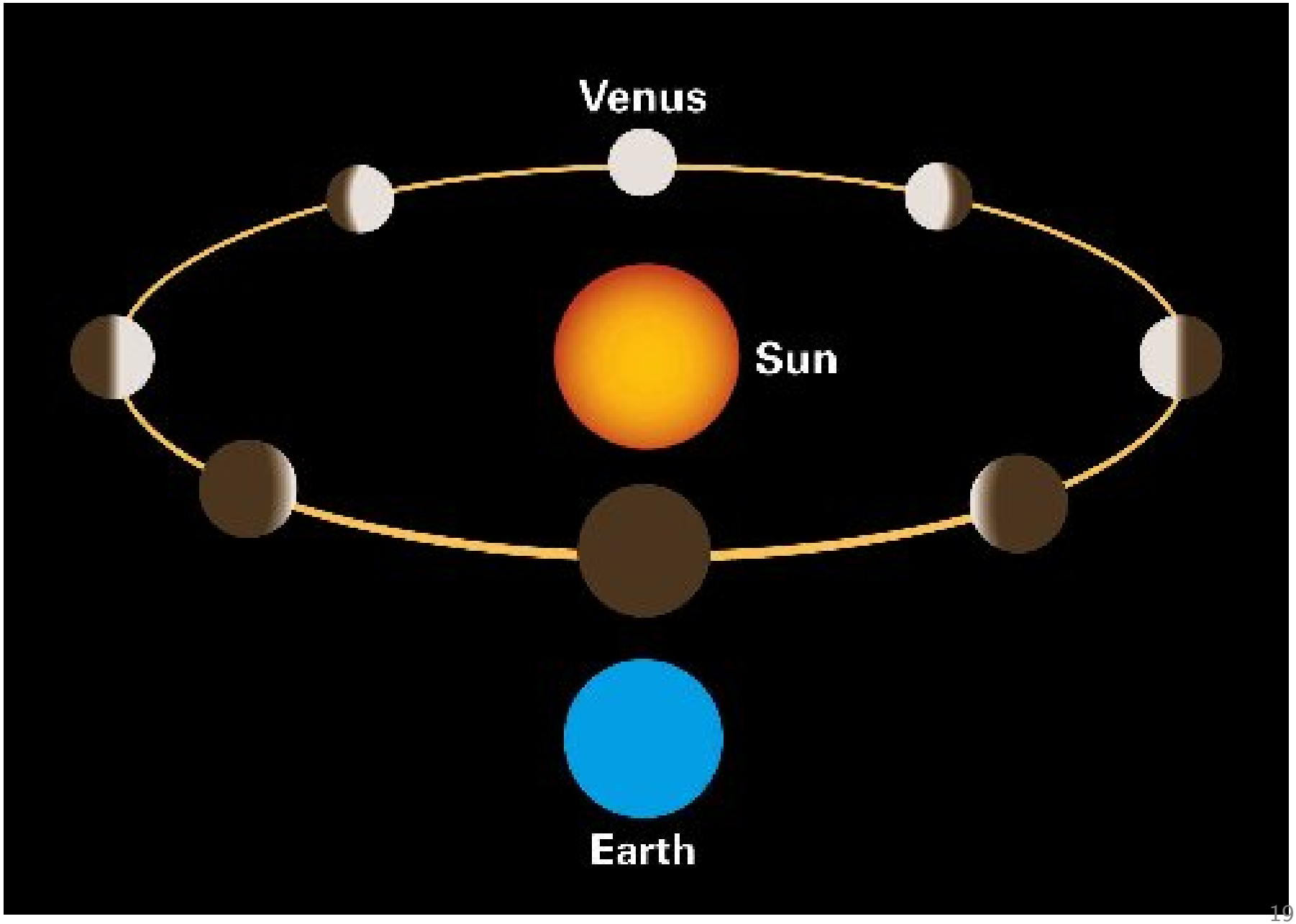
$$F = \frac{m_p v^2}{R} = \frac{Gm_pm_s}{R^2} = \frac{m_p(\frac{2\pi R}{T})^2}{R} = \frac{m_p 4\pi^2 R}{T^2}$$

$$\frac{R^3}{T^2} = \frac{Gm_s}{4\pi^2} = \text{Constant}$$

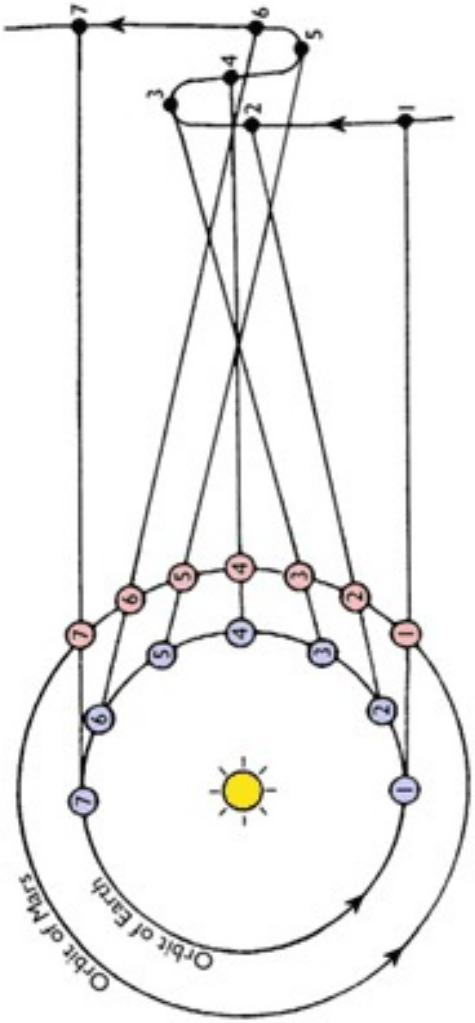
Inner and Outer Planets Appear Differently in the Sky

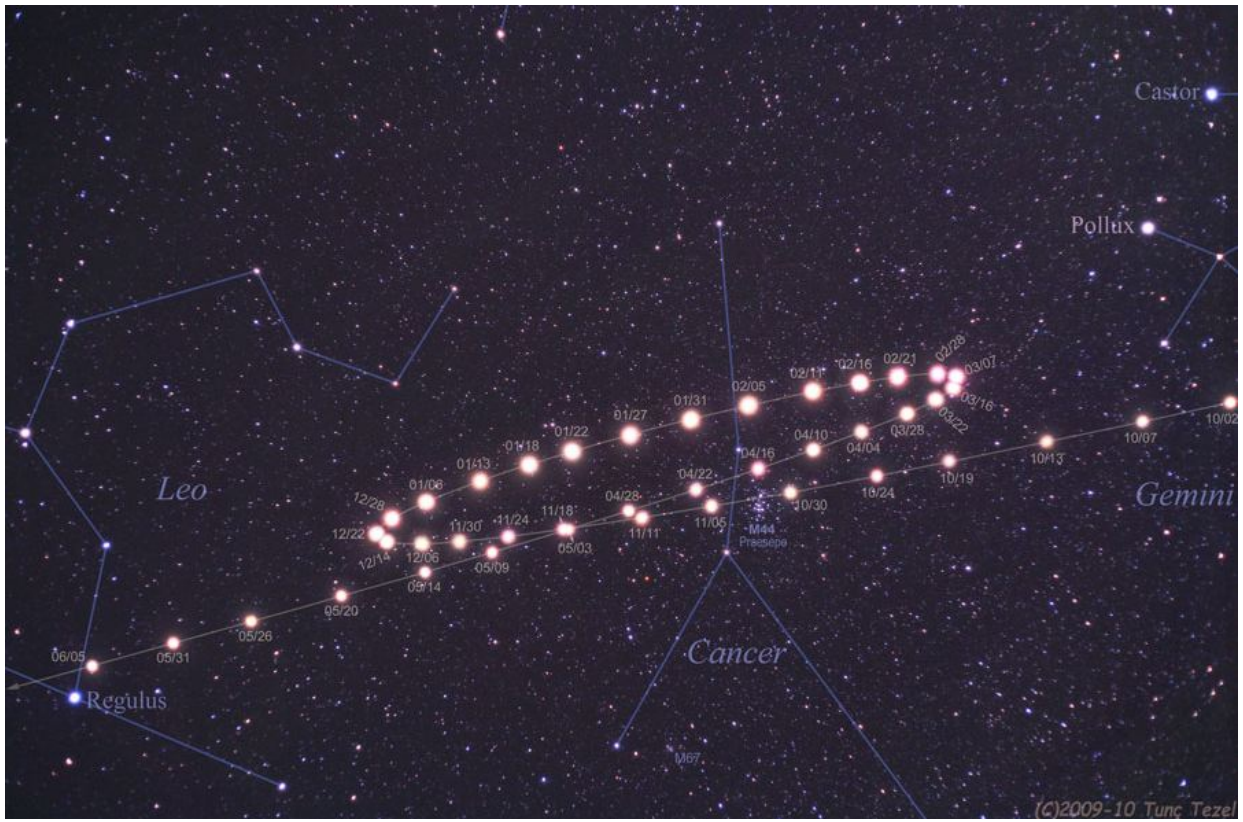


Inner Planets Show Phases like the Moon



Retrograde Motion - Mars





Summary

1. Kepler's laws describe the motion of objects in orbit.
2. Newton's laws explain orbital motion in terms of a single universal force - Gravity.
3. Bodies in orbit are permanently free falling.
4. Understanding the properties of orbits allows us to understand how the planets move in the sky.