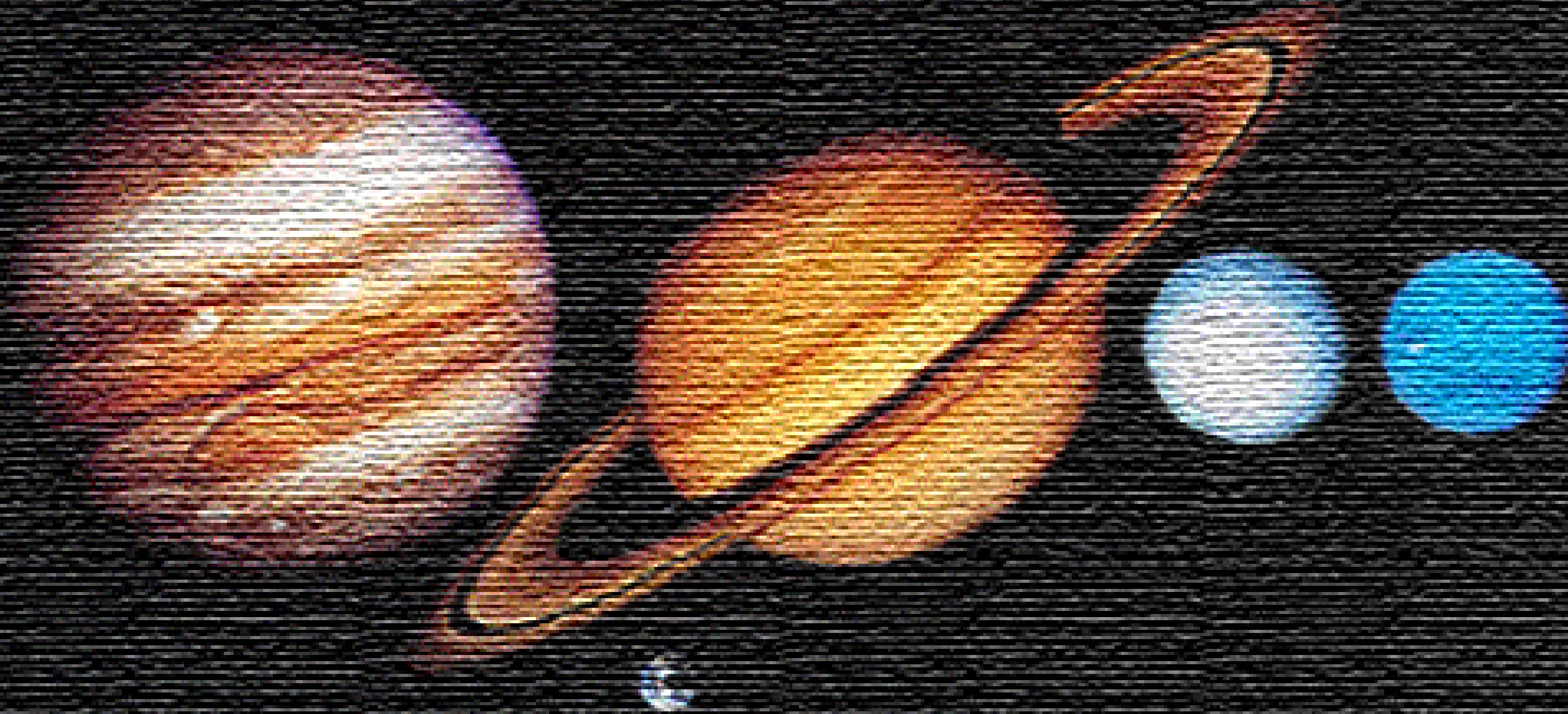
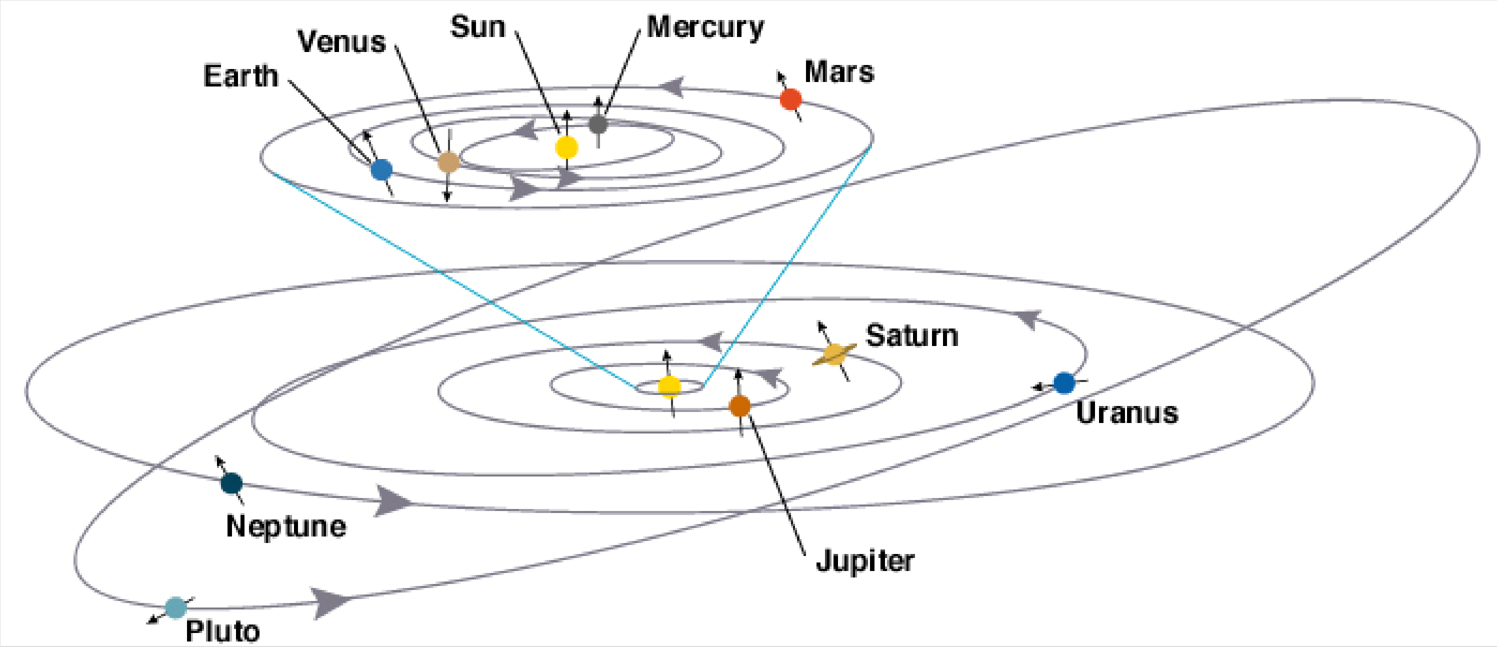
Lecture 2a The Solar System



The Layout of the Solar System

- Large bodies in the Solar System have orderly motions
  - planets orbit counterclockwise in same plane
  - orbits are almost circular
  - the Sun and most planets rotate counterclockwise
  - most moons orbit counterclockwise



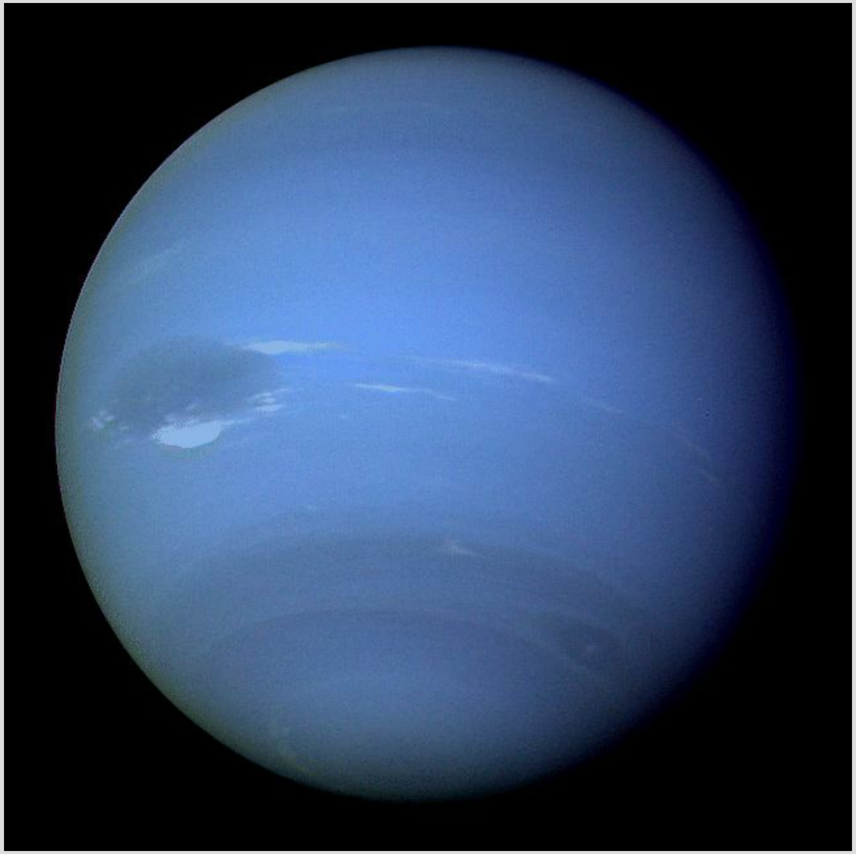
The Layout of the Solar System

- Planets fall into two main categories
  - Terrestrial (i.e. Earth-like)
  - Jovian (i.e. Jupiter-like or gaseous)

Terrestrial Planets	Jovian Planets
Smaller size and mass	Larger size and mass
Higher density (rocks, metals)	Lower density (light gases, hydrogen compounds)
Solid surface	No solid surface
Closer to the Sun (and closer together)	Farther from the Sun (and farther apart)
Warmer	Cooler
Few (if any) moons and no rings	Rings and many moons

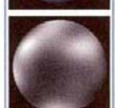
Mars

Terrestrial



Neptune

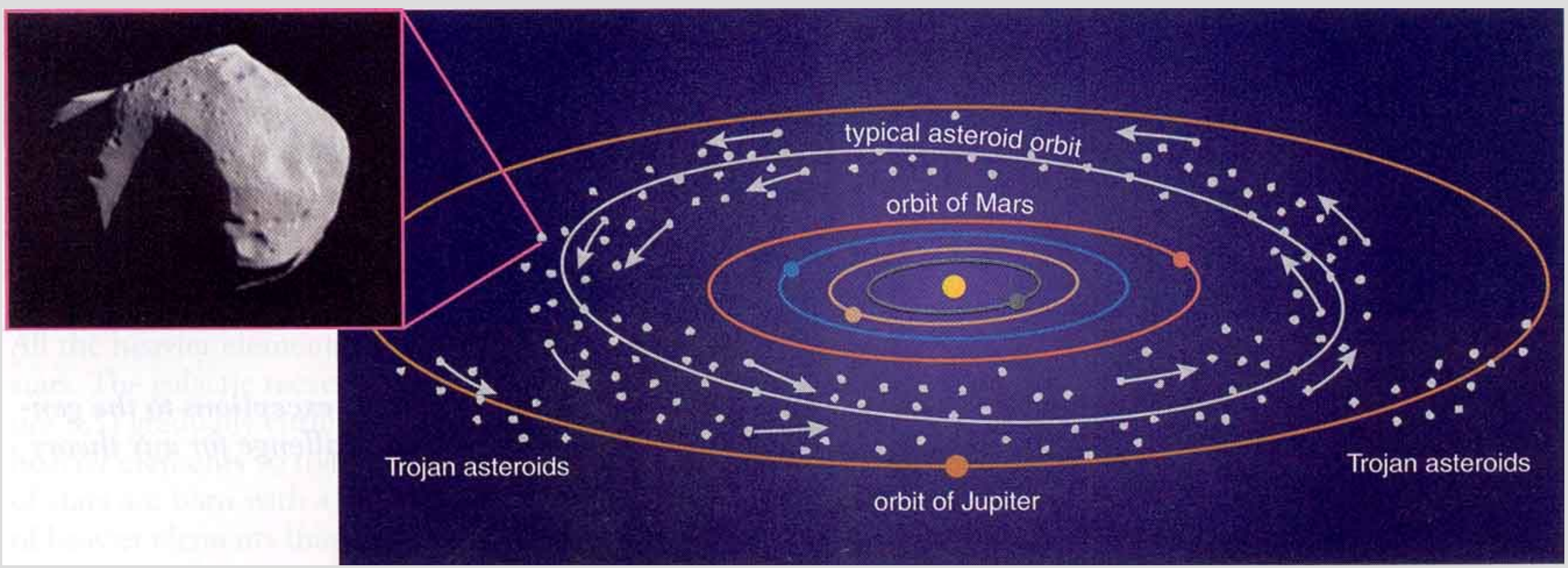
Jovian

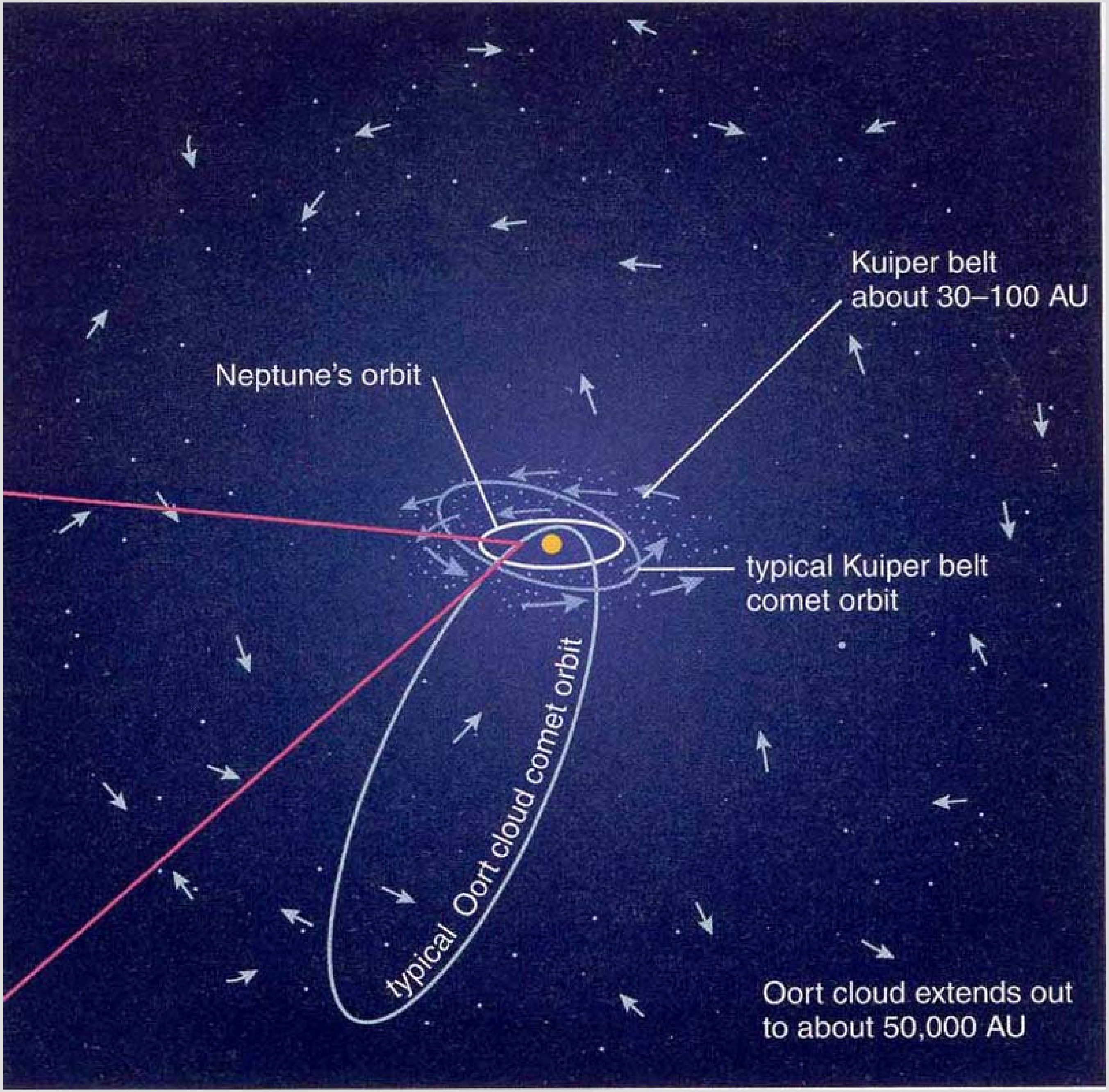
Photo	Planet	Average Distance from Sun (AU)	Temperature†	Relative Size	Average Equatorial Radius (km)	Average Density (g/cm^3)	Composition	Known Moons	Rings?
	Mercury	0.387	700 K		2,440	5.43	Rocks, metals	0	No
	Venus	0.723	740 K		6,051	5.24	Rocks, metals	0	No
	Earth	1.00	290 K		6,378	5.52	Rocks, metals	1	No
	Mars	1.52	240 K		3,397	3.93	Rocks, metals	2 (tiny)	No
	Most asteroids	2–3	170 K		≤500	1.5–3	Rocks, metals	?	No
	Jupiter	5.20	125 K		71,492	1.33	H, He, hydrogen compounds‡	28	Yes
	Saturn	9.53	95 K		60,268	0.70	H, He, hydrogen compounds‡	30	Yes
	Uranus	19.2	60 K		25,559	1.32	H, He, hydrogen compounds‡	21	Yes
	Neptune	30.1	60 K		24,764	1.64	H, He, hydrogen compounds‡	8	Yes
	Pluto	39.5	40 K		1,160	2.0	Ices, rock	1	No
	Most comets	10–50,000	A few K§		A few km?	<1?	Ices, dust	?	No

*Appendix C gives a more complete list of planetary properties.
†Surface temperatures for all objects except Jupiter, Saturn, Uranus, and Neptune, for which cloud-top temperatures are listed.
‡Includes water (H_2O), methane (CH_4), and ammonia (NH_3).
§Comets passing close to the Sun warm considerably, especially their outer layers.

The Layout of the Solar System

- Swarms of asteroids and comets populate the Solar System




Kuiper belt
about 30–100 AU
Neptune's orbit
typical Kuiper belt
comet orbit
typical Oort cloud comet orbit
Oort cloud extends out
to about 50,000 AU

A Few Exceptions to the Rules…

- Both Uranus & Pluto are tilted on their sides.
- Venus rotates “backwards” (i.e. clockwise).
- Triton orbits Neptune “backwards.”
- Earth is the only terrestrial planet with a relatively large moon.

The Sun – King of the Solar System

- How does the Sun influence the planets?
  - Its gravity regulates the orbits of the planets.
  - Its heat is the primary factor which determines the temperature of the planets.
  - It provides practically all of the visible light in the Solar System.
  - High-energy particles streaming out from the Sun influence planetary atmospheres and magnetic fields.

Origin of the Solar System

Our theory must explain the data

1. Large bodies in the Solar System have orderly motions.
2. There are two types of planets.
   - small, rocky **terrestrial** planets
   - large, hydrogen-rich **Jovian** planets
3. Asteroids & comets exist in certain regions of the Solar System
4. There are exceptions to these patterns.

Origin of the Solar System

Nebular Theory – our Solar System formed from a giant, swirling cloud of gas & dust.

Depends on two principles of Physics:

- Law of Gravity
  - gravitaional potential energy $\Rightarrow$ heat
- Conservation of angular momentum

and

- Basic chemistry

The Solar Nebula

- The nebular theory holds that our Solar System formed out of a nebula which collapsed under its own gravity.
- observational evidence
  - We observe stars in the process of forming today.
  - The are always found within interstellar clouds of gas.

newly born stars in the Orion Nebula

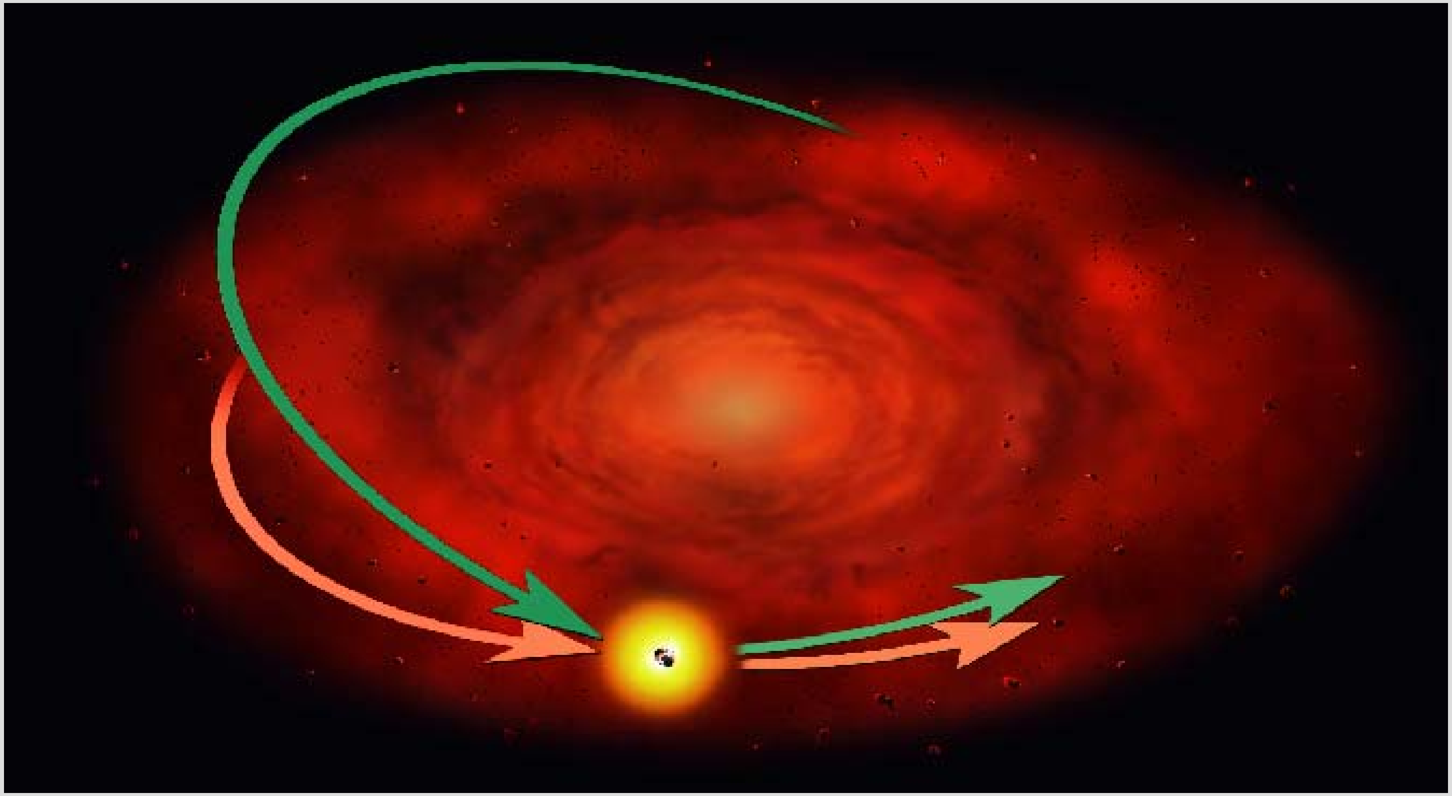
solar nebula – name given to the cloud of gas from which our own Solar System formed

Gravitational Collapse

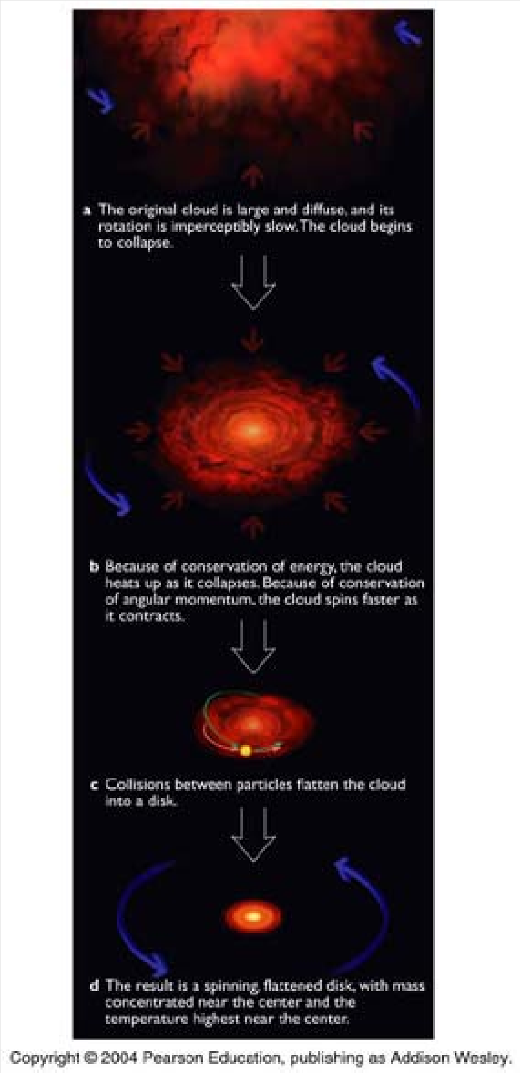
- The solar nebular was initially somewhat spherical and a few light years in diameter.
  - very cold
  - rotating slightly
- It was given a “push” by some event.
  - perhaps the shock wave from a nearby supernova
- As the nebula shrank, gravity increased, causing collapse.
- As the nebula “falls” inward, gravitational potential energy is converted to heat.
  - Conservation of Energy
- As the nebula’s radius decreases, it rotates faster
  - Conservation of Angular Momentum

Flattening of the Solar Nebula

- As the nebula collapses, clumps of gas collide & merge.
- Their random velocities average out into the nebula's direction of rotation.
- The spinning nebula assumes the shape of a disk.



As the nebula collapses, it heats up, spins faster, and flattens.



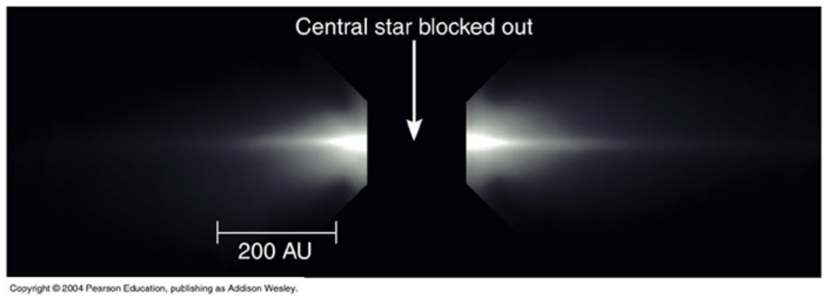
Orderly Motions in the Solar System

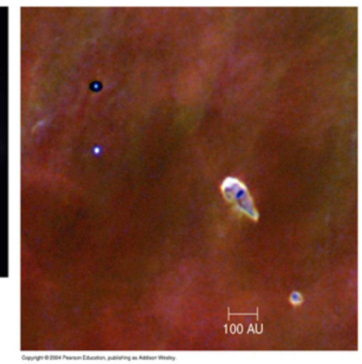
- The Sun formed in the very center of the nebula.
  - temperature & density were high enough for nuclear fusion reactions to begin
- The planets formed in the rest of the disk.
- This would explain the following:
  - all planets lie along one plane (in the disk)
  - all planets orbit in one direction (the spin direction of the disk)
  - the Sun rotates in the same direction
  - the planets would tend to rotate in this same direction
  - most moons orbit in this direction
  - most planetary orbits are near circular (collisions in the disk)

More Support for the Nebular Theory

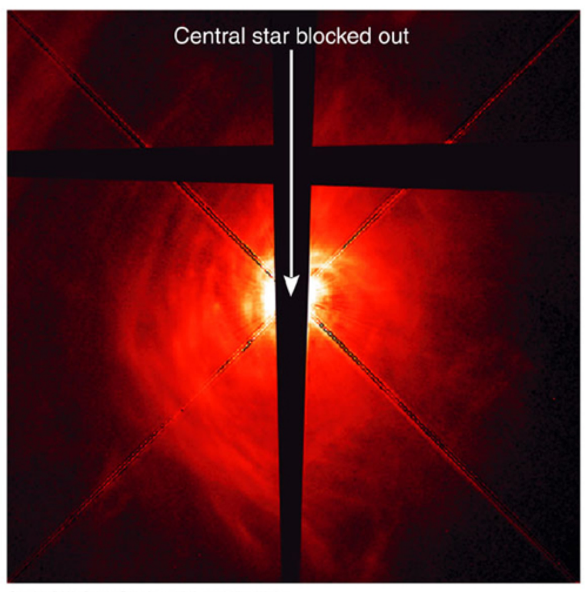
- We have observed disks around other stars.
- These could be new planetary systems in formation.

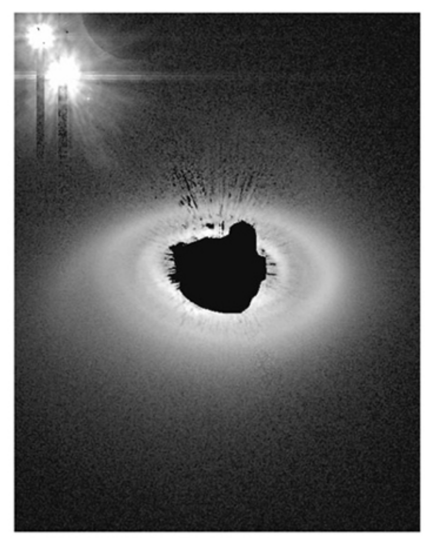
β *Pictoris*





AB Aurigae





Building the Planets

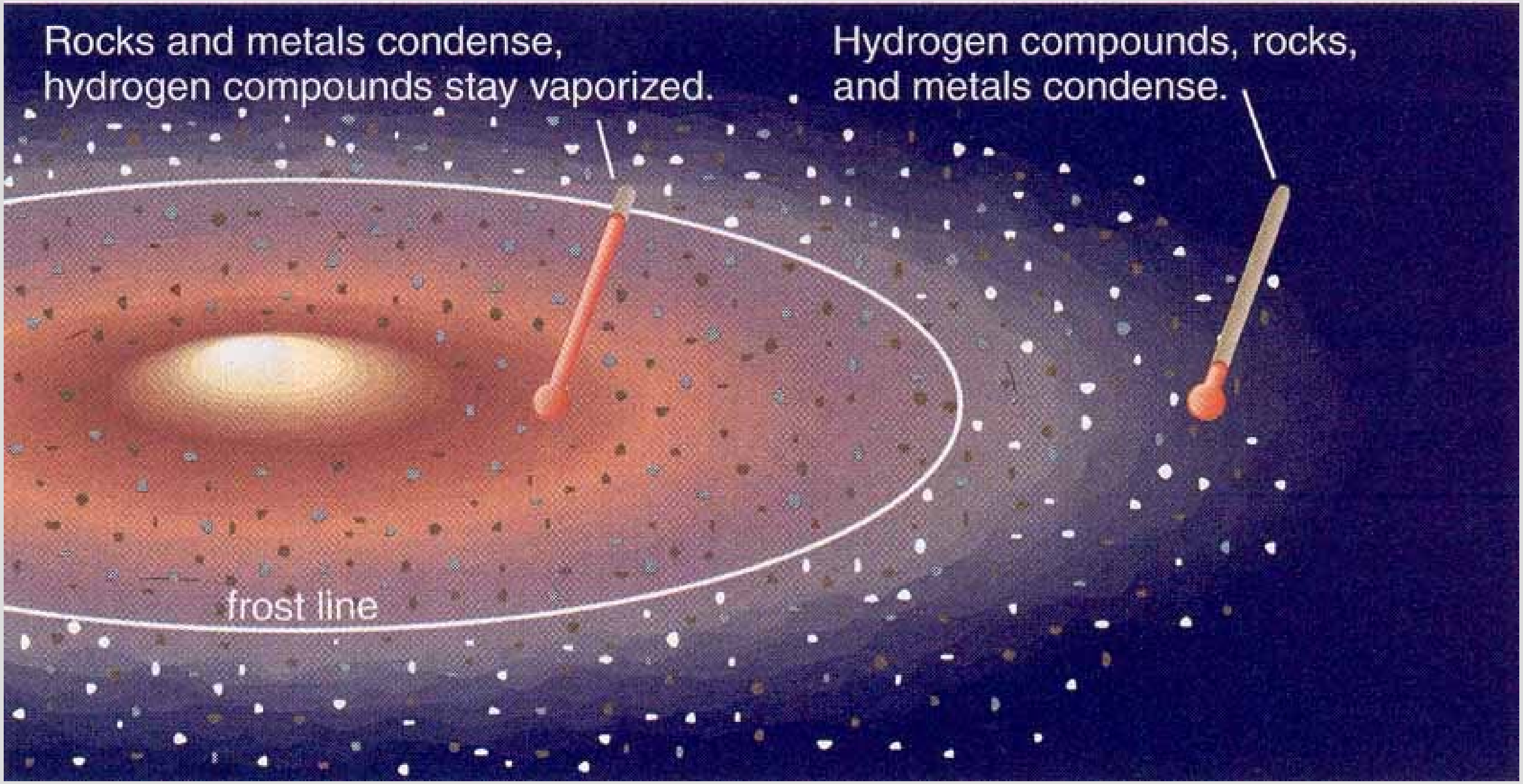
Condensation – elements & compounds began to condense (i.e. solidify) out of the nebula…. depending on temperature!

Materials in the Solar Nebula

	Metals	Rocks	Hydrogen Compounds	Light Gases
				
Examples	iron, nickel, aluminum	silicates	water (H_2O) methane (CH_4) ammonia (NH_3)	hydrogen, helium
Typical Condensation Temperature	1,000–1,600 K	500–1,300 K	<150 K	(do not condense in nebula)
Relative Abundance (by mass)	(0.2%)	(0.4%)	(1.4%)	(98%)

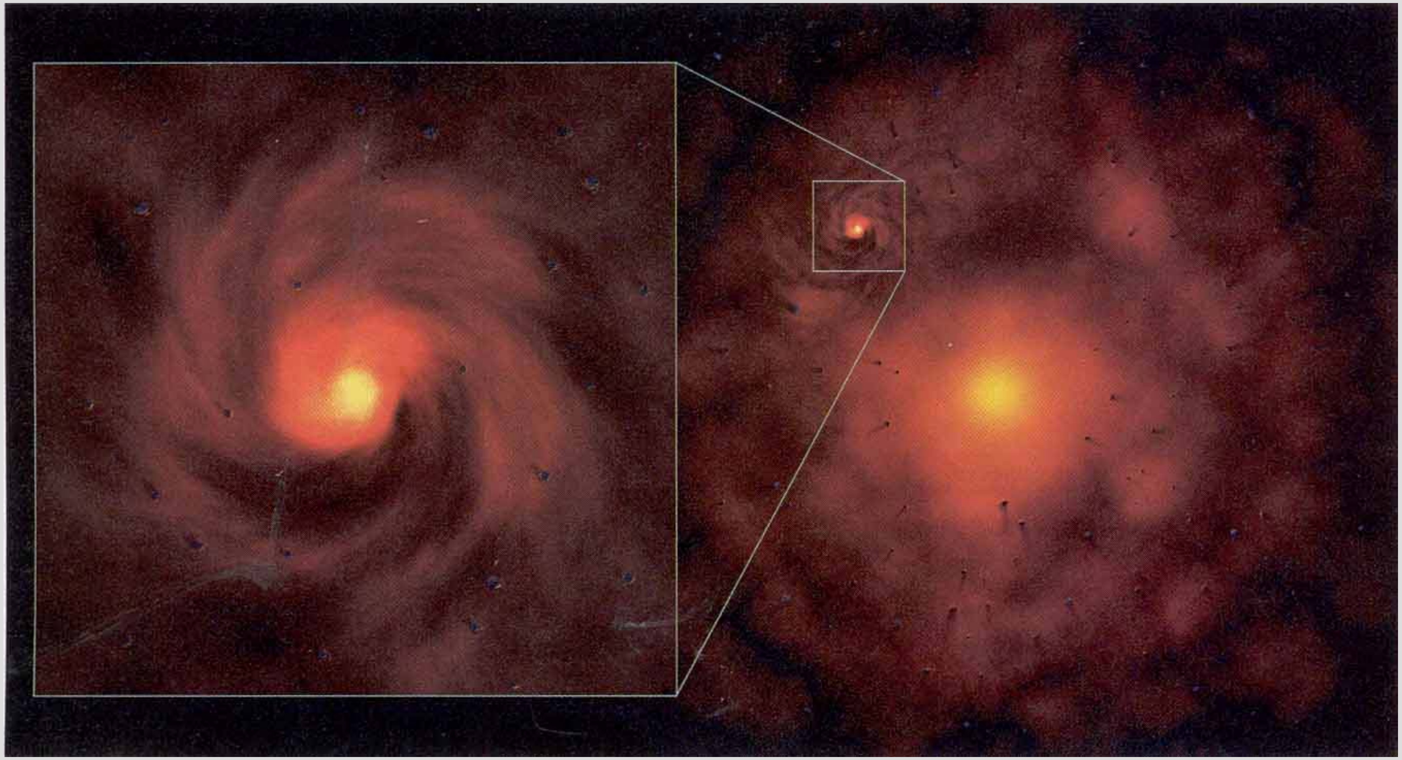
Building the Planets

So only rocks & metals condensed within 3.5 AU of the Sun… the so-called **frost line**.
Hydrogen compounds (ices) condensed beyond the frost line.



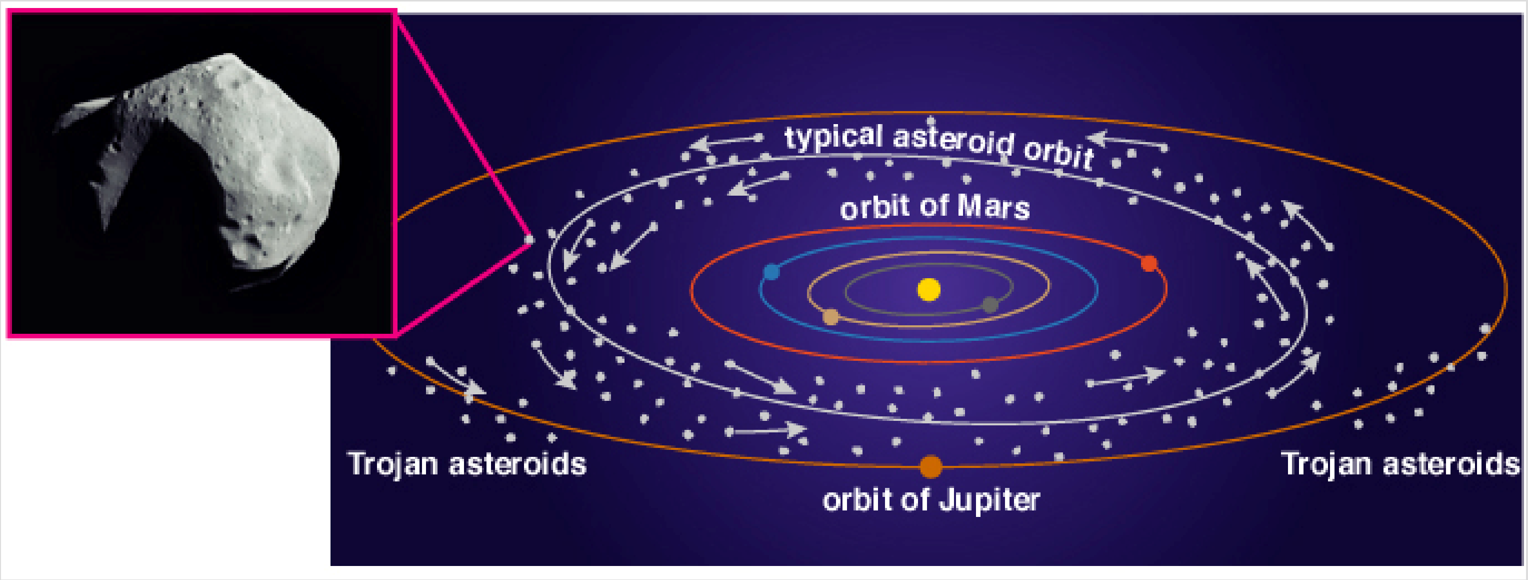
Building the Planets

- Each gas (Jovian) planet formed its own "miniature" solar nebula.
- Moons formed out of the disk.

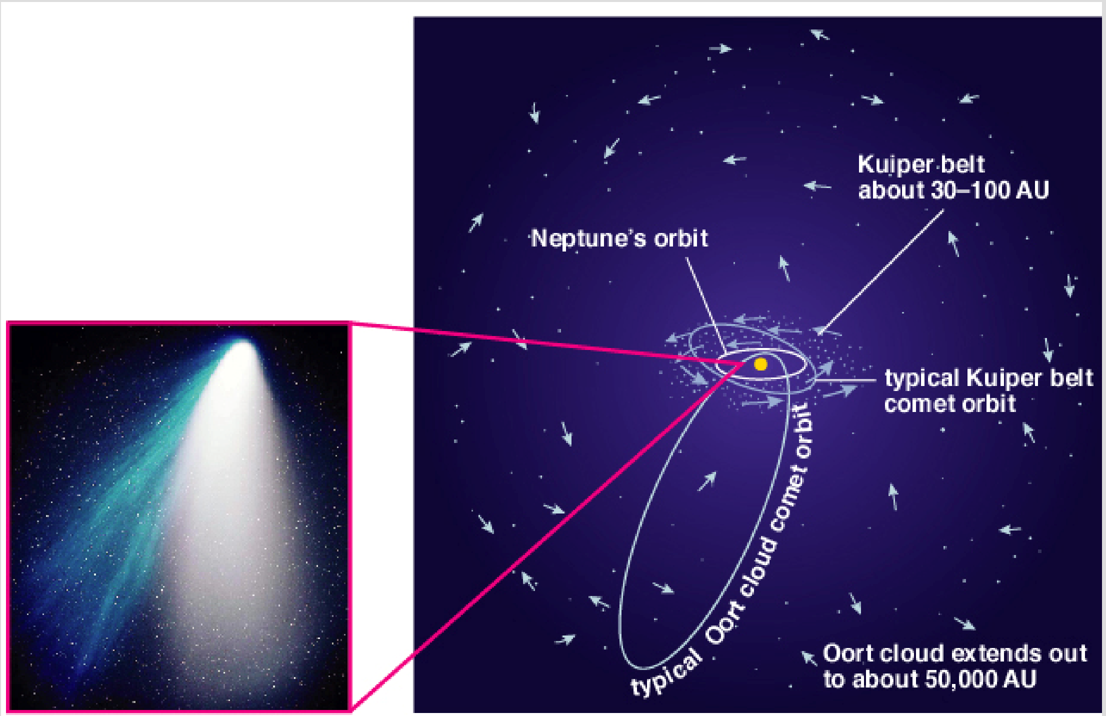


Origin of the Asteroids

- The Solar wind cleared the leftover gas, but not the leftover planetesimals.
- Those leftover rocky planetesimals which did not accrete onto a planet are the present-day **asteroids**.
- Most inhabit the **asteroid belt** between Mars & Jupiter.
  - Jupiter's gravity prevented a planet from forming there.



Origin of the Comets



- The leftover icy planetesimals are the present-day **comets**.
- Those which were located between the Jovian planets, if not captured, were gravitationally flung in all directions into the **Oort cloud**.
- Those beyond Neptune's orbit remained in the ecliptic plane in what we call the **Kuiper belt**.

The nebular theory *predicted* the existence of the Kuiper belt 40 years before it was discovered!

Exceptions to the Rules

So how does the nebular theory deal with exceptions, i.e. data which do not fit the model's predictions?

IMPACTS

- There were many more leftover planetesimals than we see today.
- Most of them collided with the newly-formed planets & moons during the first few 10^8 years of the Solar System.
- We call this the **heavy bombardment** period.

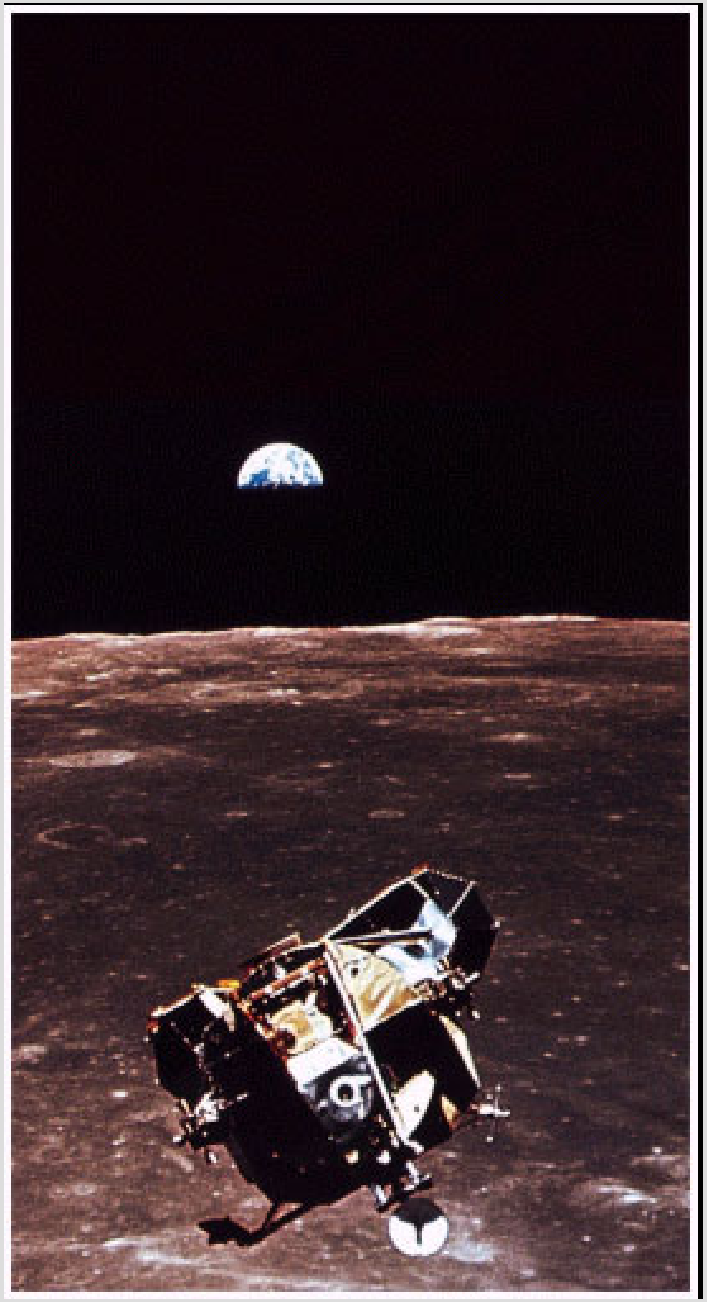
Exceptions to the Rules

Close encounters with and impacts by planetesimals could explain:

- Why some moons orbit opposite their planet's rotation
  - captured moons (e.g. Triton)
- Why rotation axes of some planets are tilted
  - impacts "knock them over" (extreme example: Uranus)
- Why some planets rotate more quickly than others
  - impacts "spin them up"
- Why Earth is the only terrestrial planet with a large Moon
  - giant impact

Formation of the Moon (Giant Impact Theory)

- The Earth was struck by a Mars-sized planetesimal
- A part of Earth's mantle was ejected
- This coalesced in the Moon.
  - it orbits in same direction as Earth rotates
  - lower density than Earth
  - Earth was "spun up"

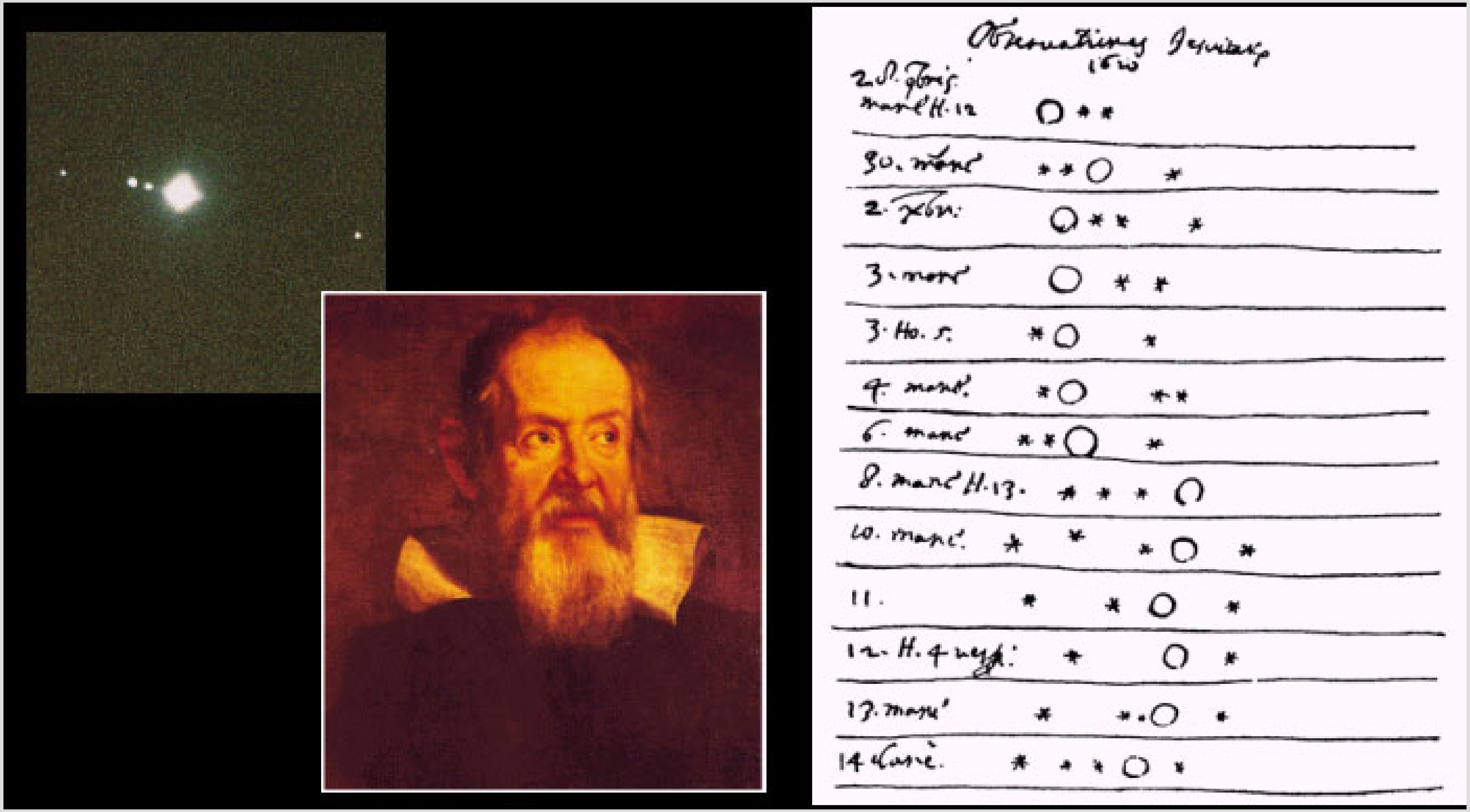


Lecture 2b

Gravitation (Newtonian)

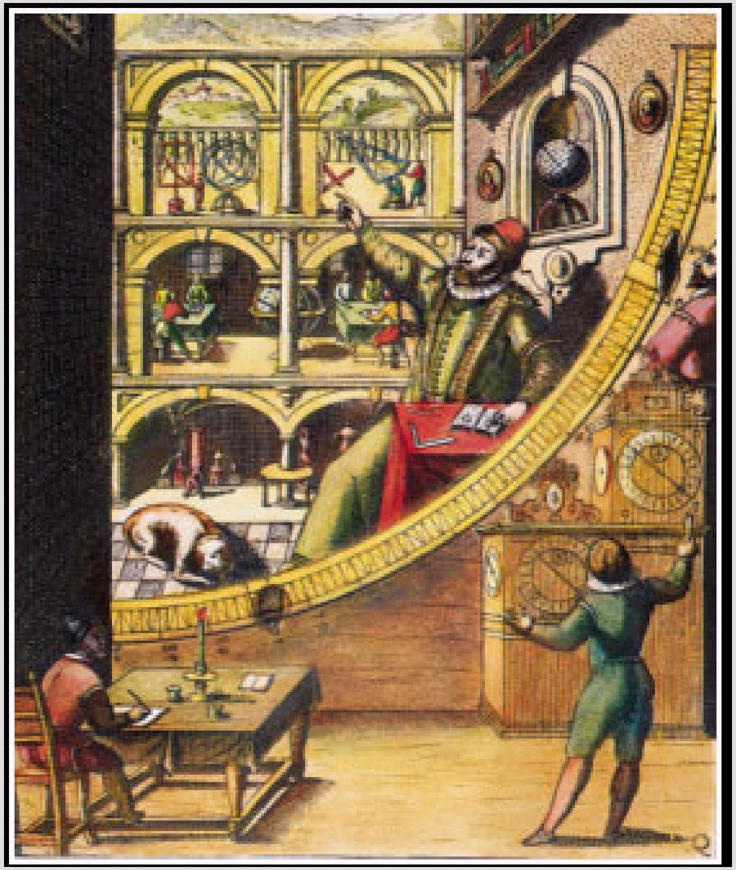
Galileo's discoveries of Jupiter's moons with his telescope showed that Earth was not the center of all orbits strongly supported a heliocentric model

even though Copernicus' model was no more accurate than Ptolemy's.



Tycho Brahe's astronomical observations disproved ancient ideas about the heavens.

Brahe constructed enormous instruments to meticulously record the precise positions of the planets in the sky to an accuracy never previously obtained.



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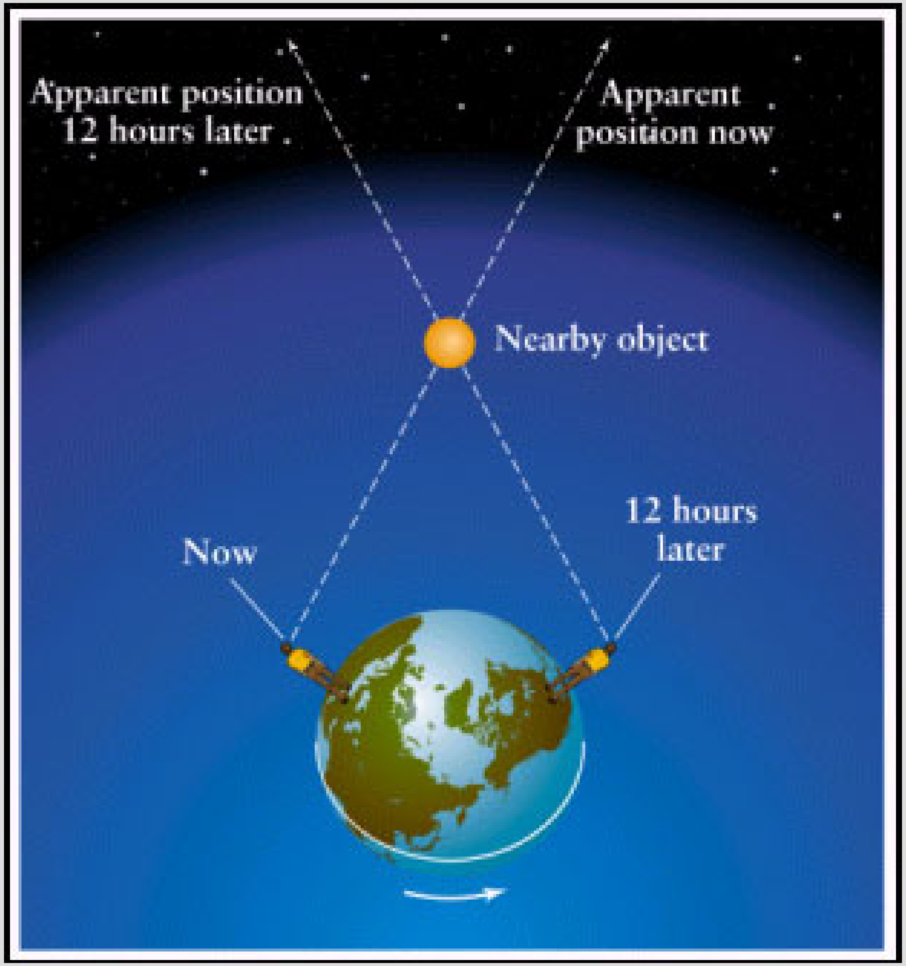
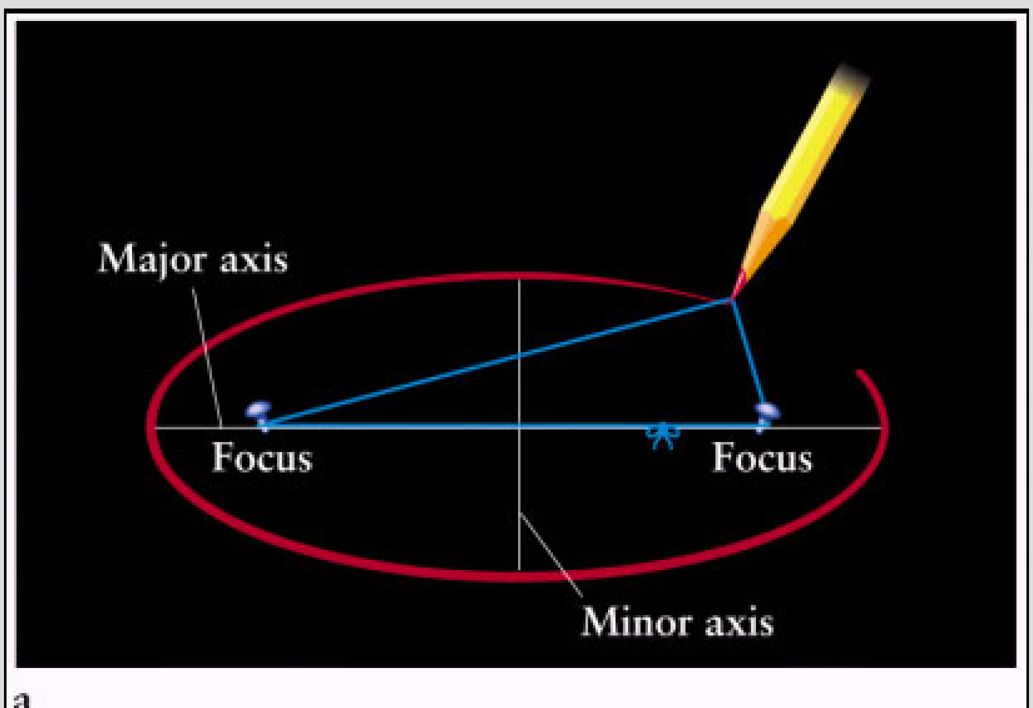


Using PARALLAX, Brahe was able to demonstrate that the comet of 1577 was beyond the Moon's orbit and that the supernova of 1572 was in "the distant realm of the stars."

Johannes Kepler proposed elliptical paths for the planets about the Sun.

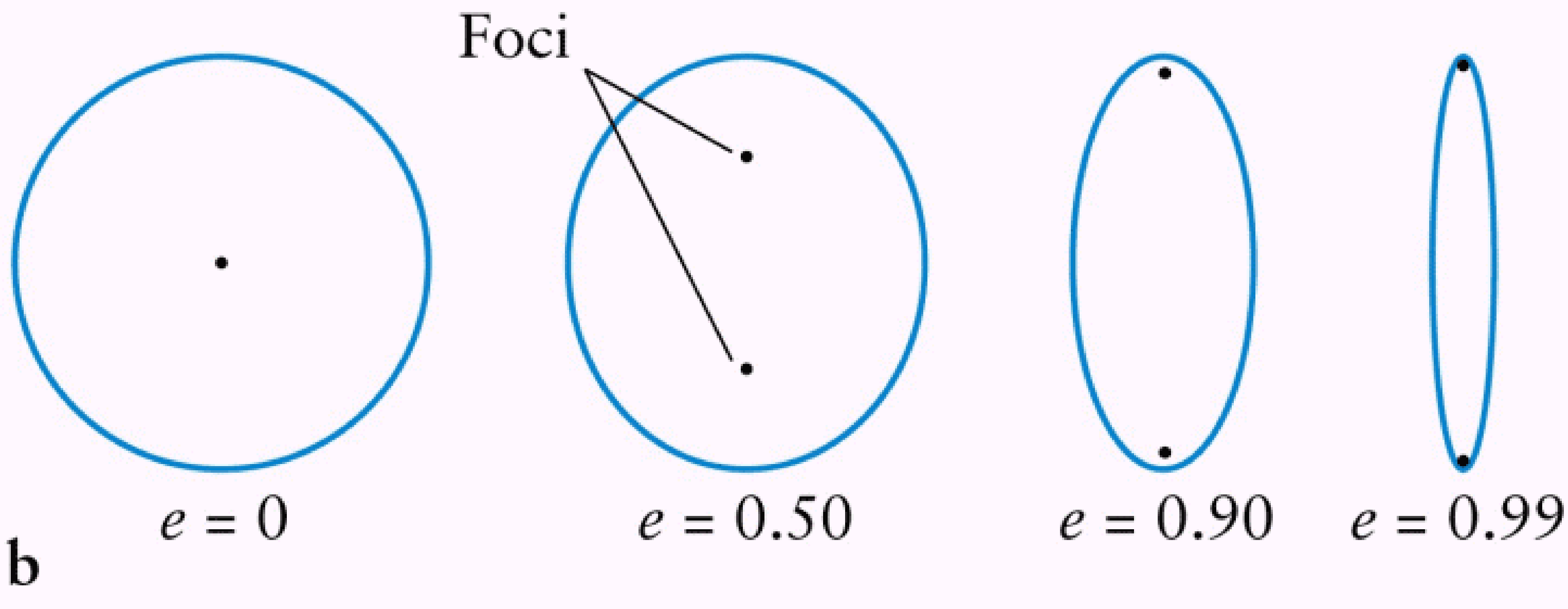
Kepler’s First Law of Planetary Motion

- *The orbit of a planet about the Sun is an ellipse with the Sun at one focus.*



Johannes Kepler proposed elliptical paths for the planets about the Sun.

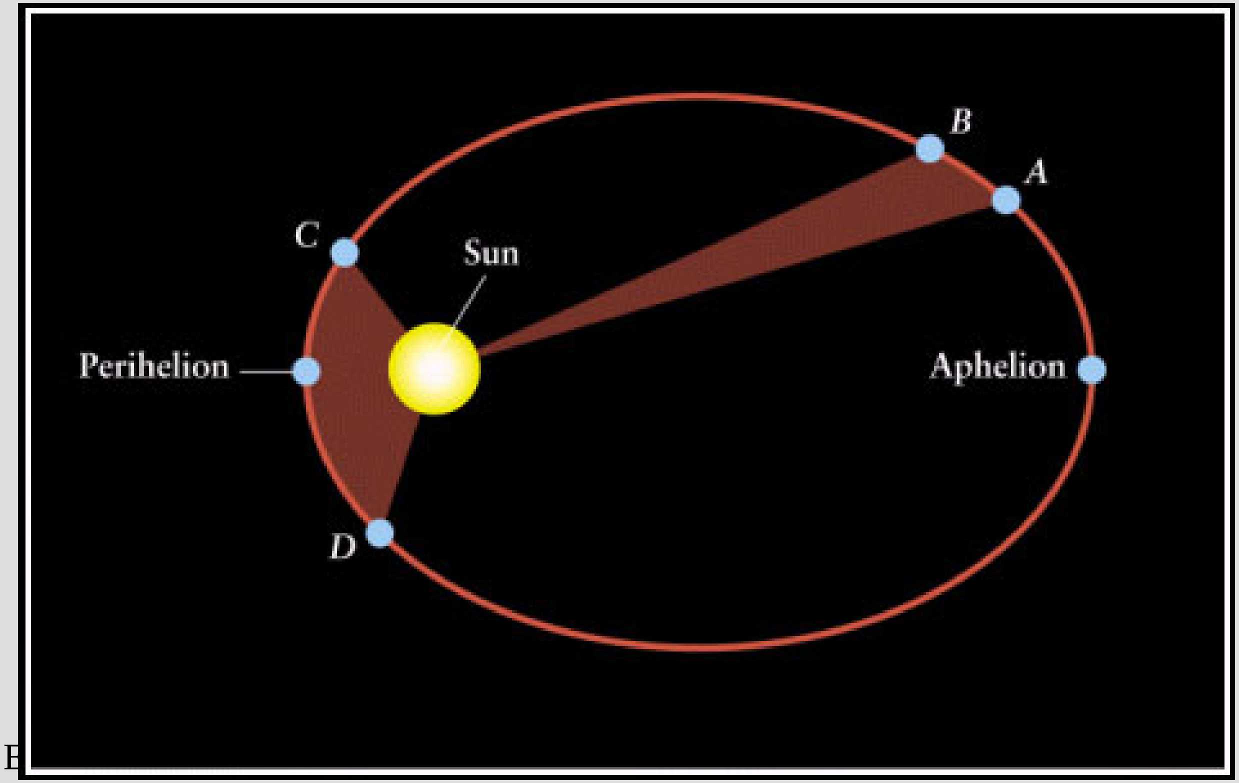
Elliptical Eccentricity (e): *a number ranging between one (for a flat line) and zero (for a perfectly round circle).*



Johannes Kepler proposed elliptical paths for the planets about the Sun.

Kepler's Second Law of Planetary Motion

- *A line joining a planet and the Sun sweeps out equal areas in equal intervals of time.*



Johannes Kepler proposed elliptical paths for the planets about the Sun.

Kepler's Third Law of Planetary Motion

- *The square of the sidereal period of a planet is directly proportional to the cube of the semi-major axis of the orbit.*

$$(p_{Yr}{}^2 = a_{AU}{}^3)$$

Kepler's laws explain how the universe works, but they do not explain "why."
The "why" explanation was given by Isaac Newton.

Table 4-3 A Demonstration of Kepler's Third Law

Planet	Sidereal period P (years)	Semimajor axis a (AU)	P^2	a^3
Mercury	0.24	0.39	0.06	0.06
Venus	0.61	0.72	0.37	0.37
Earth	1.00	1.00	1.00	1.00
Mars	1.88	1.52	3.53	3.51
Jupiter	11.86	5.20	140.7	140.6
Saturn	29.46	9.54	867.9	868.3
Uranus	84.01	19.19	7,058	7,067
Neptune	64.79	30.06	27,160	27,160
Pluto	248.54	39.53	61,770	61,770

Isaac Newton formulated three laws that describe fundamental properties of physical reality.

1. A body remains at rest, or moves in a straight line at a constant speed, unless acted upon by a net outside force.
2. $F = ma$ (the force on an object is directly proportional to its mass and acceleration).
3. Whenever one body exerts a force on a second body, the second body exerts an equal and opposite force on the first body.

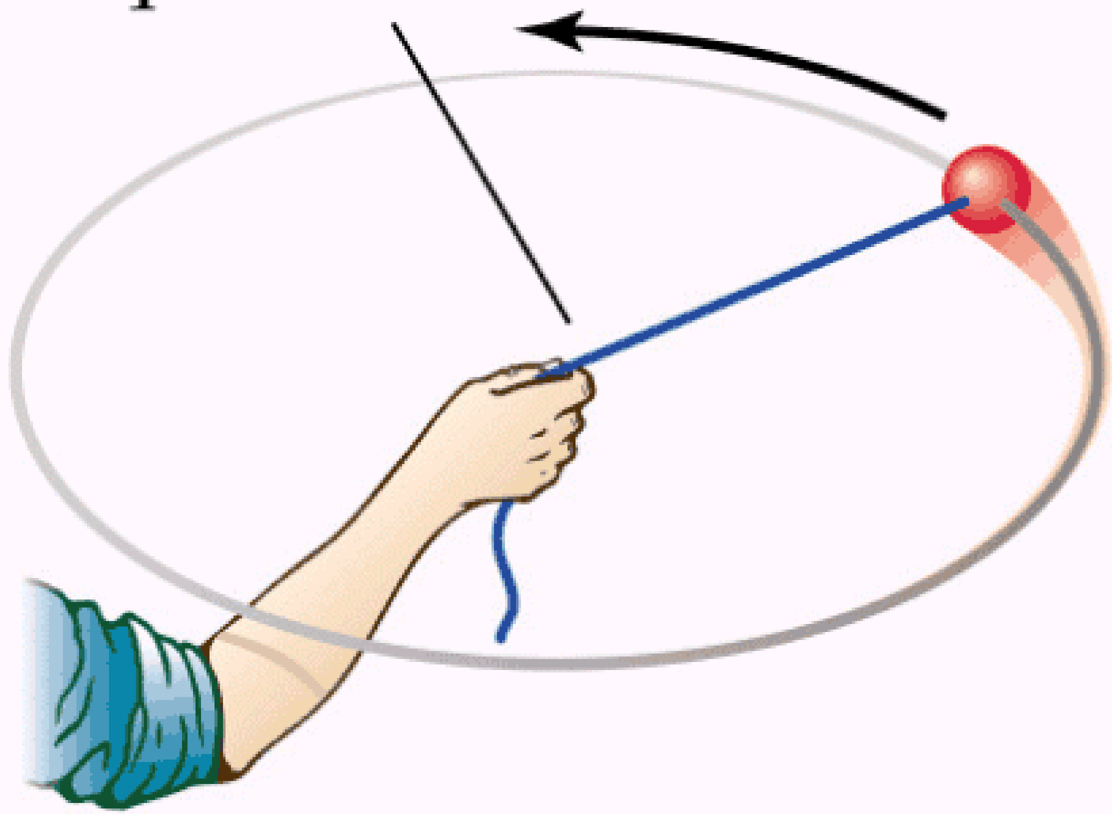
Newton’s description of gravity accounts for Kepler’s laws and explains the motions of the planets.

Newton’s Law of Universal Gravitation

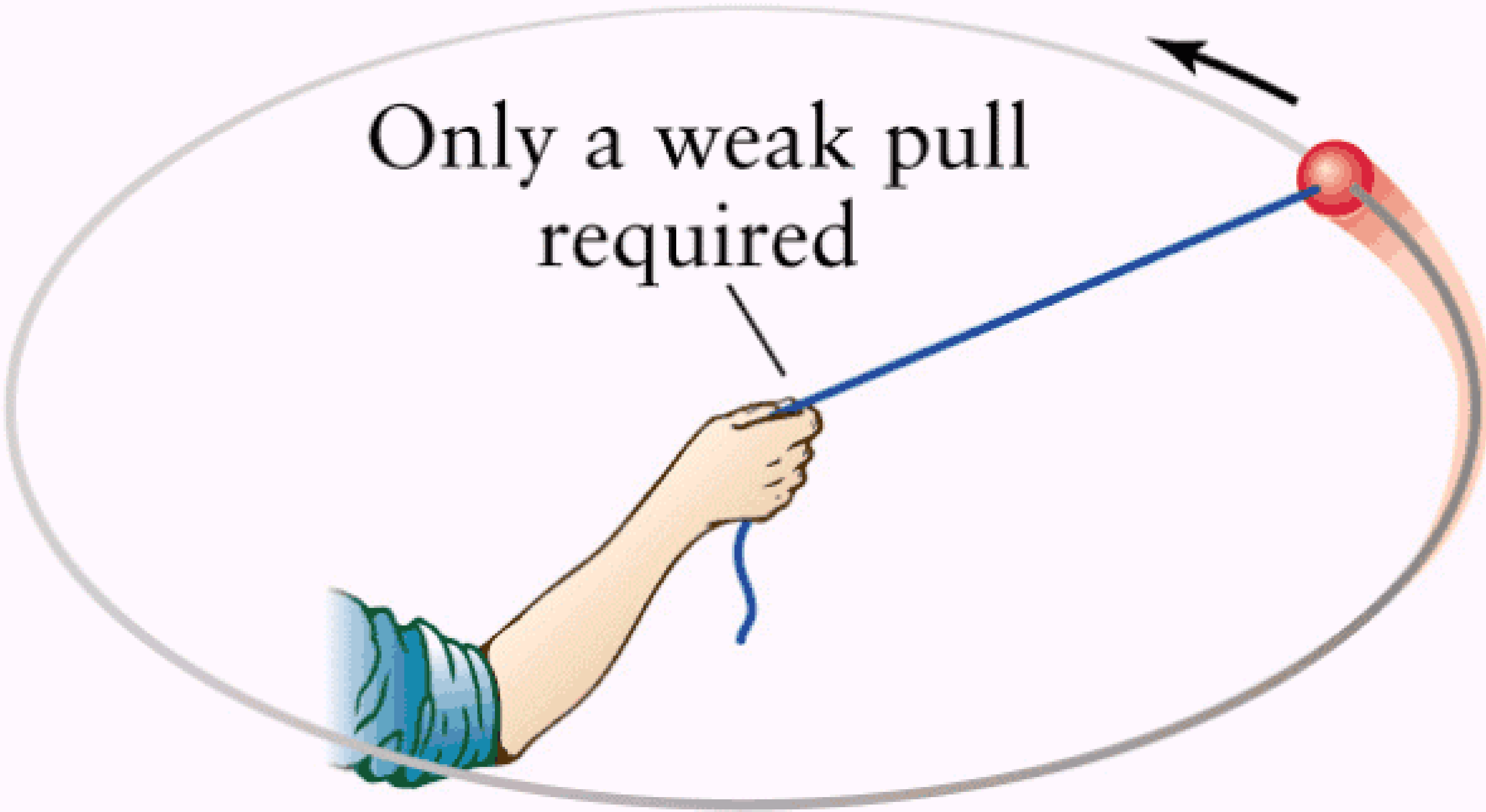
Two bodies attract each other with a force that is proportional to the mass of each body and inversely proportional to the square of the distance between them.

$$F = G\, m_1 m_2 / r^2$$

Where $G = 6.67 \times 10^{-11}$ N m^2/kg^2 and r is the distance between the objects with masses m_1 and m_2.



a Ball moves at a high speed in a small circle

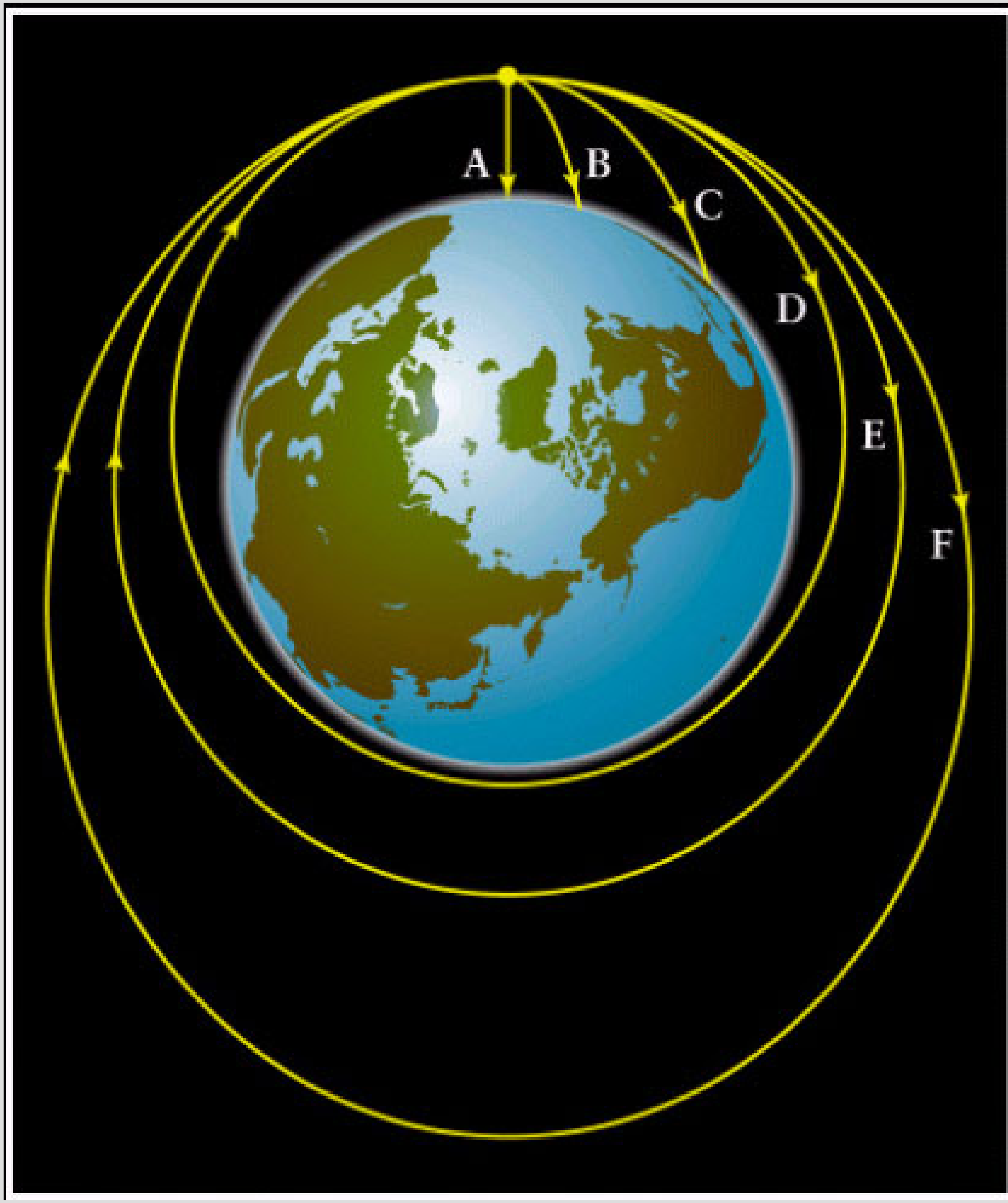


b Ball moves at a low speed in a large circle

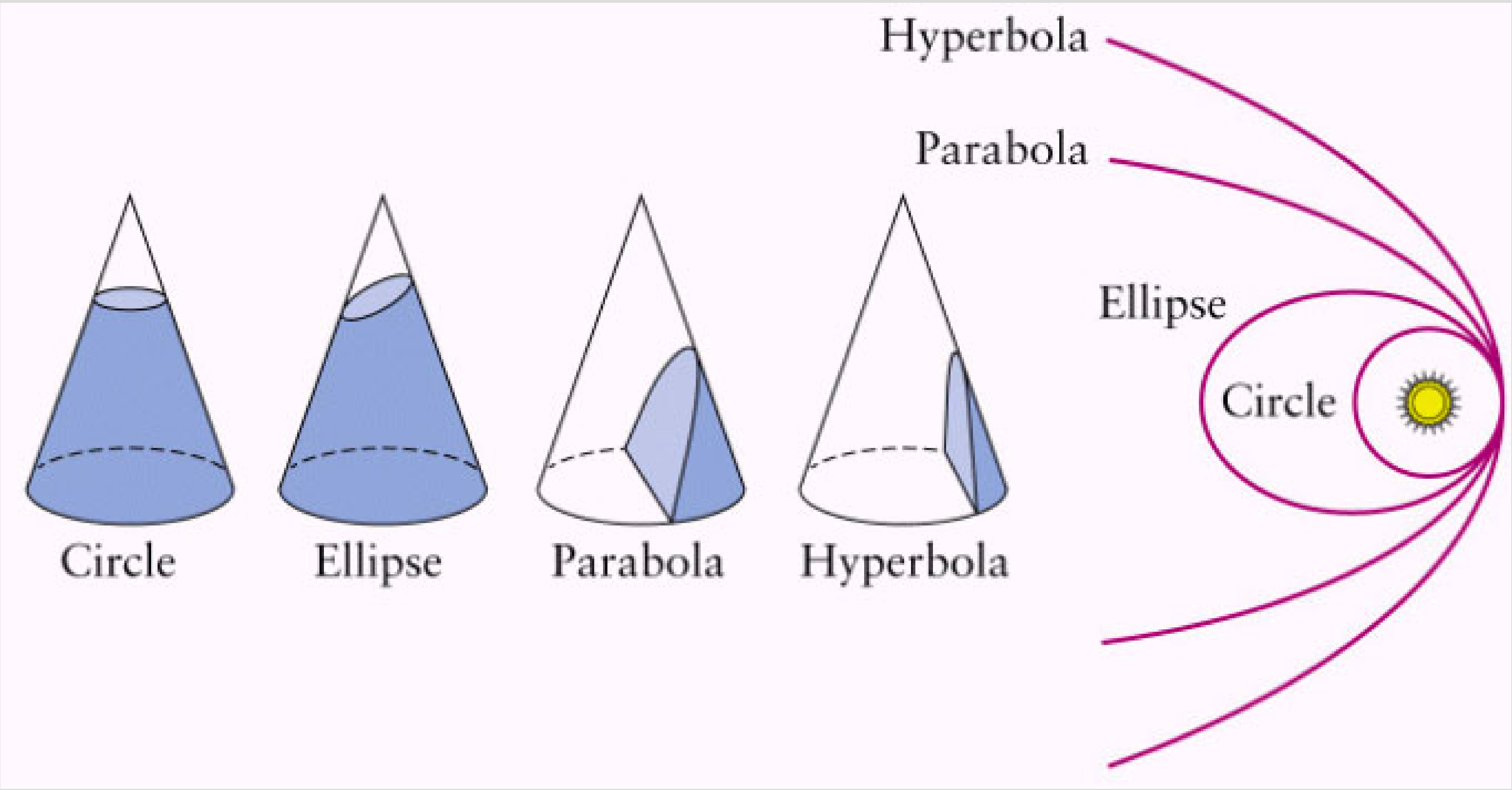
The law of universal gravitation accounts for planets not falling into the Sun nor the Moon crashing into the Earth:

Paths A, B, and C do not have enough horizontal velocity to “escape” Earth’s surface whereas Paths D, E, and F do.

Path E is where the horizontal velocity is exactly what is needed so its orbit matches the circular curve of the Earth.



Mathematically speaking, Newton discovered that orbiting bodies may follow any one of a family of curves called "conic sections."



Changing Orbits

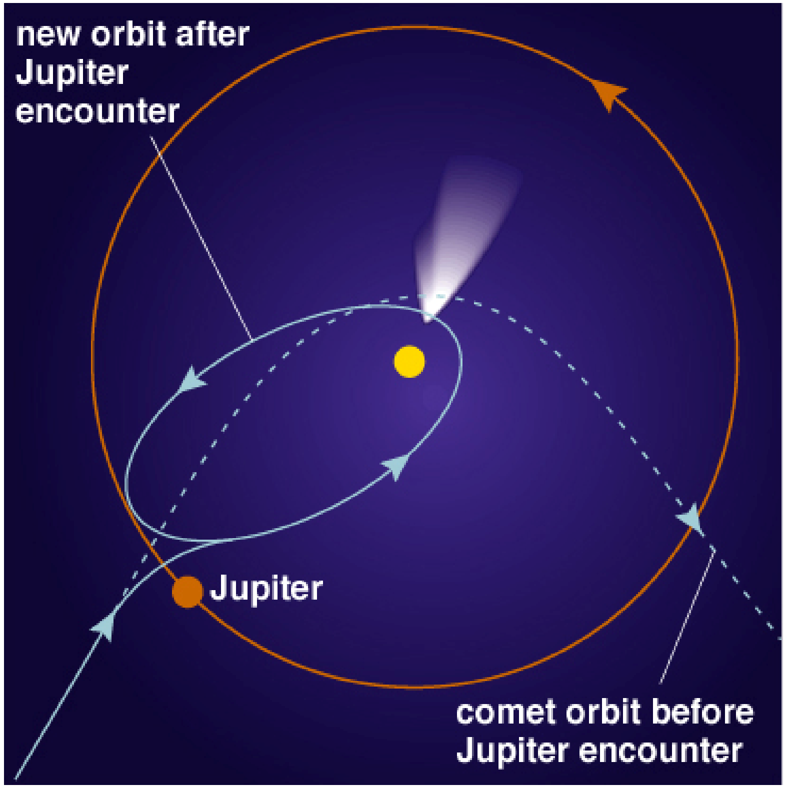
orbital energy = kinetic energy + gravitational potential energy

conservation of energy implies:

orbits can't change spontaneously

An object can't crash into a planet unless its orbit takes it there.

An orbit can only change if it gains/loses energy from another object, such as a gravitational encounter:



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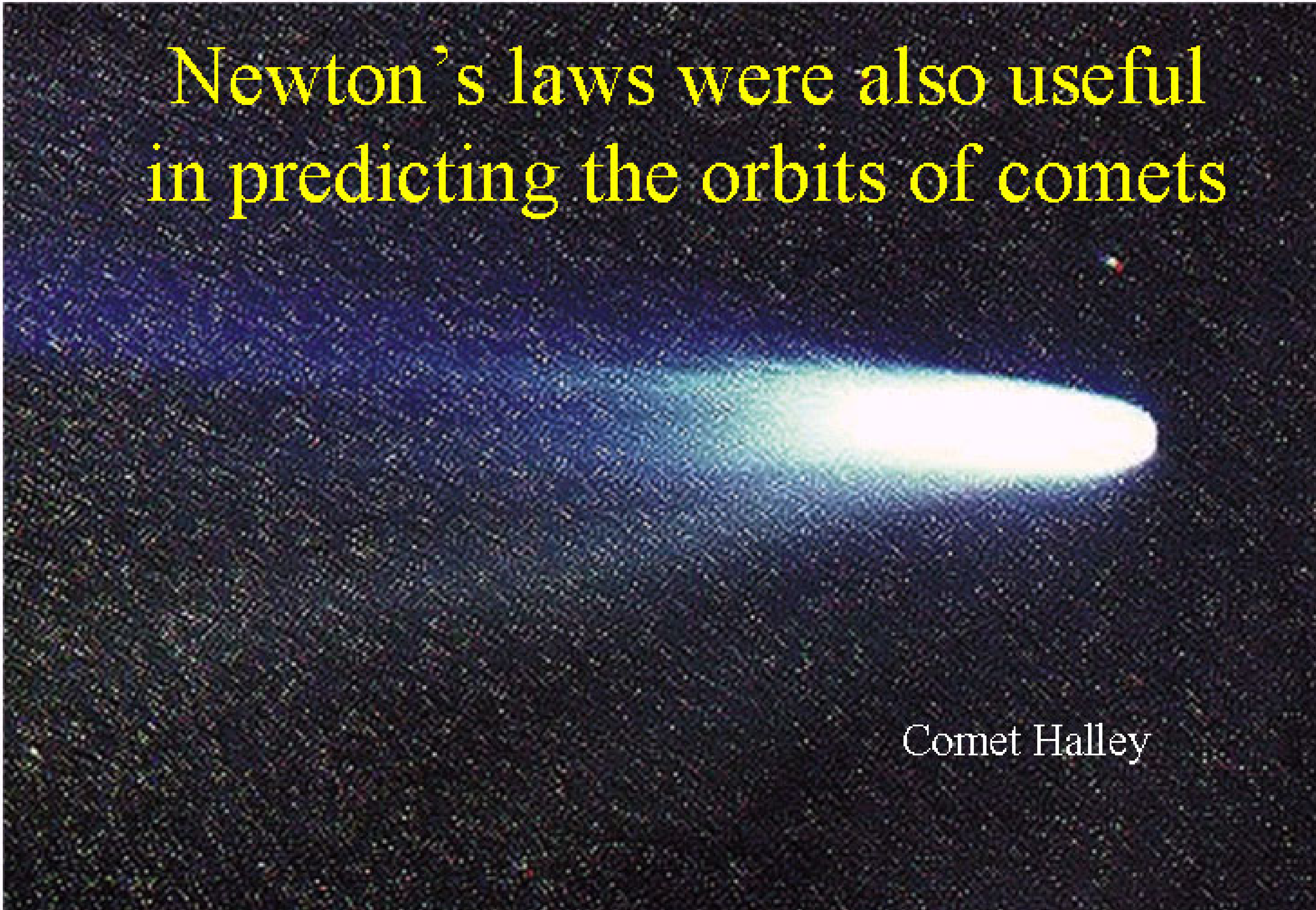
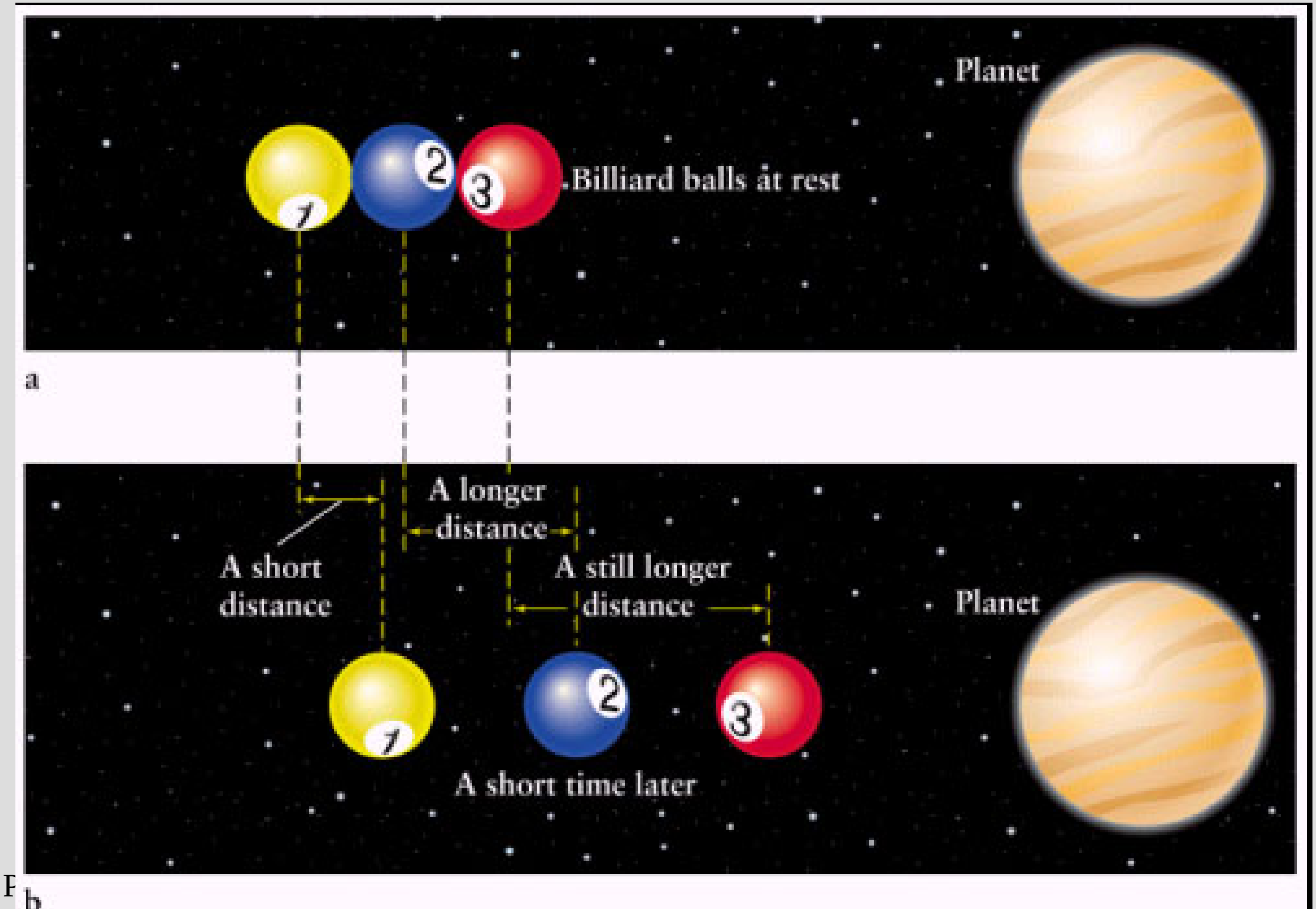
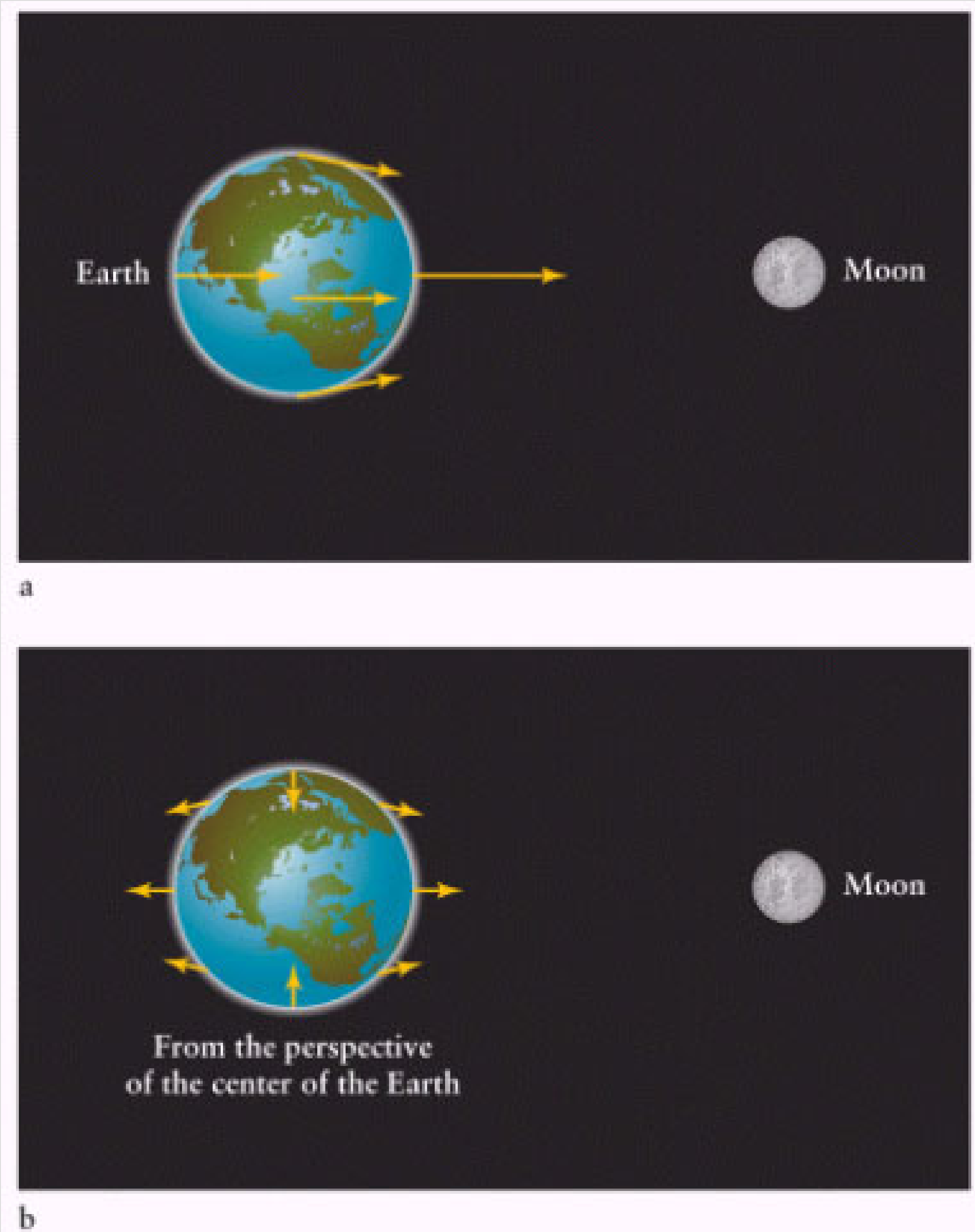
If an object gains enough energy so that its new orbit is unbound, we say that it has reached **escape velocity**.

Newton's laws were also useful in predicting the orbits of comets



Newton's laws also explain tidal forces which can deform planets, reshape galaxies.





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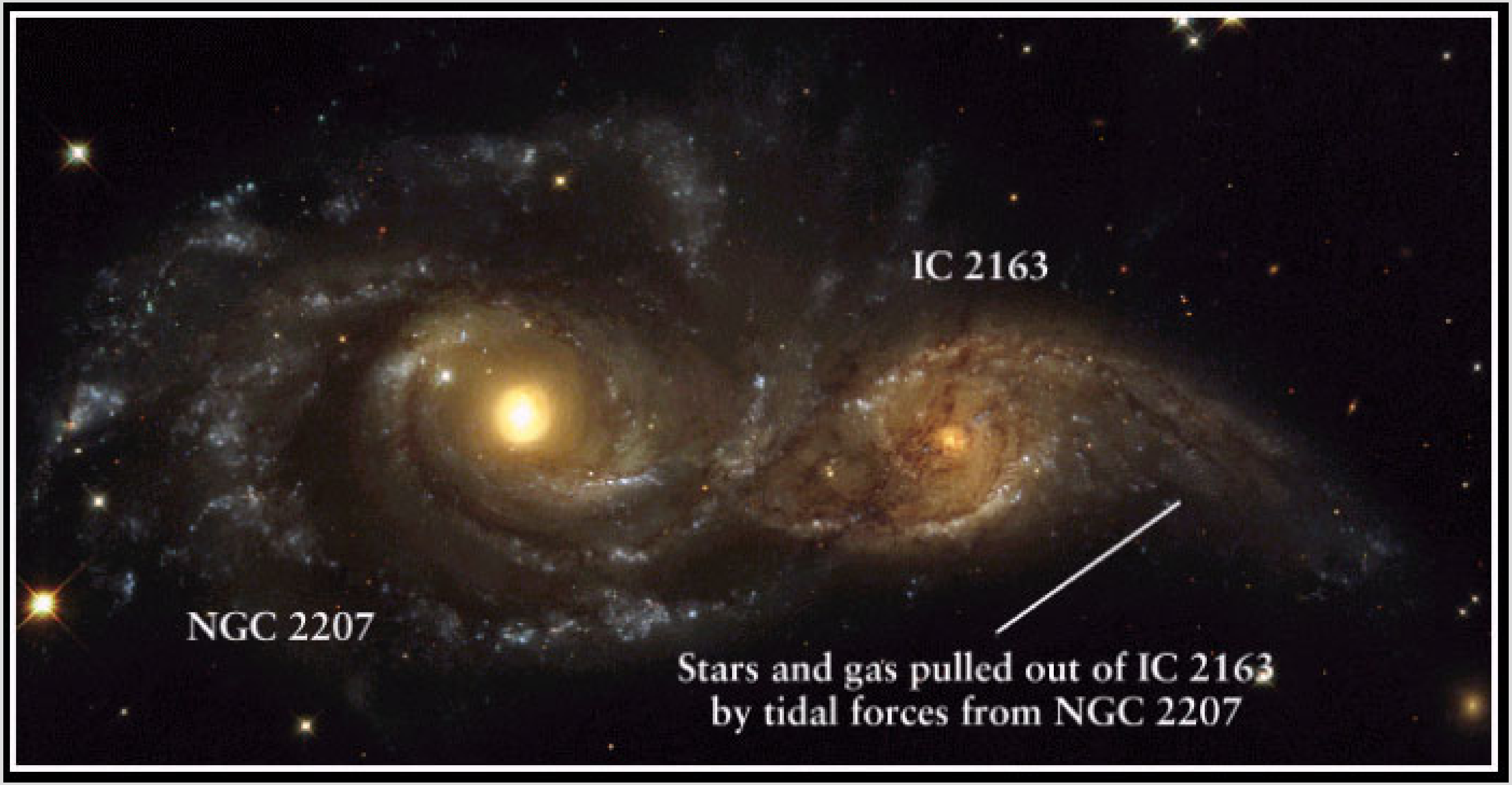
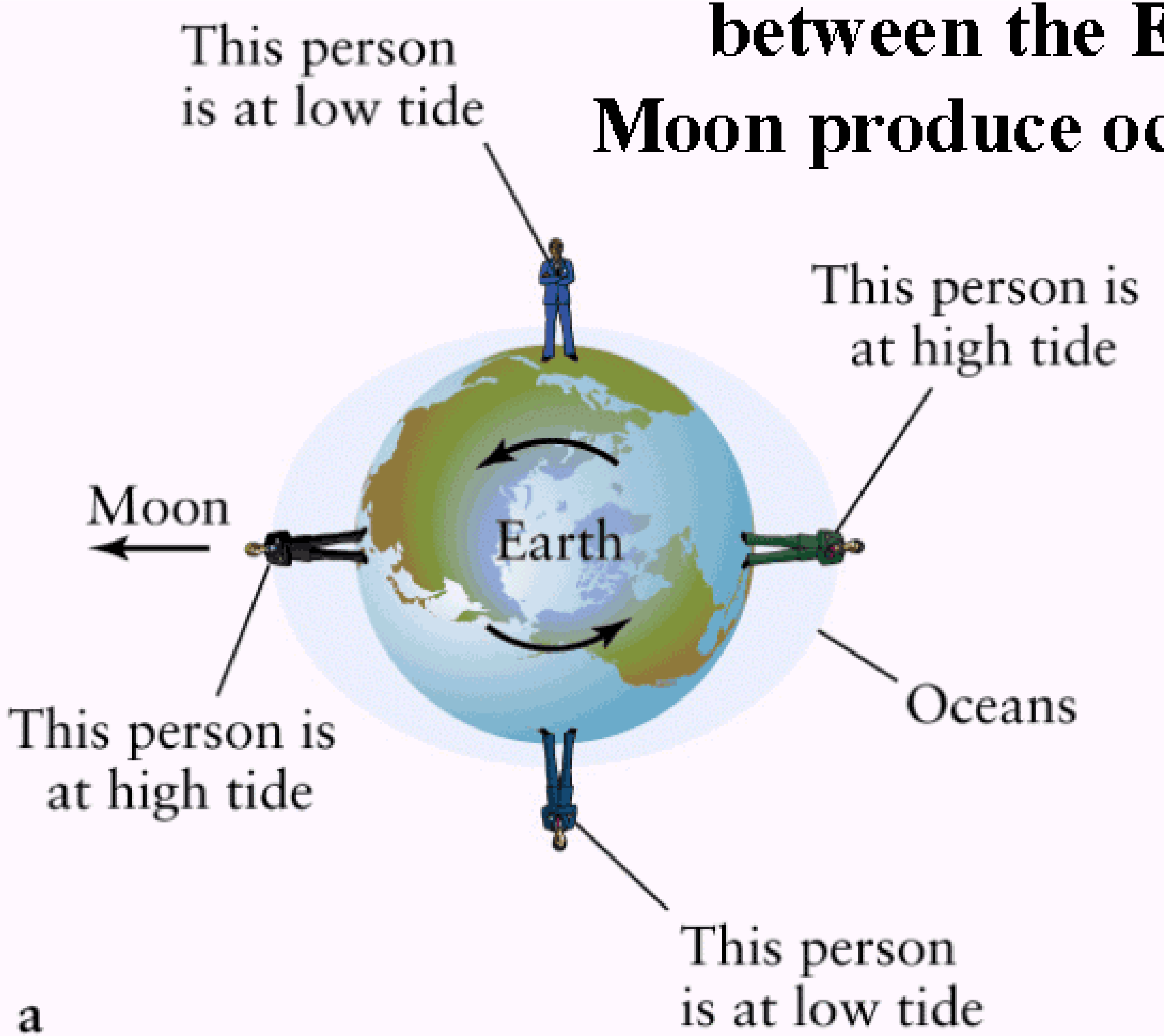


Gravitational forces between the Earth and Moon produce ocean tides



The virial theorem

- The time-averaged potential over an orbit <U> is related to the total energy by

$$\boxed{\langle U \rangle = 2E}$$

•which is actually a general result for bound systems