Today

- Gravity

Events

- Homework Due this thursday
- First Exam One Week from Thursday
  - closed book; no calculators

Extra credit
(2 points)

- List Newton's laws of motion

- Be sure to include your name and section number

- You may consult your notes, but do not communicate with anyone else

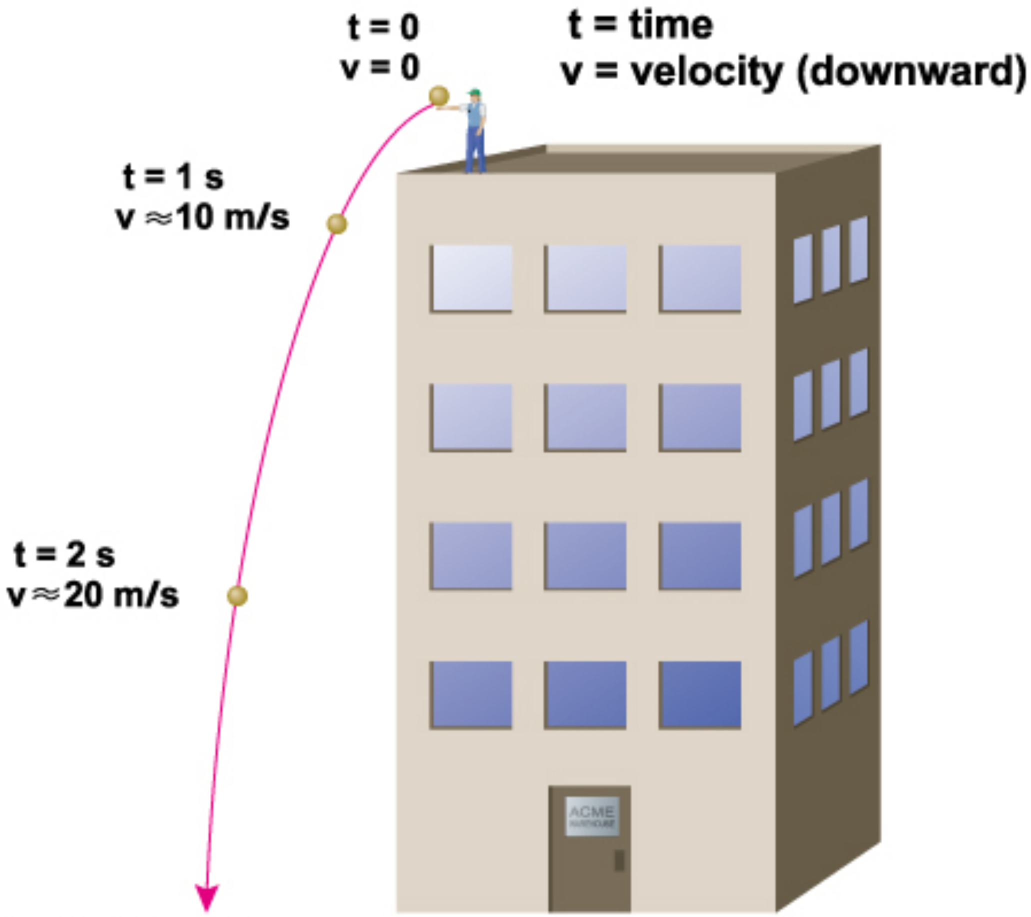
4.4 The Force of Gravity

Our goals for learning:

- What determines the strength of gravity?
- How does Newton's law of gravity extend Kepler's laws?
- How do gravity and energy together allow us to understand orbits?
- Why are large objects spherical?
- How does gravity cause tides?

Acceleration of Gravity

- All falling objects accelerate at the same rate (neglecting air resistance).
- On Earth, $g \approx 10\ \text{m/s}^2$: speed increases 10 m/s with each second of falling.



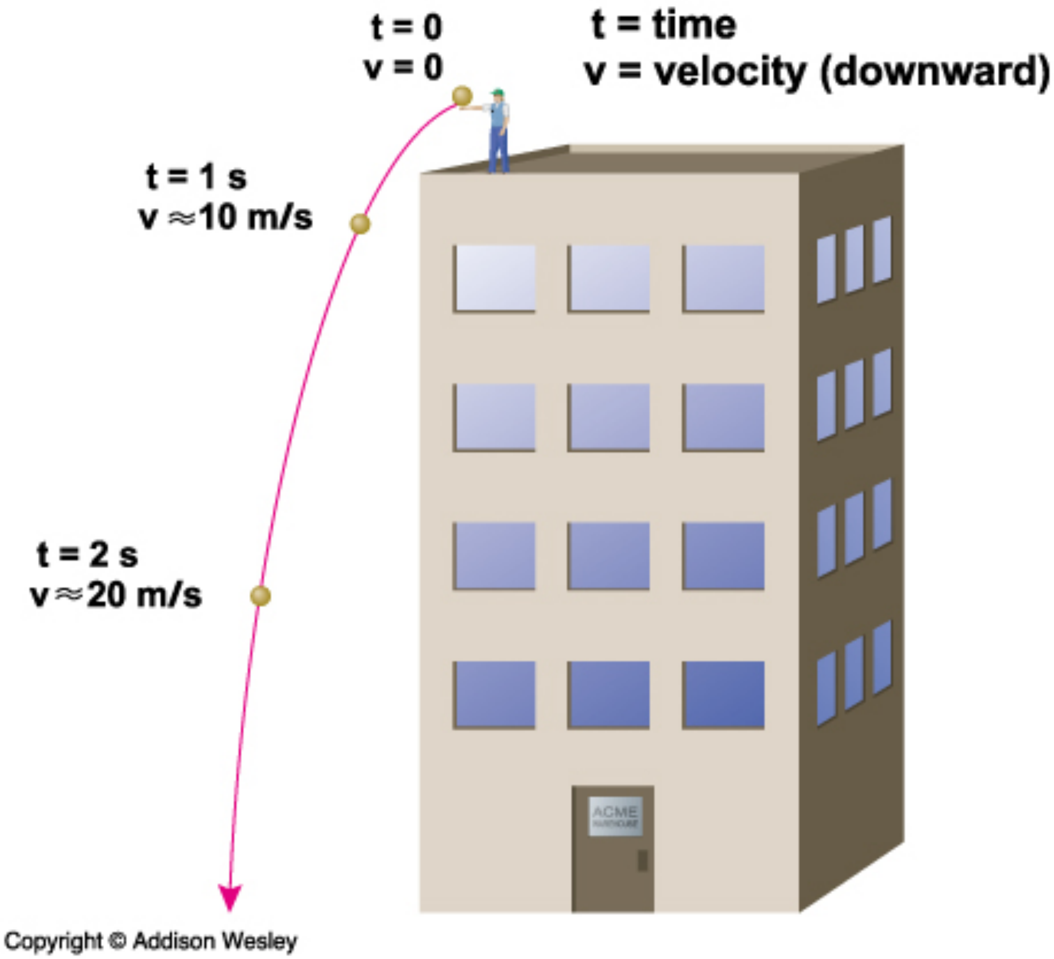
Acceleration of Gravity (*g*)

- Galileo showed that *g* is the *same* for all falling objects, regardless of their mass.

Apollo 15 demonstration

Vertical & Horizontal motion independent

- All objects accelerate at the same rate, regardless of whether
  - they fall straight down, or
  - are moving horizontally

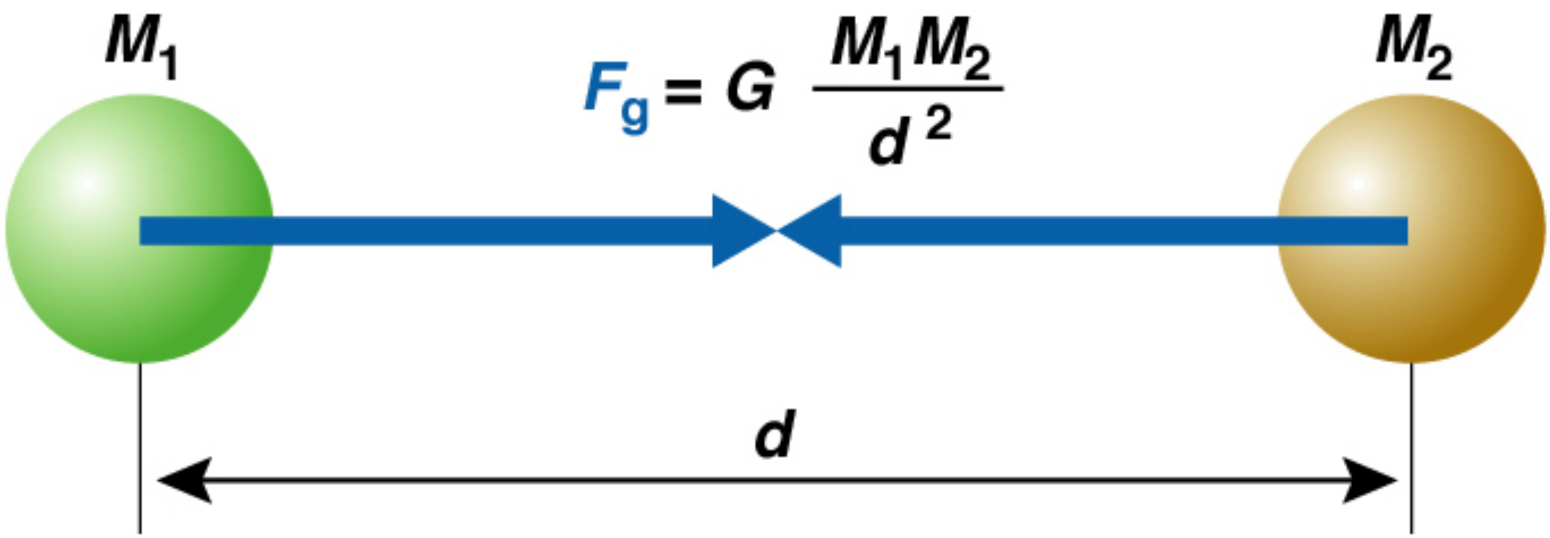



by Ham
NEWTON JUST ABOUT NEVER TO DISCOVER GRAVITY

What determines the strength of gravity?

The **Universal Law of Gravitation:**

1. Every mass attracts every other mass.
2. Attraction is *directly* proportional to the product of their masses.
3. Attraction is *inversely* proportional to the *square* of the distance between their centers.



Gravitational Force #1

Two objects are a certain distance apart. If you **increase** their distance by a factor of 3, what happens to their gravitational force?

A. The force decreases by a factor of 9

B. The force decreases by a factor of 3

C. The force increases by a factor of 3

D. The force increases by a factor of 9

E. I don't know

Gravitational Force #2

Two objects are a certain distance apart. If you **decrease** their distance by a factor of 2, what happens to their gravitational force?

A. The force decreases by a factor of 4

B. The force decreases by a factor of 2

C. The force increases by a factor of 2

D. The force increases by a factor of 4

E. I don't know

Gravitational Force #3

Two objects are a certain distance apart. If you **fix** their distance but **increase both masses** by a factor of 3, what happens to their gravitational force?

A. The force decreases by a factor of 9

B. The force decreases by a factor of 3

C. The force increases by a factor of 3

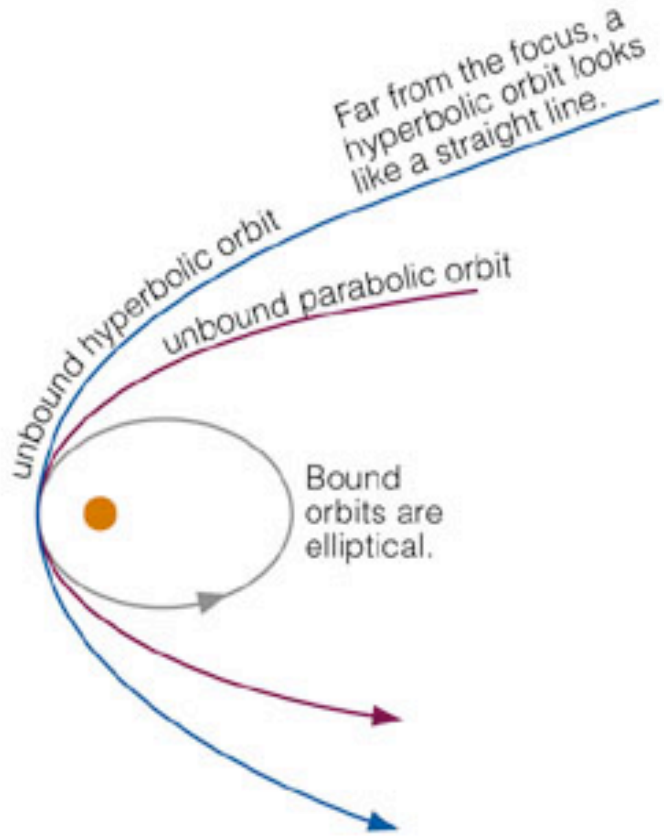
D. The force increases by a factor of 9

E. I don't know

How does Newton’s law of gravity extend Kepler’s laws?

- Kepler’s first two laws apply to all orbiting objects, not just planets. Third law applies to any object in a bound orbit.

- Ellipses are not the only orbital paths. Orbits can be:
  - — bound (ellipses)
  - — unbound
    - parabola
    - hyperbola



Newton's version of Kepler's Third Law

$$P^2 = \frac{4\pi^2}{G} \frac{a^3}{(M_1 + M_2)}$$

G=Newton's universal gravitational constant

p = orbital period

a = average orbital distance (between centers)

$(M_1 + M_2)$ = sum of object masses

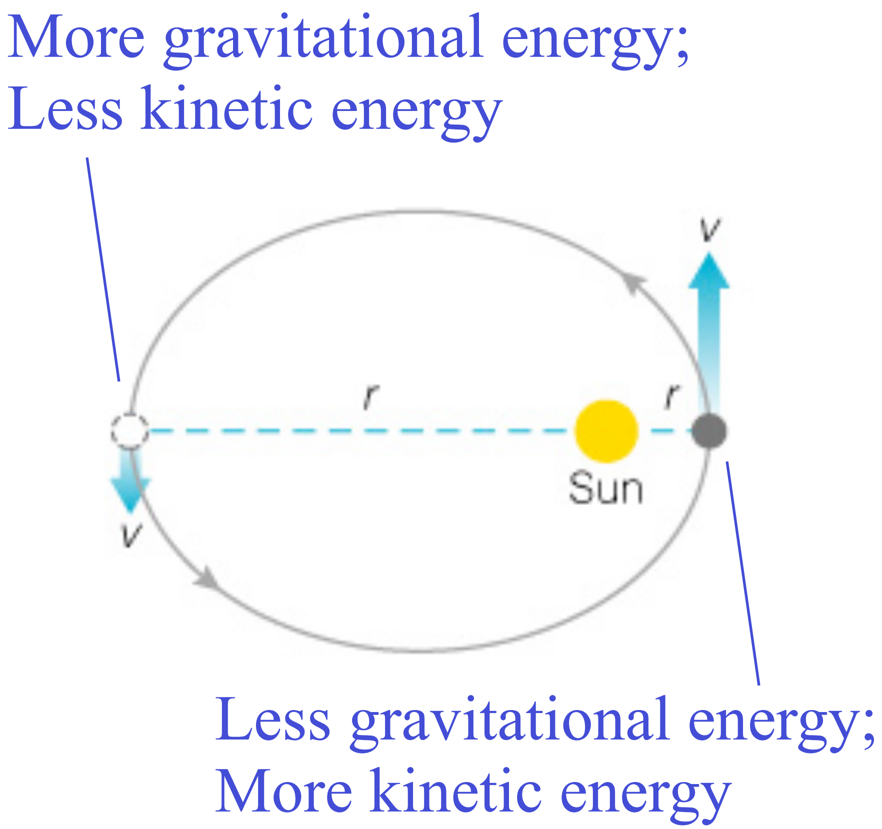
(e.g., the mass of the sun)

Orbits of the Moons of Jupiter

Moon	P (days)	a (km)	a^3/P^2 (solar masses)
Io	1.8	4×10^5	0.001
Europa	3.6	7×10^5	0.001
Ganymede	7.2	1×10^6	0.001
Callisto	16.7	2×10^6	0.001

Jupiter is 0.001 solar masses

How do gravity and energy together allow us to understand orbits?



Total orbital energy stays constant.

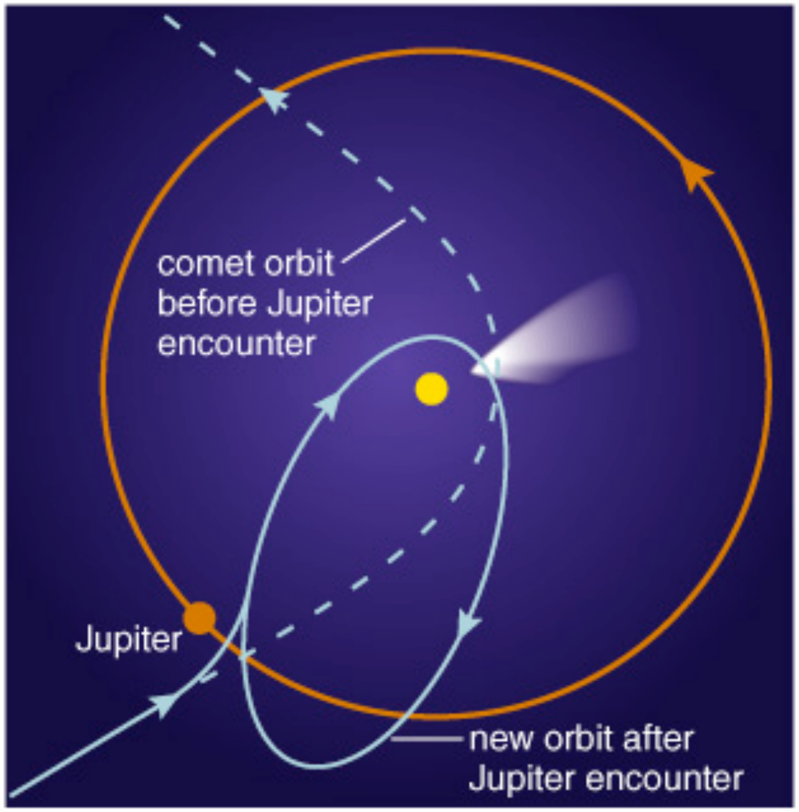
- Total orbital energy (gravitational + kinetic) stays constant if there is no external force.
- Orbits cannot change spontaneously.

Changing an Orbit

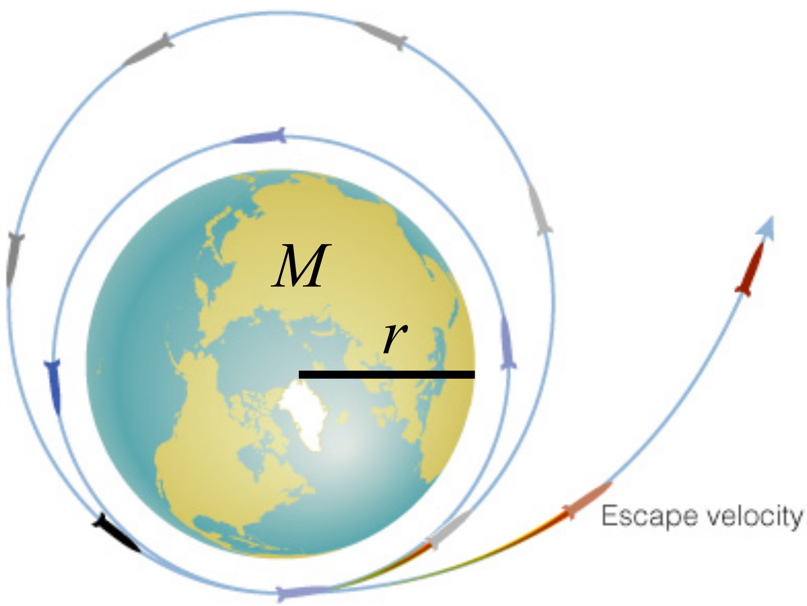
⇒ So what can make an object gain or lose orbital energy?

- Friction or atmospheric drag
- A gravitational encounter
- The thrust of a rocket

i.e., some external force

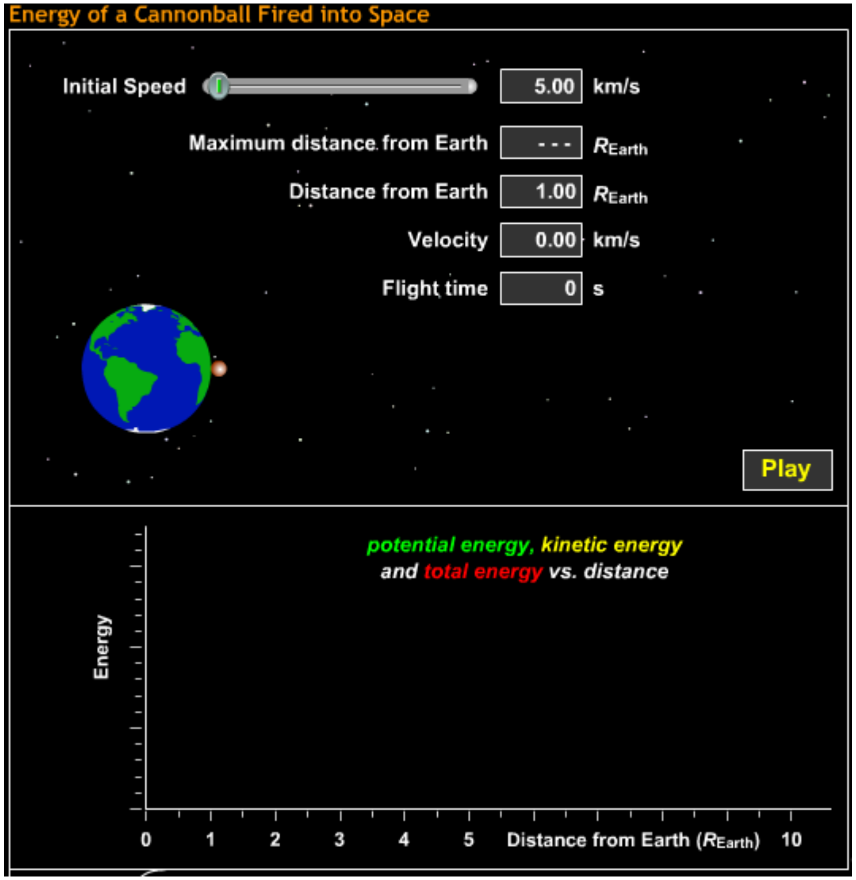


Escape Speed



- An orbit can be changed by adding or removing energy.
- If an object gains enough orbital energy, it may escape (change from a bound to unbound orbit).
- **Escape speed** from Earth ≈ 11 km/s from sea level (about 40,000 km/hr).

Escape Speed Demo



Circular & Escape speed

Circular speed:

(minimum energy orbit)

$$v_{circ} = \sqrt{\frac{GM}{r}}$$

Escape speed:

$$v_{esc} = \sqrt{\frac{2GM}{r}} = \sqrt{2}v_{circ}$$

(maximum energy orbit
where object becomes unbound)

E1-11

Examples:

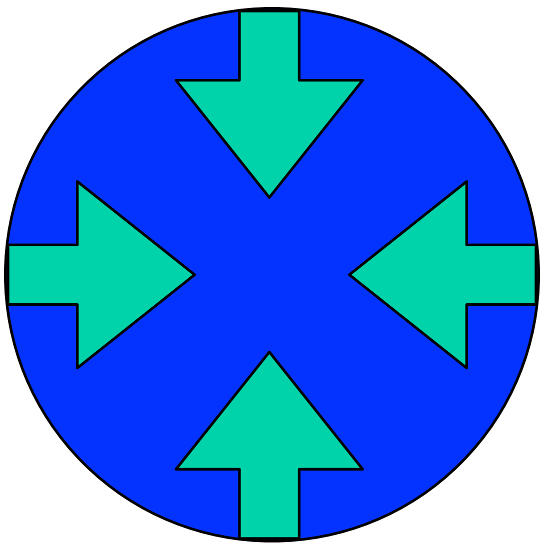
Object	circular speed at surface	escape speed from surface
Earth	7.8 km/s	11 km/s
Sun	436 km/s	617 km/s
Moon	1.7 km/s	2.4 km/s

What have we learned?

- What determines the strength of gravity?
  - Directly proportional to the *product* of the masses ($M \times m$)
  - *Inversely* proportional to the *square* of the separation
- How does Newton's law of gravity allow us to extend Kepler's laws?
  - Applies to other objects, not just planets
  - Includes unbound orbit shapes: parabola, hyperbola as well as bound ellipse
  - Can be used to measure mass of orbiting systems

Why are stars and planets spherical?

- Gravity pulls - it is an attractive force
- IF self-gravity is the most important force holding an object together, it must be spherical.



Example: Earth

- Diameter of Earth: 12,756 km
- Mt. Everest: 8.848 km above sea level
- Mariana Trench: 10.934 km below
- Maximum variation: 19.782 km

$$\frac{\text{maximum variation}}{\text{diameter}} = \frac{19.782}{12,756}$$

$$= 0.0015$$

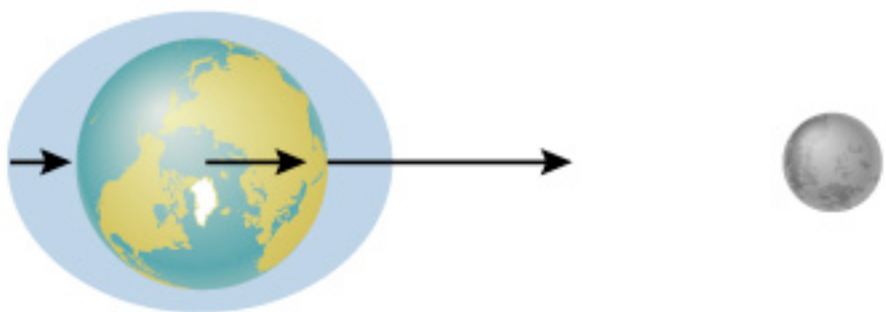
- a very smooth sphere!

- Gravity makes individual objects round
  - about 100 km in diameter is where objects start to become dominated by self-gravity
    - planets round
    - asteroids still lumpy

Why does the Moon always show the same face to Earth?

- Moon rotates in the same amount of time that it orbits…
- But why?

Tides

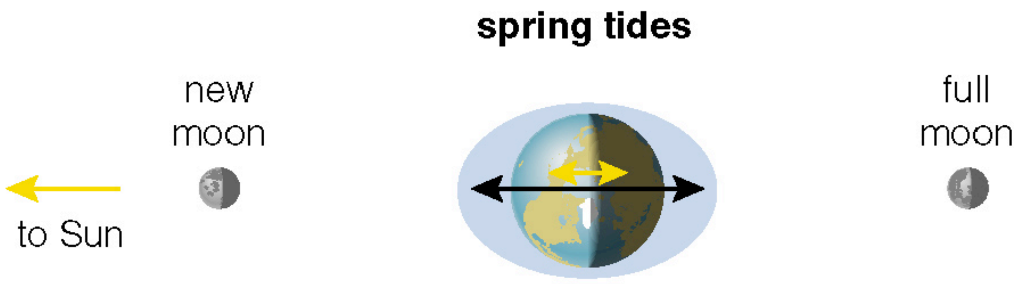


Tides are the result of differential gravity

Not to scale!

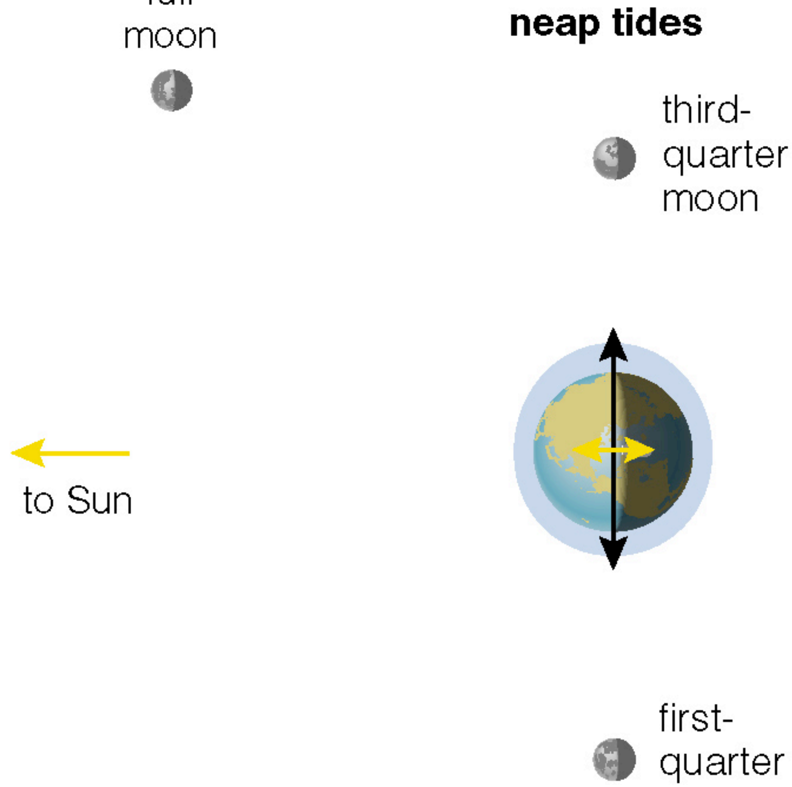
- The Moon’s gravity pulls harder on near side of Earth than on far side (inverse square law).
- The difference in the Moon’s gravitational pull stretches Earth.

Tides and Phases

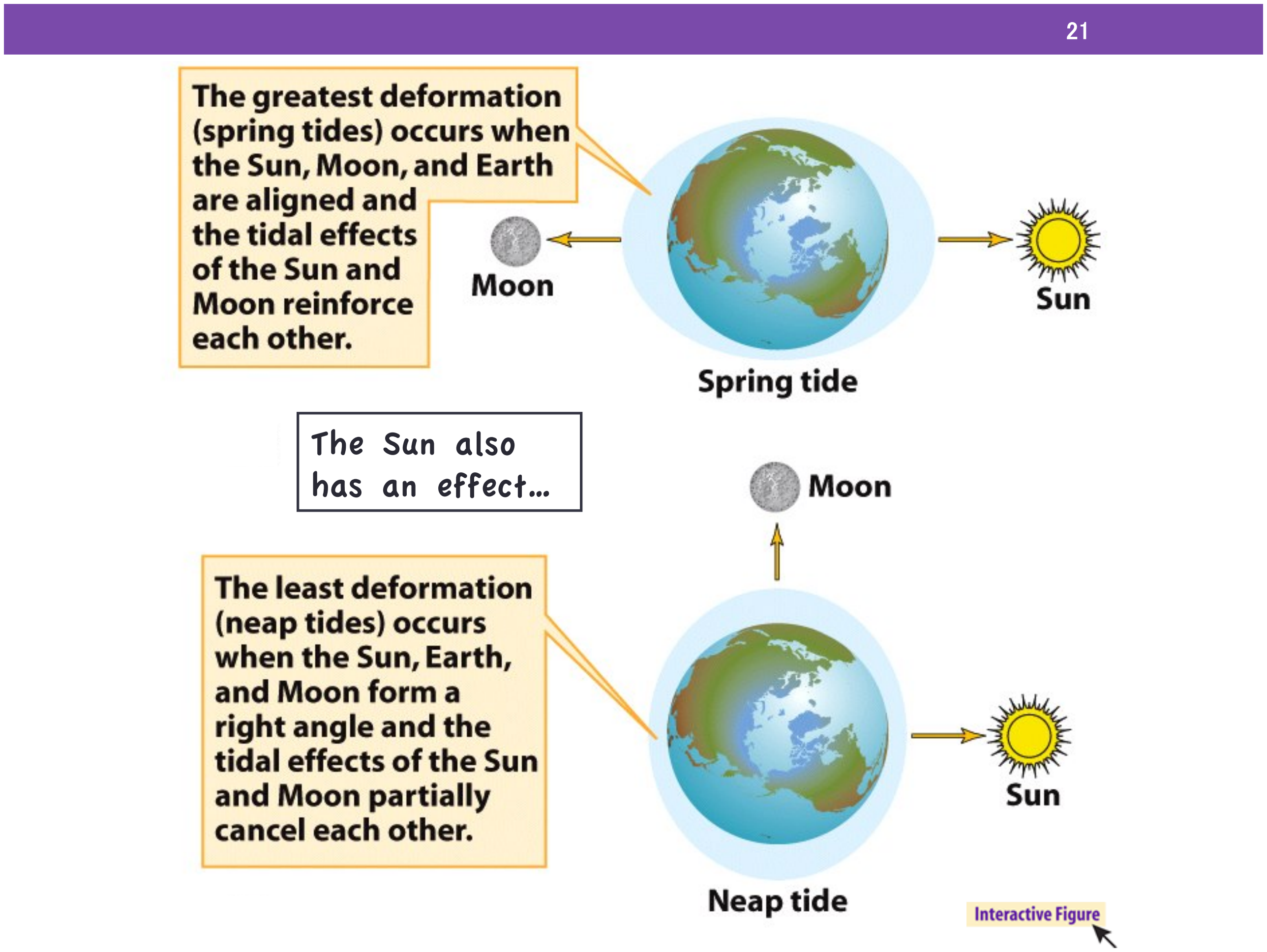


Size of tides depends on the phase of the Moon.

Spring tides are stronger than neap tides because the sun and moon team up at new & full moon.

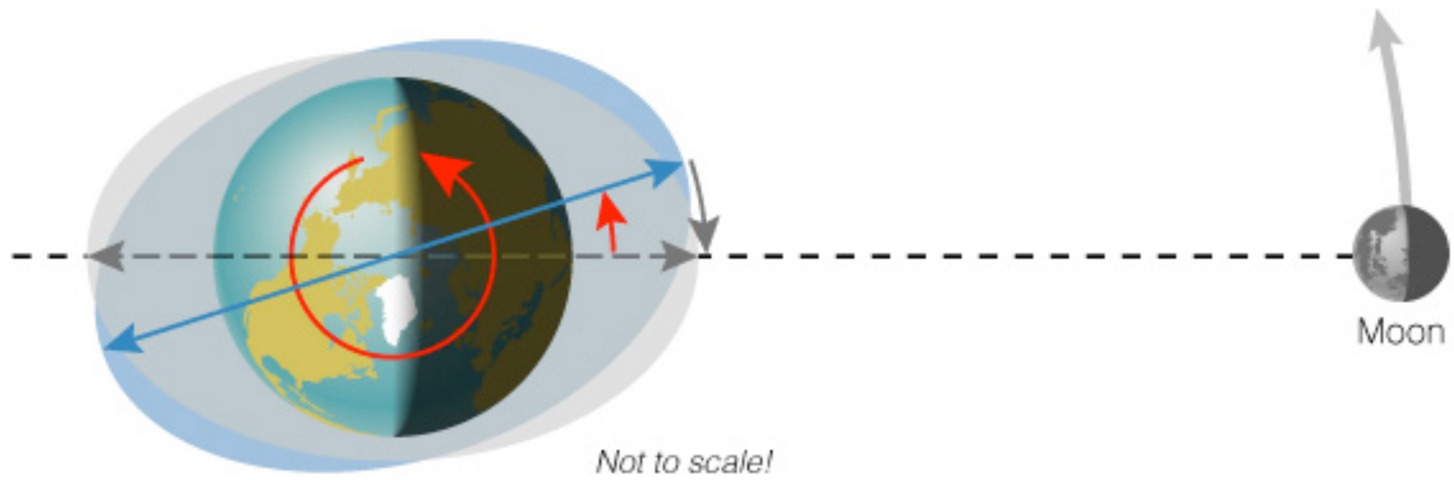


Tidal Demo



The Sun also has an effect...

Tidal Friction



0.002 seconds per day per century

- Tidal friction gradually slows Earth rotation
  - Moon gradually drifts farther from Earth   about one inch/year
  - conservation of angular momentum
- Moon once spun faster; tidal friction caused it to “lock” in synchronous rotation
  - orbit period:spin period = 1:1
  - keeps same face towards us all the time

Corner cube reflector on Moon; developed at UMd!

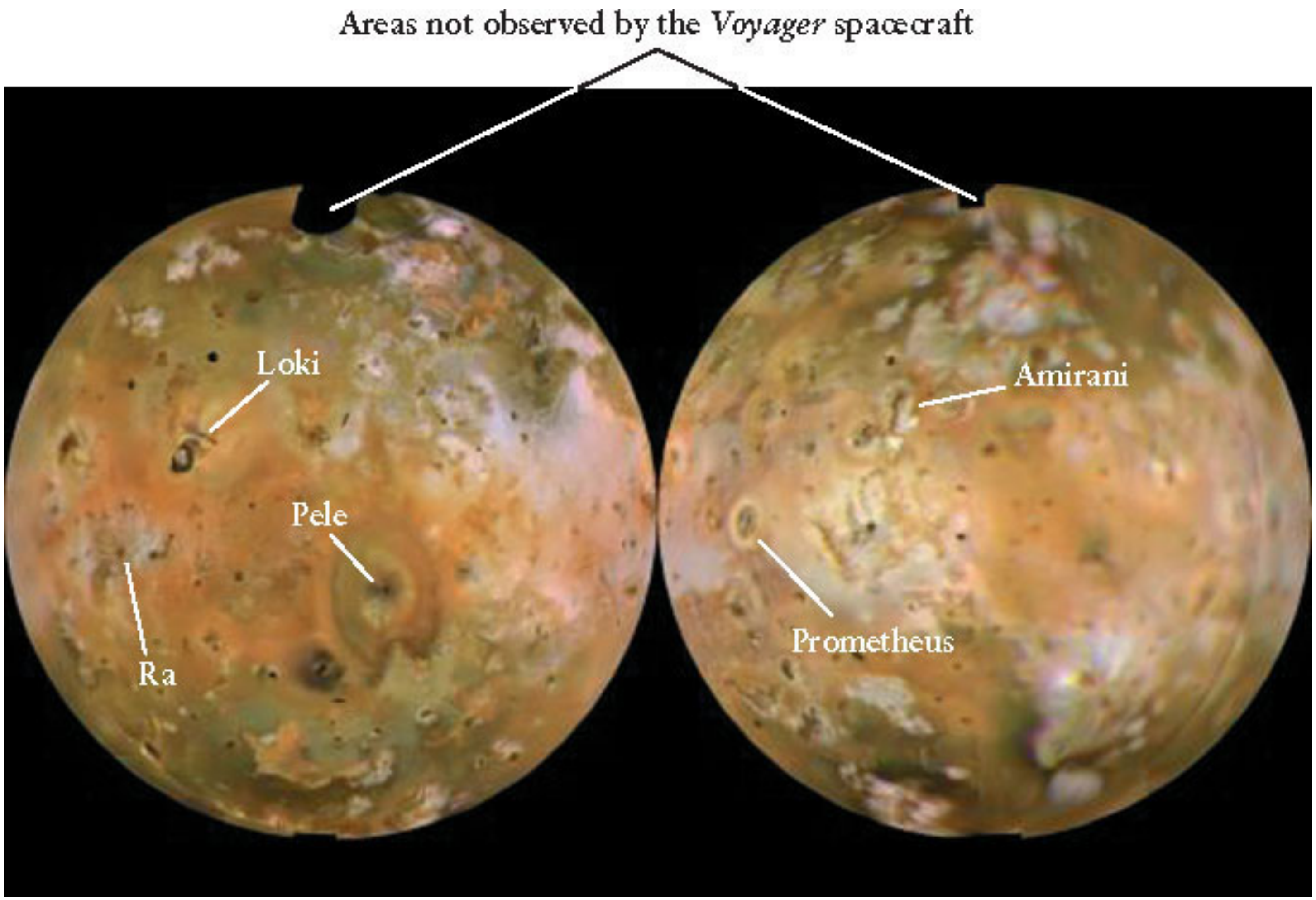
Tides Beyond the Earth-Moon System

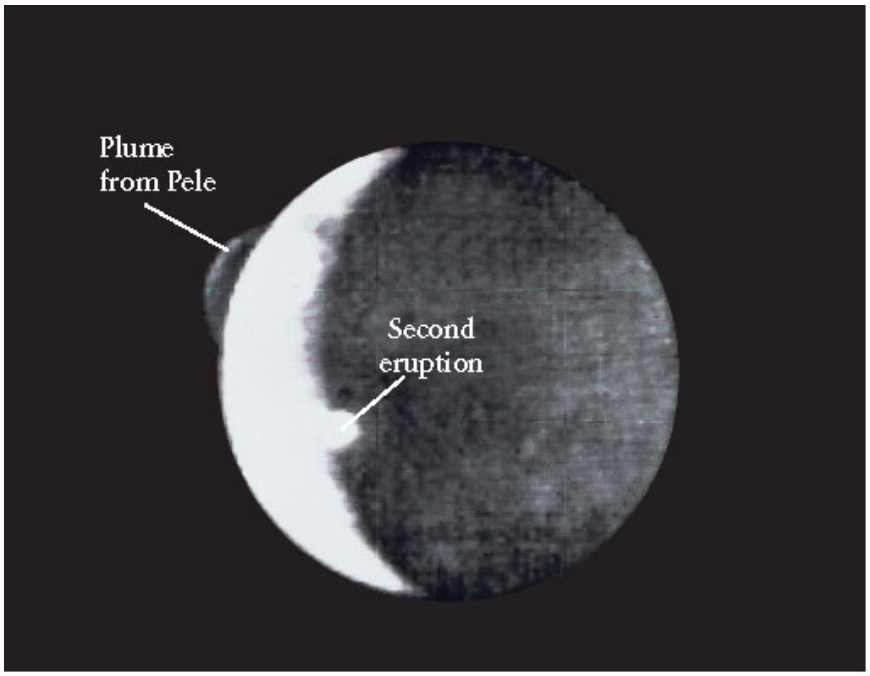
- Tides in the solar system:
  - Jupiter’s Moon Io.
  - The case of comet Shoemaker-Levy 9.

- Tides in the universe:
  - Galaxy collisions.

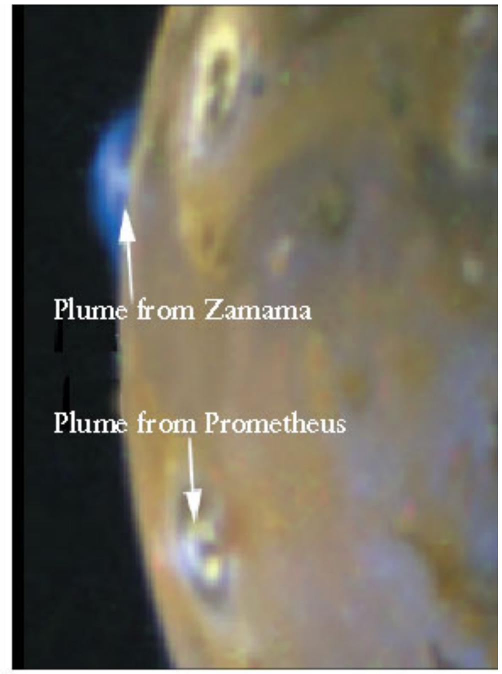
Io

- Io is a satellite of Jupiter.
  - Closest of the 4 Galilean satellites.
  - Orbits Jupiter with period of 1.77 days.
  - Tidal forces have locked it into synchronous rotation with its orbit.
- Here's where life gets interesting…
  - Perturbations from Europa and Ganymede force Io's orbit to be slightly elliptical…
  - So tidal forces slightly change over the course of the orbit.
  - The varying flexing/squeezing of Io causes its interior to be heated… drives powerful volcanic action.

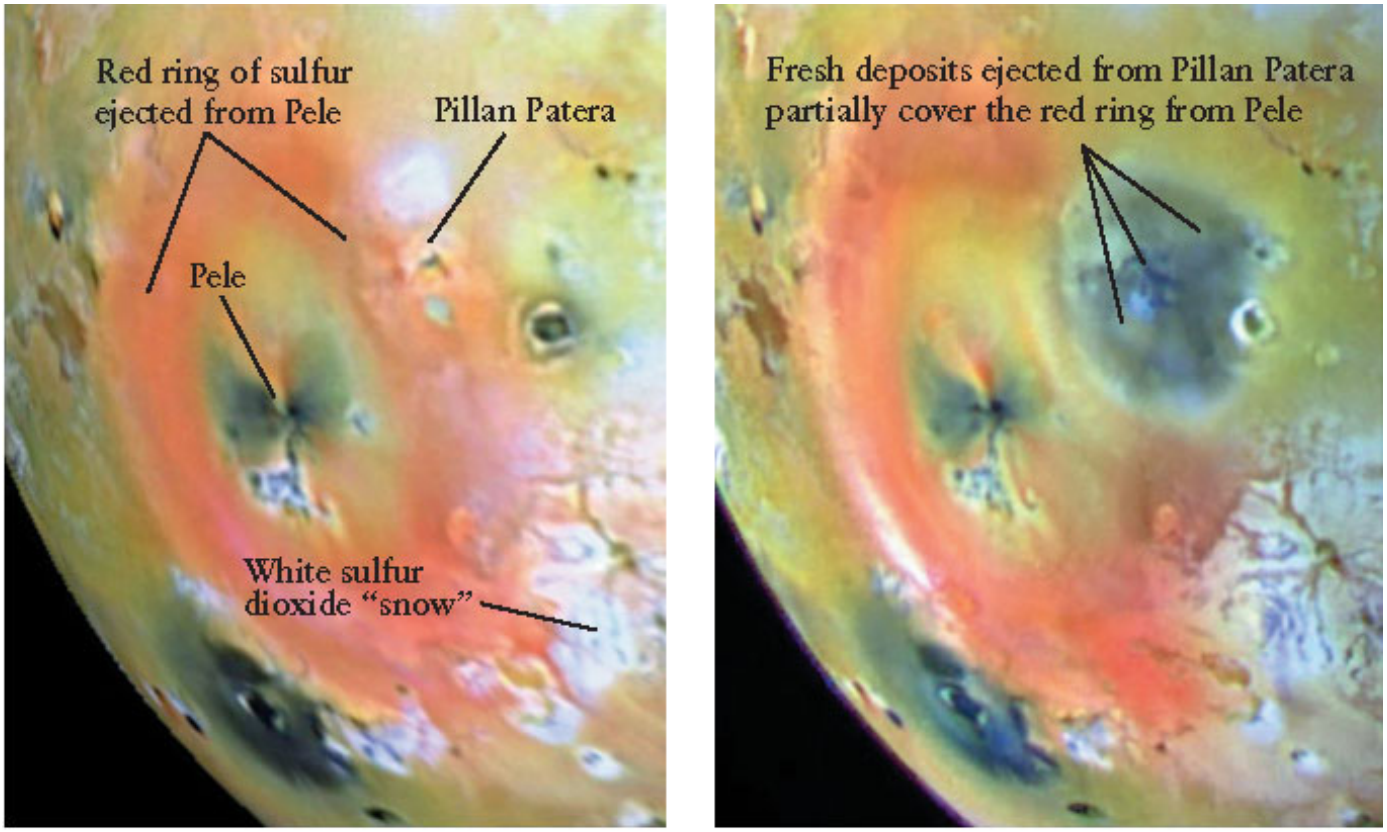

Areas not observed by the *Voyager* spacecraft
Loki
Pele
Ra
Amirani
Prometheus



(a) *Voyager 1*, March 1979



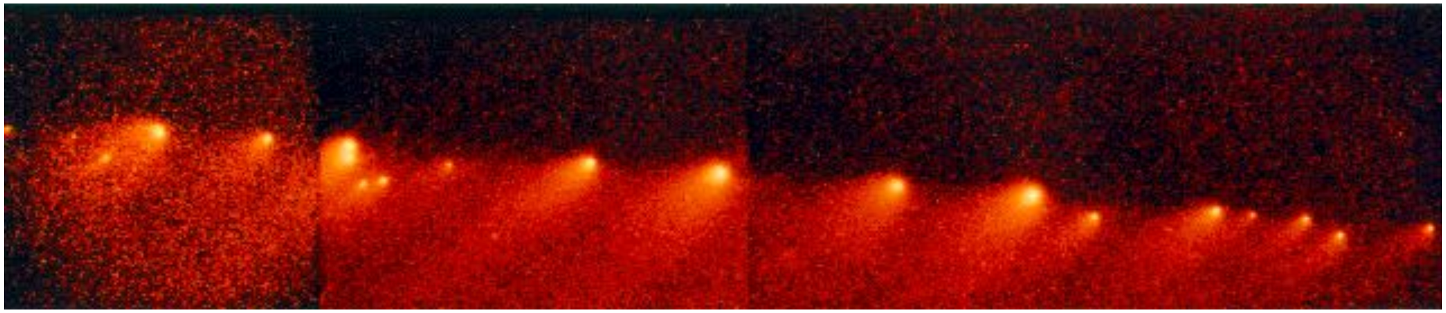
(b) *Galileo*, November 1997


Red ring of sulfur ejected from Pele
Pillan Patera
Pele
White sulfur dioxide "snow"
Fresh deposits ejected from Pillan Patera partially cover the red ring from Pele

(a) (b)

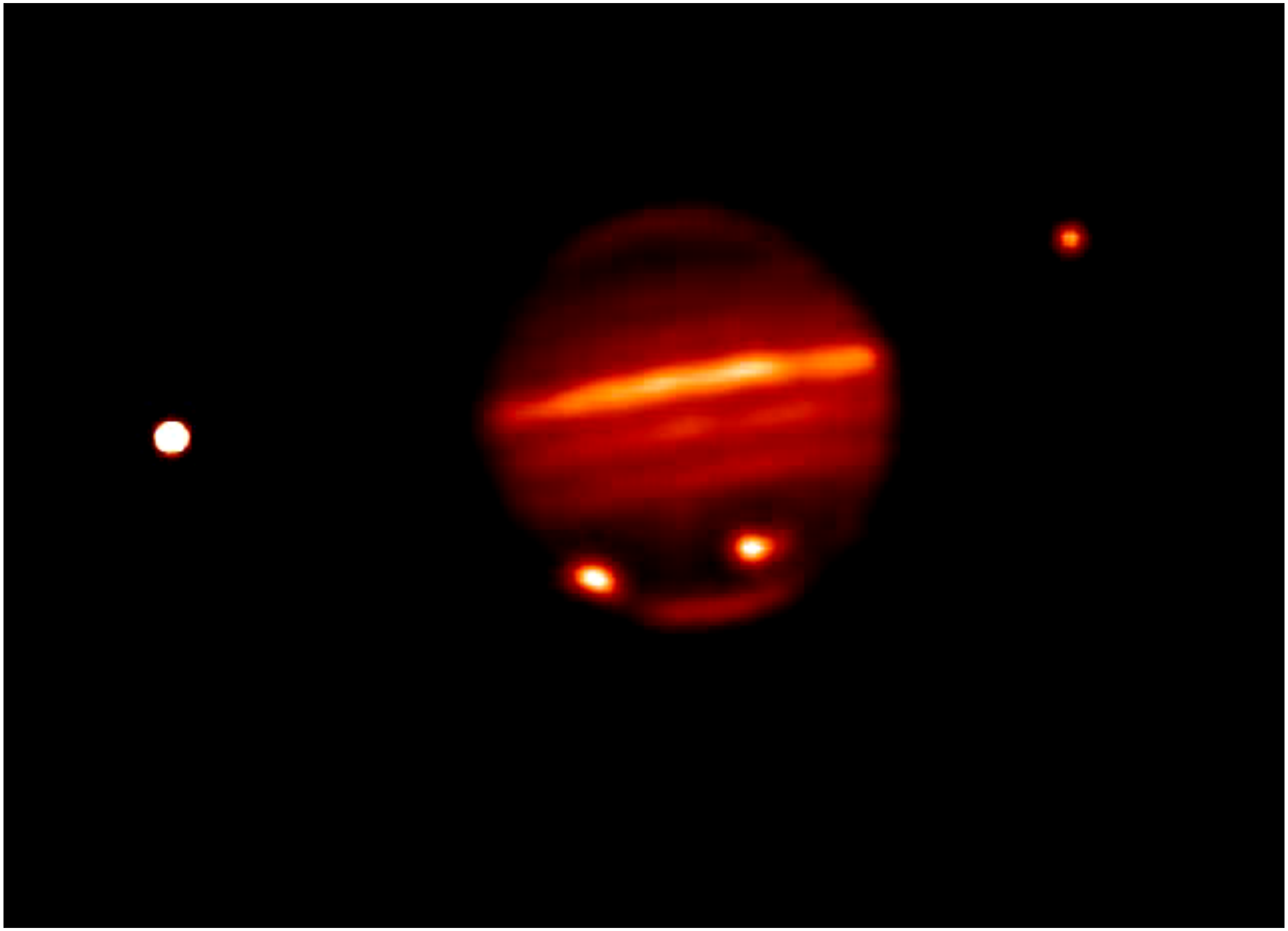
Comet Shoemaker-Levy 9

- Discovered by Eugene & Carolyn Shoemaker and David Levy on 24th March 1993.
- Unusual comet: a whole string of nuclei.



Why a string of nuclei?

- Computations of the orbit show that…
  - SL9 came very close to Jupiter in 1992.
  - Close enough for tidal forces to completely rip it to bits.
  - SL9 would hit Jupiter in 1994.
- First-ever time that modern scientists could study comet-planet collision.



Summary

- Kepler's Laws follow naturally from Newton's Universal Law of Gravity
- Gravitationally bound objects are spherical
  - e.g., planets, stars
- Tides are caused by the differential gravity of the sun and moon
  - Spring tides are cause when the sun and moon are aligned; neap tides when they are perpendicular.
- Tidal friction gradually changes
  - the orbit of the moon and the spin of the earth