

Section 11: More on Tidal Forces

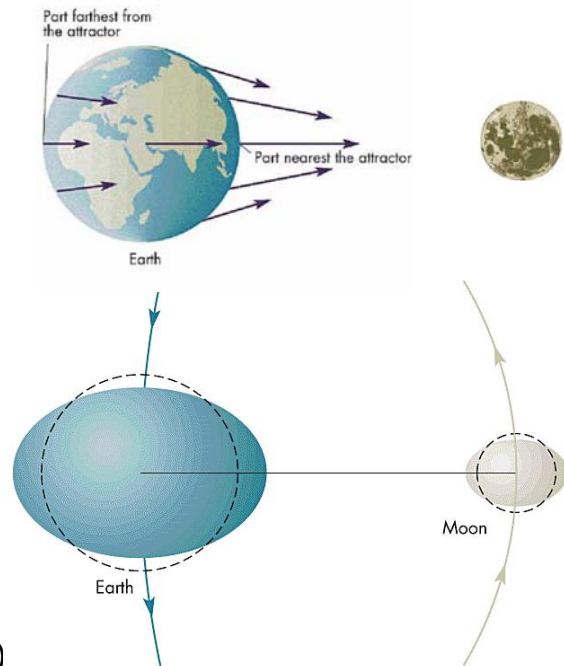
Tidal forces also have an effect (albeit less destructive) *outside* the Roche stability limit.

Consider the Moon's tide on the Earth (and vice versa).

The tidal force produces an oval bulge in the shape of the Earth (and the Moon)

There are, therefore, **two** high and low tides every ~25 hours.

(Note: not every 24 hours, as the Moon has moved a little way along its orbit by the time the Earth has completed one rotation)



The Sun also exerts a tide on the Earth.

Now, $F_T \propto \frac{M_P}{r^3}$ so

$$\frac{F_{T,\text{Sun}}}{F_{T,\text{Moon}}} = \frac{M_{\text{Sun}}}{M_{\text{Moon}}} \left(\frac{r_{\text{Moon}}}{r_{\text{Sun}}} \right)^3 \quad (11.1)$$

and

$$M_{\text{Sun}} = 1.989 \times 10^{30} \text{ kg} \quad M_{\text{Moon}} = 7.35 \times 10^{22} \text{ kg}$$

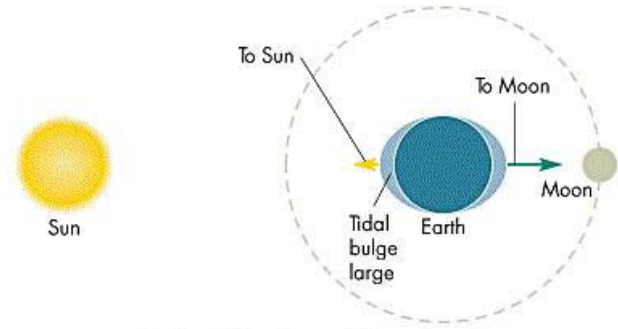
$$r_{\text{Sun}} = 1.496 \times 10^{11} \text{ m} \quad r_{\text{Moon}} = 3.844 \times 10^8 \text{ m}$$

so that

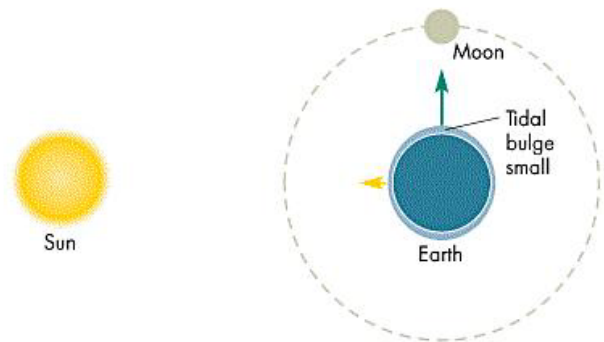
$$\frac{F_{T,\text{Sun}}}{F_{T,\text{Moon}}} = \frac{M_{\text{Sun}}}{M_{\text{Moon}}} \left(\frac{r_{\text{Moon}}}{r_{\text{Sun}}} \right)^3 \approx 0.5 \quad (11.2)$$

The Sun and Moon exert a tidal force similar in magnitude. The size of their combined tide on the Earth depends on their *alignment*.

Spring tides occur when the Sun, Moon and Earth are aligned (at Full Moon and New Moon). High tides are much higher at these times.

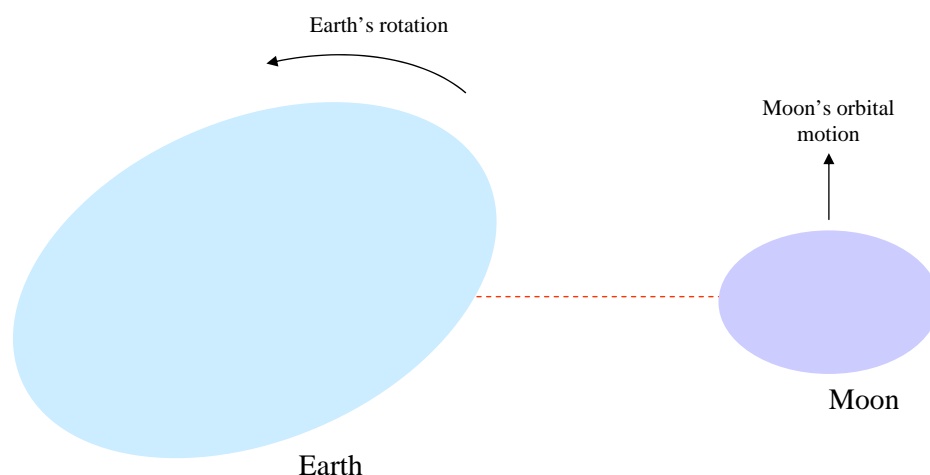


Neap tides occur when the Sun, Moon and Earth are at right angles (at First Quarter and Third Quarter). Low tides are much lower at these times.



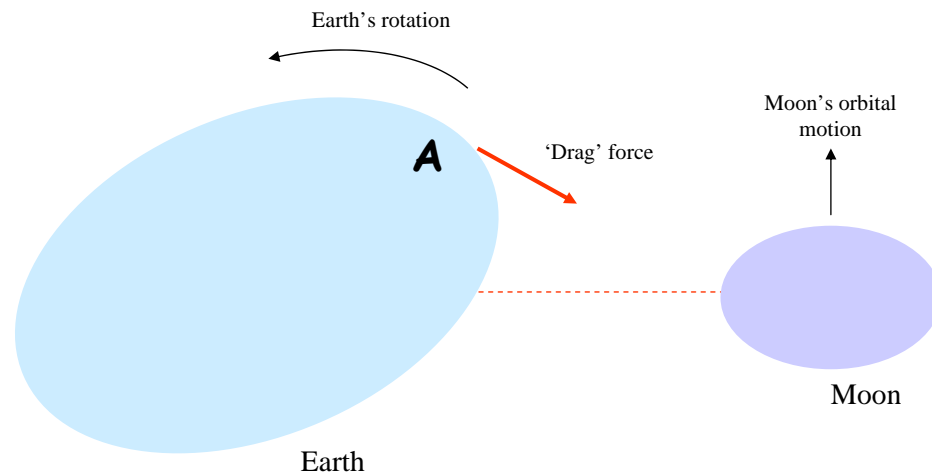
Even if there were no tidal force on the Earth from the Sun, the Earth's tidal bulge would **not** lie along the Earth-Moon axis. This is because of the Earth's rotation.

The Earth's rotation carries the tidal bulge ahead of the Earth-Moon axis. (The Earth's crust and oceans cannot instantaneously redistribute themselves along the axis due to friction)



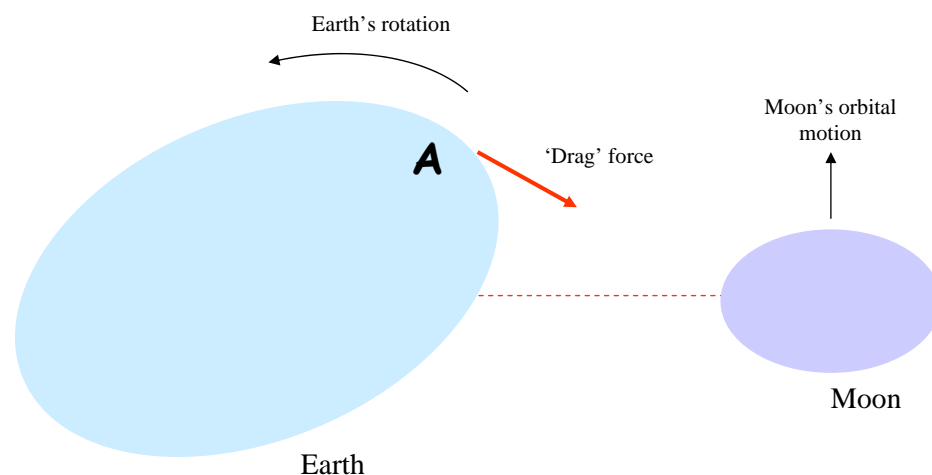
The Moon exerts a drag force on the tidal bulge at A, which slows down the Earth's rotation.

The length of the Earth's day is increasing by 0.0016 sec per century.



At the same time, bulge A is pulling the Moon forward, speeding it up and causing the Moon to spiral outwards. **This follows from the conservation of angular momentum.**

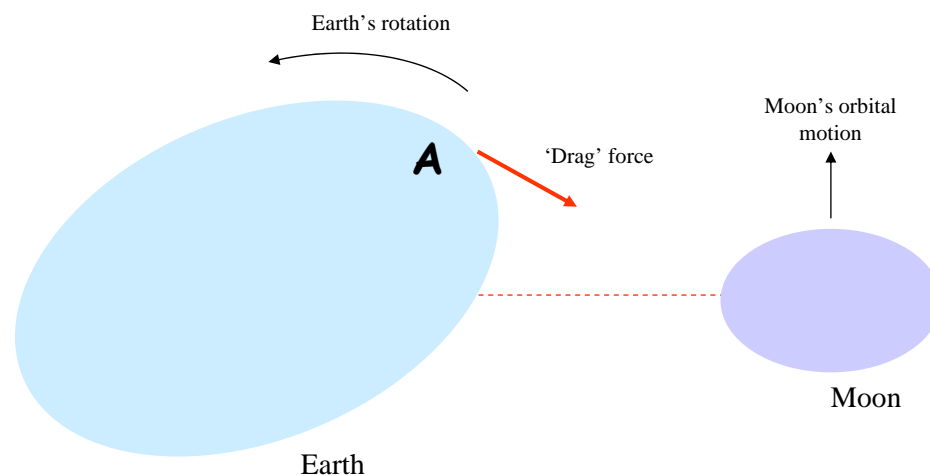
The Moon's semi-major axis is increasing by about 3cm per year.



- Given sufficient time, the Earth's rotation period would slow down until it equals the Moon's orbital period - so that the same face of the Earth would face the Moon at all times.

(This will happen when the Earth's "day" is 47 days long)

In the case of the Moon, this has *already happened !!!*



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In the case of the Moon, this has *already happened !!!*

- Tidal locking has occurred much more rapidly for the Moon than for the Earth because the Moon is much smaller, and the Earth produces larger tidal deformations on the Moon than vice versa.
- The Moon isn't exactly tidally locked. It 'wobbles' due to the perturbing effect of the Sun and other planets, and because its orbit is **elliptical**. Over about 30 years, we see 59% of the Moon's surface.

- Many of the satellites in Solar System are in synchronous rotation, e.g.

Mars: Phobos and Deimos

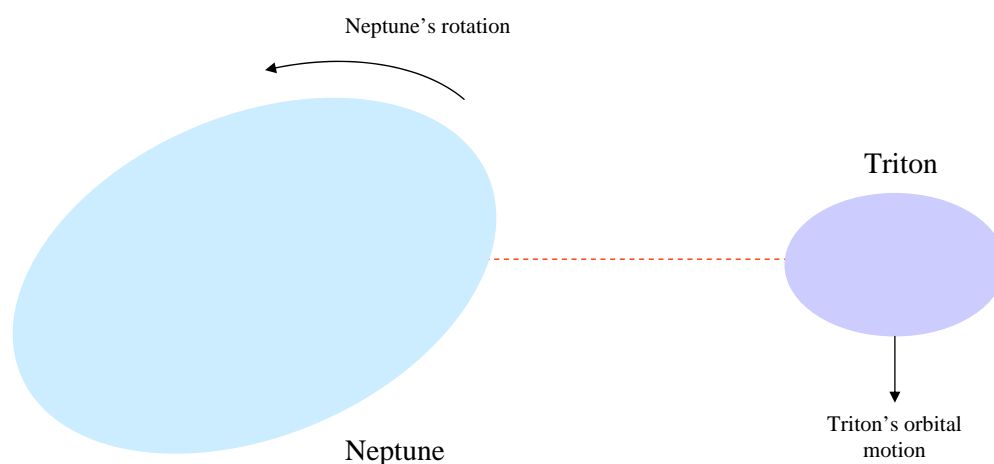
Jupiter: Galilean moons + Amalthea

Saturn: All major moons, except Phoebe + Hyperion

Neptune: Triton

Pluto: Charon

- Pluto and Charon are in mutual synchronous rotation: i.e. the same face of Charon is always turned towards the same face of Pluto, and vice versa.
- Triton orbits Neptune in a **retrograde** orbit (i.e. opposite direction to Neptune's rotation).



In this case Neptune's tidal bulge acts to *slow down* Triton. The moon is spiralling toward Neptune (although it will take billions of years before it reaches the Roche stability limit)

Section 12: The Galilean Moons of Jupiter

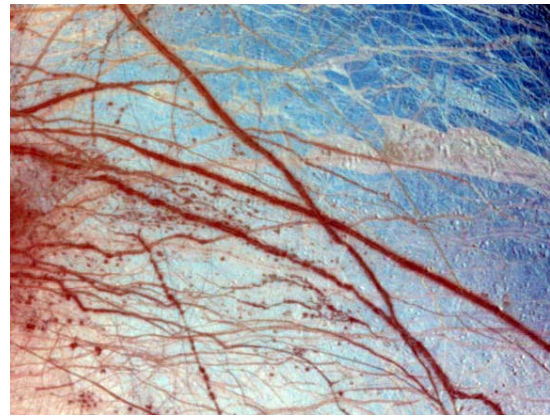
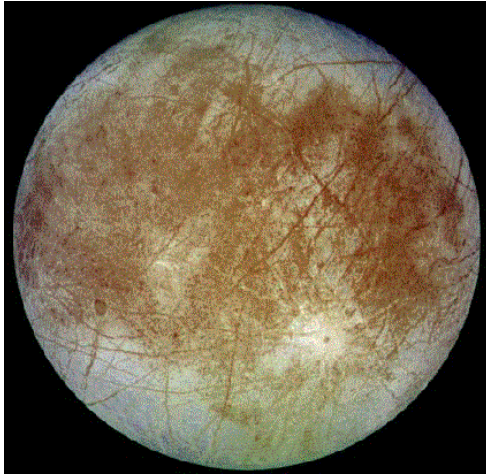
Tidal forces have a major influence on the Galilean Moons of Jupiter

Name	Diameter (m)	Semi-major axis (m)	Orbital Period (days)	Mass (kg)
Io	3.642×10^6	4.216×10^8	1.769	8.932×10^{22}
Europa	3.120×10^6	6.709×10^8	3.551	4.791×10^{22}
Ganymede	5.268×10^6	1.070×10^9	7.155	1.482×10^{23}
Callisto	4.800×10^6	1.883×10^9	16.689	1.077×10^{23}
The Moon	3.476×10^6	3.844×10^8	27.322	7.349×10^{22}
Mercury	4.880×10^6	—	—	3.302×10^{23}

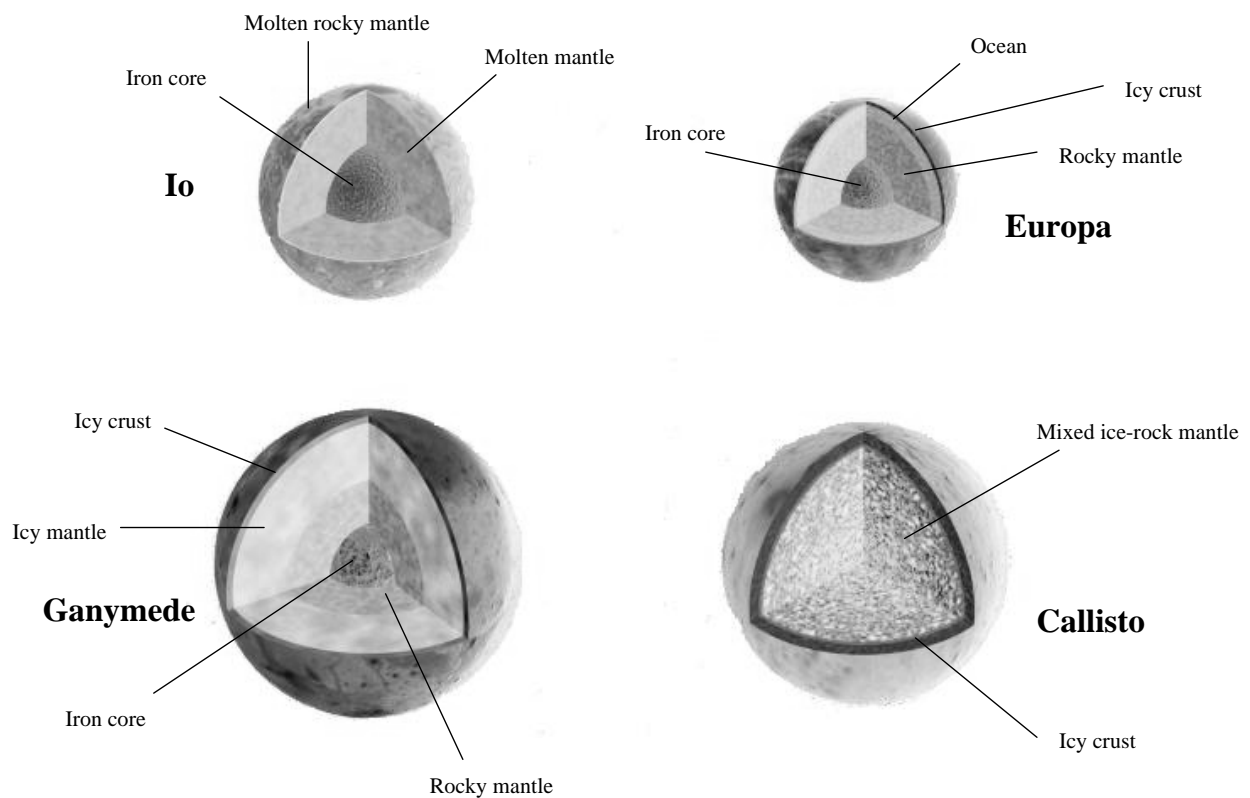
The orbital periods of Io, Europa and Ganymede are almost exactly in the ratio **1:2:4**. This leads to **resonant effects** :

- The orbit of Io is perturbed by Europa and Callisto, because the moons regularly line up on one side of Jupiter. The gravitational pull of the outer moons is enough to produce a small eccentricity in the orbit of Io. This causes the tidal bulges of Io to 'wobble' (same as the Moon) which produces large amount of **frictional heating**.
- The surface of Io is almost totally **molten**, yellowish-orange in colour due to sulphur from its continually erupting **volcanoes**.

- Tidal friction effects on Europa are weaker than on Io, but still produce striking results. The icy crust of the moon is covered in 'cracks' due to **tidal stresses**, and beneath the crust it is thought frictional heating results in a thin **ocean layer**



Interior structure of the Galilean Moons



Structure of the Galilean Moons

- Their mean density **decreases** with distance from Jupiter
- The fraction of ice which the moons contain **increases** with distance from Jupiter

This is because the heat from 'proto-Jupiter' prevented ice grains from surviving too close to the planet. Thus, Io and Europa are mainly rock; Ganymede and Callisto are a mixture of rock and ice.

- The **surface** of the Moons reflects their formation history:

Io: surface continually renewed by volcanic activity. No impact craters

Europa: surface young (< 100 million years), regularly 'refreshed' - hardly any impact craters

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- The **surface** of the Moons reflects their formation history:

Ganymede: Cooled much earlier than Io and Europa. Considerable impact cratering; also 'grooves' and ridges suggest history of tectonic activity

Callisto: Cooled even earlier; extensive impact cratering