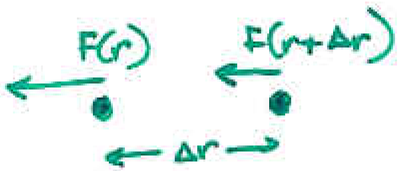
TIDES

Differential gravitational force on different sides of planet

eg on Earth from Moon

Earth from Sun

Moon from Earth .... etc



$$F = \frac{GMm}{r^2}$$

$$\Delta F = \frac{dF}{dr} \cdot \Delta r = -\frac{2GMm}{r^3} \cdot \Delta r$$

Tidal forces vary strongly with r

ie $\Delta F \propto \frac{1}{r^3}$

Q It's obvious that the Moon will produce a tidal bulge 'underneath' it on the Earth's surface, but less obvious why there is another tidal bulge on the opposite side of the Earth.

Why do we get 2 ?

Need to look at forces in Earth's frame of reference .... the whole Earth is pulled towards the Moon by gravity (Earth moves)

The nearside feels a larger force

The Earth's farside feels a smaller force.

This leads to 2 tidal bulges

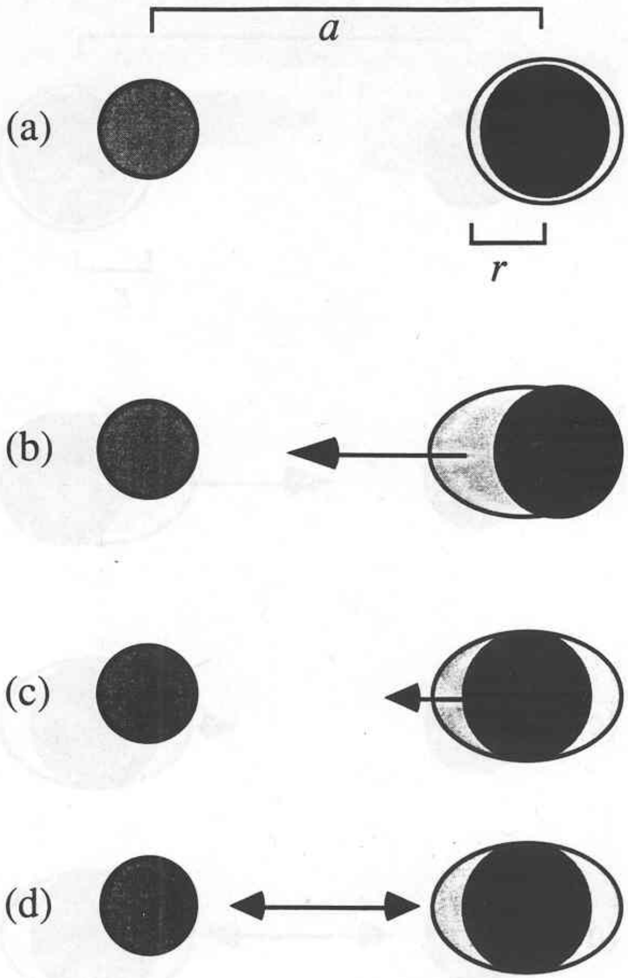


FIGURE 12.7 (a) The moon on the left pulls with its gravity on all parts of the planet to the right, but those parts nearest to the Moon get pulled the most. The material on the near side of the planet gets pulled more than the center of the planet (b), but the planet center itself gets pulled more than the material on the far side (c). As a result, the tidal bulge is symmetric on both sides of the body (d).

TIDES

Caused by differential gravitational forces

Water on Earth's surface moves ....

(75% of surface is water)

[redacted]

The Sun is much more massive than the Moon (10^8 times more) but further away (400 times) Should we worry about the tidal effects of the Sun on the Earth too? Because tidal forces are differential, they vary as $\frac{1}{d^3}$ not $\frac{1}{d^2}$ like simple gravity.

Which causes strongest tides on Earth, the Sun or the Moon?

$$\frac{M_\odot}{M_{moon}} \cdot \left(\frac{r_{moon-Earth}}{r_{\odot-Earth}} \right)^3$$

$$= 0.46$$

So both are important but the Moon has a stronger effect.

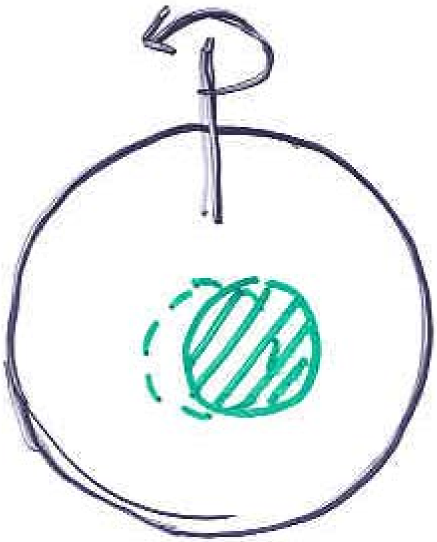
Q What relative positions of ☉, ☽, Earth give strongest tides?

→ Moon, Sun, Earth in a line (Moon at conjunction or opposition) give the very high spring tides.

Q The Moon raises a 'tidal bulge' on Earth's oceans as it passes over.

How might this bulge affect the Moon's orbit?

Tidal Evolution when Planet is Spinning



- Moon raises tidal bulge on Earth's surface

- Rotation of Earth moves ~~planet~~ bulge so it is not directly under Moon

- bulge exerts additional gravitational force on Moon
  (speeds up or slows down depending on orbital period of moon, rotational period of planet, prograde or retrograde orbit)

- Magnitude of this extra force goes as at least $1/r^5$:
  - size of bulge $\propto \frac{1}{r^3}$
  - grav. force $\propto \frac{1}{r^2}$

Synchronous point is where orbital period = rotational period

(r = 42,000 km for Earth)

So our Moon is way outside this

3 cases :

(i) Prograde orbit outside synchronous point, like Earth's Moon.

The bulge gives the Moon an extra tug in the direction it is moving, <u>adds</u> energy to Moon's orbit.

Q Does the Moon move inward or outward as its orbit gains energy ?

→ Moon slowly recedes from Earth

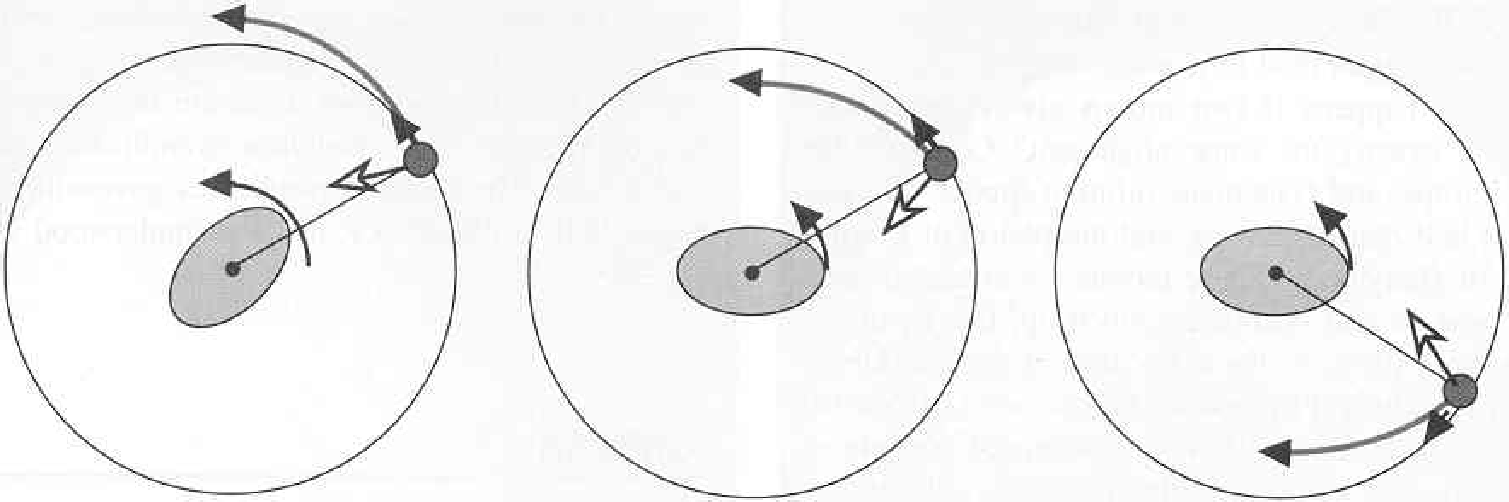


FIGURE 12.9 Outcomes of tidal evolutions. Left (case 1): The moon is outside the synchronous point; the planet spins faster than the moon moves, and so the bulge adds energy to the moon's orbit, causing it to spiral out away from the planet. Middle (case 2): The moon is closer than the synchronous point and thus orbits faster than the planet spins; the planet's bulge robs energy from the moon and pulls it towards the planet. Right (case 3): The planet spins in the opposite direction of the moon's orbit; the moon is pulled into the planet.

(ii) Prograde orbit <u>inside</u> synchronous point (eg Phobos, one of Mars' moons)

(Mars spins once every 1.03 days, Phobos orbits once every 0.32 days!)

Q Does the moon gain or lose energy? Does it move in or out?

→ moon loses energy
spirals inward

(but no water on Mars so tidal effects less)

Q Make an order-of-magnitude comparison of the tidal force exerted by the Moon on the Earth & by Phobos on Mars.

	Mass	Radius of orbit
Moon	10^{23} kg	4×10^{5} km
Phobos	10^{16} kg	10^{4} km

$$\frac{M_{moon}}{(r_{moon})^3} \Big/ \frac{M_{phobos}}{(r_{phobos})^3} = \frac{10^{23}\times(10^{4})^3}{(4\times10^{5})^3\times10^{16}}$$

$$\sim 100$$

(iii) retrograde orbit (eg Triton, moon of Neptune)

Energy always lost

moon spirals in

Triton predicted to hit Neptune in 10^8 yrs

Q When the Moon gains energy and recedes from the Earth, the energy has to come from somewhere. What <u>loses</u> energy?

Energy is dissipated in the form of heat as a result of tidal friction (some power stations run on tidal energy). This friction reduces the energy of Earth's rotation.

Currently the day length is increasing by about 0.002 sec/century.

Q Most of the tidal energy is lost at shorelines and in shallow seas. Why do you think the rate of change of day length is not constant?

A

Tidal dissipation of energy will depend on the details of coastlines, water depth, etc.

Plate Tectonics changes all of this on timescales of 10^8 years.

So the amount of energy lost will change too

So will the rate of change of the Earth's rotational period.

Body tides

The water on Earth's surface moves most readily with tidal forces from the Moon, but the solid Earth also responds ..... raising 'body tides' of a few cm.

The Moon has no water, but the Earth raises much larger body tides on it : ~ 20 times more.

Q The Moon is currently in synchronous rotation (orbital = rotational period). Assume it started with a larger rotation (smaller P) — what slowed it down ?

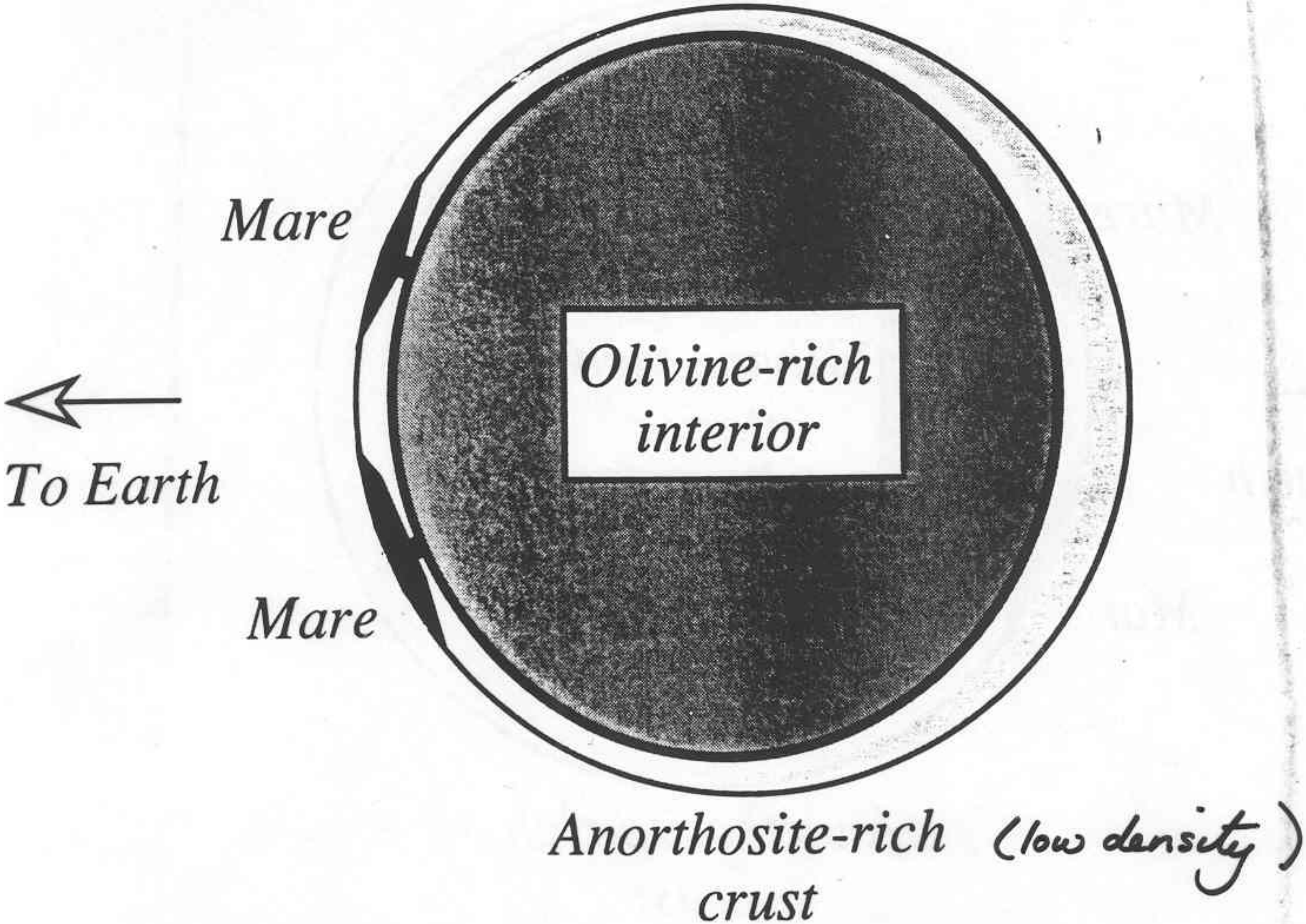


FIGURE 3.3 The distribution of material inside the Moon. The thickness of the crust is exaggerated.

Inside the Moon

Center of mass of Moon is not exactly at center :

Moon has thick crust of low-density rocks, which is thicker on its far side (mostly Highlands, not maria)

Interior is made of denser rocks like Earth's mantle (Olivine)

Core must be small, because Moon's mean density is so low

Solid, because the Moon does not have a magnetic field

Earth – Moon system history

Energy gained by Moon due to tidal interaction

Energy lost by Earth : spin slows

Measurement : fossils

- corals : growth sensitive to day length

over past few $\times 10^8$ years, days have lengthened by ~ 25 sec / 10^6 yr

- nautiloids : growth sensitive to lunar month and to day length

8×10^7 years ago : 22 days to lunar month

4×10^8 years ago: 10 days to lunar month.

Since $P^2 \propto a^3$, Moon's distance was half the current distance

Eventual fate of Earth – Moon system :

Earth will slow until one side always faces the Moon

Earth day = lunar month

$\simeq$ 50 present days.

Q Mercury's rotation, like the Moon's, is very slow, altho the ratio of rotational to orbital period is 3:2, not 1:1. What might be causing this? (have caused)

→ Body tides again. Sun's tidal force on Mercury is strong

Q Can you think of anything about Mercury's orbit that might contribute to the 3:2 coupling?

Strongly elliptical orbit, so speed varies along orbit.

Can't remain synchronous around its orbit:

If synchronous near perihelion, too fast at aphelion

If synchronous at aphelion, too slow at perihelion.

Tidal forces a strong function of R (tidal bulge force R^5 or more)

so strongest at perihelion

Orbital & rotational speeds are ~~the~~ almost the same at perihelion only