Kirchhoff's Laws

1. A hot, opaque body, or a hot, dense gas produces a continuous spectrum.

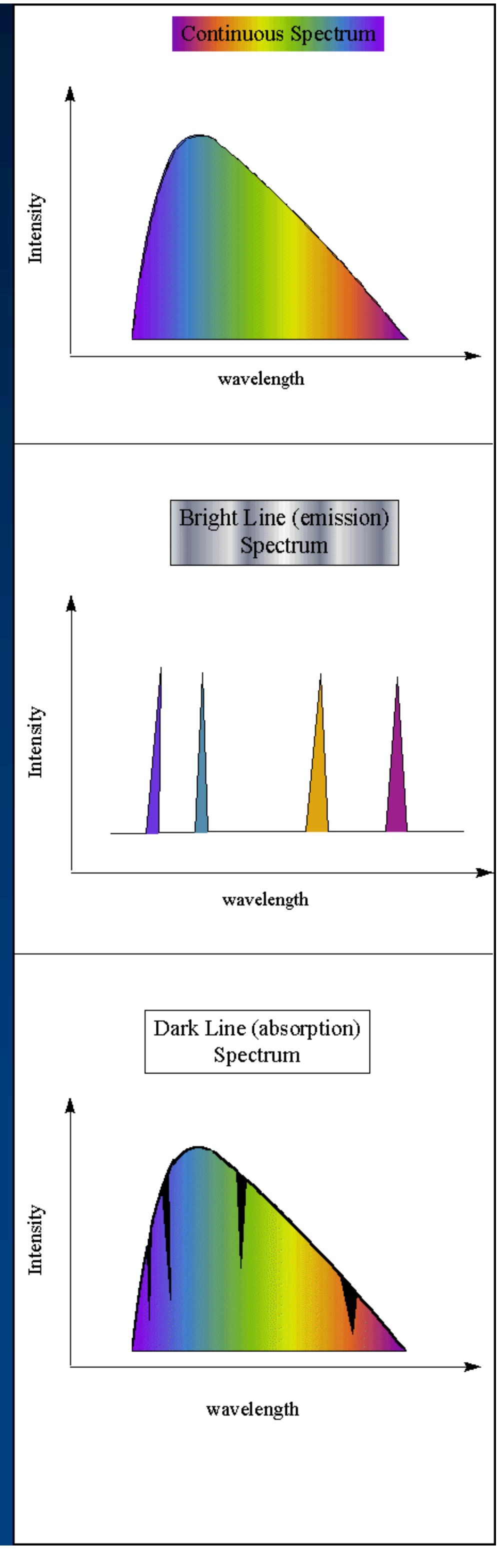
   Explained

2. A hot, transparent gas produces an emission line spectrum.

   Explained

3. A cool, transparent gas in front of a source of a continuous spectrum produces an absorption line spectrum.

   Explained



Spectroscopy

The spectrum of an objects tells us:

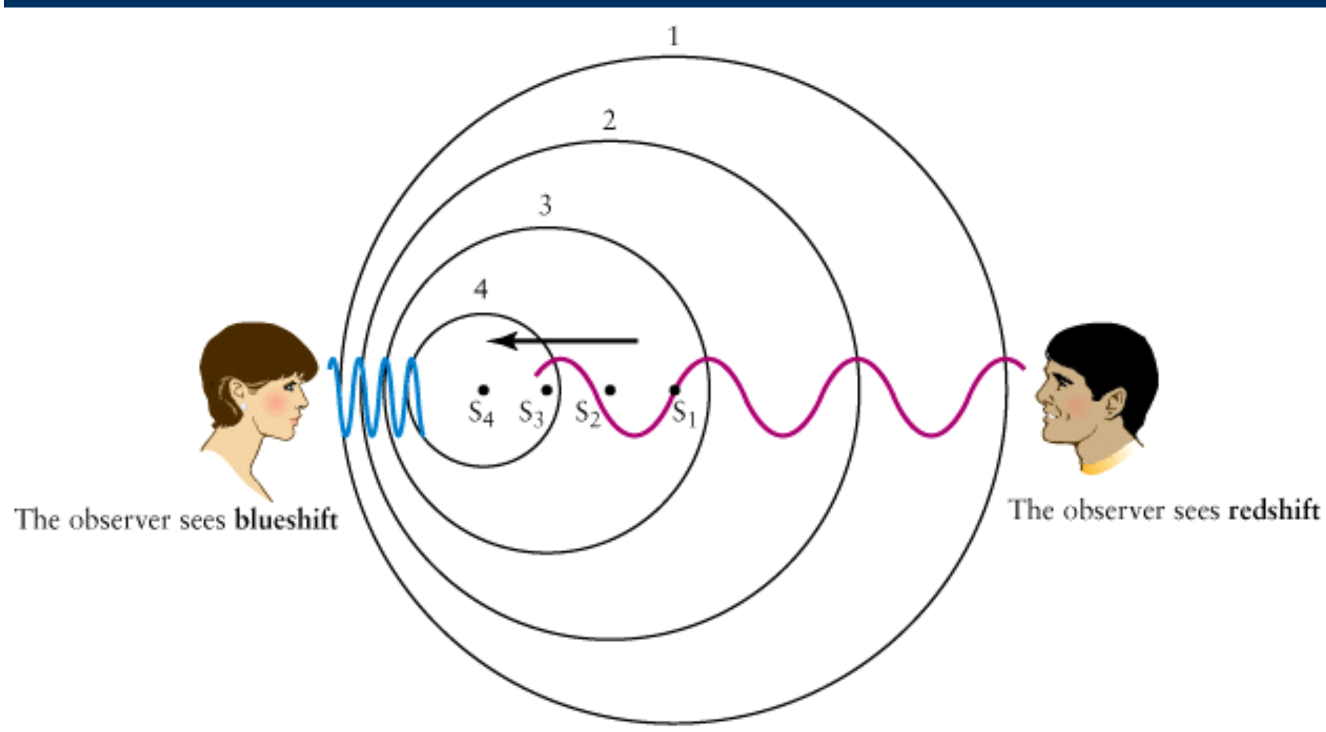
- Which atoms and molecules are present, and in which proportions
- Which atoms are ionized, and in which proportions
- How excited the atoms are, which tells us about the physical state (cold, hot)
- Motion of the object

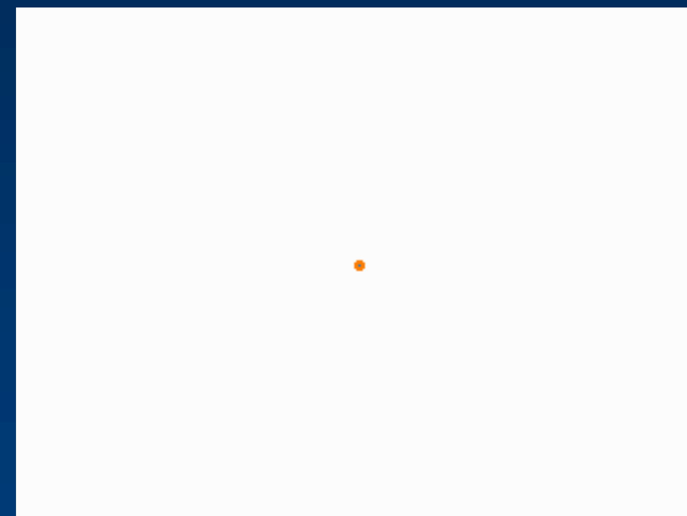
⇒Spectroscopy is a very important tool of the astronomer! (invented by Gustaf Kirchoff)

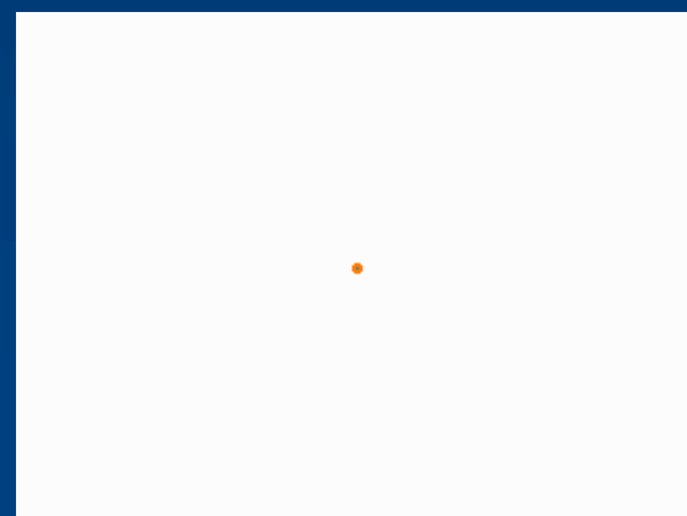
(Particles emit and absorb photons in other ways, too. We'll deal with those processes as needed.)

The Doppler shift

Frequency or wavelength of a wave depends on relative motion of emitter and receiver (along the direction of wave motion).





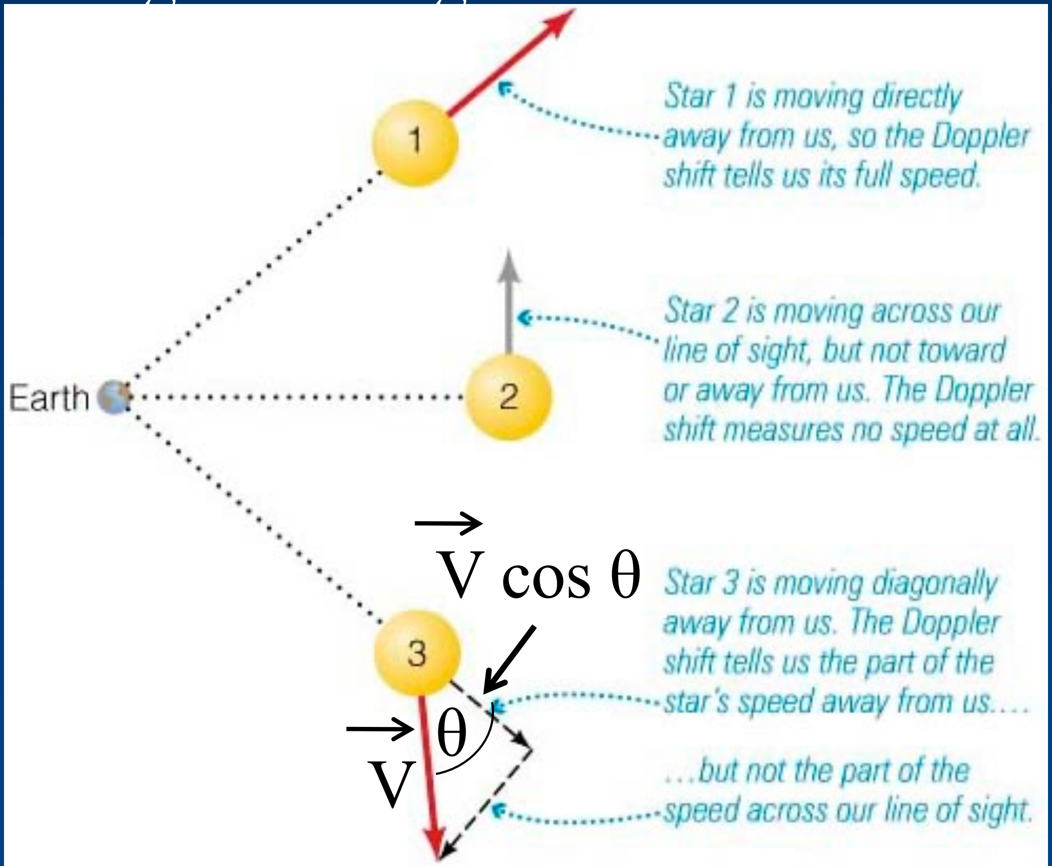


$$V = \frac{\lambda_{observed} - \lambda_{emitted}}{\lambda_{emitted}} c = \frac{\Delta\lambda}{\lambda_{emitted}} c$$

where V is the relative velocity along the line of sight, and c is the speed of light (both in same units, e.g. m/s).

If V is at some angle, only component along line of sight enters formula

Spectral lines are used to measure Doppler shift => gives us information about the motion of an object.



Example Doppler shift

- A spectral line normally seen at 300nm (its rest wavelength) is shifted to 301nm due to relative motion of a star. What is the velocity of the star? Is it approaching or receding? "Redshift" or "blueshift"?
- What is the velocity?

Fundamental forces of nature

Interactions in nature are governed by four fundamental forces:

Fundamental forces of nature

Interactions in nature are governed by four fundamental forces:

1. Gravitational force
2. Electromagnetic force
3. Strong nuclear force
4. Weak nuclear force

The interplay of forces

- Gravity dominates on largest scales: binds massive objects together, and mediates orbital motions
- Electromagnetism dominates on atomic scale: binds electrons to protons, atoms to molecules
- Strong and weak forces dominates on nuclear scales: binds protons to neutrons, mediates nuclear reactions

Gravitation Part IV

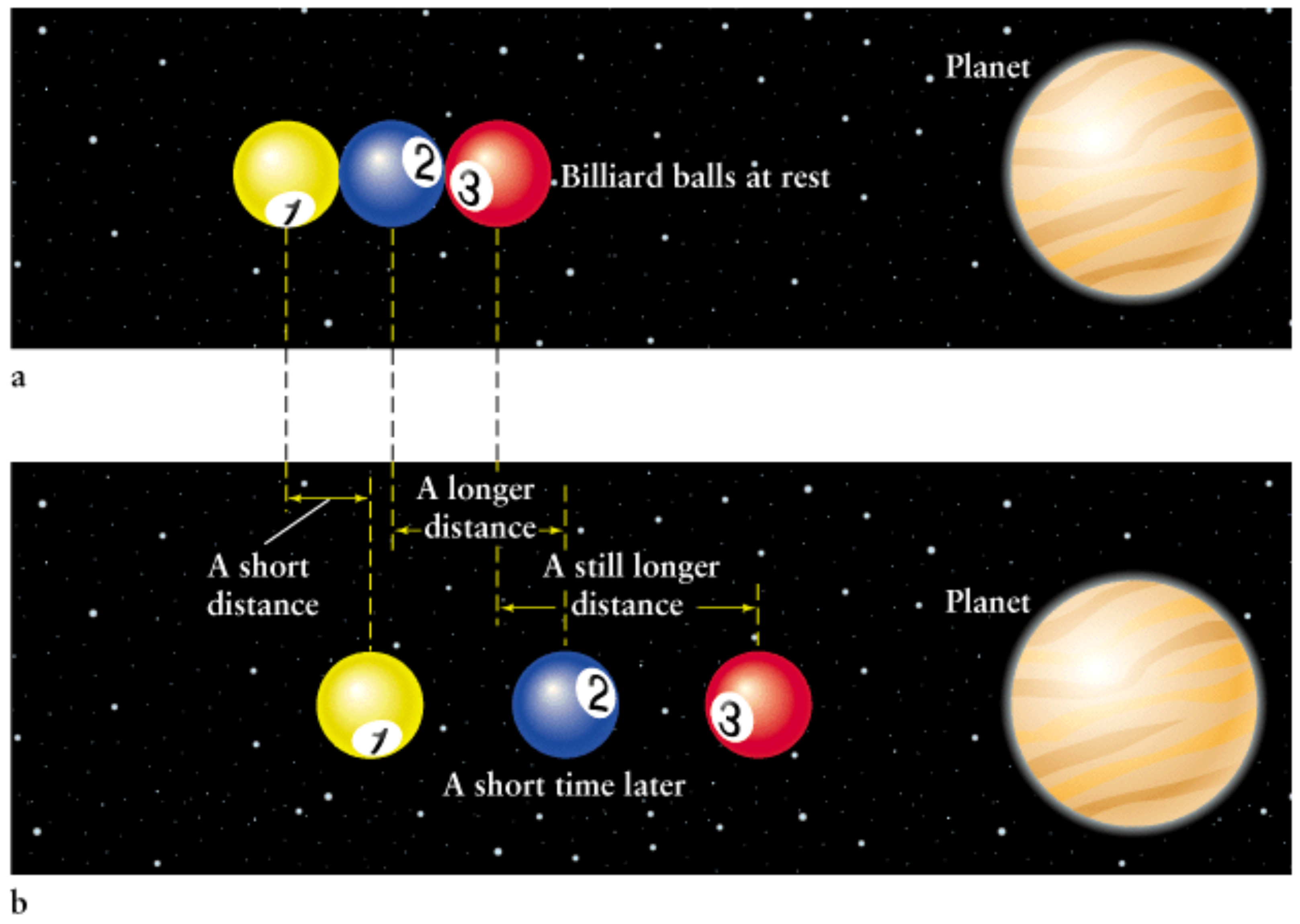
Tides

Newtonian mechanics explains why the Moon, Earth, and planets stay in their orbits.

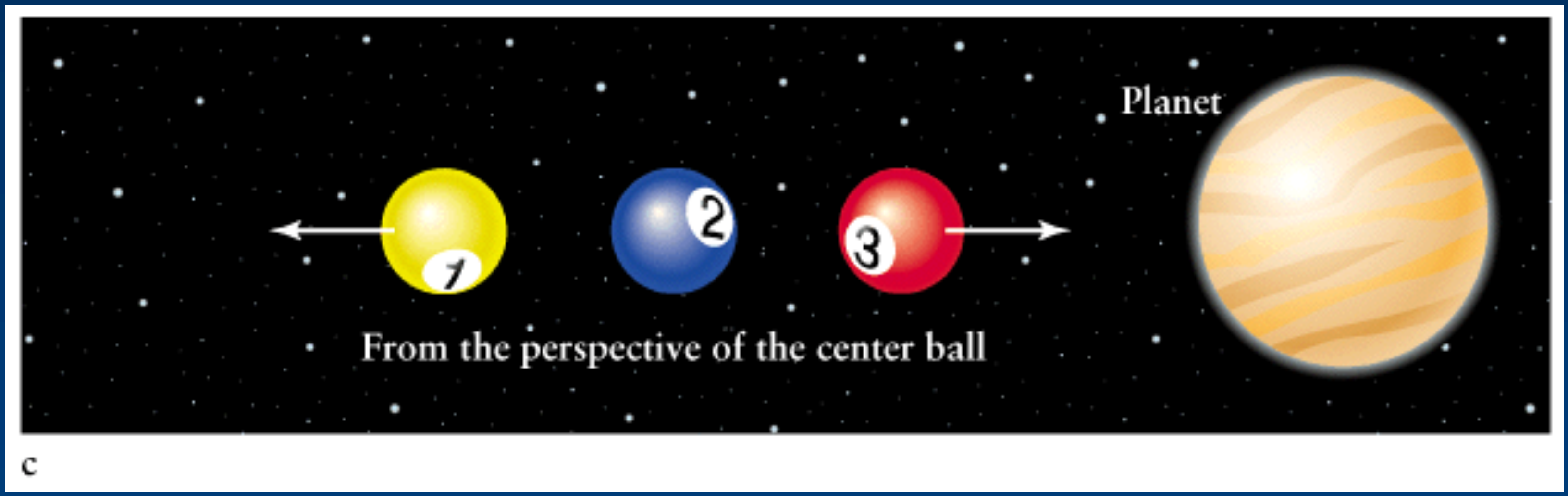
It also explains why the Moon shows one face to the Earth, and why there are ocean tides – tidal forces.

Tidal forces are differences in the gravitational pull at different points in an object.

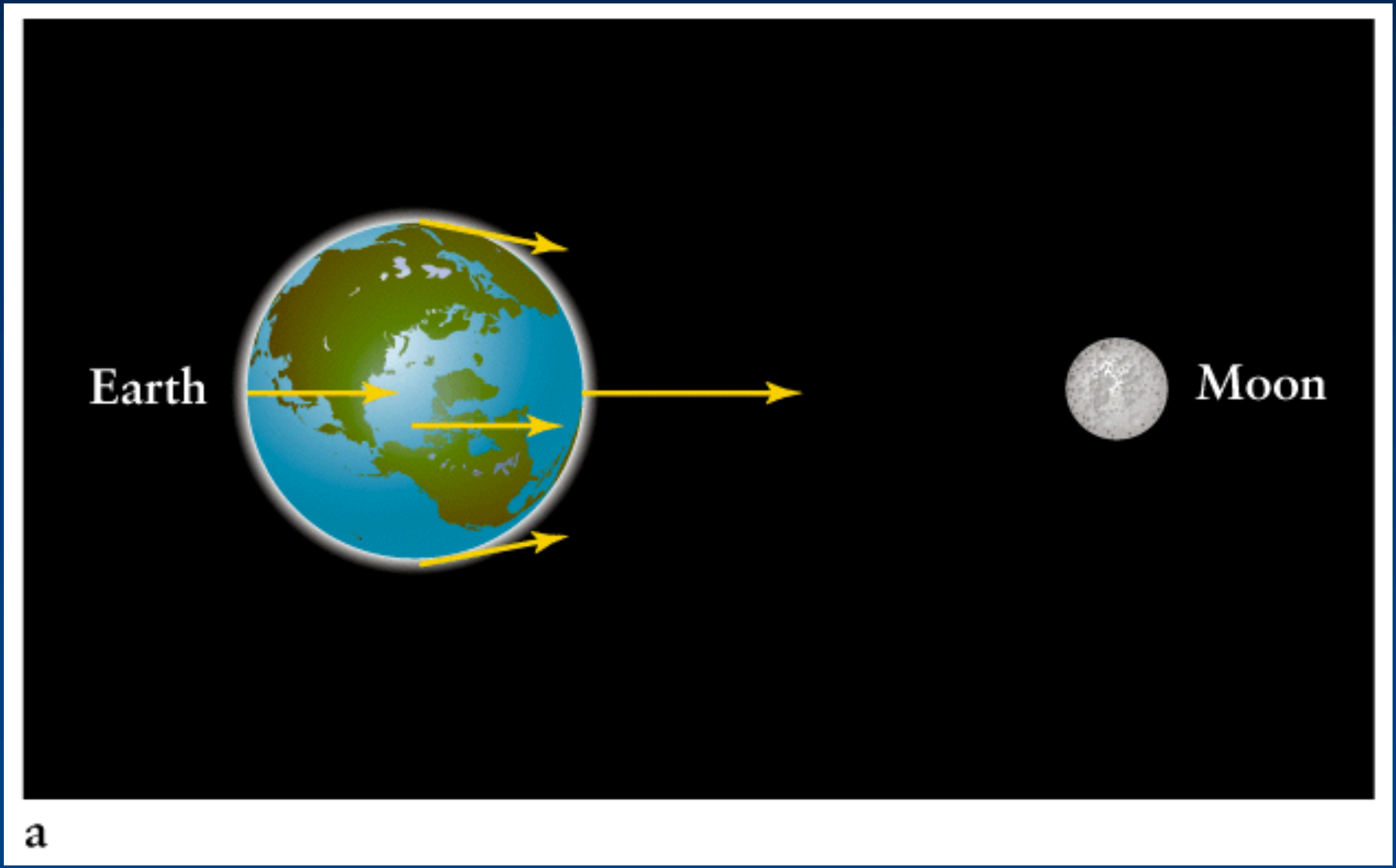
Gravitational force on ball 3 due to planet > force on ball 2 > force on ball 1.



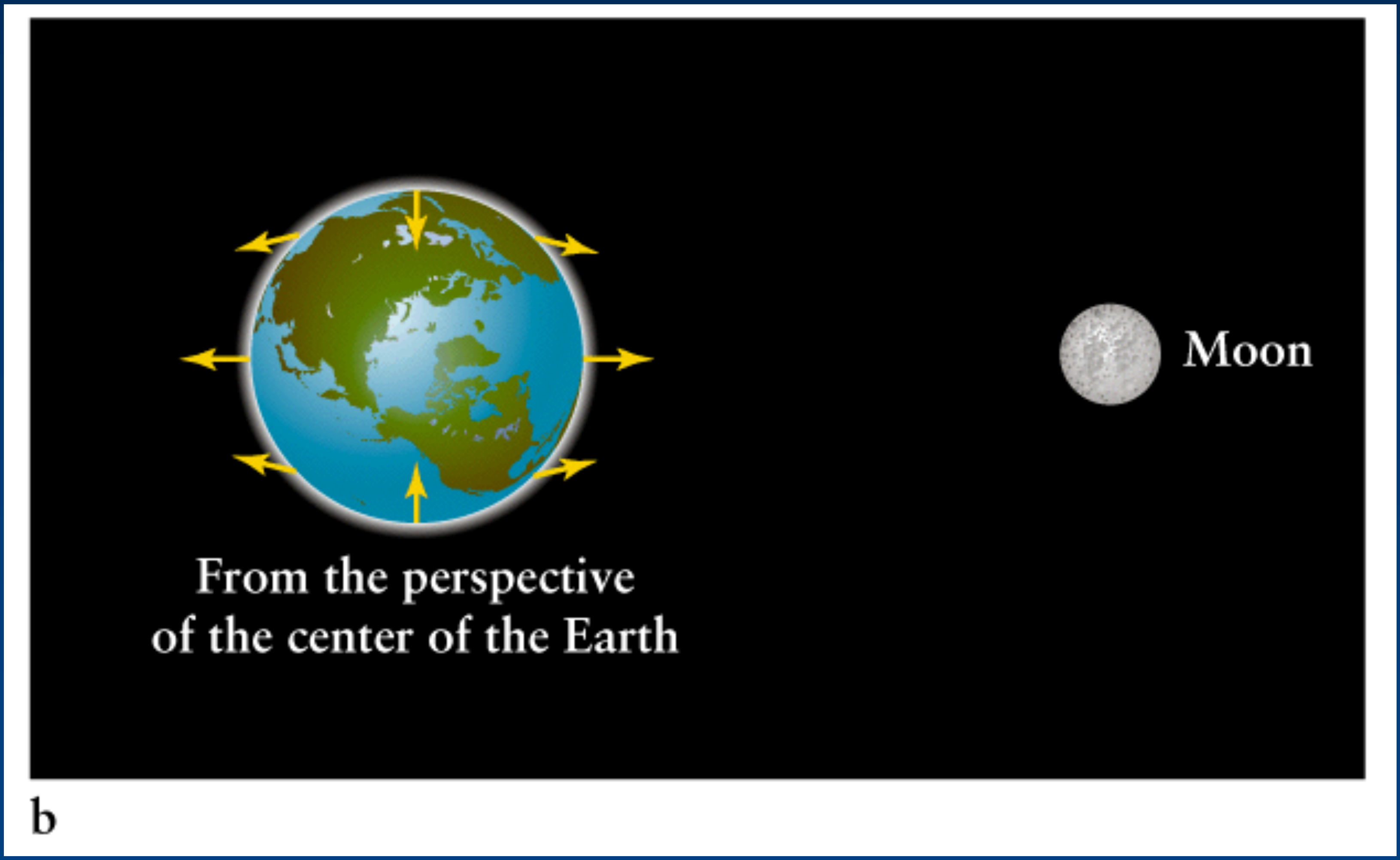
What would this look like from the perspective of ball 2? You' d see ball 1 and ball 3 moving away from you in opposite directions.



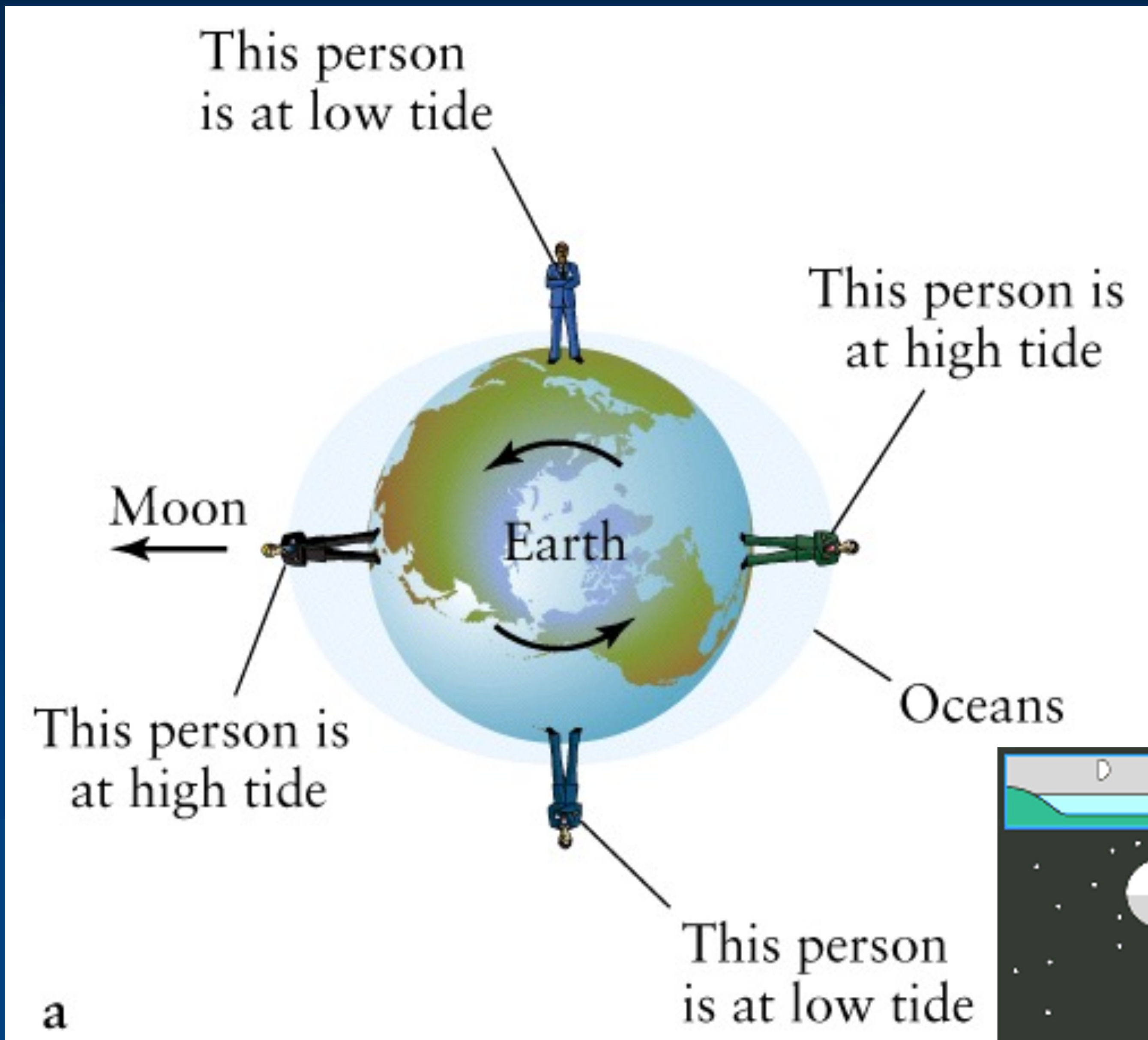
The Moon's gravitational force is unequal over the Earth due to the Earth's size.



From the perspective of the Earth, this force stretches the Earth, producing tides.



As the Earth rotates underneath the oceans, any particular place gets alternating low- and high tides.



If you live by the sea you'd notice:

- Sea level highest twice a day - high tide
- Sea level lowest twice a day - low tide
- Time between high tides 12h25m

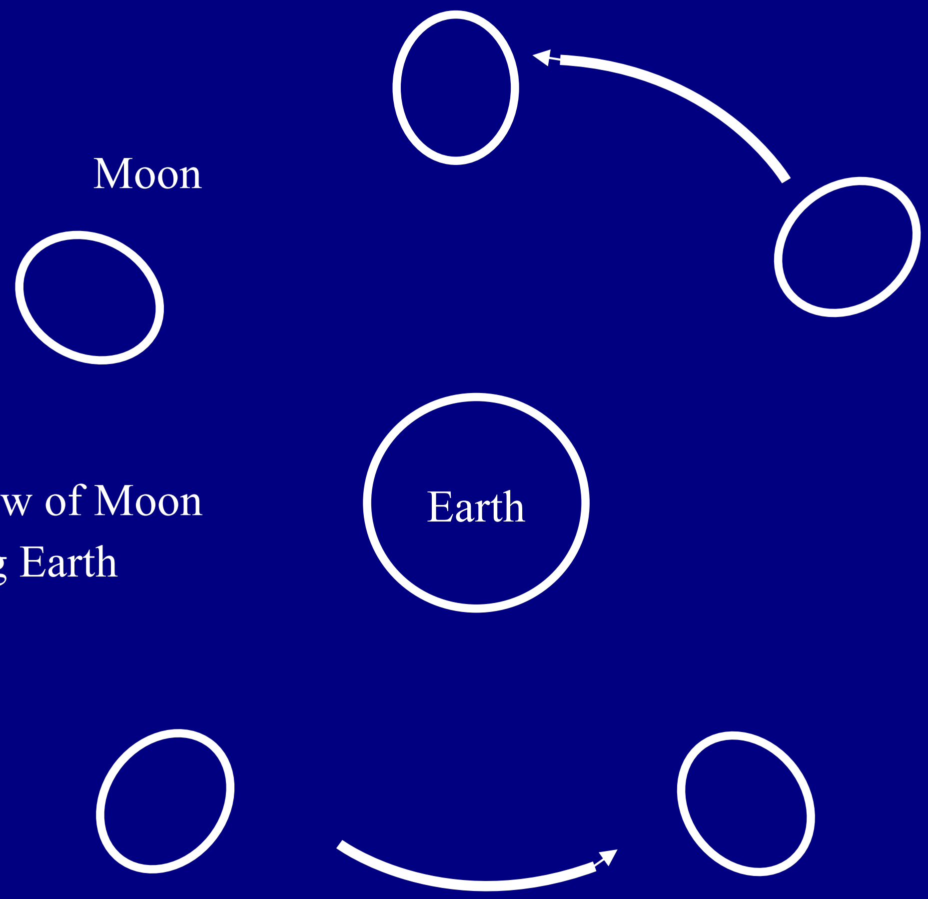
If you live by the sea you'd notice:

- Sea level highest twice a day - high tide
- Sea level lowest twice a day - low tide
- Time between high tides 12h25m
- Time between moonrises 24h50m

We always see the same face of the Moon.

So period of orbit = period of rotation

Why?

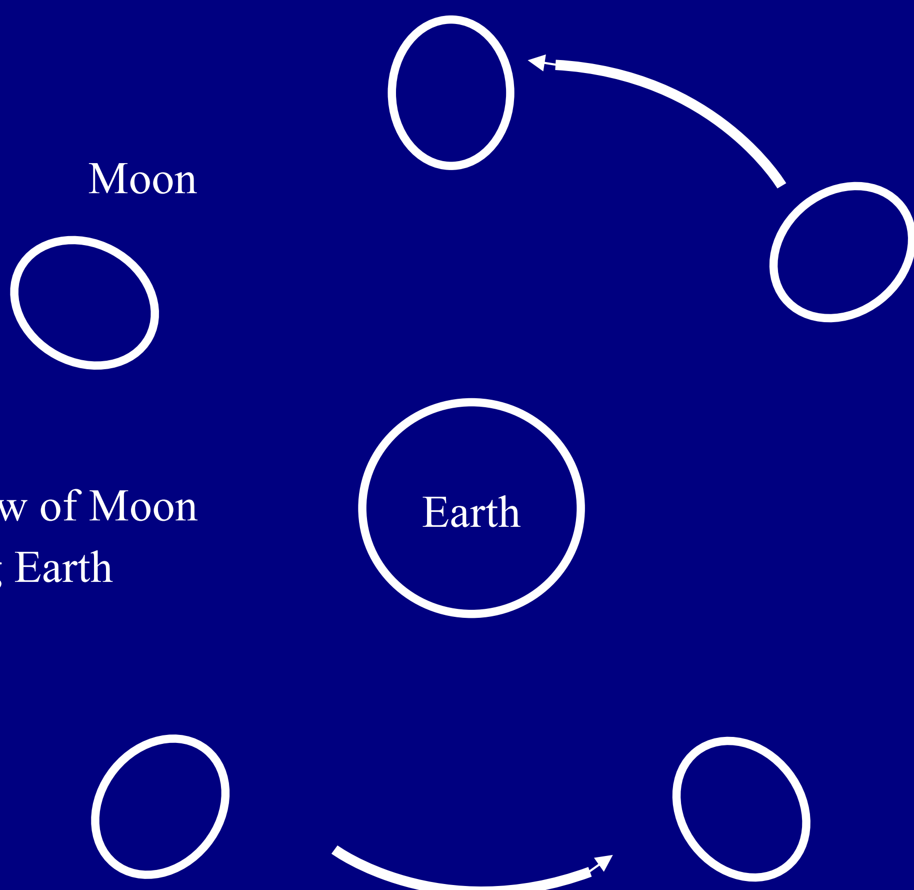


Top view of Moon orbiting Earth

We always see the same face of the Moon.

So period of orbit = period of rotation

Why?



Top view of Moon orbiting Earth

Tidal Locking

The tidal bulge in the solid Moon elongates it slightly (2-3 km) along an axis pointing to Earth.

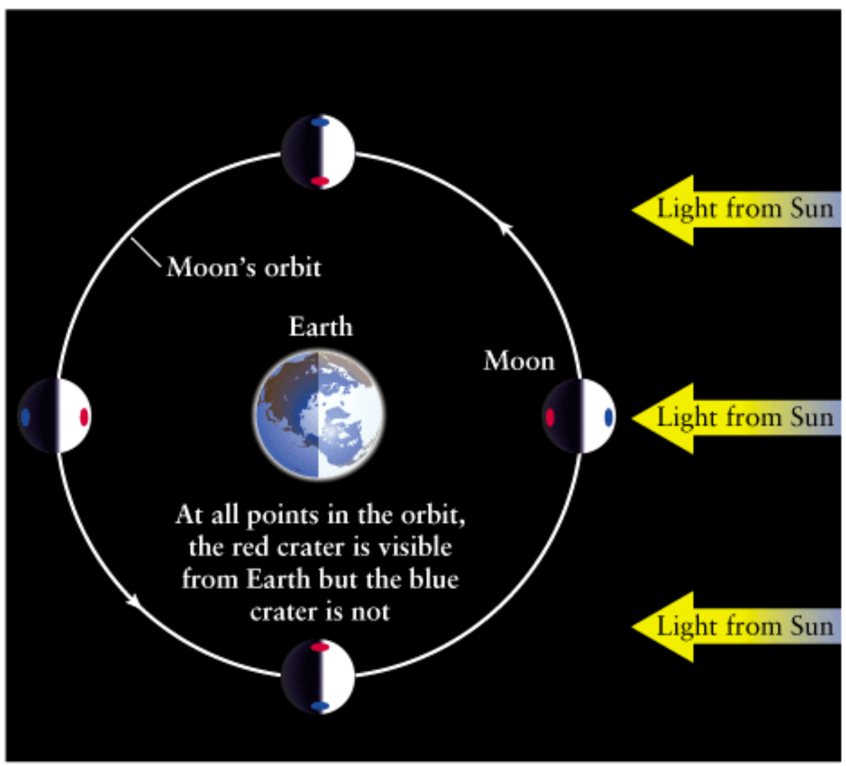
If orbit period faster than spin period, tidal bulge would have to move around surface of Moon, creating friction, which slows the Moon down until tidal bulge no longer migrates around.

Similar effect is slowing Earth's rotation!

⇒ "Tidally locked".

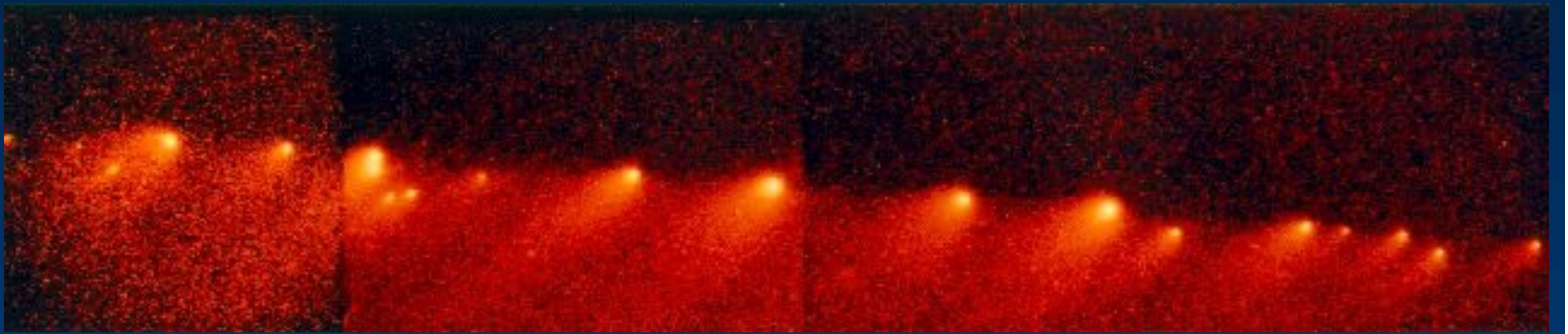
⇒ Synchronous rotation.

Most large satellites in Solar System do this!

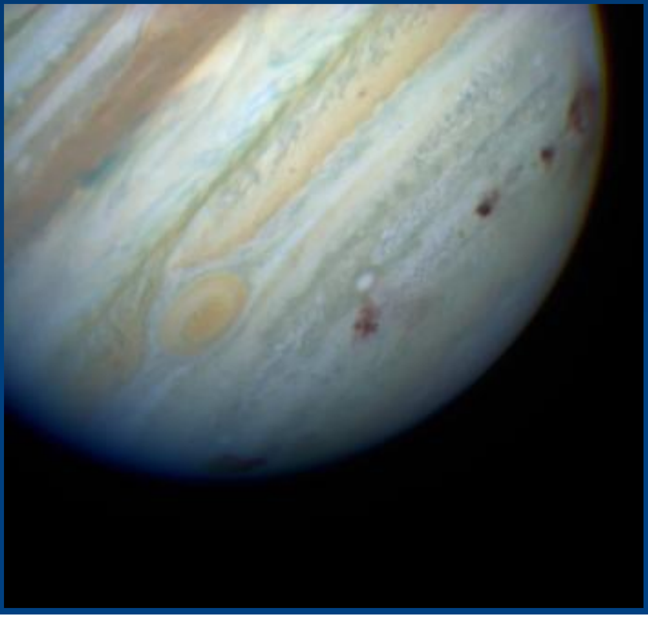


b In fact the Moon does rotate and we see only one face of the Moon

- What happens if body is, unlike Earth or Moon, not very rigid?



- Shoemaker-Levy 9 breaking apart due to tidal forces in 1992, before plunging into Jupiter 1994.



But wait – why is the Moon more important for tides than the Sun? Isn't the gravitational pull of the Sun stronger on Earth?

$$F_{Earth-Sun} = \frac{GM_E M_S}{r_{E-S}^2} >> F_{Earth-Moon} = \frac{GM_E M_M}{r_{E-M}^2}$$

Important point is that the tidal force is the difference in gravitational force across the Earth, and this force has a stronger dependence on distance than does the gravitational force, and the Moon is closer to us.

Consider 2 small rocks near a planet.
Gravitational force due to planet on the near rock will be stronger than force on the far rock.

If rocks are separated by distance *d*, and distance from near rock to planet is *r*, then force on the near rock is

$$F_{near} = \frac{GM_{planet} m_{rock}}{r^2}$$

and force on the far rock is

$$F_{far} = \frac{GM_{planet} m_{rock}}{(r+d)^2}$$

The tidal force felt by the rock combo is the difference between the gravitational force felt by the near vs. far rock.

Thus,

$$\Delta F = F_{near} - F_{far} = \frac{GMm}{r^2} - \frac{GMm}{(r+d)^2}$$

$$= GMm\left[\frac{1}{r^2} - \frac{1}{(r+d)^2}\right]$$

$$= GMm\left[\frac{(r+d)^2 - r^2}{r^2(r+d)^2}\right]$$

$$= GMm\left[\frac{r^2 + 2dr + d^2 - r^2}{r^2(r+d)^2}\right] = GMm\left[\frac{2dr + d^2}{r^2(r+d)^2}\right]$$

$$= GMm\left[\frac{d(2r+d)}{r^2(r+d)^2}\right]$$

Because r is much larger than d, we can approximate

$$2r + d \approx 2r$$

$$r + d \approx r$$

So

$$\Delta F = GMm \frac{d(2r)}{r^2 r^2}$$

$$\Delta F = 2GMm \frac{d}{r^3}$$

The Point: tidal force $\propto$ inverse cube of the distance. This is why influence of Moon is greater than influence of Sun for our tides.

Aside: derivation is really easy with calculus.

The "differential gravitational force" is given by

$$\frac{dF}{dr} = -2G\frac{Mm}{r^3}$$

or

$$dF = -2G\frac{Mm}{r^3}dr$$

where dF is the differential gravitational force directed along r (minus sign: F decreases with r)

Quantitative example: Why is tidal force on Earth from Moon more important than from Sun?

Tidal force on Earth by Sun:

$$\Delta F_{Earth-Sun} = 2GM_E M_S \frac{D_E}{r_{E-S}^3}$$

Similarly, tidal force on Earth by the Moon:

$$\Delta F_{Earth-Moon} = 2GM_E M_M \frac{D_E}{r_{E-M}^3}$$

To compare, take ratio of the two forces:

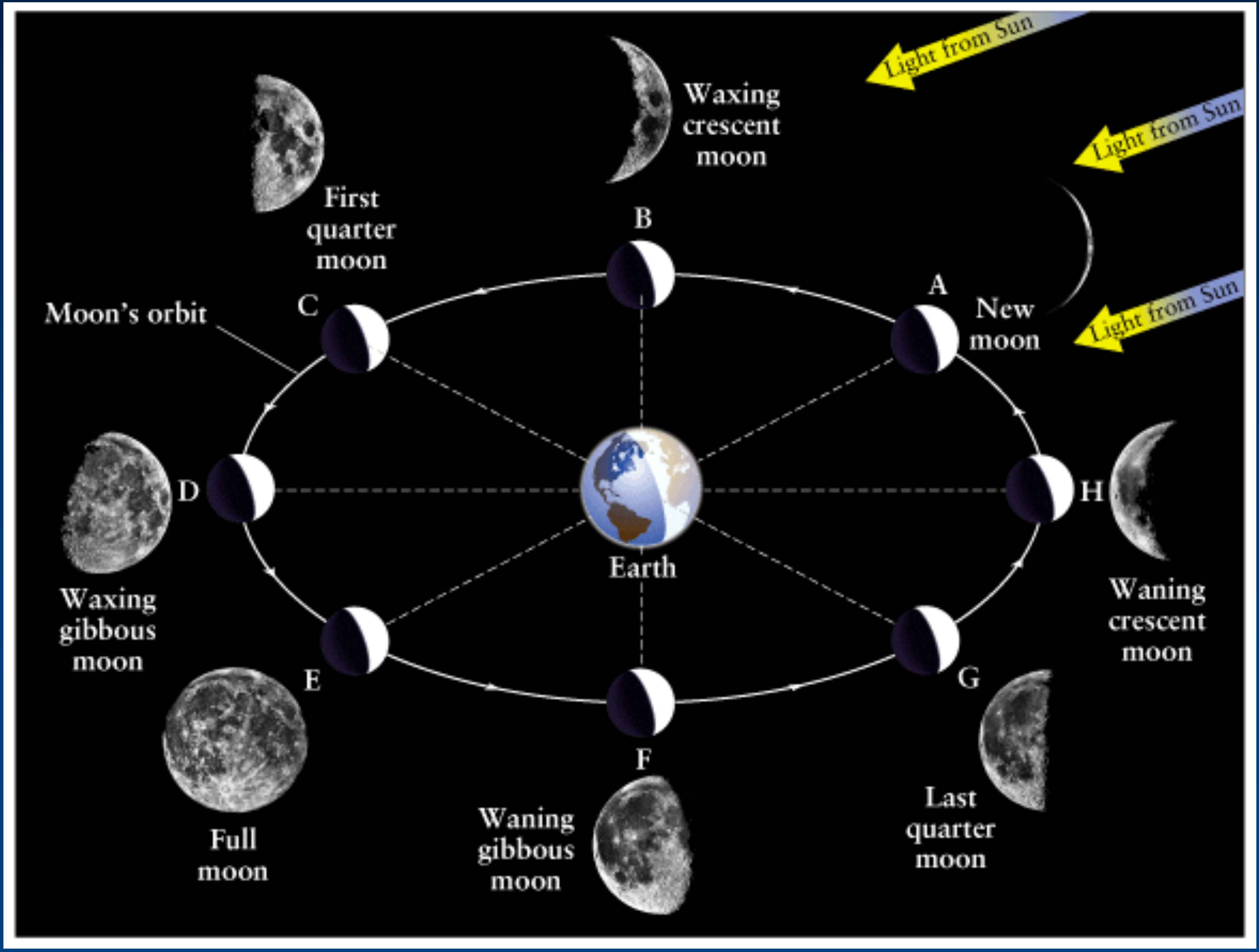
$$\frac{\Delta F_{E-S}}{\Delta F_{E-M}} = \frac{\dfrac{2GM_E M_S D_E}{r_{E-S}^{\ 3}}}{\dfrac{2GM_E M_M D_E}{r_{E-M}^{\ 3}}} = \frac{\dfrac{M_S}{r_{E-S}^{\ 3}}}{\dfrac{M_M}{r_{E-M}^{\ 3}}}$$

$$= \frac{M_S}{M_M}\left(\frac{r_{E-M}}{r_{E-S}}\right)^3 = \frac{1.99\times10^{30}\ \text{kg}}{7.35\times10^{22}\ \text{kg}}\left(\frac{3.84\times10^{5}\ \text{km}}{1.50\times10^{8}\ \text{km}}\right)^3$$

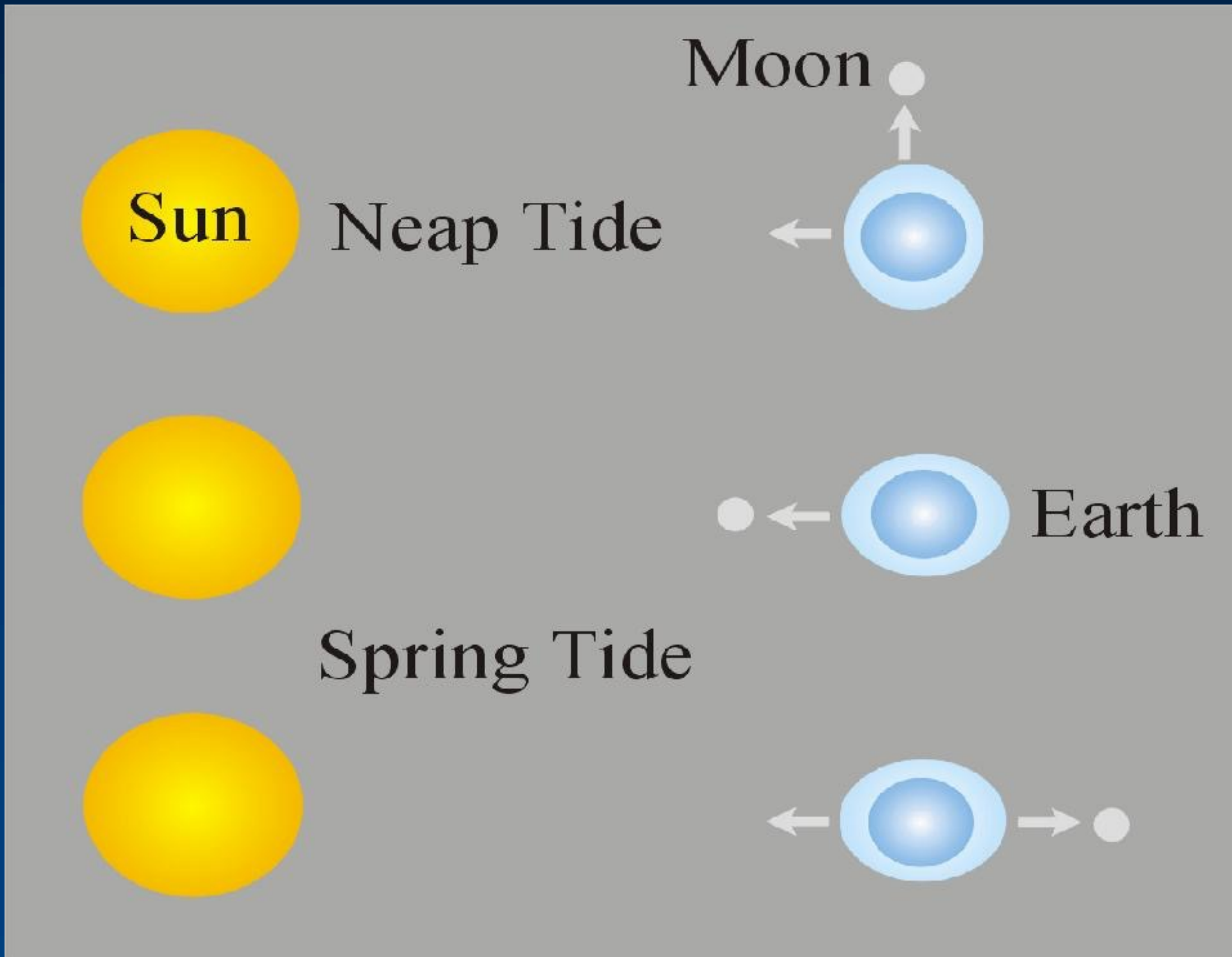
$$= 0.45$$

So the tides are mainly produced by the Moon, but the Sun is not negligible (0.45).

How do the tides due to the Moon and Sun work together?



Neap tides occur when the Moon and the Sun are at right angles (during first and last quarter Moon).



Which will be more extreme: neap or spring tides?

Spring tides occur when the Moon and the Sun are lined up (at new and full Moon).

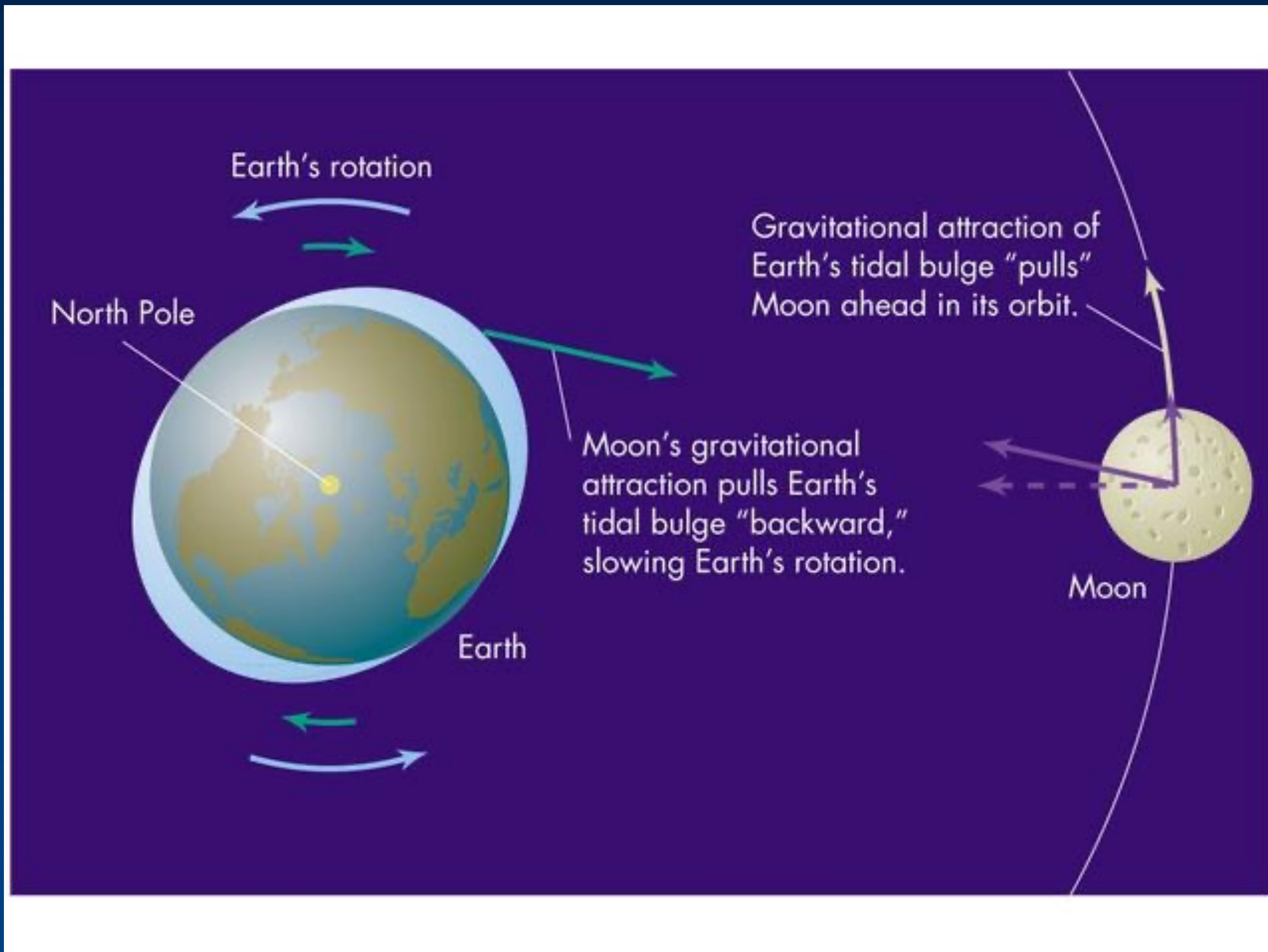
Tidal braking of the Earth

- Earth rotates faster than the Moon orbits the Earth (1 day versus 27 days)

- This causes friction between water and ocean floor

- => will drag the "ocean bulge" in eastward direction ("forward" in rotation)

Causes the ocean tides to *lead* the Moon by about 10 degrees.

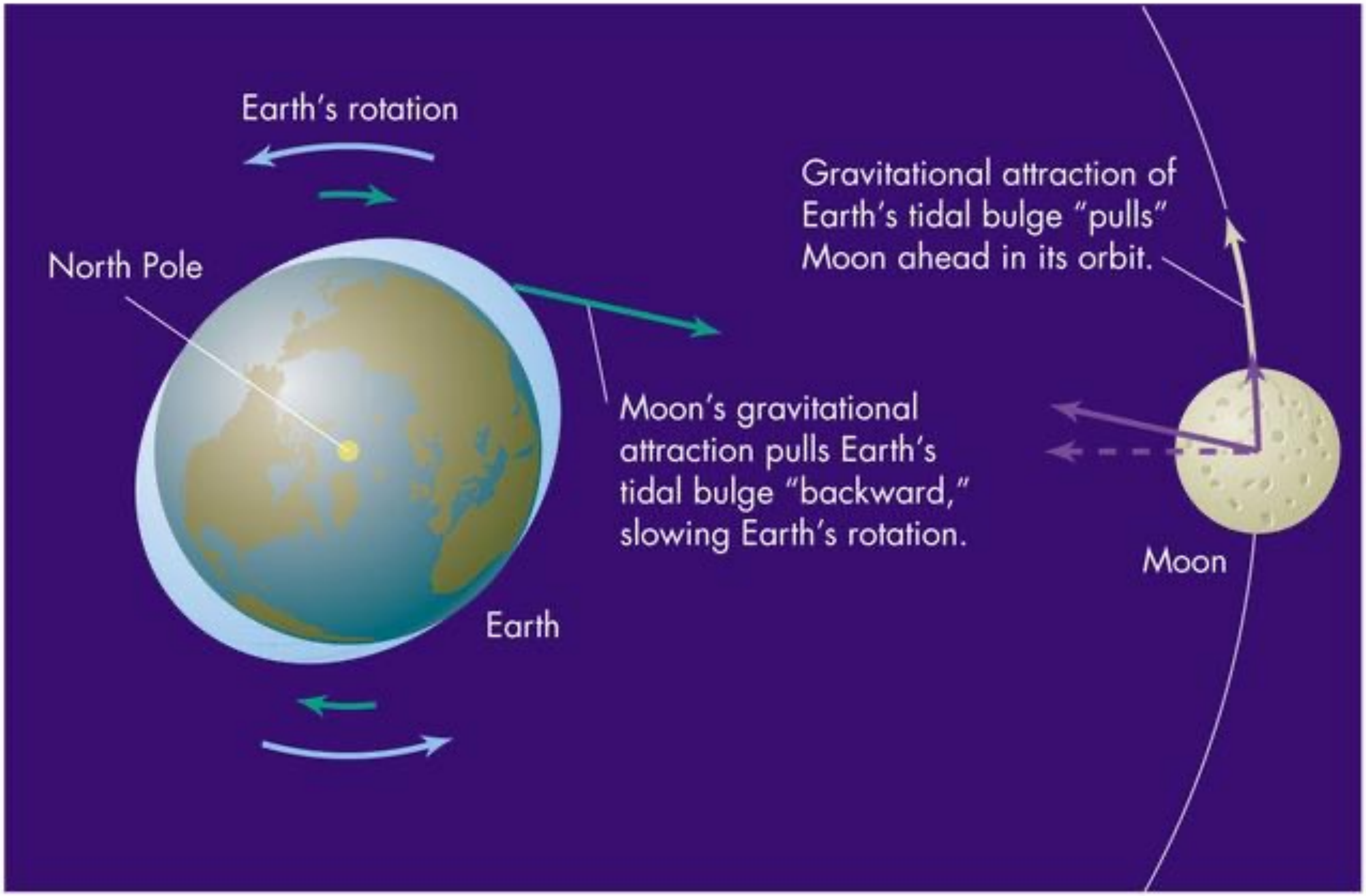


Tidal braking effect 1

- This friction takes away rotational energy from the Earth and acts like a brake
- It therefore slows the rotation of the Earth by a small amount

What does that mean in terms of the length of a day?

The day is getting *longer* by 0.0023 seconds per century.


Earth's rotation
North Pole
Gravitational attraction of Earth's tidal bulge "pulls" Moon ahead in its orbit.
Moon's gravitational attraction pulls Earth's tidal bulge "backward," slowing Earth's rotation.
Moon
Earth

Tidal braking effect 2

- Additional mass in the ocean bulges leading the Moon causes a net forward pull.

  => net forward acceleration of the Moon

  => Moon will move to a larger orbit

This is called *lunar recession,* and the Earth-Moon distance increases 3.8 cm per year.

What effect will this have on solar eclipses?

- Day gets longer by 0.002 seconds per 100 years
- The Moon recedes by 3.8 meters per 100 years

After ~50 billion years:

The Moon will be 50% farther away

The lunar sidereal month will be 47 days (from which law?)

The Earth's day will be 47 days long. Braking effect will stop.

Earth and Moon will be locked in a 1:1 tidal resonance.

(Estimate: at closest approach, month was 6.5 hours long, day was 5 hours long, Moon was only 18,000 km away and covered 11° !)

Tidal phenomena

- Tidal locking (Pluto - Charon system)
- Tidal resonances determining rotation periods (Moon, Mercury)
- Tidally induced heating (Io-Jupiter, Triton-Neptune)

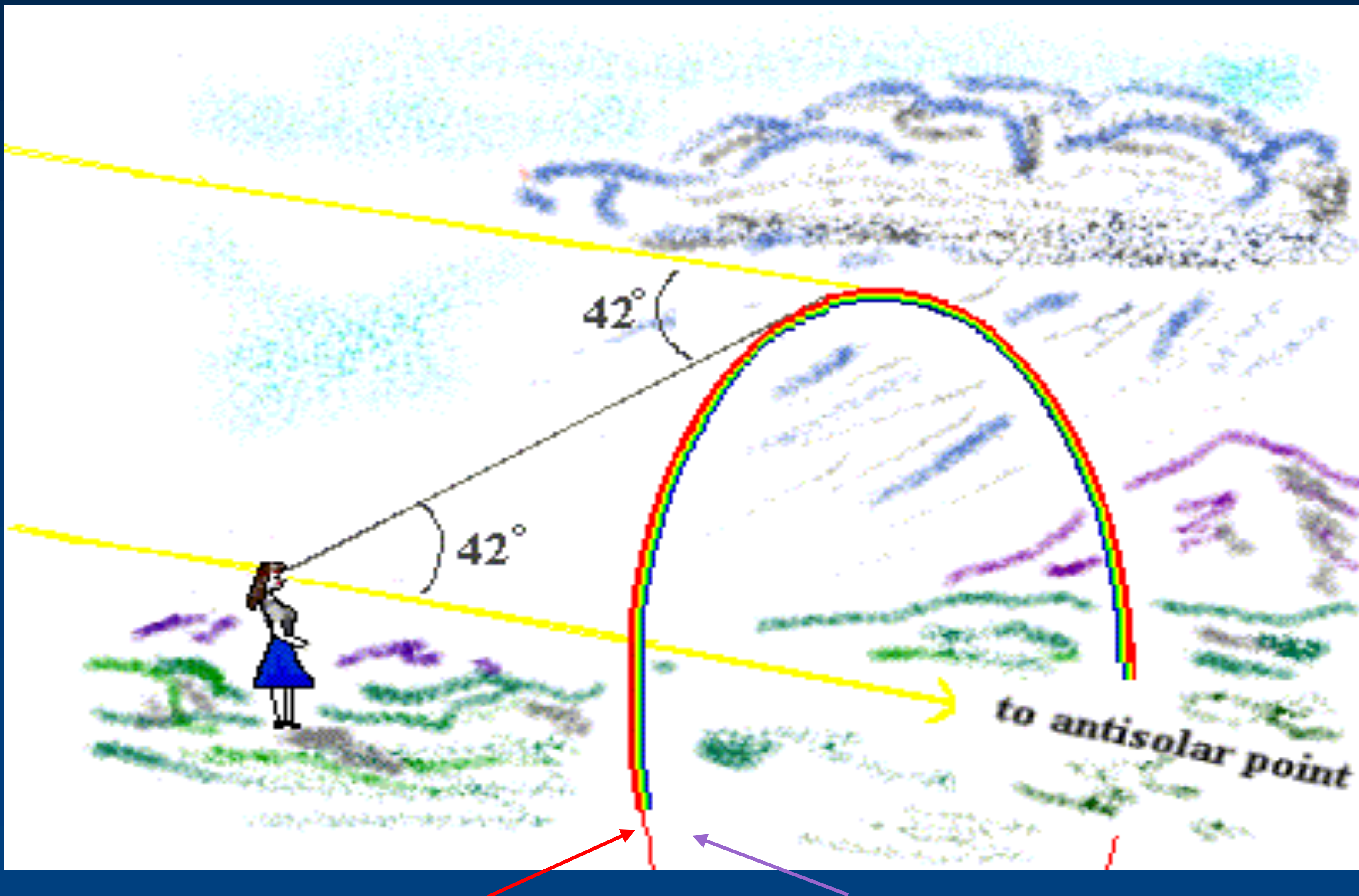
Tides are important to understand the dynamical evolution of the Solar system!

Tides are important for stars and galaxies, too

Rainbows

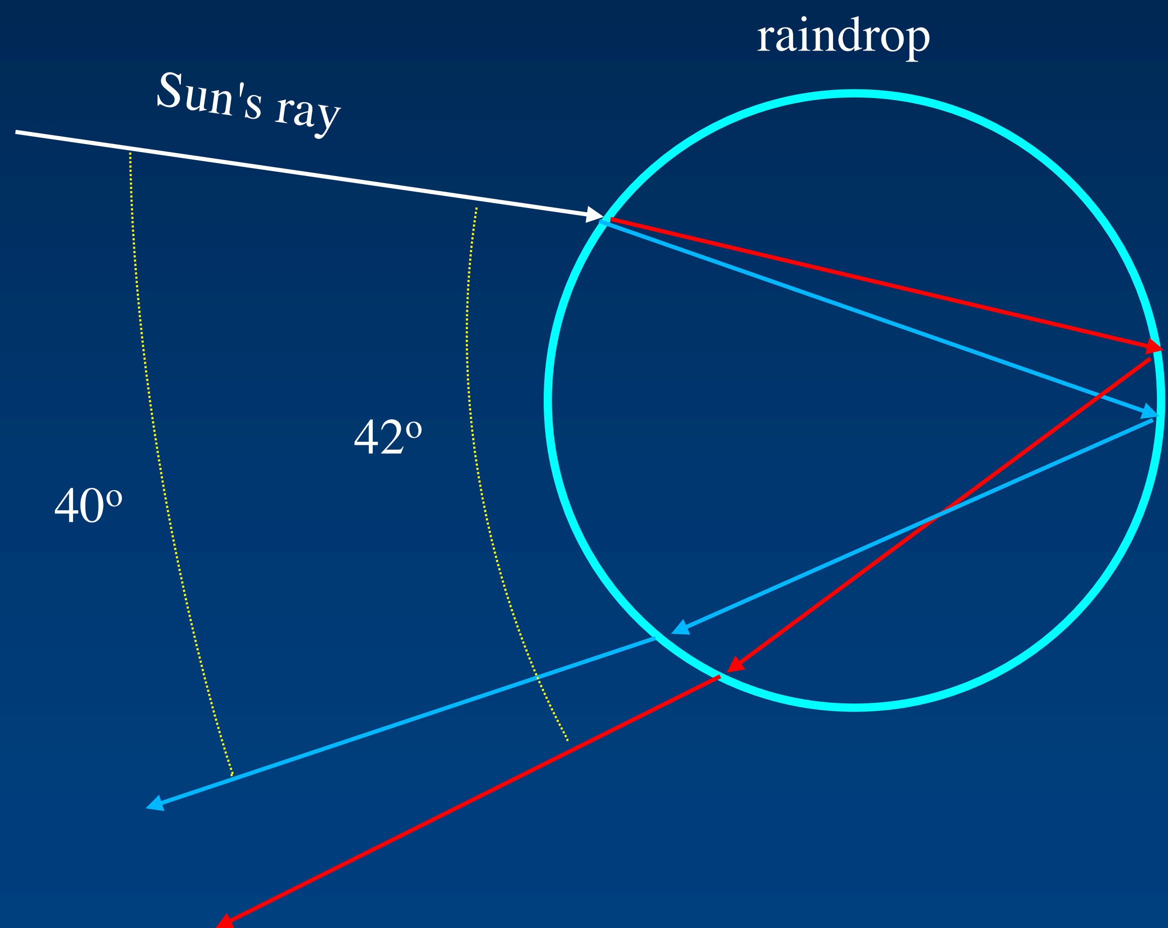
Rainbows

Rainbows

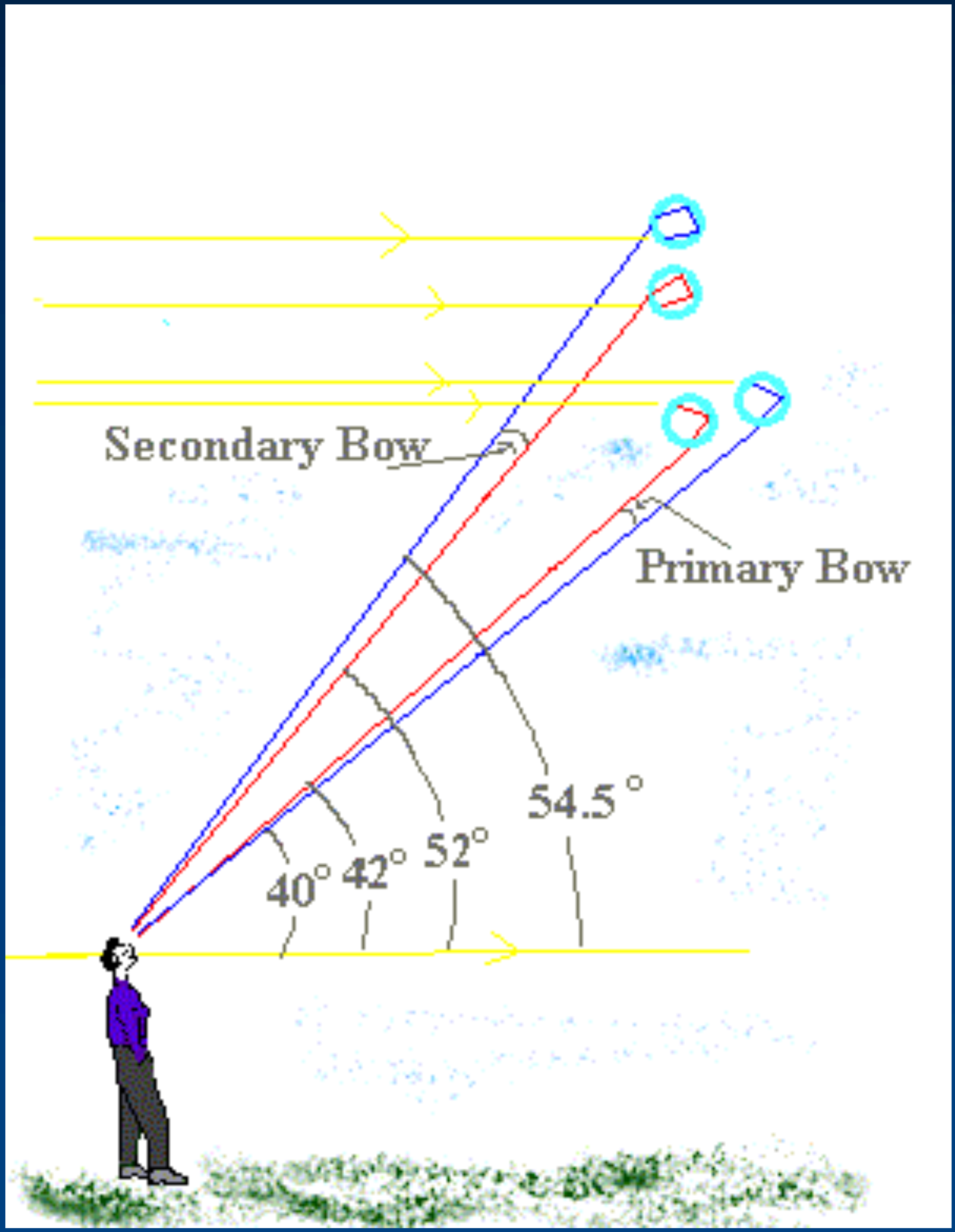


rred orange yellow green blue violet

What's happening in the cloud?



Double Rainbows



Sun Dogs and Crazy Clouds