Chapter 3

Lunar phases, Tides and Eclipses

Lunar phases, Tides and Eclipses

3.1 Phase cycle

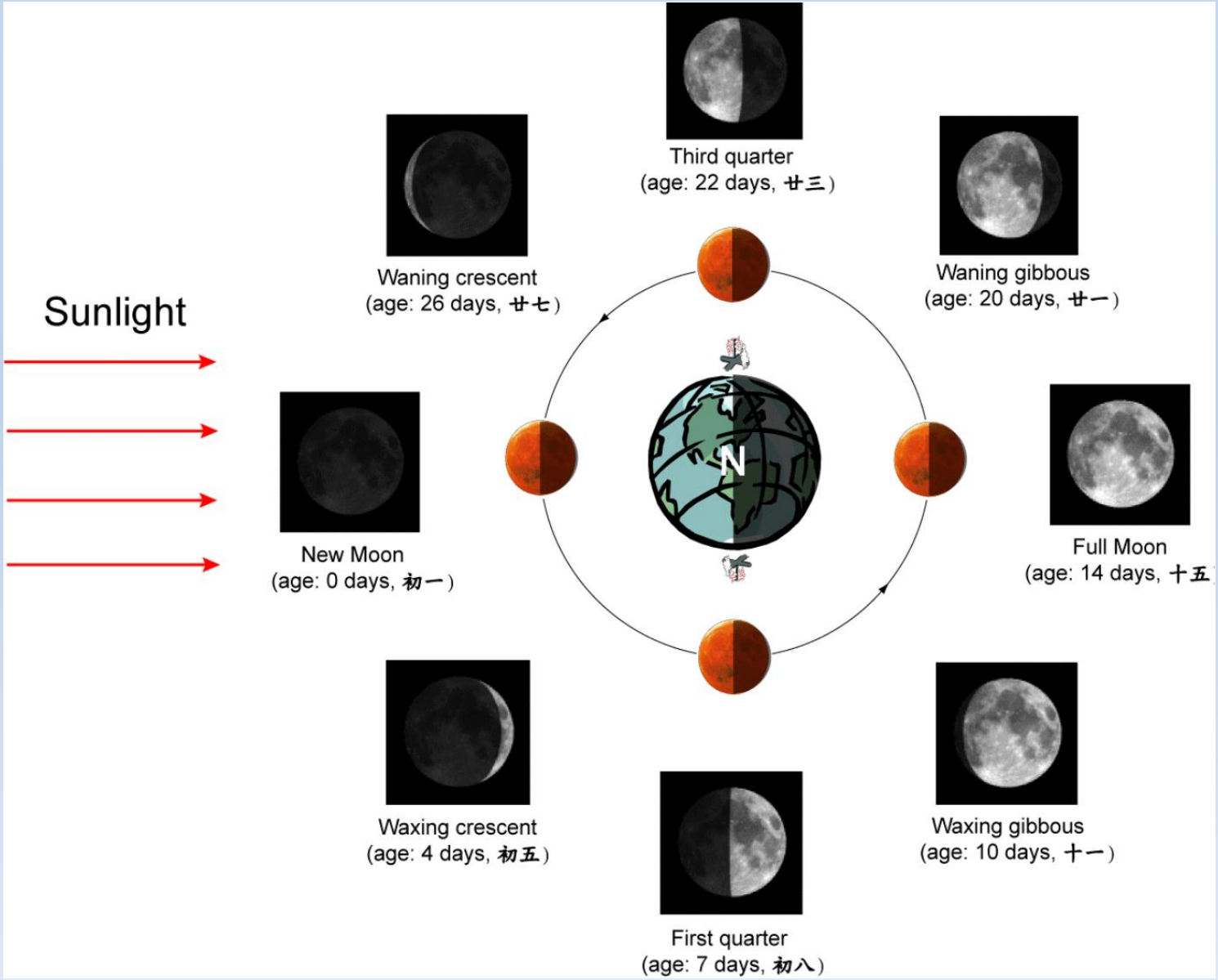
3.2 The Moon's orbit

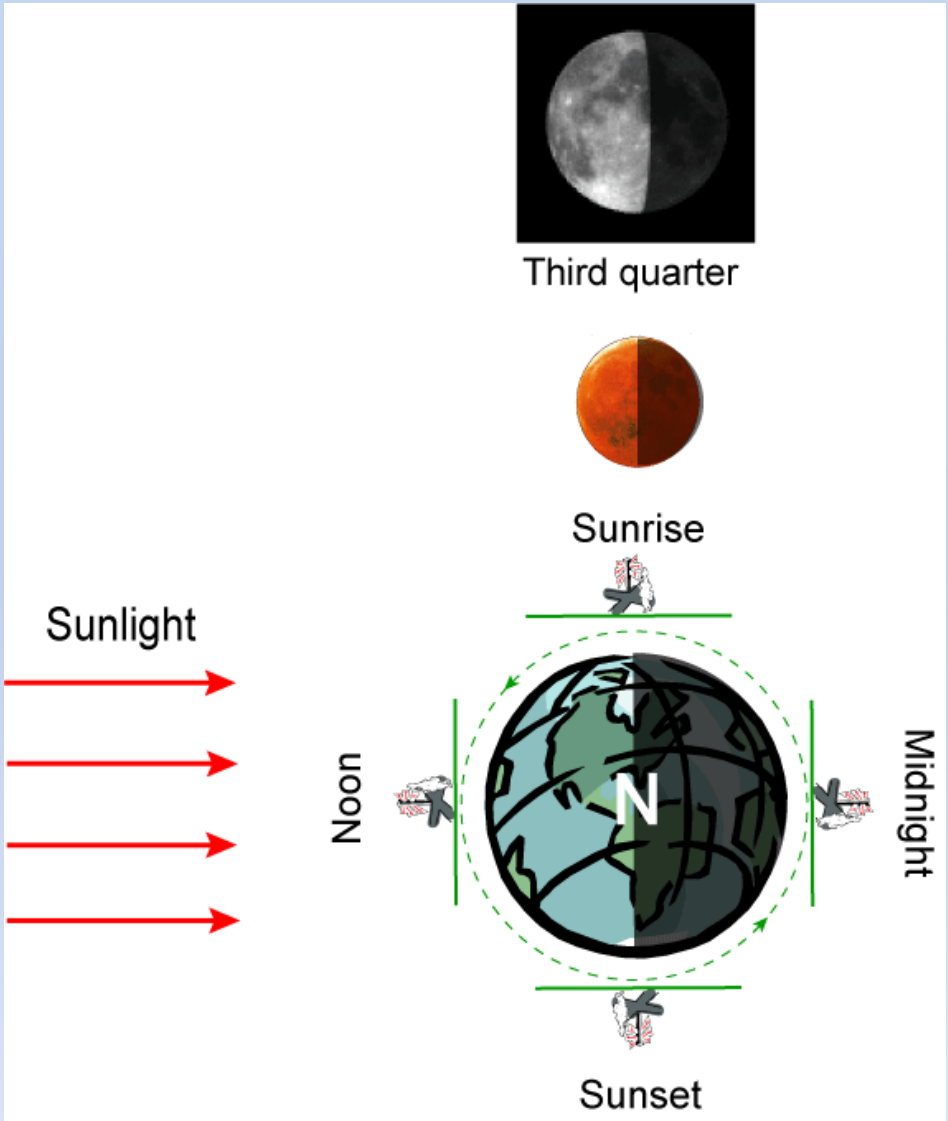
3.3 Tides

3.4 Eclipses

3.1 Phase Cycle

月球轨道逆时针旋转

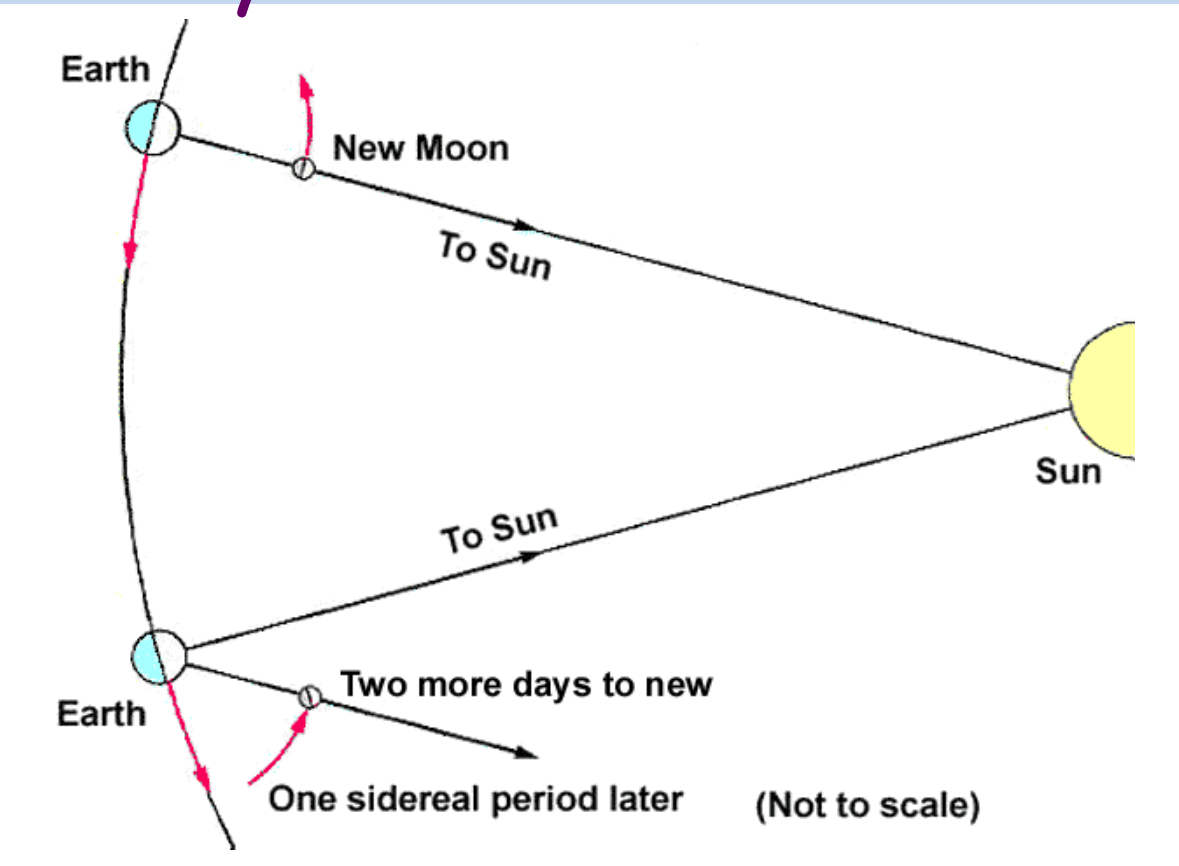




Question: When does the Third-quarter Moon rise and set? When does it cross the upper meridian?

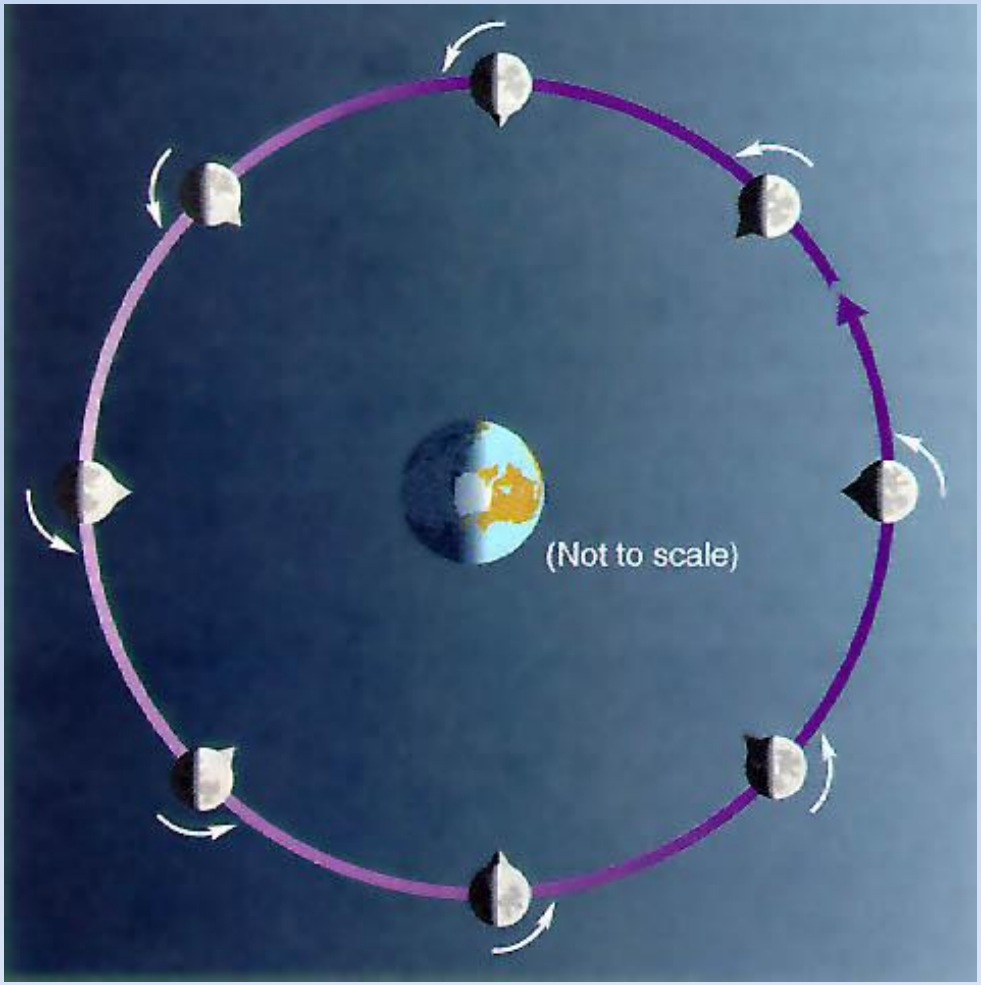
- ✓Drawing a line to represent observer's horizon
- ✓The Moon rises at the eastern horizon at midnight
- ✓Sets at western horizon at noon
- ✓Cross the upper meridian at about 6pm

3.1 Phase Cycle



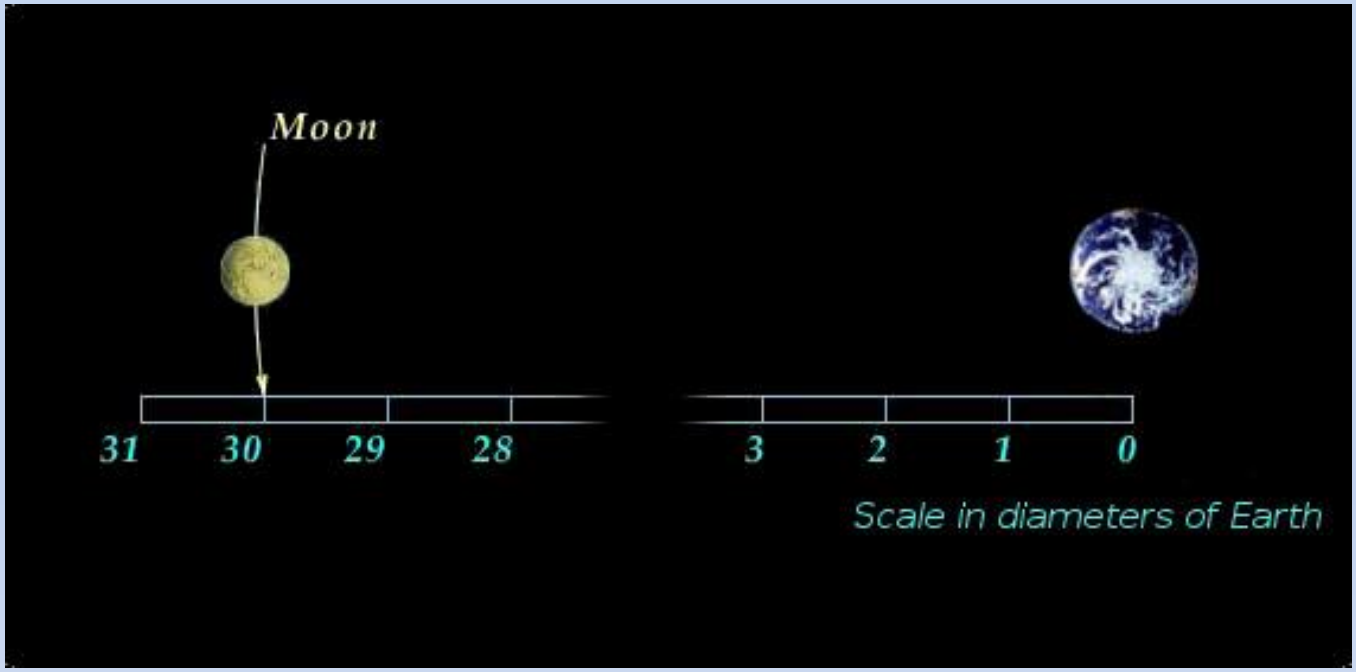
- ✓ Sidereal period: time to orbit around the Earth once relative to distant stars, ~ 27.32 mean solar days
- ✓ Synodic period: lunar phase period, i.e., from a New Moon to another, ~ 29.53 mean solar days

3.1 Phase Cycle



- ✓ Self-rotation period of the Moon is *about the same* as the sidereal period,
- ✓ always see the same half of the Moon from the Earth! (no matter what the phase is.)

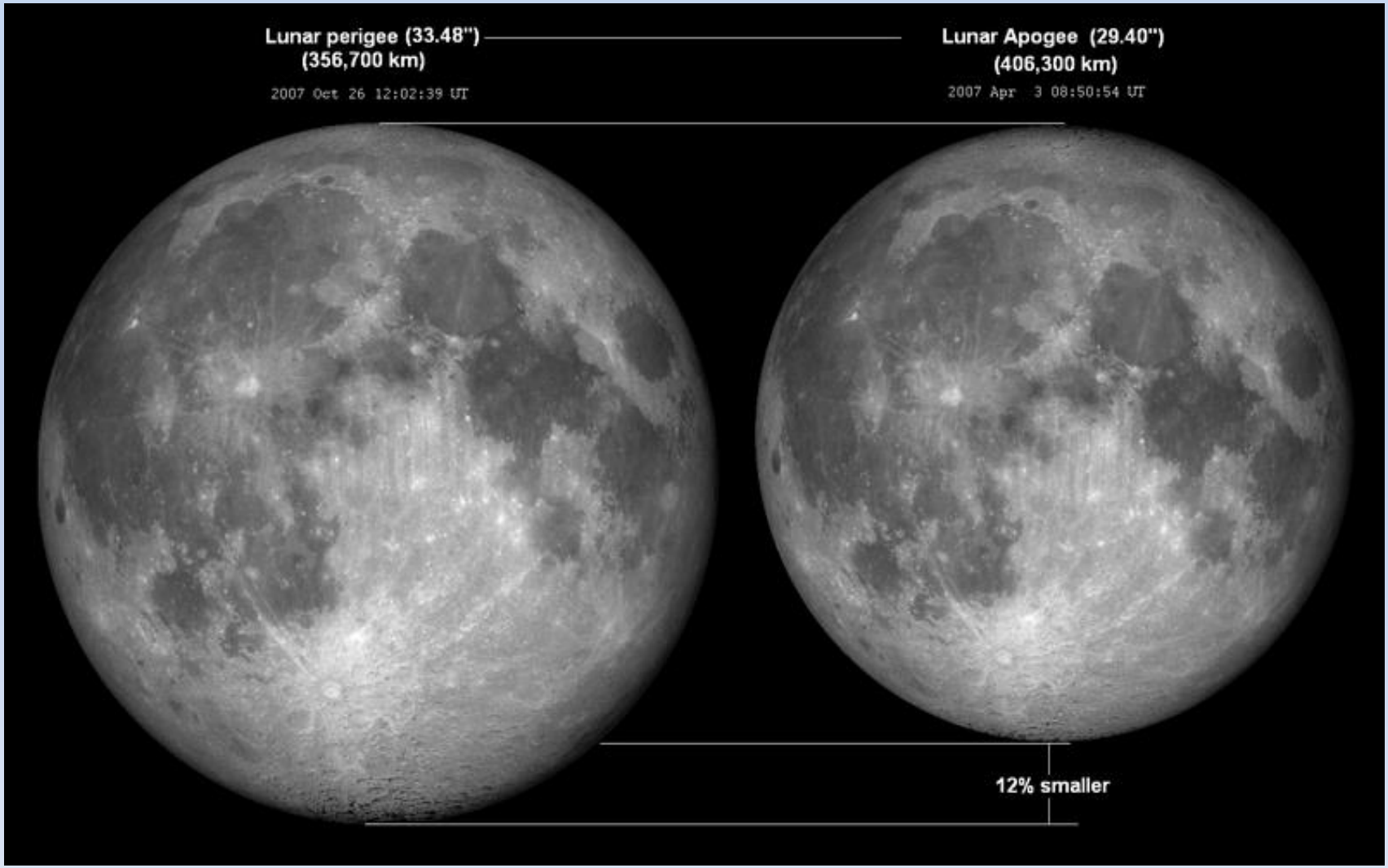
3.2 The Moon's orbit



- ✓ Earth-Moon distance ≈ 30 Earth's diameters
- ✓ The orbital plane of the Moon is tilted by 5.1° to the Earth's (the Moon always near to the ecliptic)
- ✓ The Moon's orbit is elliptical

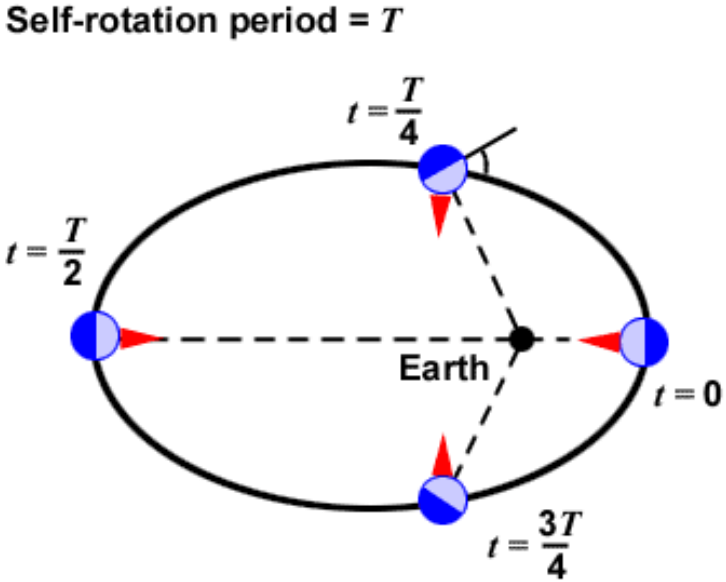
  → Distance from the Earth changes, and angular size changes (still, ~0.5°)

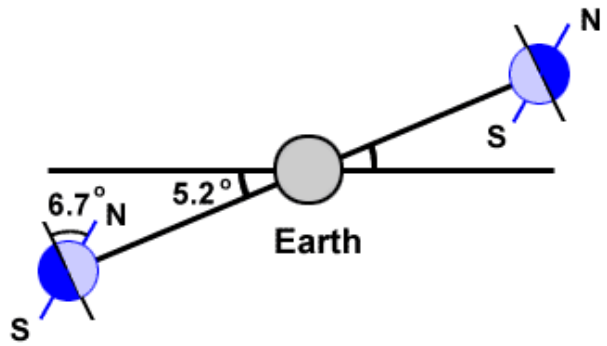
3.2 The Moon's orbit



Super Moon!

3.2 The Moon's orbit





Libration in longitude

- ✓ Moon moves at different speeds in its elliptical orbit,
- ✓ but self-rotates at a fairly steady rate,
- ✓ Moon appears east-west "rocking" of the Moon by ~7.9°

Libration in latitude:

- ✓ The lunar orbit inclined ~5.1° to the ecliptic,
- ✓ Moon appears north-south "nodding" motion

We see ~59% of the total lunar surface!!

Oct 10 – Nov 9, 2007

Credit: Tom Ruen; Wikimedia Commons

3.3 Tides

C
B
A

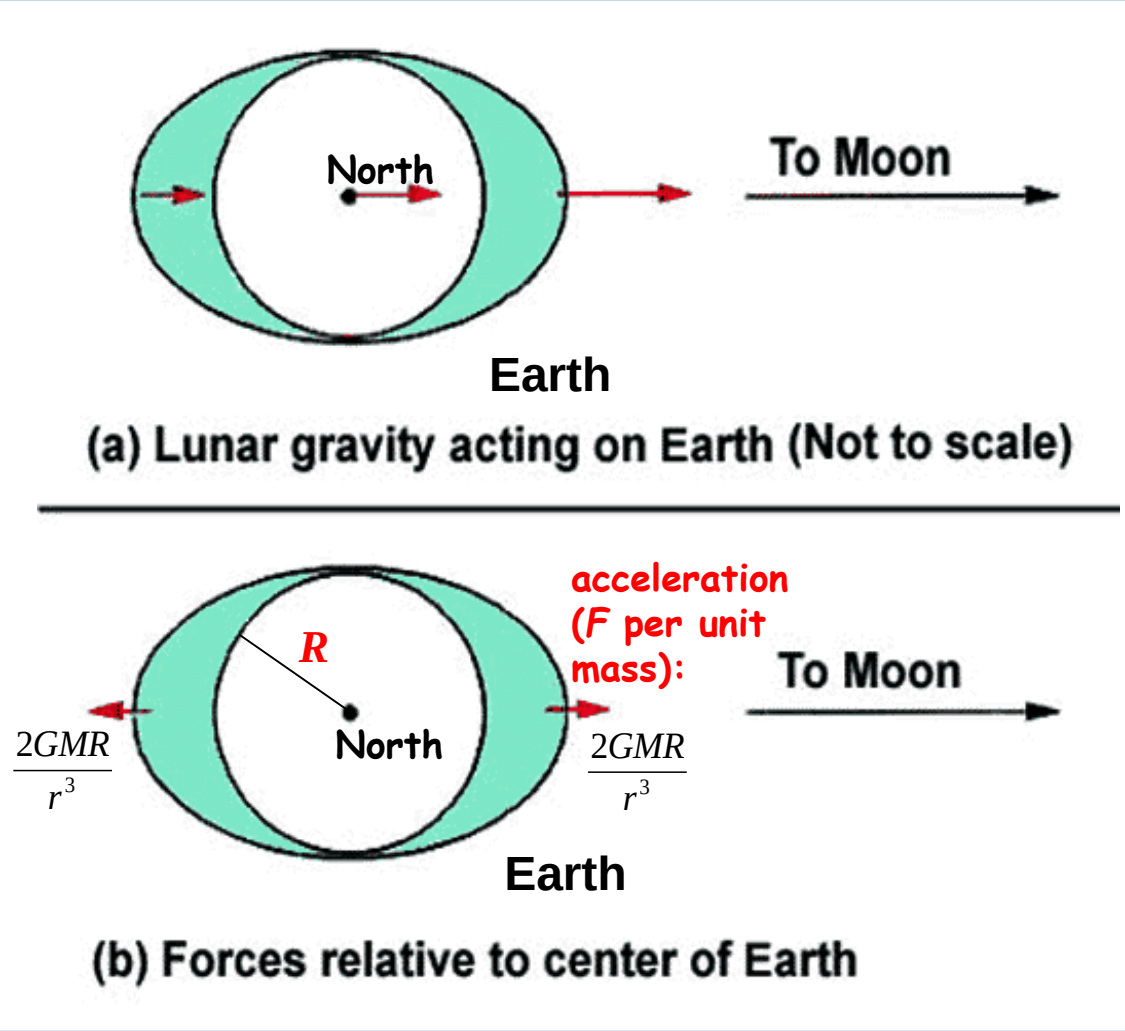
C
B
A

- ✓ Consider three balls in free-falling motion
- ✓ If gravity is uniform, separations between the falling balls do not change.

3.3 Tides

- ✓ If gravity is not uniform (increases with distance in this case), upper/lower ball experiences weaker/stronger gravity.
- ✓ Upper/lower ball falls slower/faster
- ✓ Separation increases!

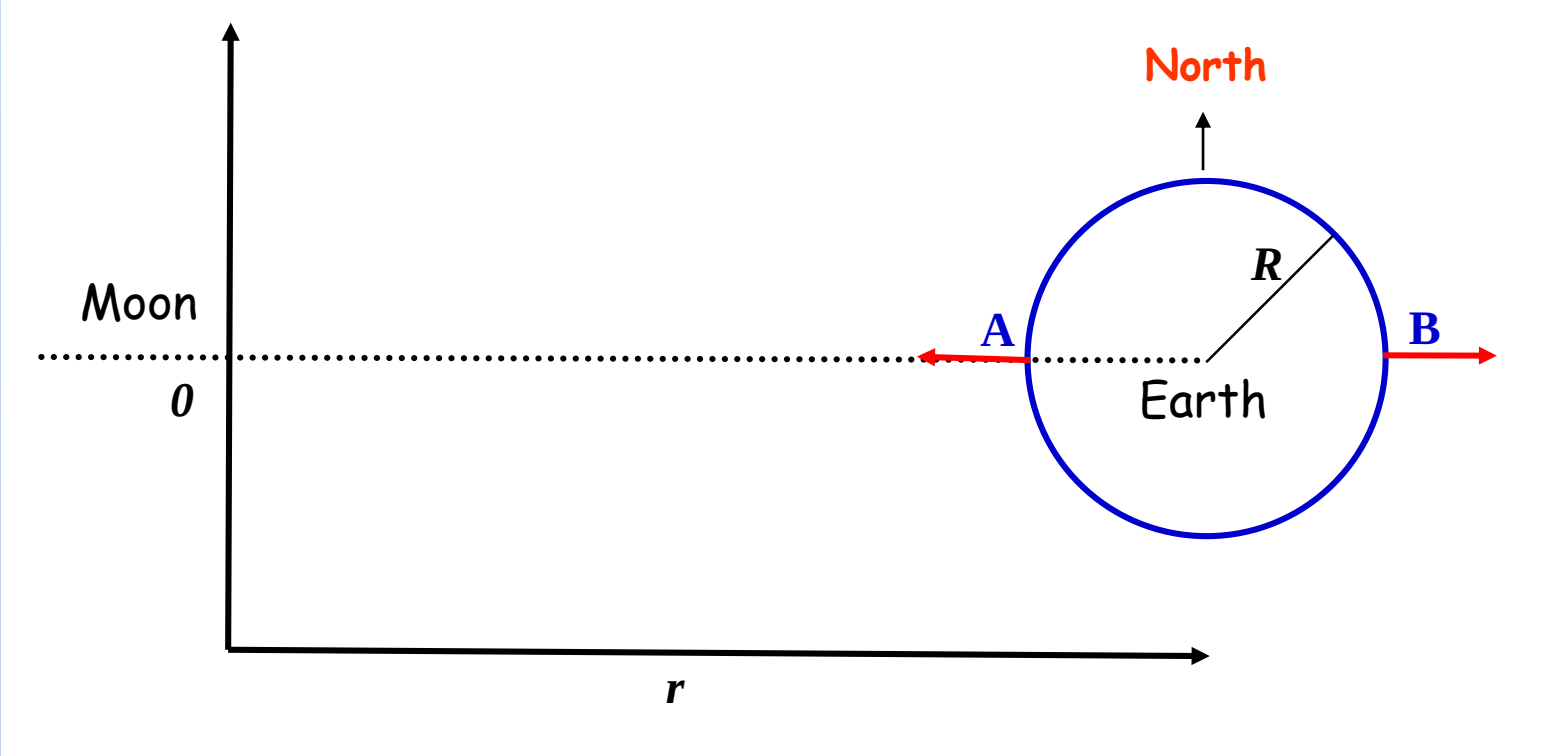
3.3 Tides



- ✓ Because of the gravitational pull by the Moon, the Earth experiences *Tidal force* and bulges on both sides.
- ✓ Two high tides
- ✓ The tidal force per unit mass is

$$F_{tidal} = \frac{2GMR}{r^3}$$

- ✓ Tidal effect of the Sun is about 1/2 of that of the Moon



- ✓ Gravitational force per unit mass is $F(r) = \frac{GM}{r^2}$
- ✓ Relative to the centre of the Earth, the force per unit mass at **B** is $(R)\frac{dF}{dr} = \frac{2GMR}{r^3}$ away from the Moon
- ✓ The force per unit mass at **A** is $(R)\frac{dF}{dr} = \frac{2GMR}{r^3}$ towards the Moon

3.3 Tides

Ocean tides are complicated. Latitude affects the tidal range (and even the number of tides). Geography also affects the tidal range.

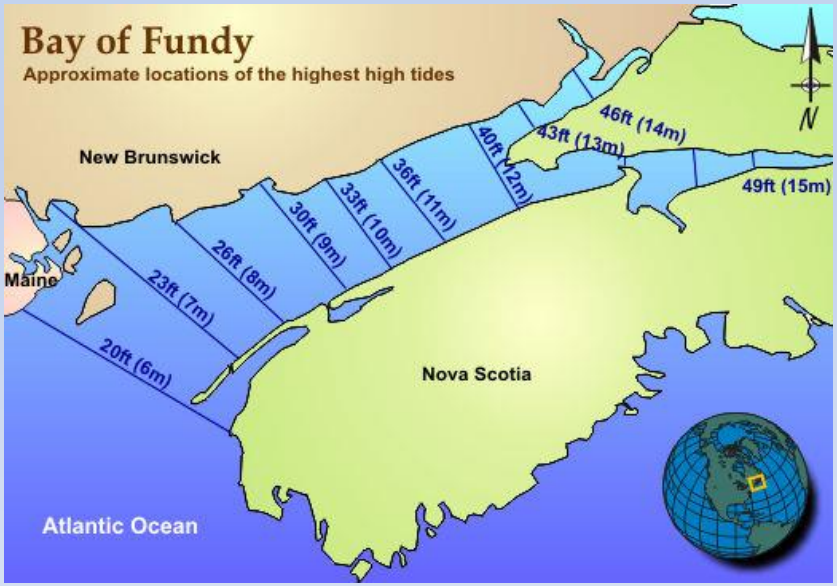


Image: NOAA

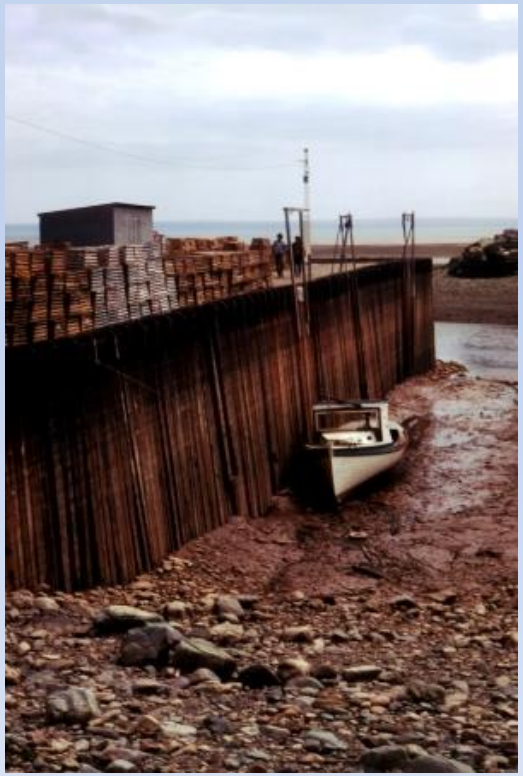
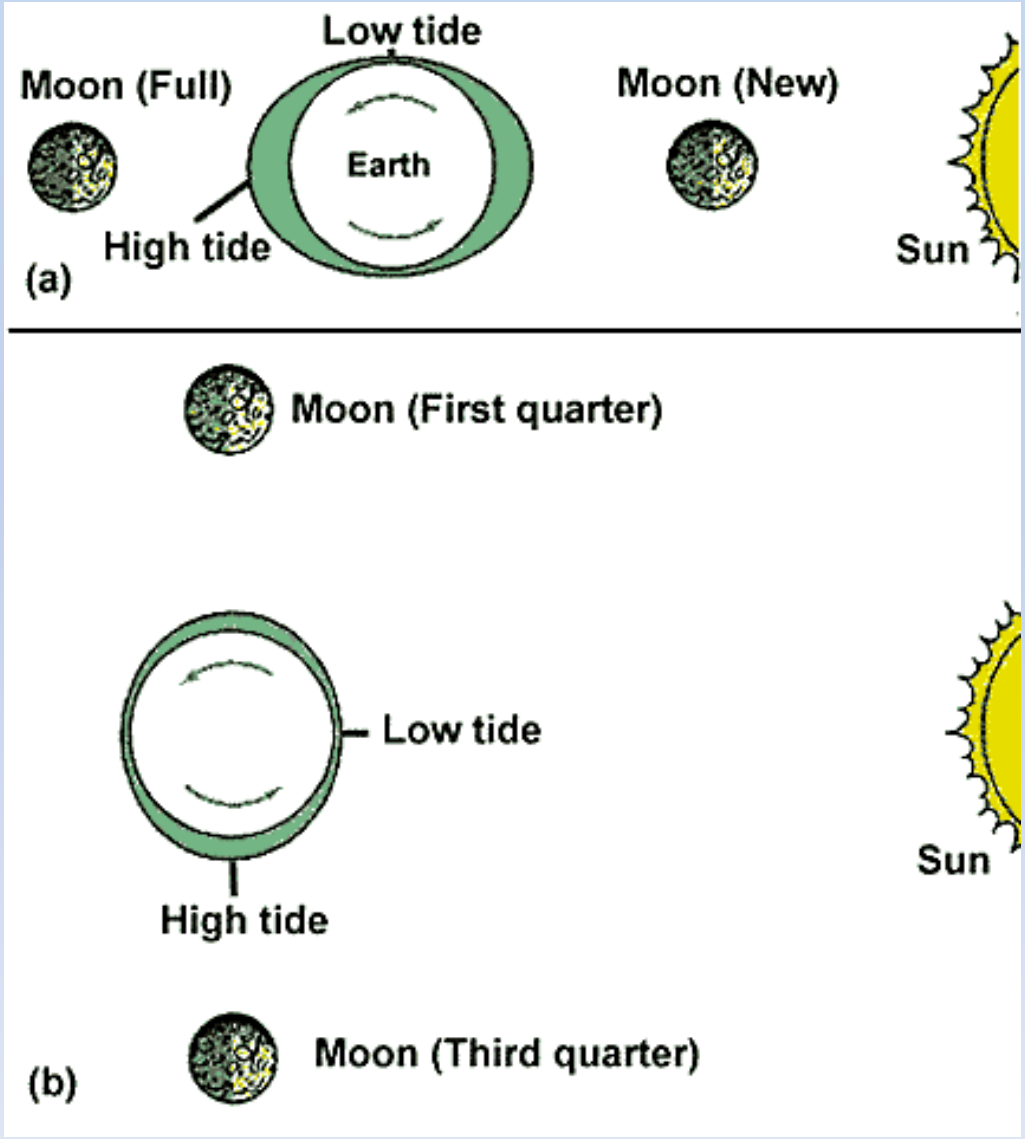


Image: Wikimedia Commons

We won't spend time on the location-dependent effects.

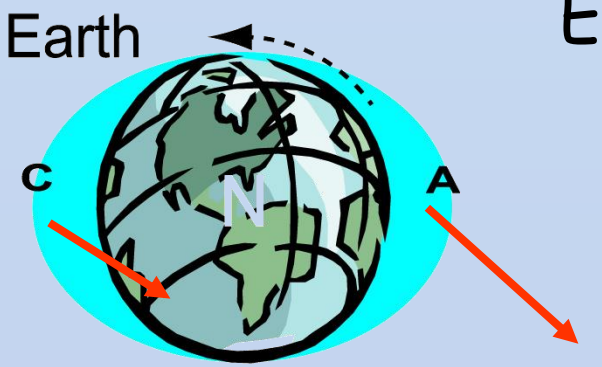
3.3 Tides



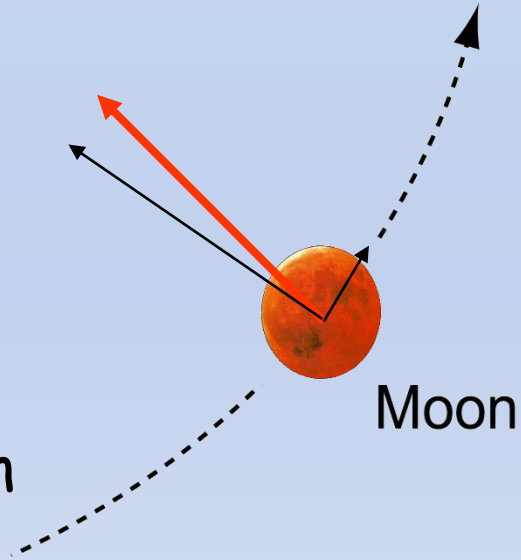
Spring tides
(朔望潮)

Neap tides
(弦潮)

Effect of tides: Moon's orbit



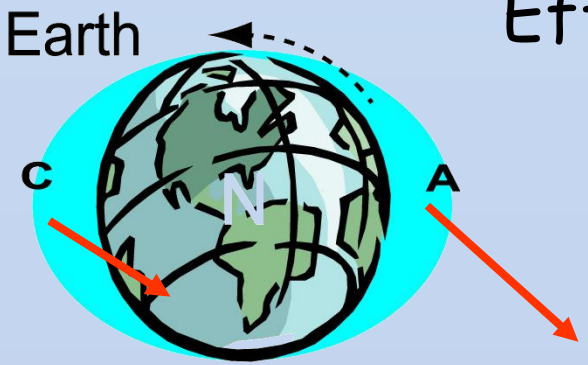
Net force of bulges A and C pulls the Moon forward. Larger angular momentum → a "higher" orbit.



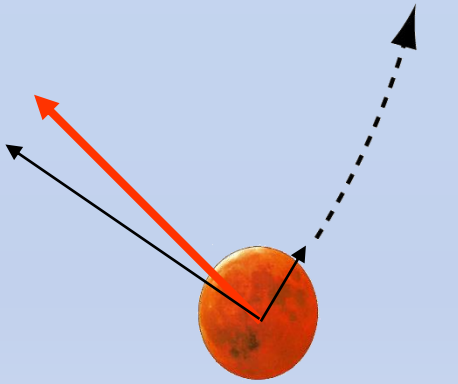
Because of Earth's rotation, the bulges ahead of the line connecting the Earth and Moon

It pulls the Moon forward. The distance to the Earth increases slowly (**~3cm/year**). The distance is measured by bouncing laser beams off the mirrors left on the Moon.

Effect of tides: Earth's rotation



The Moon pulls the budges backward, and slows the Earth's rotation.



The net torque exerted on the Earth is slowing Earth's rotation, rotation period of the Earth increases by **0.0016 second per century**.

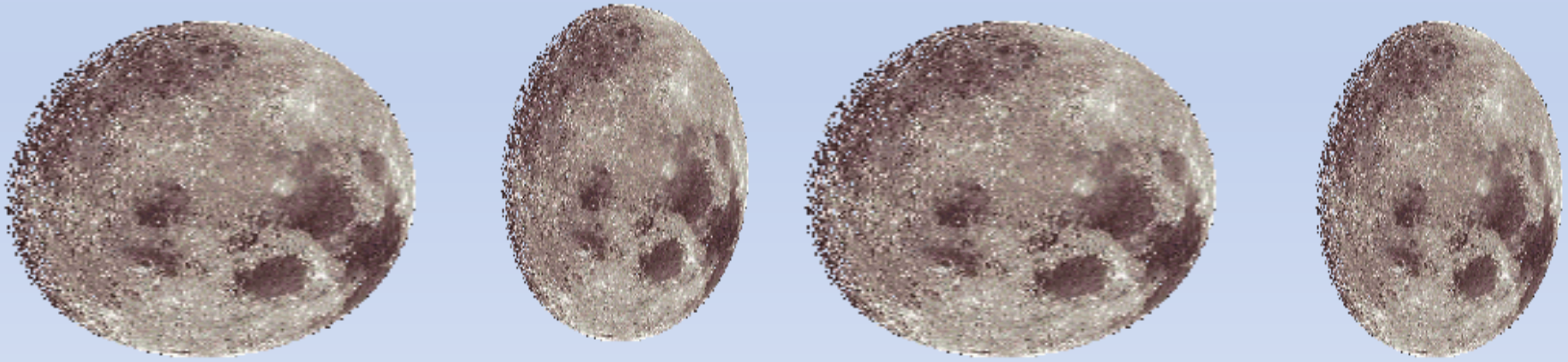
Fossils of marine animals confirm that about 400 million years ago the Earth's day was 22 hours.

The Earth's rotational angular momentum is decreasing, the orbital angular momentum of the Moon increases.

3.3 Tides

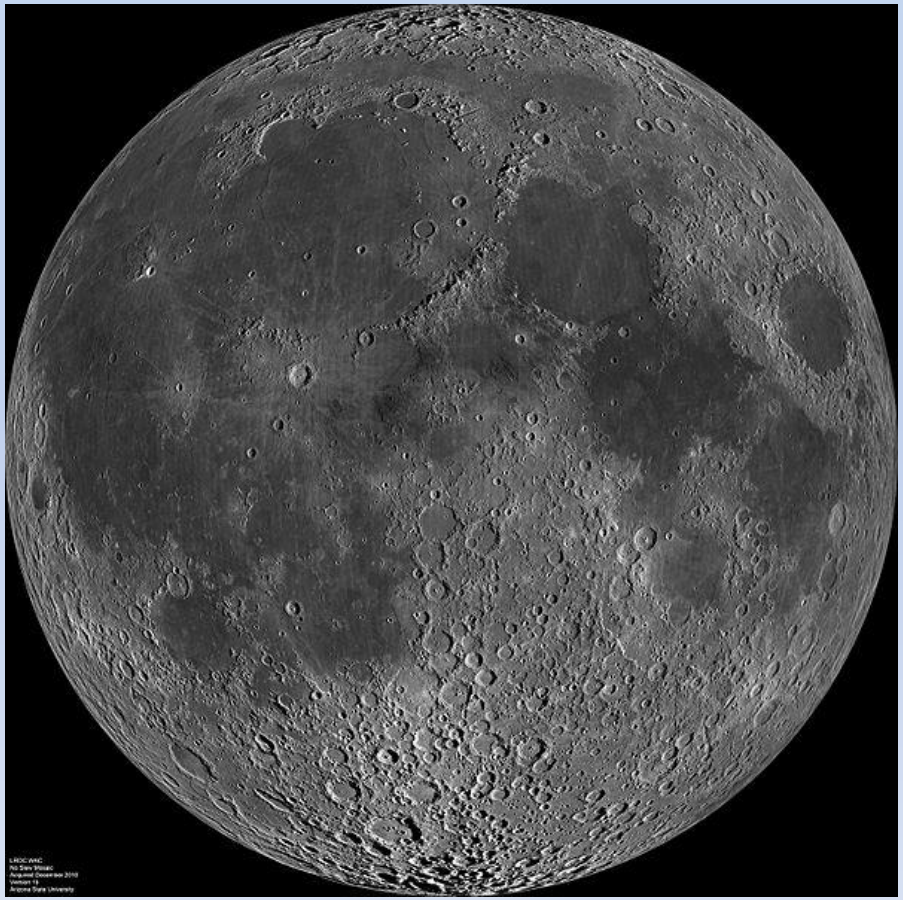
Another effect of tides: The Moon always shows the same face towards the Earth.

- ✓ If the Moon were spinning too fast/slow, …



…, it would undergo constant deformation.
The Moon is not stable unless…

3.3 Tides



Nearside of the Moon

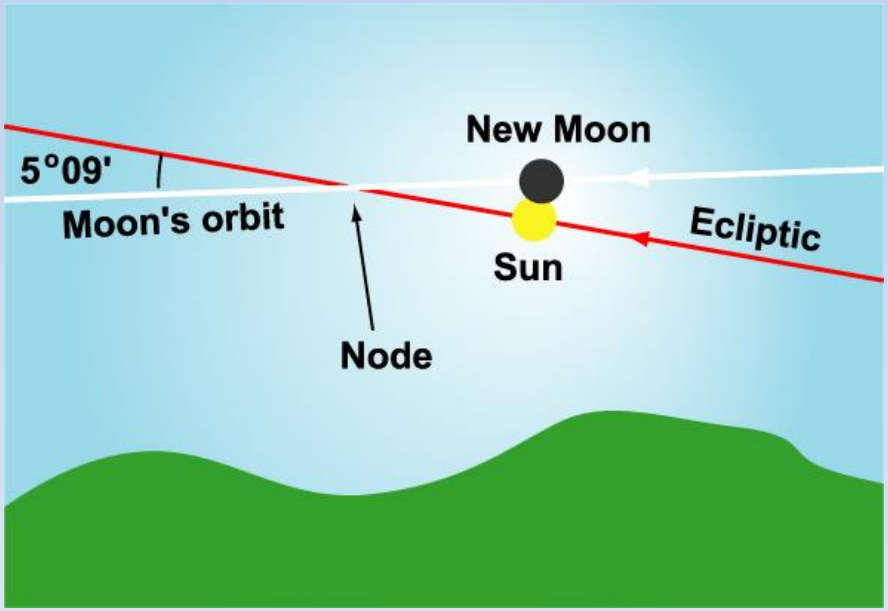
- ✓ The Moon's self-rotation period changes slowly until it is almost the *same* as its orbital period.
- ✓ The effect is known as tidal coupling (潮汐耦合)
- ✓ The Moon always shows the same face towards the Earth
- ✓ Given sufficient time, the Earth will show the same face to the Moon! By then, the length of a day ~ 47 current days

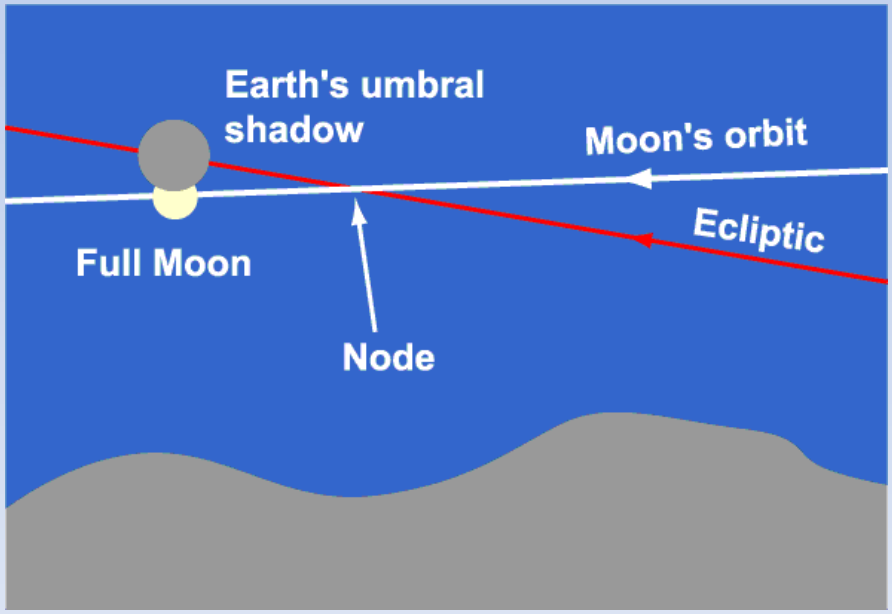
Image: NASA/GSFC/Arizona State University

3.4 Eclipses

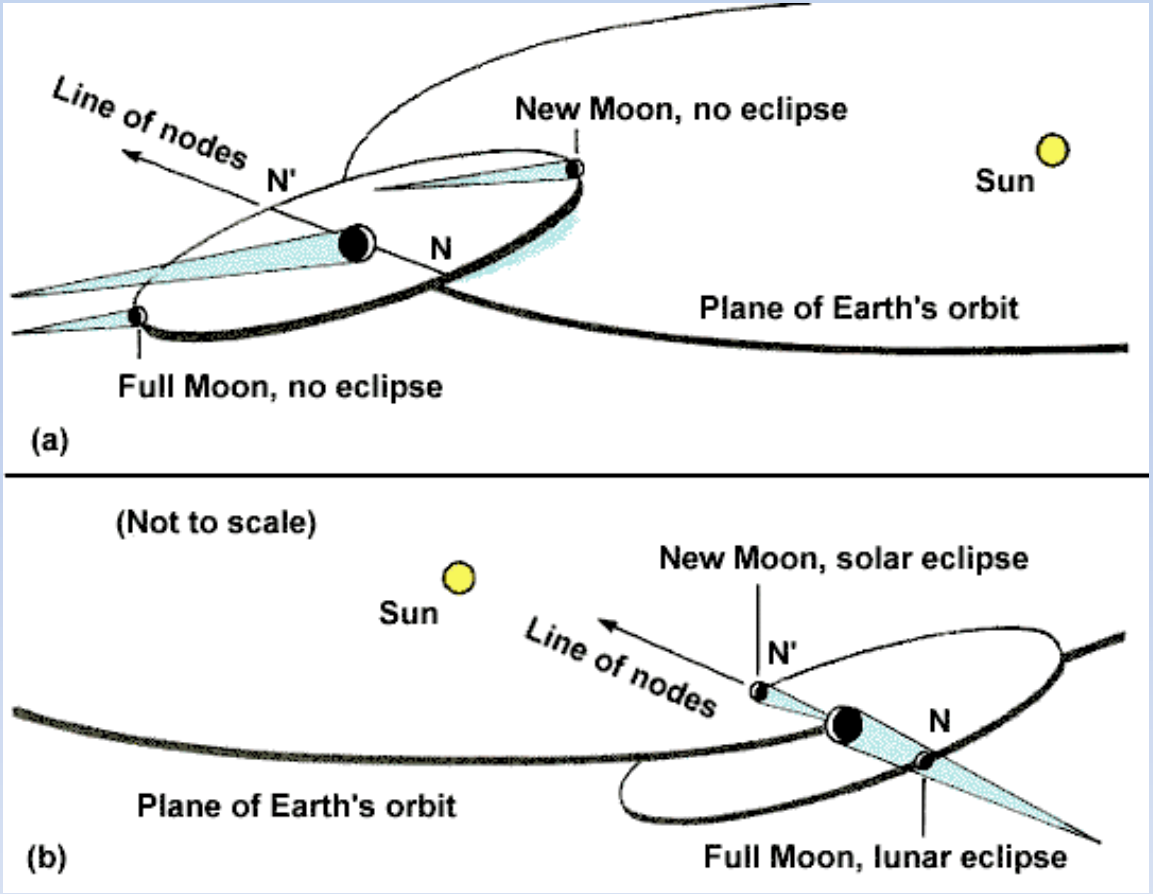
3.4 Eclipses

- ✓ The Moon's orbit and the ecliptic intersect at two nodes.
- ✓ An eclipse occurs when *both* the Sun and the Moon are close to the nodes.



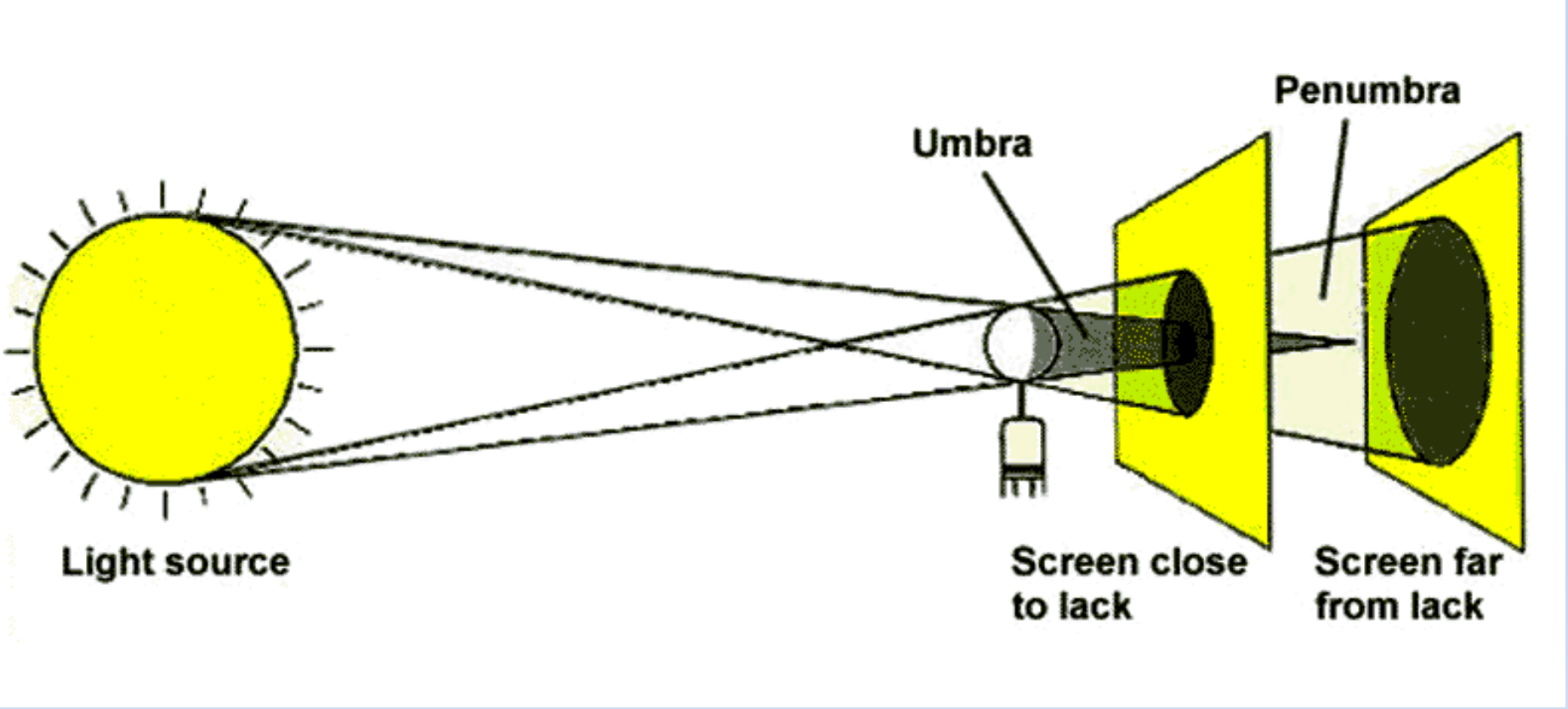


3.4 Eclipses



- ✓ Moon's orbit inclines by about $5.1°$ to the Earth's orbit, the Moon appear near the ecliptic.
- ✓ The Moon's orbital plane crosses the ecliptic at the *line of nodes*
- ✓ both the Sun and Moon lie close to the line of nodes, an eclipse occurs

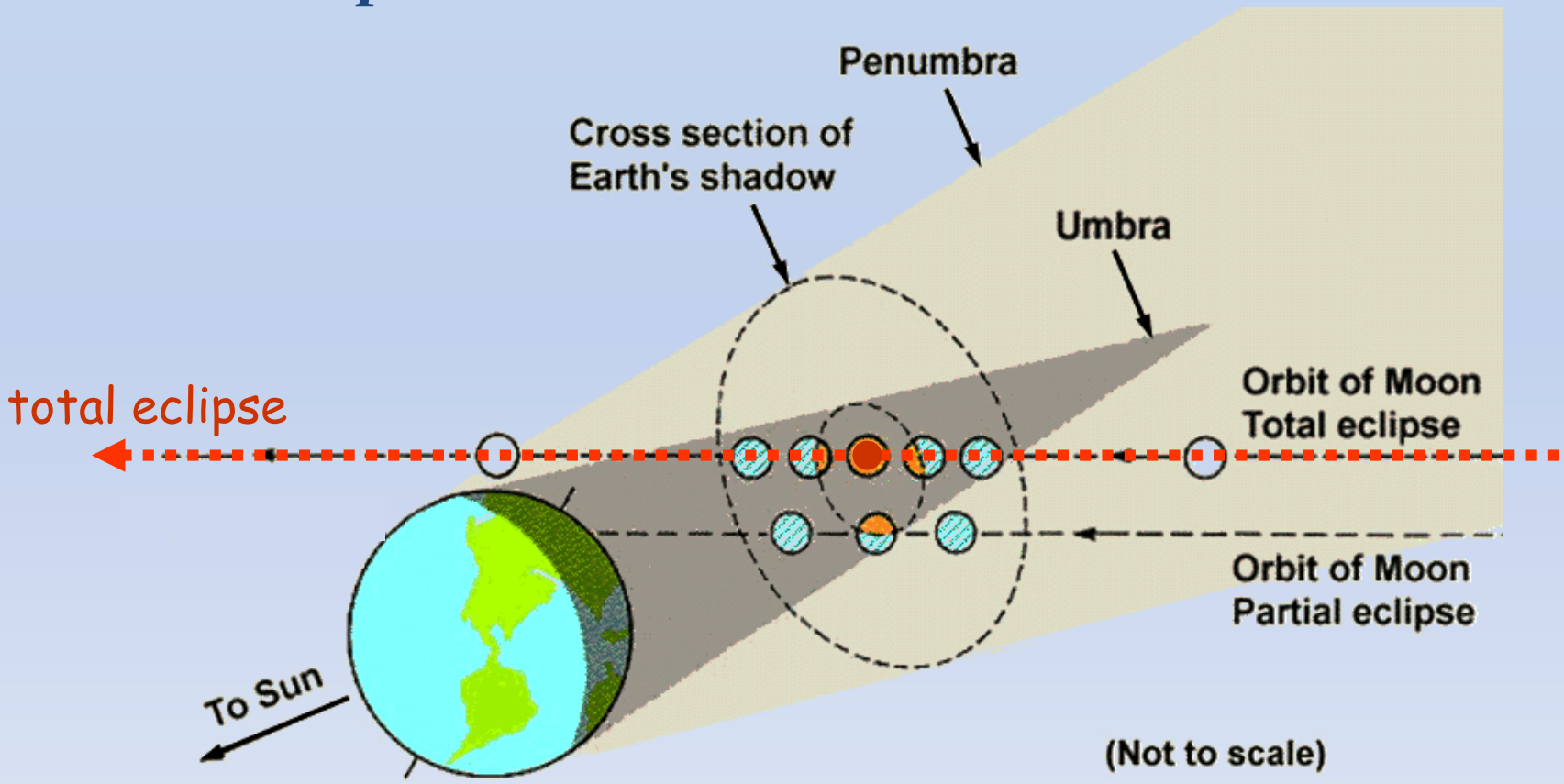
3.4 Eclipses



- ✓ Two regions in a shadow:
  Umbra 本影 - total darkness
  penumbra 半影 - partial darkness

3.4 Eclipses

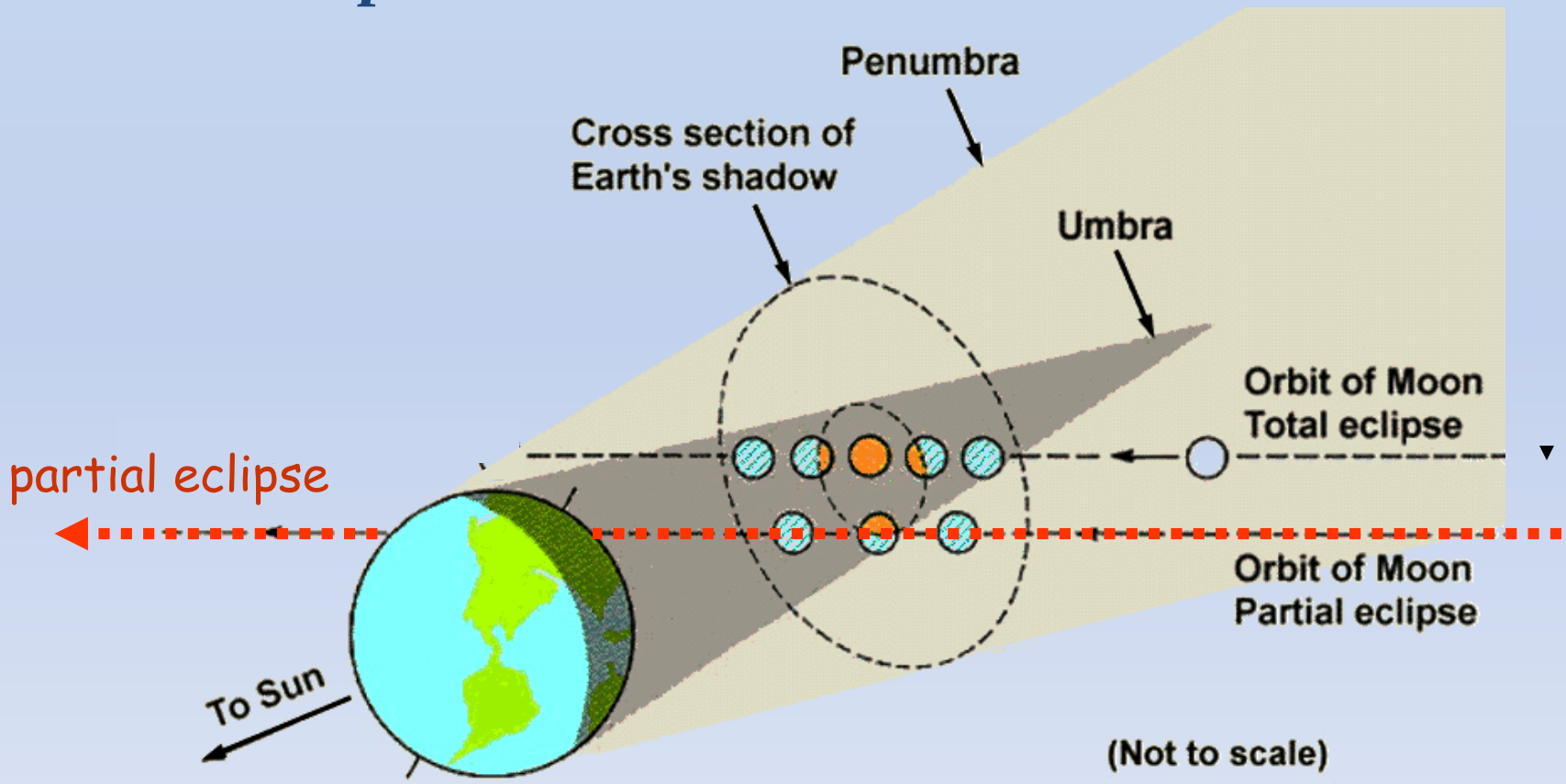
Lunar eclipses



The Moon enters the Earth's shadow

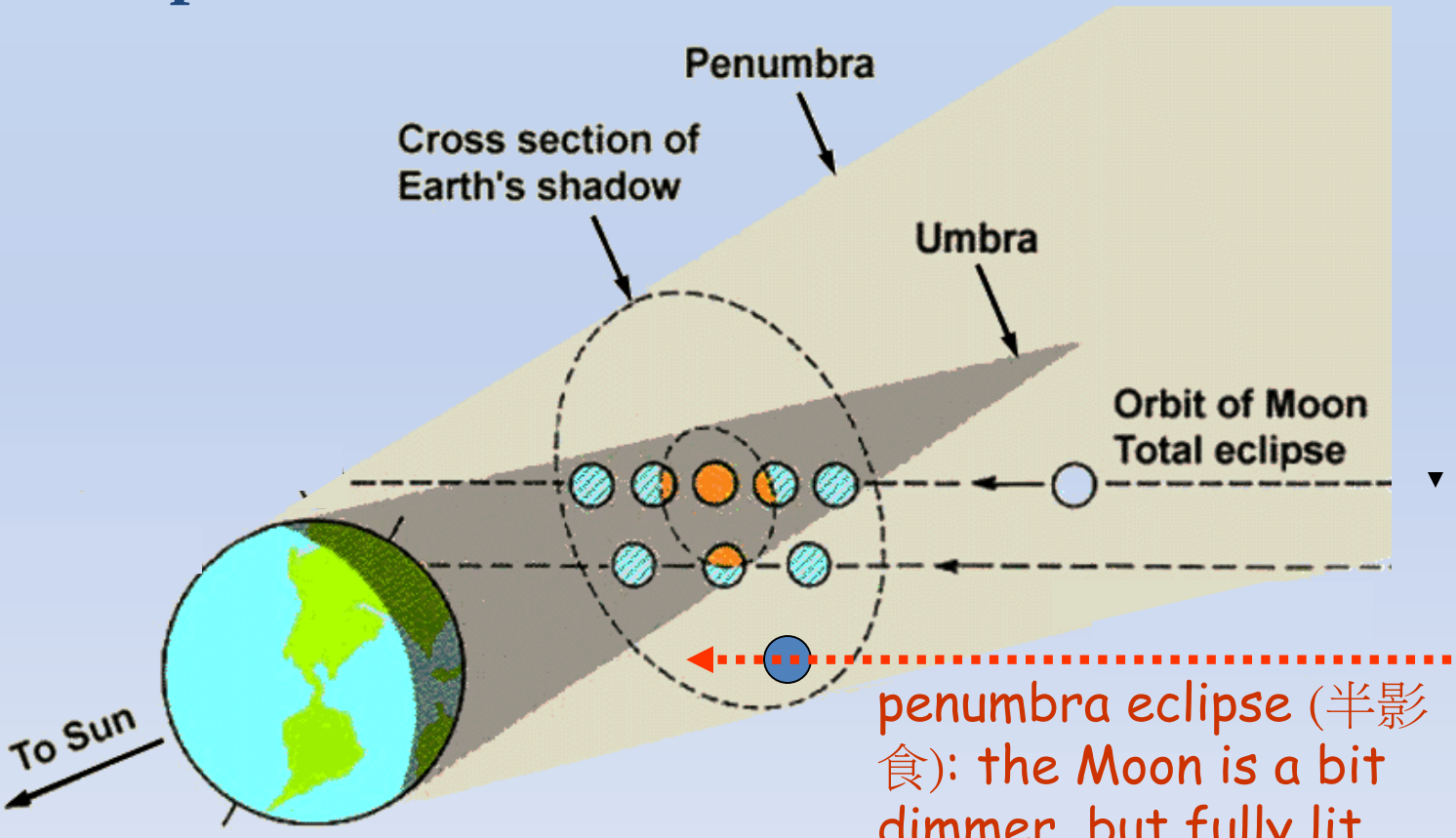
3.4 Eclipses

Lunar eclipses



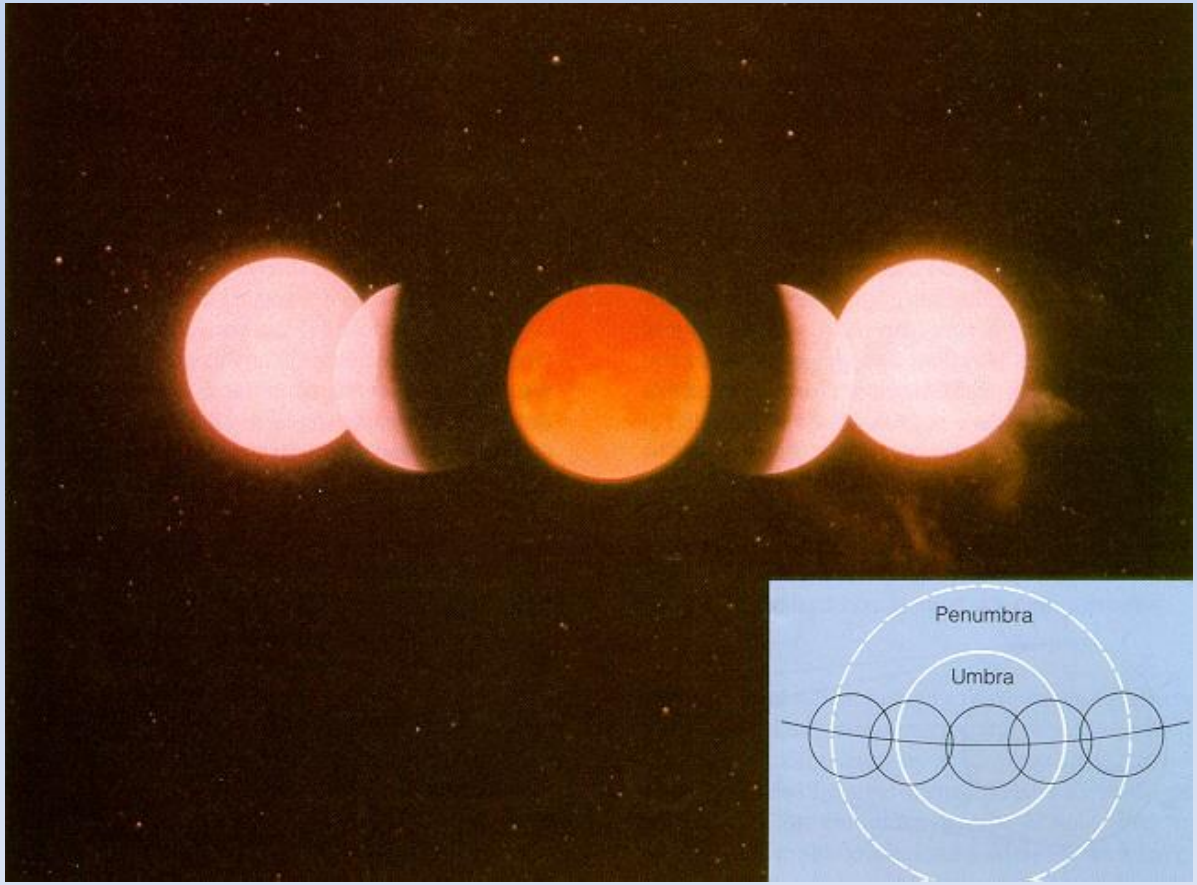
3.4 Eclipses

Lunar eclipses



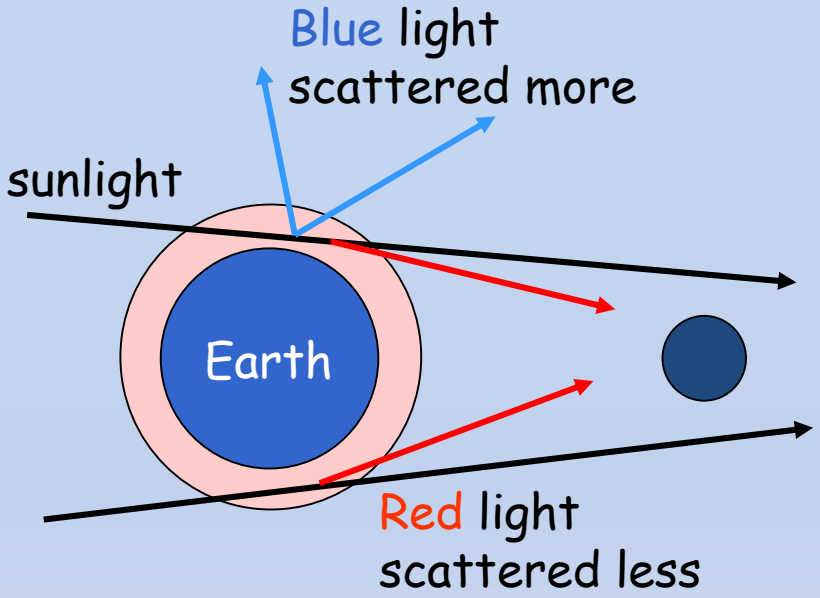
penumbra eclipse (半影食): the Moon is a bit dimmer, but fully lit

3.4 Eclipses



- ✓ *Total eclipse* (全食)
- ✓ *Partial eclipse* (偏食): The Moon only enters the umbra partially: only a part of the Moon is lit
- ✓ *Penumbral eclipse* (半影食): The Moon only enters the penumbra: the Moon is a little bit dimmer than usual, but is fully lit

3.4 Eclipses



- ✓ The Earth's atmosphere scatters sunlight
- ✓ **blue** light is scattered *more* than **red** light
- ✓ so the Moon appears reddish and dim

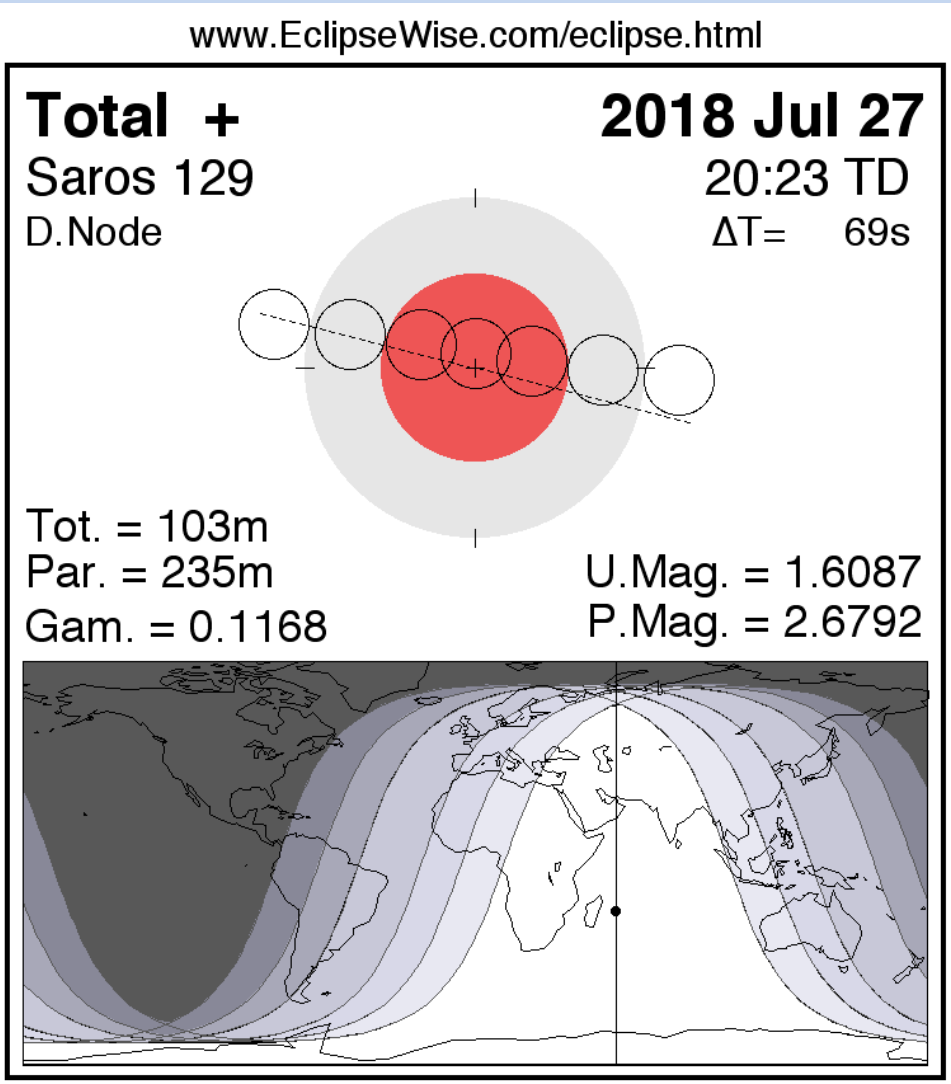
3.4 Eclipses

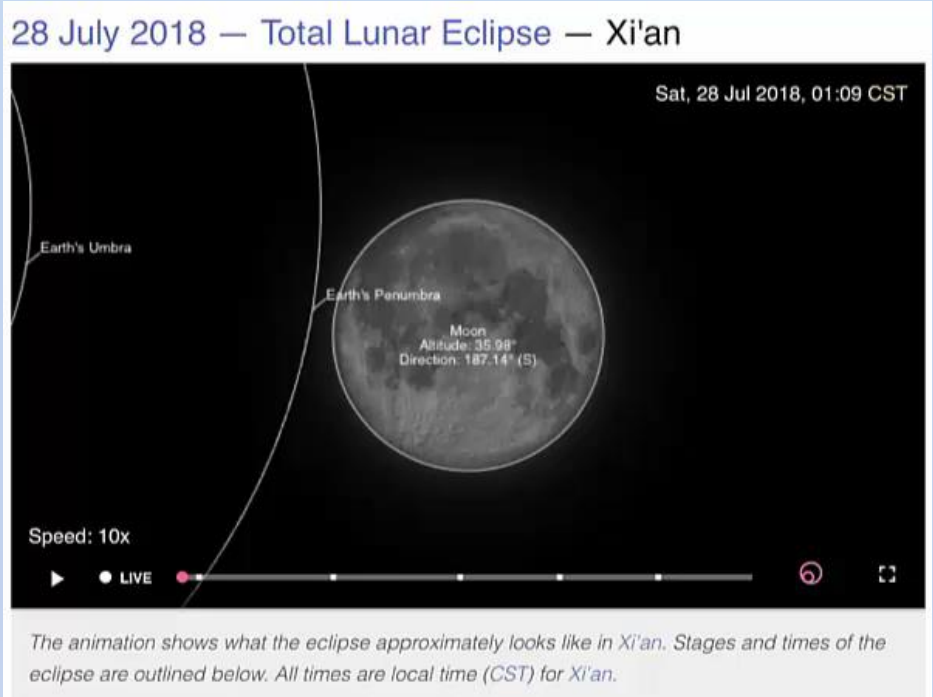
Total lunar eclipses

Shape of the Earth's shadow tells the spherical shape of the Earth.

3.4 Eclipses

Credit: timeanddate.com

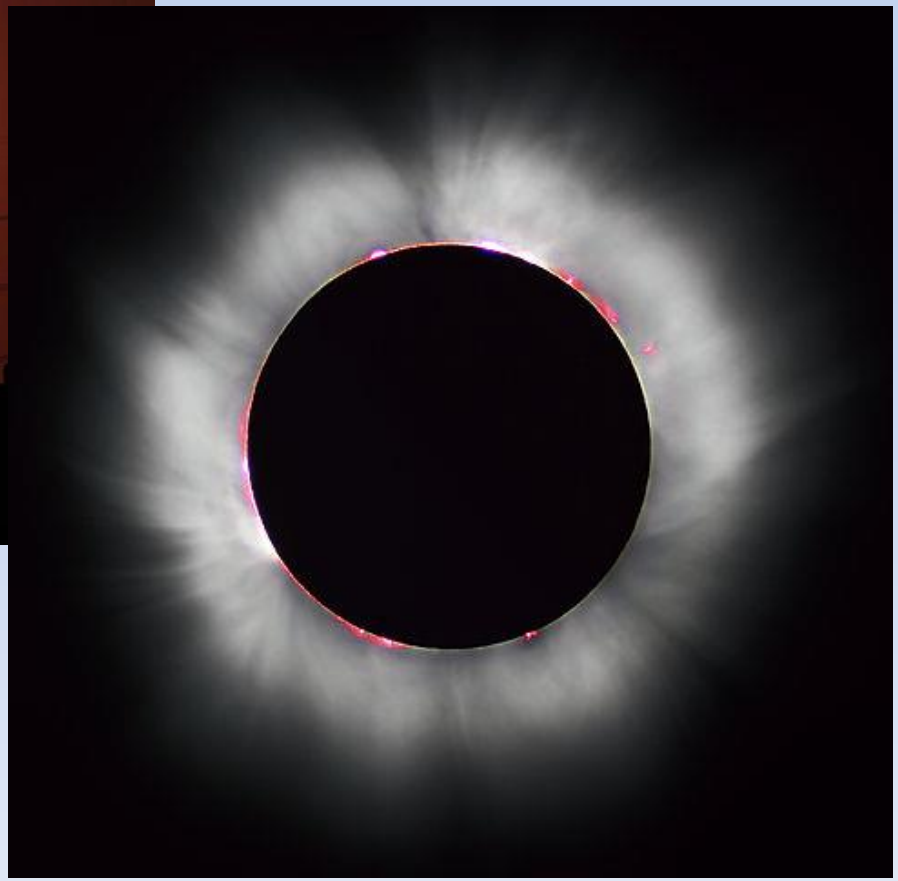




- ✓ There was a total lunar eclipse, observable from Xi'an on 28 July 2018, ~1am to ~6am (local time).

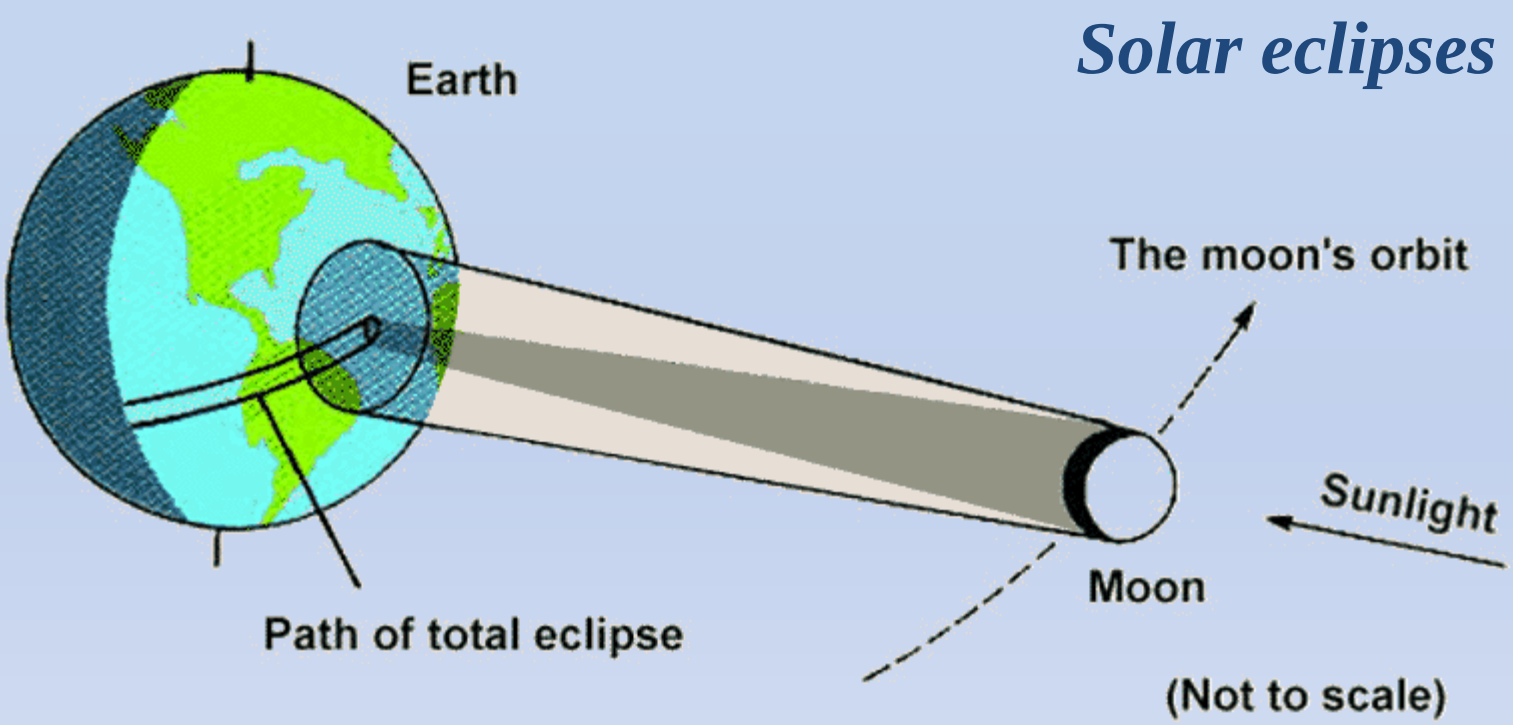
3.4 Eclipses

Solar eclipses



Images: Wikimedia Commons

3.4 Eclipses

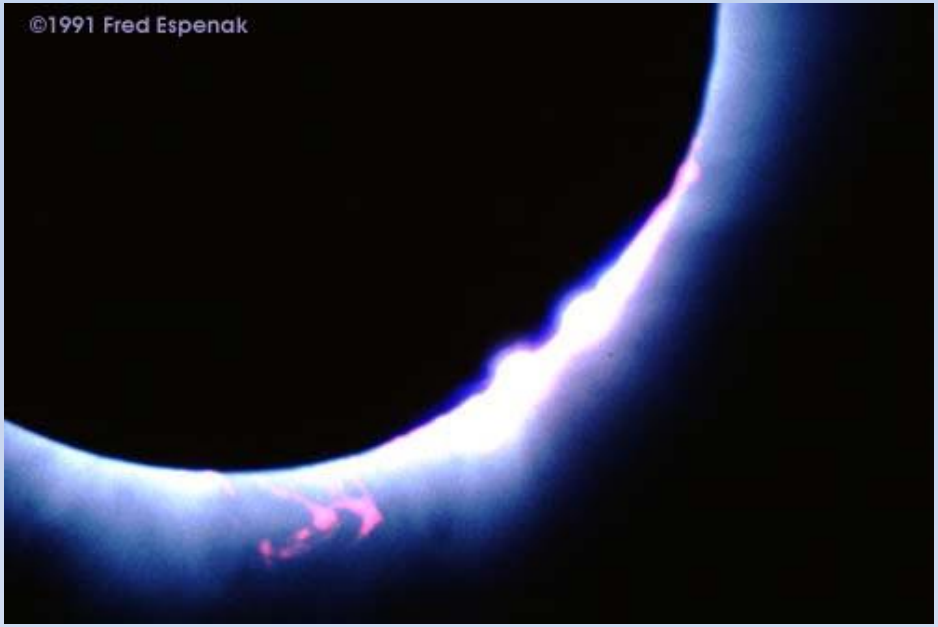


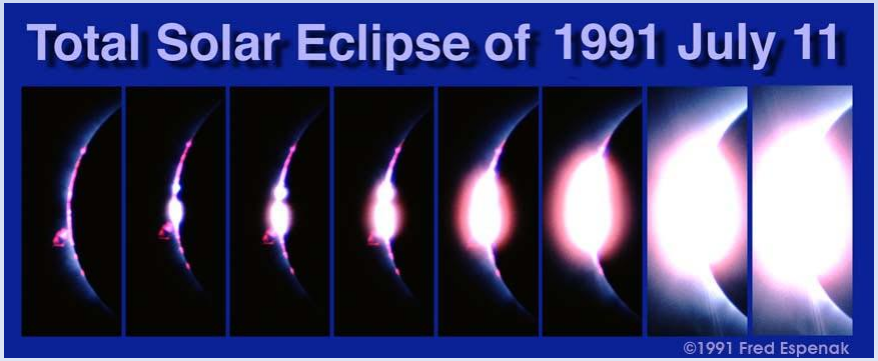
- ✓ The Moon's umbral shadow is at most ~270 km in diameter on Earth (c.f., the whole city of Xi'an about 100 km N to S, and 200 km E to W; radius of the Earth about 6400 km)
- ✓ Only a small region on Earth can see a total solar eclipse


Shadow of the Moon
(Image: Mir; CNES)

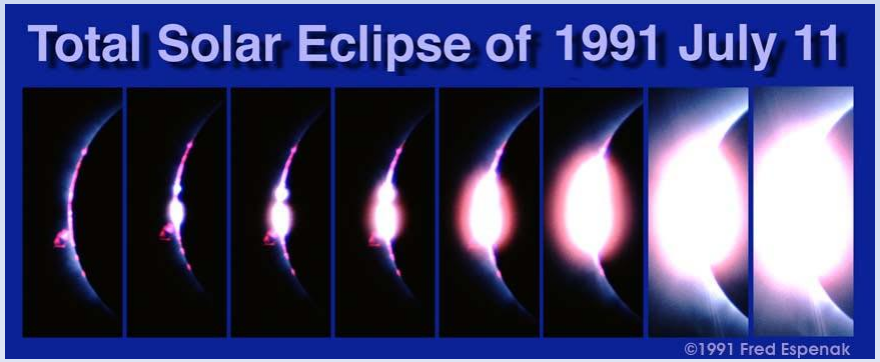
3.4 Eclipses

Solar eclipses





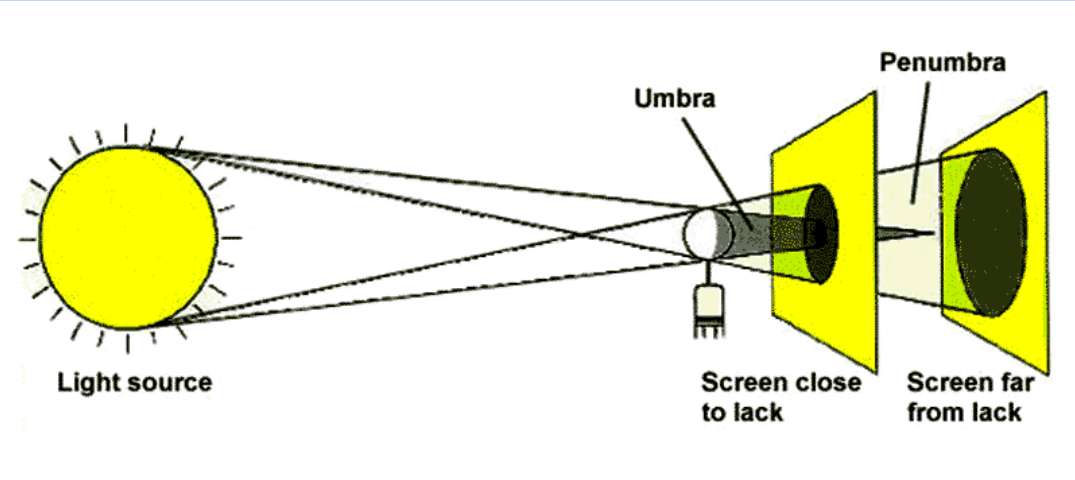
3.4 Eclipses



Solar eclipses

- ✓ Total solar eclipse provides an opportunity for observing the solar atmosphere
  (more about it later)
- ✓ The one in 1919 provided first verification of light bending by gravity
  (again, more about it later)

3.4 Eclipses



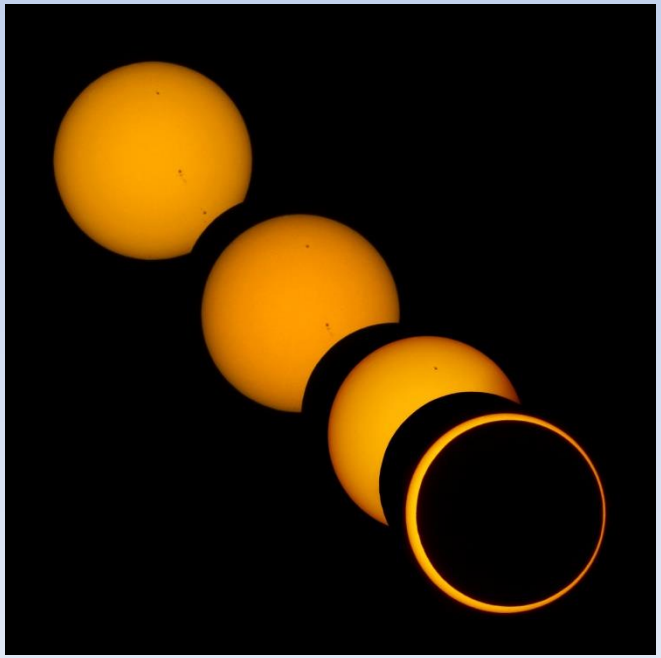


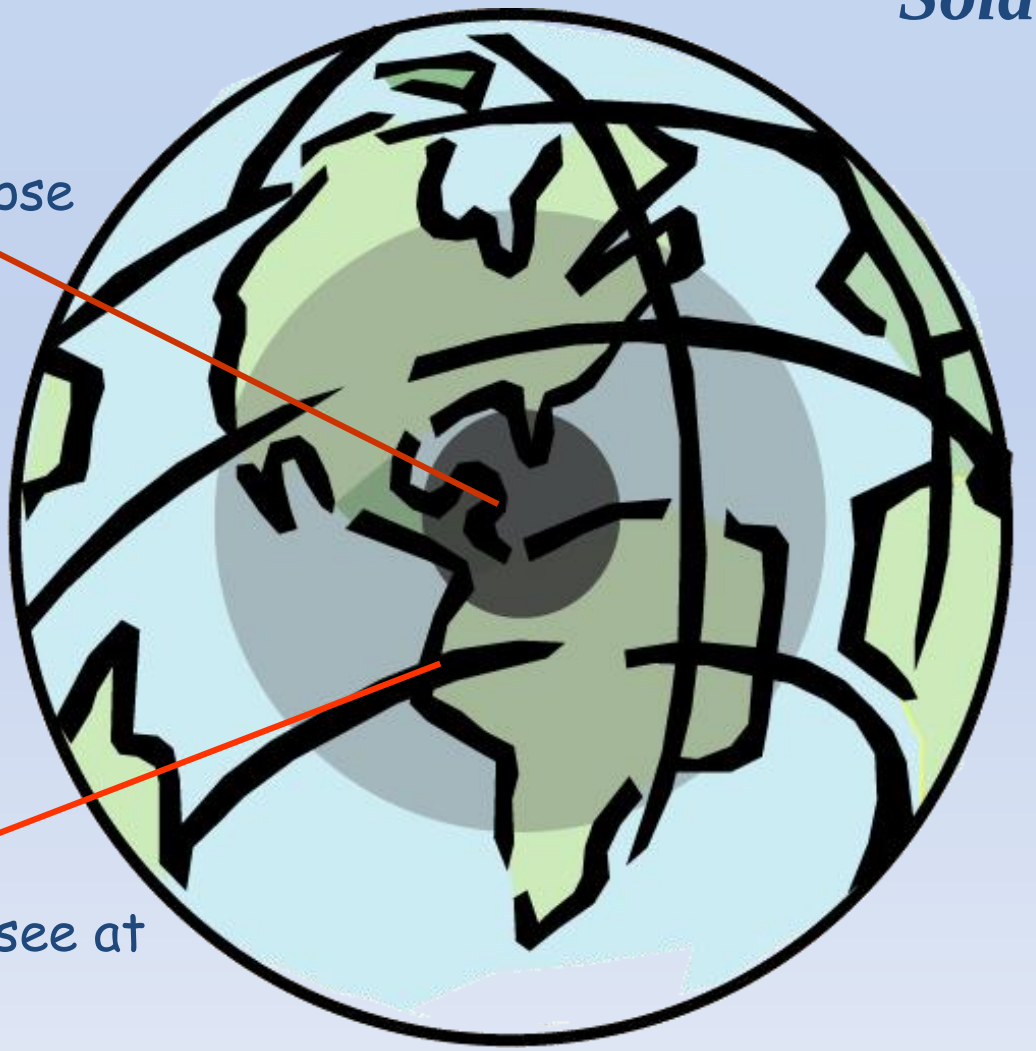
Image: Wikimedia Commons

Solar eclipses

- ✓ The apparent sizes of both the Sun and the Moon are ~0.5°, and
- ✓ the orbits are ellipses
- ✓ *Annular eclipses*: The Moon is too far from the Earth to cover the Sun completely; the umbra does not reach the Earth. The Sun appears to be ring-shaped

3.4 Eclipses

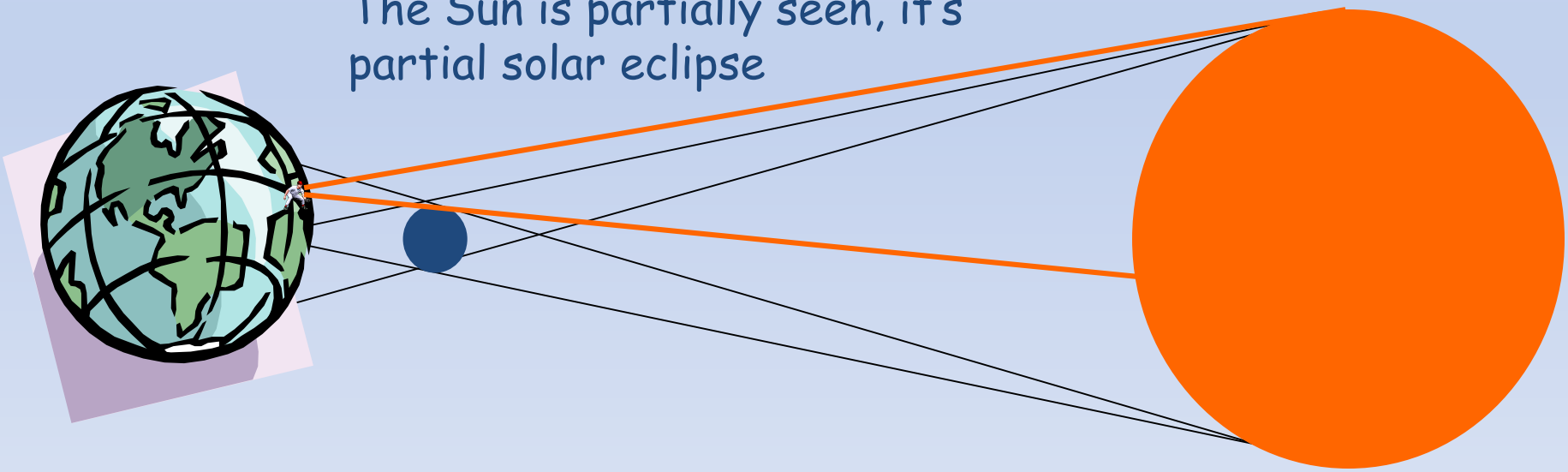
Solar eclipses



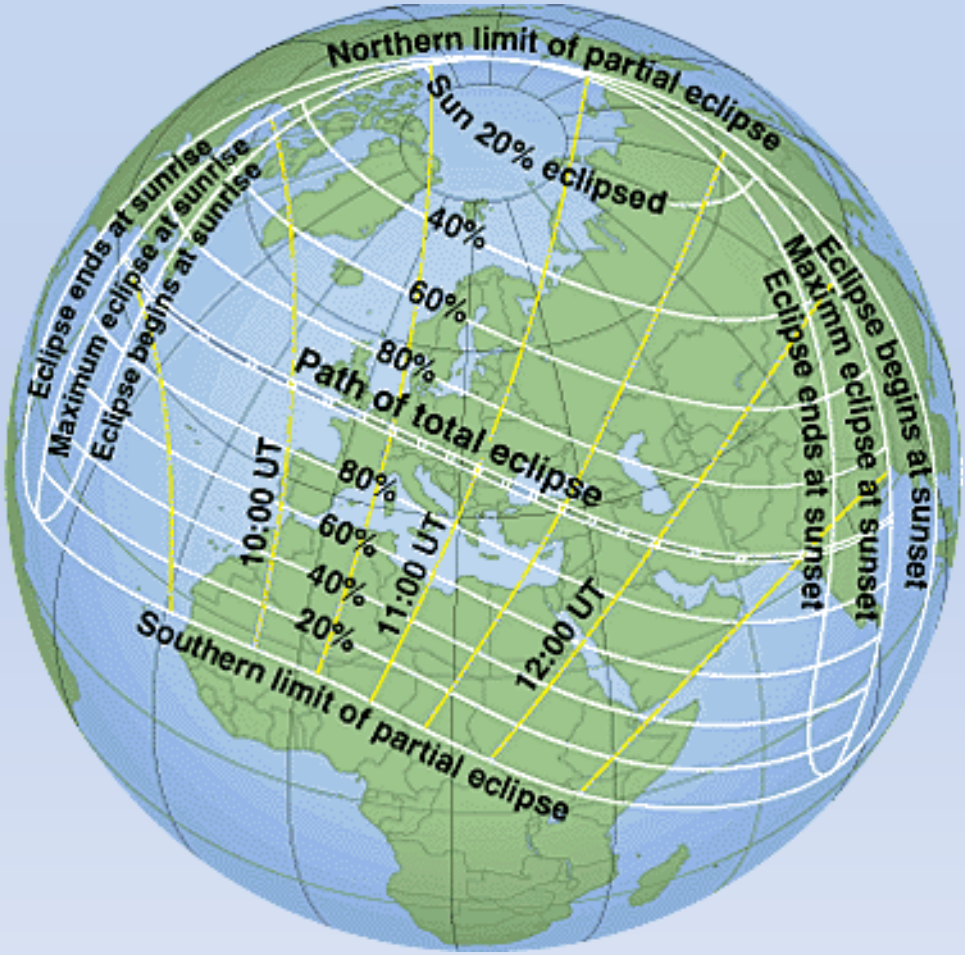
3.4 Eclipses

Solar eclipses

The Sun is partially seen, it's partial solar eclipse



3.4 Eclipses

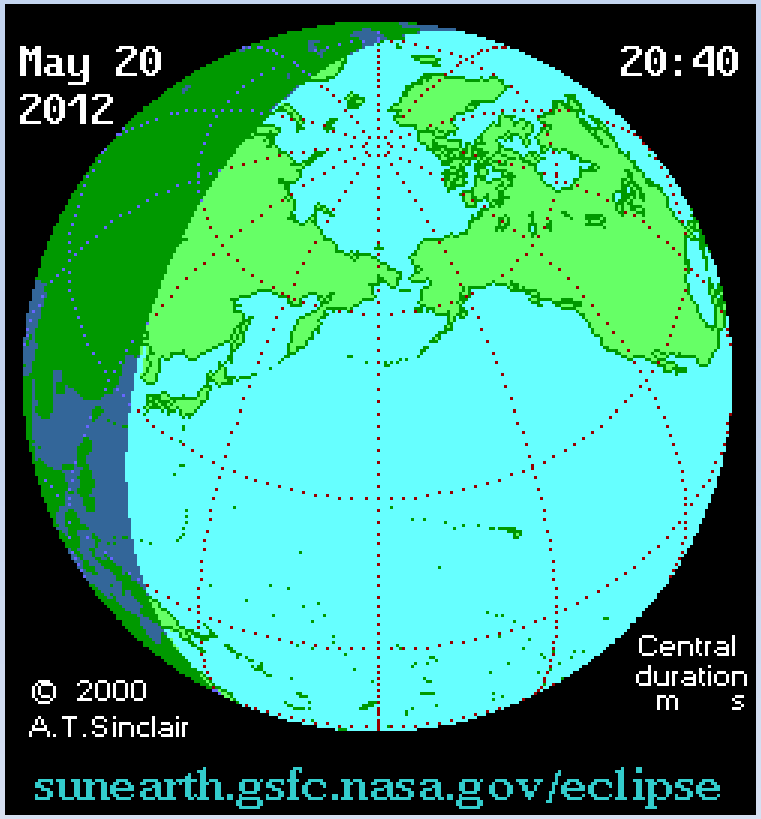


Solar eclipse in Europe in 1999

Solar eclipses

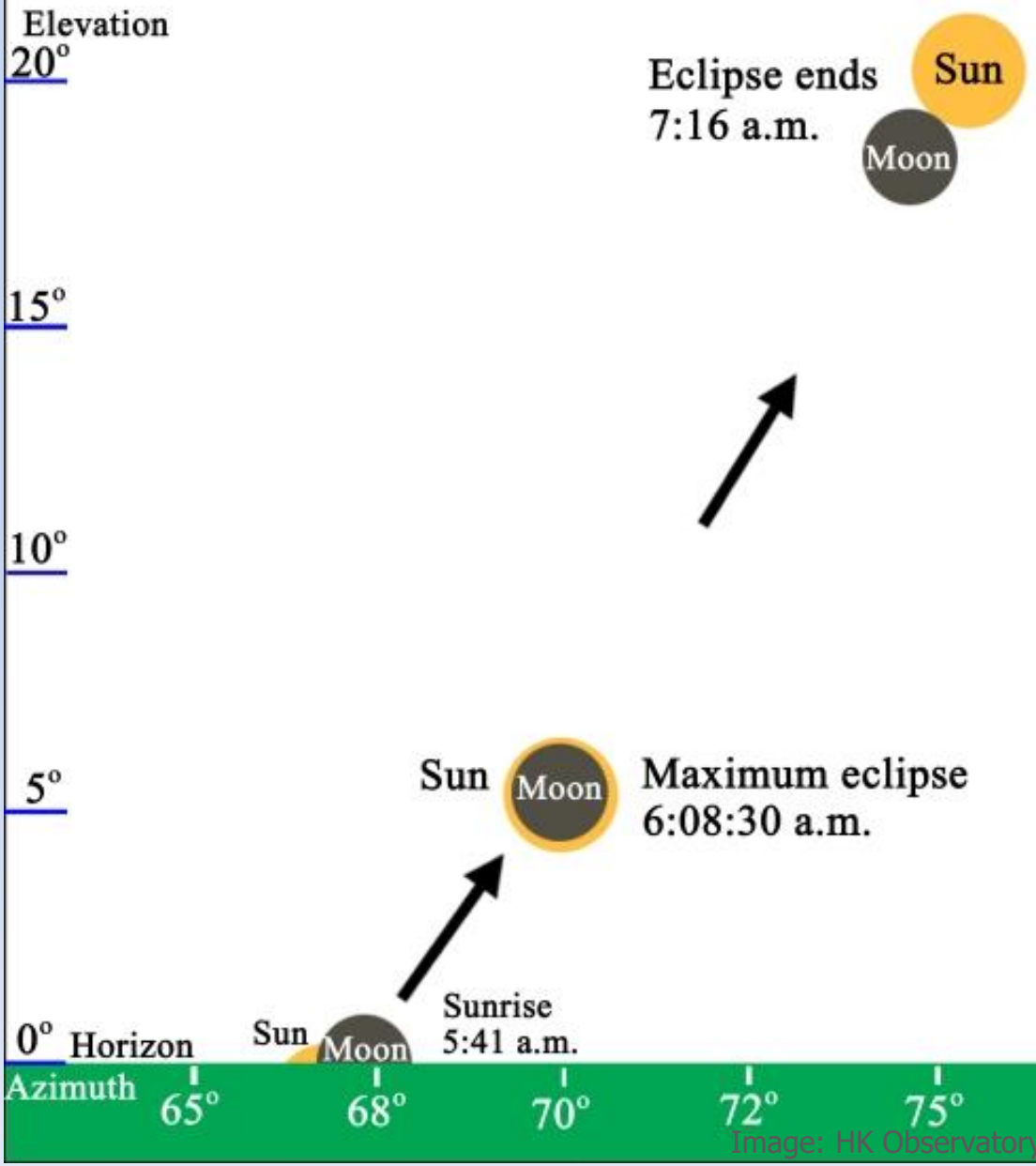
- ✓ Because the Earth rotates & the Moon moves, the shadow sweeps a path
- ✓ Total or annular eclipse lasts for at most a few minutes at each location on Earth

3.4 Eclipses



Annular solar eclipse in 2012

The scene that an observer in Hong Kong would see.
Notice the different speeds of the Sun and the Moon.



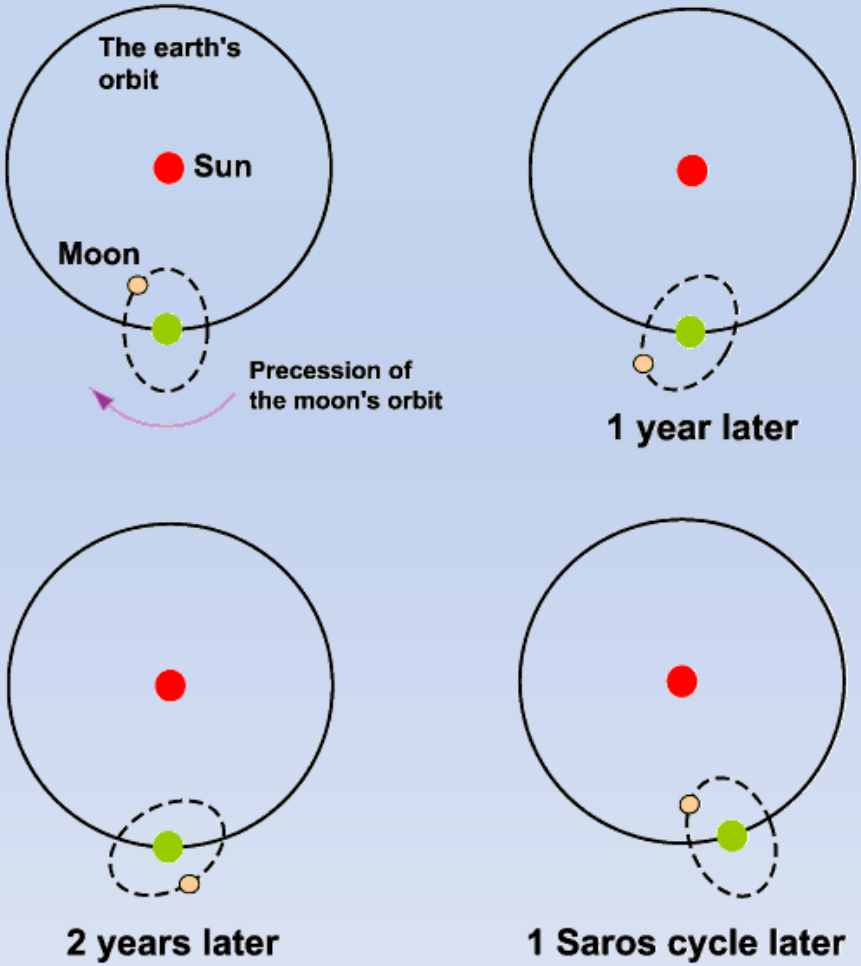
Solar eclipses

3.4 Eclipses

Eclipse seasons: the only times during a year eclipses can occur. Each season lasts from 31 to 37 days, recurring about every 6 months. Thus, at least two, and at most three eclipses, will occur during every eclipse season.

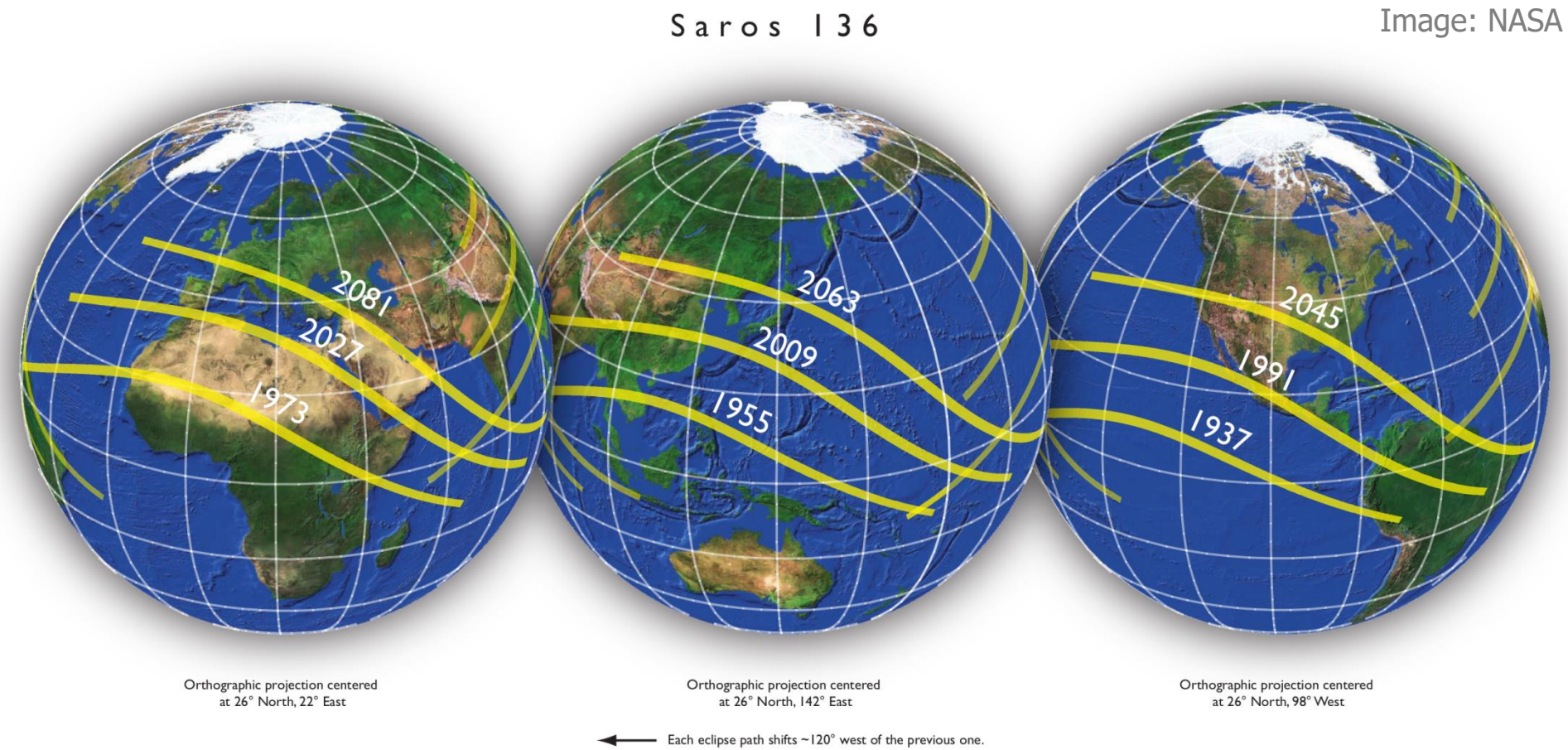
Do eclipses occur at the same time every year? No. Why?

3.4 Eclipses



- ✓ Due to the precession of the Moon's orbit, the Sun, the Earth and Moon do not return to the same relative positions after one year.
- ✓ They return to the same *relative* position every 18 years 11.3 days
- ✓ This period is called the Saros cycle (沙羅周期).

Image: NASA



- ✓ One Saros cycle equals to 18 years 11.3 days
- ✓Repetition of eclipses after one Saros cycle. The shadow sweeps across paths with similar pattern.
- ✓But not visible from the same places on Earth since the number of self-revolutions of Earth in a Saros cycle is not an integer.