Astronomy and time

Astronomical observations led to the development of the modern calendar

The day is based on the Earth’s rotation

The year is based on the Earth’s orbit

The month is based on the Moon's orbit

Note 'based on', not 'equal to'! None of these quantities are exactly constant, so astronomers use the average or mean day and leap years to keep the calendar and time consistent

Leap Years

The Earth orbits the Sun in 365.2425 days. Therefore, the calendar year of 365 days drifts by 0.2425 days each year.

With an extra day every four years, the drift is reduced to -0.0075 days per year, or -0.75 days per century.

Century years are *not* leap years, unless they are also divisible by 400 (so 2000 *was* a leap year).

By missing three leap days every four centuries, the 0.75 days per century drift is corrected.

The tiny remaining drift will not need correcting for millennia yet.

Leap Years – a historical digression

The current leap year rules form the basis of the *Gregorian Calendar*. This replaced the earlier *Julian Calendar*, in which every fourth year was a leap year.

The Julian calendar slowly drifted relative to the seasons. On the adoption of the Gregorian Calender in Britain in 1752, the large drift accumulated over 1500 years was corrected by skipping straight from Wednesday 2 September to Thursday 14 September.

Nobody rioted! This is a historical misunderstanding, based on a painting by William Hogarth called *An Election Entertainment*.

Leap Years – a historical digression

Leap Years – a historical digression

England in 1750 was viciously anti-catholic. So, adopting the 'popish' calendar was a controversial political issue. Hogarth was depicting election campaigning, not public rioting.

Russia did not adopt the Gregorian Calendar until 1922. So, the revolution that happened on 7 November 1917 by the Julian Calendar is called the October Revolution.

The Hunt for Red November...?

Leap Seconds

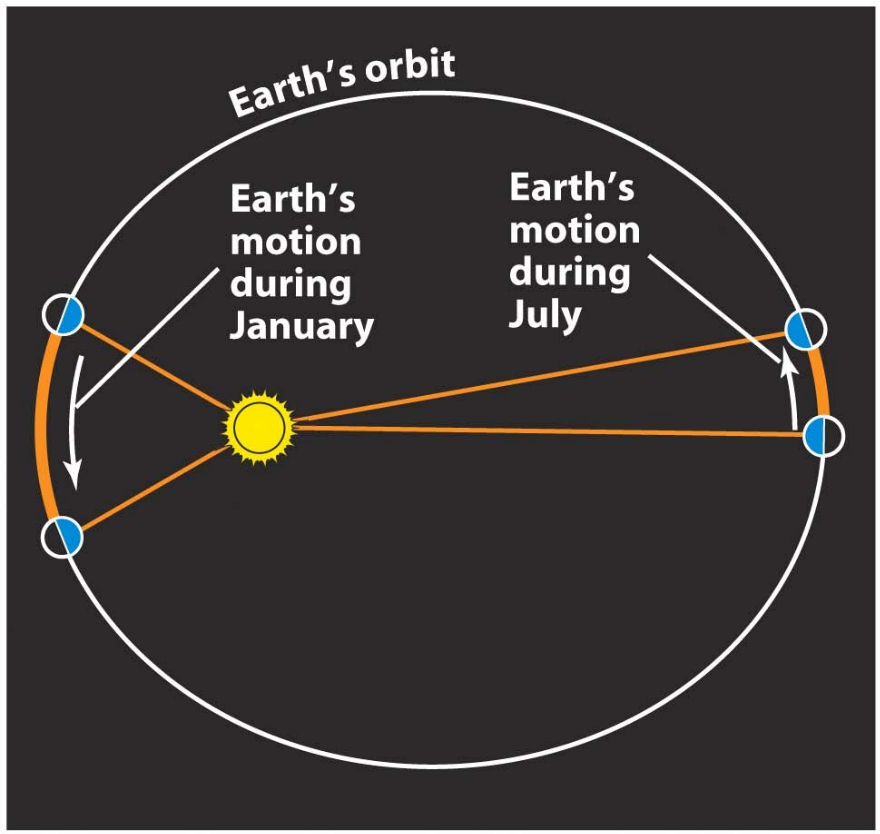
Leap seconds are occasionally added to Coordinated Universal Time – the international standard measure of time.

They are necessary because the Earth's rotation speed is not quite constant. It is slowing by 1.7 ms per century, and the length of the day now is very slightly different to what it was when the second was originally defined as a unit of time.

The length of the day can change for other reasons: the 2004 Indian Ocean tsunami caused the day to shorten by 0.00268 ms.

The 'Equation of Time'

The motion of the Sun across the sky is not uniform. It is faster in the northern hemisphere winter than it is in the summer. This is because the Earth's orbit is elliptical.



(a) A month's motion of the Earth along its orbit

The 'Equation of Time'

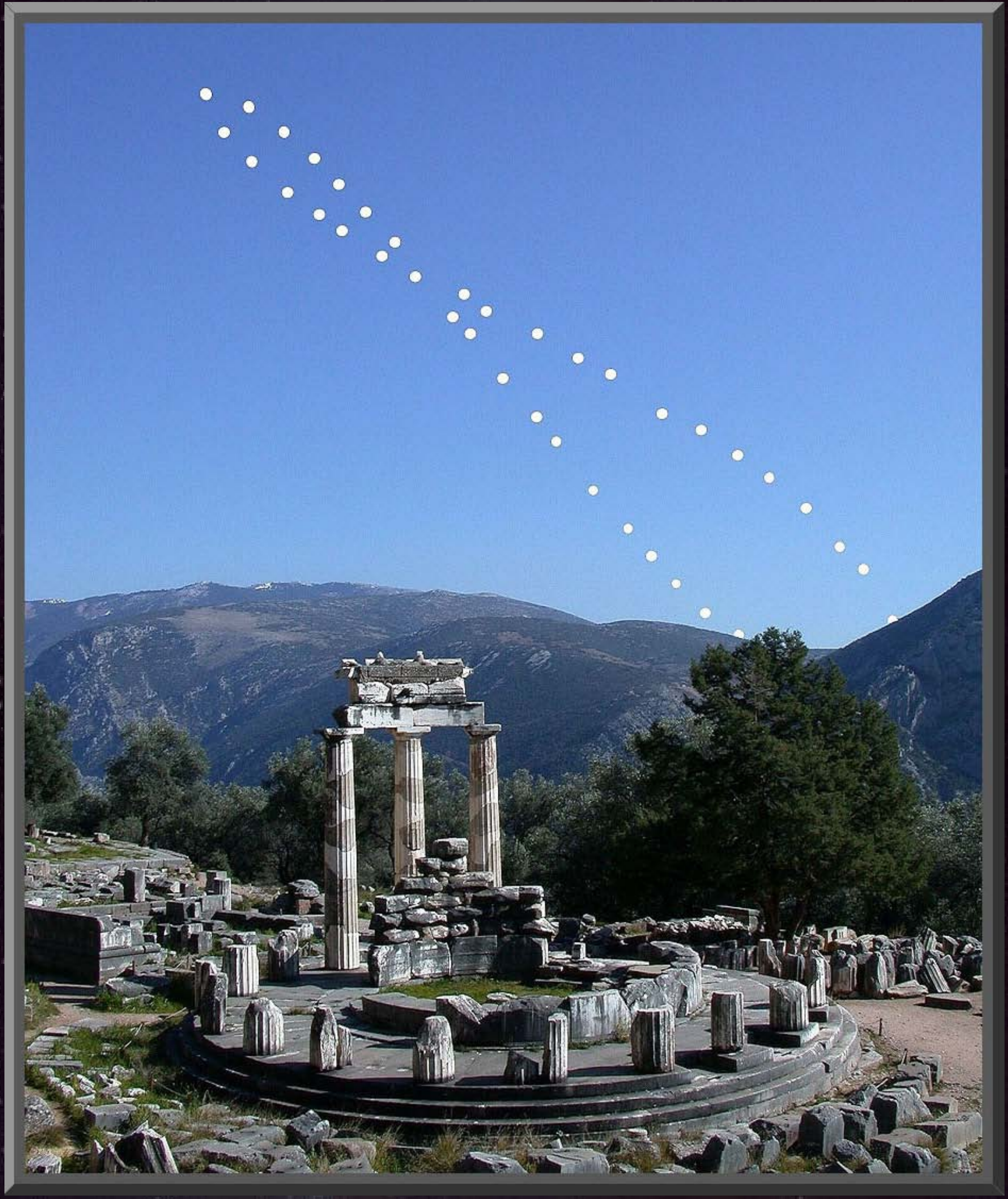
Days in our Winter are thus slightly longer than 24 hours, while days in Summer are slightly shorter than 24 hours.

This means that if you measured the exact time at which the Sun was due south every day, you would find that your 'clock' based on this was not quite accurate, running fast in the summer and slow in the winter.

Clocks are thus based on the *mean sun*, a hypothetical object moving at a uniform rate across the sky. The *equation of time* is the name given to the difference between the position of the mean sun and the actual sun.

The 'Equation of Time' and the analemma

The equation of time gives rise to the *analemma*. If you take a photo of the Sun at exactly the same time every day for a year, you will see that it follows a figure-of-eight path:



Right Ascension and Declination summary

The *declination* of an object in the sky is its angular distance from the celestial equator.

The Sun appears to move around the sky along a path called the *ecliptic*, which is inclined at 23.5 degrees to the celestial equator because the Earth's rotational axis is tilted by that amount.

The *First Point of Aries* is the point where the ecliptic crosses the celestial equator.

The *Right Ascension* of an object is the time in hours between when the First Point of Aries crosses the meridian, and when the object crosses the meridian.

Right Ascension and Declination summary

Because of the gravity of the Moon and Sun on the Earth's equatorial bulge, the direction in which the Earth's rotational axis points revolves with a period of 26,000 years.

Hence, the First Point of Aries moves, and the Right Ascension of an object changes with time.

So, the year in which the Right Ascension is correct must be specified. RAs are currently all given for 1 January 2000.

Tropics and polar regions

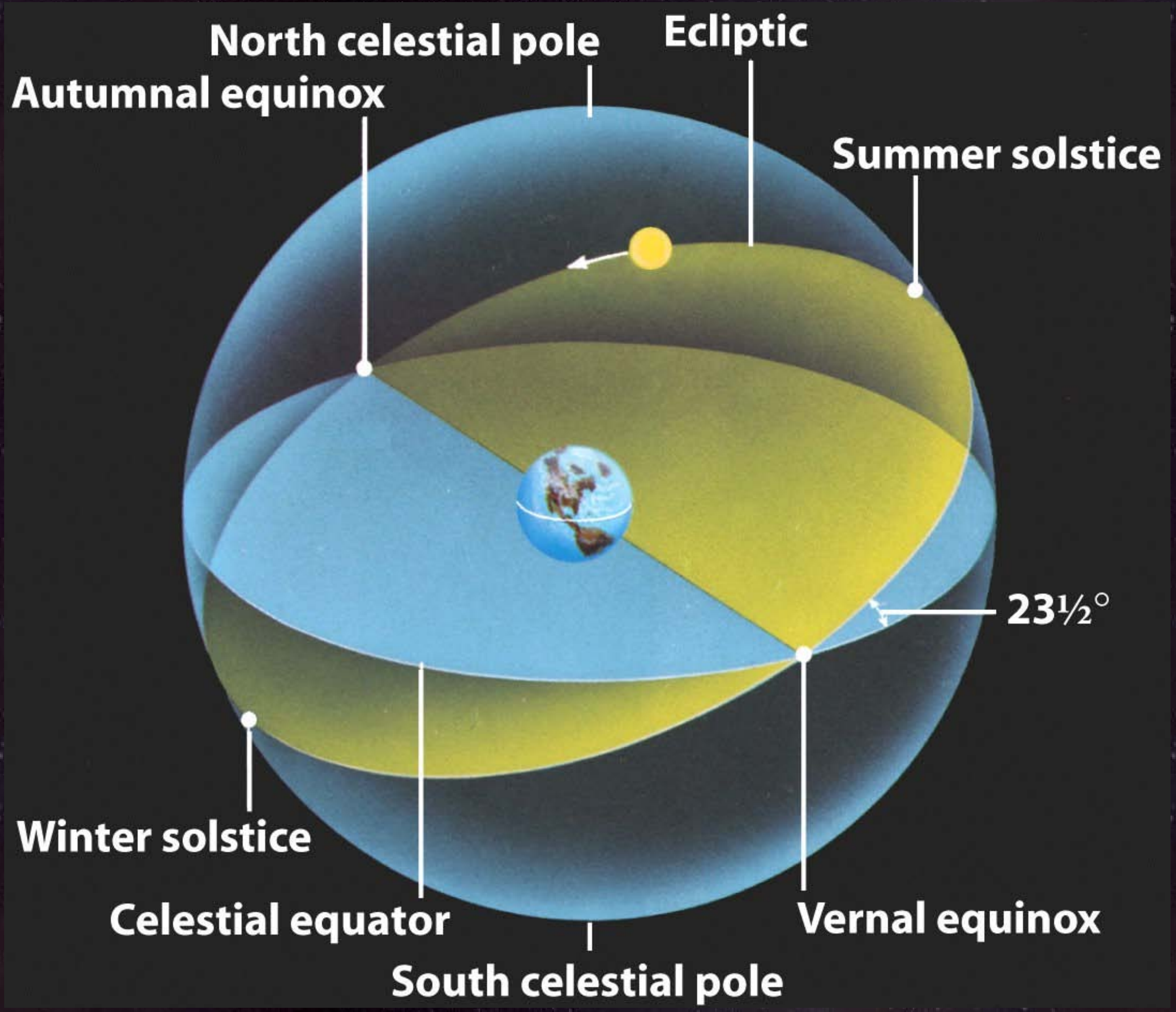
The Earth's polar circles and tropics are defined by the position of the Sun at particular times of year.

When the Sun reaches its northernmost declination (June 21)
- it is directly overheard at midday as seen from locations on the Tropic of Cancer (23.5N)
- it is on the horizon as seen from locations on the Antarctic Circle (66.5S)

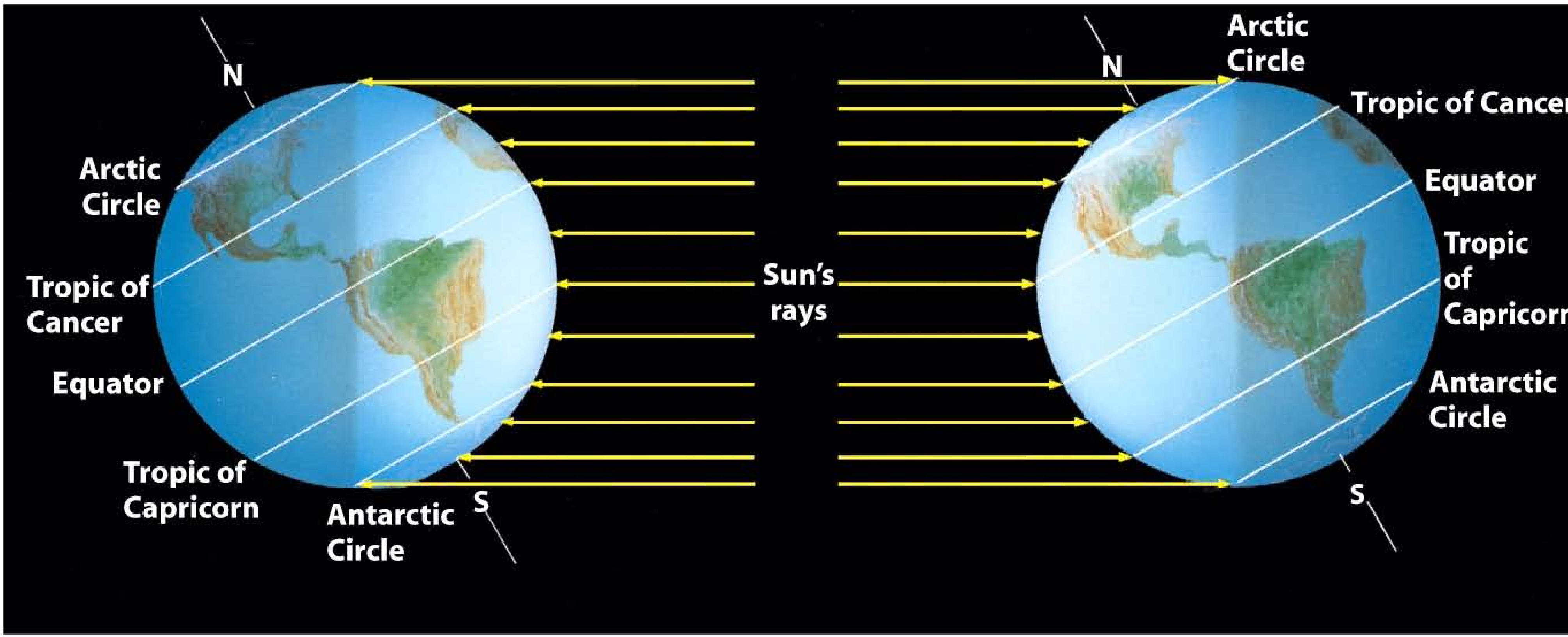
When the Sun reaches its southernmost declination (December 21)

- it is directly overheard as seen from the Tropic of Capricorn (23.5S)
- it is on the horizon as seen from the Arctic Circle (66.5N)

Tropics and polar regions



Tropics and polar regions



(a) Earth at winter solstice **(b)** Earth at summer solstice

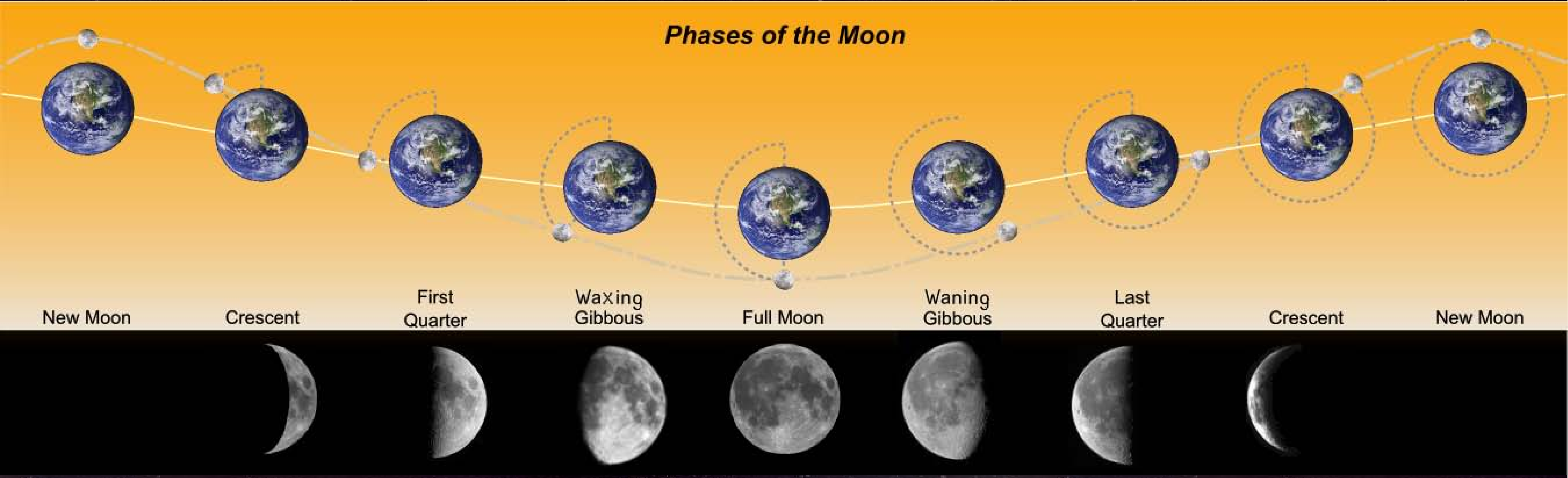
Chapter 3 – Eclipses and the motion of the Moon

Lunar Phases

The Moon orbits the Earth about once every four weeks.

One half is always lit by the Sun, but depending on where the Moon is in its orbit, the amount of the lit half that we see changes.

This causes an astronomical phenomenon that everyone is familiar with: the phases of the moon.

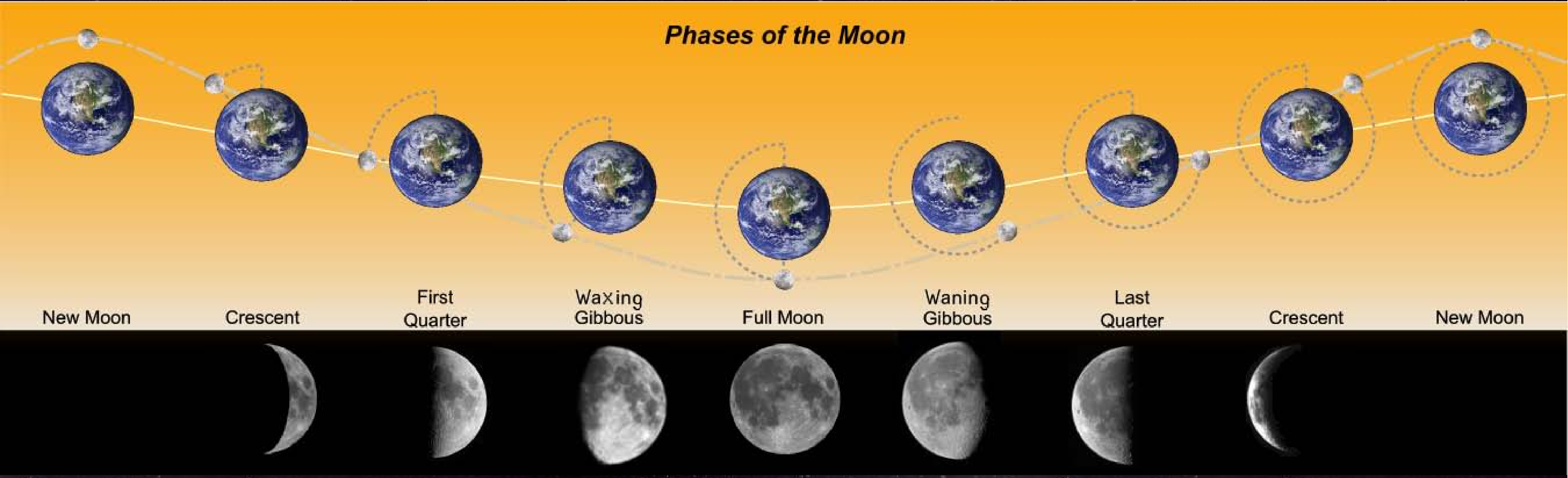


Lunar phases

The phase of the moon is related to the time of day that it is visible.

Full Moon occurs when the Moon lies directly opposite the Sun in the sky, so the moon rises at sunset, and sets at sunrise.

New moon is the opposite.



Lunar phases - terminology

When the Moon is *half*-illuminated as seen from Earth, it is said to be either a *first quarter* or *last quarter* moon – it is either a quarter or three quarters of the way through its phases.

For half of a month, the amount of moon illuminated from Earth is increasing – the moon is *waxing*. For the other half, the visible part is decreasing – the moon is *waning*.

If less than half of the moon's face is illuminated, it is a *crescent moon*. If more than half is illuminated, it is a *gibbous moon*.

Lunar phases – terminology II

Dark side of the moon = 1. the unlit half of the moon
2. Pink Floyd album.

Far side of the moon = the half of the moon that is never visible from Earth.

Lunar phases - Earthshine

Whatever the phase of the Moon as seen from Earth, the phase of the Earth as seen from the Moon is the opposite.

So, when we see a thin crescent moon, the Earth is almost full in the Lunar sky.

The bright Earth lights the dark moon – much fainter than the sunlit half, but still easily visible.

Rotation of the Moon

From Earth, we only ever see one side of the Moon. This is because the Moon's *orbital period* is the same as its *rotational period*.

This phenomenon is called *synchronous rotation*. Many moons in the solar system have synchronous rotation around their parent body.

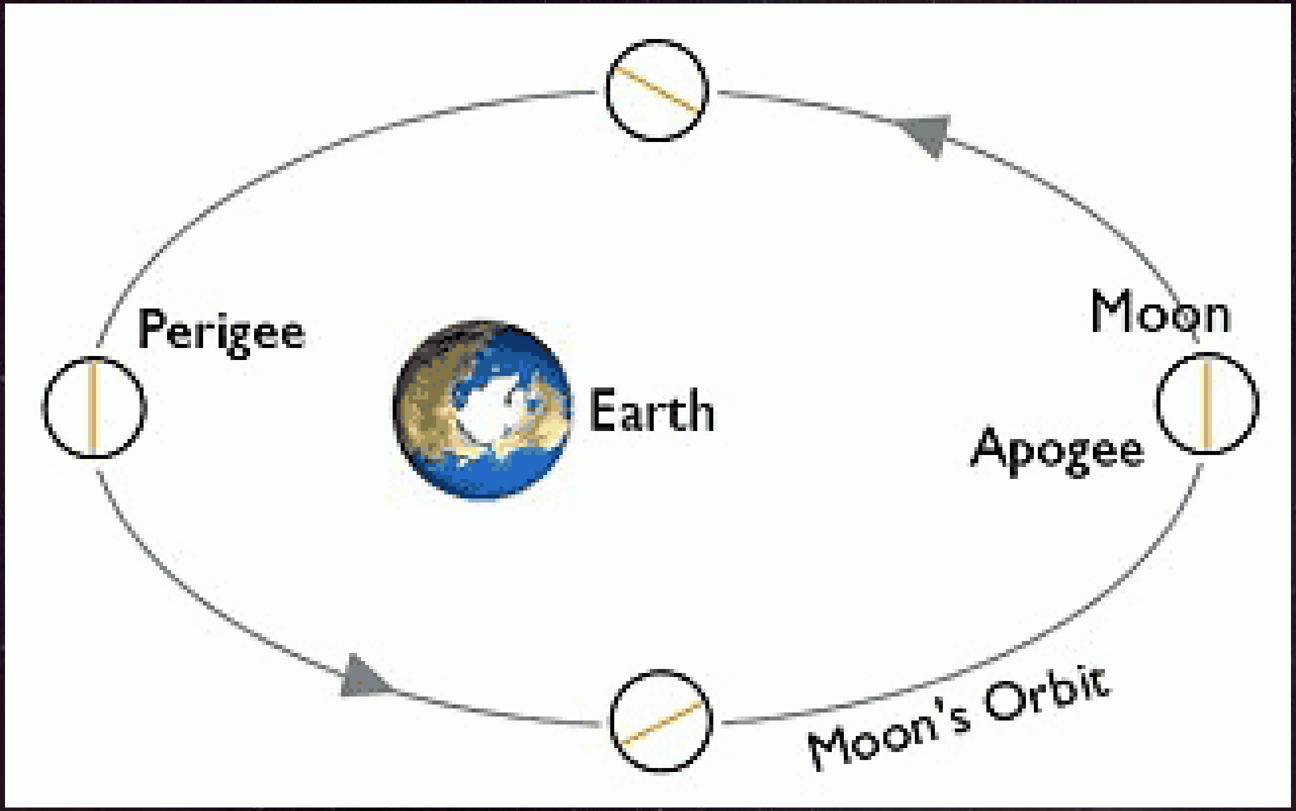
Synchronous rotation is caused by *tidal locking*: the Moon is not uniform, and its heavier side is pulled towards the Earth.

Libration

Actually, over time, we can see slightly more than 50% of the Moon's surface. This is because of three effects, collectively called *libration*.

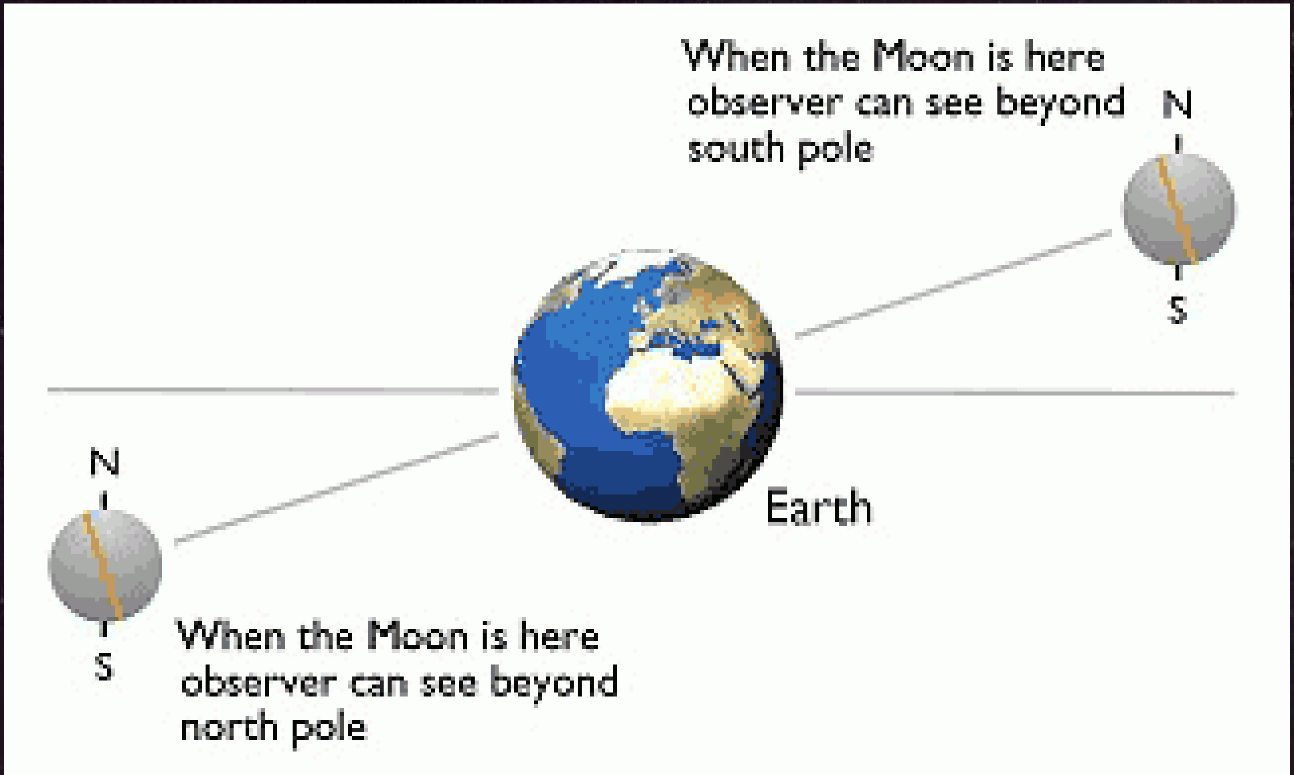
Libration

The Moon's orbit is not perfectly circular, and so its orbital speed varies. Its rotational speed *is* constant, and so different parts are brought into view. This is called *libration in longitude*



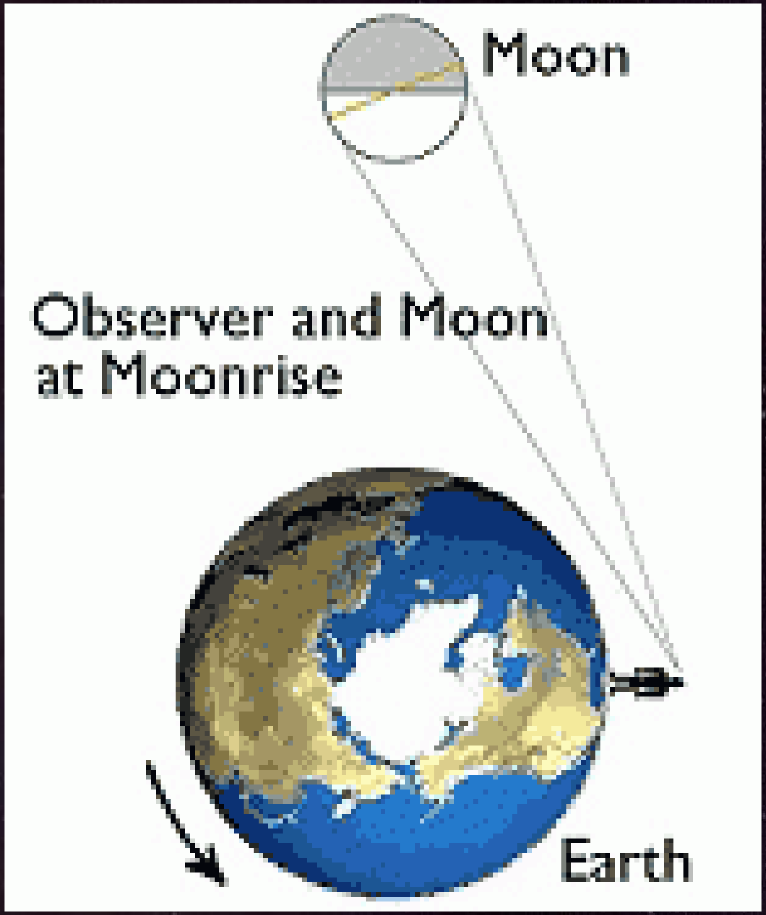
Libration

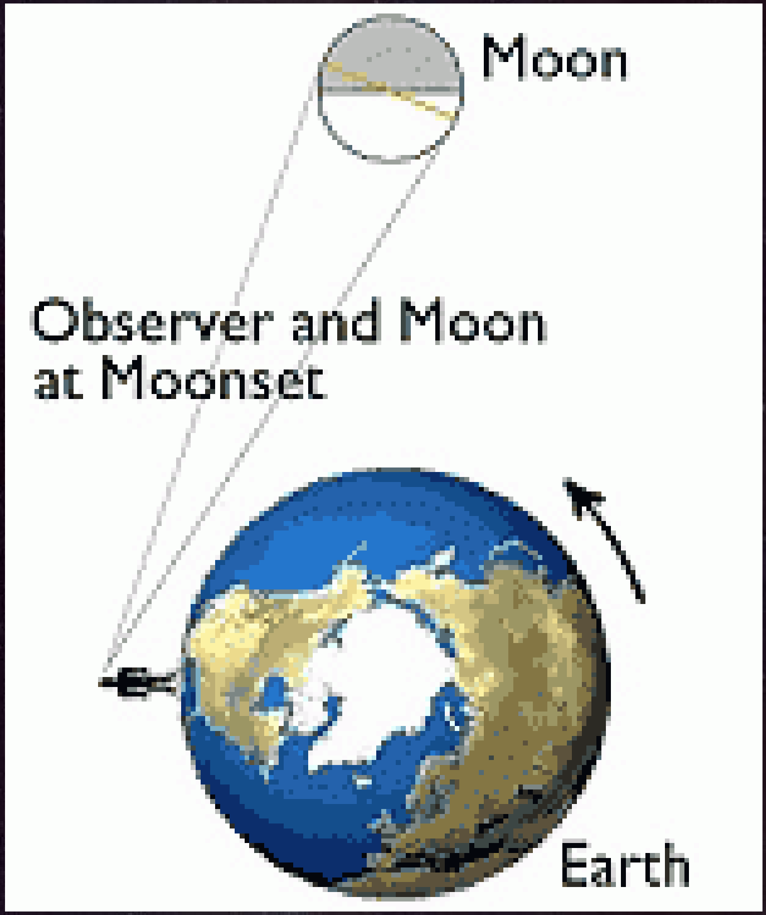
The plane of the Moon's orbit is inclined by about 5 degrees to the plane of the Earth's orbit around the Sun, so as it orbits we alternately see slightly 'underneath' it, and slightly 'over' it. This is called *libration in latitude*.



Libration

From moonrise to moonset, an observer on Earth moves by about 7,500 miles, relative to the line joining the centres of the Earth and the Moon. This is called *diurnal libration*





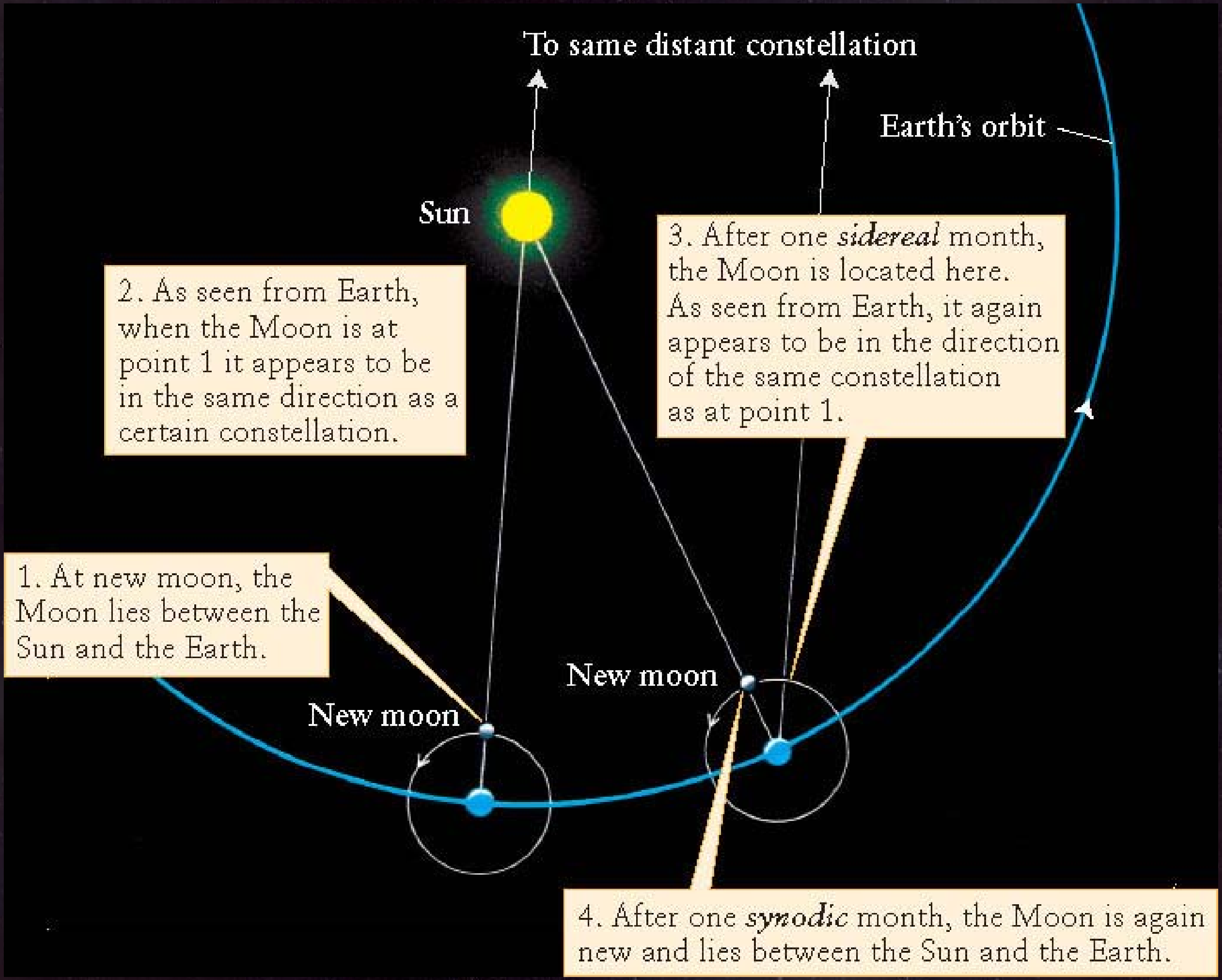
Months

Because of the rotational and orbital motions of the Moon and the Earth, there are a few closely related periods relating to lunar phenomena, all called months.

The *sidereal month* is the rotation period of the moon, measured relative to the stars. It is 27.32 days.

The *lunar* or *synodic month* is the time taken to complete one cycle of phases. It is longer, because the Earth has moved along about 1/12 of its orbit and so the position of the Sun has changed.

Months

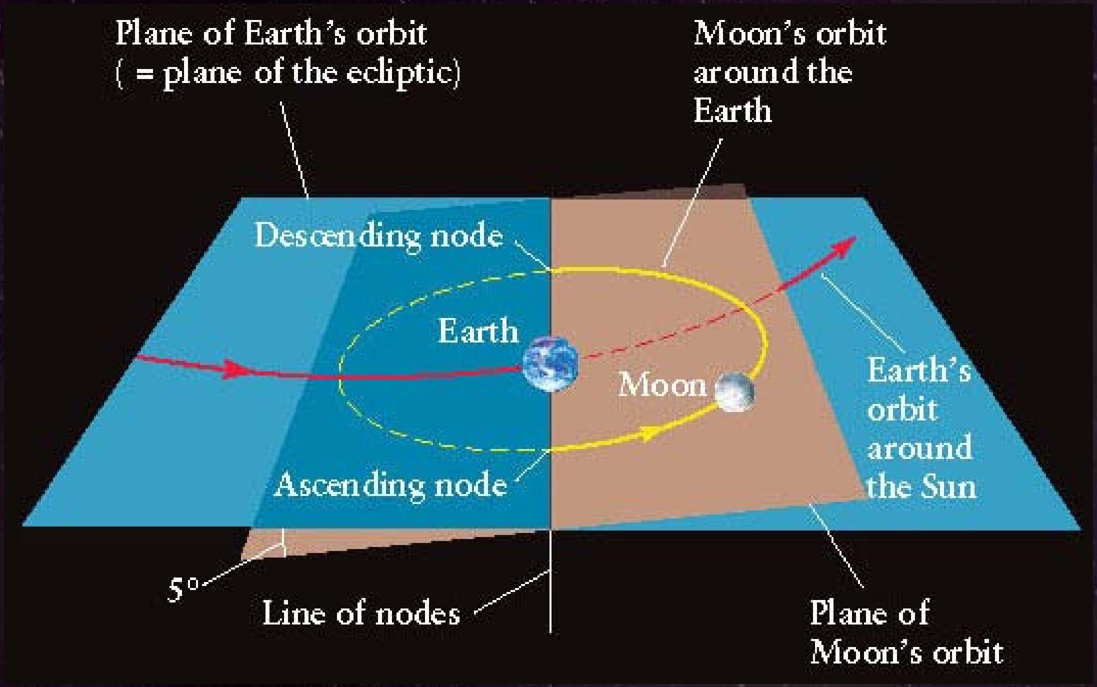


To same distant constellation
Earth's orbit
Sun
2. As seen from Earth, when the Moon is at point 1 it appears to be in the same direction as a certain constellation.
3. After one *sidereal* month, the Moon is located here. As seen from Earth, it again appears to be in the direction of the same constellation as at point 1.
1. At new moon, the Moon lies between the Sun and the Earth.
New moon
New moon
4. After one *synodic* month, the Moon is again new and lies between the Sun and the Earth.

Eclipses

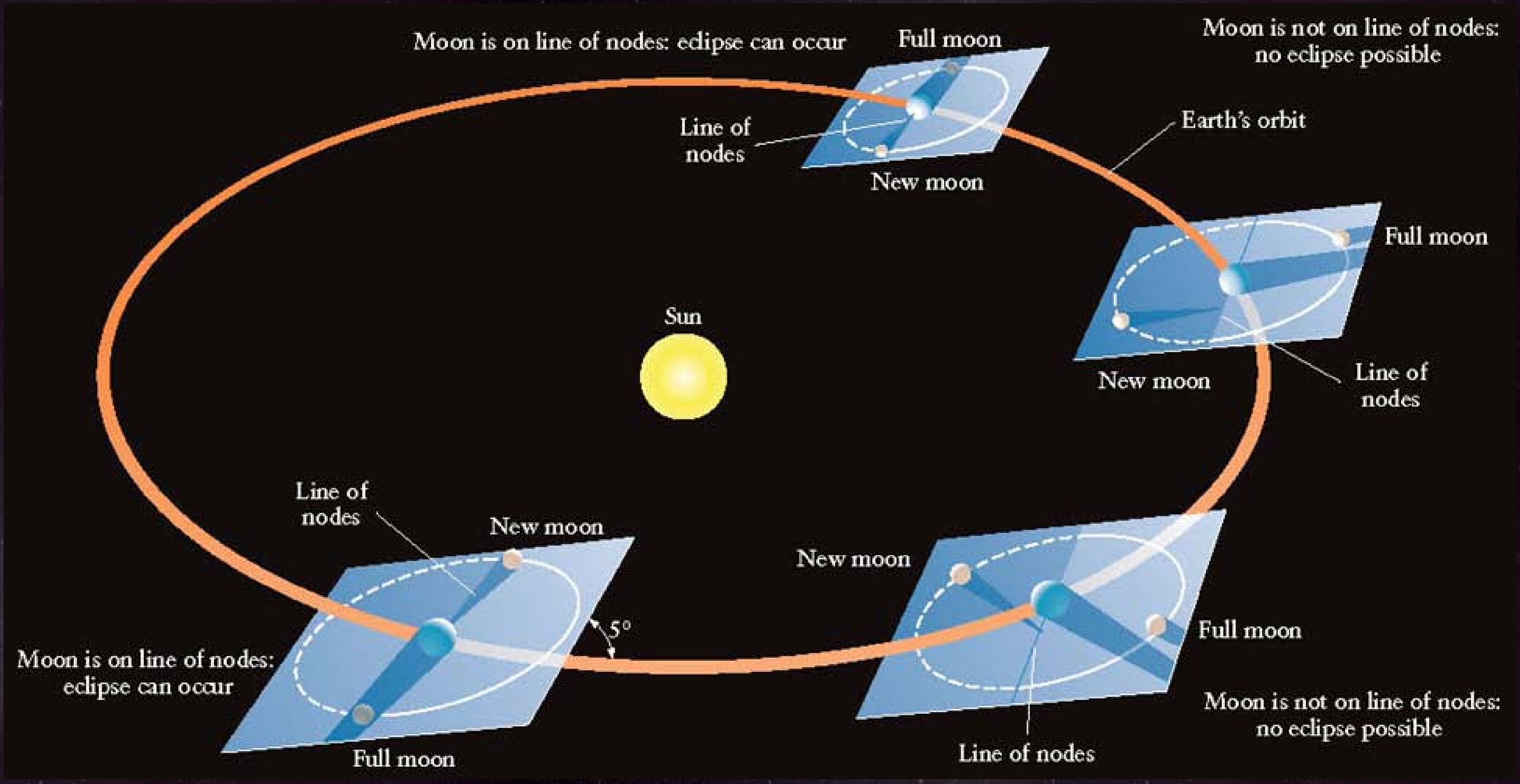
When the Earth, Moon and Sun all lie on a straight line, the shadow of the Moon may fall on the Earth, or that of the Earth may fall on the Moon.

If the Moon orbited the Earth in the same plane as the Earth orbits the Sun, there would be eclipses every month. But it does not, and so eclipses happen much less frequently.



Eclipses

The line of intersection between the two orbits is called the *line of nodes*. Eclipses can only happen when the Sun and Moon both lie on the line of nodes.



Precession of the nodes

The line of the nodes precesses with a period of about 9 years, due to the gravity of the Sun. So the time of year that eclipses are visible changes constantly.

In 2007, eclipses occurred around March and September

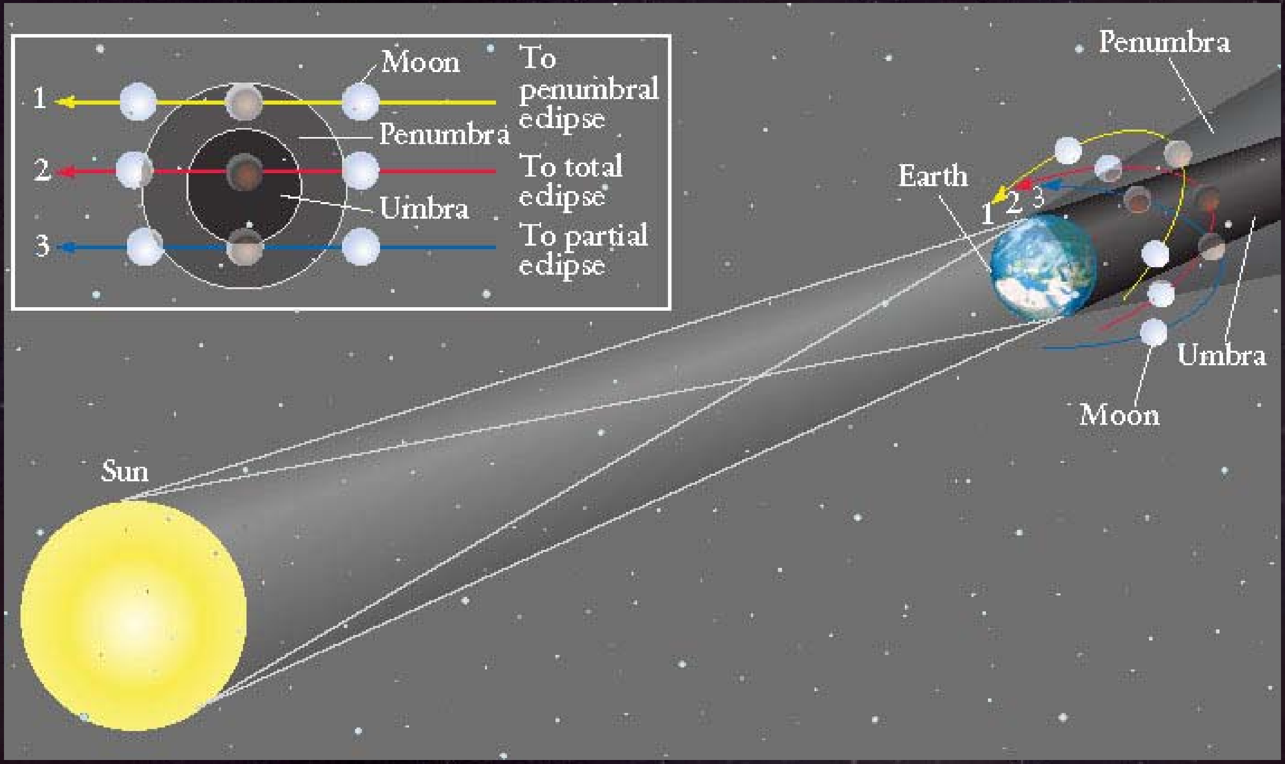
In 2008, they have occurred in February and August.

Next year, they will occur in Jan/Feb, Jul/Aug and December

Lunar Eclipses - types

The shadow of the Earth extends 1.5 million kilometres out into space. The Moon orbits at a distance of 384,000 km, so it can pass through the Earth's shadow.

The shadow of the Earth consists of an *umbra* and a *penumbra*. This results in three possible types of eclipse.



Lunar Eclipses – types

If the Moon passes entirely into the umbra, there will be a *total lunar eclipse*.

If the umbra only partly covers the Moon, there is a *partial lunar eclipse*.

If the Moon passes only through the penumbra (because it is only close to, not on, the line of the nodes), there will be a *penumbral lunar eclipse*.

Penumbral lunar eclipses are hardly noticeable.

Lunar Eclipses - visibility

A lunar eclipse is visible from one entire hemisphere of the Earth. Wherever it is night, the eclipse will be visible.

If the Moon passes right through the centre of the umbra, the eclipse will last about one hour and forty minutes.

If it passes through the umbra off-centre, the duration will be shorter.

Lunar Eclipses - appearance

A lunar eclipse is visible from one entire hemisphere of the Earth. Wherever it is night, the eclipse will be visible.

If the Moon passes right through the centre of the umbra, the eclipse will last about one hour and forty minutes.

If it passes through the umbra off-centre, the duration will be shorter.

Lunar Eclipses - appearance

The Moon does not entirely disappear during a lunar eclipse. Instead, it turns a deep red.

This is because light is refracted by the Earth's atmosphere, but blue light is strongly scattered. (this is also why the sky is blue)

So, some red light actually fills the Earth's shadow.

Lunar Eclipses - appearance

Lunar Eclipses - appearance

The appearance of the Moon changes from eclipse to eclipse, as it is highly dependent on conditions in the Earth's atmosphere.

Sometimes it doesn't appear much less bright than normal. Other times it is barely visible. Volcanic eruptions have a major effect, as they can inject a lot of dust into the upper atmosphere.

<-1982 July

1992, after Pinatubo ->

<- 1982 Dec, after eruption of El Chichón

Lunar Eclipses - appearance

One way to quantify this is on the *Danjon Scale*:

L=0 : very dark, moon almost invisible
L=4 : very bright

L=1-3 for intermediate levels of brightness.

This scale is rather arbitrary and imprecise, but still commonly used.

Lunar Eclipses - frequency

There are normally at least two lunar eclipses per year. There may be none, and the maximum number is three.

In 1982 there were three total lunar eclipses. This won't happen again until 2485.

The next total lunar eclipse will be on 21 December 2010. It will be visible from here, but the moon will set during the eclipse.

The next total lunar eclipse visible in its entirety from here is not until 28 September 2015.

Lunar Eclipses – a mystery

One strange thing about lunar eclipses is that the size of the Earth's shadow is about 2% larger than you'd expect from the geometry.

Is it the atmosphere? For the atmosphere to enlarge the Earth's shadow by 2%, it would have to be opaque 100km above the Earth's surface. But 90% of the atmosphere is below 15km.

The effect is not completely understood. By timing the movement of lunar craters into and out of the umbra, the amount of enlargement can be measured – this is easy for amateurs to do.

Solar Eclipses

Solar eclipses are very different to lunar eclipses. Technically, they are not even eclipses but *occultations*

Eclipse = one body moving into the shadow of another body
Occultation = one body being hidden behind another body

But they are always called eclipses.

Solar Eclipses - types

Total lunar eclipses happen if the Earth, Moon and Sun all lie along the line of the nodes.

For total solar eclipses to happen, this also needs to be true, but another condition also needs to be satisfied: the Moon must also appear larger than the Sun in the sky.

If the Moon is near its *perigee* – closest approach to Earth during its elliptical orbit – and the Earth is near *aphelion* – furthest from the Sun – the size of the Moon relative to the Sun is maximised.

If the moon is near its *apogee* and Earth is near *perihelion*, there will be an *annular eclipse*, in which a bright ring of Sun is visible around the Moon.

Solar Eclipses - types

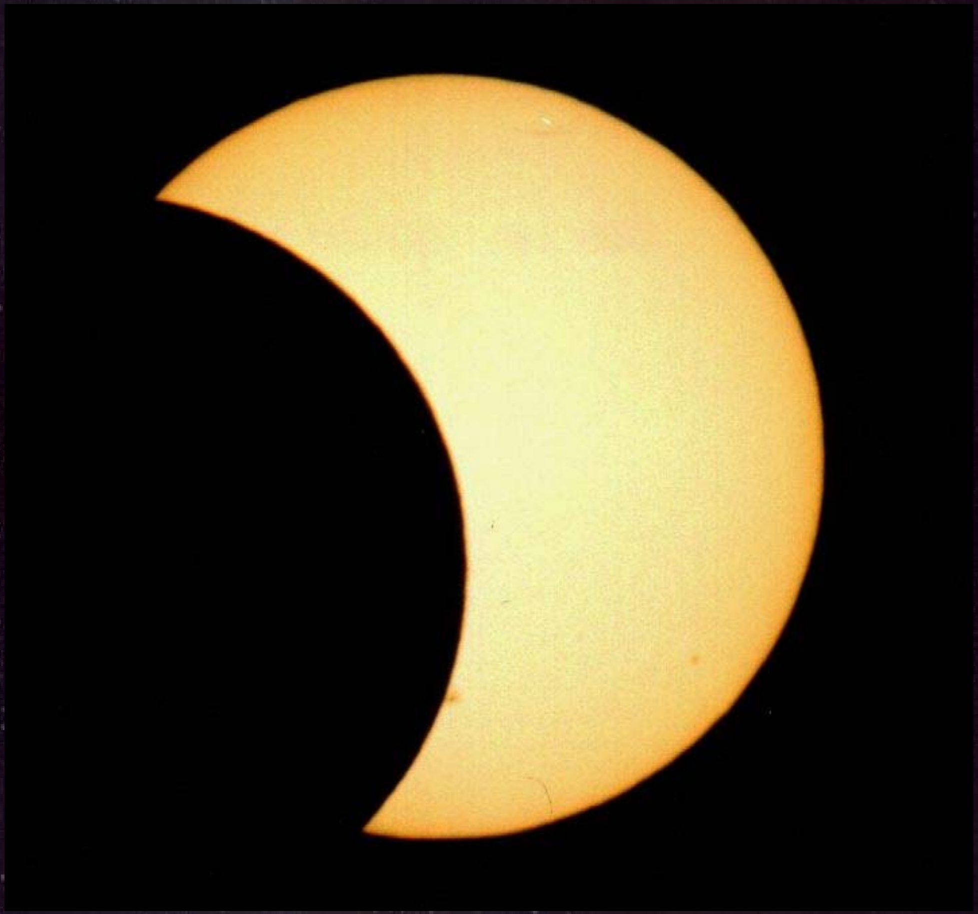
Solar Eclipses - types

But if the Moon is large enough, you get a *total solar eclipse* – one of nature's great spectacles. When the bright face of the Sun is obscured, its much fainter tenuous outer atmosphere (*corona*) becomes visible.

Solar Eclipses - types

If the Moon or Sun doesn't quite lie on the line of nodes, or just before or after the alignment is perfect, you see a *partial solar eclipse*.

If the Moon is covering less than about 90% of the Sun, you will hardly notice the reduction in light.

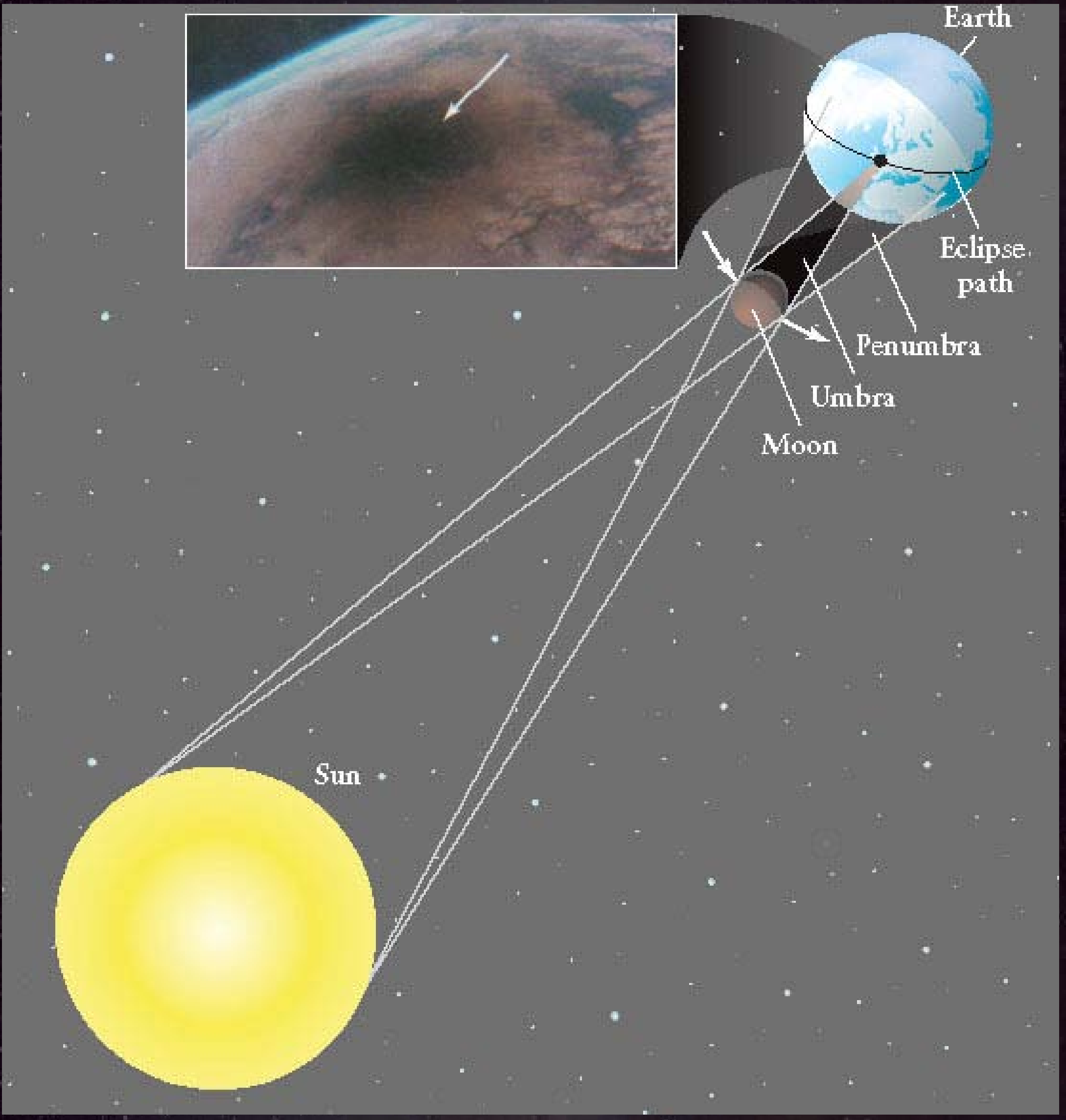


If you are watching a total eclipse approaching, things happen extremely slowly for a long time, and then extremely quickly very suddenly!

Solar Eclipses - visibility

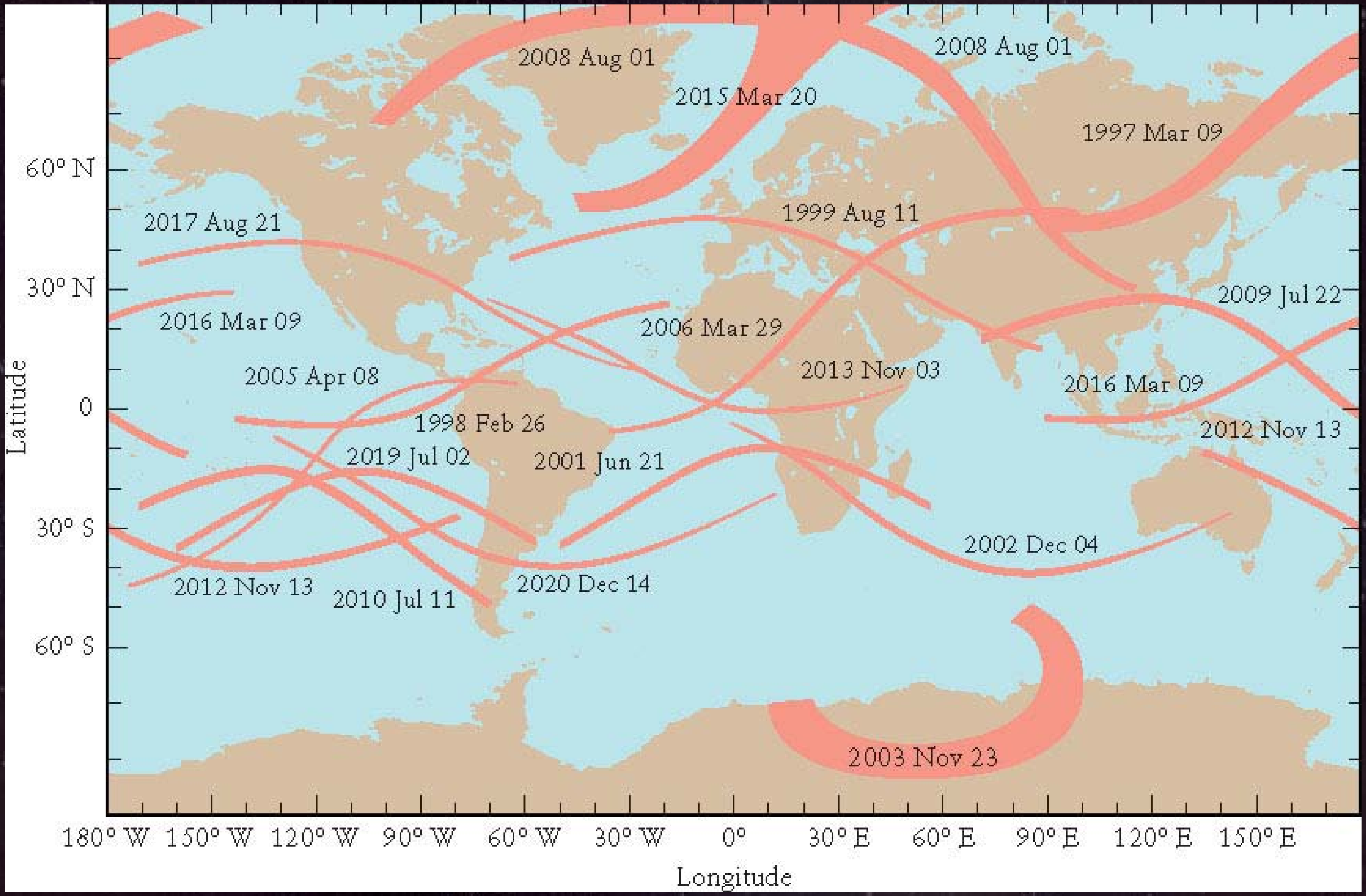
A lunar eclipse is visible from one entire hemisphere of the Earth. This is because the Earth's shadow is much bigger than the Moon.

In contrast, a solar eclipse is visible from a very small part of the Earth, because the Moon's shadow is only 160 miles across at most.



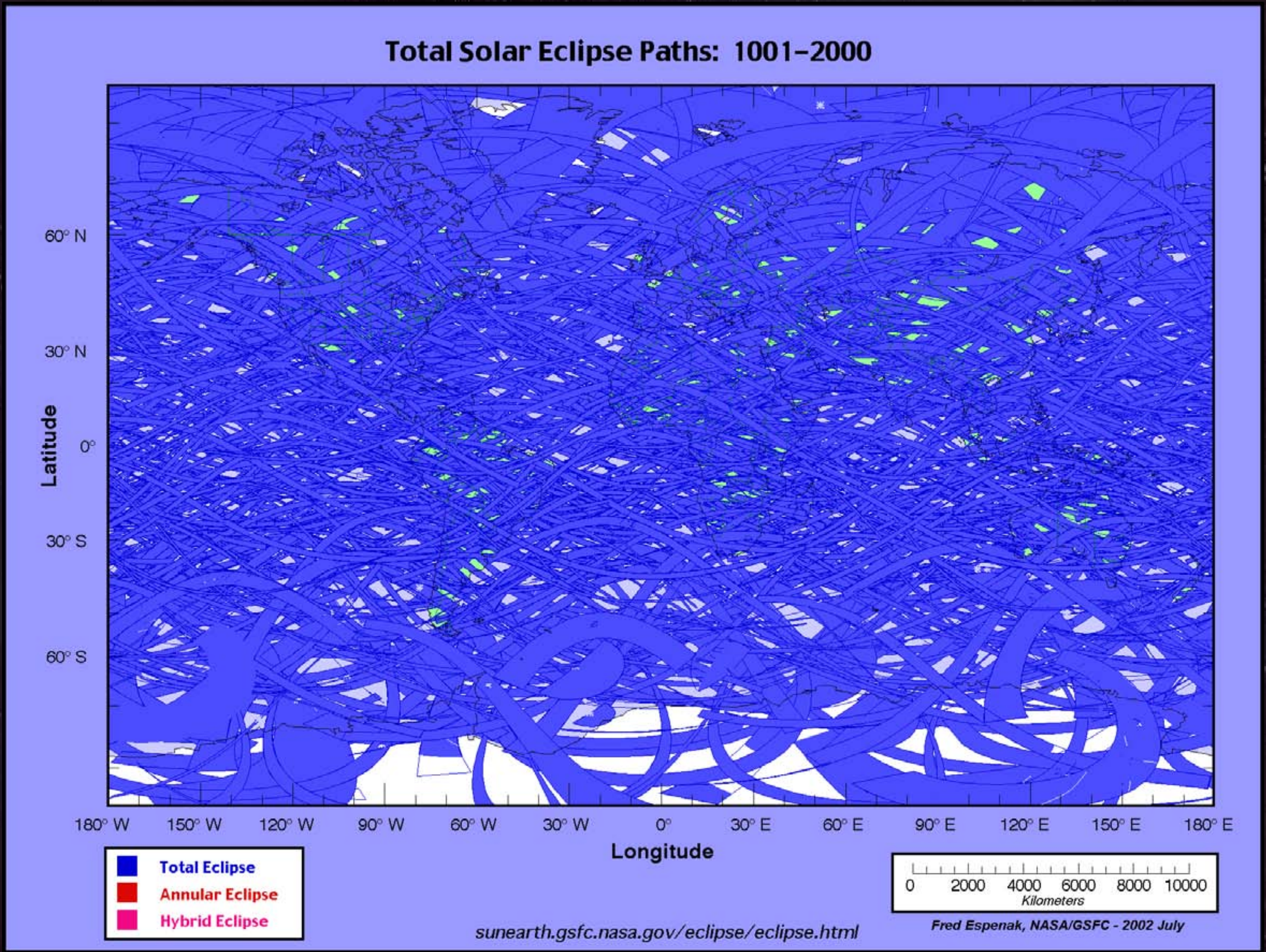
Solar Eclipses - visibility

So, although solar eclipses are fairly common, happening about every 18 months on average, an eclipse in a given location only happens once every 370 years on average. But some places are very lucky...



Solar Eclipses - visibility

Over 1000 years, almost every part of the Earth's surface will see at least one total solar eclipse:



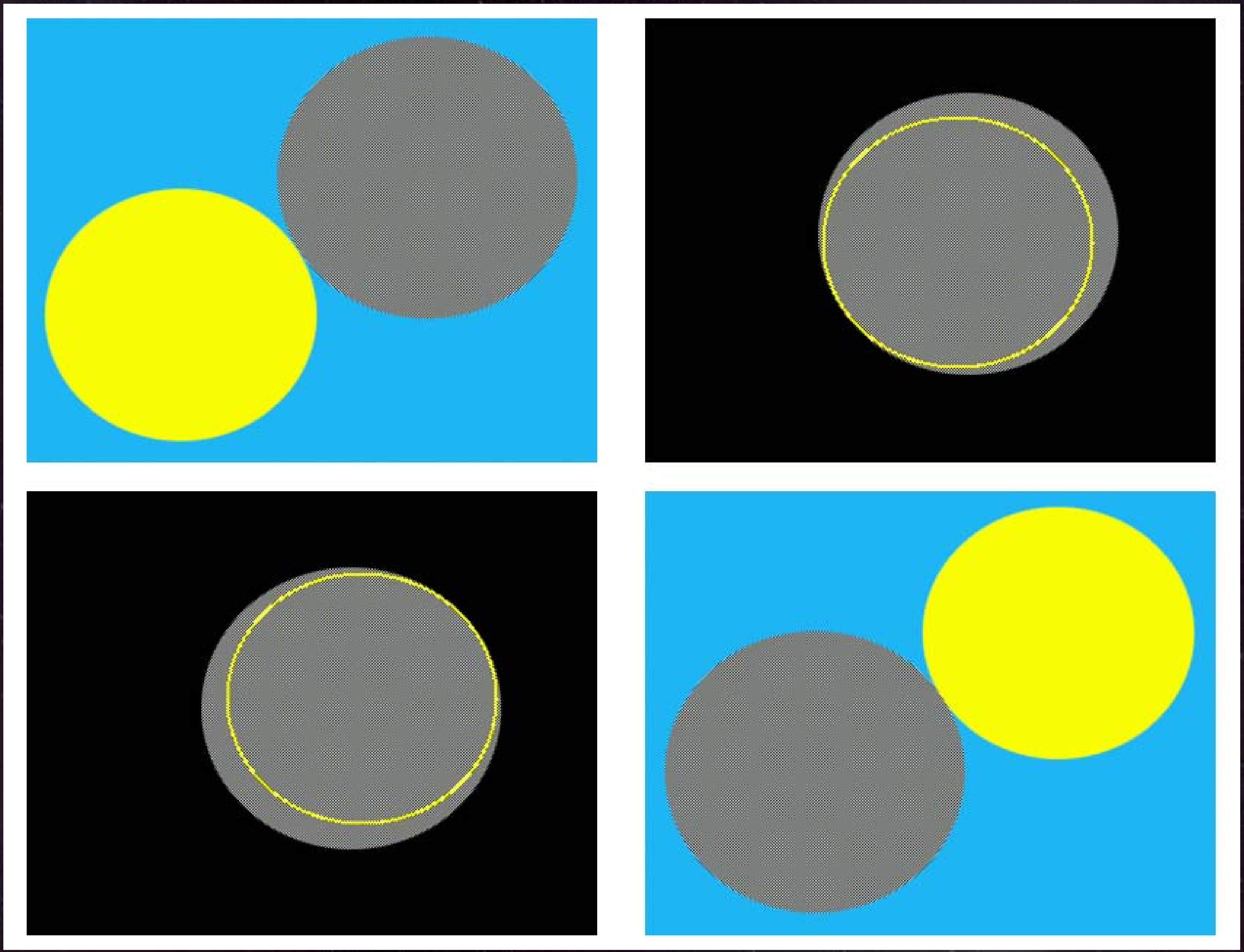
Solar Eclipses - phases

For both lunar and solar eclipses, there are key stages called *contacts*. For solar eclipses:

Stage	Occurrence
First contact	Leading edge of Moon moves onto face of Sun
Second contact	Leading edge of Moon reaches edge of Sun
Third contact	Trailing edge of Moon leaves face of Sun
Fourth contact	Trailing edge of Moon leaves face of Sun

Totality is between second and third contacts. For partial eclipses, only the first and fourth contacts occur.

Solar Eclipses - phases



In this figure the moon is moving from top right to bottom left. The figures shows first contact (top left), second contact (top right), third contact (bottom left) and fourth contact (bottom right)

Lunar Eclipses - phases

For lunar eclipses, there are six contacts:

Stage	Occurrence
First contact	Leading edge of Moon enters penumbral shadow
Second contact	Leading edge of Moon enters umbral shadow
Third contact	Trailing edge of Moon enters umbral shadow
Fourth contact	Leading edge of Moon leaves umbral shadow
Fifth contact	Trailing edge of Moon leaves umbral shadow
Sixth contact	Trailing edge of Moon leaves penumbral shadow

Totality is between third and fourth contacts.

Solar Eclipses - phenomena

As second contact approaches, and less and less of the Sun is visible, its light dwindles to a smaller and smaller region.

The visible Sun finally breaks into points of light as it is partly obscured by mountains on the edge of the Moon. This is called *Bailey's Beads*, after Francis Bailey who explained the phenomenon in 1836.

Solar Eclipses - phenomena

Bailey's Beads dwindle to a single point of light. The corona is now visible, and the combined effect is called the *diamond ring*

Solar Eclipses - phenomena

Just before and just after totality, when the visible part of the Sun is extremely small, you may see *shadow bands.* Patterns of dark and light ripple across the landscape.

The cause of the shadow bands is not entirely understood. Most astronomers think they are due to the almost-eclipsed Sun being the same apparent size as atmospheric eddies.

Some disagree – a paper published earlier this year claimed that infrasound caused by the rapid cooling then warming of the atmosphere during the eclipse was the cause.

Solar Eclipses – a temporary phenomenon

Because of tides, the Moon is moving away from the Earth at about 3.8cm per year on average. So, eventually, it will be too small to completely obscure the Sun.

At the same time, the Sun is very slowly getting larger as it evolves. These two effects mean that in about 600 million years, there will be no more solar eclipses.