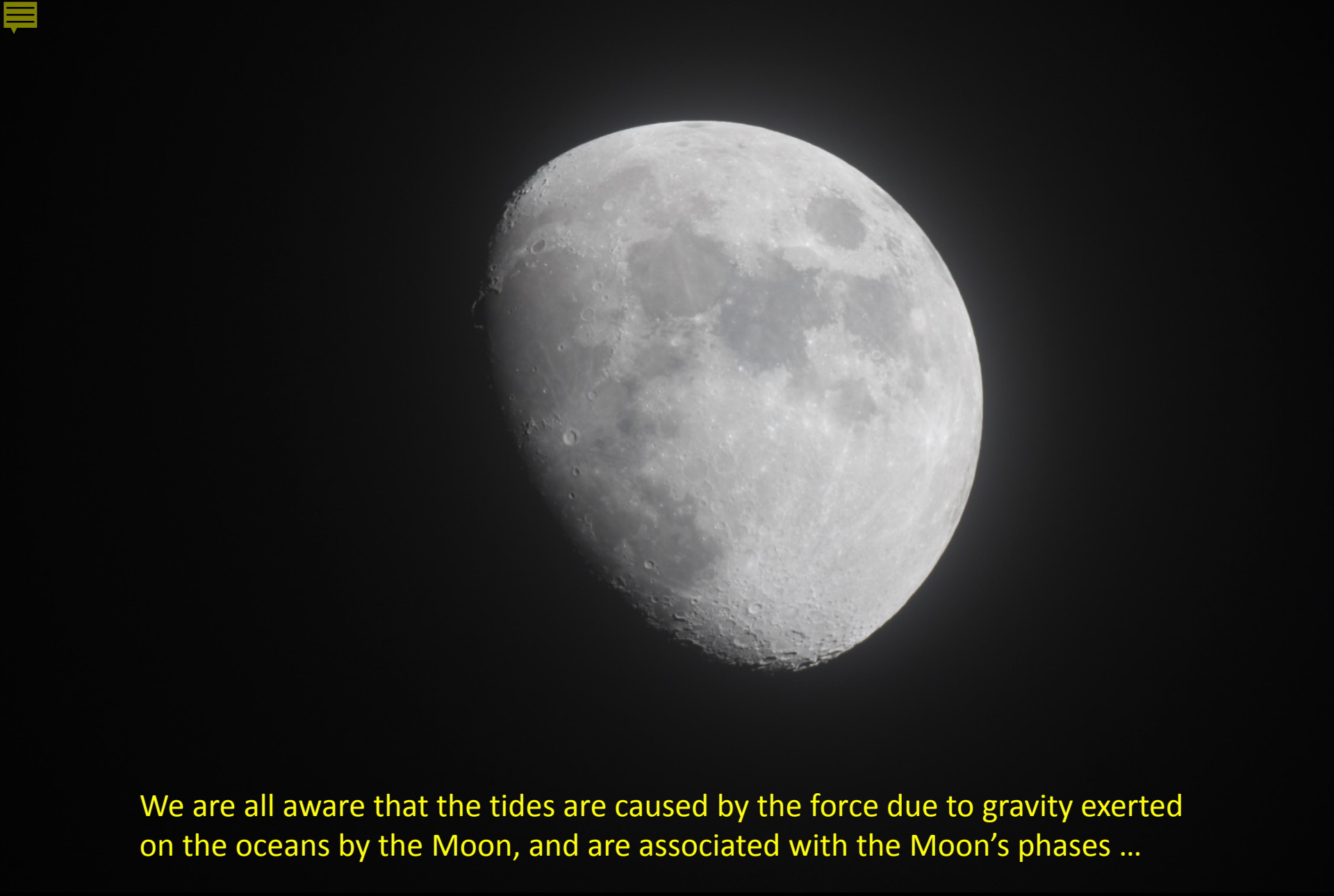
Tides – An astronomical explanation

(Put sound on for sound effect)

David Le Conte, FRAS

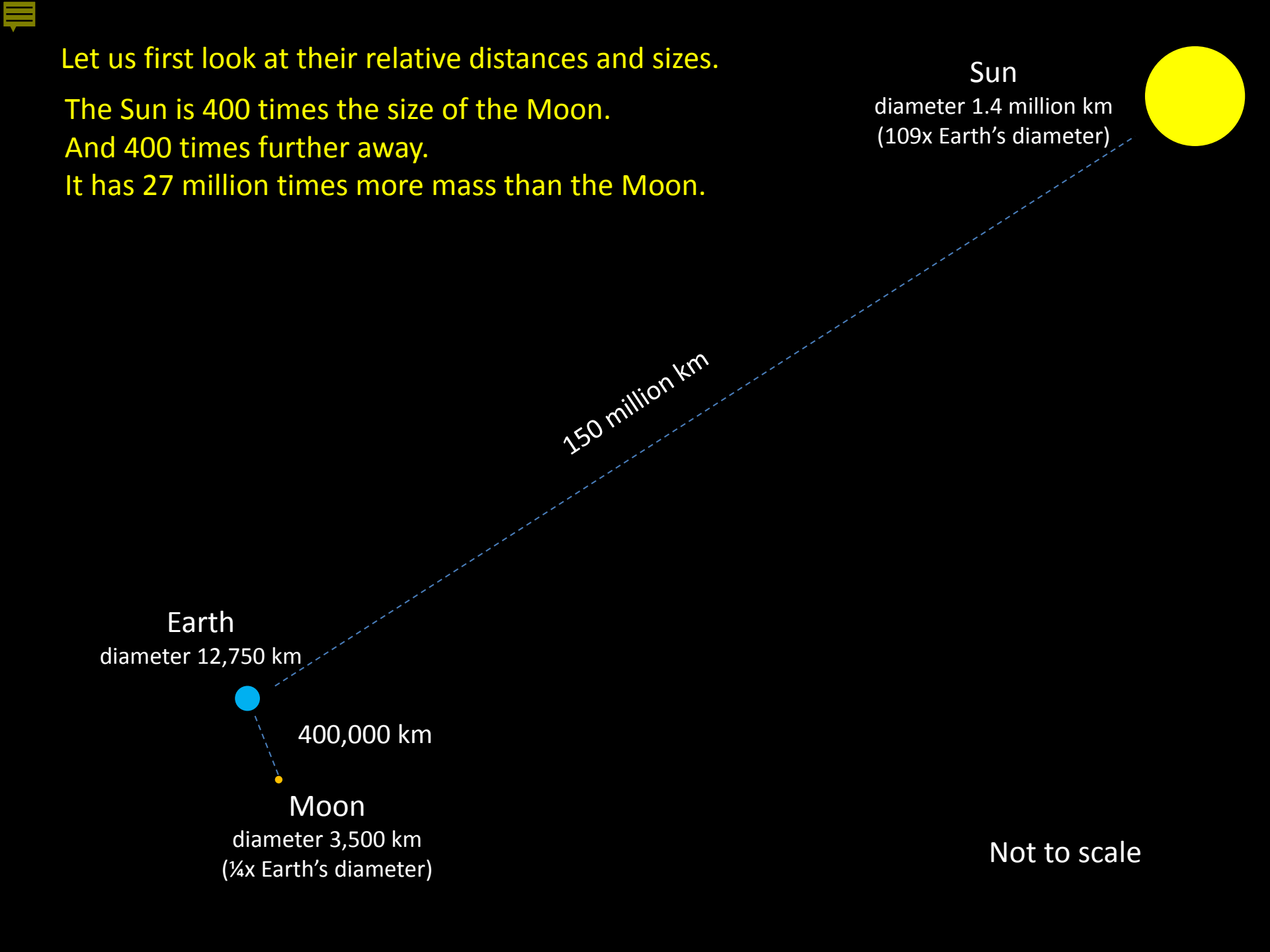


We are all aware that the tides are caused by the force due to gravity exerted on the oceans by the Moon, and are associated with the Moon's phases …


… and that the tides are affected to a lesser extent by the Sun.

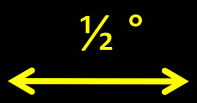
Let us first look at their relative distances and sizes.

The Sun is 400 times the size of the Moon.
And 400 times further away.
It has 27 million times more mass than the Moon.



This shows the relative sizes of the Sun, Earth and Moon. Over a million Earths could fit inside the Sun!

Sizes to scale



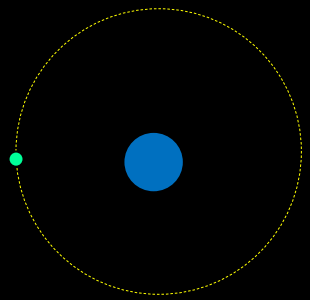
The Sun and the Moon both subtend an angle of ½°.

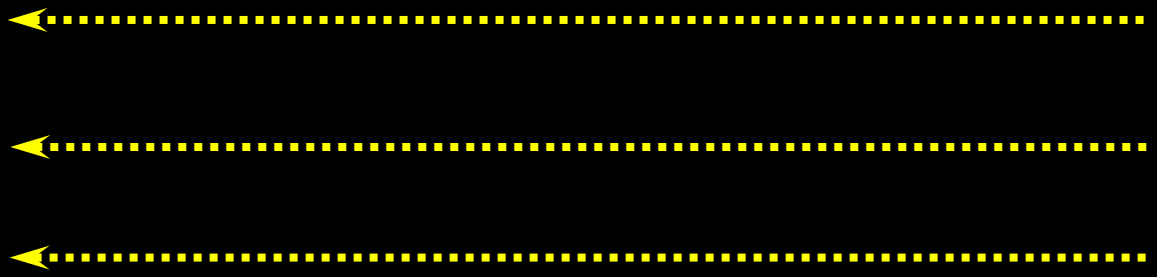
The fact that the Sun is 400 times larger than the Moon, and 400 times further away results in them appearing to us to be the same size, but this is purely a coincidence.

It produces spectacular eclipses when the Moon exactly covers the Sun, enabling the solar corona to be visible.

Total solar eclipse, Wyoming
21 August 2017
David Le Conte/ Jean Dean

The Moon revolves about the Earth (with respect to the Sun) once every 29½ days.
This produces the phases of the Moon.





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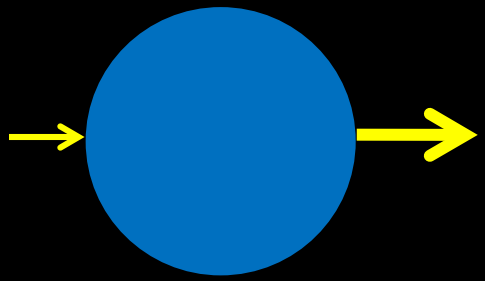
The gravitational force of the Moon is greater on the side of the Earth facing the Moon than it is on the other side because it is closer to the Moon, and the gravitational force falls off by the square of the distance.

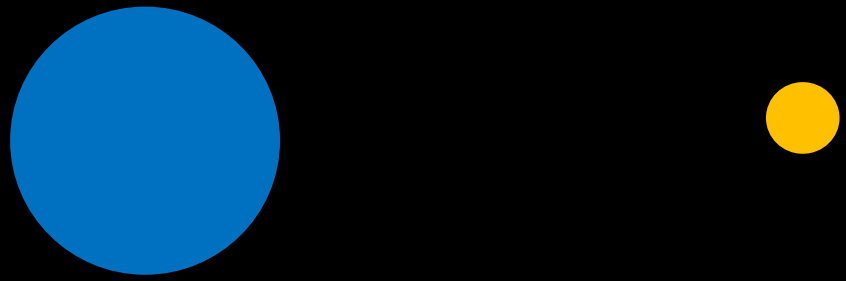


Earth

Moon

Not to scale

The Moon revolves around the Earth, but not around the centre of the Earth, as here.



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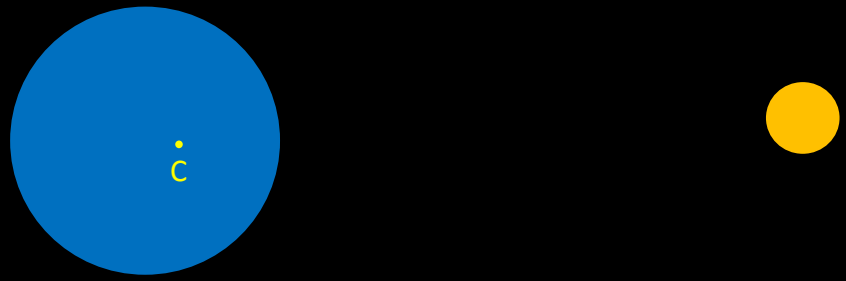
The Moon and the Earth orbit around a common centre of mass C, which is inside the Earth, making the Earth wobble.



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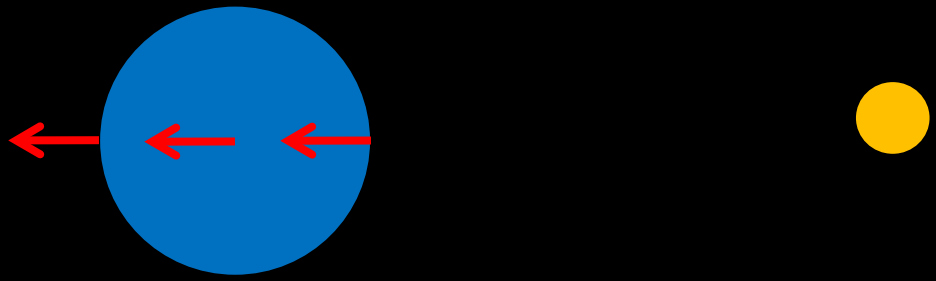
This produces a centrifugal force on the Earth away from the Moon, and that force acts equally everywhere on and inside the Earth.



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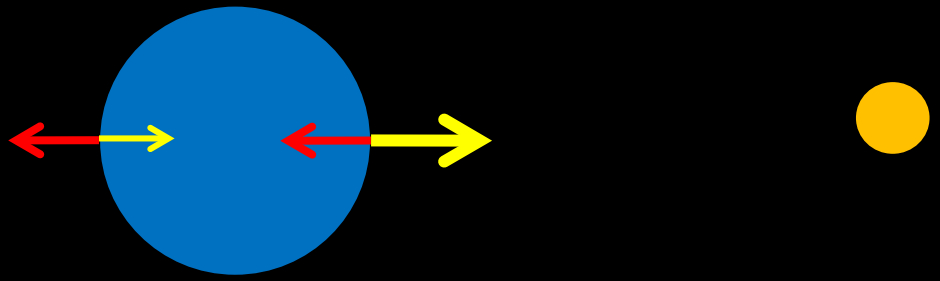
On the side of the Earth facing the Moon the Moon's gravitational force (yellow arrow) exceeds the centrifugal force (red arrow), pulling the oceans towards the Moon.
But on the other side the centrifugal force exceeds the gravitational force.



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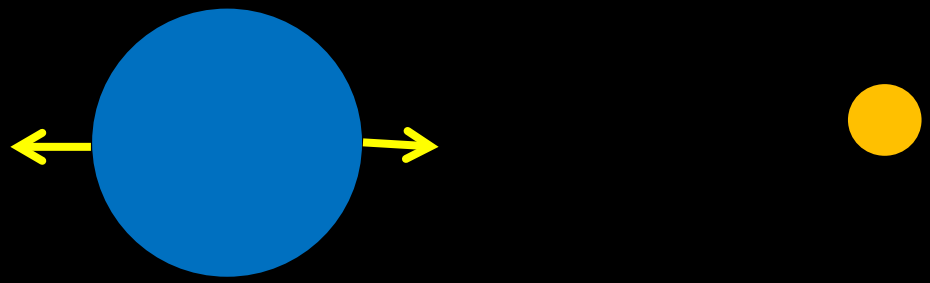
This produces a net force towards the Moon on the side of the Earth facing it, but away from the Moon on the other side.



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The oceans are therefore pulled towards the Moon on the side of the Earth facing it, and away from the Moon on the other side.

Not to scale

The inertia of masses of water results in a lag of the tides behind the direct gravitational attraction of the Moon, so the tides lag a couple of days behind the Moon phases.

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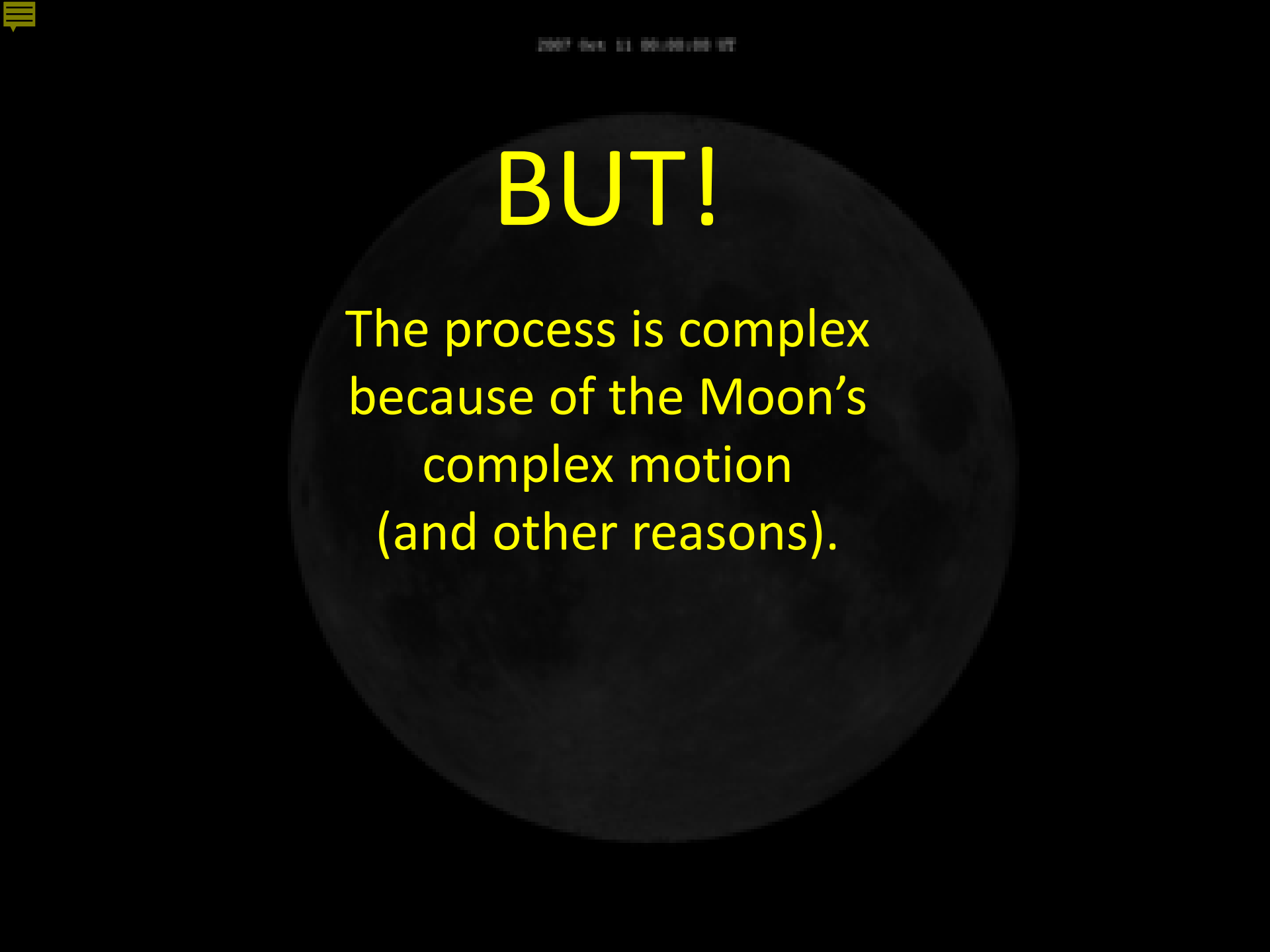
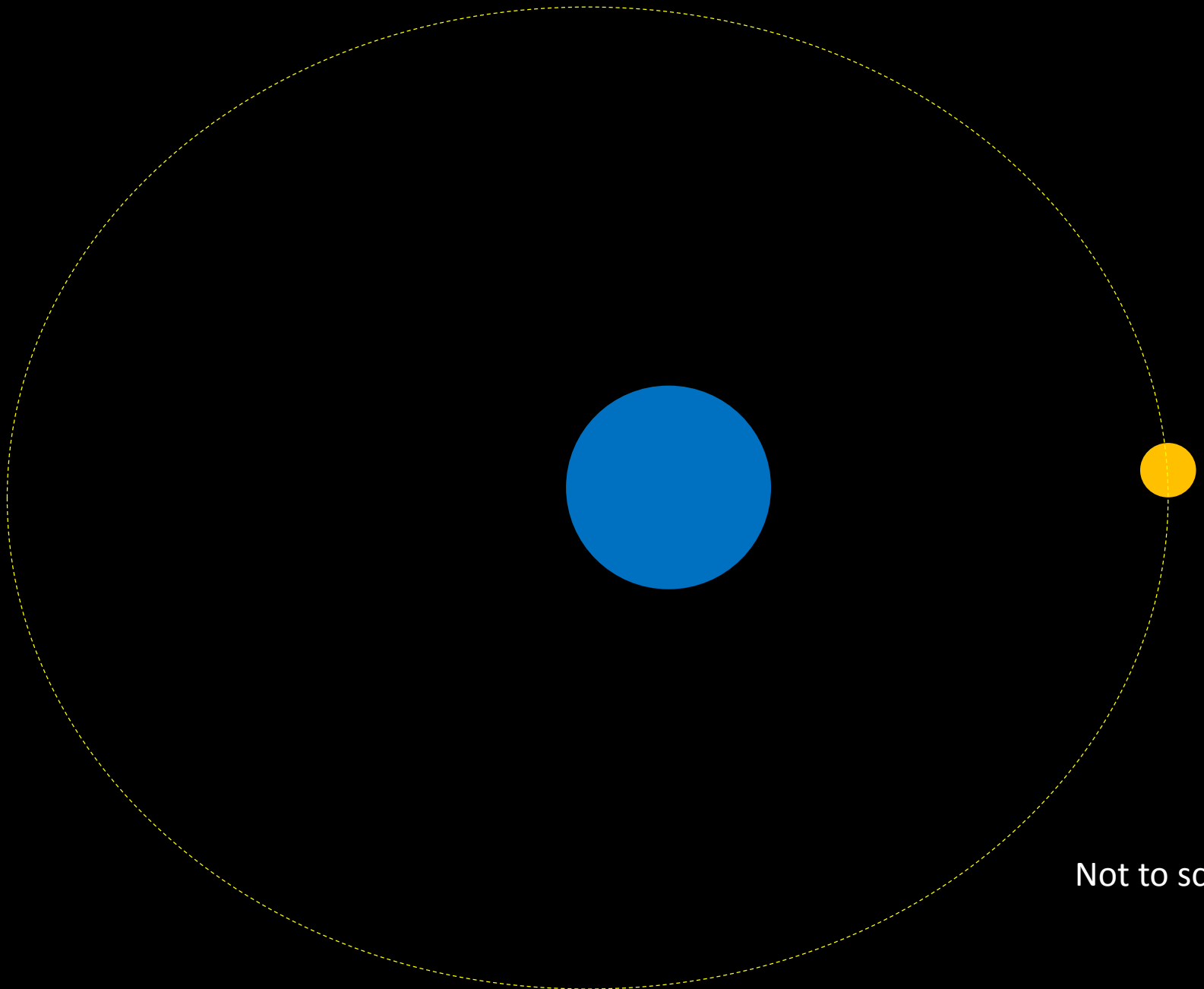

BUT!
The process is complex
because of the Moon's
complex motion
(and other reasons).

The Moon’s orbit is not circular but elliptical.



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This makes the Moon appear to wobble and get larger and smaller.

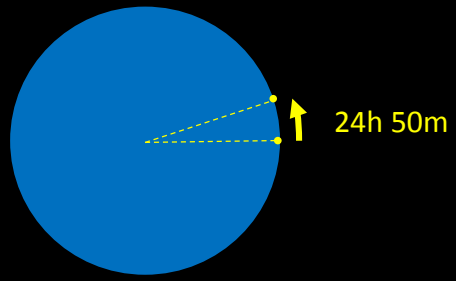
So during its orbital cycle it is alternately further from and nearer to the Earth by 12%.

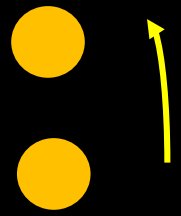
Moon at perigee

Moon at apogee

The Earth rotates with respect to the Moon with a period of 24 hrs 50 min.
Hence the tide times progress over the lunar month. As shown in this table.

	June-July 2014 Low water		
	Date	Time	Difference
New Moon	27	00:29	
	28	01:10	00:41
	29	01:46	00:36
	30	02:19	00:33
	1	02:51	00:32
	2	03:21	00:30
	3	03:52	00:31
	4	04:26	00:34
First Quarter	5	05:07	00:41
	6	06:01	00:54
	7	07:11	01:10
	8	08:27	01:16
	9	09:36	01:09
	10	10:39	01:03
	11	11:36	00:57
	12	12:30	00:54
Full Moon	13	13:21	00:51
	14	14:09	00:48
	15	14:54	00:45
	16	15:38	00:44
	17	16:22	00:44
	18	17:08	00:46
Last Quarter	19	18:00	00:52
	20	19:04	01:04
	21	20:24	01:20
	22	21:41	01:17
	23	22:40	00:59
	24	23:29	00:49
New Moon	26	00:12	00:43
	Average		00:47





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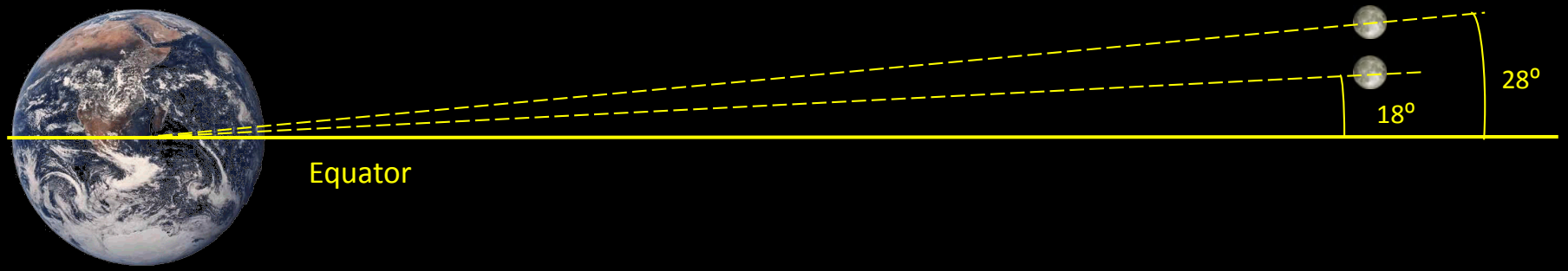
The Moon's declination (its angle to the Earth's equator) changes between 18° and 28° over an 18-year period.



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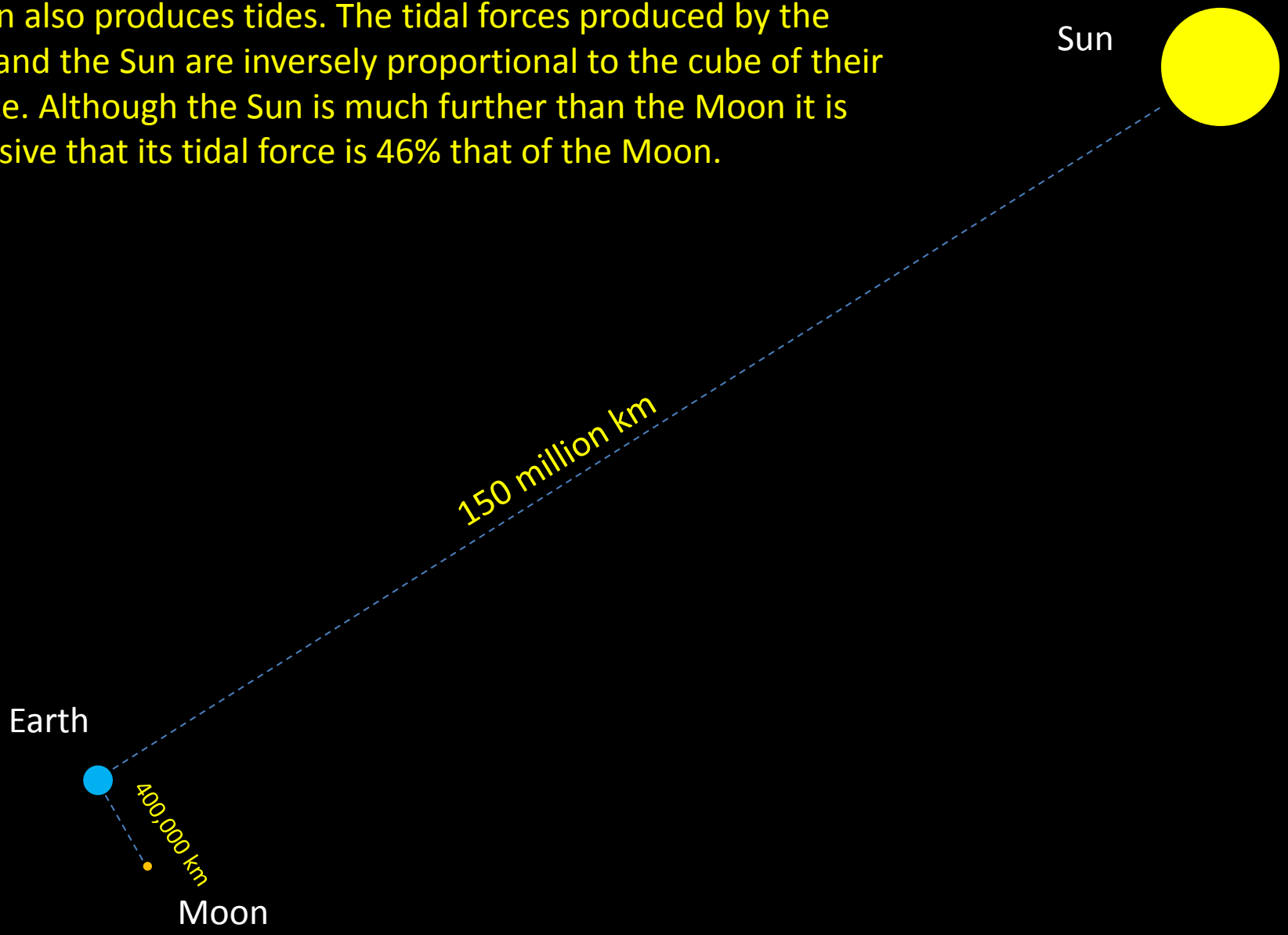
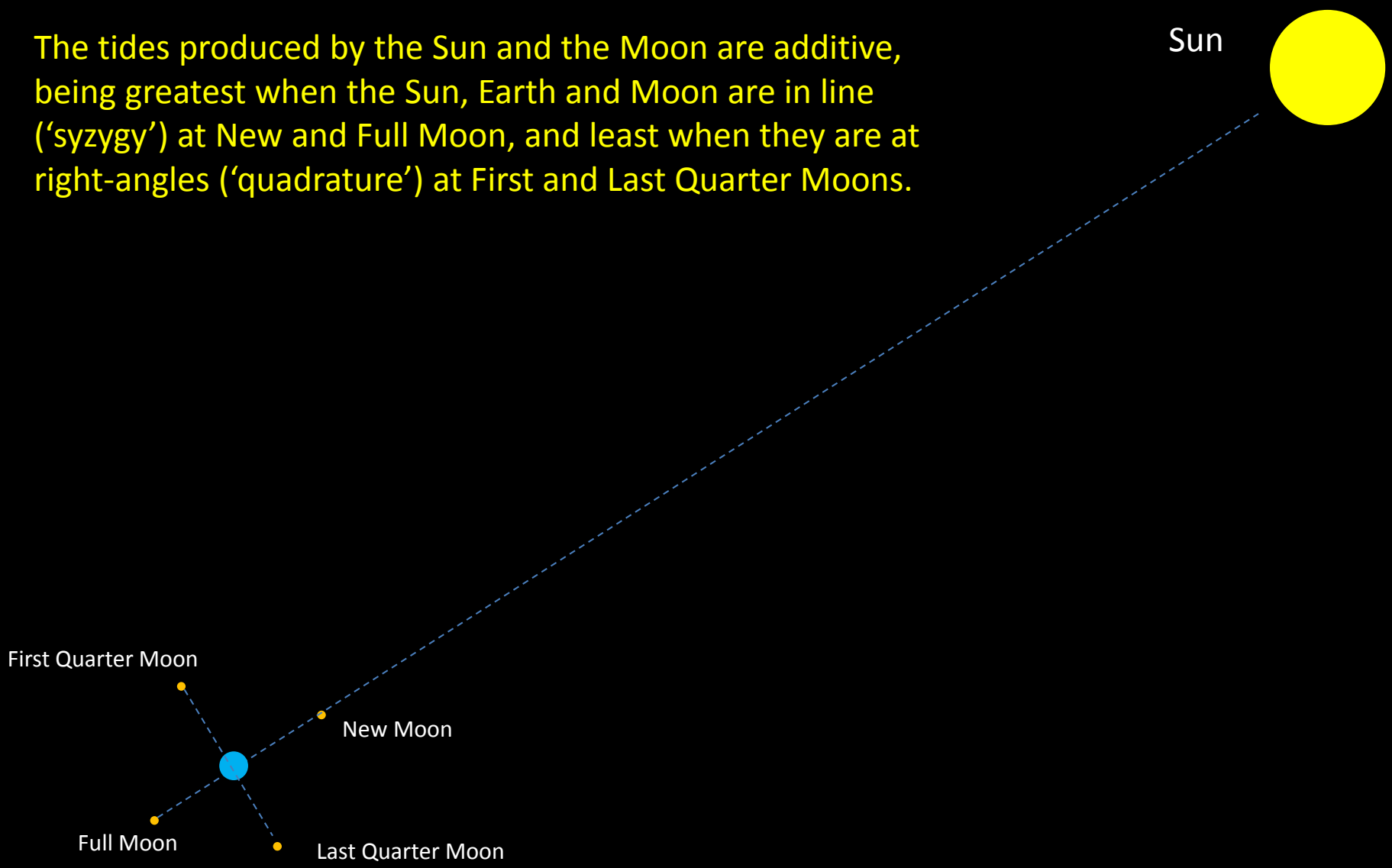
The Sun also produces tides. The tidal forces produced by the Moon and the Sun are inversely proportional to the cube of their distance. Although the Sun is much further than the Moon it is so massive that its tidal force is 46% that of the Moon.



The tides produced by the Sun and the Moon are additive, being greatest when the Sun, Earth and Moon are in line (‘syzygy’) at New and Full Moon, and least when they are at right-angles (‘quadrature’) at First and Last Quarter Moons.



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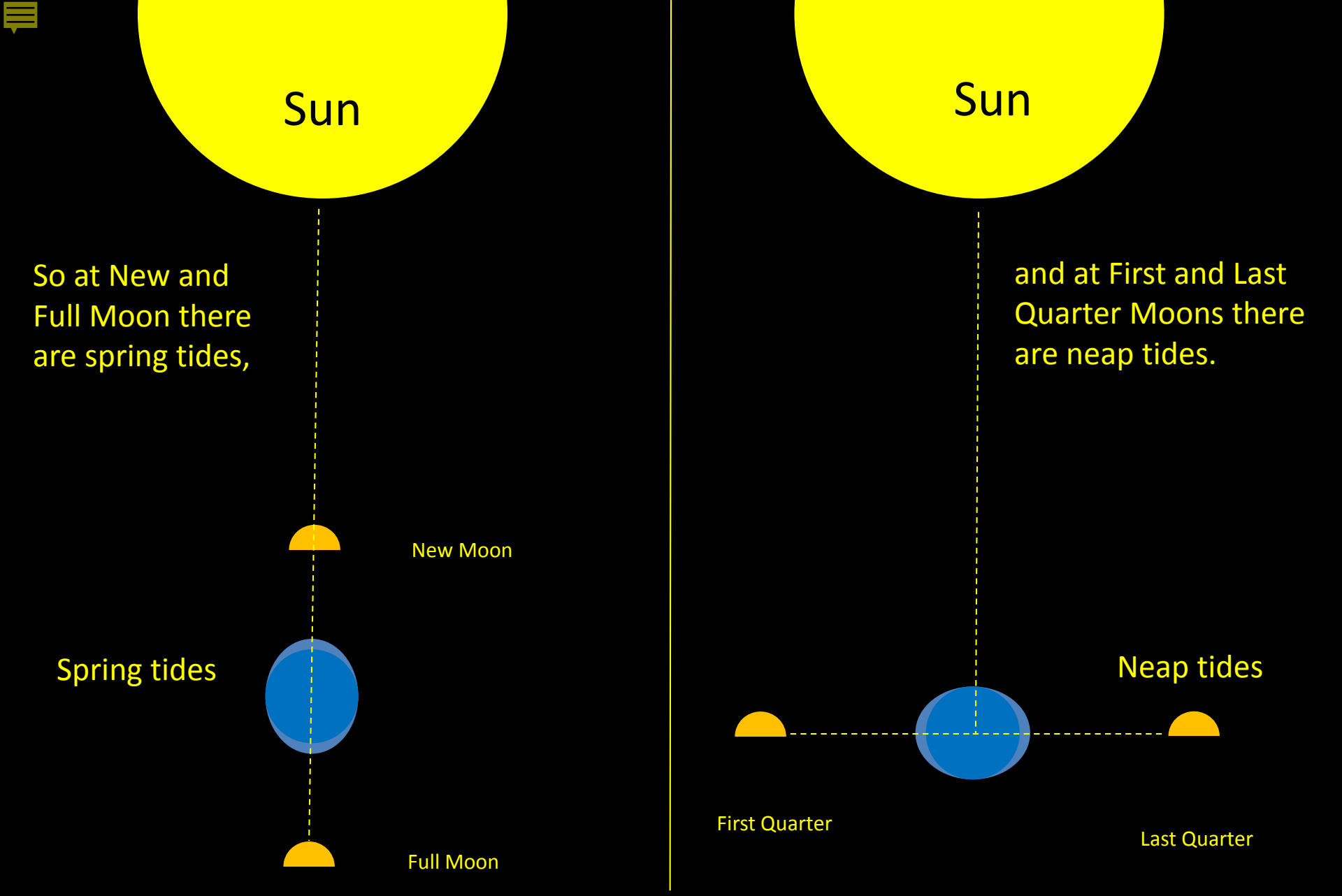

The full cycle of two neaps and two springs therefore takes 29½ days, corresponding to the phases of the Moon (the 'synodic period').

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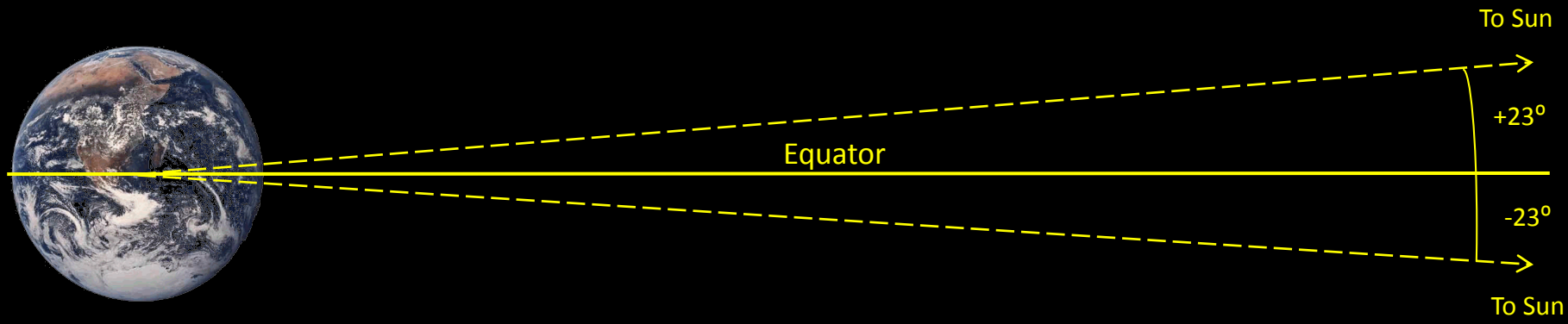
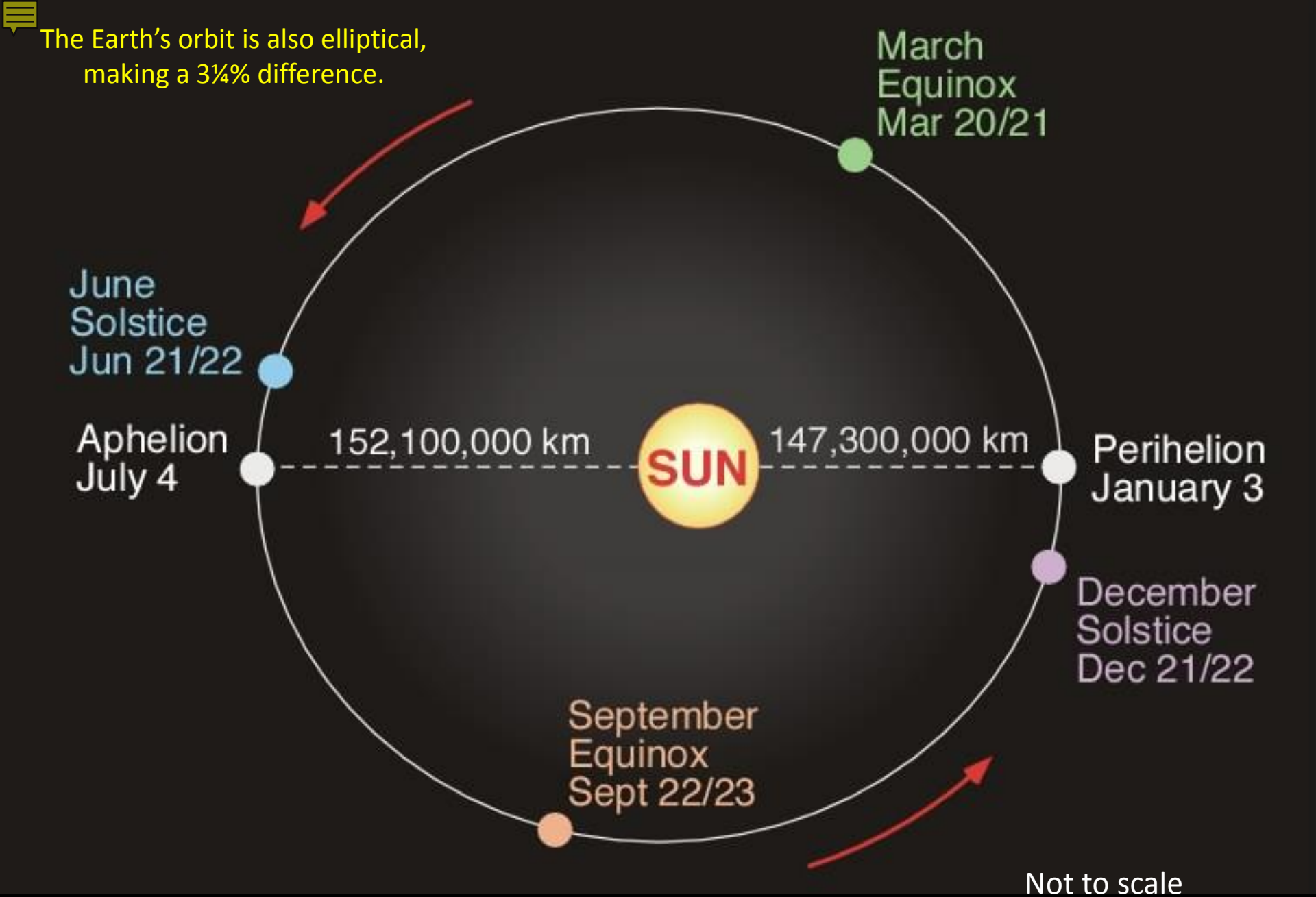
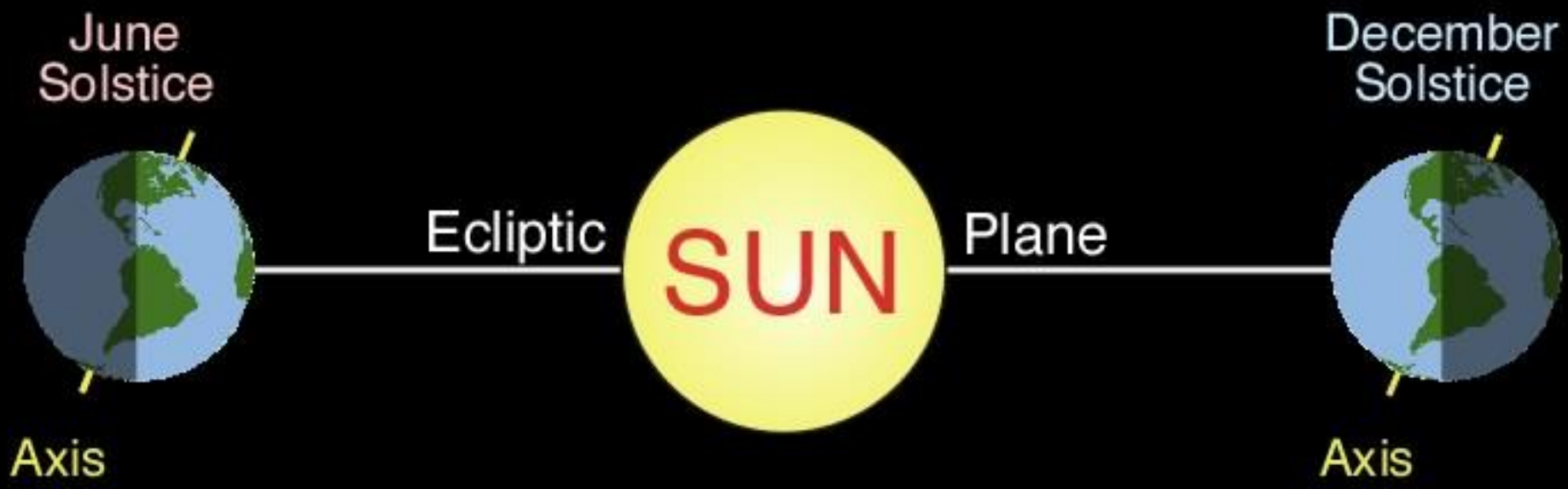
The Sun’s declination also changes by ±23° over a 6-month period.



The Earth's orbit is also elliptical, making a 3¼% difference.



The Earth's axis of rotation is inclined by 23½ degrees to the plane of the Ecliptic.



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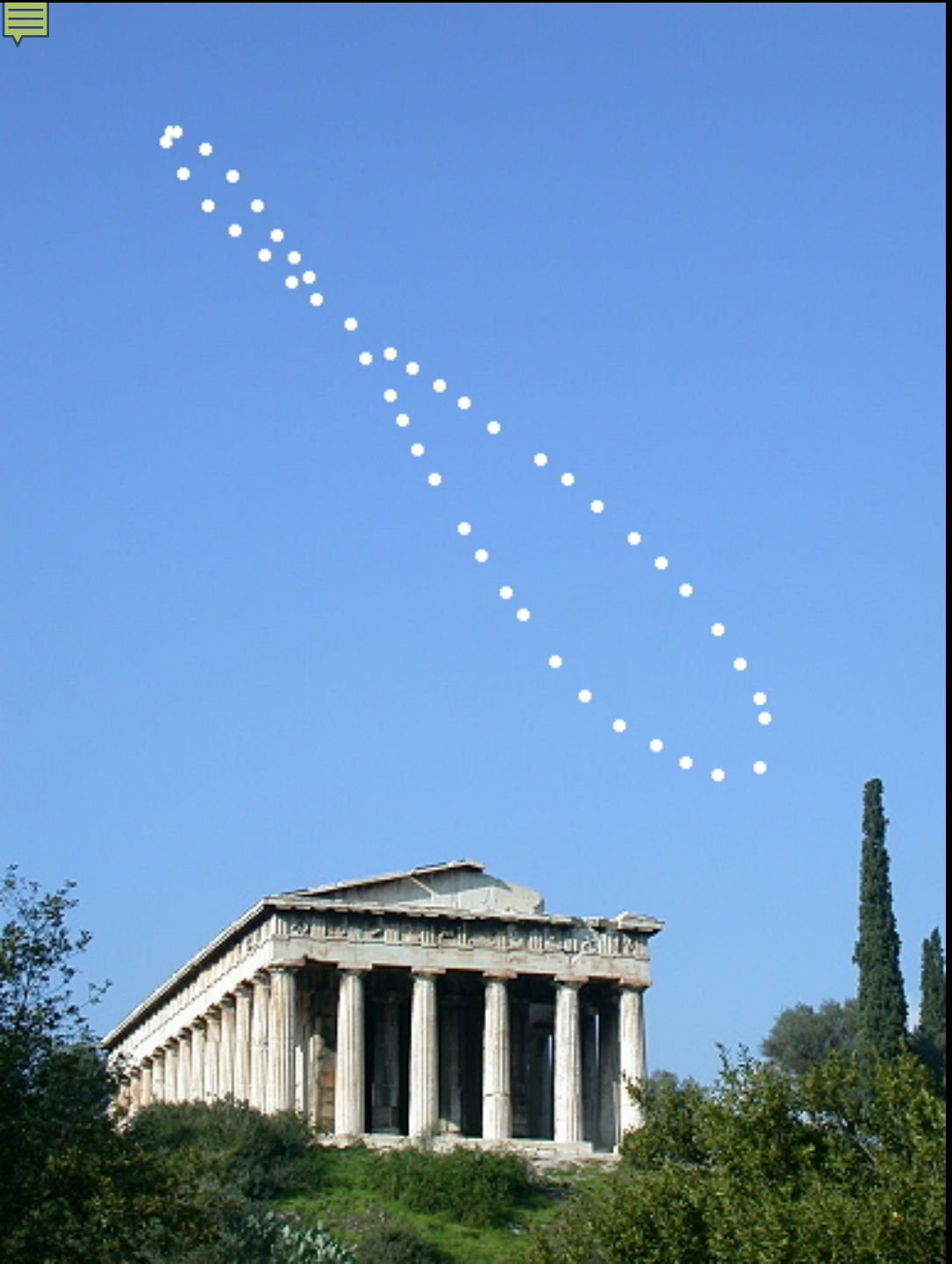
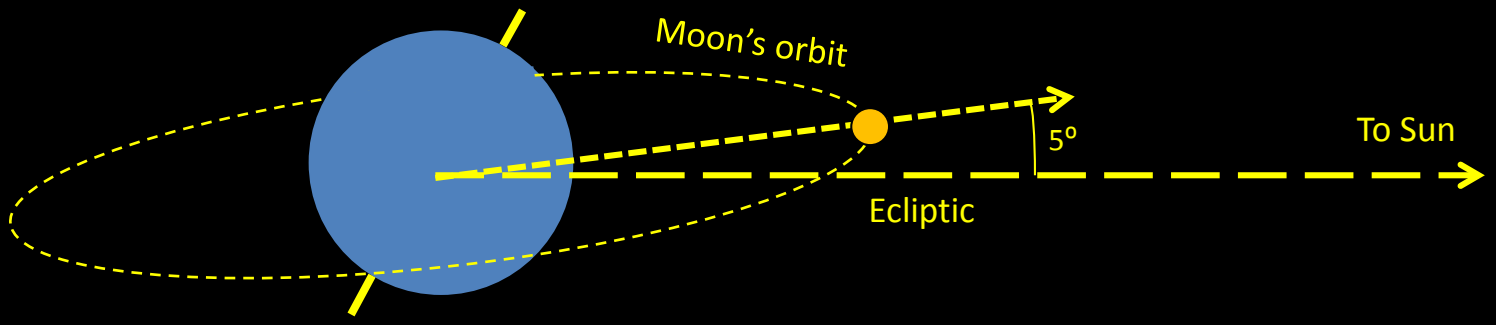


These two effects (the ellipticity of the Earth's orbit and the Earth's inclination to the ecliptic) result in the 'analemma'.

This picture shows the Sun's position at 10.00am during a whole year.

Anthony Ayiomamitis

The Moon’s orbit is inclined at 5 degrees to the Ecliptic.

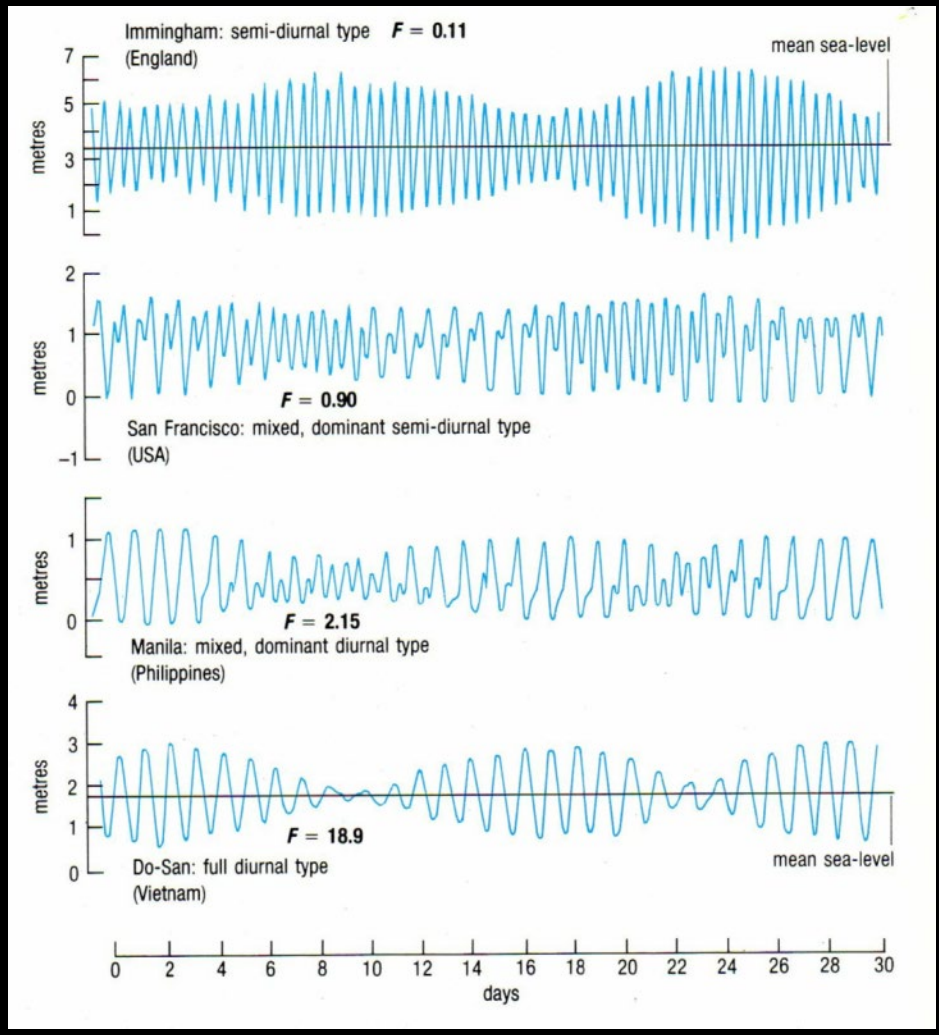


Tides are also very much affected by topography (as here, in the Bay of Mont St Michel), by atmospheric pressure, and by wind.

Tide predictions rely on a harmonic method: the tides are made up of many components called ‘partial tides’.

Name of tidal component	Symbol	Period in solar hours	Coefficient ratio ($M_2 = 100$)
Principal lunar	M_2	12.42	100
Principal solar	S_2	12.00	46.6
Larger lunar elliptic	N_2	12.66	19.2
Luni–solar semi-diurnal	K_2	11.97	12.7
Luni–solar diurnal	K_1	23.93	58.4
Principal lunar diurnal	O_1	25.82	41.5
Principal solar diurnal	P_1	24.07	19.4
Lunar fortnightly	M_f	327.86	17.2
Lunar monthly	M_m	661.30	9.1

Sone principal tidal components



Examples of different types of tide curve

Source: *Waves, Tides and Shallow-Water Processes*. The Open University

The dependence of the tides on the position of the Moon means that the tide times are fairly consistent with the Moon phases. For example, at New and Full Moon high tide occurs around 6.30 am, while at First and Last Quarter high tide is around 11.00 am. At those times the New Moon would be rising, the Full Moon setting, First Quarter Moon rising, and Last Quarter Moon setting.

Comparison of high tide times and Moon phases

Earliest times in red **Latest times in blue**

Month 2014	New Moon	First Quarter	Full Moon	Last Quarter
Jan	**06:03**	11:33	06:35	11:19
Feb	06:42	11:41	**06:51**	**11:54**
Mar	06:26	**11:53**	06:25	11:38
Apr	**06:50**	11:15	06:31	11:32
May	06:26	11:47	06:42	11:25
Jun	06:04	11:07	06:21	11:10
Jul	06:27	11:15	06:05	11:36
Aug	06:47	11:25	06:43	10:59
Sep	06:23	10:52	06:25	11:06
Oct	06:29	**10:32**	**06:03**	**10:30**
Nov	06:33	11:29	06:24	10:49
Dec	06:04	11:18	06:03	11:04
Average	**06:26**	**11:20**	**06:25**	**11:15**
Median	**06:26**	**11:21**	**06:25**	**11:14**
	Rising	Rising	Setting	Setting

Here are the heights of high water for the various phases of the Moon.

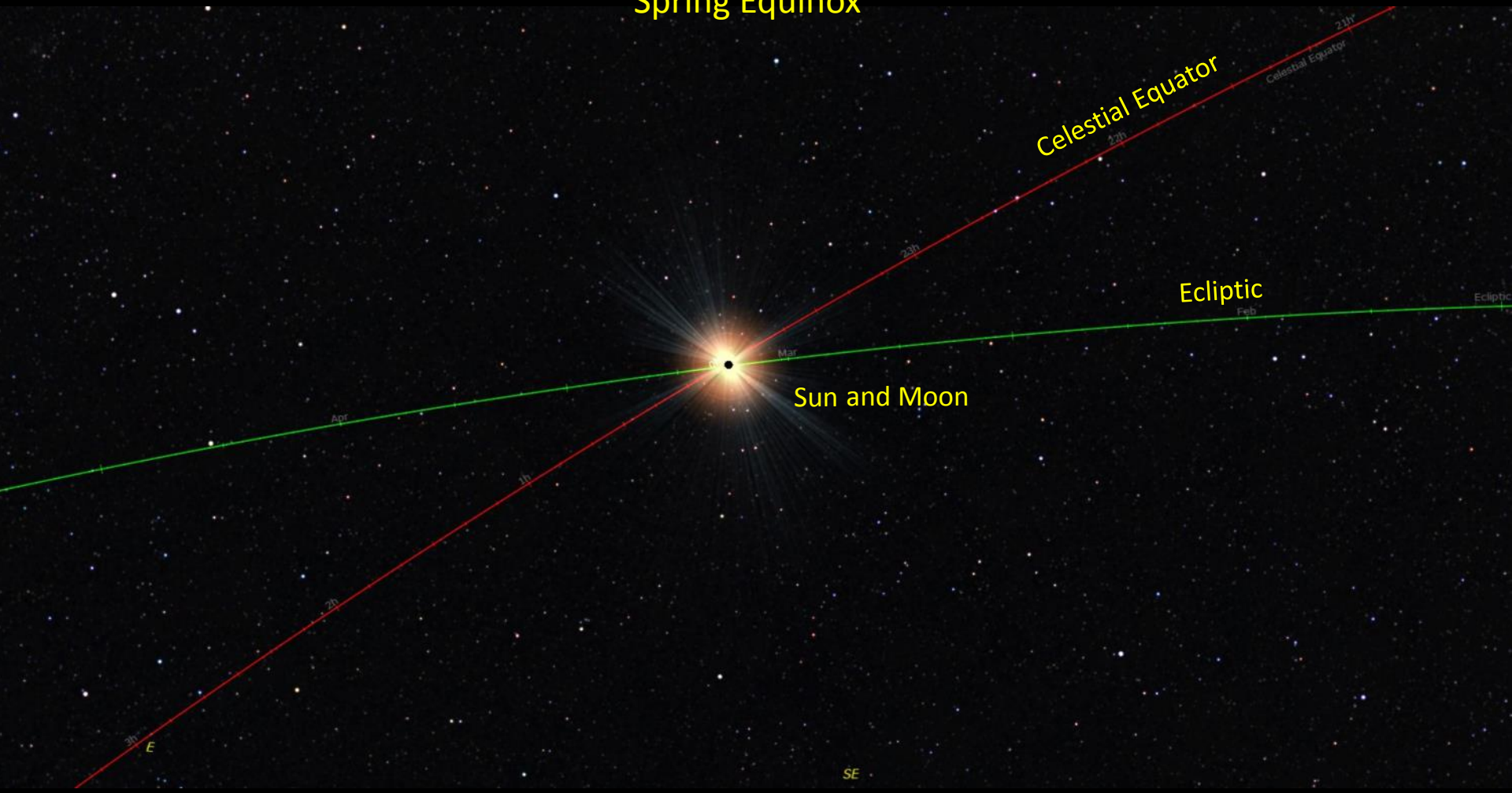
These are <u>not</u> the highest tides because those occur a couple of days after the phase.

Heights of high water

Lowest heights in red **Greatest heights in blue**

Month 2014	New Moon	First Quarter	Full Moon	Last Quarter
Jan	9.4	**8.0**	**8.8**	7.5
Feb	9.8	7.3	8.9	**7.2**
Mar	9.8	**6.6**	8.9	7.3
Apr	**9.9**	6.7	9.0	7.4
May	9.4	6.7	9.1	7.8
Jun	8.8	7.1	9.0	**8.2**
Jul	**8.5**	7.3	8.9	7.9
Aug	**8.5**	7.3	9.5	8.0
Sep	8.6	7.5	**9.7**	7.3
Oct	8.9	7.7	**9.7**	7.4
Nov	9.1	7.6	**9.7**	**7.2**
Dec	9.1	8.0	**9.2**	**7.2**
Average	**9.2**	**7.3**	**9.2**	**7.5**
Median	**9.1**	**7.3**	**9.1**	**7.4**

Spring Equinox



At the equinoxes the Sun (on the ecliptic) lies on the celestial equator, resulting in higher tides. If the Moon is also on the celestial equator and the ecliptic at that time (as shown here), coinciding with the Sun, even larger tides will be produced. And if the Moon is also at perigee then very large spring tides can result.

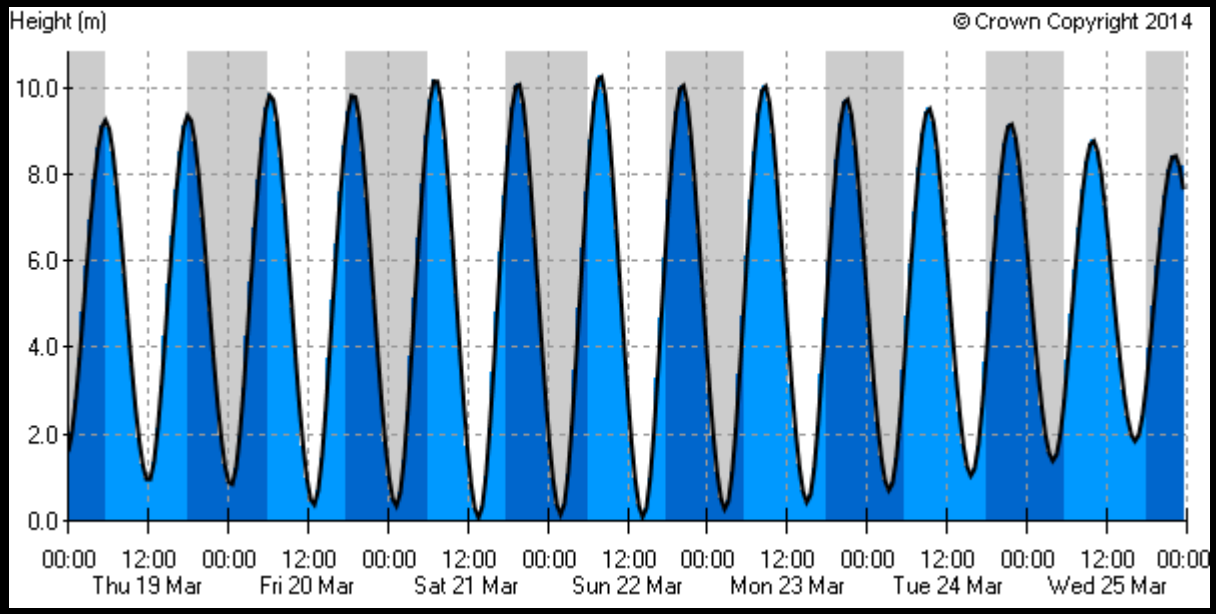
Equinox tides, March 2015

An example of these very high tides was at the spring equinox in 2015.

Lunar perigee: 19 March, 19:39

New Moon: 20 March, 09:36

Equinox: 20 March, 22:45

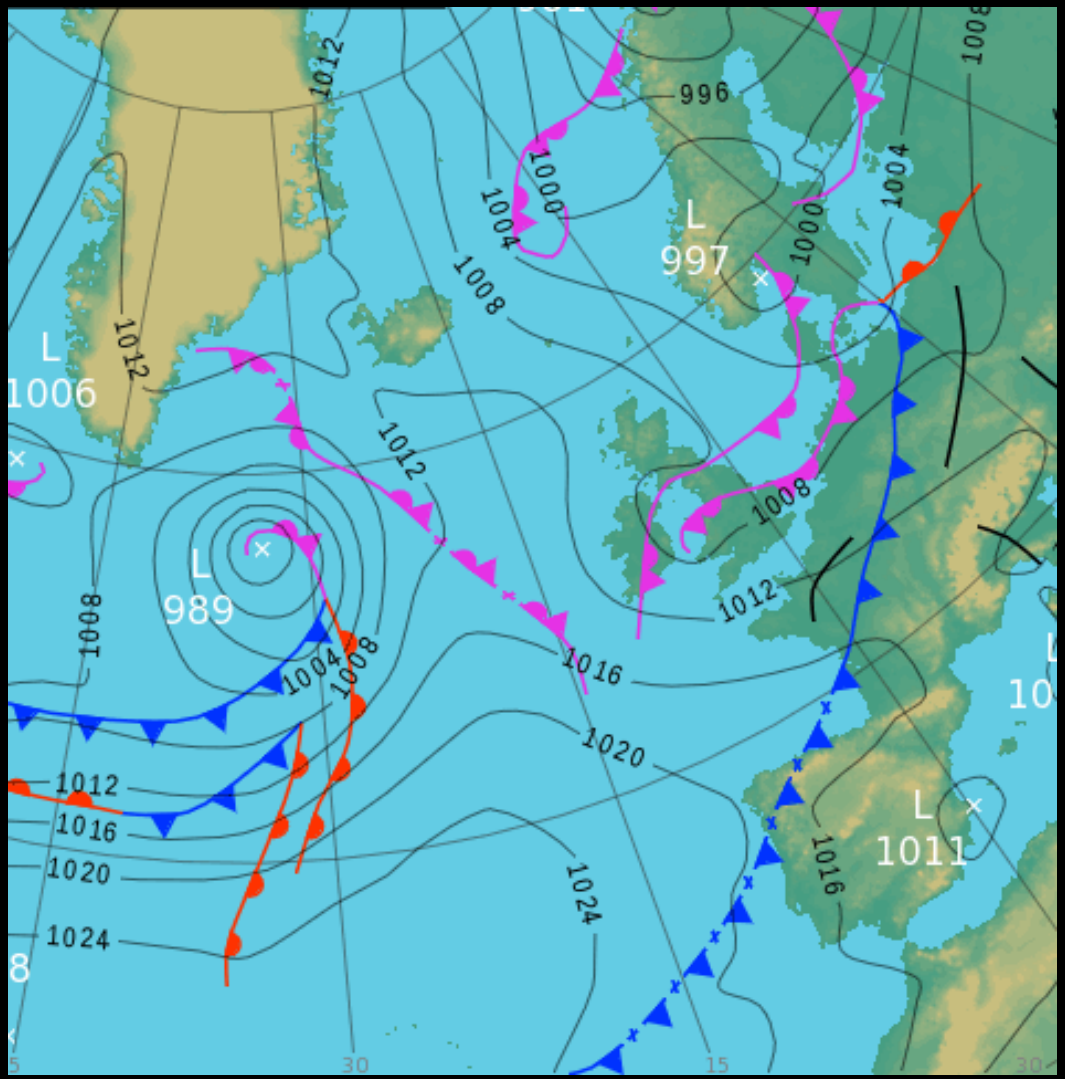


Equinox tides, March 2015

March		Low water		High water		Low water		High water	
2015		Time	Metres	Time	Metres	Time	Metres	Time	Metres
19				05:34	9.2	12:02	0.9	18:01	9.4
20		00:25	0.8	06:23	9.8	12:50	0.5	18:48	9.9
21		01:25	0.3	07:09	10.2	13:35	0.1	19:32	10.1
22		01:56	0.2	**07:52**	**10.3**	**14:17**	**0.1**	20:13	10.1
23		02:37	0.3	08:33	10.0	14:57	0.4	20:51	9.7
24		03:15	0.7	09:13	9.5	15:34	1.0	21:29	9.2
25		03:53	1.4	09:51	8.8	16:11	1.8	22:05	8.4

UK Hydrographic Office, *EasyTide*

Finally, atmospheric pressure affects the heights of tides.
A high pressure depresses the tide, while a low pressure results in a higher tide.



And strong winds can create higher tides, resulting in storm surges.

So in summary tidal processes are complex because:

1. The Moon's orbit is not circular but elliptical. So during its orbital cycle of 27 days it is alternately further from and nearer to the Earth by 12%
2. The Earth rotates with respect to the Moon with a period of 24 hrs 50 min.
3. The Moon's declination (the amount by which it deviates from the celestial equator) changes from 18 to 28° over an 18-year period.
4. The Sun also produces tides, with a force of 46% that of the Moon.
5. The tides produced by the Sun and the Moon are additive. The effect of this additive process is greatest when the Sun, Earth and Moon are in line. This occurs at New and Full Moons, and results in spring tides.
6. The Sun's declination changes by ±23° over a 6-month period.
7. The effect is least when the Sun, Earth and Moon are in quadrature. This occurs at First and Last Quarter Moons, and results in neap tides.
8. The full cycle of two neaps and two springs takes 29.5 days, corresponding to the phases of the Moon (the synodic period).
9. The inertia of masses of water results in a lag of the tides behind the direct gravitational attraction of the Moon and Sun.
10. Actual tides are made up of many components called 'partial tides'.
11. They are also affected by atmospheric pressure (being higher in low pressure, and lower in high pressure).
12. And by winds. Strong winds can result in storm surges.

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