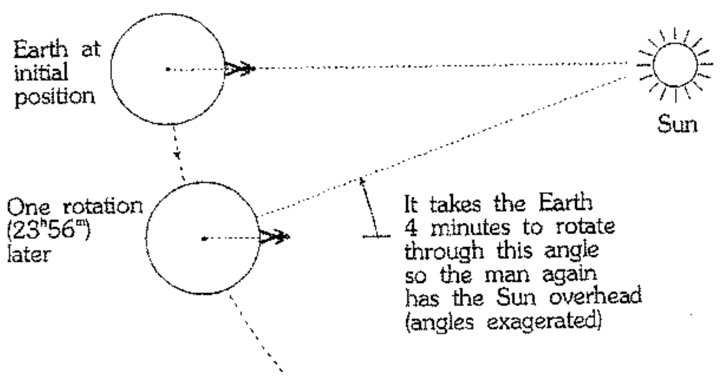
Tony Fairall - AST 1000F PART 3
THE EARTH-SUN-MOON SYSTEM

THE ROTATION AND REVOLUTION OF THE EARTH



The Earth both rotates (spins on the axis passing through the North and South Poles) and revolves about the Sun, once a year. Currently the Earth rotates once in 23h56m, or 366 and a quarter times in a year. Due to the action of it moving around the Sun in its orbit, and because the sense of rotation is the same as that of its revolution, its rotational period RELATIVE TO THE SUN is 24hOOm, or 365 and a quarter times a year. The Earth's orbit about the Sun is elliptical, not circular. The Earth is closest to the Sun early January (PERIHELION, distance 147 million km) and furthest from the Sun in early July (APHELION, distance 152 million km). The average distance of the Earth from the Sun is 149.5 million km, known as one ASTRONOMICAL UNIT (A.U.). (Astronomical units are a convenient measure of distances within the solar system).

SOLAR RADIATION

The survival of life on Earth is, of course, dependent on the warmth provided by the Sun. The Sun's heat is conveyed by radiation. The shorter wavelengths of the Sun's radiation, ultra-violet and near X-ray, are absorbed by the Earth's upper atmosphere, in particular by the ozone layer. The Sun follows an 11-year cycle. At solar 'maximum' in this cycle, there is considerably more short-wavelength radiation and at these times, the upper atmosphere absorbs more and expands upwards (thereby putting increased drag on spacecraft in low orbits). There may also be 'storms' of particles that interact with the Earth's magnetosphere, creating vast electrical currents that manifest as luminous auroras near the Earth's magnetic poles.

The bulk of solar radiation is, however, visible light (and some near infrared), for which the Sun's output is constant. At anyone time, about 50% of the Earth's surface is covered by cloud (within the lower atmosphere). Virtually all the light that hits the top of these clouds is scattered back into space and therefore plays no part in heating the Earth. Where there is no cloud, the light passes through the atmosphere with very little absorption (or heating) and strikes the ground, heating the solid surface of the Earth. Thus the lower atmosphere is warmed from beneath, and not from the top). Clouds at night work in reverse - they stop radiant energy from escaping. Since most of the Earth's surface is water, most of the heating goes into the ocean. The enormous reservoir of heat in the oceans, in turn, drives the weather patterns in the atmosphere.

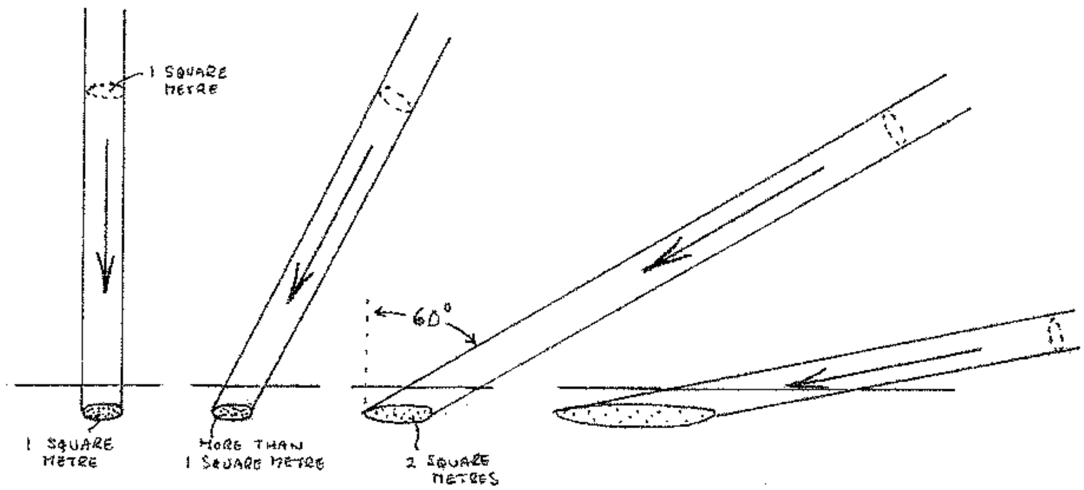
INSOLATION

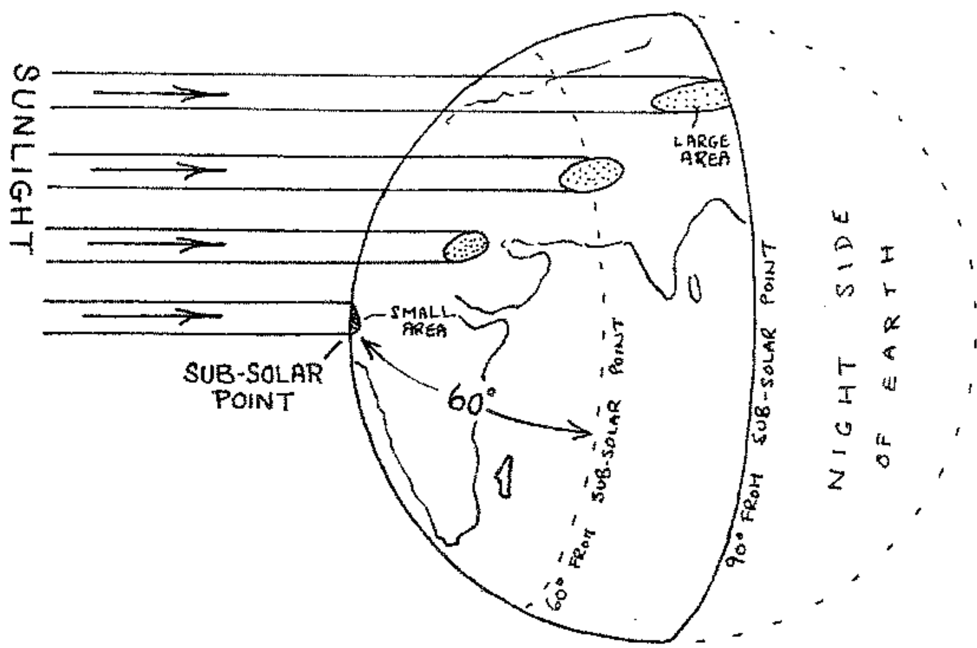
This term is given to the radiant energy received from the Sun at the Earth's surface. If the atmosphere is clear, then the insolation depends on only one factor - the angle at which the incoming radiation strikes the ground (or the surface of the ocean).

Suppose, as in the accompanying diagram, we consider a beam of sunlight, with cross section one square metre. If it strikes the ground perpendicularly, then its energy is spread over one square metre. If, however, it strikes at an angle, the same energy is spread over an area greater than a square metre. Thus the energy is diluted and the heating effect is less. If it struck the ground, at an angle 60 degrees off the vertical, the beam would be spread over two square metres and the heating effect would be halved.

At anyone time, a hemisphere of the Earth's surface is lit up and heated by the Sun - see diagram. Only at one point on the Earth's surface is the Sun overhead. That point is termed the 'sub-solar point' and is the only place on Earth where the Sun's radiation strikes perpendicularly, so that the heating effect is at its maximum.

At any other place - whether north or south, east or west of the sub-solar point, the heating effect is less. At 60 degrees from the sub-solar point (see diagram), it is only a half. It diminishes to zero at 90 degrees from the sub-solar point - the 'terminator', the boundary between night and day. For any observer on Earth, the higher the Sun is in the sky, the closer he or she is to the sub-solar point and the greater the heating.

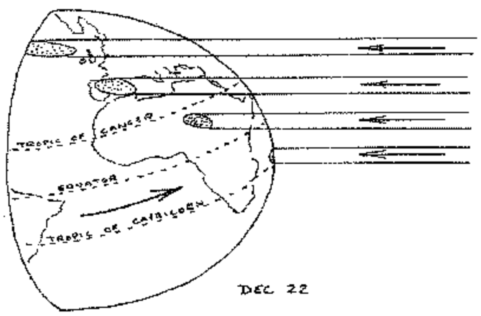


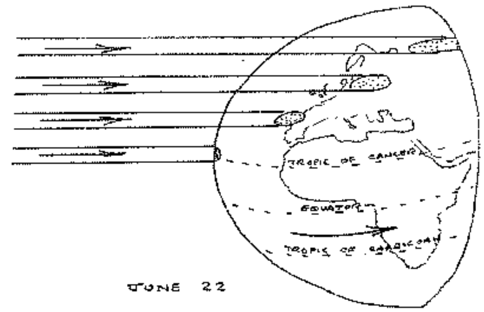


However the sub-solar point moves westwards as the Earth rotates. Places on the Earth experience virtually no heating at sunrise, increasing to maximum heating at midday (when closest to the sub-solar point) and decreasing back to zero at sunset.

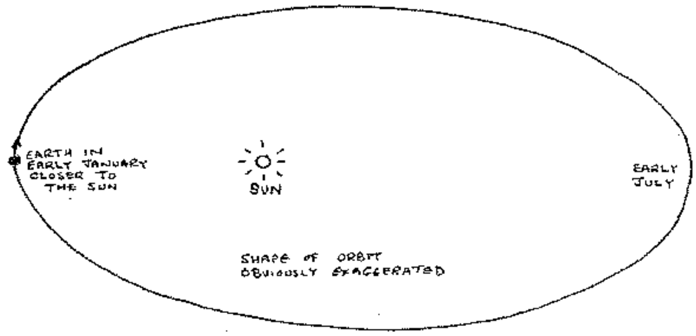
SEASONAL VARIATION

Since the Earth's axis is tilted, the sub-solar point also migrates north and south with the seasons. At our midsummer Solstice (December 22), it lies on the Tropic of Capricorn. Thereafter it moves northwards, crossing the equator on the Autumn Equinox (March 21) and reaching the Tropic of Cancer on our midwinter Solstice (June 22). Then it returns south, crossing back across the Equator during Spring Equinox (September 23). (Note – after leap years are inserted, the calendar dates of solstices and equinoxes may be a day earlier.)

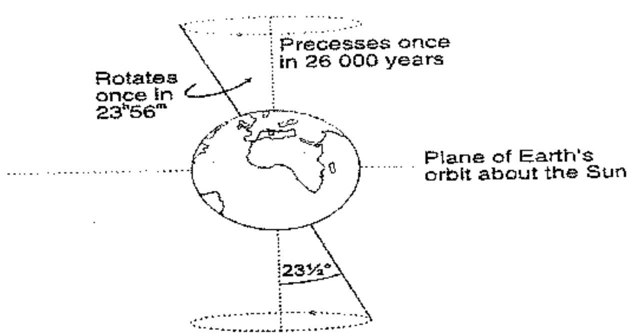




LONG TERM VARIATIONS
At present the Earth's axis is tilted by 23.5 degrees and the Tropics of Capricorn and Cancer therefore lie at latitudes 23.5 South and 23.5 North respectively. Over long periods of time (> 10000 years) the tilt of the Earth probably varies between 18 degrees (seasons much milder) and 28 degrees (Seasons much more extreme), thus there are long term effects on climate.



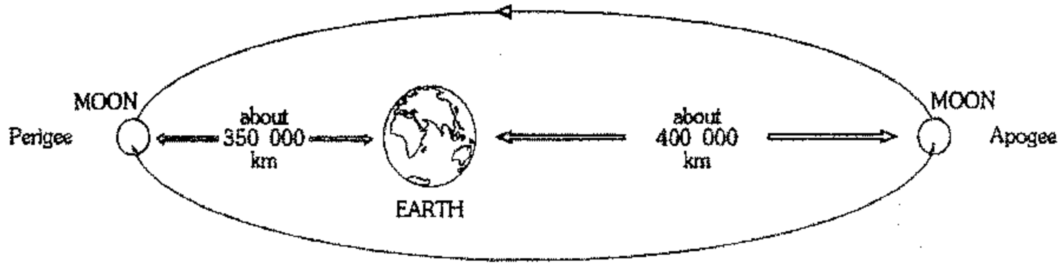
A further complication is that the Earth's orbit is slightly elliptical (see diagram). In early January, the Earth is closest to the Sun and receives 6% more insolation than in early July. Thus the southern hemisphere experiences warmer summers and cooler winters, while the northern hemisphere has cooler summers and warmer winters - but the effect is counteracted by the greater amount of ocean in the southern hemisphere.



The Earth's axis also precesses over a period of 26000 years - see diagram. Consequently in 13000 years time, it will be the northern hemisphere - not the southern hemisphere - that will have the more extreme seasons, and the effect will be exacerbated by the greater amount of land surface in the northern hemisphere. After a further 13000 years time the situation will have returned to that of the present - where our midsummer Solstice (December 22) is close to Perihelion (January 4).

Finally, there is a very long-term variation (> 100000 years) in the eccentricity of the Earth's orbit. At times it could be perfectly circular (no Perihelion or Aphelion) with uniform insolation. At other times, it eccentricity could be much greater than at present so at Perihelion, there might be more than 10% more insolation than at Aphelion.

THE MOON'S ORBIT ABOUT THE EARTH
The Moon revolves once around the Earth in 27.3d. It also rotates once in that same period, such that it keeps the same face permanently turned towards the Earth. Its orbit is quite elliptical. The closest approach of the Moon (Perigee) is about 350000 km and the furthest distance is about 400000 km (Apogee).
Relative to the stars, the Moon revolves 13.4 times around the Earth in a year. Relative to the Sun, it revolves 12.4 times (just as the Earth rotates 366.25 times relative to the stars, but 365.25 times relative to the Sun). The interval between successive New Moons is therefore 365.25/12.4 = 29.5 days - the origin of the calendar month.
Since the phases of the Moon are readily visible, they have often been used as a calendar.



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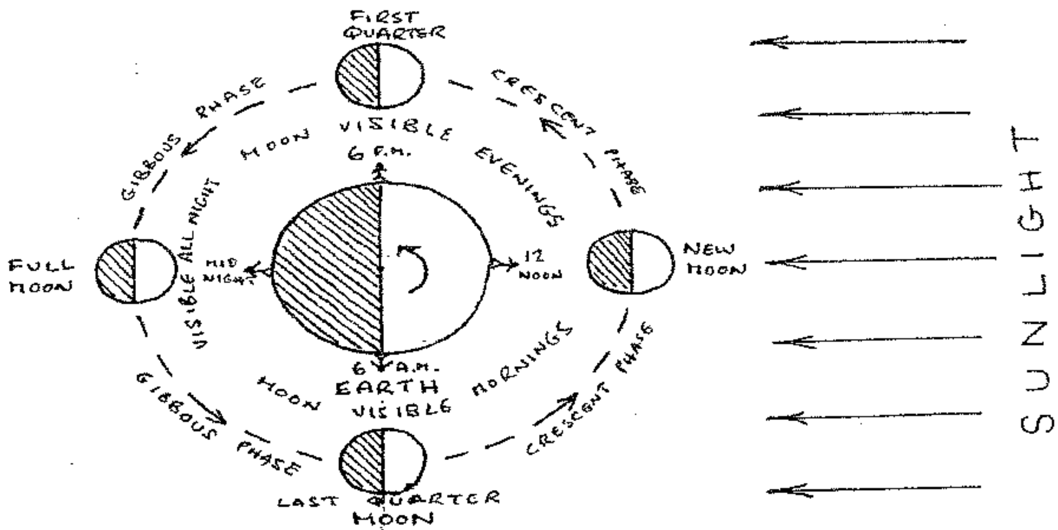
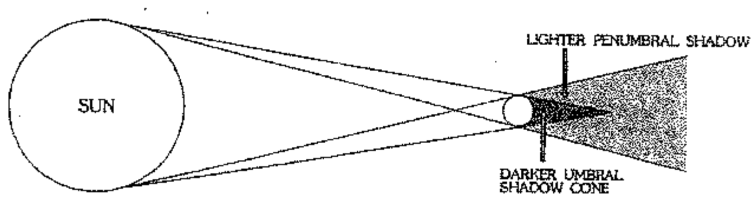


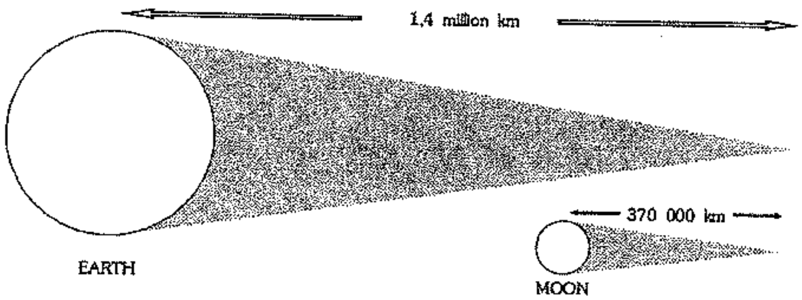
e plane of the Moons orbit around the Earth is inclined by 5 degrees to the plane of the Earth's orbit around the Sun - the intersection of the planes is known as the 'line of nodes'. When the line of nodes is close to the New Moon - Full Moon axis, eclipses can occur.

ECLIPSES



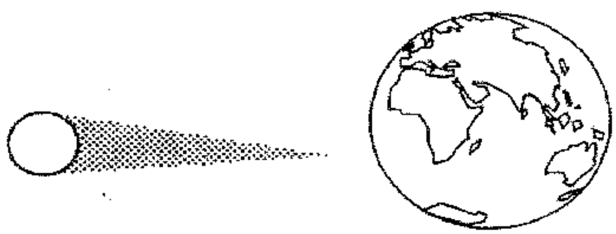
Since both the Earth and the Moon are illuminated by the Sun, they must cast shadows. When we experience night time, we are effectively passing through the Earth's shadow. Both the Earth's and Moon's shadow extend into space, but since they are lost against the blackness of space, they are not readily visible like the familiar shadows we experience in everyday life.

The Sun is much larger than either Earth or Moon, so their shadows have the form suggested in the diagram.
The diagram is not to scale - in reality the Sun would be a hundred times the diameter of the Earth or four hundred times the diameter of the Moon, the separation would be much greater and the umbral shadow cone much longer.
As seen in the diagram, there are two parts to the shadow - umbra and penumbra. The penumbra is the lighter shadow. An observer in a spacecraft that flew into the penumbral shadow would see the Sun only partially obscured. Towards the outer edge of the penumbral shadow, little obscuration would occur, whilc. towards the umbral cone, obscuration would increase and the shadow would deepen. If our observer flew into the umbral cone, the Sun would be totally obscured. Thus the umbral cone is the shadow proper - from where the Sun is completely hidden.
The next diagram indicates length of umbral shadow cones. The Earth and Moon are shown at their correct relative sizes, but if drawn to scale the shadow cones would be much longer.

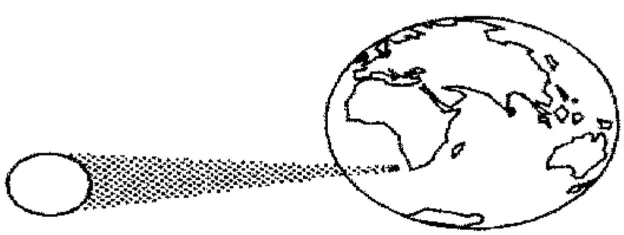


The figure above also suggests that the Moon could be completely immersed in the Earth's umbral shadow. This is what happens during a total eclipse of the Moon. The Moon can take up to a couple of hours to pass through the Earth's umbral cone. One might expect the eclipsed Moon to be in complete darkness, but usually it is still slightly visible - with a dull reddish hue - due to a small amount of light refracted by the Earth's atmosphere into the umbral cone.
A partial eclipse of the Moon is when only a portion of the Moon's disk is immersed in the umbral shadow.
'Penumbral eclipses' are when the Moon passes through the Earth's penumbral shadow, but the decrease in the Moon's brightness is not even perceptible to the eye.

While the Moon can be completely immersed in the Earth's shadow, the opposite is not the case, since the Moon is much smaller and its shadow cone much shorter. Quite remarkably, the length of the umbral shadow cone of the Moon is about equal to the Earth-Moon distance. This is the same as saying that the size of the Moon appears in the sky is the same as the size the Sun appears. Of course, the Sun is enormous compared to the Moon; its diameter is about four hundred times greater, but it is also four hundred times further away. So the angles the Sun's and Moon's disk subtend are virtually equal.

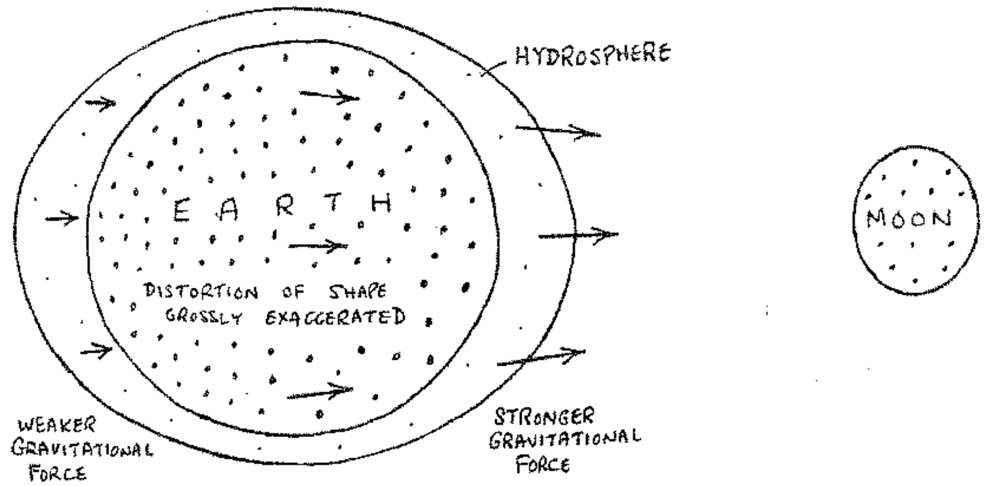


The Earth-Moon distance varies between Perigee and Apogee. The Moon's umbral shadow is longer than the perigee distance but shorter than the apogee distance. If the Moon were to eclipse the Sun when it was near its furthest distance, the umbral shadow cone would not quite reach Earth - so no total eclipse would be seen from Earth. Instead, observers on line with the Sun-moon axis would see the disk of the Moon to be smaller than the disk of the Sun. Thus the disk of the Moon would not manage to completely cover the Sun and a bright ring would be left. This is called an annular eclipse (from annulus, a ring). Since the Sun's disk is not totally covered, the sky would not darken so much and the Sun's corona (see later) could not be seen. Such an annular eclipse did occur in Cape Town in 1963.
When the Moon is not near its further distance, the umbral shadow cone just manages to reach the Earth during an eclipse. Since the cone is so close to its point of convergence, all the shadow amounts to is a small dark spot - usually around 100 km across - on the Earth's surface.



This is what makes a total eclipse of the Sun so special: it can only be seen from a very restricted area on Earth. An observer must be positioned within the small dark umbral spot in order to see the Sun totally obscured. Immediately outside that spot, the Sun would not be completely obscured (it is partially eclipsed). However, the Moon's orbital motion makes the spot move across the face of the Earth. Even so, the area traced out by the spot is minimal, and an observer at a fixed location on Earth would only see a total eclipse of the Sun on an average of once every several hundred years!
Total eclipse tracks have crossed Southern Africa in 1940, 2001 and 2002. In 1992 and 1994, the paths of total eclipses passed just south of the subcontinent.

TIDES



Due to their close proximity, the Earth and the Moon exert strong gravitational forces on each other. As shown in the diagram, the Moon's gravitational force on the Earth is greatest in the portion of the Earth closest to it, less at the centre of the Earth, and less still on the portion of the Earth furthest from it. Thus the Moon attempts to pull that part closest to it away from the centre of the Earth. In the same way, it pulls the centre of the Earth away from that portion of the Earth furthest from it. Thus the moon attempts to stretch the Earth - the 'solid' body responds only slightly, but the liquid hydrosphere deforms to create tidal bulges on the side of the Earth closest to the Moon, and on the side of the Earth furthest from the Moon.

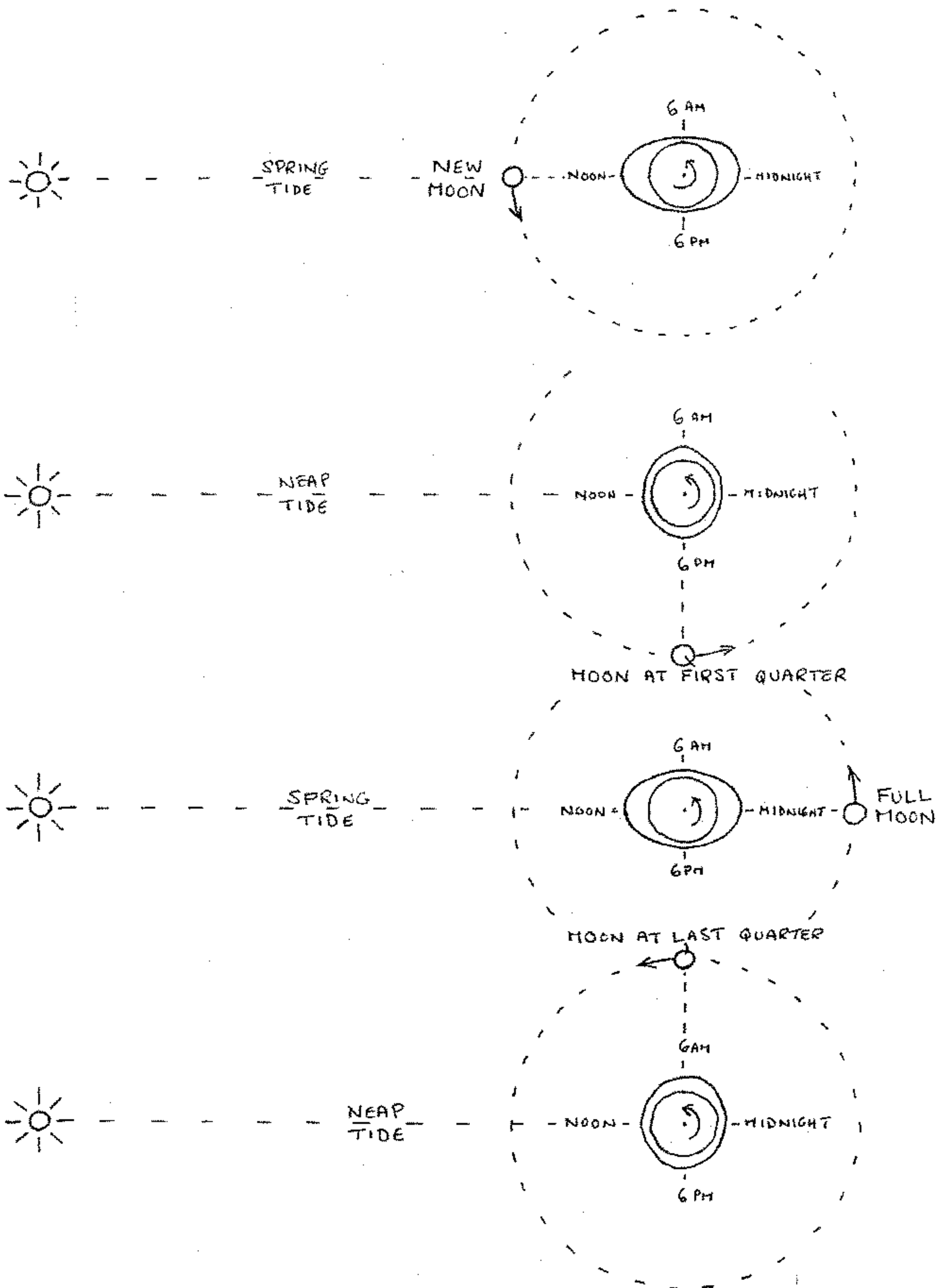
The Sun has a similar but smaller tidal effect on the Earth. At New Moon and Full Moon, the tidal effects of Sun and Moon are combined to form the extreme spring tides, (High tides around Midnight and Midday) when at First and Last Quarter, they act against each other to form neap tides (Low tides around Midnight and Midday) (see diagram on next page).

Aside from this, the Moon's distance from Earth varies. When it is closest, its tidal effect is much stronger than when it is further away.

LONG TERM EFFECTS

Tides exert a drag on the Earth's rotation. Thus the rotation period of the Earth is increasing - enough that our uniform time system has to have a 'leap second' added about once in two years. Thus angular momentum lost by the Earth is transferred to the Moon, such that the Earth-Moon distance is gradually increasing. Eventually the Moon will take 40d (present Earth days) to go once around the Earth and the Earth will rotate once in 40d. Thus one side of the Earth will be turned permanently towards the Moon, the other side permanently away.

The tidal drag on the Moon's rotation would have been very much greater - thus the Moon has long ago reached the situation where it turns one side permanently to the earth, one side away.


SPRING TIDE
NEW MOON
NOON
MIDNIGHT
6 AM
6 PM
NEAP TIDE
NOON
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6 AM
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MOON AT FIRST QUARTER
SPRING TIDE
NOON
MIDNIGHT
6 AM
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FULL MOON
MOON AT LAST QUARTER
NEAP TIDE
NOON
MIDNIGHT
6AM
6 PM