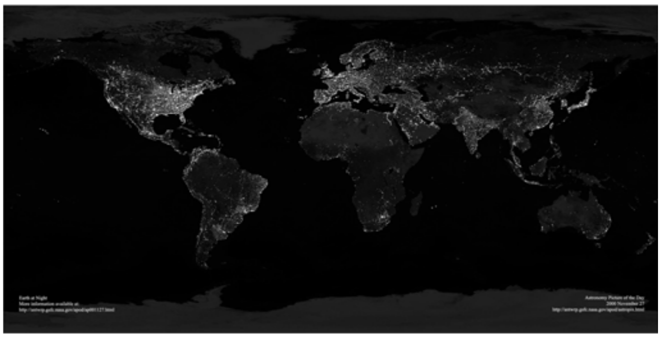
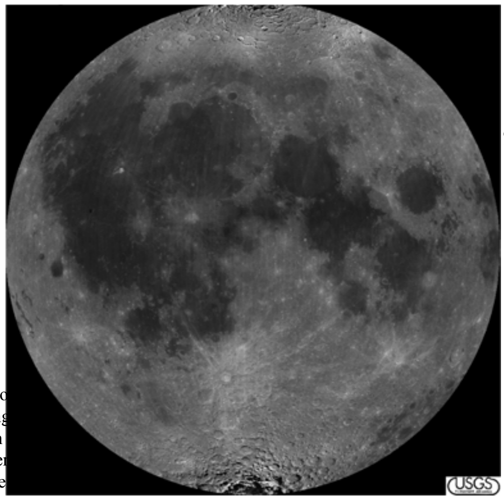
Earth – Moon system



❖



The Moo
showing
variation
albedo over
surface

The Size of the Earth

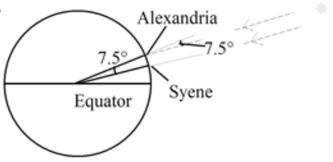
❖ Eratosthenes (276 – 195 BC) measured the size of the Earth using an astronomical technique

❖ He measured how many degrees in latitude Alexandria was north of Syene by the different height of the Sun in the sky at midday **and** how far north Alexandria was in distance. [See over]→

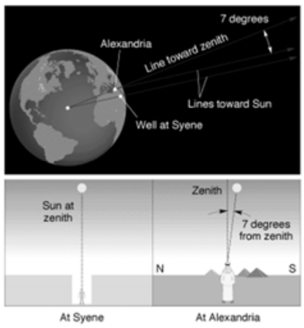
$7.5° = 5000$ *stadia*

$360° = 48 \times 5000$ *stadia*

$\therefore$ *diameter* $= 15{,}300$ *km*



Measuring the circumference of the Earth



Eratosthenes' measurement

Acetate 74 (Figure 6-1)

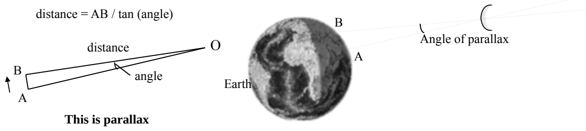
Courtesy: K & K

Distance to the Moon

❖ *Parallax* is the change in the direction of view as your observation position moves

For small angles:-

distance = AB / tan (angle)



This is parallax

Ancient Greek values: AB = 2000 km

angle = 0.33°

distance = 350,000 km

Modern value: 376,000 km

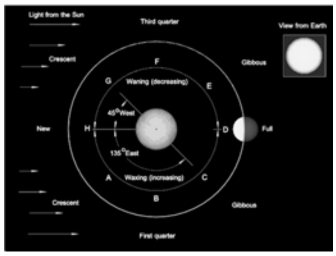
~ 60 times the radius of the Earth, measured from the centre of the Earth

---

Moon's Waxing & Waning

❖ Moon is lit by the Sun and viewed from the Earth. It *waxes* and *wanes*

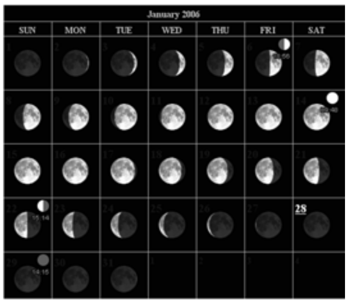
❖ Phases of the Moon: *new - crescent - first quarter - gibbous - full - gibbous ... ... new*



Animated, courtesy: K & K

Phases of the Moon

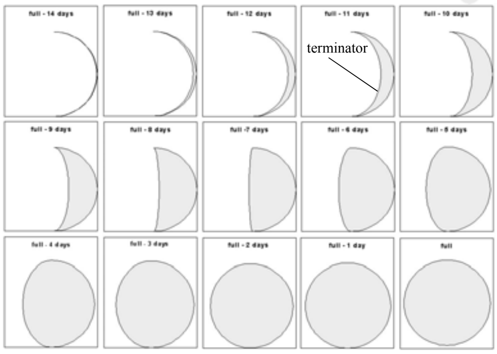
- ❖ Schematic of a lunar month
  - ✪ just chance that 2006 began with New Moon at start of year
  - ✪ tilt of Moon in sky not shown



Calculation using Sky Café applet

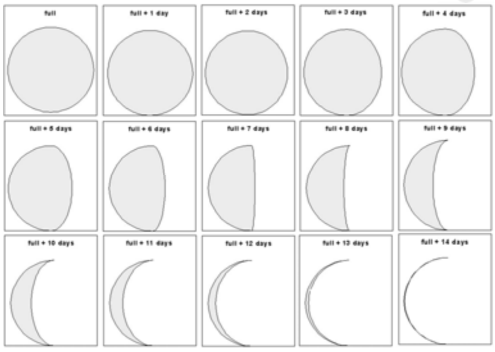
Waxing Moon

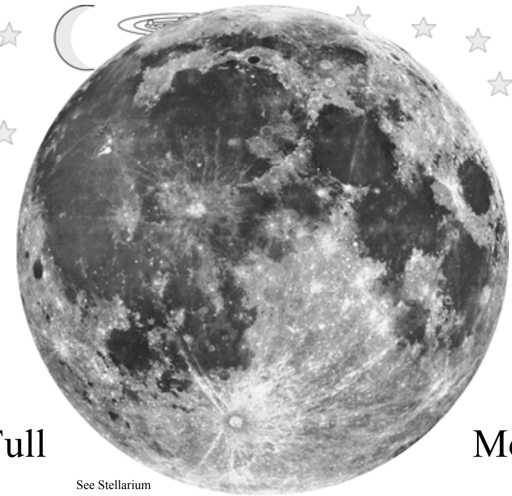
- ❖ The *terminator* is the longitude on the Moon at the edge of the shadow region
- ❖ The appearance and location of the terminator changes each day



Waning Moon

- ❖ In reality the terminator is a spectacular wavy line showing the rims and bowls of the Moon's craters



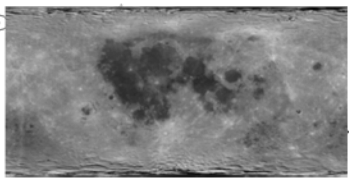


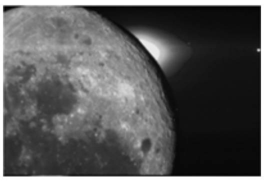
Full Moon

See Stellarium

Mercator projection of entire Moon. →

Courtesy DSPSE Clementine

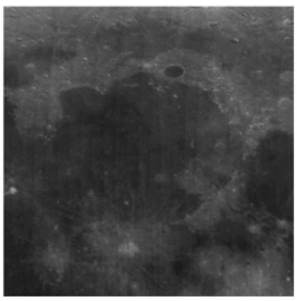


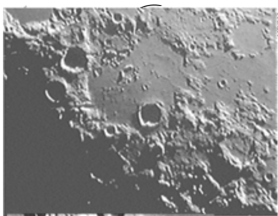


↑ Pre-dawn Earth-lit Moon with solar corona and Venus. Courtesy DSPSE Clementine

Mare Imbrium →

Courtesy DSPSE Clementine



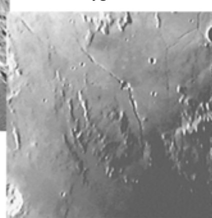


← Hipparchus

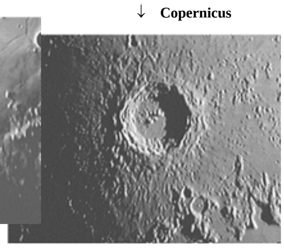
Cleomedes→

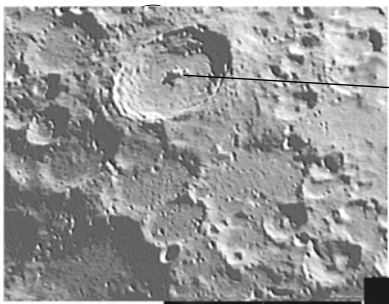
↑Alphonsus

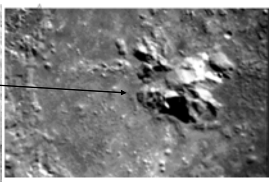
↓ Hygnius rille



↓ Copernicus





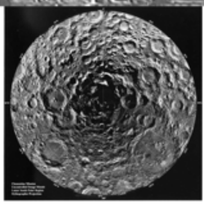


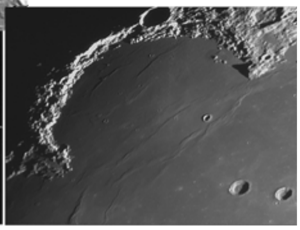
Centre of **Tycho** ↑
Courtesy DSPSE Clementine

Sinus Iridium ↓

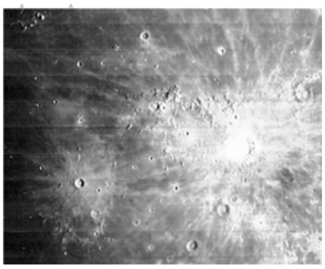
Tycho ↑

Moon's **South Pole** Courtesy DSPSE Clementine →

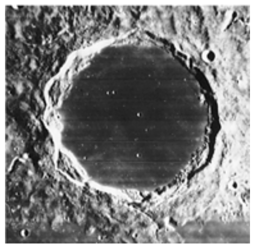




More Lunar features



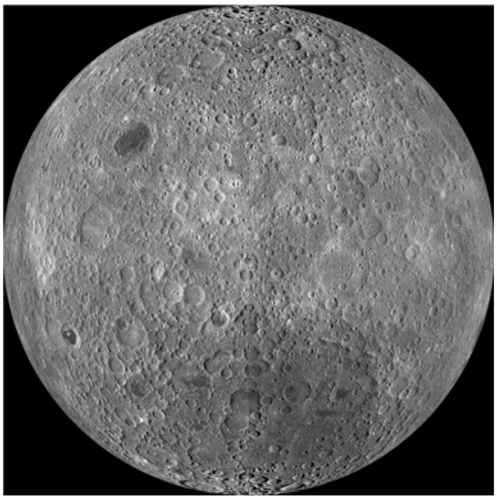
← Rayed craters **Copernicus** (right, ~110 km diam) and **Kepler** (left ~30 km diam)



The flooded crater **Plato** ~100 km diam →

Images from Digital Lunar Orbiter Photographic Atlas of the Moon

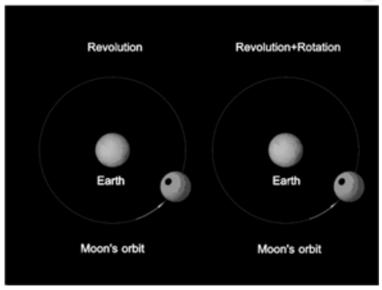
Far side of the Moon, from the **L**unar **R**econn-aissance **O**rbiter



Moon Keeps Same Face to Earth

← Full Earth from near the Moon

Courtesy DSPSE Clementine



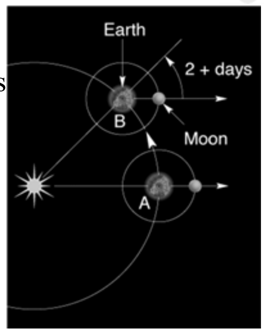
Courtesy: K & K (animated) ↑

Lunar librations

Our wobbling moon courtesy:
http://www.astro.washington.edu/balick/lunar_librations.html

Synodic Period of Moon 29.531 days

Courtesy: K & K



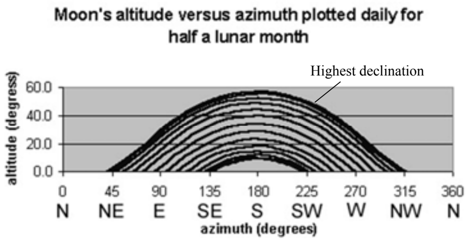
- Time between full moons is *synodic period* of 29.531 days
- Synodic month doesn't fit exactly into a year
  - the Moon's phase is 11 days different in the same month on successive years
- 19 solar years is almost 235 synodic months, a repeat period known as the *Metonic cycle*, after Meton circa 430 BC

Moon's Orbit

- ❖ Moon goes from West to East through the stars, moving about 13° per day
  - ✪ as a result, the Moon rises about 50 minutes later each day
- ❖ If the Moon's orbit were in the same plane as the Sun's apparent motion, the Moon too would go *around the ecliptic* (once in 27.322 days)

Where is the Moon in the sky?

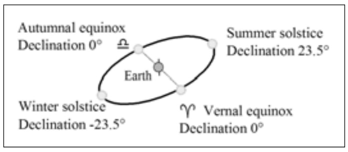
- ❖ Looking S, tracks of the Moon's position in the sky over 2 weeks at Aberdeen

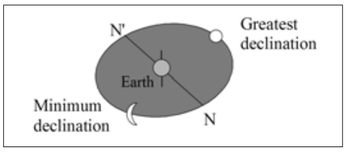


- ❖ Which track is the full moon changes through the year
- ❖ Examples: mid-summer, mid-winter, autumn equinox

Comparison of Orbits of the Sun and the Moon

- ❖ Stop the Earth spinning on its axis and the Sun would appear to go around once per year
- ❖ The Moon goes around every ~28 days
- ❖ Its range of declinations depends on the tilt of the orbit about the line of nodes NN'

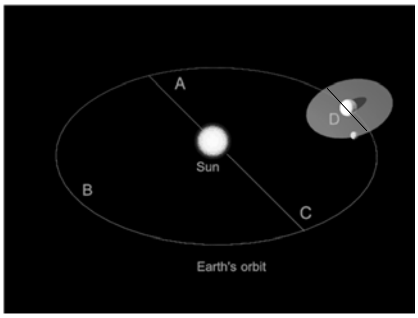




The Moon's Inclined Orbit

(animated)

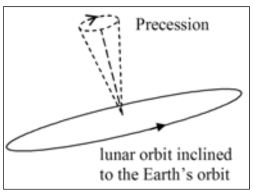
The Moon's orbit is inclined at 5.15° to the Earth's orbit



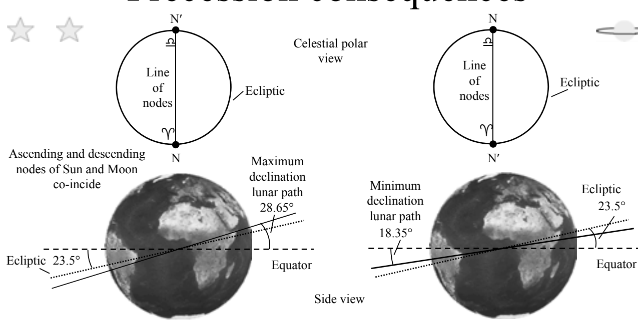
Courtesy: K & K

Precession of Moon's Orbit

- ❖ The line of nodes NN' rotates round clockwise (looking down on the Earth), going round once in 18.6 years
  - ✪ (this is over 1000 times faster than the Earth's axis precesses)
- ❖ As a result the Moon's orbit alters its tilt relative to the celestial equator by 10.3° over a time of 9.3 years
  - ✪ this is relevant to both its position in the sky and to eclipses
  - ✪ see next slide



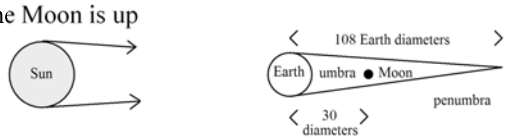
Precession consequences



- ❖ Maximum and minimum inclinations of lunar orbit in sky

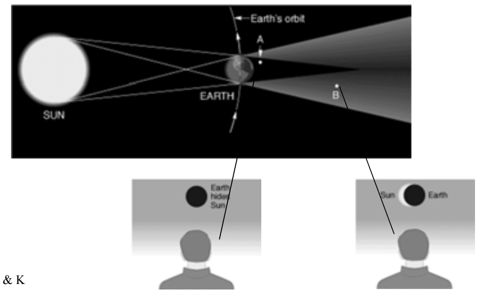
Lunar Eclipses

- ❖ Moon passes through Earth's shadow
  - ✪ eclipses always occur at full Moon [fig. over]→
  - ✪ they are visible from all points on Earth where the Moon is up



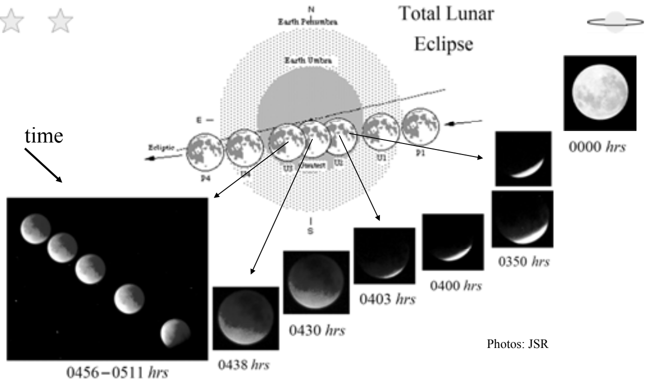
  - ✪ because of the inclination of Moon's orbit, may get *no eclipse, partial eclipse or total eclipse*
  - ✪ the maximum duration of totality is 1.8 hours

Views from behind the Earth



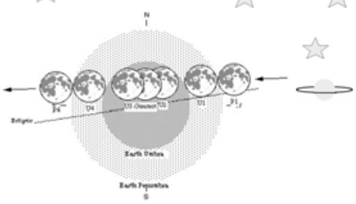
Courtesy: K & K

21st Jan 2000



Photos: JSR

9th January 2001



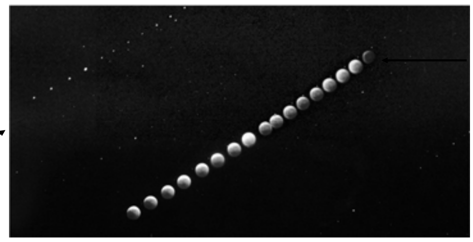
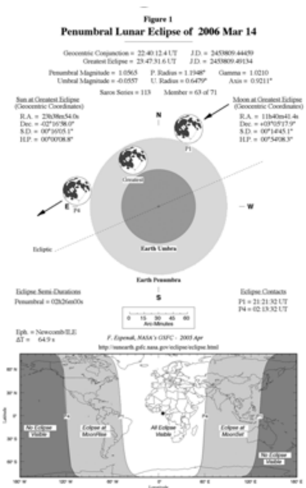


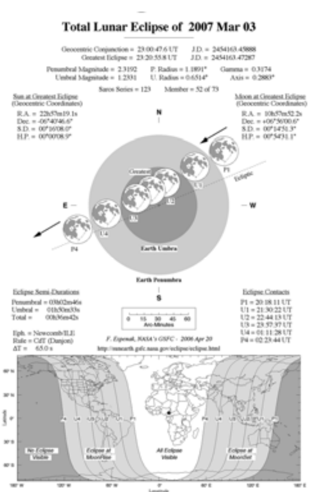
Photo: JSR



The Following Eclipses

- ❖ There was no total lunar eclipse in 2005 or 2006
- ❖ Best eclipse from here for many years: March 3rd 2007
  - ✪ see next two slides

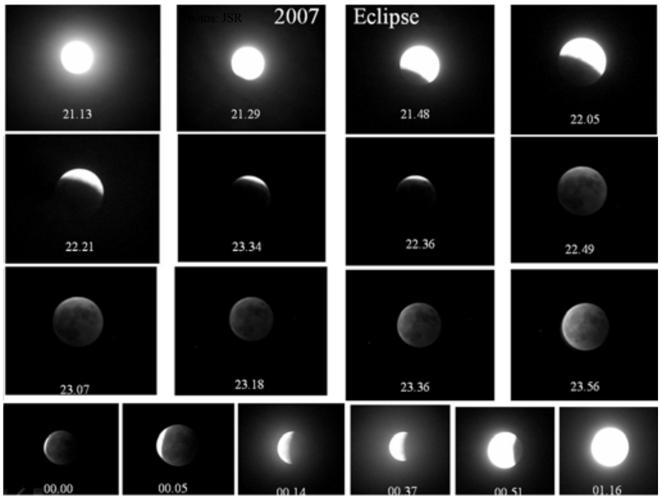
Penumbral lunar eclipse in March 2006



3rd March 2007

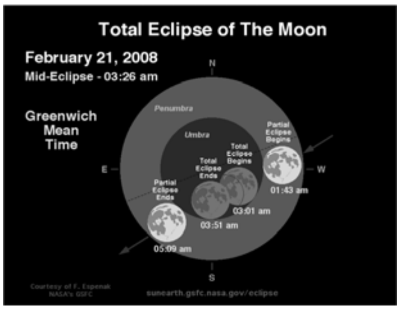
- ✪ totality lasted 73 minutes
- ✪ mid point at 23.21 hrs
- ✪ Moon high in the sky near due South

✪ http://sunearth.gsfc.nasa.gov/eclipse/OH/OH2007.html#2007Mar03T



2008 Lunar Total Eclipse

❖ Next fully visible eclipse in UK in 2015



Courtesy: http://sunearth.gsfc.nasa.gov/eclipse/LEmono/TLE2008Feb21/image/TLE2008Feb21-GMT.GIF

When do Eclipses Occur?

❖ Study the Moon's orbit and its relationship to the Sun

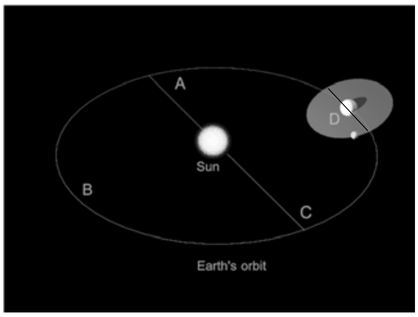
❖ The most important feature of the orbit is the direction of the line of nodes of the Moon's orbit

- ✪ the line of nodes must be pointing towards the Sun
- ✪ look again at the animation (next slide)

Second look at the Moon's inclined Orbit

(animated)

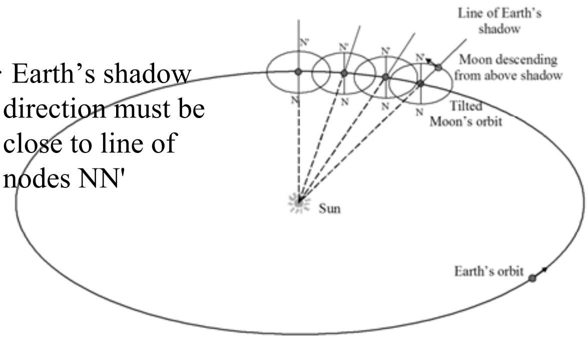
Line of nodes of Moon's orbit lies parallel to AC



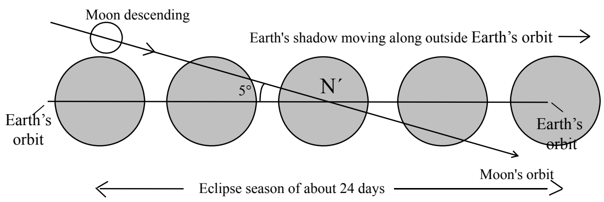
Courtesy: K & K

When do Eclipses Occur?

❖ Earth's shadow direction must be close to line of nodes NN'



The Eclipse Season

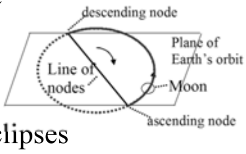


View from behind the Earth looking towards N′

The Earth's shadow is in the right position to give some sort of lunar eclipse for about 24 days

Eclipse Years

- The nodes of the Moon's orbit slowly rotate around in space in 18.6 years, against the direction of the Moon, shortening the time between eclipses



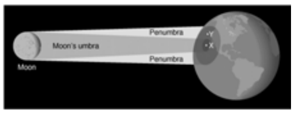
  - the eclipse year is 346.62 days, which is the time taken for the line of nodes to point again in the same direction towards the Sun
  - eclipses won't repeat with this interval because it is not exactly a whole number of synodic months

The Saros

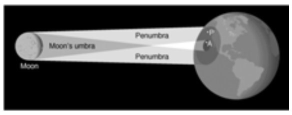
- The pattern of eclipses repeats in 223 synodic months ≅ 19 eclipse years, i.e. in 18 years 11.3 days. This period is called a **Saros** and was discovered by the ancients
  - within each Saros period there are on average 43 eclipses of the Sun and 28 of the Moon (ratio about 4:3)
  - eclipses in the same (numbered) Saros are separated by 18 years 11.3 days. They don't *precisely* repeat and over a period of ~600 years the Moon gradually moves out of the alignment needed and the Saros terminates

Solar Eclipses

- The Moon's shadow falls on the Earth
  - if the Moon is close to the Earth, then the umbra just reaches the Earth, creating an area of **total eclipse** [animation] →



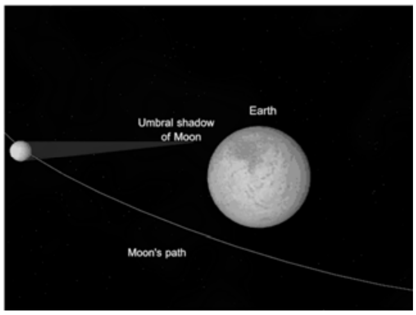
  - if the Moon is a bit further away, then it never blocks out the Sun completely and we get an **annular eclipse**



Courtesy K & K

Total Solar Eclipse

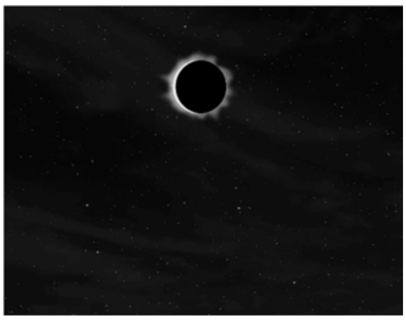
(animated)



Courtesy K & K

Simulation of Solar Eclipse

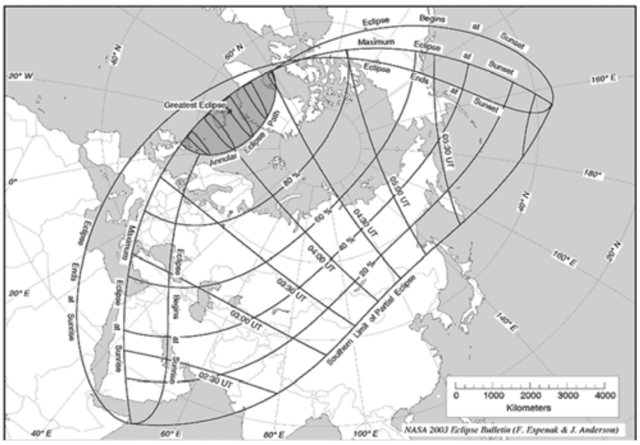
(animated)



Courtesy K & K

Annular Solar Eclipse of 2003 May 31

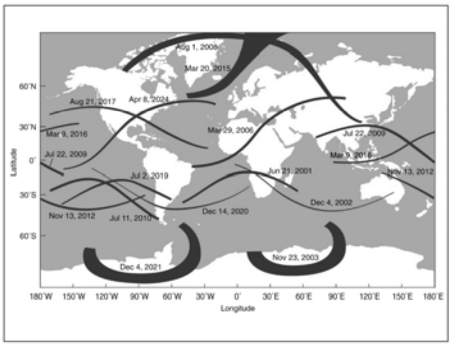
FIGURE 1.2 - STEREOGRAPHIC PROJECTION MAP OF THE ECLIPSE PATH



Eclipse Atlas

The map shows the path of the Moon's shadow during total solar eclipses for the period 2001-2025. On each path, the position of greatest eclipse is marked.

Figure 6.25

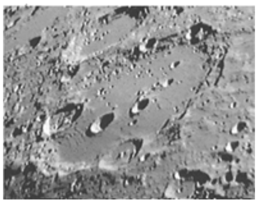


Courtesy: K & K

The Moon's Surface

- ❖ No water, no atmosphere; maria & craters
  - ✪ how do we know the Moon has no atmosphere?
- ❖ Surface is over 100°C on the equator in the sun and -100°C at night
- ❖ Back of the Moon first photographed in October 1959
- ❖ 59% visible from Earth, due to:
  - ✪ inclination of the Moon's orbit
  - ✪ elliptical nature of the Moon's orbit
  - ✪ tilt of the rotation axis by 6° to the orbital plane

The KE to Form Craters



- ❖ Kinetic energy of a modest meteorite is huge
- ❖ Consider the impact of a meteorite 1 *km* cubed

$$KE = \frac{1}{2} m v^2$$

$$mass\ (m) = density \times volume = 3000\ \text{kg m}^{-3} \times 10^9\ \text{m}^3 = 3 \times 10^{12}\ \text{kg}$$

$$velocity\ (v) = 20\ \text{km s}^{-1} = 2 \times 10^4\ \text{m s}^{-1}$$

$$KE = 6 \times 10^{20}\ \text{J} \equiv 150{,}000\ \ megatons\ \ of\ TNT$$

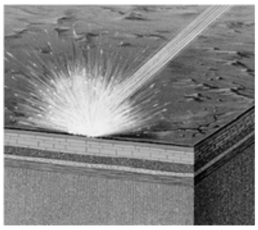
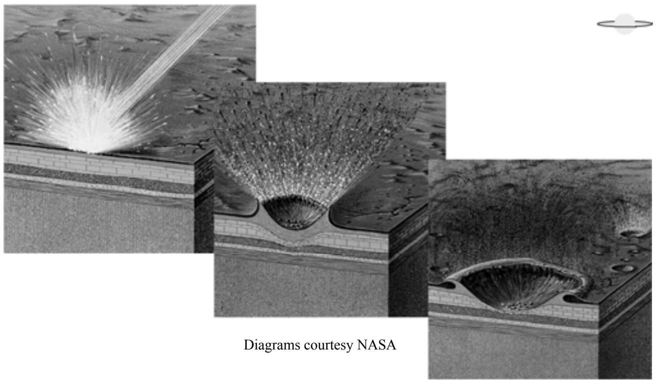


Diagram courtesy NASA

Formation of Craters



Diagrams courtesy NASA

Craters

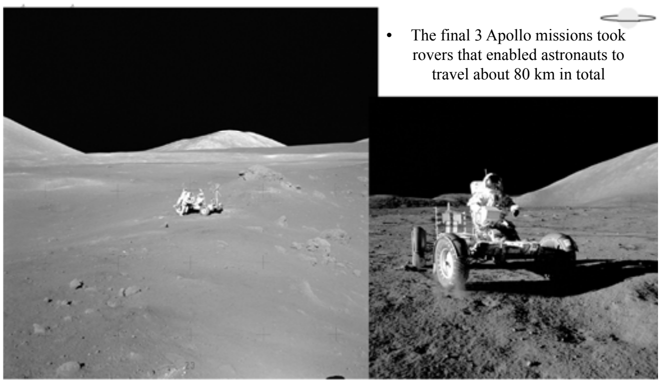
- ❖ Impacting meteorites penetrate the surface and create an explosion of material.
  - ✪ crater floors are lower than surrounding rocks
  - ✪ larger craters have small central cones
  - ✪ craters are circular whatever the impact angle
- ❖ Volcanic craters are generally raised
- ❖ Maria have been formed by large basaltic lava flows emerging from cracks
  - ✪ almost no maria on far side of Moon

Man on the Moon

Plaque on the Moon

- ❖ <u>Kennedy initiates Moon mission (animated)</u>
- ❖ <u>Historic call from surface of Moon (animated)</u>

Moon roving



- The final 3 Apollo missions took rovers that enabled astronauts to travel about 80 km in total

Digression - *space tourism*

- *You see one planet. You see how small and fragile it is against the background of the universe, and you tell yourself, wow, this is my home…..It affects your behaviour – you can't help it.*
- Anousheh Ansari spent 8 days in the International Space Station in Sept. 2006

Anousheh Ansari 2006

http://www.anoushehansari.com/

More Moon Shine

- The Moon's albedo is 0.07
  - characteristic of volcanic rock
- A quarter Moon (half circle) shines with 1/9th light of a full Moon
  - this implies a rough surface creating lots of shadows in sloping illumination
- The Moon's temperature drops by ~200K during a total lunar eclipse
  - this implies the surface is very fine dust which is a poor heat conductor
- Rangers – Lunar Orbiters – Surveyors – Luna missions

Rocks of the Moon

- Moon formed about 4.6 billion years ago
  - no primordial rocks survive in a primitive state
- 3 dominant rock types
  - dark, dense basalt of the maria
  - high melting point anorthositic rocks rich in $CaAl_2Si_2O_8$. Most of the Moon to a depth of 50 - 100 *km* is made of this
  - a scattering of low melting point KREEP norite, rich in **K** (potassium) **R**are **E**arth **E**lements and **P**hosphorous; also Uranium and Thorium

History of the Moon

- Rocks hold the clues to the Moon's evolution

1 200 *km* deep skin of molten lava

2 anorthositic crust cools at surface (1300°C)

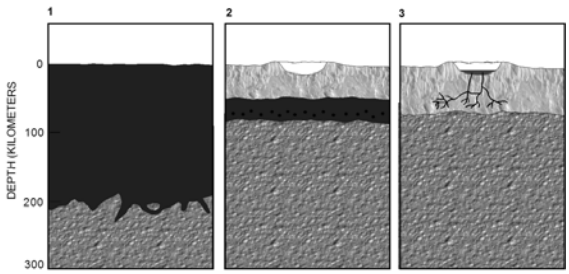
3 norites extruded through volcanic fissures

4 crashing bombardment by planetessimals

5 deeper fissures created basaltic lava flows for up to 1 billion years

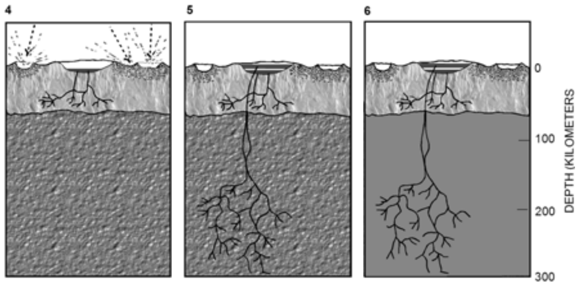
6 quiescent phase as moon cools and solidifies over past 3 billion years

Evolution stages 1 - 3



Molten surface | Crust solidifies | KREEP norites

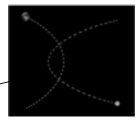
Evolution stages 4 - 6



Bombardment | Maria formed | Quiescent cooling

Origin of the Moon

- Double planet theory
- Fission hypothesis
- Capture theory
- Aggregation of circulating matter
- Large impact theory – 'the big splat'
  - current front runner
  - collision between young Earth and a body about 1/10th its mass resulted in a bigger Earth and fragment(s) that became the Moon
    - spot the mistakes in the animation



(animated)

Courtesy K & K

(animated)

More on the Impact Theory

- The idea takes on board that the Moon's rocks are similar to those of the Earth's crust but not the same, and are notably free of water
- Working back in time from the Moon's tidal drift, the Moon's position 4.6 billion years ago was only ~20,000 km from the Earth
  - the Earth was rotating once every 4 hours
- Towards the end of the aggregation period of formation of the solar system, large planetessimals would have been present in some numbers
- The main difficulty is why ejected material went into orbit and didn't fall back or escape?
  - a substantial amount of ejected material could have been vapour
  - both Earth and early Moon would have glowed red hot or even white hot