

Gravity and the Rise of Modern Astronomy

Galileo Galilei 1564 - 1642 Isaac Newton 1642 - 1727

Galileo's telescopes

- * Galileo was an academic
- * He made telescopes to his own optical design

Galilean telescopes on display in the Institute & Museum of the History of Science, Florence. Photos JSR, courtesy IMSS

Galileo (1564 - 1642)

- * First to direct a telescope at the night sky and report the results
 - saw the mountains and craters on the moon
 - discovered 4 moons of Jupiter
 - discovered sunspots
 - saw thousands more stars
 - observed complete set of phases of Venus →
- * 1610 published *Siderius Nuncius*

Ptolemaic View of Venus's Phases

Courtesy: K & K Fig. 3-5 (animated)

Copernican View of Venus's Phases

Courtesy: K & K Fig. 3-6 (animated)

Galileo's Problems

Photo: JSR

Frieze depicting Galileo demonstrating his telescope. Photo: JSR

- * Admonished in 1616 under Papal orders not to 'hold, teach or defend' his cosmology

Galileo's finger in the Institute & Museum of the History of Science, Florence. Photo JSR, courtesy IMSS



Galileo and the Inquisition

Pannini's painting of the prison of the Inquisition.
Photo JSR, courtesy: NTS

* In 1632 published *Dialogo sopra i due Massimi Sistemi del Mondo*

❖ this lead to a 'rigorous examination' by the Inquisition. Alleged to have said after his recantation 'E pur si muove'



Galileo & Mechanics

Galileo's apparatus for experiments on falling bodies in the Institute & Museum of the History of Science, Florence. Photo JSR, courtesy IMSS

* In 1638 published *Discorsi intorno a due Nuove Scienze* summarising his investigations and thoughts on mechanics



Galileo's Legacy

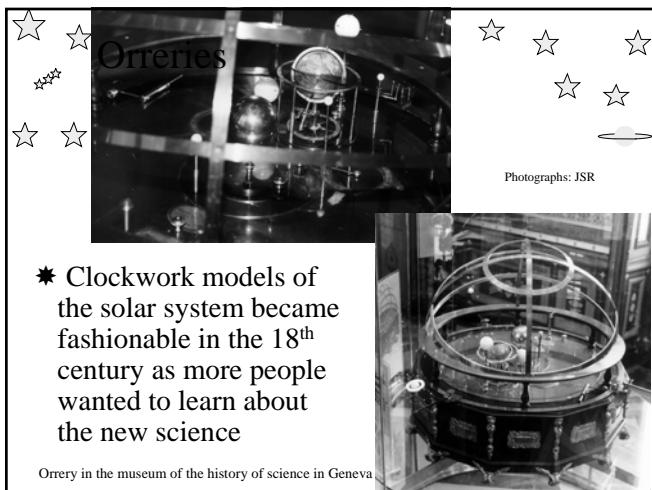


* The telescope as an astronomical tool
* Knowledge advances through observation and interpretation

Galileo's tomb in Santa Croce, Florence. Photo: ajr

Isaac Newton (1642 - 1727)

* Concept of universal gravitation, an attractive force between all masses, and the law it obeyed
* Three mathematical 'Laws of Motion' that allow the behaviour of all mechanical systems to be predicted
* Designed first useful reflecting telescope
* Discovered that white light could be spread out into its spectral components



* Clockwork models of the solar system became fashionable in the 18th century as more people wanted to learn about the new science

Orrery in the museum of the history of science in Geneva

Newton's Laws of Motion

* 1) An object will move at constant speed in a straight line if no force is acting on it
* 2) A force on a body accelerates it, the acceleration being inversely proportional to the body's mass. $F = ma$. Force is measured in *Newtons*, mass in *kg*, acceleration in ms^{-2}
* 3) If something exerts a force on a body, the body exerts back an equal and opposite force

Illustrating Newton's 1st Law

Motion of whirling rock when string breaks

Fig 3-10 (animated)

Courtesy: K & K

Universal Gravitation

- * Every little bit of mass in the Universe attracts every other bit with a force
- * The force of attraction between two masses m_1 and m_2 is proportional to the product of the masses and the inverse square of the distance d between them

$$F = G \frac{m_1 m_2}{d^2}, G = 6.67 \times 10^{-11} \text{ m}^3 \text{kg}^{-1} \text{s}^{-2}$$

- * a sphere attracts like a point mass located at its centre

How Strong is Gravity?

- * Attraction between you and your neighbour
↳ ~1 μN
- * Between you and the Earth
↳ ~500 – 1000 N
↳ 25% of our weight comes from the attraction between us and the hemisphere furthest from us
- * Between you and the Sun
↳ ~ 0.3 N
↳ this force keeps us in orbit around the Sun
- * Between Earth and Sun
↳ ~ 10^{22} N

Effects of Gravity

- * On the surface of a planet or moon, the gravitational force on a body is called its weight
- * weight is a force, hence is measured in Newtons

$$W = mg = m \frac{Gm_{\text{earth}}}{r_{\text{earth}}^2}$$

- * Gravity doesn't stop, it just fades away
- * Gravity controls not only the solar system but the large scale structure of the universe

Gravity elsewhere

- * The gravitational constant g on the Moon is only 1/6th of its value on Earth
 - ↳ Moon is 1.2% as massive as the Earth
 - ↳ radius of Moon is 0.27 times radius of Earth
 - ↳ result: lunar surface gravity 1/6th of Earth's
- * Earth has strongest gravity of anywhere you could stand in the solar system

Orbiting bodies

- * Two isolated bodies will orbit around their common **centre of mass**

Fig 3-14 (animated)

Courtesy: K & K

Tides

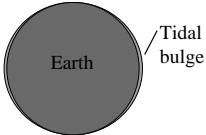
- * Tides are obvious in the sea but also occur in the earth
- * Tides affect moons that are close to their parent bodies
- * Close binary stars will also raise tidal bulges on each other
- * Matter is ripped apart by tidal forces close to the event-horizon of a black hole
- * artist's impression of a white dwarf pulling matter from a normal star in orbit around it to create an accretion disk





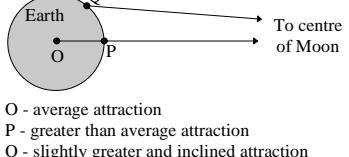
Underlying Cause of our Tides

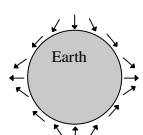
- * **Attraction of the Sun and Moon on the Earth varies over the Earth**
 - * the average attraction is responsible for the orbit of the Earth
 - * the **difference in attraction** on different parts of the Earth raises the tides
- * The tidal bulge moves around the Earth because
 - * the Earth rotates on its axis
 - * relative to the Earth, the Sun & Moon move around



Variation of Attraction of the Moon

- * A spherical body (e.g. the Moon) exerts a gravitational attraction towards its centre
 - * the Moon exerts this attraction on all points of the Earth

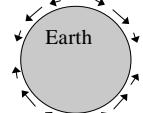




Difference between actual attraction and average attraction

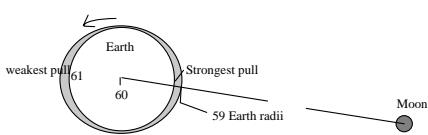
Tidal Forces Caused by Moon

- * In general the tidal forces are partly vertical and partly horizontal
 - * the horizontal components, shown in the sketch, are the basic cause of the tides
 - * the vertical components simply add or subtract a little to gravity
- * The tide affects the oceans most but there is also an Earth tide of about 0.3 m in height



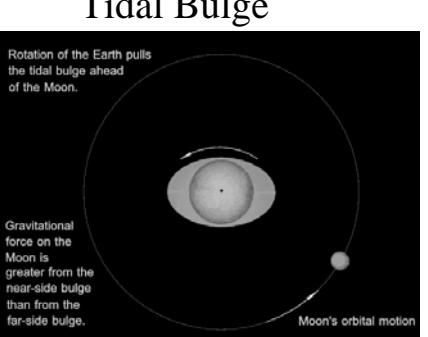
Consequences of the Double Tidal Bulge

- * Two high tides per 24 hrs 50 mins
- * Because of the friction between water and land, the tidal bulge occurs ahead of the direct line to the Moon (i.e. further East)



Earth's Rotation Affecting Tidal Bulge





Courtesy: K & K

Combined Effects of Sun & Moon

- * The Sun also causes tides, about 45% of the height of the Moon induced tides

*** Spring tides**
⊕ effects add

*** Neap tides**
⊖ effects reduce

A Digression

Photo: JSR

Effects of the Tides

- * Two high tides per 24 hrs 50 mins
- * Tidal component caused by the Sun, resulting in spring and neap tides according as the effect of the Sun adds to that of the Moon or not
- * The Earth's rotation period is slowing, giving the Moon more energy. The Moon is receding. Eventually, a day will be as long as a lunar month, which will then be about 60 of our present days
- * This is not the end of the story!

Precession of Earth's axis

- * The Earth's axis precesses in space (i.e. slowly rolls around) once in ~26,000 years. The equinoxes move round the ecliptic
- ⊕ this has an indirect effect on the climate

Courtesy: K & K
(animated)

Precession of the Ecliptic

- * The Earth's orbit is fixed in space and the equator tilt varies because of the precession
- * But we use the (celestial) equator as a reference to define the positions of stars
- * Hence relative to our view from Earth, it is the ecliptic that precesses
- ⊕ this precession is usually described by saying that the "line of nodes" precesses

Lagrangian Points

Joseph-Louis Lagrange 1736 - 1813

- * Points associated with Sun & Earth that rotate around the Sun with the same period as the Earth

Einstein's contribution

- * The current 'last word' on gravity is Einstein's General Theory of Relativity
- * It predicts non-Newtonian effects that have all been observed
 - ❖ precession of the orbit of Mercury
 - ❖ light deflected by stars
 - ❖ lens-like imaging of light from distant galaxies by the gravity of intermediate matter
 - ❖ 'microlensing' of distant stars by intermediate (dark) matter

Courtesy
NASA HST

Reflection

- * Astronomy is about human understanding of the universe

← Virgo cluster, the centre of our local supercluster, courtesy
<http://www.seds.org/messier/more/virgo.html>

Cosmic microwave background, courtesy
NASA/WMAP Science Team →