

# 1 Lecture 4 and 5: Planetary Motion/Newton's Laws of Motion

- Read chapter 2 in the textbook
- Exercises: Do all “Review and Discussion” and all “Conceptual Self-Test”; Problems 1), 6), 10)
- *\*most quantitative lecture in the course*

## 1.1 Early beginnings

- ancient peoples observed the sky carefully
- mysterious – religious significance – constellations and stories
- practical reasons – agricultural concerns: planting season, flooding season, navigation etc.
- ancients “noticed” the stars more than lay-people do today – no light pollution!
- ancients built structures to follow objects in the sky – stonehenge, etc.
- cosmology – stories about creation, stories about the reasons for motion – not science

## 1.2 Geocentric Universe

- obvious – everything goes around the earth
- cannot feel the earth move
- movements of the visible planets seemed strange, but still appear to go around the earth (ultimately these strange motions would lead to a whole new way of looking at our place in the Universe)
- planet – from the Greek for wander
- planets wander in the sky – they stay close to the ecliptic plane (move through the Zodiac) and generally move in the same direction as the sun, west to east, but sometimes they reverse direction – called retrograde motion
- Plato, Aristotle 300's BCE – everything goes around the earth in a perfect circle, stars fixed to the celestial sphere
- Ptolemy circa 140 CE presents complete model in the Almagest, based on earlier ideas but with modifications

- Ptolemy’s model had circles on circles (deferents and epicycles) to explain retrograde motion of the planets
- DIAGRAM OF EPICYCLES
- epicycles of Venus and Mercury stay in front of the sun
- epicycles of other planets (Mars, Jupiter, Saturn) move independently from the sun on their own deferent
- model worked!
- predictions matched quite well with observations
- as people made more careful observations, the model required modification – more epicycles (epicycles on epicycles)
- model became more and more complicated as more and more data came in
- suggests something is wrong. . .

### 1.3 The heliocentric model begins

- 1500’s Nicolaus Copernicus suggests a heliocentric Universe
- he reasoned that only the moon goes around the earth
- he reasoned that the stars must be much farther away than the earth-sun distance – reason for no observed parallax of stars
- he reasoned that the earth rotates, explaining the daily motion of the sky
- he reasoned that retrograde motion of the planets as relative motion with the earth’s orbit
- organized his ideas into seven points (see textbook)
- kept the idea of perfect circles and therefore still required epicycles to get observations correct
- model, predictive and matched observation, but model did not improve on Ptolemy’s model and in many cases was worse
- Ptolemy’s model had the benefit of centuries of “tinkering” with epicycles
- science is hard – in this case we see how hard it is to tell which model is better!
- “human objections” – Copernican model contradicted accepted orthodoxy, his works eventually prohibited by the Roman Catholic Church

- early 1600's Galileo Galilei observed the sky with a telescope
- noticed four small objects that went around Jupiter – realized that they were moons
- evidence that at least some things in the sky do not go around the earth
- observed the sun and noticed sunspots (dark marks on the sun) – the sunspots also move in such a way that demonstrated that sun rotates
- he also observed that the moon had mountains and craters
- he also observed the phases of Venus, strongly suggesting that Venus went around the sun
- he strongly supported the Copernican model
- the Roman Catholic Church placed him under house arrest for the rest of his life in 1633 and condemned his works – not “forgiven” until 1992!
- most important contribution by Galileo Galilei – the scientific method
- he emphasized observation and empirical methods – applied mathematics to his discoveries
- the father of experimental science

#### 1.4 The heliocentric model comes into its own

- at roughly the same time that Galileo was making his discoveries – Tycho Brahe and Johannes Kepler
- Tycho Brahe made careful measurements of the stars and planets with the unaided eye
- used instruments to determine angular size and location of celestial objects – decades of observations
- Kepler inherited Tycho Brahe's works after his death
- Kepler used this data to determine the shapes of planetary orbits – many years of very hard work – resulted in three laws
- Kepler's laws
  - The orbital paths of the planets are elliptical – not circular – with the sun at one focus.
  - An imaginary line connecting the sun to any planet sweeps out equal areas in equal intervals of time.

- The square of the planet’s orbital period is proportional to the cube of its semi-major axis ( $P^2 \propto a^3$ ).
- DIAGRAM OF ELLIPSE – define eccentricity
- Kepler’s model much more accurate than Ptolemy’s geocentric model
- model makes predictions – any new object discovered orbiting the sun would have to obey these laws (which has been borne out through future observations)
- model can only determine the size of orbits relative to earth’s – Kepler had to use the earth’s orbit as a baseline – afterall, he lived on earth!
- the convenient unit of length – the earth-sun distance – the astronomical unit
- example: Kepler’s laws determine that Jupiter has a semimajor axis of 5.203 AU, orbital period of 11.86 years eccentricity, 0.048 (see your text for other planets)
- Kepler could not determine the actual length of the astronomical unit
- before the middle part of the 20th century, AU determined by transit of Venus using parallax –  $1 \text{ AU} = 1.5 \times 10^8 \text{ km}$

## 1.5 The Newtonian revolution

*“I do not know what I may appear to the world, but to myself I seem to have been only like a boy playing on the sea-shore, and diverting myself in now and then finding a smoother pebble or a prettier shell than ordinary, whilst the great ocean of truth lay all undiscovered before me.”* — Issac Netwon

- one of the three (four) greatest mathematical/scientific minds in humanity – Archimedes, Newton, Gauss, (Witten)
- born 1642 (the same year Galileo died)
- studied at Trinity College Cambridge – sent home because of the plague
- in his early twenties he invented calculus, developed the laws of motion (Newtonian mechanics), developed a theory of gravity, explained Kepler’s laws from first principles, and explained the tides!
- prompted by Edmund Halley (of Halley’s comet), Newton published his findings in 1687 – *Philosophiae Naturalis Principia Mathematica*
- certainly the most influential book in science ever written – maybe most influential book in history
- changed the way we look at the world – opened the way for modern physics

- Three laws of motion:
  - Every body continues to stay at rest or stay in a state of uniform motion in a straight line, unless it is compelled to change by a force acting on it.
  - When a force  $F$  acts on a body of mass  $m$ , it produces in it an acceleration equal to the force divided by the mass.  $F = ma$
  - To every action, there is an equal and opposite reaction.
- Newton's First Law
  - goes against common sense – ancients though the rule was everything wants to be a rest with respect to the earth
  - the tendency for objects to keep moving at the same speed and in the same direction (velocity), keep doing what they are doing, is the property of inertia – measure of inertia is mass
  - the more inertia (the more mass) the more “influence” required to making the object change its velocity
  - mass measured in kilograms – weight  $\neq$  mass
  - the rate of change of velocity called acceleration – does not just mean to speed up
  - acceleration – change in direction and/or speed – measured in  $m/s^2$
- Newton's Second Law
  - acceleration requires an influence – force
  - force causes acceleration
  - force = Mass  $\times$  Acceleration
  - force measured in Newton's
  - weight is force – pounds  $\leftrightarrow$  Newton's – 1 Newton = 0.22 pounds
  - mass does not change where you are – your weight less on the moon, but your mass is the same! – remember mass is a measure of inertia
- Newton's Third Law
  - can't touch without being touched
  - if you push on something with a force,  $F$ , it pushes back on you with the same force
  - imagine standing on an ice rink on skates holding a basketball – now throw the ball
  - throwing the ball means you exerted a force on the ball, but the Third Law tells us that the ball pushes you with the same force – you move back

- your acceleration is less than the ball because you have more mass – but the force is the same!
- Energy
  - actually an abstract concept – requires a bit of effort to understand
  - subtle idea connected to the ability to cause things to move or change – the ability to do Work
  - $\text{Work} = \text{Force} \times \text{Distance}$ , where Distance is along the direction of the Force
  - stored energy – potential energy – has the potential to do work. Example: a stretched spring – the spring has the ability to do work if we let it go
  - energy of motion – kinetic energy – the object has the ability to do work on another object by hitting it
  - energy can be transferred between systems – Work done on one system by another
  - Heat is a form of energy – can transfer heat energy into mechanical energy and vice-versa: braking a car heats the brake pads (kinetic energy of the car goes into heat); hot gases expanding inside a car's engine and drives the pistons (heat to mechanical) – thermodynamics, gem of 19th century physics
  - energy is conserved in all process if you follow all its forms through the systems – heat, mechanical, etc.
  - energy not created or destroyed – conservation of energy (connected to symmetries in nature, powerful mathematical methods in modern physics)

## 1.6 Gravity

- Newton realized that the same force that holds you on the ground is the same force that holds the moon and the planets in their orbits – not a trivial thing
- Galileo realized – by observation – that all things fall with the same acceleration regardless of mass (10 tonne boulder and 5 kg bowling ball dropped from the CN Tower would hit the ground at the same time – any discrepancy is the result of air resistance)
- SHOW APOLLO 15 MOVIE CDR David Scott
- remember weight and mass are not the same thing
- gravity is universal – all mass feels it the same way, not important what the material is
- every particle of matter attracts every other particle with a force that is directly proportional to the product of the masses and inversely proportional to the square of the distance between them:

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$$F_g = G_N \frac{M_1 \times M_2}{r^2}$$

- the acceleration due to gravity on the earth's surface is  $9.8\text{m/s}^2$
- recall that acceleration means change in velocity – direction and/or speed
- things going in a circle at a constant speed are accelerating – direction constantly changing
- force required to maintain circular motion – gravity does this for planets and the moon – Newton's laws!
- when in freefall it appears that gravity is “shut off”
- imagine being in an elevator in a tall building and the cable snaps – don't imagine the impact!
- ELEVATOR DIAGRAM
- everything in the elevator falls with you with the same acceleration  $9.8\text{m/s}^2$  – including the elevator itself
- you experience “weightlessness”!
- in the elevator case, the motion is linear down the shaft
- BUT, the same argument applies to everyone in freefall, including those falling “around” the earth
- CANNONBALL DIAGRAM
- astronauts are weightless not because gravity is weak where the space shuttle orbit, but because they are in freefall!
- DIAGRAM OF FREEFALL
- acceleration due to gravity at the shuttle's altitude is about  $9.5\text{m/s}^2$  – not weak at all
- read **More Precisely 2-2** carefully – don't worry about the mathematical details
- planetary motion can now be understood properly
- Kepler's laws follow directly from Newton's laws of motion – terrestrial observations led to understanding the physical universe
- example of the scientific method – Kepler's laws arise from more fundamental principles: Newton's law's and Newton's law of gravity

- Kepler's laws contained inside Newton's laws – consistency
- Newton's laws make more predictions and has a wider range of applicability
- does NOT take energy (no work done) to keep something in orbit – the force is perpendicular to the motion; recall that Work requires the force to be in the same direction as the motion