The Newtonian Revolution

Outline
- New technology: Tycho Brahe
- Cosmology vs. computation
- New technology: the telescope
- Galileo Galilei: physics
- Newton
- Descartes vs. Newton

Literature
- Pannekoek
- Koestler: The Sleepwalkers (esp. chapter on Kepler)
- Westfal: Never at Rest (biography of Newton)
- Dijksterhuis: Mechanization of the World Picture (Dutch: Mechanisering van het wereldbeeld)
- lecture by Albert van Helden
Cosmology versus technical astronomy

**Cosmology**
- part of natural philosophy
- aim: describe *causes*
- basis: physics of Aristoteles:
  - mass strives toward center in sublunar world
  - circular motion in supra-lunar world
  - practitioners: universities

**Technical astronomy**
- part of mathematics
- aim: computation of planet position
- basis: methods outlined in Copernicus (before him: Ptolemaios)
- whether constructions are real is not important (annotations in *De revolutionibus* only in technical sections!)
- Brahe, Kepler: trained at universities, work mostly outside universities
New technology: Tycho Brahe 1546 – 1601

General in Europe
- improved techniques e.g. metal-working
- book printing

Tycho Brahe
- astronomical tables for planets are wrong by as much as a month
- problem for astrology...
- new, more accurate measurements
  - special observatory
  - instrument design
- observatory and instruments described in book!
New technology: Tycho Brahe

instrument design

Improved accuracy

Nova Stella 1572

Frank Verbunt (Astronomical Institute Utrecht)

The Newtonian Revolution

July 15, 2011
A new, very bright star: 1572

Observations

- Digges (Cambridge)  
  $\beta$ Cep $\leftrightarrow$ $\alpha$ Cas and  
  $\iota$ Cep $\leftrightarrow$ $\delta$ Cas

- Mästlin (Tübingen)  
  $\iota$ Cep $\leftrightarrow$ $\delta$ Cas and  
  $\beta$ Cas $\leftrightarrow$ $\lambda$ UMa

- no parallax $\leftrightarrow$ at larger distance than Moon

- comets also above moon orbit
Improved accuracy

Ptolemaios

Brahe
Improved accuracy

Ptolemaios

Accuracy Star Catalogue

- Ptolemaios FWHM $\sim 40'$
- Brahe FWHM $\sim 5'$
- Brahe individual measurements: mural quadrant $\sigma = 35''$
- 777 stars in first edition 1602
- 1004 (−12 doubles) stars in edition by Kepler 1627

Brahe
Identification of Catalogued Stars: results

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Kepler (from Linz) to Father Guldin

You ask me what I did with myself during the long siege. You ought to ask what one could do in the midst of the soldiery... The ears were constantly assailed by the noise of the cannon, the nose by evil fumes, the eye by flames. All doors had to be kept open for the soldiers who, by their comings and goings, disturbed sleep at night, and work during day time.

cited in Koestler: The Sleepwalkers
Scientific method

- struggles between medieval and modern outlook
  - ‘medieval’: Mysterium Cosmographicum: nested regular polygons
  - ‘modern’: law of areas from diminishing influence of Sun at larger distances
- modern: details should also be in order
- good mathematics
- had very difficult life
Orbit of Mars

- use observations from same point of Earth orbit
- use constant increase of angle from equant (or equivalent alternatives)
- ⇒ orbit of Mars
- oval ‘flattened circle’
- deviation: 8’
- distance Sun from center: (‘eccentricity’) 0.0926
- flattening: 0.00429
- \(0.5 \times 0.0926^2 = 0.00429\)

Ellips mathematics

\[ b = a(1 - e^2)^{1/2} \Rightarrow \frac{a - b}{a} \approx \frac{e^2}{2} \]
Laws of Kepler

1. orbit planet is ellipse, Sun in focal point
2. radius sweeps equal areas in equal time
3. period $P$, semimajor axis $a$ are related via $P^2 = \text{constant} \ a^3$; constant same for all planets

- Kepler computes horoscopes
- book on Nova Stella discusses astrological effects
Galileo Galilei 1564 – 1642: the astronomer

Invention of telescope

- made possible by improved glass
- first in Netherlands
- Galilei made his own and discovered:
  - new stars (what use?)
  - moons around Jupiter (center of motion ≠ Earth)
  - phases of Venus
  - sun spots (not perfect)
  - moon mountains (note: Jan van Eyck 1430)
- comets are atmospheric disturbance
Galileo Galilei the physicist

Experiments

- separation horizontal-vertical
- acceleration along inclined plane
- modern notation:

\[ v = gt; \quad s = \frac{1}{2}gt^2 \]

- Huygens: concept of momentum:
- circular orbit requires force:

\[ \frac{v^2}{r} \]
Philosophy is written in that great book which ever lies before our eyes – I mean the universe – but we cannot understand it if we do not first learn the language and grasp the symbols in which it is written. This book is written in the mathematical language, and the symbols are triangle circles and other geometrical figures, without whose help it is humanly impossible to comprehend a single word of it, and without which one wanders in vain through a dark labyrinth.

but Galilei never understood Kepler’s work…
Further development of telescopes

- Johannes Wiesel (Augsburg)
- Eustachio Divini (Rome)
- Christiaan Huygens
- Giuseppe Campani (Rome)

Further discoveries

- Huygens
  - rings of Saturn
  - Titan
- Cassini
  - division in ring of Saturn
- Römer
  - velocity of light
Römer discovers velocity of light: 1676
Sphere of stars or infinite universe?

Thomas Digges 1546 – 1596

Huygens: life on planets?
Revival of atomism

Pierre Gassendi 1592 – 1655

Tenets of atomism

- Lucretius *De rerum natura*
- known throughout middle ages
- matter is made up of indivisible particles *a-tomos*
- natural processes must be explained by size, shape, and motion of these particles
- atoms move in vacuum
- forces governing motion of planets are mysterious
Descartes 1596 – 1650 and vortices

- Stars are centers of vortices
- Mechanical philosophy:
  - Causal explanations in terms of mechanical actions: pushes or impact
  - No vacuum
  - Find mathematical descriptions for phenomena on earth and in sky
Synthesis: Isaac Newton 1643 – 1727

Portait in 1689

Multi-faceted scientist

- mathematics: invents calculus (‘fluxions’); also Leibniz
- theoretical physics: explains planetary orbits
- practical astronomy: builds best telescope of his time: mirror telescope (with ball bearing)
- chemistry: weighs ingredients in reactions (writings not published)
- theology: Arian heretic (Christ as Son of God is 3rd century invention) based on detailed bible study
- optics: white light consists of colours

Frank Verbunt (Astronomical Institute Utrecht)
Definitions

- The quantity of matter is the measure of the same, arising from its density and bulk conjointly.
- The quantity of motion is the measure of the same, arising from the velocity and quantity of matter conjointly.
- The vis insita, or innate force of matter is the power of resisting by which every body, as much as in it lies, continues in its present state, whether it be of rest or of moving uniformly forward in a right line.
Absolute Time

Absolute, true, and mathematical time, of itself and from its own nature, flows equably without relation to anything external, and by another name is called ‘duration’; relative, apparent, and common time is some sensible and external (whether accurate or unequable) measure of duration by means of motion, which is commonly used instead of true time, such as an hour, a day, a month, a year.

Absolute Space

Absolute space, in its own nature, without relation to anything external, remains always similar and immovable. Relative space is some movable dimension or measure of the absolute spaces, which our senses determine by its position to bodies and which is commonly taken for immovable space.
Laws of motion

1. Every body continues in its state of rest or of uniform motion in a right line unless it is compelled to change that state by forces impressed on it.

2. The change of motion is proportional to the motive force impressed and is made in the direction of the right line in which that force is impressed.

3. To every action there is always opposed an equal reaction; or, the mutual actions of two bodies upon each other are always equal and directed to contrary parts.

Law of gravity

\[ F = \frac{GMm}{r^2} \]

powerful mathematics! but what is the physics? ‘actio in distans’
Second edition 1713

But hitherto I have not been able to discover the cause of those properties of gravity from phenomena, and I frame no hypotheses; for whatever is not deduced from the phenomena is to be called a hypothesis, and hypotheses, whether metaphysical or physical, whether of occult qualities or mechanical, have no place in experimental philosophy.

Laws of equal areas

- no force: $Bc = AB$ in equal time interval
- at $B$: force in direction $S$
- $Cc \parallel BS$ hence area $BSC = \text{area } BSc = \text{area } ABC$
The apple and the moon

\[ \frac{g_{\text{Moon}}}{g_{\text{earth}}} = \left( \frac{R}{a} \right)^2 \]

Galilei:

\[ g_{\text{earth}} = 30 \text{ feet/s} \]

Moon, with Huygens,

\[ g_{\text{moon}} = \frac{v^2}{a} = \left( \frac{2\pi a}{P} \right)^2 \frac{1}{a} \]

\[ a \approx 60R \Rightarrow g_{\text{moon}} = 0.0073 \text{ feet/s} \]

Discrepancy of \(~\) one in eight due to inaccurate Earth radius

Reaction

- very impressive! Newton greatest physicist
- but... actio in distans difficult to accept
- France: we stick to Descartes’ vortices
- await the return of the comet!
Halley’s list of comets – 1705; next appearance 1758?

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Three technological developments were crucial to the Copernican and Newtonian revolutions. Describe briefly for each of these why they were so important.

Kepler, Huygens and Galilei each contributed important knowledge about (celestial) mechanics that Newton embedded in his theory of gravity. Describe these three contributions, and explain how they are contained in Newton’s theory.