THE UNIVERSITY OF WARWICK

PX 144: Introduction to Astronomy

Jörn Wilms

Spring 2006

email: `j.wilms@warwick.ac.uk`

Office: PS006

`http://www2.warwick.ac.uk/go/px144`

THE UNIVERSITY OF WARWICK

Introduction

THE UNIVERSITY OF WARWICK

Syllabus

Aims: To introduce the constituent objects of the Universe and the physics which allows us to estimate their distances, sizes, masses and natures. The module will show how our knowledge of the Universe beyond Earth relies entirely upon the application and extrapolation of physics developed in the laboratory. This will develop an appreciation of the wide range of applicability of physical principles, while touching upon areas under active development. The module will help the development of problem solving skills.

Objectives: At the end of the module you should be able to:

- List the main constituents of the Universe and give a basic description of them
- Describe methods for measuring the distances of stars and galaxies and work out example computations.
- Work out the masses of stars and galaxies given information on size or angle & distance and speed.
- Understand how the surface temperature of stars can be measured and how one can deduce physical conditions of their interiors.

Syllabus:

Description of the main constituents of the Universe with typical sizes, masses and distances covering: the Solar System. Stars and star clusters. Angles, distances & sizes: angular size and the small-angle approximation; trigonometric parallax; simple telescopes; distance methods based upon the inverse square law of brightness.
Masses: the Doppler effect and the measurement of speed from spectra; the use of speeds and sizes to derive masses in the Solar System, binary stars, star clusters and galaxies.
Physical properties of stars: stellar temperatures; spectra and elemental compositions. Physical conditions within stars
Galaxies: normal & active; the Milky Way; galaxy interactions; galaxy clusters.
The Universe: Hubble's discovery of the expansion of the Universe; implication of a finite age; the Cosmic Microwave Background; the composition of the Universe.

Commitment: 15 Lectures + 5 problems classes

⇒ Physics students: these are your normal problems classes, and are assessed the usual way!
⇒ Maths students: there are examples classes Thursdays at 13:00 in P521A, contact Rachel Edwards (`phscav@warwick.ac.uk`) if you cannot attend these classes for time reasons. The examples are not assessed.
⇒ All others: The examples are not assessed, but please try to do the homeworks as practising now will save you time later when preparing for the exam.

Assessment: 1 hour examination

Contents

Textbooks

ZEILIK & GREGORY, 1998, *Introductory Astronomy & Astrophysics*, 4th ed., Thomson Learning, £ 45 , 600 pp.
Intermediate level, requires calculus, self contained, but sometimes chaotic order.
Official textbook of this module.

KUTNER, 2003, *Astronomy: A Physical Perspective*, Cambridge: Cambridge Univ. Press, £ 35, 580 pp.
Modern physics and calculus based textbook. Recommended.

CARROLL & OSTLIE, 1996, *Modern Astrophysics*, Reading: Addison-Wesley, £ 47 (softcover), 1400 pp.
Advanced level, calculus based, expects good physics background.
Recommended if you want to continue with "Stars" and/or "Galaxies".

YOUNG & FREEDMAN, 2004, University Physics, 11th Edition, Pearson/Addison Wesley, £ 48, 1800 pp.
Important background reading for all 1st year physics modules.

Homework

There will be weekly homeworks:

- given out Mondays, due back in problems classes (for the physics students only) as indicated on the individual homework sheets.
- Maths students: examples classes are Thursdays, 13:00, P521A (non-assessed)
- there is one problem you are required to solve, plus two others, which you should at least try to attack.
- example solutions for assessed questions will be available from undergraduate office after the module is over, will be posted on WWW for the other questions.

Exam paper:

- Example exam questions are available on the WWW
- Looking at the homework *will* help you!

Class Notes

- Viewgraphs and additional material are available *after* each lecture via

  `http://www2.warwick.ac.uk/go/px144`

  for online viewing and download (PDF-Format).
- Discussions on module and the homework (but not solution posting!) are encouraged at the module forum, reachable via the above link.

And finally...

> Please complain and ask questions if you think you haven't understood something.

History of Astronomy

Introduction

Together with theology, astronomy one of the oldest professions in the world.

So what?

Astronomical nomenclature is still strongly influenced by this tradition

$\Longrightarrow$ appreciation of history of astronomy is required for understanding even today's astronomy (many terms used are based on this history).

Babylon

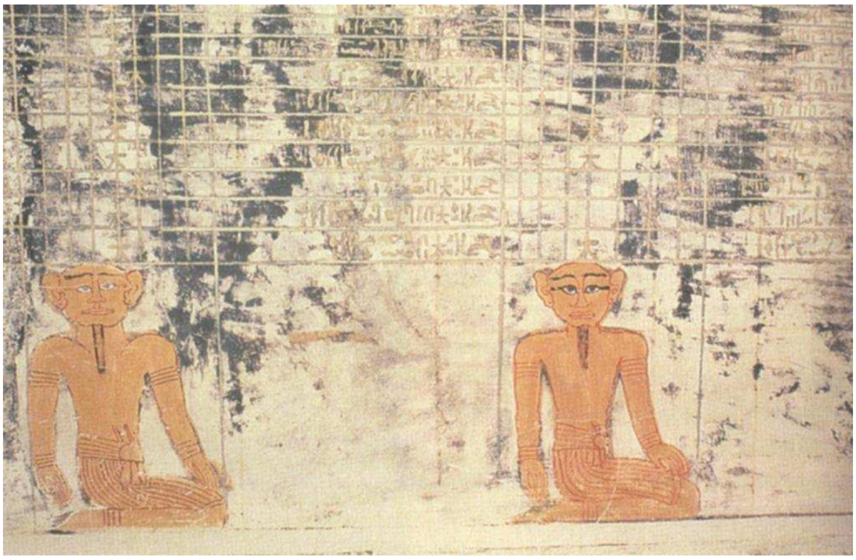
Babylonian astronomy: Earliest astronomy with influence on us: $\sim$360 d year
$\Longrightarrow$ sexagesimal system [360:60:60], 24h day, 12$\times$30 d year,. . .

Enuma Elish myth ($\sim$1100BC): Universe is place of battle between Earth and Sky, born from world parents.

Note similar myth in the Genesis. . .

Image: Mul.Apin cuneiform tablet (British Museum, BM 86378, 8 cm high), describes rising and setting of constellations through the babylonian calendar. Summarizes astronomical knowledge as of before $\sim$690 BC.

Egypt



Egyptian coffin lid showing two assistant astronomers, 2000. . . 1500 BC; hieroglyphs list stars (“decans”) whose rise defines the start of each hour of the night.

(Aveni, 1993, p. 42)

$\sim$2000 BC: 365 d calendar (12$\times$30 d plus 5 d extra), fixed to Nile flood (heliacal rising of Sirius), star clocks.

heliacal rising: first appearance of star in eastern sky at dawn, after it has been hidden by the Sun.

Greek/Roman, I

Atlas Farnese, 2c A.D., Museo Archeologico Nazionale, Napoli

Early Greek astronomy: folk tale astronomy (Hesiod (730?–? BC), *Works and Days*). Constellations.

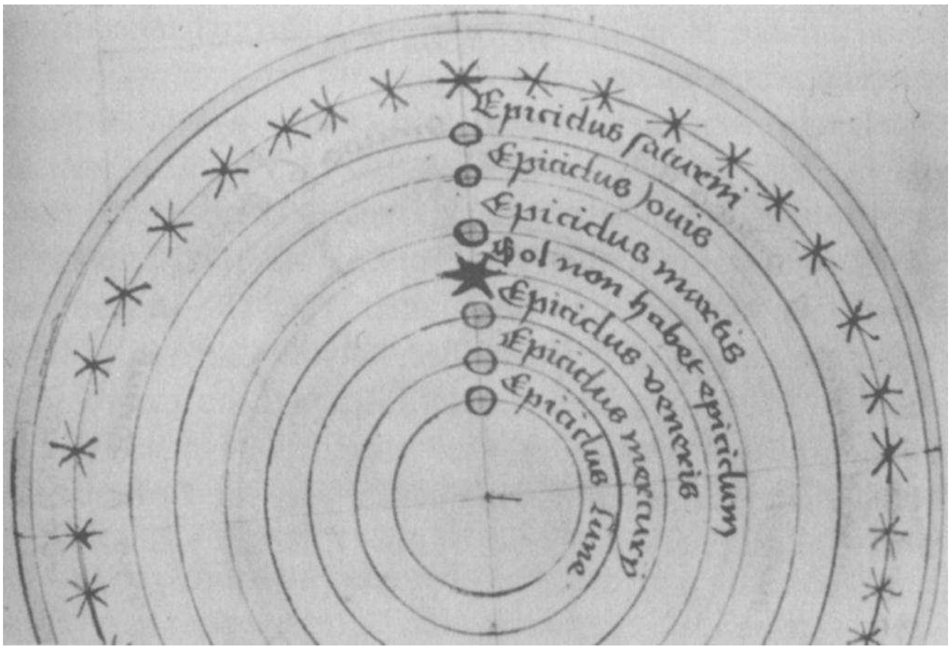
Thales (624–547 BC): Earth is flat, surrounded by water.

Anaxagoras (500–428 BC): Earth is flat, floats in nothingness, stars are far away, fixed on sphere rotating around us. Eclipses: due to Earth’s shadow.

Eudoxus (408–355 BC): Geocentric, planets affixed to concentric crystalline spheres. First real model for planetary motions!

Aristarchus (310–230 BC): Determination of relative distance to Moon and Sun (factor 20).

Greek/Roman, II



Aristotle (384–322 BC, *de caelo*): Refinement of Eudoxus model: add spheres to ensure smooth motion

⟹ Universe filled with crystalline spheres (*nature abhors vacuum*).

⟹ Central philosophy until ∼1450AD!

Hipparchus (?? – ∼127 BC): Refinement of geocentric Aristotelian model into tool to make predictions.

Greek/Roman, III

(Aveni, 1993, p. 58)

Ptolemaeus (∼140AD): *Syntaxis* (aka Almagest): Refinement of Aristotelian theory into model useable for computations

⟹ Ptolemaic System.

Renaissance, III

(Gingerich, 1993, p. 165)

Nicolaus Copernicus (1473–1543): Earth centred Ptolemaic system is too complicated, a Sun-centred system is more elegant:

De revolutionibus orbium coelestium: "In no other way do we perceive the clear harmonious linkage between the motions of the planets and the sizes of their orbs."

Copernican principle: The Earth is not at the center of the universe.

Renaissance, IV

Tycho Brahe (1546–1601): Visual planetary positions of highest precision reveal flaws in Ptolemaic positions.

Renaissance, V

Johannes Kepler (1571–1630):
Planets orbit on ellipses around Sun, not on circles, laws of motion.

Galileo Galilei (1564–1642): Moons of Jupiter, moving around Jupiter (Kepler $\Longrightarrow$ similar to heliocentric model!)...

Newton

(Newton, 1730)

Isaac Newton (1642–1727): Newton's laws, physical cause for shape of orbits is gravitation (*De Philosophiae Naturalis Principia Mathematica*, 1687).

$\Longrightarrow$ Begin of modern physics based astronomy.

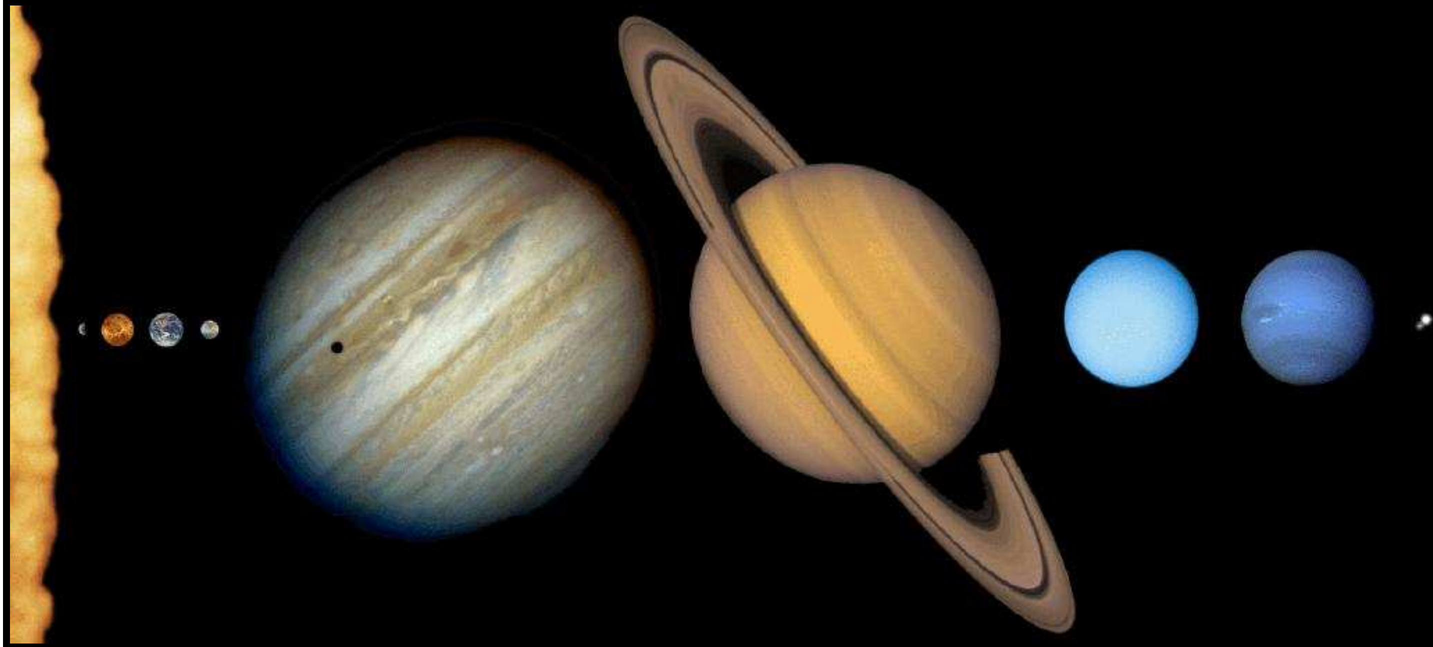
The Planets

THE UNIVERSITY OF WARWICK

The aim of this chapter is to introduce the physics of planetary motion and the general properties of the planets.

Useful background reading includes:

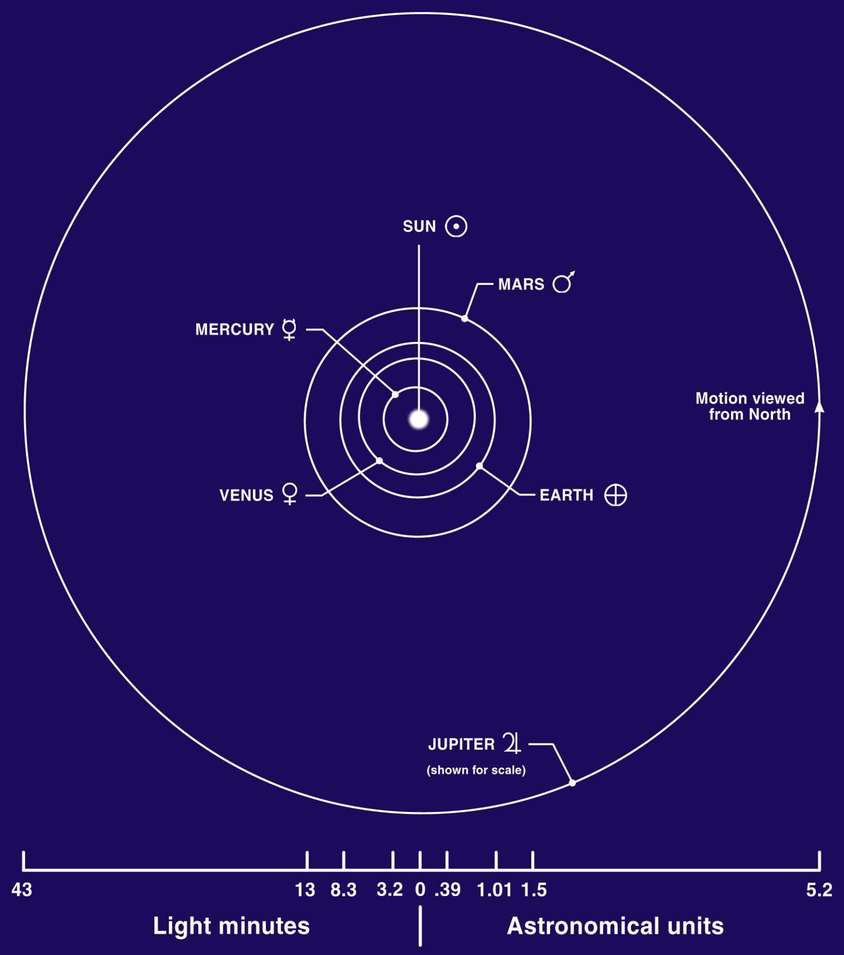
- Young & Freedman:
  - section 12.1 (Newton's Law of Gravitation),
  - section 12.3 (Gravitational Potential Energy),
  - section 12.4 (The Motion of Satellites),
  - section 12.5 (Kepler's Laws and the Motion of Planets)
- Zeilik & Gregory:
  - chapter P1 (Orbits in the Solar System),
  - chapter 1 (Celestial Mechanics and the Solar System),
  - chapter 2 (The Solar System in Perspective),
  - section 4-3 (Interiors),
  - section 4-5 (Atmospheres),
  - chapter 5 (The Terrestrial Planets),
  - chapter 6 (The Jovian Planets and Pluto).
- Kutner:
  - chapter 22 (Overview of the Solar System),
  - section 23.3 (The atmosphere),
  - chapter 24 (The inner planets, especially section 24.3),
  - chapter 25 (The outer planets).



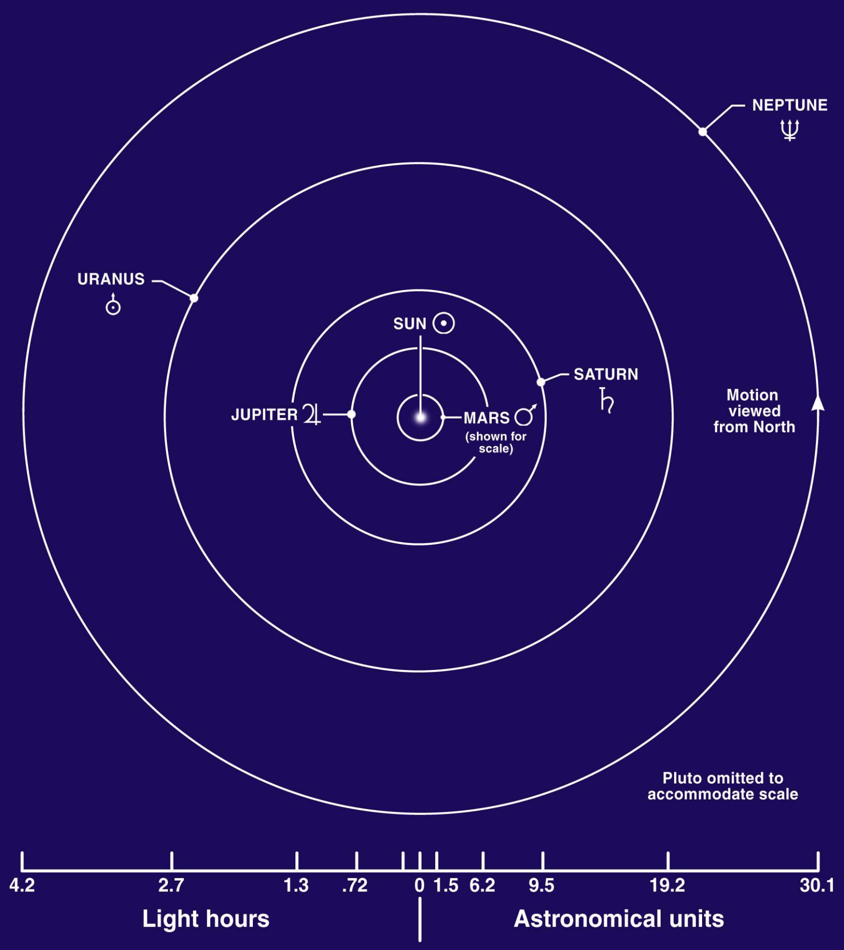
Relative sizes of the Sun and the planets

Venus Transit, 2004 June 8

Elio Daniele, Palermo



The Inner Planets (SSE, NASA)



The Outer Planets (SSE, NASA)

Planets: Properties

		a [AU]	P_{orb} [yr]	i [°]	e	P_{rot}	$M/M_\oplus$	$R/R_\oplus$
Mercury	☿	0.387	0.241	7.00	0.205	58.8 d	0.055	0.383
Venus	♀	0.723	0.615	3.40	0.007	−243.0 d	0.815	0.949
Earth	⊕	1.000	1.000	0.00	0.017	23.9 h	1.000	1.00
Mars	♂	1.52	1.88	1.90	0.094	24.6 h	0.107	0.533
Jupiter	♃	5.20	11.9	1.30	0.049	9.9 h	318	11.2
Saturn	♄	9.58	29.4	2.50	0.057	10.7 h	95.2	9.45
Uranus	⛢	19.2	83.7	0.78	0.046	−17.2 h	14.5	4.01
Neptune	♆	30.1	163.7	1.78	0.011	16.1 h	17.1	3.88
(Pluto	♇	39.2	248	17.2	0.244	6.39 d	0.002	0.19)

After Kutner, Appendix D;

a: semi-major axis P_{orb}: orbital period i: orbital inclination (wrt Earth's orbit)
e: eccentricity of the orbit P_{rot}: rotational period M: mass
R: equatorial radius
1 AU $= 1.496 \times 10^{11}$ m.

Structure

Questions that we will deal with:

1. How do the planets move?

   Kepler's laws and their physical interpretation

2. What do planetary surfaces look like?

   craters, plate tectonics, volcanism

3. How do planetary atmospheres work?

   hydrostatic structure

4. What is the internal structure of the planets?

   hydrostatic structure (again)

5. Is the solar system normal?

   Are there planets elsewhere?

Introduction

Johannes Kepler: Motion of planets governed by three laws:

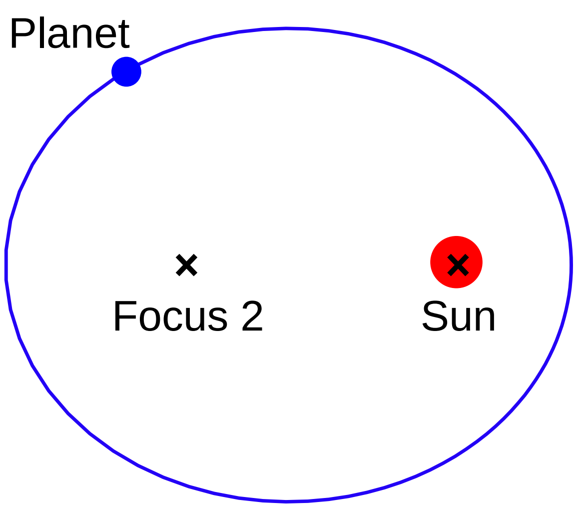
1. Each planet moves in an elliptical orbit, with the Sun at one focus of the ellipse. ("Astronomia Nova", 1609)
2. A line from the Sun to a given planet sweeps out equal areas in equal times. ("Astronomia Nova", 1609)
3. The square of the orbital periods of the planets is proportional to the cube of the major axes. ("Harmonice Mundi", 1619)

Isaac Newton ("Principia", 1687): Kepler's laws are consequence of gravitational interaction between planets and the Sun, and the gravitational force is

$$\mathbf{F}_1 = -\frac{G m_1 m_2}{r_{12}^2} \frac{\mathbf{r}_{21}}{r_{12}}$$

where $\mathbf{F}_1$ is the gravitational force exerted on object 1, m_1, m_2 are the masses of the interacting objects, r their distance, and $\mathbf{r}_{21}/r_{12}$ the unit vector joining the objects, $\mathbf{r}_{21} = \mathbf{r}_2 - \mathbf{r}_1$, $\mathbf{r}_{12} = -\mathbf{r}_{21}$ and $r_{12} = |\mathbf{r}_{12}| = |\mathbf{r}_{21}|$.

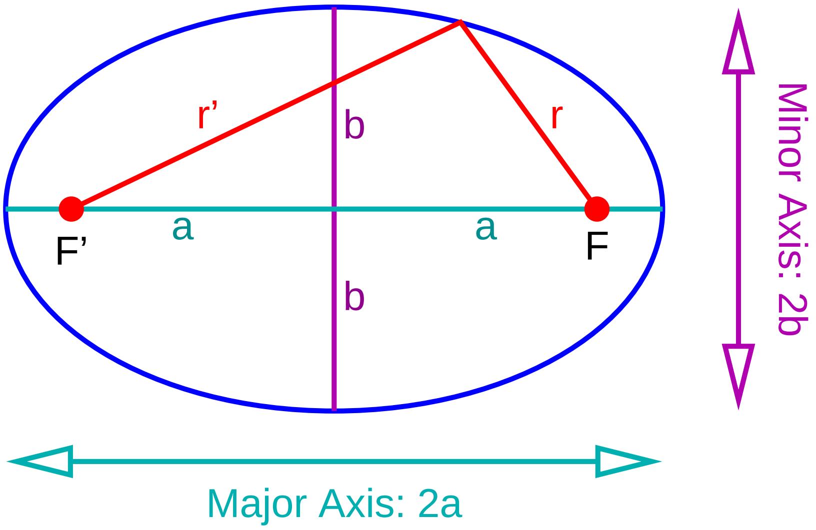
Keplers 1st Law



Kepler's 1st Law: The orbits of the planets are ellipses and the Sun is at one focus of the ellipse.

For the planets of the solar system, the ellipses are almost circular, for comets they can be very eccentric.

Keplers 1st Law

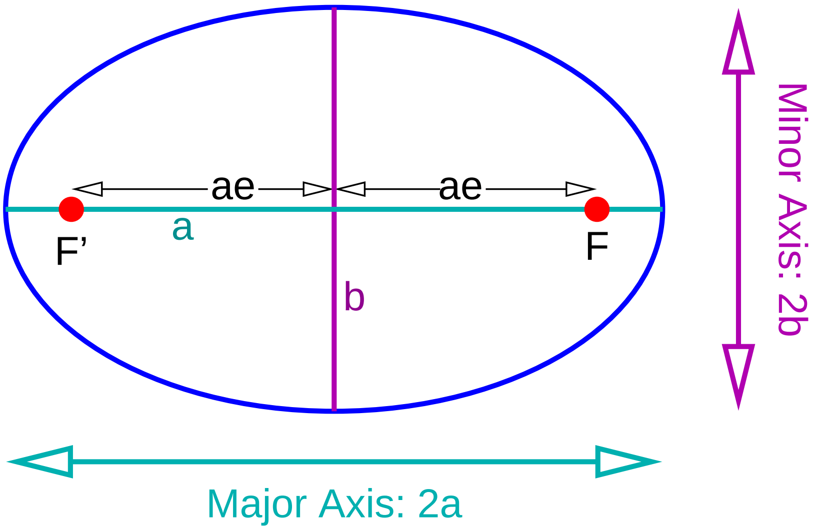


Definition: Ellipse = Sum of distances r, r' from any point on ellipse to two fixed points (foci, singular: focus), F, F', is constant:

$$r + r' = 2a$$

where a is called the semi-major axis of the ellipse.

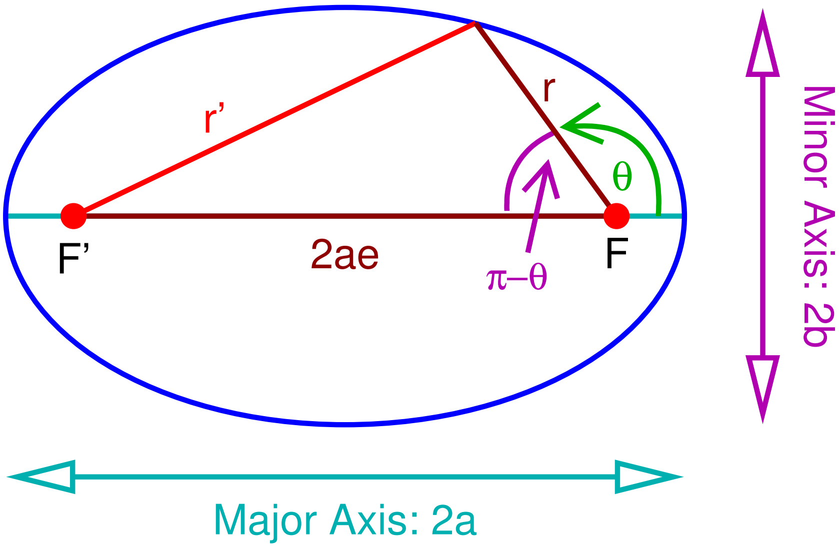
Keplers 1st Law



Definition: Eccentricity e: ratio between distance from centre of ellipse to focal point and semi-major axis.

So circles have $e = 0$.

Keplers 1st Law

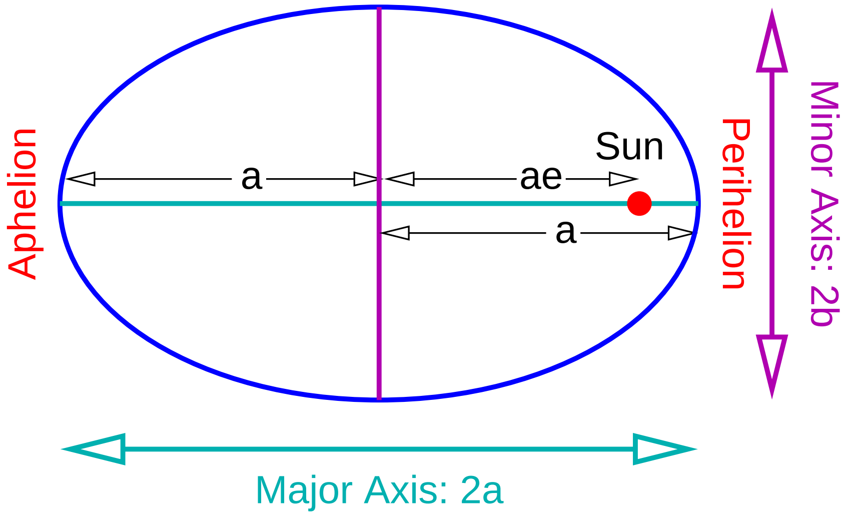


Law of cosines: $r'^2 = r^2 + (2ae)^2 - 2 \cdot r \cdot 2ae \cdot \cos(\pi - \theta)$
use $r + r' = 2a$ and solve for r to find the polar coordinate form of the ellipse:

$$r = \frac{a(1-e^2)}{1 + e\cos\theta}$$

Check this for yourself! θ is called the *true anomaly*.

Keplers 1st Law

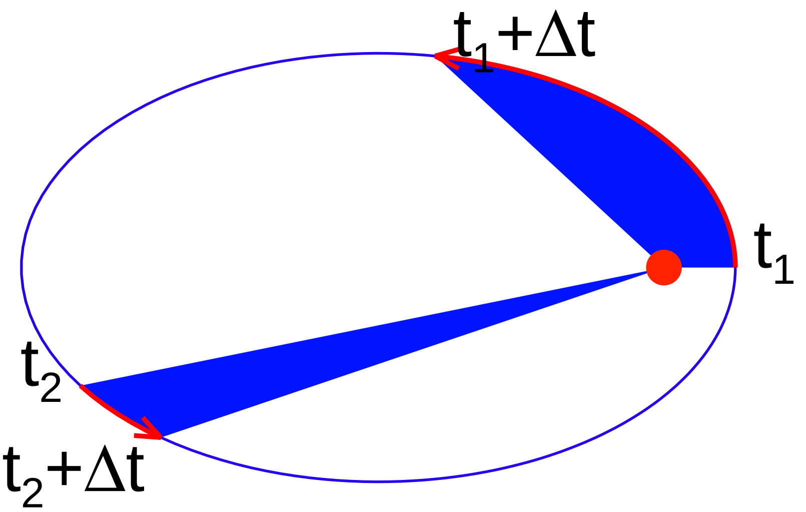


Finally, we need the closest and farthest point from a focus:

$$\text{closest point}: d_{\text{perihelion}} = a - ae = a(1-e)$$
$$\text{farthest point}: d_{\text{aphelion}} = a + ae = a(1+e)$$

for stars: periastron and apastron,
for satellites circling the Earth: perigee and apogee.

2nd Law



Kepler's 2nd Law: The radius vector to a planet sweeps out equal areas in equal intervals of time.

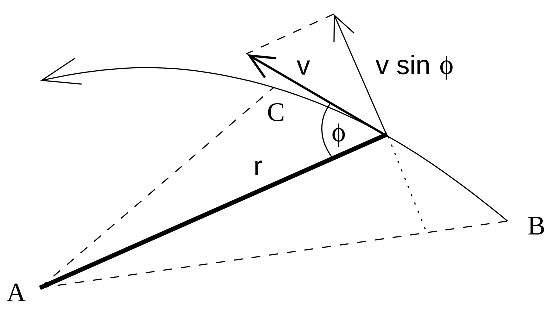
1. Kepler's 2nd Law is also called the *law of areas*.
2. perihelion: planet nearest to Sun $\Longrightarrow$ planet is fastest
3. aphelion: planet farthest from Sun $\Longrightarrow$ planet is slowest

Kepler's 2nd law is a direct consequence of the conservation of angular momentum. Remember that angular momentum is defined as

$$\mathbf{L} = \mathbf{r} \times \mathbf{p} = \mathbf{r} \times m\mathbf{v} \tag{3.1}$$

and its absolute value is

$$L = mrv \sin\phi \tag{3.2}$$



To interpret the angular momentum, look at the figure at the left. Note that $v\sin\phi$ is the projection of the velocity vector perpendicular to the radius vector r, and the distance traveled by the planet in an infinitesimally short time Δt is given by $\Delta x = \Delta t \cdot v \sin\phi$. Therefore, the area of the triangle ABC is given by

$$\Delta A = \frac{1}{2} r \Delta x = \frac{1}{2} r \Delta t v \sin\phi = \frac{L}{2m}\Delta t$$

Kepler's 2nd law states that the "sector velocity" $\mathrm{d}A/\mathrm{d}t$ is constant with time:

$$\frac{\mathrm{d}A}{\mathrm{d}t} = \lim_{\Delta t \to 0} \frac{\Delta A}{\Delta t} = \frac{L}{2m} = \text{const.}$$

To confirm that this claim is true, we need to prove that

$$\frac{\mathrm{d}}{\mathrm{d}t}\frac{\mathrm{d}A}{\mathrm{d}t} = \frac{1}{2m}\frac{\mathrm{d}L}{\mathrm{d}t} = 0$$

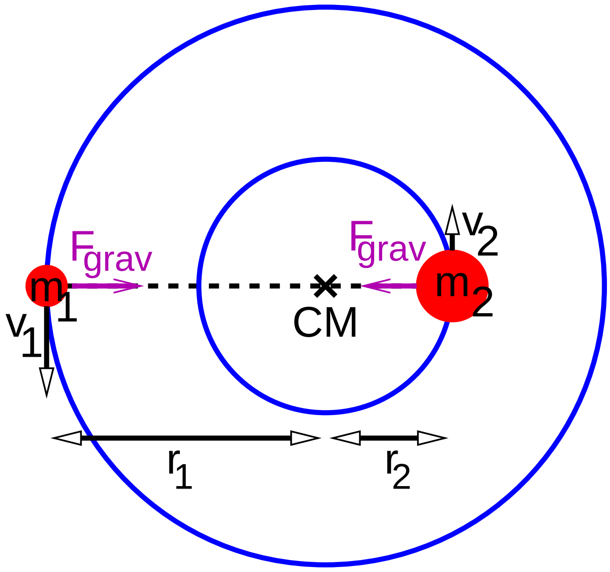
But $\mathrm{d}L/\mathrm{d}t$ is given by

$$\frac{\mathrm{d}\mathbf{L}}{\mathrm{d}t} = \frac{\mathrm{d}\mathbf{r}}{\mathrm{d}t} \times \mathbf{p} + \mathbf{r} \times \frac{\mathrm{d}\mathbf{p}}{\mathrm{d}t} = \mathbf{v} \times \mathbf{p} + \mathbf{r} \times \mathbf{F} = \mathbf{v} \times m\mathbf{v} + \mathbf{r} \times \frac{GMm}{r^2}\frac{\mathbf{r}}{r} = 0$$

since the cross product of a vector with itself is zero. Therefore, Kepler's 2nd law is true and is a consequence of the conservation of angular momentum for a central field.

3rd Law

Kepler's 3rd Law: The squares of the periods of the planets, P, are proportional to the cubes of the semimajor axes, a, of their orbits: $P^2 \propto a^3$.

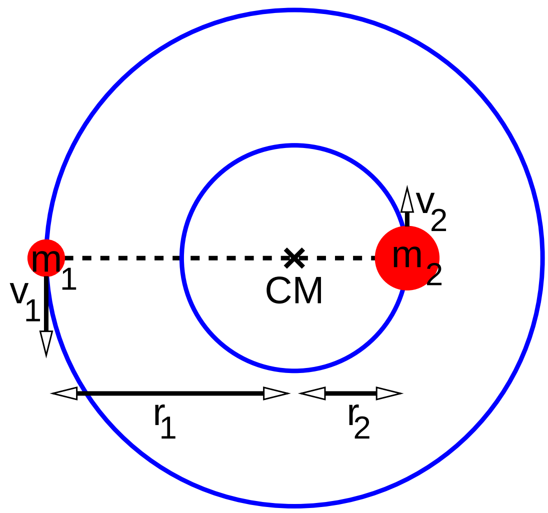


Computing the motion of two bodies of mass m_1 and m_2 in gives Newton's form of Kepler's third law:

$$P^2 = \frac{4\pi^2}{G(m_1 + m_2)} R^3$$

where $r_1 + r_2 = R$ (for elliptical orbits: R is the semi-major axis).

Circular Motion



For an interpretation of Kepler's third law, consider the motion of two bodies with masses m_1 and m_2 on circular orbits with radii r_1 and r_2 around a point CM (see figure).

The reason for doing the computation with circular orbits is that the following discussion will be *much* easier, however, all results from this section also apply to the general case of elliptical motion.

The attractive force between the two points is given by Newton's law:

$$F_{\text{grav}} = G\frac{m_1 m_2}{R^2} = G\frac{m_1 m_2}{(r_1 + r_2)^2}$$

In order to keep the two bodies on circular orbits, the gravitational force needs to be equal the centripetal force keeping each body on its circular orbit.

The centripetal force is

$$F_{\text{cent},\,1} = \frac{m_1 v_1^2}{r_1} = \frac{4\pi^2 m_1 r_1}{P^2}$$
$$F_{\text{cent},\,2} = \frac{m_2 v_2^2}{r_2} = \frac{4\pi^2 m_2 r_2}{P^2}$$

where I used $v = 2\pi r/P$ to compute the velocity of each of the bodies. Setting the centripetal force equal to the gravitational force then gives

$$\frac{4\pi^2 m_1 r_1}{P^2} = G\frac{m_1 m_2}{(r_1 + r_2)^2}$$
$$\frac{4\pi^2 m_2 r_2}{P^2} = G\frac{m_1 m_2}{(r_1 + r_2)^2}$$

canceling m_1 and m_2 gives

$$\frac{4\pi^2 r_1}{P^2} = G\frac{m_2}{(r_1 + r_2)^2}$$
$$\frac{4\pi^2 r_2}{P^2} = G\frac{m_1}{(r_1 + r_2)^2}$$

Dividing these two equations by each other results in

$$\frac{r_1}{r_2} = \frac{m_2}{m_1} \quad \text{or} \quad m_1 r_1 = m_2 r_2$$

This is the definition of the *center of mass*.

The total distance between the two bodies is

$$R = r_1 + r_2 = r_1 + \frac{m_1}{m_2} r_1 = r_1 \left(1 + \frac{m_1}{m_2}\right)$$

Inserting into one of the above equations gives

$$\frac{4\pi^2}{P^2} \cdot R \cdot \frac{m_2}{m_1 + m_2} = \frac{G m_2}{R^2}$$

such that

$$\frac{4\pi^2}{P^2} = \frac{G(m_1 + m_2)}{R^3} \quad \text{or} \quad P^2 = \frac{4\pi^2}{G(m_1 + m_2)} R^3$$

This is *Newton's form of Kepler's 3rd law*.

3rd Law

Newton's form of Kepler's 3rd law is the most general form of the law.

However, often shortcuts are possible.

Assume one central body dominates, $m_1 = M \gg m_2$:

$$\frac{P^2}{a^3} = \frac{4\pi^2}{m_2} = \text{const.} = k$$

So, if we know P and a for one body moving around m_1, can compute k.

For the Solar System, use Earth:

- $P_\oplus = 1\,\text{year}$ (by definition!)
- $a_\oplus = 1\,\text{AU}$ (Astronomical Unit, $1\,\text{AU} = 149.6 \times 10^6\,\text{km}$)

$\Longrightarrow k = 1\,\text{yr}^2\,\text{AU}^{-3}$

Jupiter: $a_{♃} = 5.2\,\text{AU}$. What is its period?