Einführung in die Astronomie I

Jörn Wilms

Sommersemester 2011

Büro: Dr. Karl Remeis-Sternwarte, Bamberg
Email: joern.wilms@sternwarte.uni-erlangen.de
Tel.: (0951) 95222-13

http://pulsar.sternwarte.uni-erlangen.de/wilms/teach/intro

Friedrich–Alexander–Universität Erlangen–Nürnberg

1–1

Introduction

1–2

Astronomie im Bachelorstudiengang Physik

NF im Bachelor/Master: Zwei Module (Je 10 ECTS):
- NW1 (Grundkenntnisse) kann gewählt werden im 1./2., 3./4. oder 5./6. Semester
- NW2 (vertieft) kann gewählt werden u.a. im 4./5. Semester oder als NW im Masterstudium

PW im Bachelorstudium: Modul für PW-1, PW-2, oder PW-3

PW im Masterstudium: geplant: PW-1, PW-2 und/oder PW-3 alternativ im Masterstudiengang

1–3

Astronomie für LAG-Physik, BA Informatik und Mathematik

physikalisches Wahlfach im LAG: NW-1 (10 ECTS):
- kann vorzugsweise gewählt werden im 5./6. Semester

NF im Bachelor Informatik: Erweiterter NW-1 (15 ECTS):
- Besteht aus NW1 plus verpflichtende Übungen und kann gewählt werden im 5./6. Semester

NF im Bachelor Mathematik: 35 ECTS:
- 1. und 2. Semester: Einführung in die Experimentalphysik I und 2 (je 7.5 ECTS)
- 3. und 4. Semester: Astonomie NW-1 (10 ECTS)
- 5. und 6. Semester: Astronomie NW-2 (10 ECTS), PW-1 (5 ECTS)

weitere Fächer: Anfrage beim jeweiligen Prüfungsamt

1	**NW-1**	**Einführung in die Astronomie (Introduction to Astronomy)**	**10 ECTS**
2	**Lehrveranstaltungen**	WS: Vorlesung Einf. in die Astronomie 1 (2 SWS) SS: Vorlesung Einf. in die Astronomie 2 (2 SWS) Blockpraktikum Astronomie mit Tutorium (7+1 SWS) Das Praktikum kann auch im WS absolviert werden, wenn die Warteliste dies erfordert	3.0 ECTS 3.0 ECTS 4.0 ECTS
3	**Dozenten**	Prof. Dr. Horst Drechsel Prof. Dr. Ulrich Heber Prof. Dr. Jörn Wilms	

4	**Modul-verantwortliche**	Die Dozenten des Astronomischen Instituts
5	**Inhalt**	Das Modul gibt eine Beschreibung der wesentlichen Bestandteile des Universums und der naturwissenschaftlichen Methoden, die es uns erlauben, ihre Entfernungen, Größenskalen, Massen und physikalische Natur zu verstehen. Im Einzelnen werden behandelt: • Geschichtlicher Hintergrund der Astronomie • Sonnensystem: Planetenbewegung und Keplersche Gesetze, Eigenschaften der Planeten und der kleinen Objekte im Sonnensystem (Auswahl aus: innerer Aufbau der Planeten, planetare Oberflächen, Atmosphären, Ringe), extrasolare Planeten. • Sterne: Entfernungen, Temperaturen, Spektren, Massen, Hertzsprung-Russell-Diagramm, innerer Aufbau, Entstehung und Entwicklung, Endstadien der Sternentwicklung, Doppelsterne. • Milchstraße und andere Galaxien: Aufbau und Entwicklung, Klassifikation, kosmischer Materiekreislauf, Galaxienhaufen, ausgewählte Methoden der Entfernungsbestimmung. • Das Universum: Entstehung, Hubblesches Gesetz, 3K Hintergrundstrahlung, Entwicklung des Universums. • Astronomische Messmethoden: Aufbau und Benutzung astronomischer Teleskope, Spektroskopie, Detektoren
6	**Lernziele und Kompetenzen**	Die Studierenden • entwickeln ein physikalisches Verständnis der wichtigsten Bestandteile des Universums und ihrer Entwicklung. • lernen Methoden zur Messung der Entfernungen von Sternen und Galaxien kennen und können diese auf Messungen anwenden. • können aus Messdaten Massen und Temperaturen astronomischer Objekte ableiten. • können einfache astronomische Messungen selbst durchführen und auswerten. • erfahren ein Verständnis über die weite Anwendbarkeit

		naturwissenschaftlicher Methoden durch die in der Astronomie notwendige Extrapolation von Ergebnissen von Labormessungen auf astronomische Skalen. • entwickeln Fähigkeiten zur Lösung naturwissenschaftlicher Probleme, einschließlich der Fähigkeit zur Bedienung typischer astronomischer Instrumente.
7	**Voraussetzungen für die Teilnahme**	Keine; spezielles Zulassungsverfahren für Frühstudierende.
8	**Einpassung in Musterstudienplan**	Ab Studiensemester 1, Frühstudium, Gasthörer
9	**Verwendbarkeit des Moduls**	• Bachelorstudiengang Physik (nichtphysikalischer Wahlbereich) • Lehramt Physik am Gymnasium (Wahlbereich) • Studierende anderer Fächer: Wahlbereich
10	**Studien- und Prüfungsleistungen**	Zwei 60-minütige Klausuren zu den Vorlesungen (PL), Teilnahme am Tutorium und an den Praktikumsterminen, Durchführung der Versuche, Testate (SL)
11	**Berechnung Modulnote**	Mittelwert der Klausurnoten
12	**Turnus des Angebots**	Jährlich
13	**Arbeitsaufwand**	Präsenzzeit: 180 h Eigenstudium: 120 h
14	**Dauer des Moduls**	2 Semester (ggf. 3 Semester, falls das Praktikum im Wintersemester absolviert wird)
15	**Unterrichtssprache**	Deutsch und Englisch
16	**Vorbereitende Literatur**	• H. Karttunen, P. Kroger, H. Oja, *Fundamental Astronomy*, Springer, 2003 • M. Kutner, *Astronomy: A Physical Perspective*, Cambridge Univ. Press, 2003

Benotung

Idee: Kumulative Abschlüsse in den Nebenfächern, keine modulübergreifende Prüfung.

$\Longrightarrow$ Impliziert Notengebung!

$\Longrightarrow$ KLAUSUR am 19. Juli 2011

Klausur führt zu einer *Note*

Physiker: Noten aus dem 1. & 2. Bachelor-Semester gehen *NICHT* in die Bachelor-Note ein.

Übungen und Hausaufgaben

Um den Stoff zu vertiefen gibt es freiwillige Übungen, verpflichtend für BA-Informatik.

Terminfindung:

10 MAI, 17:45 (Nach der Vorlesung)

Betreuung: Maria Obst

Wir werden Übungsblätter austeilen, die in den Übungen besprochen werden.

Ebenso sind Vorschläge und Fragen für die Übungen sehr erwünscht.

Praktikum

Praktikum wird an der Dr. Karl Remeis-Sternwarte, Bamberg, als Blockpraktikum durchgeführt werden.

Termine:

- 05.09.–16.09.2011
- 19.09.–30.09.2011
- 04.10.–14.10.2011

$\Longrightarrow$ 21 Plätze pro Termin

$\Longrightarrow$ Wir lassen $63 + x$ Personen zu ($x \geq 0$).

Anmeldung: jetzt, *vorläufige* Zulassung erfolgt wird Mitte Juli mitgeteilt, hängt aber von Bestehen der klausur ab

Zum Bestehen des Moduls sind für *alle* das Praktikum sowie Bestehen der zwei Klausuren Astronomie I und II erforderlich.

Textbooks

KARTUNNEN, KRÖGER, OJA, POUTANEN & DONNER , 2007, *Fundamental Astronomy*, 5th ed., Heidelberg: Springer, €64 (hardcover), 510 pp.
Good general overview of astronomy.
Recommended, especially for exam preparation.

KUTNER, 2003, *Astronomy: A Physical Perspective*, 2nd ed., Cambridge: Cambridge Univ. Press, €51, 600 pp.
Modern physics based textbook, easy to read. Recommended.

BENNETT ET AL., 2009, *Astronomie: Die kosmische Perspektive*, Pearson Studium, €79.95, 1200 pp.
Modern and good; German translation is not bad, Recommended.

Textbooks

UNSÖLD & BASCHEK, 2006, *Der neue Kosmos. Einführung in die Astronomie und Astrophysik*, 7. Auflage, Berlin: Springer, €60, 577 pp.
Intermediate level: Good overview of stellar astronomy
Good secondary reading.

ZEILIK & GREGORY, 1998, *Introductory Astronomy & Astrophysics*, 4th ed., Thomson Learning, ca. €65, 672 pp.
Intermediate level, self contained, but sometimes chaotic order.

CARROLL & OSTLIE, 2006, *An Introduction to Modern Astrophysics*, 2nd ed., Reading: Addison-Wesley, ca. €100 (hardcover), 1400 pp.
Advanced level, expects good physics background.
Recommended if you want to specialize in astronomy.

Contents

03 May	**Organisation, Introduction**
10 May	History of Astronomy
17 May	Planets I
24 May	Planets II
31 May	Planets III
07 Jun	Planets: Transneptunians, Asteroids, Comets, Meteorites
21 Jun	Measurement Methods: Telescopes, Coordinates
28 Jun	Stars, Distances, Luminosity, HRD
05 Jul	Stars: Binaries, Masses & Radii
12 Jul	Exoplanets
19 Jul	*Exam!*
26 Jul	Stars: Formation

History of Astronomy

Stonehenge: 2500 BC; solar observatory?

Disk of Nebra: 1600 BC

first reproduction of the night sky, constellation of Moon and Pleiades

measures solstices and equinoxes $\Longrightarrow$ calendar

History

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

Astronomical nomenclature is still strongly influenced by this tradition.

$\Longrightarrow$ appreciation of history of astronomy is required for understanding even of today's astronomy. Many terms used are based on this history, e.g. magnitudes by the greek astronomer Hipparcos ($\sim$150 BC)

Early Cosmology

Composite of images of Mars spaced ∼ a week apart – from late July 2005 (bottom right) through February 2006 (top left).

Explain observations:

- daily motions of Sun, Moon, planets & stars from E to W
- much slower motion of Sun & Moon with respect to stars
- occasional retrograde motions of planets (E to W)
- solar and lunar eclipses

Babylon

Babylonian astronomy: Earliest astronomy (flourish ∼700 BC) with influence on us:

$\Longrightarrow$ sexagesimal system [360:60:60], 24 h day, 12×30 d year,. . .

$\Longrightarrow$ Observations of Sun and Moon

$\Longrightarrow$ stellar constellations, 12 signs of zodiac

$\Longrightarrow$ bookkeeping on solar and lunar eclipses, Saros cycle: 18 yr 11 d

$\Longrightarrow$ description of planet movement

$\Longrightarrow$ cataloging stellar positions

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 ∼690 BC.

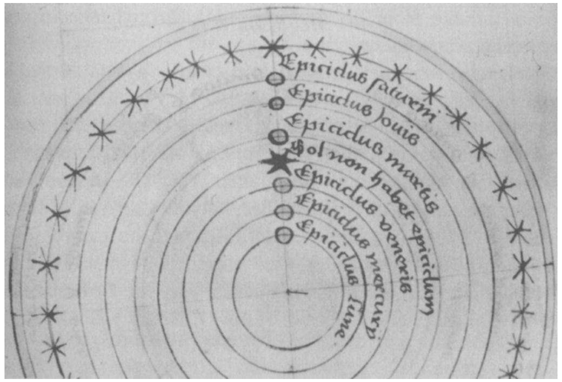
Greek

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

Greek Astronomers: "Mathematicians"
development of the geocentric world model

- Thales (624–547 BC): Earth is flat, surrounded by water. Founder of Natural Philosophy
- Pythagoras (ca. 570–510 BC): Earth is a sphere. "Everything is number" A harmonic universe (music) requires orbital motions in certain ratios of integer numbers (see Kepler: Harmonices mundi)
- Plato (427–347 BC): the circle is the perfect geometric form, uniform circular motion is eternal $\Longrightarrow$ "the hex of circles"
- Eudoxus (408–355 BC): Geocentric, planets affixed to concentric crystalline spheres. 27 spheres to account for non-uniform motions (does not work for Mars and Venus). First real model for planetary motion!

Greek



Aristotle (384–322 BC, *de caelo*): Refinement of Eudoxus model: add spheres to ensure correct motions of all planets: >50 nested and linked spheres, driven by the outermost sphere.

$\Longrightarrow$ Central philosophy until ∼1450AD!

Greek

Hipparchus (?? – ∼127 BC): First Greek observer:

- Star catalog: 850 stars
- Magnitudes of stars: $0^{\mathrm{m}} \ldots 6^{\mathrm{m}}$
- Parallax of the Moon
- Table of chords (early trigonometry)
- Discovery of precession (shift of the vernal equinox) by comparison with Babylonian star catalog
- Seasons have unequal length
- used geocentric world model of Aristotele to make predictions (Epicycle).

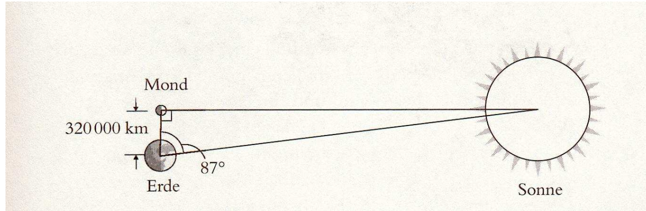
Greek

(Aveni, 1993, p. 58)

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

$\Longrightarrow$ Ptolemaic System.

Greek



Development of the heliocentric world model: Aristarchus (310–230 BC) determines of the radius of the Sun

1st and last quarter of Moon:

observed $\angle(\text{Moon, Sun}) = 1/4\,\text{circle} - 1/30 \times 1/4\,\text{circle} = 87^\circ$

$\Longrightarrow$ distances: $D(\text{Sun} - \text{Earth}) = 19 \times D(\text{Moon} - \text{Earth})$

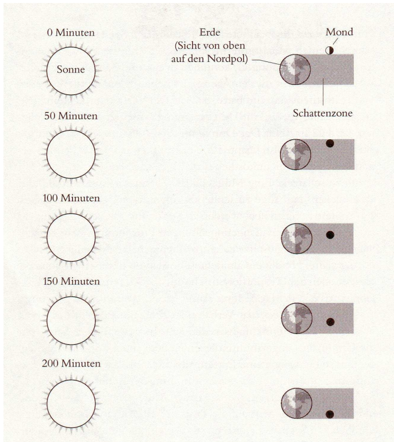
Cassini (1672): Parallax of Mars, which gives $D(\text{Sun} - \text{Earth})$ = 140 Mio. km (using Kepler's 3rd law).

Since angular diameters of Sun and Moon are almost equal:

$$R(\text{Sun}) = 19 \times R(\text{Moon})$$

Greek

Development of the heliocentric world model:
Aristarchus (310–230 BC) radius of the Sun



lunar eclipses:

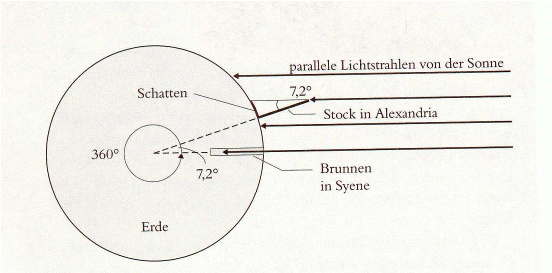
Moon fits into earth shadow twice
(in fact: 3.68 times)

$\Longrightarrow$ Radii: R(Sun)=9.5×R(Earth)

$\Longrightarrow$ common sense: smaller body moves around the larger one!

Heliocentric world model

Greek



Eratosthenes (276–195 BC): measurement of the earth's radius

Idea: measure culmination of the Sun at two places of known distance (N to S) on the same day.

Syene: Sun at zenith, Alexandria: 7.2° away from Zenith

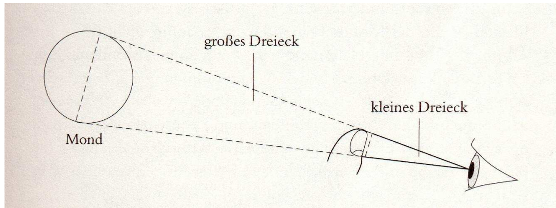
$\Longrightarrow$ Distance between Alexandria and Syene: $d/(2\pi R) = 7.2/360$

Measured: 5000 Stades

Some historians believe that this distance corresponds to ∼820 km, so if true then the radius of the Earth would have been determined to 6264 km

in fact: 6378km; repeated: 1671: Paris-Amiens (J. Picard)

Greek



The distance to the Moon and the Sun:
angular diameter of the Moon equals width of finger as seen from 1 m away

$\Longrightarrow R_{\text{moon}}/d_{\text{moon}} = 1/200$

Lunar occultations: $R_{\text{moon}} = 1/2 R_{\text{earth}}$

$\Longrightarrow R_{\text{earth}}/d_{\text{moon}} = 1/100$

$$d_{\text{moon}} = 100 \times R_{\text{earth}} = 626400\,\text{km}$$

$\Longrightarrow$ distance to the Sun:

$$d_{\text{sun}} = 19 \times d_{\text{moon}} = 11.9\,\text{Mio km}$$

Renaissance

Regiomontanus: Johannes Müller from Königsberg (Franconia) (1436–1476):

- Studies at Leipzig (1447) and Vienna (1450): Maths and Astronomy
- *Epytoma Joanis de monte regio in almagesti ptolemei* (1461–1463): translation to latin with much improved maths
- *De triangulis omnimodis* (1462–1464): foundation of modern trigonometry
- *Ephemerides astronomicae ab anno 1475–1506*: most accurate ephemerides

  $\Longrightarrow$ Navigation: Columbus & Vasco da Gama

Renaissance

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

Renaissance

(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.”

Renaissance

(Gingerich, 1993, p. 165)

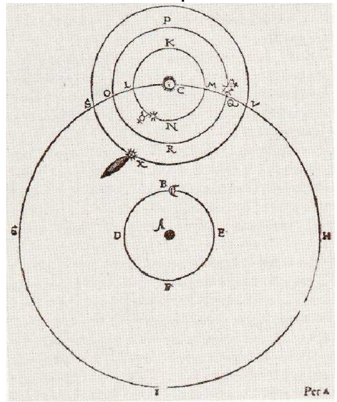
Nicolaus Copernicus (1473–1543): Earth centred Ptolemaic system is too complicated, a Sun-centred system is more elegant:

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.”

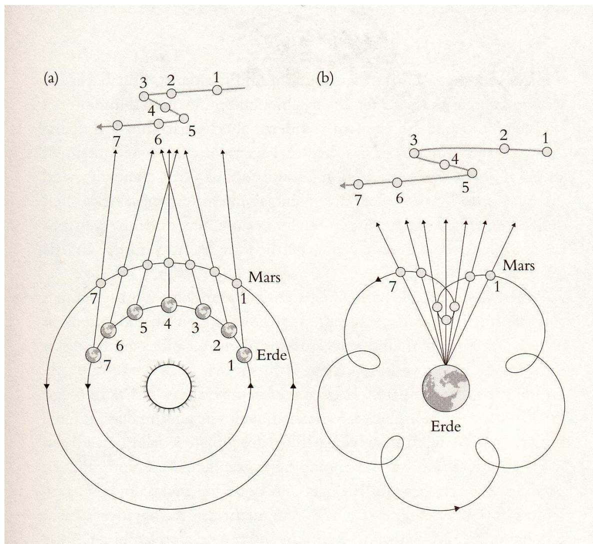
Copernican principle: The Earth is not at the center of the universe.

Renaissance

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



Renaissance



Retrograde motion: heliocentric vs geocentric model

Renaissance

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

Galileo Galilei (1564–1642): Telescopic observations, discovery of four moons of Jupiter

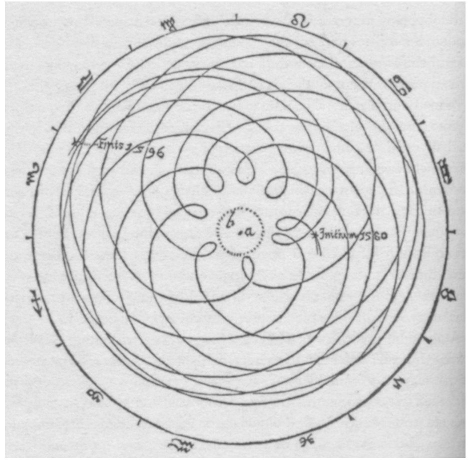
Renaissance

Johannes Kepler (1571–1630):

- born 27.12.1571, Weil der Stadt
- Studies Tübingen with Maestlin
- 1594–1600: Graz
- 1596: Mysterium Cosmographicum
- 1600–1612: Prag, assistant of Tycho Brahe, then Mathematician of emperor Rudolf II, discovered Supernova of 1604,. . .

1609: Astronomia Nova

Renaissance



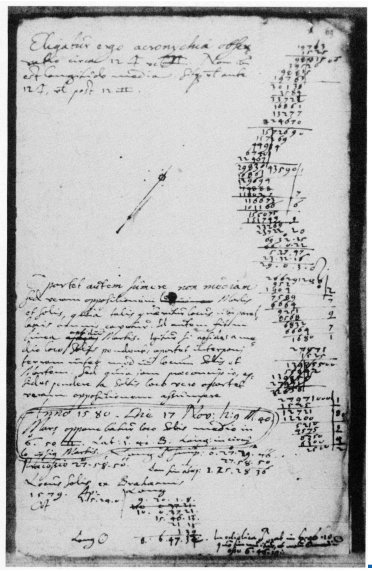
Astronomia Nova, Kapitel 1: motion of Mars in the epicycle theory between 1560 and 1596

Astronomia nova (Prag, 1609)

Critic of the epicycle theory: "panis quadragesimalis" (Osterbrezel)

$\Longrightarrow$ Inelegant!

Renaissance

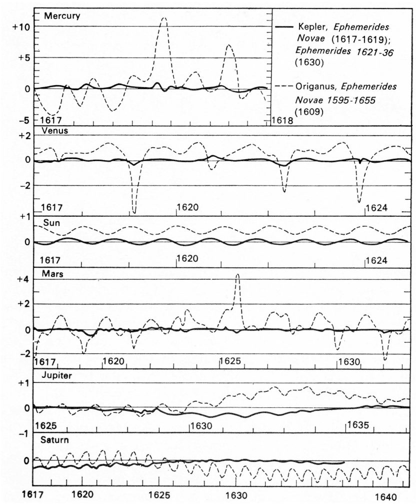


Result of Kepler's investigations:
The Keplerian laws:

1. Planets move on elliptical orbits, Sun in focus.
   ("Astronomia Nova", 1609)
2. Motion is not uniform, planet moves fast when close to the Sun.
   ("Astronomia Nova", 1609)
3. Third law comes 10 years later
   ("Harmonice Mundi", 1619)

2–23

Renaissance



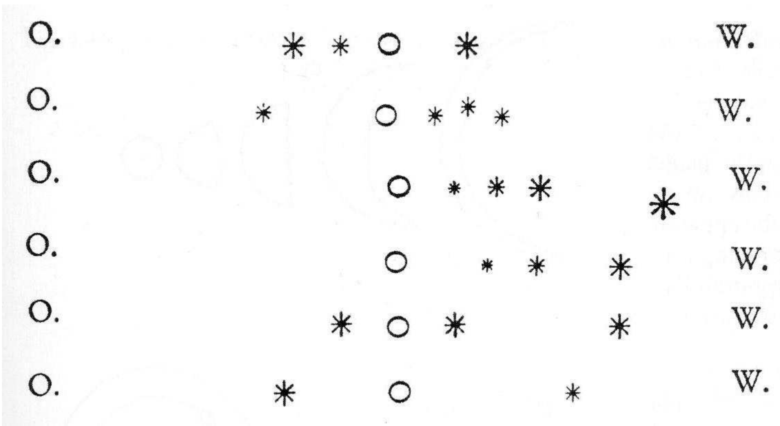
Tabulae Rudolphinae, 1627

Most precise positions of planets ever: 30× smaller errors than before

(Gingerich, 1993)

2–24

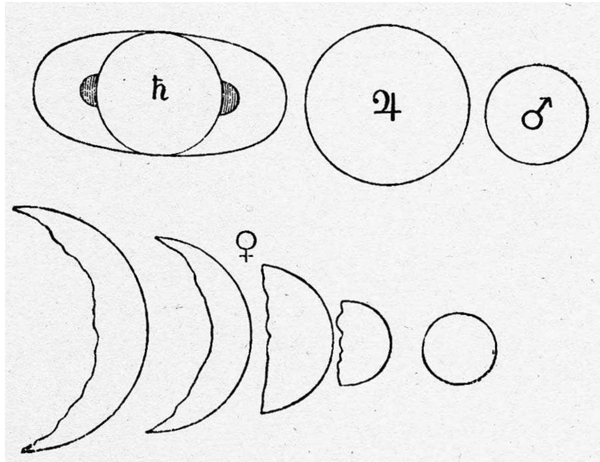
Renaissance



Moons move around Jupiter
(⟹ similar to heliocentric model!). . .

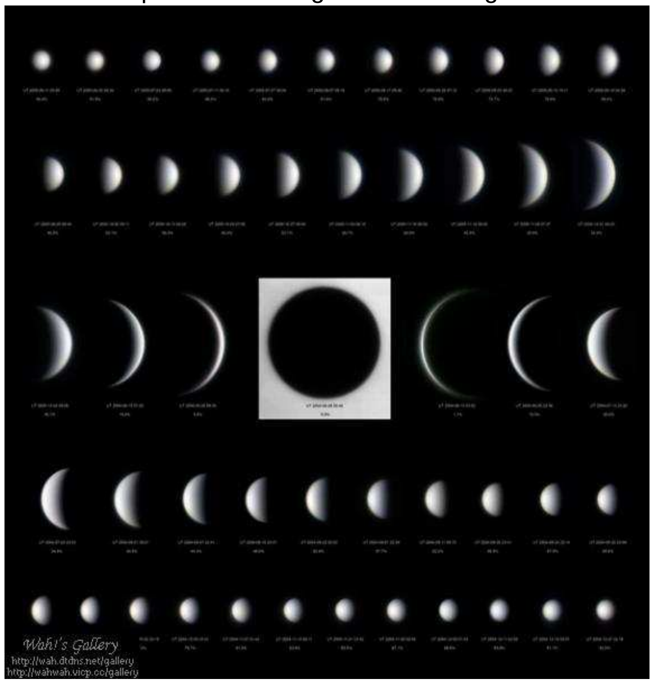
2–25

Renaissance

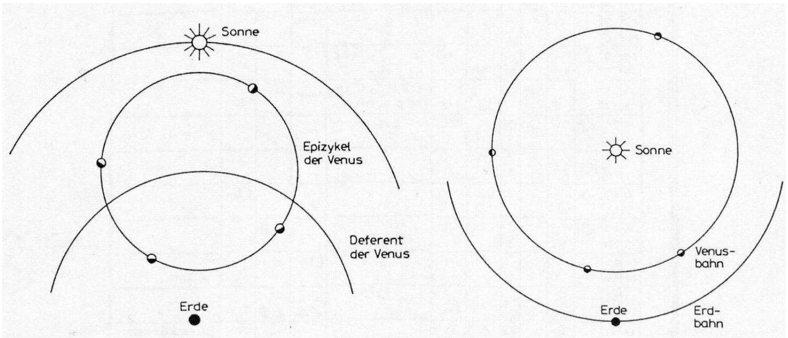


Discovery of phases of Venus (Il Saggiatore, 1623)

Observed phases and angular size changes of Venus

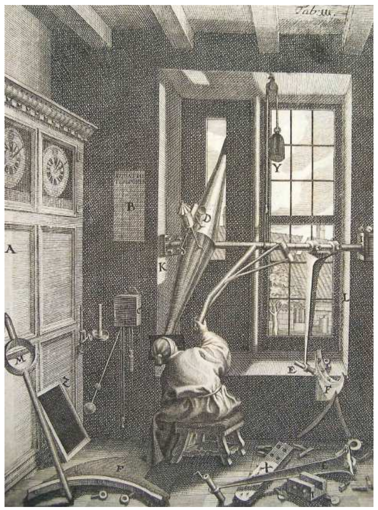


Renaissance



The observed phase changes of Venus can be explained by the heliocentric world model, but also in Tycho´s geocentric.

Rømer



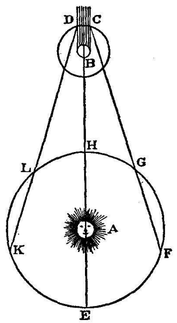


Fig. 70.

Rømer, 1676

Ole Rømer (1644–1710): measurement of the speed of light

Times of occultation of Io shift by up to 20 minutes during the year.

(Peter Horrebouw, Basis astronomiae sive astronomiae machina, Kopenhagen, 1735)

Newton

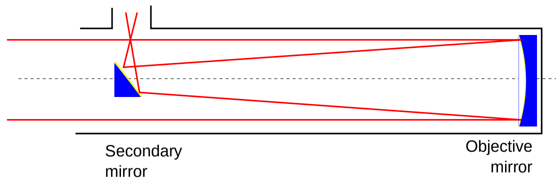
(Newton, 1730)

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

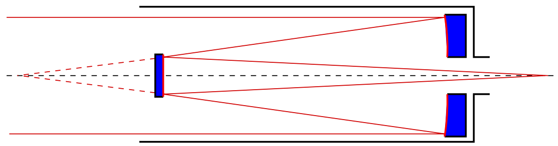
$\Longrightarrow$ Begin of modern physics based astronomy.

Telescopes

Newton telescope



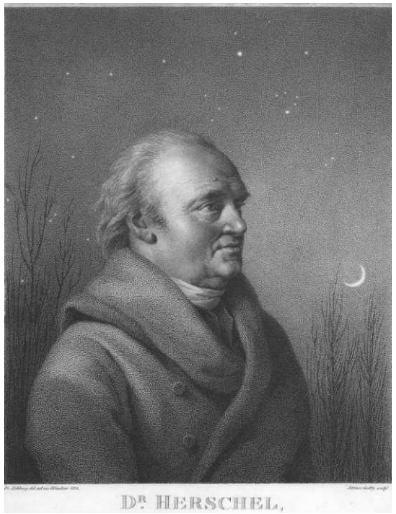
Cassegrain telescope

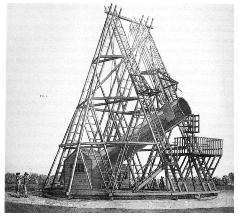


Newton (1668), Gregory (1670), Cassegrain (1672): Mirror telecopes

(mirror made polished metal [copper/zink alloy])

Herschel

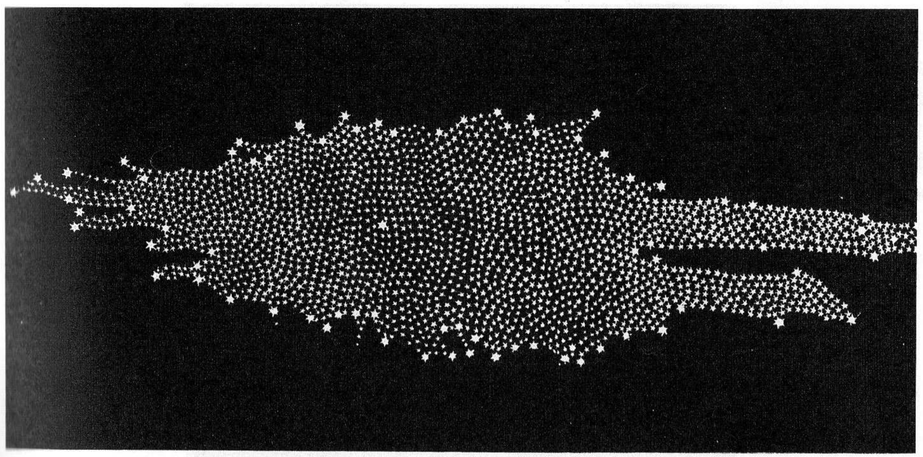




William Herschel (1738–1822):

- 15.11.1738: born in Hannover
- Musician (Oboist)
- 1759: emigration to England
- builds large reflecting telescopes
- 1781: Discovery of Uranus
- study of Nebulae
- Star counts (with his sister Caroline)

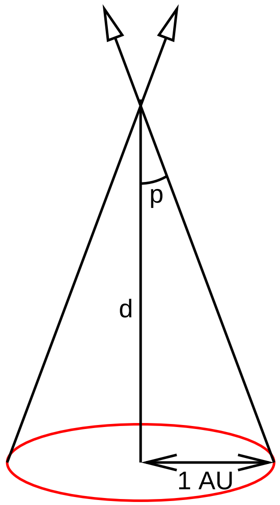
Herschel



Geometry of the Milky Way according to William Herschel (1785)

Sun is close to the centre of the Milky Way

Herschel



$\Longrightarrow$ Wanted: Measurement of a yearly parallax of a star.

Parallax (small angles):

$$p = \frac{1\,\mathrm{AU}}{d}$$

(p measured in radian)

Problem since antiguity: p is small because the stars are so far away.

Bessel

Friedrich Wilhelm Bessel (1784–1846)

Bessel (1839): first distance measurement of a star

ASTRONOMISCHE NACHRICHTEN.

№. 365. 366.

Bestimmung der Entfernung des 61sten Sterns des Schwans.

Von Herrn Geheimen-Rath und Ritter *Bessel.*

Als es *Bradley* gelungen war, seine Beobachtungen in *Kew* und *Wansted*, welche die Entdeckungen der Aberration und Nutation herbeiführten, durch diese allein genügend zu erklären, ohne dazu der Annahme einer jährlichen Parallaxe der beob- … ist nicht zu bezweifeln; allein wenn eine Untersuchung über die jährliche Parallaxe eines Fixsterns unternommen werden soll, so sind sie dennoch die einzigen, welche seine Wahl leiten können.

61 Cyg: Parallax 0.3″

$\Longrightarrow$ distance 11 light years

The great debate

Whirlpool nebula
(Lord Rosse, ≈ 1850)

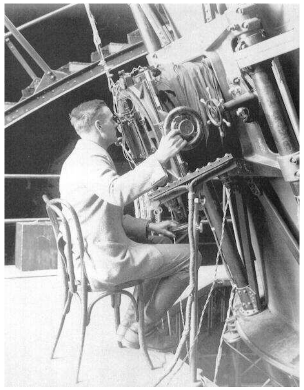
19th century: Astronomy evolves into a modern natural science:

- precise stellar position ("Durchmusterungen"=surveys)
- Photography
- Spectroscopy (Astro*physics*)

The nature of the nebulae?
The great debate: 26.4.1920
protoplanetary nebulae
or
island universe ("Welteninsel"):
Harlow Shapley vs. Heber Curtis

Hubble

Mount Wilson 2.5 m Telescope



Edwin Hubble, 1922

Aveni, A. F., 1993, Ancient Astronomers, (Washington, D.C.: Smithsonian Books)
Gingerich, O., 1993, The Eye of Heaven – Ptolemy, Copernicus, Kepler, (New York: American Institute of Physics)
Newton, I., 1730, Opticks, Vol. 4th, (London: William Innys), reprint: Dover Publications, 1952

The Planets: Overview

What is a planet?

First, need to look at the definition of a planet.

Historical background:

- antiquity–1781: 6 planets: Mercury, Venus, Earth, Mars, Jupiter, Saturn

What is a planet?

First, need to look at the definition of a planet.

Historical background:

- antiquity–1781: 6 planets: Mercury, Venus, Earth, Mars, Jupiter, Saturn
- 1781: Wilhelm Herschel discovers Uranus $\Longrightarrow$ 7 planets

What is a planet?

First, need to look at the definition of a planet.

Historical background:

- antiquity–1781: 6 planets: Mercury, Venus, Earth, Mars, Jupiter, Saturn
- 1781: Wilhelm Herschel discovers Uranus $\Longrightarrow$ 7 planets
- 1801: Giuseppe Piazzi: Ceres $\Longrightarrow$ 8 planets

What is a planet?

First, need to look at the definition of a planet.

Historical background:

- antiquity–1781: 6 planets: Mercury, Venus, Earth, Mars, Jupiter, Saturn
- 1781: Wilhelm Herschel discovers Uranus $\Longrightarrow$ 7 planets
- 1801: Giuseppe Piazzi: Ceres $\Longrightarrow$ 8 planets
- 1802: Heinrich Olbers: Pallas $\Longrightarrow$ 9 planets, Herschel coins term “asteroid”.

What is a planet?

First, need to look at the definition of a planet.

Historical background:

- antiquity–1781: 6 planets: Mercury, Venus, Earth, Mars, Jupiter, Saturn
- 1781: Wilhelm Herschel discovers Uranus $\Longrightarrow$ 7 planets
- 1801: Giuseppe Piazzi: Ceres $\Longrightarrow$ 8 planets
- 1802: Heinrich Olbers: Pallas $\Longrightarrow$ 9 planets, Herschel coins term “asteroid”.
- 1804: Karl Harding: Juno $\Longrightarrow$ 10 planets

What is a planet?

First, need to look at the definition of a planet.

Historical background:

- antiquity–1781: 6 planets: Mercury, Venus, Earth, Mars, Jupiter, Saturn
- 1781: Wilhelm Herschel discovers Uranus $\Longrightarrow$ 7 planets
- 1801: Giuseppe Piazzi: Ceres $\Longrightarrow$ 8 planets
- 1802: Heinrich Olbers: Pallas $\Longrightarrow$ 9 planets, Herschel coins term “asteroid”.
- 1804: Karl Harding: Juno $\Longrightarrow$ 10 planets
- 1807: Heinrich Olbers: Vesta $\Longrightarrow$ 11 planets

What is a planet?

First, need to look at the definition of a planet.

Historical background:

- antiquity–1781: 6 planets: Mercury, Venus, Earth, Mars, Jupiter, Saturn
- 1781: Wilhelm Herschel discovers Uranus $\Longrightarrow$ 7 planets
- 1801: Giuseppe Piazzi: Ceres $\Longrightarrow$ 8 planets
- 1802: Heinrich Olbers: Pallas $\Longrightarrow$ 9 planets, Herschel coins term “asteroid”.
- 1804: Karl Harding: Juno $\Longrightarrow$ 10 planets
- 1807: Heinrich Olbers: Vesta $\Longrightarrow$ 11 planets
- 1845: Karl Hencke: Astrea $\Longrightarrow$ 12 planets

What is a planet?

First, need to look at the definition of a planet.

Historical background:

- antiquity–1781: 6 planets: Mercury, Venus, Earth, Mars, Jupiter, Saturn
- 1781: Wilhelm Herschel discovers Uranus $\Longrightarrow$ 7 planets
- 1801: Giuseppe Piazzi: Ceres $\Longrightarrow$ 8 planets
- 1802: Heinrich Olbers: Pallas $\Longrightarrow$ 9 planets, Herschel coins term “asteroid”.
- 1804: Karl Harding: Juno $\Longrightarrow$ 10 planets
- 1807: Heinrich Olbers: Vesta $\Longrightarrow$ 11 planets
- 1845: Karl Hencke: Astrea $\Longrightarrow$ 12 planets
- 1846: Johann Gottfried Galle discovers Neptune $\Longrightarrow$ 13 planets

What is a planet?

First, need to look at the definition of a planet.

Historical background:

- antiquity–1781: 6 planets: Mercury, Venus, Earth, Mars, Jupiter, Saturn
- 1781: Wilhelm Herschel discovers Uranus $\Longrightarrow$ 7 planets
- 1801: Giuseppe Piazzi: Ceres $\Longrightarrow$ 8 planets
- 1802: Heinrich Olbers: Pallas $\Longrightarrow$ 9 planets, Herschel coins term “asteroid”.
- 1804: Karl Harding: Juno $\Longrightarrow$ 10 planets
- 1807: Heinrich Olbers: Vesta $\Longrightarrow$ 11 planets
- 1845: Karl Hencke: Astrea $\Longrightarrow$ 12 planets
- 1846: Johann Gottfried Galle discovers Neptune $\Longrightarrow$ 13 planets
- 1847: Karl Hencke: Hebe $\Longrightarrow$ 14 planets

What is a planet?

First, need to look at the definition of a planet.

Historical background:

- antiquity–1781: 6 planets: Mercury, Venus, Earth, Mars, Jupiter, Saturn
- 1781: Wilhelm Herschel discovers Uranus $\Longrightarrow$ 7 planets
- 1801: Giuseppe Piazzi: Ceres $\Longrightarrow$ 8 planets
- 1802: Heinrich Olbers: Pallas $\Longrightarrow$ 9 planets, Herschel coins term “asteroid”.
- 1804: Karl Harding: Juno $\Longrightarrow$ 10 planets
- 1807: Heinrich Olbers: Vesta $\Longrightarrow$ 11 planets
- 1845: Karl Hencke: Astrea $\Longrightarrow$ 12 planets
- 1846: Johann Gottfried Galle discovers Neptune $\Longrightarrow$ 13 planets
- 1847: Karl Hencke: Hebe $\Longrightarrow$ 14 planets
- 1848: Andrew Graham: Metis $\Longrightarrow$ 15 planets

What is a planet?

First, need to look at the definition of a planet.

Historical background:

- antiquity–1781: 6 planets: Mercury, Venus, Earth, Mars, Jupiter, Saturn
- 1781: Wilhelm Herschel discovers Uranus $\Longrightarrow$ 7 planets
- 1801: Giuseppe Piazzi: Ceres $\Longrightarrow$ 8 planets
- 1802: Heinrich Olbers: Pallas $\Longrightarrow$ 9 planets, Herschel coins term “asteroid”.
- 1804: Karl Harding: Juno $\Longrightarrow$ 10 planets
- 1807: Heinrich Olbers: Vesta $\Longrightarrow$ 11 planets
- 1845: Karl Hencke: Astrea $\Longrightarrow$ 12 planets
- 1846: Johann Gottfried Galle discovers Neptune $\Longrightarrow$ 13 planets
- 1847: Karl Hencke: Hebe $\Longrightarrow$ 14 planets
- 1848: Andrew Graham: Metis $\Longrightarrow$ 15 planets
- 1849: Annibale de Gasparis: Hygiea $\Longrightarrow$ 16 planets

What is a planet?

First, need to look at the definition of a planet.

Historical background:

- antiquity–1781: 6 planets: Mercury, Venus, Earth, Mars, Jupiter, Saturn
- 1781: Wilhelm Herschel discovers Uranus $\Longrightarrow$ 7 planets
- 1801: Giuseppe Piazzi: Ceres $\Longrightarrow$ 8 planets
- 1802: Heinrich Olbers: Pallas $\Longrightarrow$ 9 planets, Herschel coins term “asteroid”.
- 1804: Karl Harding: Juno $\Longrightarrow$ 10 planets
- 1807: Heinrich Olbers: Vesta $\Longrightarrow$ 11 planets
- 1845: Karl Hencke: Astrea $\Longrightarrow$ 12 planets
- 1846: Johann Gottfried Galle discovers Neptune $\Longrightarrow$ 13 planets
- 1847: Karl Hencke: Hebe $\Longrightarrow$ 14 planets
- 1848: Andrew Graham: Metis $\Longrightarrow$ 15 planets
- 1849: Annibale de Gasparis: Hygiea $\Longrightarrow$ 16 planets
- 1849: Annibale de Gasparis: Parthenope $\Longrightarrow$ 17 planets

What is a planet?

First, need to look at the definition of a planet.

Historical background:

- antiquity–1781: 6 planets: Mercury, Venus, Earth, Mars, Jupiter, Saturn
- 1781: Wilhelm Herschel discovers Uranus $\Longrightarrow$ 7 planets
- 1801: Giuseppe Piazzi: Ceres $\Longrightarrow$ 8 planets
- 1802: Heinrich Olbers: Pallas $\Longrightarrow$ 9 planets, Herschel coins term “asteroid”.
- 1804: Karl Harding: Juno $\Longrightarrow$ 10 planets
- 1807: Heinrich Olbers: Vesta $\Longrightarrow$ 11 planets
- 1845: Karl Hencke: Astrea $\Longrightarrow$ 12 planets
- 1846: Johann Gottfried Galle discovers Neptune $\Longrightarrow$ 13 planets
- 1847: Karl Hencke: Hebe $\Longrightarrow$ 14 planets
- 1848: Andrew Graham: Metis $\Longrightarrow$ 15 planets
- 1849: Annibale de Gasparis: Hygiea $\Longrightarrow$ 16 planets
- 1849: Annibale de Gasparis: Parthenope $\Longrightarrow$ 17 planets
- Sometime in late 1800s: Asteroids are not planets $\Longrightarrow$ 8 planets

What is a planet?

- 1930: Clyde Tombaugh: Pluto ($d = 2400$ km) $\Longrightarrow$ 9 planets

What is a planet?

- 1930: Clyde Tombaugh: Pluto ($d = 2400$ km) $\Longrightarrow$ 9 planets
- 2002: Chad Trujillo & Michael Brown 50000 Quaoar ($d \sim 1300$ km)

What is a planet?

- 1930: Clyde Tombaugh: Pluto ($d = 2400$ km) $\Longrightarrow$ 9 planets
- 2002: Chad Trujillo & Michael Brown 50000 Quaoar ($d \sim 1300$ km)
- 2003: Brown et al.: 90377 Sedna (1200 km $\lesssim d \lesssim$ 1800 km)

What is a planet?

- 1930: Clyde Tombaugh: Pluto ($d = 2400$ km) $\Longrightarrow$ 9 planets
- 2002: Chad Trujillo & Michael Brown 50000 Quaoar ($d \sim 1300$ km)
- 2003: Brown et al.: 90377 Sedna (1200 km $\lesssim d \lesssim$ 1800 km)
- 2005: Brown et al.: 2003 UB313 (aka "Xena") ($d \sim 2400$ km)

  $\Longrightarrow$ 136199 Eris

  $\Longrightarrow$ 10 planets ?!?

What is a planet?

- 1930: Clyde Tombaugh: Pluto ($d = 2400$ km) $\Longrightarrow$ 9 planets
- 2002: Chad Trujillo & Michael Brown 50000 Quaoar ($d \sim 1300$ km)
- 2003: Brown et al.: 90377 Sedna (1200 km $\lesssim d \lesssim$ 1800 km)
- 2005: Brown et al.: 2003 UB313 (aka "Xena") ($d \sim 2400$ km)

  $\Longrightarrow$ 136199 Eris

  $\Longrightarrow$ 10 planets ?!?
- BUT: High frequency of discovering transneptunian objects

What is a planet?

- 1930: Clyde Tombaugh: Pluto ($d = 2400$ km) $\Longrightarrow$ 9 planets
- 2002: Chad Trujillo & Michael Brown 50000 Quaoar ($d \sim 1300$ km)
- 2003: Brown et al.: 90377 Sedna (1200 km $\lesssim d \lesssim$ 1800 km)
- 2005: Brown et al.: 2003 UB313 (aka "Xena") ($d \sim 2400$ km)

  $\Longrightarrow$ 136199 Eris

  $\Longrightarrow$ 10 planets ?!?
- BUT: High frequency of discovering transneptunian objects

Summer 2006: International Astronomical Union General Assembly, Prague

$\Longrightarrow$ Resolution GA26/5 and 6:Definition of a planet

$\Longrightarrow$ 8 planets

RESOLUTION 5

Definition of a Planet in the Solar System

Contemporary observations are changing our understanding of planetary systems, and it is important that our nomenclature for objects reflect our current understanding. This applies, in particular, to the designation "planets". The word "planet" originally described "wanderers" that were known only as moving lights in the sky. Recent discoveries lead us to create a new definition, which we can make using currently available scientific information.

The IAU therefore resolves that planets and other bodies, except satellites, in our Solar System be defined into three distinct categories in the following way:

(1) A planet[1] is a celestial body that
- (a) is in orbit around the Sun,
- (b) has sufficient mass for its self-gravity to overcome rigid body forces so that it assumes a hydrostatic equilibrium (nearly round) shape, and
- (c) has cleared the neighbourhood around its orbit.

(2) A "dwarf planet" is a celestial body that
- (a) is in orbit around the Sun,
- (b) has sufficient mass for its self-gravity to overcome rigid body forces so that it assumes a hydrostatic equilibrium (nearly round) shape[2],
- (c) has not cleared the neighbourhood around its orbit, and
- (d) is not a satellite.

(3) All other objects[3], except satellites, orbiting the Sun shall be referred to collectively as "Small Solar System Bodies".

1 The eight planets are: Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, and Neptune.

2. An IAU process will be established to assign borderline objects into either dwarf planet and other categories.

3. These currently include most of the Solar System asteroids, most Trans-Neptunian Objects (TNOs), comets, and other small bodies.

3–3

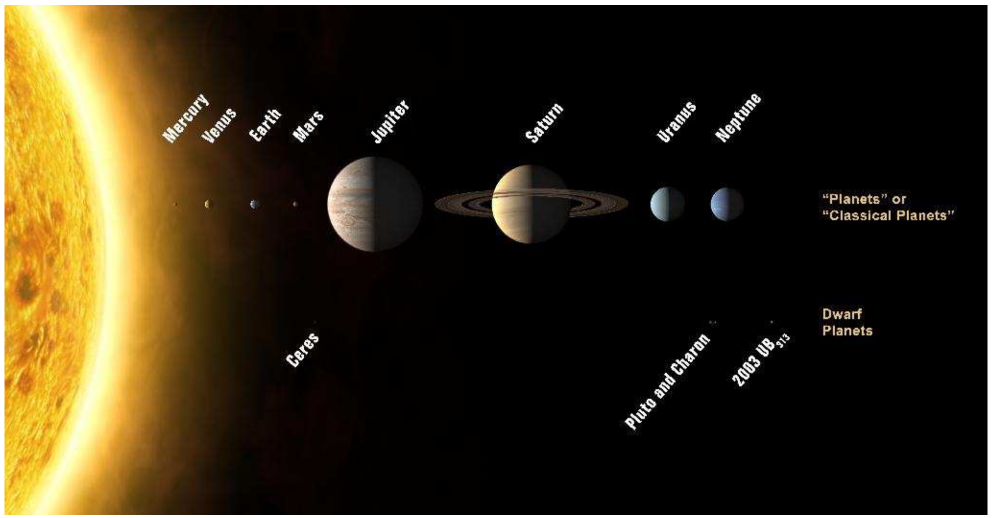
RESOLUTION 6

Pluto

The IAU further resolves:

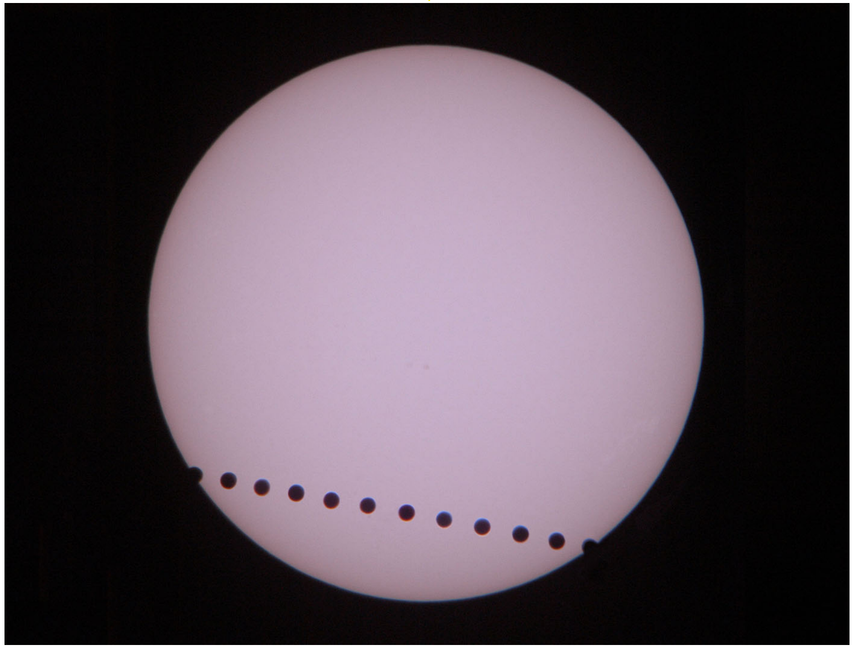
Pluto is a "dwarf planet" by the above definition and is recognized as the prototype of a new category of Trans-Neptunian Objects[1].

1 An IAU process will be established to select a name for this category.



8 Planets and 3 dwarf planets IAU0603

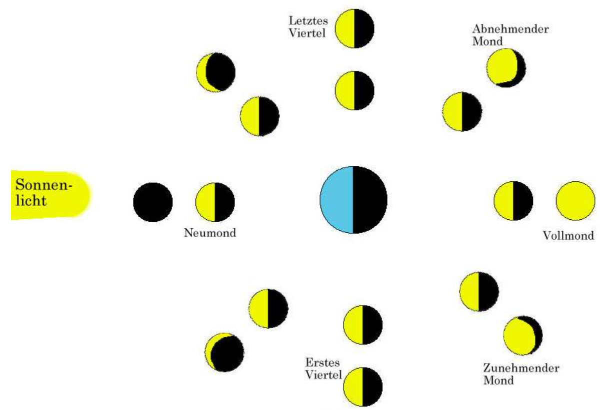
Venus Transit, 2004 June 8



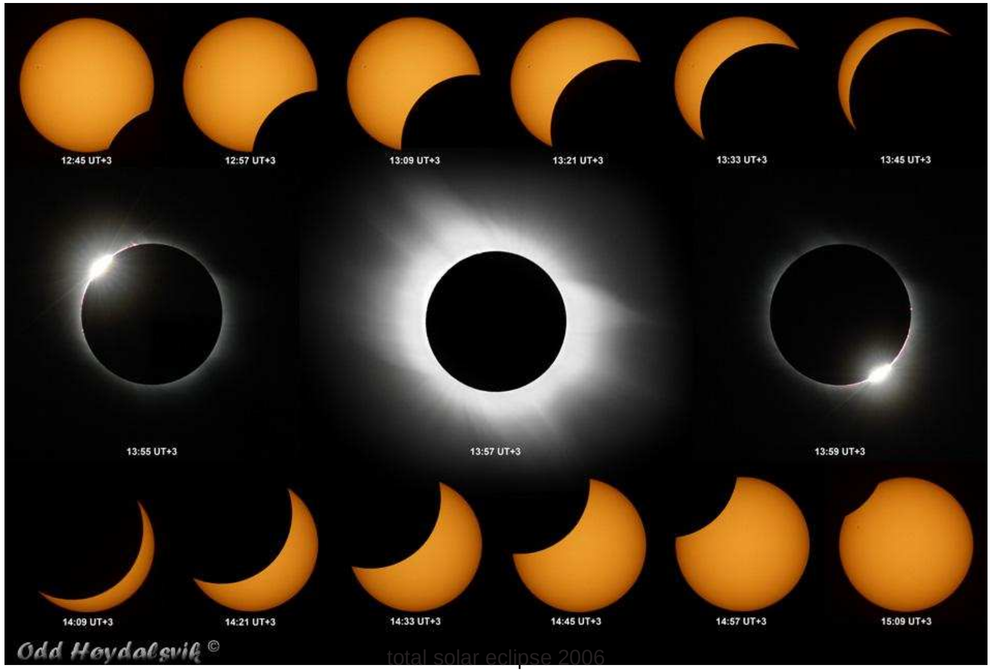
Elio Daniele, Palermo

3–6

Earth-Moon system



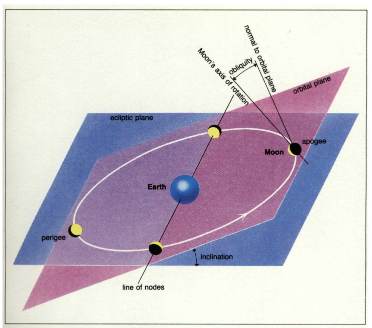
Phases of the moon (credit: Uni Kiel)



Moon and Sun have very similar apparent diameters: Eclipses

3–8

Eclipses



- Ecliptic: orbital plane of the Earth around the Sun.
- orbital plane of the moon inclined wrt. ecliptic by $i = 5^\circ$
- line of nodes: intersection of the two orbital planes
- eclipses occur only when Moon is close to one of the nodes

  $\Longrightarrow$ two eclipse seasons per year

3–9

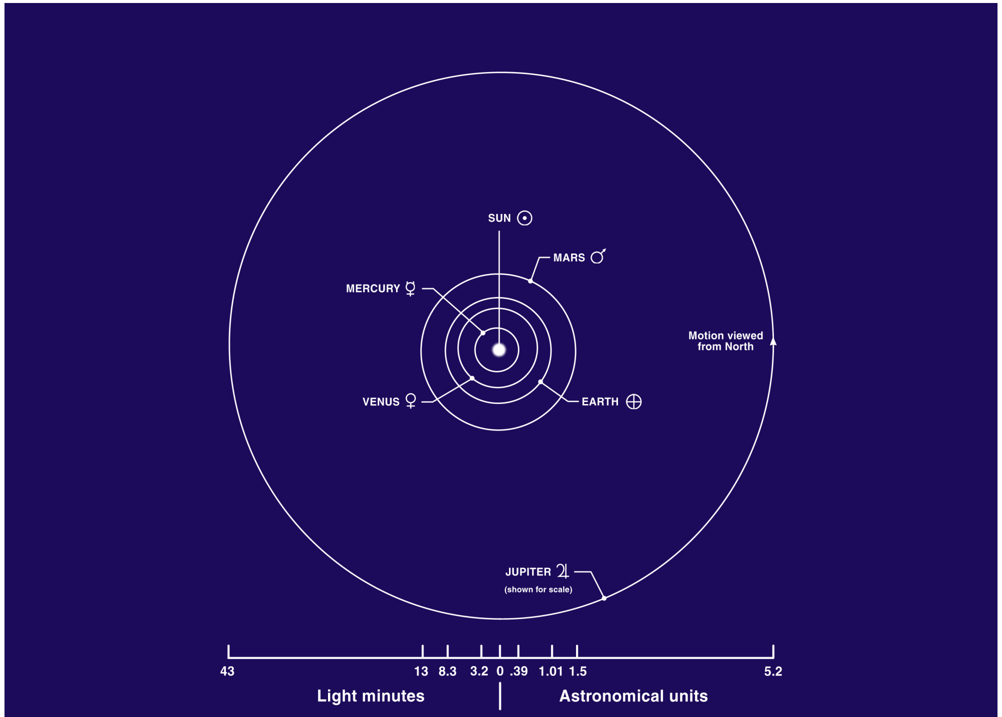
Overview

Division of Solar System into two major types of planets:

1. Inner "Terrestrial" Planets: Mercury, Venus, Earth/Moon, Mars:

   $\Longrightarrow$ all similar to Earth ("rocks").

   $\Longrightarrow$ *no moons* (Earth/Moon better called "twins")



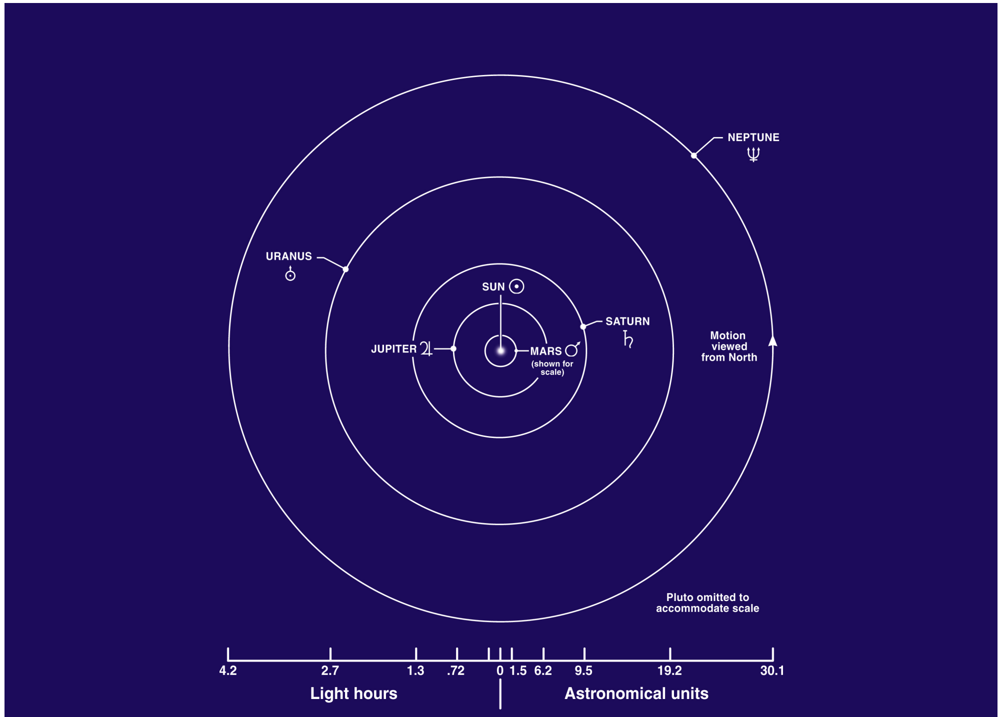
The Inner Planets (SSE, NASA)

Overview

Division of Solar System into two major types of planets:

1. Inner “Terrestrial” Planets: Mercury, Venus, Earth/Moon, Mars:
   $\Longrightarrow$ all similar to Earth (“rocks”).
   $\Longrightarrow$ *no moons* (Earth/Moon better called “twins”)
2. Outer Planets: Jupiter, Saturn, Uranus, Neptune:
   $\Longrightarrow$ “gas giants”
   $\Longrightarrow$ all have *extensive moon systems*

Although not planets (i.e., motion not around Sun), large moons of gas giants are very similar in structure to terrestrial planets.



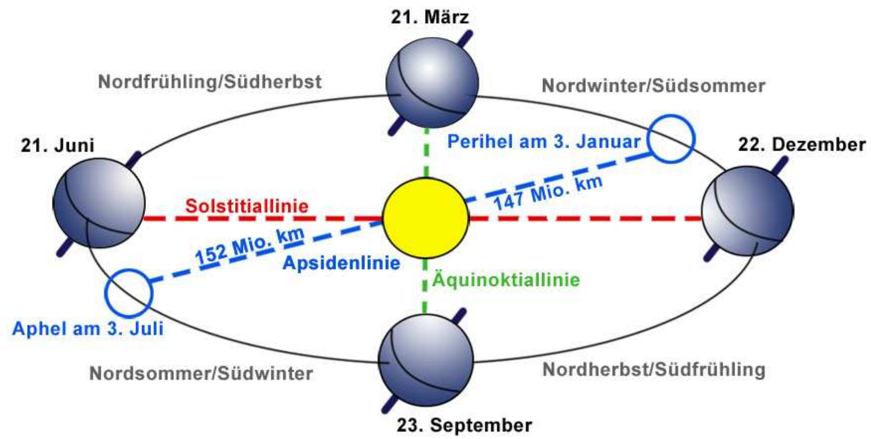
The Outer Planets (SSE, NASA)

Planets: Properties

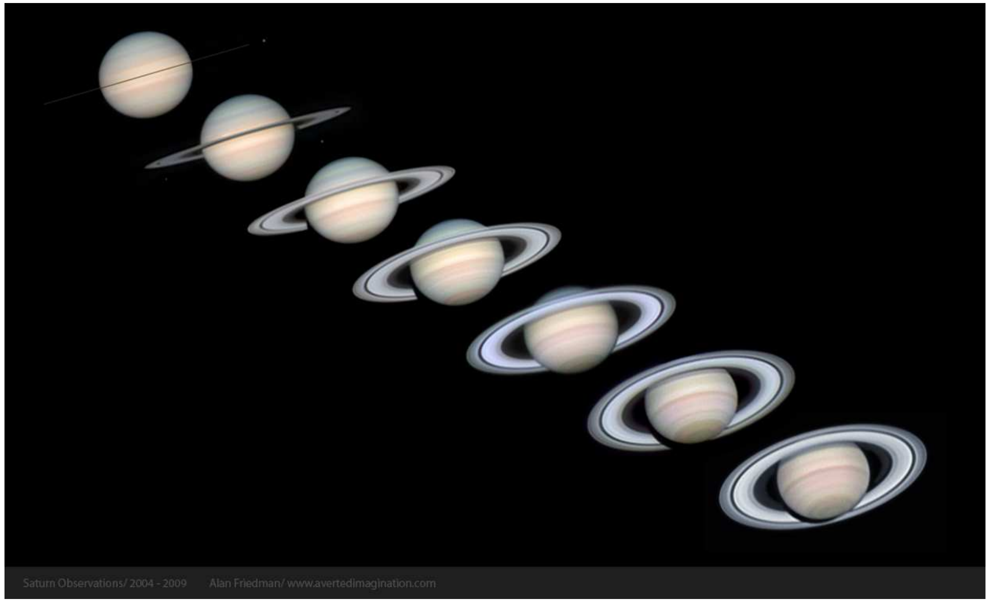
		a [AU]	P_{orb} [yr]	i [°]	e	P_{rot}	$M/M_\oplus$	$R/R_\oplus$
Mercury	☿	0.387	0.241	7.00	0.205	58.8 d	0.055	0.383
Venus	♀	0.723	0.615	3.40	0.007	−243.0 d	0.815	0.949
Earth	⊕	1.000	1.000	0.00	0.017	23.9 h	1.000	1.00
Mars	♂	1.52	1.88	1.90	0.094	24.6 h	0.107	0.533
Jupiter	♃	5.20	11.9	1.30	0.049	9.9 h	318	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;

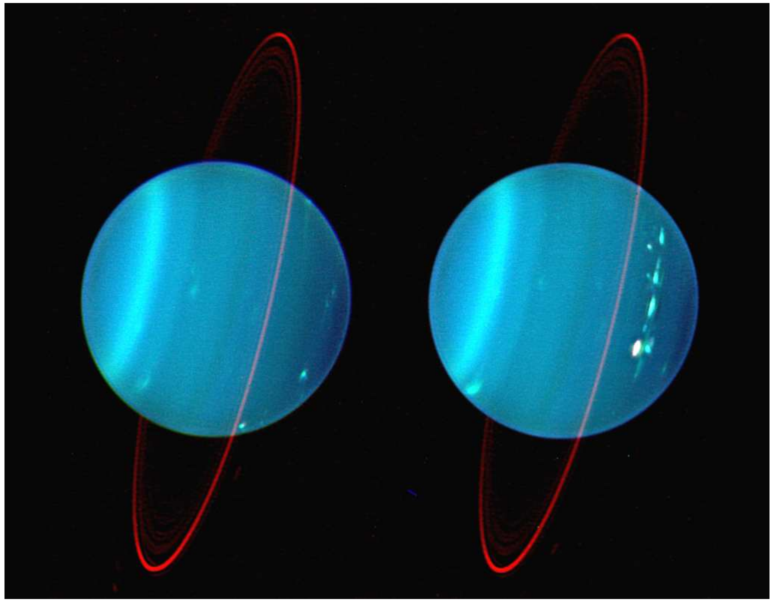
a: semi-major axis P_{orb}: orbital period i: orbital inclination (wrt Earth's orbit)
e: eccentricity of the orbit P_{rot}: rotational period M: mass 1 AU = 1.496 ×
R: equatorial radius
10^{11} m.



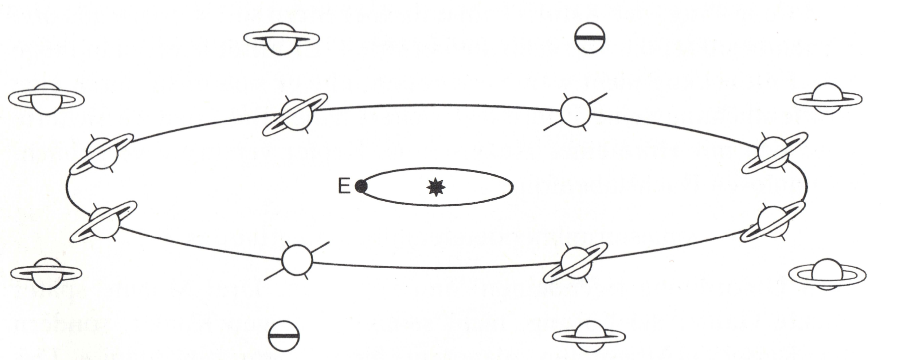
Earth orbit, inclination of the rotation axis and the seasons of the year.
Perihelion: January 3. Sun is closest in northern winter.



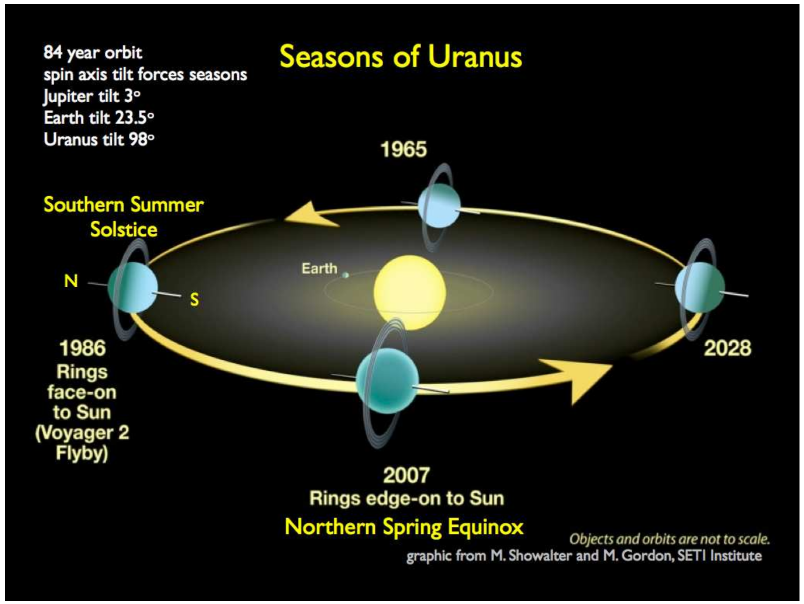
2004–2009: Seasons on Saturn: 6 years of Saturns orbit.



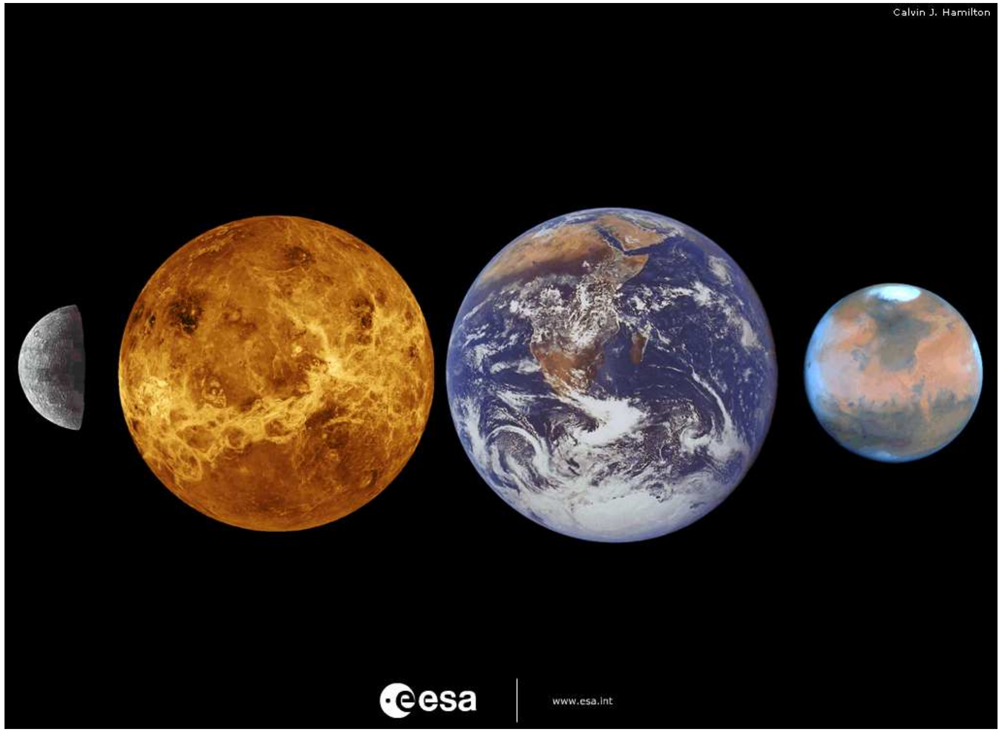
Uranus: rings and tilted rotation
Credit: Lawrence Sromovsky, (Univ. Wisconsin-Madison), Keck Observatory

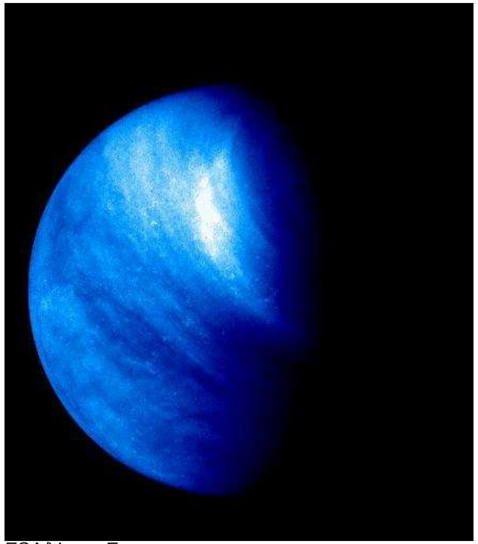


Seasons on Saturn
Kippenhahn: Unheimliche Welten



Uranus: Seasons
Credit: Space Science & Engeneering Center (Univ. Wisconsin-Madison)



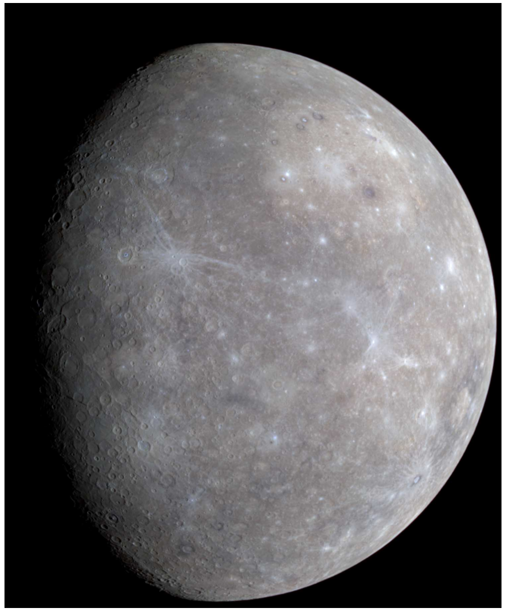


ESA/Venus Express

Venus:

- similar size to Earth, similar structure
- insolation $\sim 2\times$ Earth
- very slow rotation (243 d, retrograde; $\Longrightarrow$ no B-field)
- very dense atmosphere: surface pressure $\sim 90\times$ Earth
- atmosphere: 96.5% CO_2, 3.5% N
  $\Longrightarrow$ strong greenhouse effect
  $\Longrightarrow$ surface temperature $\sim 460°$C.
- acid rain (yes, sulphuric acid!)

Information mainly from radar surveying from Earth and from Magellan (1990–1994), plus images from Pioneer Venus Probe (1979). Several landings (Venera, 1975/1981). Currently studied by ESA's Venus Express probe (launch April 2005, arrival April 2006, mission until end-2012).



NASA/MESSENGER, 2008 Jan

Mercury:

- not much larger than Moon
- densest of all terrestrial planets
- no evidence for atmosphere
- Rotation period: 59 d, $2/3$ of orbital period.
- surface: impact craters
- Early information available from Mariner 10 (three flybys, 1974/1975)
- NASA mission "Messenger"
  (launched 2004 August 3, flybys 2008 and 2009, in orbit from 2011 on)
- ESA Mission Bepi Colombo, planned for $\sim$ 2014, arrival 2020

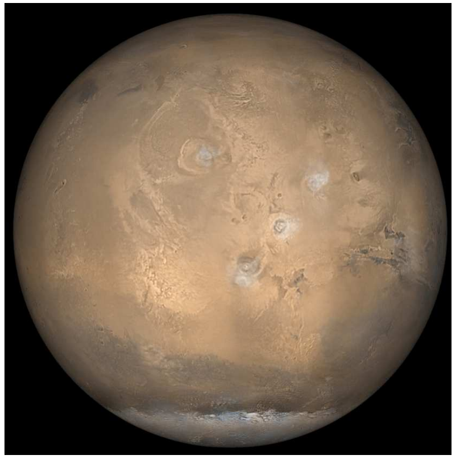
Earth/Moon, seen from Mars (NASA/Malin)

Earth:

- double planet system
- Earth surface: *dominated by plate tectonics, erosion*
- atmosphere: 80% N_2, 20%O_2
  $\Longrightarrow$ moderate greenhouse effect
  $\Longrightarrow$ surface temperature $>0°$C.
- water present

Moon:

- very similar to Mercury, overall
- Mariae (plains from massive impacts) and impact craters
- Rotation synchronous to orbit around Earth

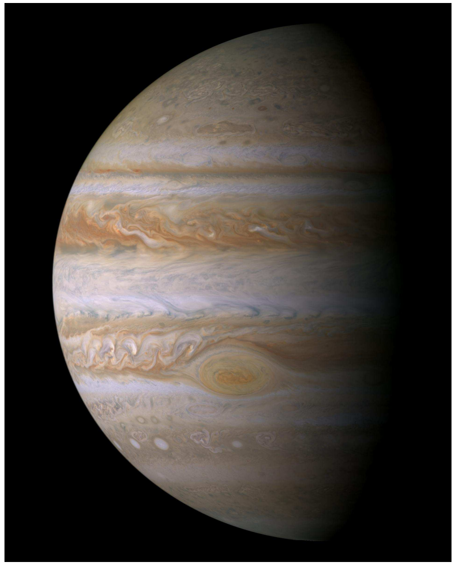


Mars:

- smaller than Earth
- very low density ($\langle\rho\rangle \sim 3\,\mathrm{g\,cm^{-3}}$)
  $\Longrightarrow$ small core, probably Fe and Fe_xS_y,
- polar caps, seasons
- thin atmosphere, clouds, fog,. . .
- water sublimes
  $\Longrightarrow$ no liquid water today
- Volcanism (large shield volcanoes
  $\Longrightarrow$ no (?) plate tectonics)
- atmosphere: 95% CO_2
  $\Longrightarrow$ weak greenhouse effect
- two moons (captured asteroids)

NASA, Mars Global Surveyor

Early Exploration through Mariner missions and Viking 1 and Viking 2 orbiters and landers in 1970s, recently, strong interest (NASA Mars Global Surveyor [MGS], ESA Mars Express, plus several landers). Currently best surveyed planet except for Earth.

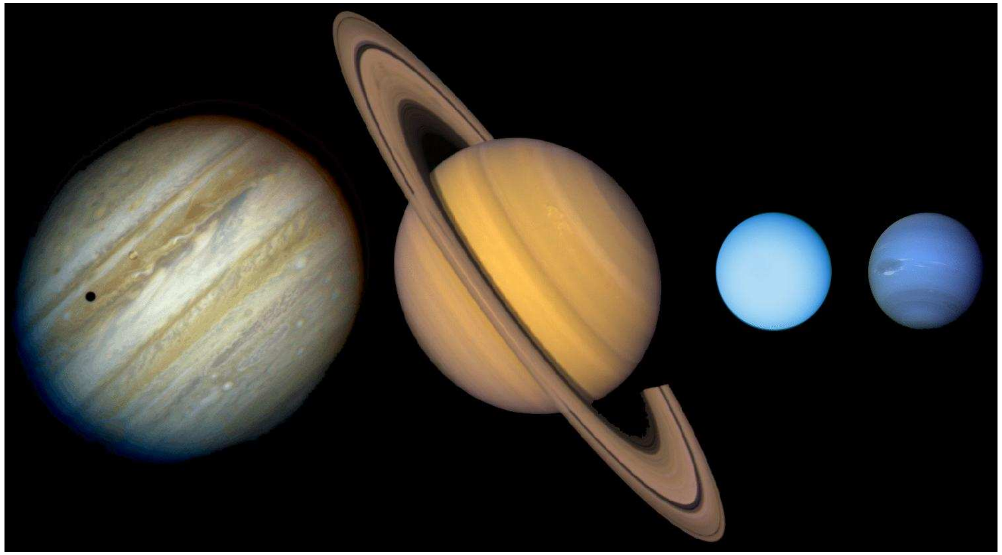


Jupiter:

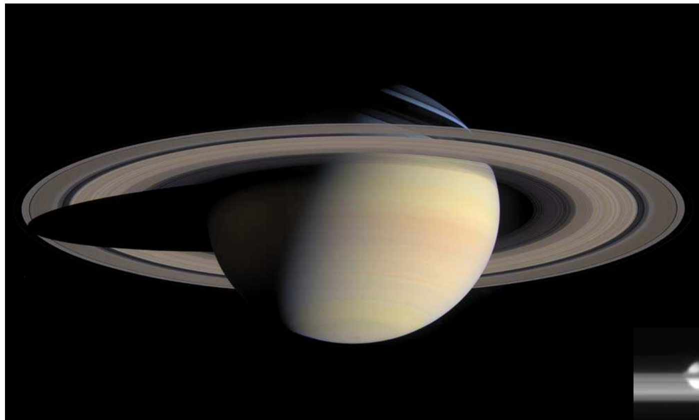
- Largest planet in solar system
- rapid rotation $\Longrightarrow$ severely flattened, banded atmosphere (Coriolis force), Great Red Spot
- strong magnetic field (strong radio emission)
- atmosphere: 75% H, 24% He (by mass), very close to solar
- differential rotation (rotation period 9 h 50 m at equator, 9 h 55 m at poles)
- strong magnetic field
- four major “Galilean” moons plus 59 small ones (as of Nov 2010; captured asteroids)

NASA/ESA, Cassini-Huyghens

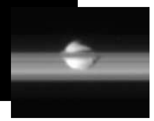
Early Exploration 1970s through Pioneer 11 and 12, and then through the Voyager probes. Intensively studied by NASA’s Galileo project (ended 2003 Sep 14).



The jovian planets, ©C.J. Hamilton



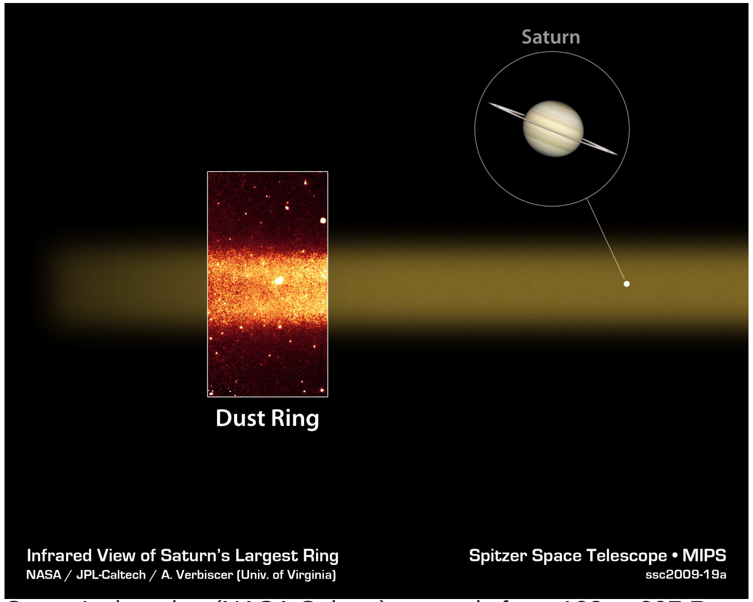
NASA/ESA Cassini, 2004 Oct.



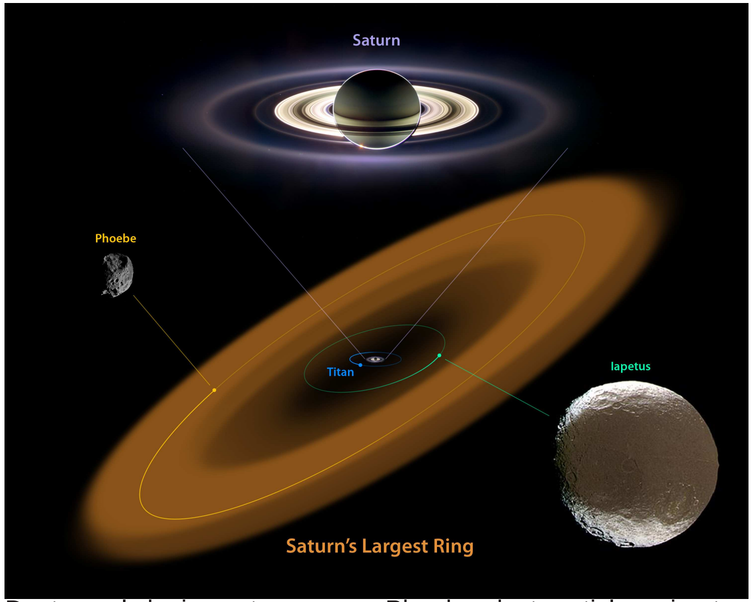
NASA/ESA Cassini

Saturn:

- similar to Jupiter, slightly smaller
- rapid rotation $\Longrightarrow$ flattened, banded atmosphere
- atmosphere: 75% H, 24% He (by mass), molecules etc. similar to Jupiter
- Rings!
- six major moons plus 61 small ones (as of Nov 2010; mainly captured asteroids)
- Early Exploration in 1970s with Pioneer 11 and 12 and the Voyager probes.
  Studied since 2004 July 1 by NASA/ESA Cassini-Huygens project (duration until 2017)



Saturn's dust ring (NASA Spitzer): extends from 128 to 207 R_S, 40 R_S thick. (Verbiscer et al. 2009, Science October 22)



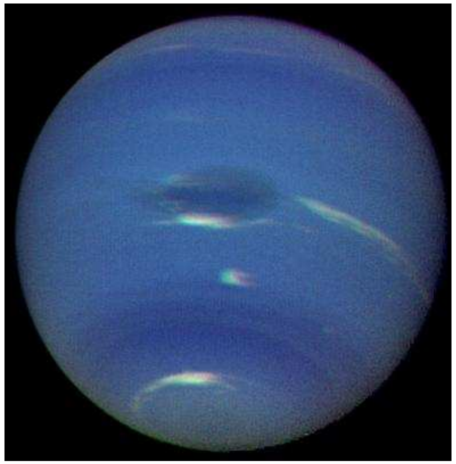
Dust supply by impacts on moon Phoebe, dust particles migrate inwards and are swept up by Iapetus

NASA Voyager 2, 1986 Jan 10

Uranus:

- atmosphere cold (59 K = −214°C) $\Longrightarrow$ ammonia has frozen out
- methane, hydrogen, and helium detected so far (less He than expected from Jupiter and Saturn!) $\Longrightarrow$ bluish color
- inclination of rotation axis: 98° ("rolling on ecliptic plane").
- small ring system
- five major moons in equatorial plane plus 22 small ones (as of Nov 2010; captured asteroids)

Flyby of Voyager 2 in 1986 January, since then only remote sensing from Hubble Space Telescope (HST) and ground based instruments.



NASA Voyager 2

Neptune:

- atmosphere similar to Uranus, but more active; bright methane clouds above general cloud layer
- ring system (5 individual rings)
- Two major moons (Triton, 2720 km diameter(!) and Nereid 355 km), 11 captured asteroids

Flyby in 1989 August by Voyager 2, only HST since then (showed in 1995 that dark spot has vanished, detected new storm system)

Structure

Questions that we will deal with:

- How do the planets move?
  Kepler's laws and their physical interpretation
- What do planetary surfaces look like?
  craters, plate tectonics, volcanism
- What is the internal structure of the planets?
  hydrostatic structure
- How do planetary atmospheres work?
  hydrostatic structure (again)
- What is the nature of the minor bodies?
- How did the planetary system form?
- Is the solar system normal?
  Are there planets elsewhere? (Later)