Planets and Astrobiology

Plan of the course

Planets and planetary systems

The Solar System
Extrasolar planets and planetary systems
Planetary formation

Interstellar medium and astrochemistry

Diffuse ISM, molecules, dust

Astrobiology

Terrestrial life in an astronomical context
Search for life and habitable environments outside Earth

The Solar System: an overview

Planets and Astrobiology (2015-2016)
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Importance of the study of the Solar System

Solar System bodies are a unique laboratory were a large variety of geophysical and geochemical conditions, as well as N-body dynamical interactions, can be tested

The laws of mechanics, gravitation and general relativity have been initially tested in the Solar System

Solar System bodies are the reference for studies of extrasolar planets (exoplanets)

Only Solar System bodies can be studies with sufficient detail to characterize their physical and geochemical properties

Definitions

- Planet
  - Distinction between planet and star
    - Planets have a mass lower than the critical mass for triggering the thermonuclear reaction of deuterium burning
      - Limit mass ~ 13 $M_{Jupiter}$
    - Bodies with higher mass, with thermonuclear fusion of deuterium, but not of hydrogen, are called *brown dwarfs*
      - Mass interval of brown dwarfs 13 $M_{Jupiter} < M <$ ~ 75-80 $M_{Jupiter}$
  - Distinction between planets, dwarf planets and minor bodies
    - See IAU definition next slide
- Satellite
  - Astronomical body orbiting a planet
    - with $M_{satellite} < M_{planet}$, but there is no quantitative definition

Planets, dwarf planet, minor bodies
IAU definition – valid for the Solar System

(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 to the dwarf planet or to another category.
[3] These currently include most of the Solar System asteroids, most Trans-Neptunian Objects (TNOs),comets, and other small bodies.

Dichotomy of the mean density
Rocky planets vs. gaseous/icy

Dichotomy in mass/radius
Giants planets vs. small (terrestrial) planets

There is a remarkable gap in the masses:
no planet with mass intermediate between the Earth mass and icy giants (~14 Earth masses) is known to exist

Rocky planets and gaseous/icy planets

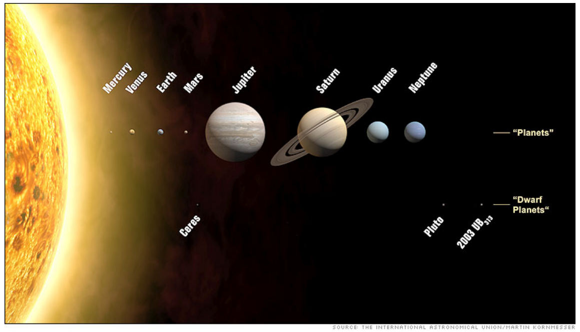
	Object	R_e	M	ρ	A	*	**
	Sun	695700	$1.99 \cdot 10^{33}$	1.41	-	Ionized H and He	H,He
Rocky	Mercury	2439	$3.30 \cdot 10^{26}$	5.42	0.12	Igneous rocks	None
Rocky	Venus	6052	$4.87 \cdot 10^{27}$	5.25	0.59	Basaltic rocks	CO_2
Rocky	Earth	6378	$5.98 \cdot 10^{27}$	5.52	0.39	Water, basaltic and granitic rocks	N_2, O_2
Rocky	Mars	3398	$6.42 \cdot 10^{26}$	3.94	0.15	Basaltic rocks, dust	CO_2
Gaseous/icy	Jupiter	71900	$1.90 \cdot 10^{30}$	1.31	0.44	-	H_2, He
Gaseous/icy	Saturn	60330	$5.69 \cdot 10^{29}$	0.69	0.46	-	H_2, He
Gaseous/icy	Uranus	25700	$8.68 \cdot 10^{28}$	1.22	0.56	-	H_2, He, CH_4
Gaseous/icy	Neptune	24750	$1.03 \cdot 10^{29}$	1.66	0.51	-	H_2, He, CH_4
	Pluto	1100	$1.2 \cdot 10^{28}$	2.1	0.6	CH_4, H_2O ices	Thin CH_4

Table 14.2. Physical properties of the planets and the sun. The columns show: R_e, the equatorial radius in km; M, the mass in g; ρ, the mean density in g/cm³; A, the visual albedo; *, the surface materials; **, the main constituents of the atmosphere.

Dichotomy of masses, radii, mean densities

Solar System: planetary architecture

- Rocky (terrestrial planets) ➔ d < 2 AU
  - Mercury, Venus, Earth, Mars ➔ R ~ 0.4 − 1 R_{terra}
- Giant planets ➔ d ~ 5 − 10 AU
  - Jupiter, Saturn ➔ R ~ 9 − 11 R_{terra}
- Icy/giant planets ➔ d ~ 20 − 30 AU
  - Uranus, Neptun ➔ R ~ 4 R_{terra}



The "ice line"

Object	a (AU)
Sun	-
Mercury	0.387
Venus	0.723
Earth	1.000
Mars	1.524
Jupiter	5.203
Saturn	9.539
Uranus	19.182
Neptune	30.058
Pluto	39.44

Rocky: Mercury, Venus, Earth, Mars

ice line (between Mars and Jupiter)

Gaseous/icy: Jupiter, Saturn, Uranus, Neptune, Pluto

1 AU $= 149.5 \times 10^6$ km

Dichotomy in heliocentric distance

Rocky planets lie close to the Sun

Giant/icy planets lie far away from the Sun

Other constituents of the Solar System

Satellites

Very few around rocky planets

Many around giant planets

Minor bodies (dwarf planets, asteroids, comets)

Inner Solar System: **asteroid belt** ($a \sim 2 – 4$ AU)

ice line

Outer Solar System: **Kuiper belt** ($a \sim 30 - 50$ AU)

Outermost Solar System: **Oort cloud** ($a \sim 100 – 1000$ AU and beyond)

Interplanetary dust

First detected as zodiacal light

Mass of the Solar System constituents

Sun

$M_{sun} = 2.0 \times 10^{33}$ g

Planets and satellites

$M_{planets} = 2.67 \times 10^{30}$ g

Earth

$M_{Earth} = 5.97 \times 10^{27}$ g

Jupiter

$M_J = 1.898 \times 10^{30}$ g $= 317.8\ M_{Earth}$

Dwarf planets and minor bodies

$M_{minor\ bodies} \sim 2 \times 10^{24}$ g

Observational/experimental techniques for the study of the Solar System from Earth

Classical astronomical observations

from ground (optical and radio)

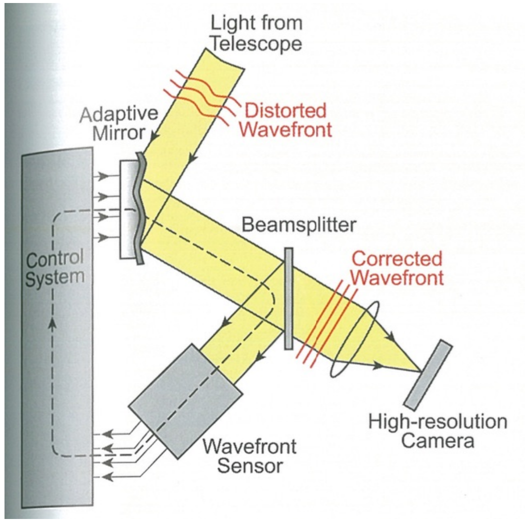
from space (X rays, UV, IR)

Radar techniques

Analysis of samples of Solar System material collected on Earth

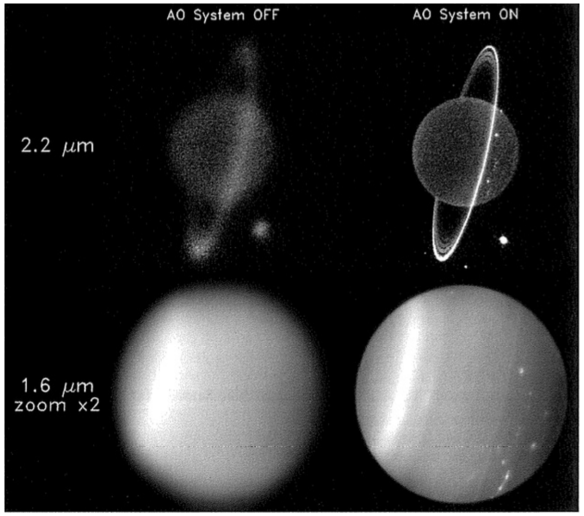
(Meteorites, Interplanetary dust)

Advances in ground-based astronomical observations: Adaptive Optics (AO)



Solar System observations with adaptive optics

Uranus observed without and with AO

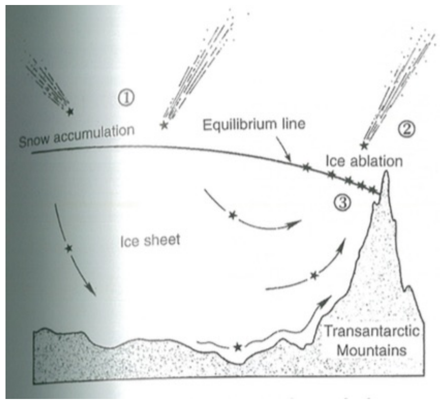


Samples collected on Earth

Meteorites

- Solid bodies originated in the Solar System that hit the surface after crossing the Earth's atmosphere as *meteoroids*
- The current number of collected meteorites is ~ 1.7 x 10^4
- So far, mostly found in unhabited regions
  - Antarctica, deserts (Australia, North Africa)
- Systematic surveys in inhabited areas are being developed
  - Fast recovery of the meteorite
  - Determination of orbital parameters

Meteoritic samples collected in Antarctica



Planetary radar

Study of Solar System bodies by transmitting a radio signal toward the target and then receiving and analysing the echo

Advantage: high degree of control exercised by the observer on the transmitted signal used to illuminate the target

Disadvantage: for a given power emitted, the power of the echo scales as ~$1/R^4$, where R is the distance to the target

The radiotelecope must be equipped with the most powerful radio transmitters

Observations from Earth require radiotelescopes with very large aperture (e.g. Arecibo, Puerto Rico, 305 m)

With space probes it is possible to perform detailed maps of Solar System bodies (e.g. Magellan mission around Venus)

Observational/experimental techniques for the study of the Solar System with space missions

Imaging: geological/geophysical history

Spectroscopy: composition – mineralogy – gas emission – interaction with ionized particles

Nuclear spectroscopy: remote chemical sensing - shallow depths of the surface

Magnetometers: magnetic fields (planetary interiors)

Gravitometers: mass distribution in planetary interiors

Radio observations: atmosphere and internal structure of gaseous giant planets - radio waves from ionized plasma

Radar: surface structure, dielectric properties

Dust analysers: study of ice and dust grains

Observational/experimental techniques for the study of the Solar System with space missions

Analysis of samples collected by space probes

Composition – Mineralogy

Samples analysed "in situ"

examples:

Mars (starting from the *Viking* missions)

Samples returned to Earth

examples:

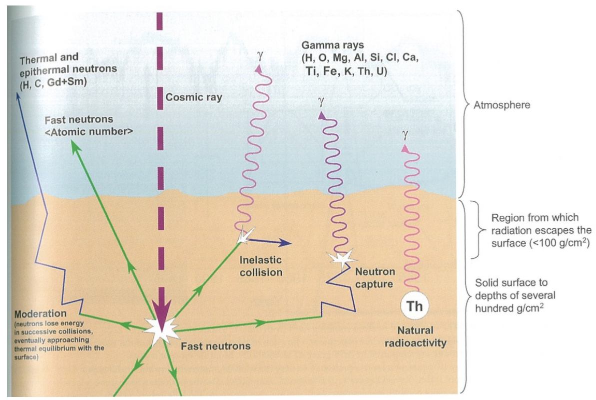
Lunar samples: *Apollo* missions

Cometary/interstellar dust: *Stardust* mission

Remote chemical sensing using nuclear spectroscopy

Nuclear spectroscopy techniques are used to determine the elemental composition of planetary surfaces and atmospheres

Radiation, including gamma rays and neutrons, is produced steadily by cosmic ray bombardment of the surfaces and atmospheres of planetary bodies and by the decay of radionuclides within the solid surface

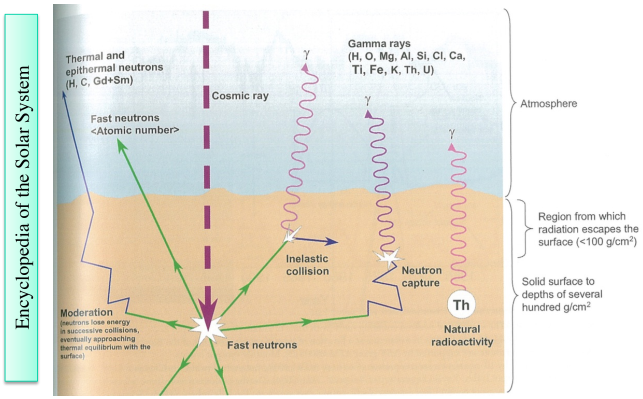


Encyclopedia of the Solar System

The leakage flux of gamma rays and neutrons contains information about the abundance of major elements, selected trace elements, and light elements such as H and C

Gamma rays and neutrons can be measured from high altitudes (less than a planetary radius), enabling global mapping of elemental composition by an orbiting spacecraft

Radiation that escapes into space originates from shallow depths (~1 m within the solid surface)



Planetary exploration
a short list of succesful space missions

Mercury
Mariner 10 (1973-1974) NASA

Messenger (2004-2009) NASA

Venus
Venera 4 through *16* (1967-1983) USSR

Magellan (1989) NASA orbiter

Radar map of the entire planet surface

Planetary exploration
a short list of succesful space missions

Moon
Luna 1, 2 and *3* (1959) USSR: first escape from Earth's gravity

Ranger 7, 8, and *9* (1964,1965) NASA: first high resolution images

Zond 3, 5, 6, 7, 8 (1965,1970) USSR: detailed imagery of the surface

Luna 9 and *13* (1966) USSR: first succesful lunar touchdown

Surveyor 1, 3, 5 6, and 7 (1966,1967) NASA: imagery, soft landing

Apollo 8, 10 11, 12, 13, 14, 15, 16, and 17 (1968-1972) NASA: orbiters, lunar landing modules, manned missions, sample return

Luna 16, 17, 20, 21, and 24 (1970-1976) URSS: lunar landing, soil sampler, sample return, rover

Planetary exploration
a short list of succesful space missions

Mars
Viking 1 and *2* (1975-1976) NASA orbiter/landers

Mars Pathfinder (1996) NASA rover

Global Surveyor (1996) NASA orbiter

Mars Odyssey (2001) NASA orbiter

Spirit and *Opportunity* (2003) NASA rovers

Mars Express (2003) ESA orbiter

Planetary exploration
a short list of succesful space missions

Asteroid belt and beyond

Dawn (2007-present time) NASA
Ceres (dwarf planet) and Vesta (asteroid)

Stardust (1999) NASA, Comet Wild 2
Imaging data and sample return on Earth

Rosetta (2004-2016) ESA, Comet 67/P Churyumov-Gerasimenko

Planetary exploration
a short list of succesful space missions

Outer Solar System

Pioneer 10 and *11* (1972-2003) NASA: Jupiter, Saturn

Voyager 1 and *2* (1977) NASA:
Jupiter, Saturn, Uranus, Neptun, heliopause

Galileo (1989) NASA: Jupiter and its moons

Cassini-Huygens (1997) NASA/ESA: Saturn, Titan

New Horizons (2006-present) NASA: Pluto, Charon