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

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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 studied 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
Mercury	2439	$3.30 \cdot 10^{26}$	5.42	0.12	Igneous rocks	None
Venus	6052	$4.87 \cdot 10^{27}$	5.25	0.59	Basaltic rocks	CO_2
Earth	6378	$5.98 \cdot 10^{27}$	5.52	0.39	Water, basaltic and granitic rocks	N_2, O_2
Mars	3398	$6.42 \cdot 10^{26}$	3.94	0.15	Basaltic rocks, dust	CO_2
Jupiter	71900	$1.90 \cdot 10^{30}$	1.31	0.44	-	H_2, He
Saturn	60330	$5.69 \cdot 10^{29}$	0.69	0.46	-	H_2, He
Uranus	25700	$8.68 \cdot 10^{28}$	1.22	0.56	-	H_2, He, CH_4
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

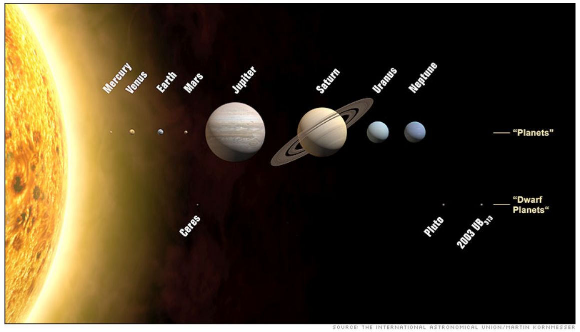
Rocky: Mercury, Venus, Earth, Mars
Gaseous/icy: Jupiter, Saturn, Uranus, Neptune

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

The architecture of the Solar System

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



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 – Mars)

ice line (between Mars and Jupiter)

Gaseous/icy (Jupiter – Pluto)

= 149.5×10^6 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)

Resolution enhancement for ground-based observations

- Adaptive optics

Consists in the real-time control of the optics of a telescope to counteract atmospheric turbulence

At variance with active optics, adaptive optic systems must be very fast since atmospheric turbulence varies with a time scale of order ~1 millisec

Adaptive optics requires an ancillary system that senses the instantaneous shape of the atmospheric wavefront

Wavefront sensing is performed using a bright reference star and/or the atmospheric reflection of a laser beam which acts as an artificial star

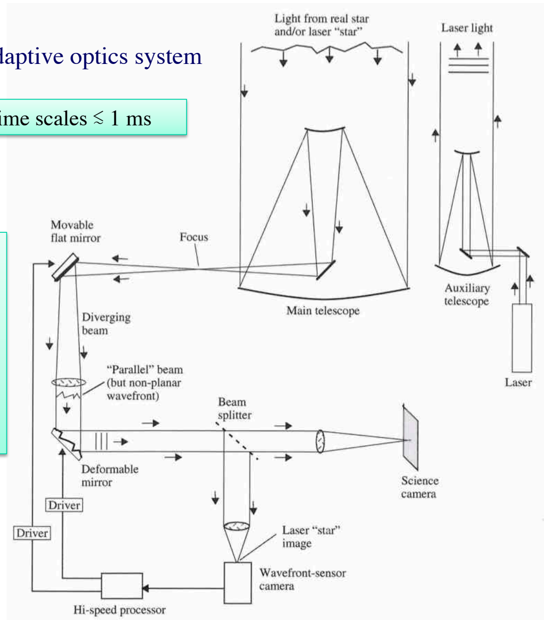
The information on the wavefront is sent to hardware and analysis software which detects deviations from a planar wave with proper centroid location

Corrections are then applied to deformable mirrors located along the optical path; the modified beam is then sensed and the process continues in this feedback-loop mode

Sketch of a complete adaptive optics system

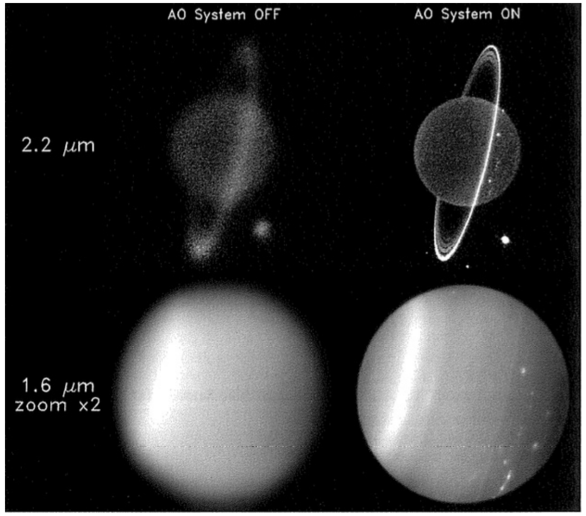
The loop must work on time scales ≲ 1 ms

The movable flat mirror moves the image centroid to keep it in a single position in the focal plane; this reduces the excursions required on the actuators of the deformable mirror



Solar System observations with adaptive optics

Uranus observed without and with AO

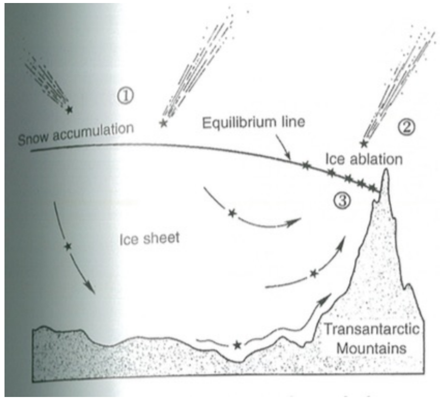


Samples collected on Earth

Meteorites

- Solid bodies originated in the Solar System that hit the Earth's surface after crossing the atmosphere as *meteoroids*
- The current number of collected meteorites is ~ 1.7×10^4
- 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 $\sim 1/R^4$, 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 <u>with space missions</u>

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 microscopic solid component around Solar System bodies and in the interplanetary medium (ice and dust grains)

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

Analysis of samples collected by space probes

Composition – Mineralogy

<u>Samples analysed "in situ"</u>

examples:

Mars (starting from the *Viking* missions)

<u>Samples returned to Earth</u>

examples:

Lunar samples: *Apollo* missions

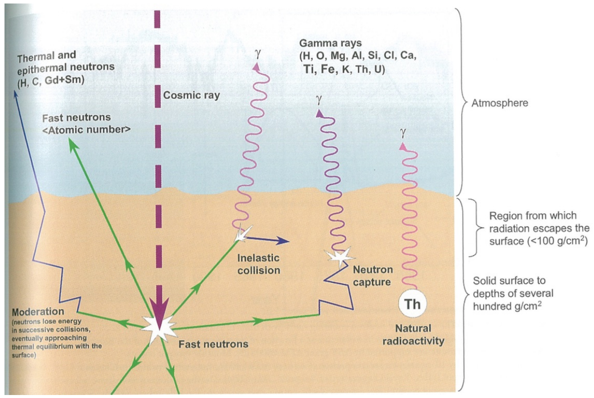
Cometary/interstellar dust: *Stardust* mission

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)

Encyclopedia of the Solar System