BHARATHIDASAN UNIVERSITY

Tiruchirappalli- 620024, Tamil Nadu, India

Programme: M.Tech., GEOLOGICAL TECHNOLOGY AND GEOINFORMATICS

Course: Remote Sensing Application in Planetary Studies

Code : MTIGT1004

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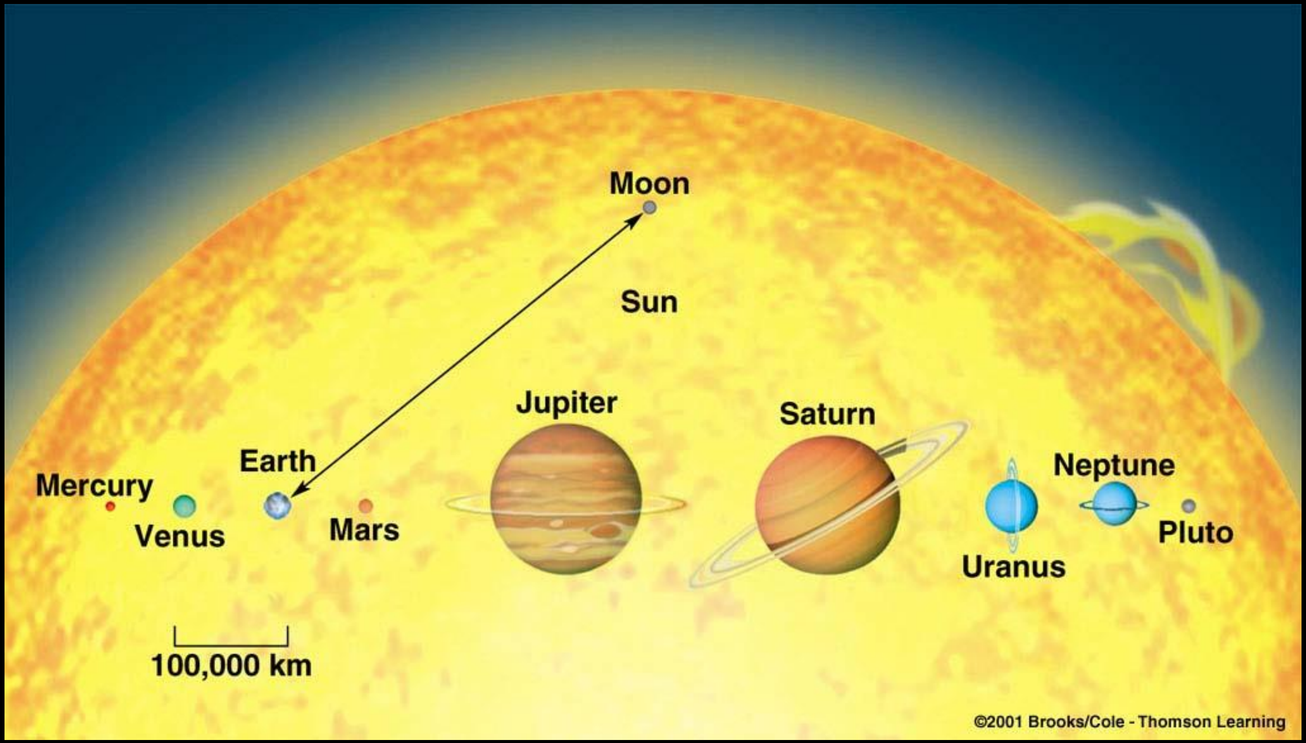
Unit-2. General Characteristics of the Solar System: Significant features of Terrestrial and Jovian planets - Mercury, Venus, Earth, Mars, Earth Moon, Jupiter, Major Jupiter Moons, Saturn, Major Saturn Moons, Uranus, Neptune – Asteroids – Comets – Meteoroids.

Remote Sensing techniques applicable to planetary exploration: Gamma-Ray Spectroscopy, X-ray Fluorescence spectrometry, Ultraviolet Spectrometry, Photometry, Laser Altimeter, Mars Orbiter Laser Altimeter (MOLO), Lunar Orbiter Laser Altimeter (LOLA), NEAR Laser Rangefinder (NLR), Reflectance spectroscopy, Emission spectroscopy, Vacuum ultraviolet spectroscopy and Color Photometry.

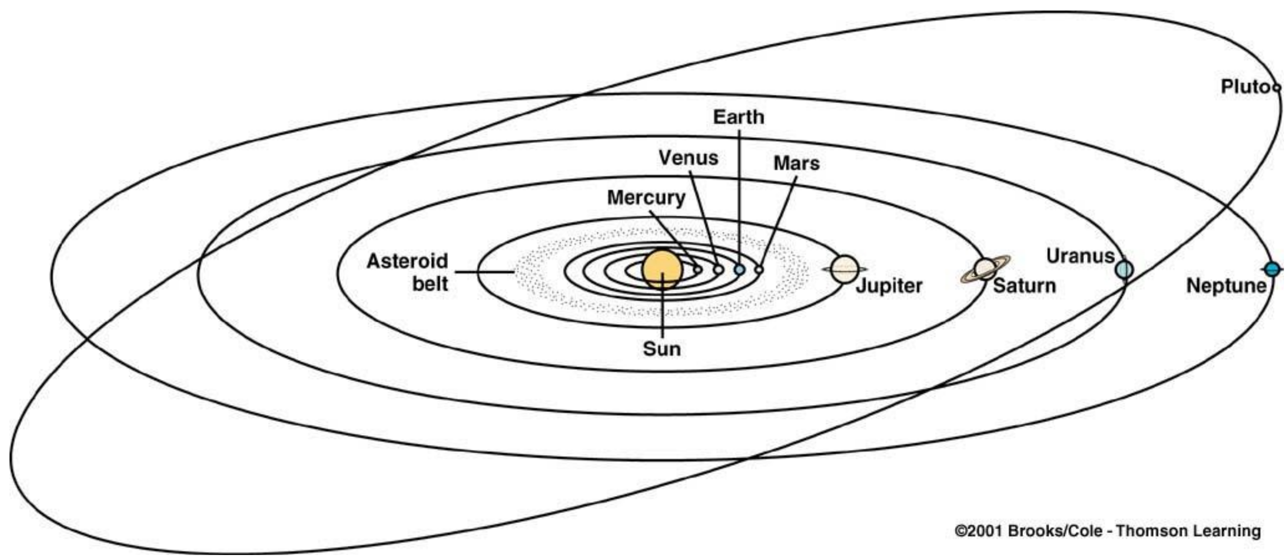
The Solar System



- Our solar system, part of the Milky Way galaxy, consists of the Sun, nine planets, 64 known moons, many asteroids, millions of comets and meteorites, as well as interplanetary dust and gases

General Characteristics of the Solar System

- **Planetary orbits and rotation**
  - **planet and satellite orbits are in a common plane**
  - **nearly all planet and satellite orbital and spin motions are in the same direction**
  - **rotation axes of nearly all planets and satellites are roughly perpendicular to the plane of the ecliptic**

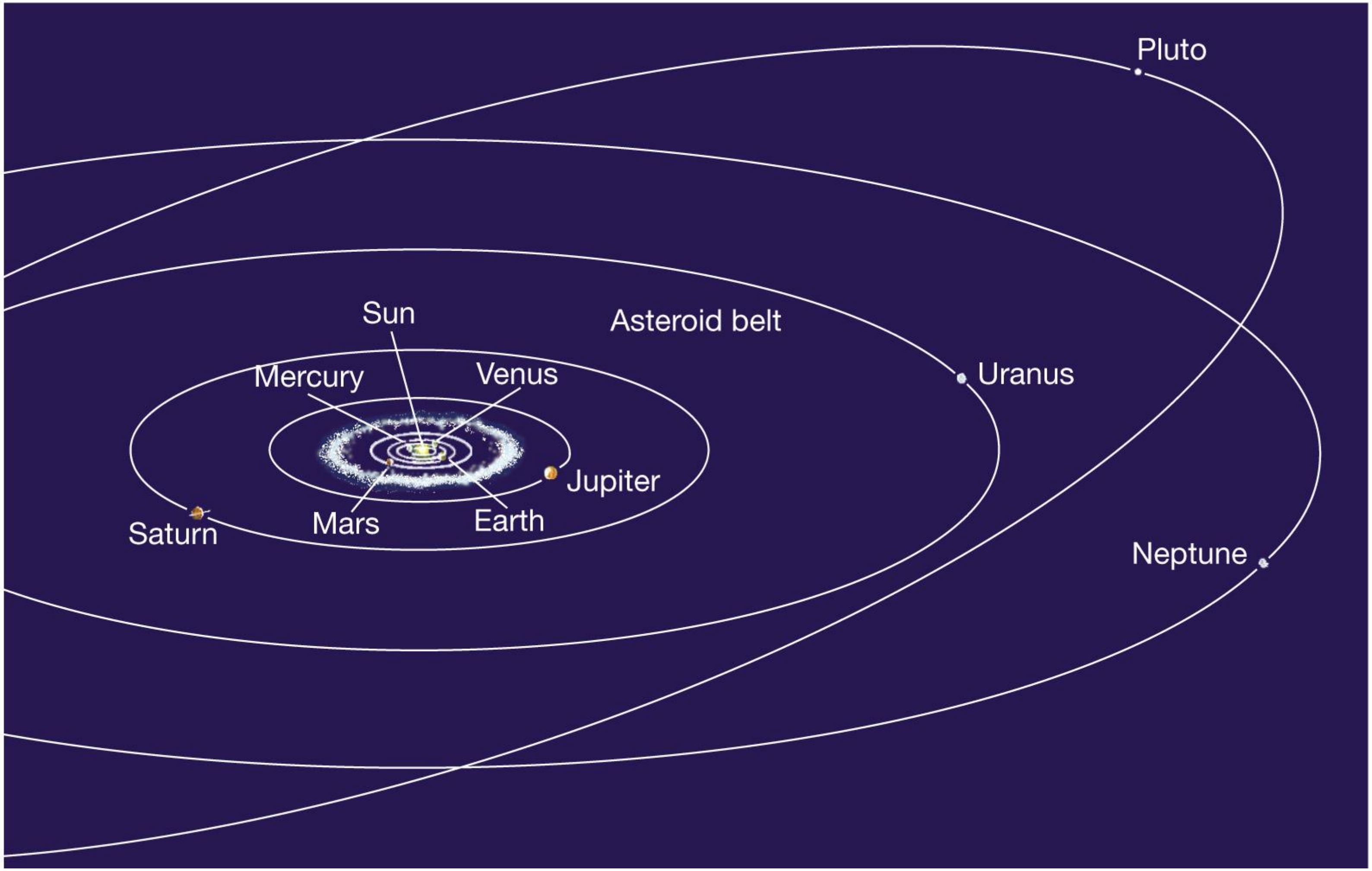


- Chemical and physical properties of the planets
  - the terrestrial planets are small, have a high density, and are composed of rock and metallic elements
  - the Jovian planets are large, have a low density, and are composed of gases and frozen compounds
- Slow rotation of the Sun
- Interplanetary material
  - existence and location of asteroid belt
  - distribution of interplanetary dust

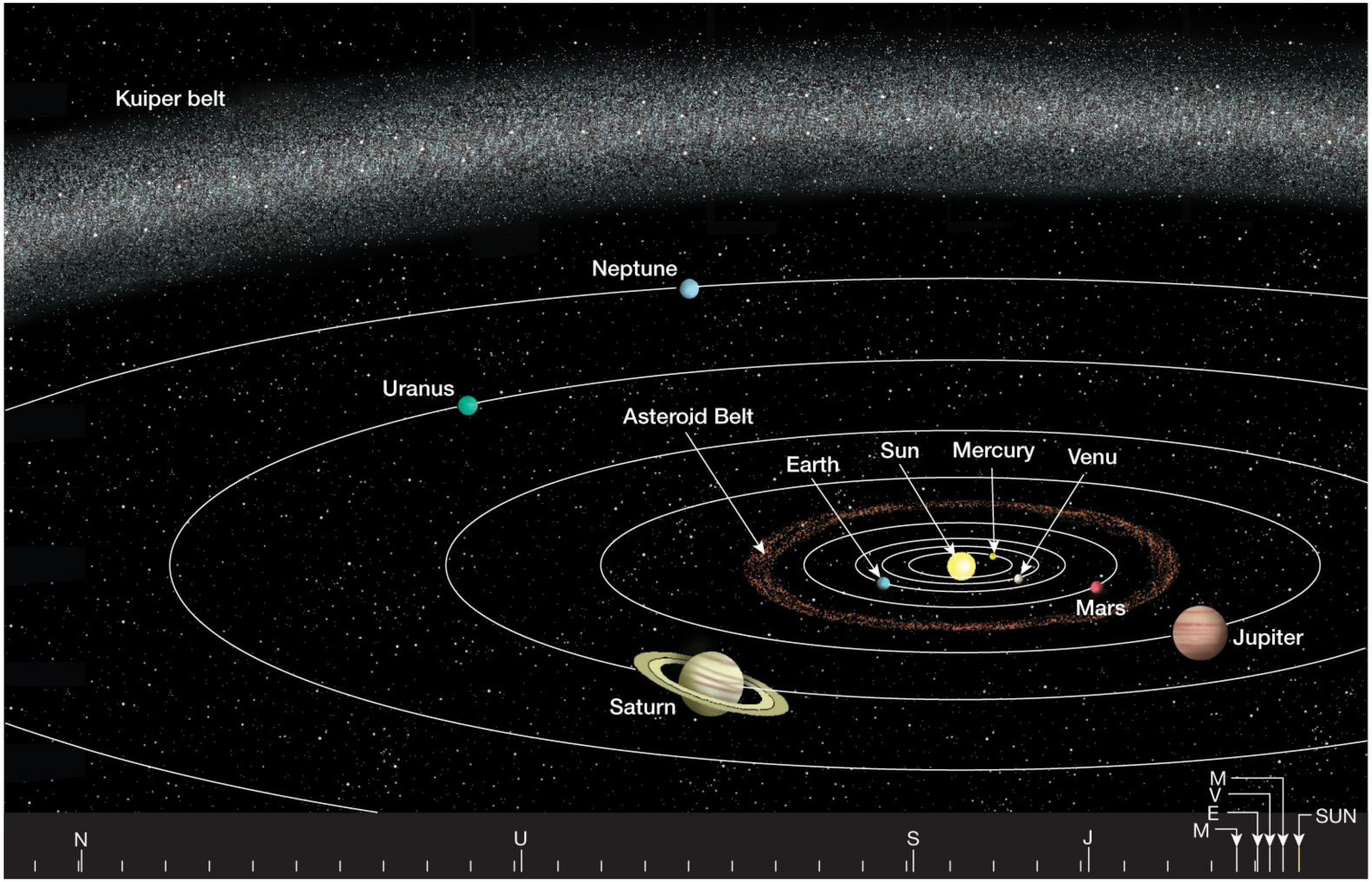
The Overall Layout of the Solar System

All orbits paths are close to the ecliptic plane

Pluto's orbit does not (17° tilt)

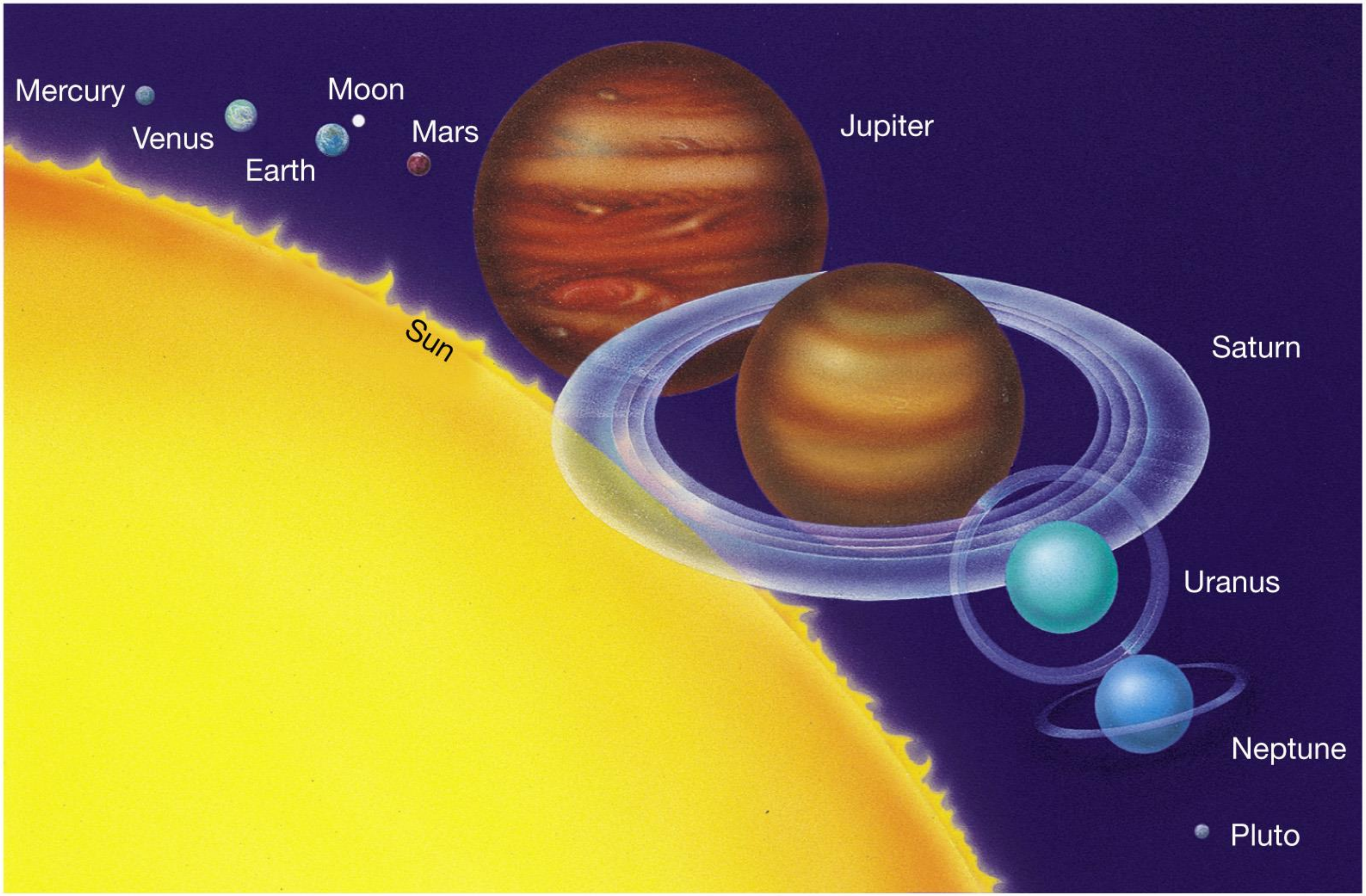


Planet order plus the asteroid and Kuiper Belts



Terrestrial and Jovian Planets

Relative sizes of the Sun & Planets



Terrestrial and Jovian Planets

Terrestrial planets:

Mercury, Venus, Earth, Mars

Jovian planets:

Jupiter, Saturn, Uranus, Neptune

Pluto is neither but a new class called the

Dwarf planets

TABLE 6.2 Comparison of the Terrestrial and Jovian Planets

Terrestrial Planets	Jovian Planets
close to the Sun	far from the Sun
closely spaced orbits	widely spaced orbits
small masses	large masses
small radii	large radii
predominantly rocky	predominantly gaseous
solid surface	no solid surface
high density	low density
slower rotation	faster rotation
weak magnetic fields	strong magnetic fields
few moons	many moons
no rings	many rings

Terrestrial and Jovian Planets

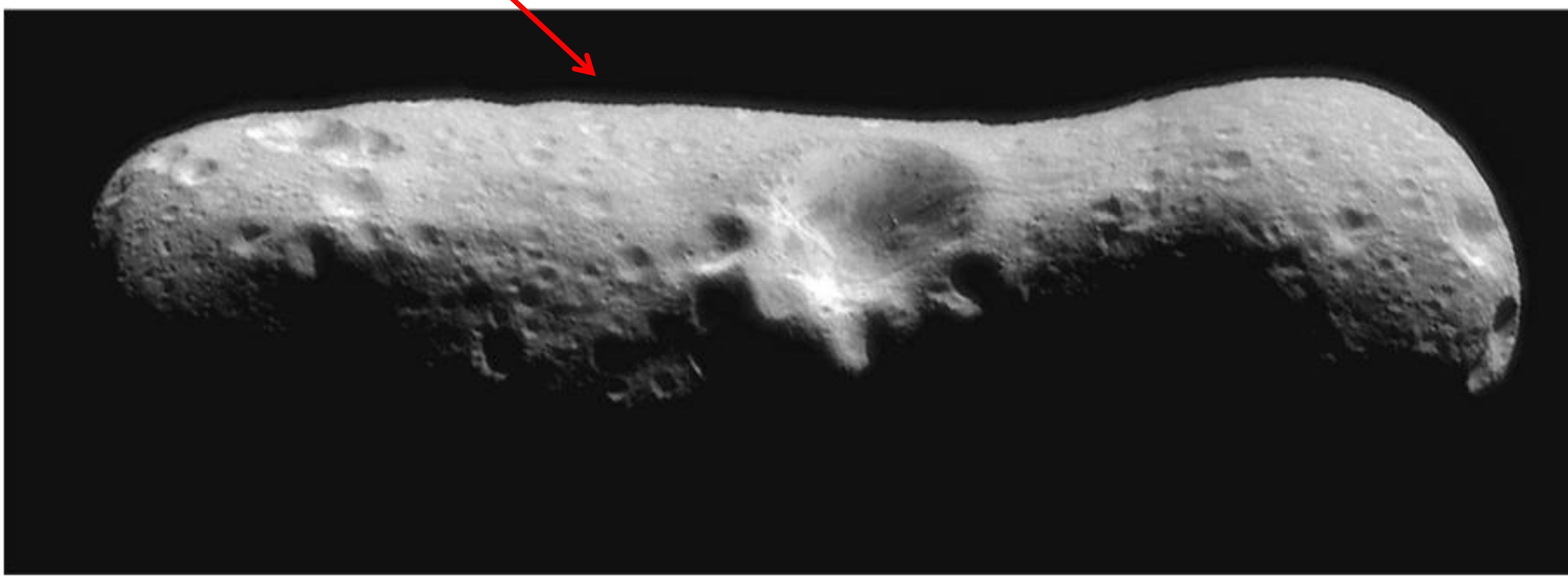
Differences (*Comparative Planetology*) between the terrestrial planets:

- **Atmospheres** and **surface conditions** are very dissimilar
- Only Earth has **oxygen** in atmosphere and **liquid water** on surface
- Earth and Mars **rotate** at about the same rate; Venus and Mercury are much slower, and Venus rotates in the opposite direction
- Earth and Mars have **moons**; Mercury and Venus don't
- Earth and Mercury have **magnetic fields**; Venus and Mars don't

Interplanetary Debris

Asteroids and **meteoroids** have rocky composition; asteroids are bigger

Asteroid Eros is 34 km long:

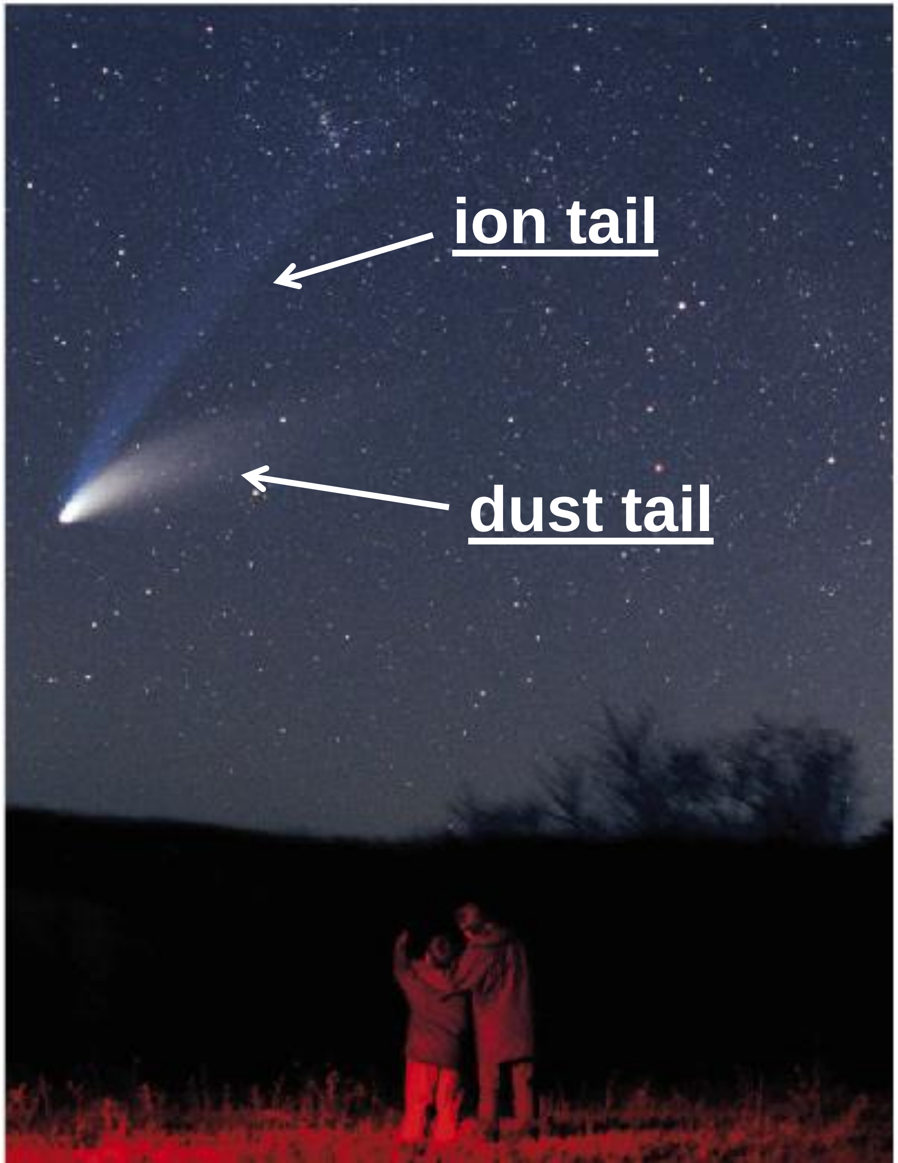


Interplanetary Debris

Comets are icy, with some rocky parts.

Comet Hale–Bopp

(1997)



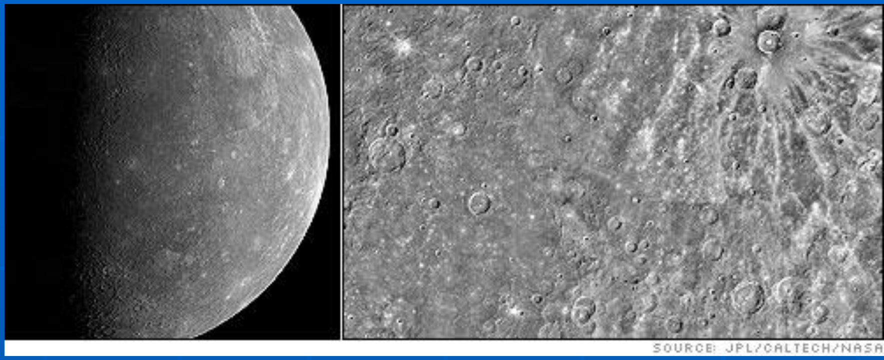
6.2 Planetary Properties

TABLE 6.1 Properties of Some Solar-System Objects

Object	Orbital Semimajor Axis (A.U.)	Orbital Period (Earth Years)	Mass (Earth Masses)	Radius (Earth Radii)	Number of Known Satellites	Rotation Period* (days)	Average Density (kg/m^3)	Average Density (g/cm^3)
Mercury	0.39	0.24	0.055	0.38	0	59	5400	5.4
Venus	0.72	0.62	0.82	0.95	0	−243	5200	5.2
Earth	1.0	1.0	1.0	1.0	1	1.0	5500	5.5
Moon	—	—	0.012	0.27	—	27.3	3300	3.3
Mars	1.52	1.9	0.11	0.53	2	1.0	3900	3.9
Ceres (asteroid)	2.8	4.7	0.00015	0.073	0	0.38	2700	2.7
Jupiter	5.2	11.9	318	11.2	61 **63**	0.41	1300	1.3
Saturn	9.5	29.4	95	9.5	31 **60**	0.44	700	0.7
Uranus	19.2	84	15	4.0	27	−0.72	1300	1.3
Neptune	30.1	164	17	3.9	12 **13**	0.67	1600	1.6
Pluto	39.5	248	0.002	0.2	1	−6.4	2100	2.1
Comet Hale–Bopp	180	2400	1.0×10^{-9}	0.004	—	0.47	100	0.1
Sun	—	—	332,000	109	—	25.8	1400	1.4

**A negative rotation period indicates retrograde (backward) rotation relative to the sense in which all planets orbit the Sun.*

Mercury



- Smallest
- Densest
- Craters and lava flows visible
- Cooled, lacks tectonic activity
- Thin layer of gases
- Magnetic field
- Perhaps ice at poles
- Extreme temperatures:
  - Sunny side 950 degrees F
  - Dark side: -346 degrees F

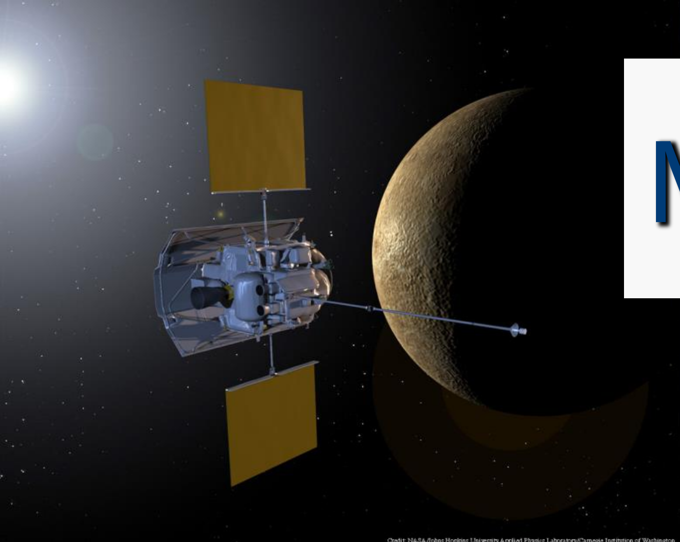
Physical Character:

- **Radius: 2439 km (compared with 1738 for the Moon, 6357 for Earth)**
- **Density: 5.43 x 103kg m-3 (compared with 3.34 for the Moon, 5.51 for Earth (what's up?))**

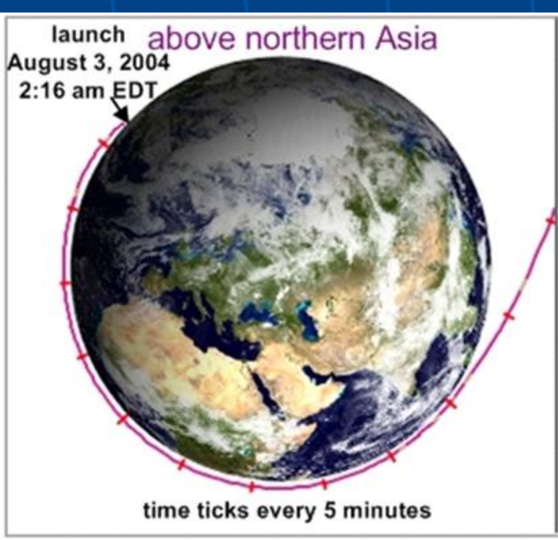
Orbital Character:

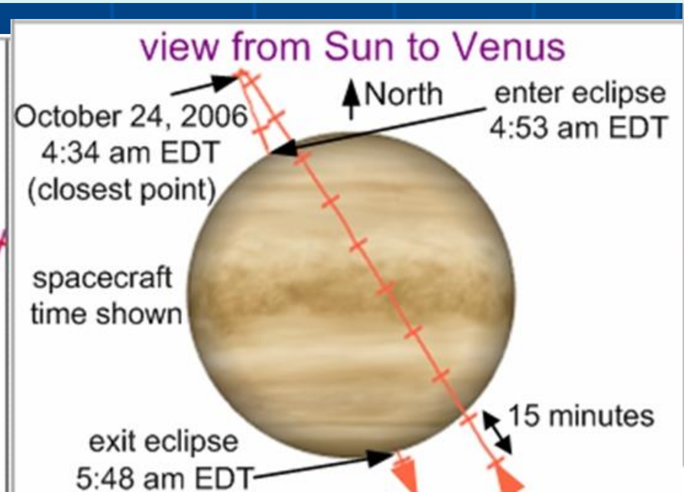
- **Average distance from sun: 0.39 AU (57.91 x 106 km)**
- **Axial rotational period (length of day with reference to background stars): 58.6 days**
- **Orbital period: 88 days**
- **Orbital eccentricity: 0.206 (compared with 0.017 for Earth)**
- **Orbital inclination: 7 deg. (compared with 0.0 for Earth)**

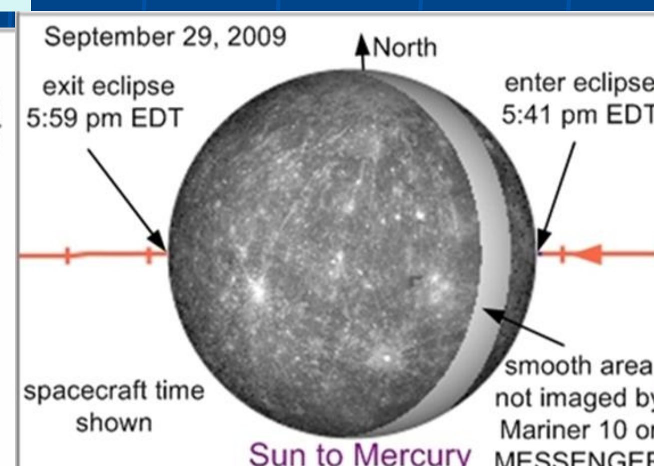
Messenger spacecraft



- Launched 2004
- Orbit Mercury, March 18, 2011

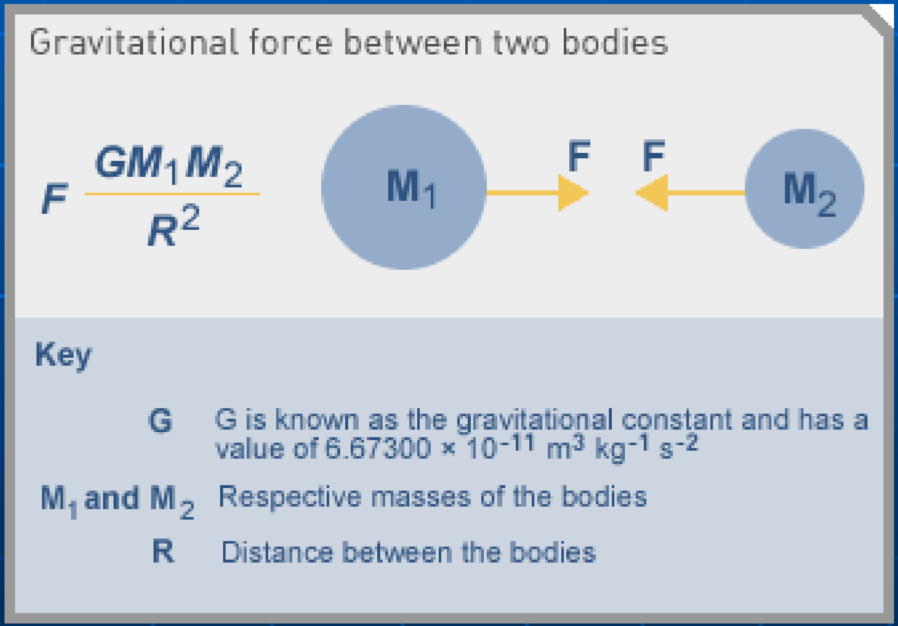






Gavitational pull

- Earth: 150 pounds
- Mercury: 57 pounds



Venus

- Slightly smaller than Earth
- Very hot: 900 degrees F
- Retrograde rotation (opposite the Earth)
- Visible in the sky: the morning "star"

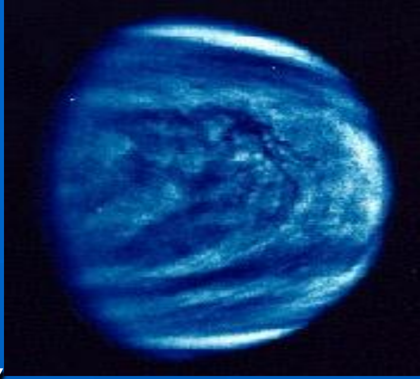
Physical Character:

- Radius: 6052 km (compared with 1738 for the Moon, 6357 for Earth)
- Density: 5.20 x 103 103kg m-3 (compared with 3.34 for the Moon, 5.51 for Earth)

Orbital Character:

- Average distance from sun: 0.72 AU (108.21 x 106 km)
- Axial rotational period (length of day with reference to background stars): 243 days (but it is retrograde!)
- Orbital period: 224.7 days
- Orbital eccentricity: 0.007 (compared with 0.017 for Earth)
- Orbital inclination: 3.4 deg.

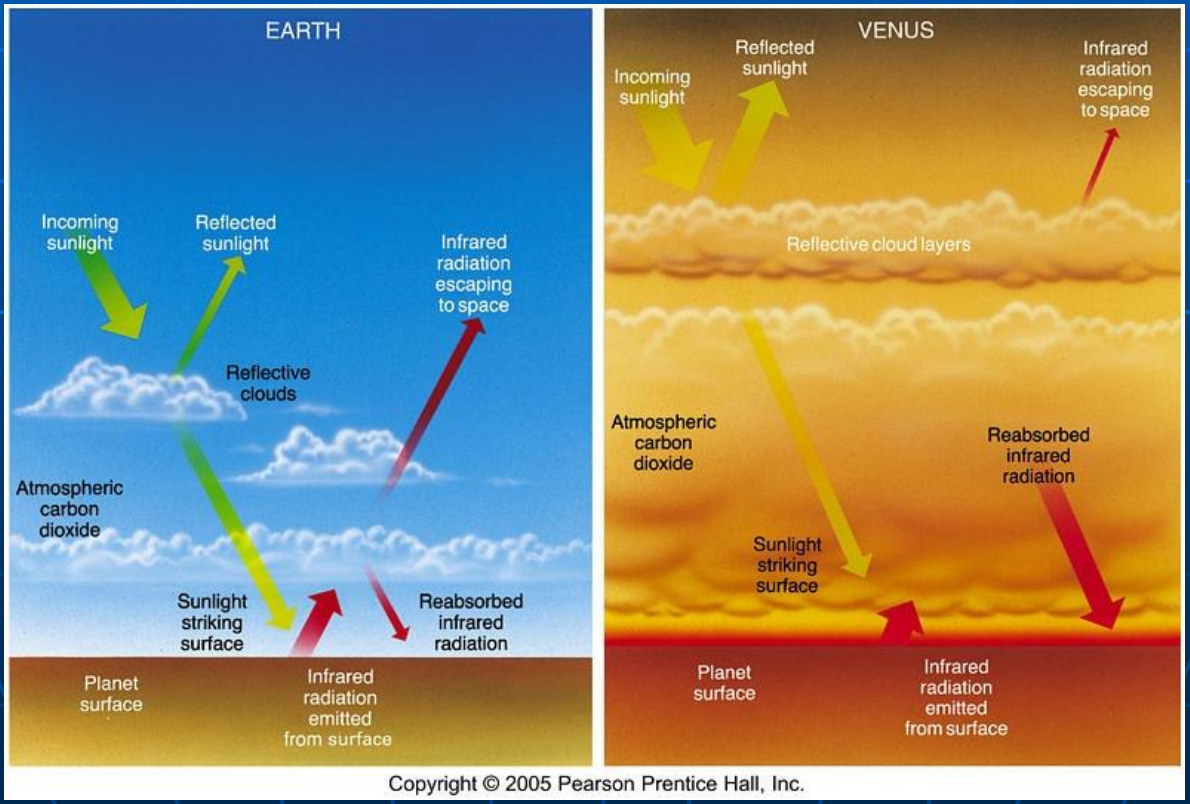
Venus' Atmosphere



- Water and carbon dioxide:97%
- No liquid water
- Extreme pressure: 92 X pressure on Earth at sea level (same as .6 miles deep in ocean)
- Electrical storms within the clouds
- Sulfuric acid clouds
  - Can move at 350 KM/hr

Greenhouse effect: explanation to why Venus' surface is so hot

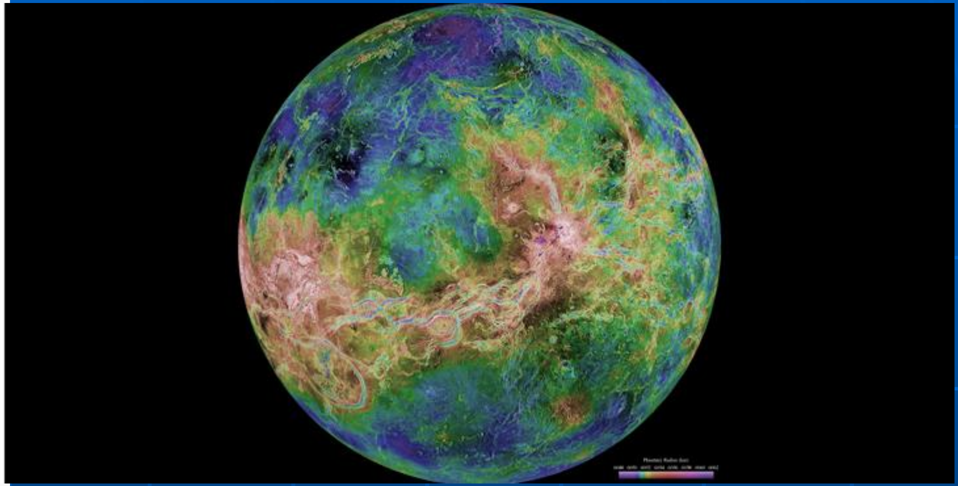
- 97%CO_2 ,3% N



Water vapor and Carbon dioxide absorb infrared radiation

Venus

- **Tectonic activity**
- Mantle convection
- Upwelling of mantle material
- Down-welling of mantle material
- Basaltic volcanism
- Lack of crater impacts implying mobile surface



Radar data enabled scientists to penetrate Venus' thick clouds and create simulated views of the surface.

Exploring Venus

- Magellan, 1990-1995
- Radar images of Venus' surface

Earth

Physical specs:

Radius: 6357 km (compared with 1738 for the Moon)

Density: 5.51 x 103 103kg m-3 (compared with 3.34 for the Moon)

Orbital specs:

Average distance from sun: 1.00 AU (149.6 x 106 km)

Axial rotational period (length of day with reference to background stars): 0.997 days

Orbital period: 365.26 days

Orbital eccentricity: 0.017

Orbital inclination: 0.0 deg. (But then, it would be.)

Earth's atmosphere is 77% nitrogen, 21% oxygen, and has traces of argon, CO_2 and water. The last two are greenhouse gasses that trap solar energy as heat. Earth's average surface temperature is 288 K (15 deg. C). Without an atmosphere this temperature would be roughly 14 degrees C. lower.
It is the only planet that can support large permanent bodies of liquid water. 71% of its surface is covered by oceans. The evaporation and precipitation of water creates a hydrologic cycle as part of which, water flows across land surfaces as streams.
Because liquid water is a good medium for life, Earth has an extensive biosphere that radically alters its atmospheric and oceanic chemistry. E.G. photosynthesizers consume CO_2 and release oxygen.

Plate tectonics schematic from Prof. J. Tarney, University of Leicester
Earth is the only planet that currently experiences plate tectonics. I.e., its uppermost layers are divided into rigid plates that glide across deeper layers. A consequence of plate tectonics is the segregation of the rocks of the upper layers into:
Continental crust: Relatively light, rich in silica (SiO_2), collects in topographically high-standing continents.
Oceanic crust: Relatively heavy, rich in iron and magnesium (Fe and Mg), Forms the broad flat plains of the ocean floors.

The Moon

Physical specs:

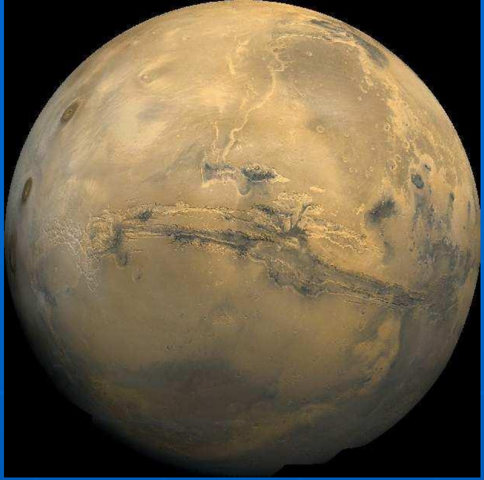
- Radius: 1738 km.
- Density: 3.34 x 10^3 10^3kg m^{-3}

Orbital specs:

- Average distance from sun: 1.00 AU (149.6 x 10^6 km)
- Average distance from Earth: 384 x 10^3 km - 0.0025 AU)
- Axial rotational period (length of day with reference to background stars): 27.3 days
- Orbital period: 27.3 days
- Orbital eccentricity: 0.055
- Orbital inclination: 5.2 deg.

- **The only extraterrestrial planetary body to have been visited by humans.**
- **Synchronous rotation: The moon, like many natural satellites, rotates on its axis in the same interval as it orbits its primary. Thus, it presents the same face to Earth. (An observer on the moon would see Earth hanging in the same place in the sky but undergoing phases.)**
- **The moon has no atmosphere or magnetic field, and orbits outside Earth's magnetic field. Thus, like Mercury, its surface is directly struck by solar radiation and the solar wind.**
- **Like Mercury, the moon's surface is dominated by impact craters.**
- **Distinctive feature: The surface presents a dichotomy between bright-colored ancient highlands dominated by the rock anorthosite, and slightly less ancient dark maria (sing. mare) - giant basalt lava flows. The maria are concentrated on the Earth-facing side. The far side consists almost entirely of highlands.**

Mars



- 4th planet, red planet
- Temperature: -207 degrees to 32 degrees F
- Atmosphere: 95 % carbon dioxide
- Water once flowed on surface
- Sea existed perhaps 5 million years ago

Physical specs:

Radius: 3375 km (compared with 6357 for Earth 1738 for the Moon)

Density: 3.93 x 103 kg m-3 (compared with 5.51 for Earth 3.34 for the Moon)

Orbital specs:

Average distance from sun: 1.52 AU (227.9 x 106 km)

Axial rotational period (length of day with reference to background stars): 1.03 days

Orbital period: 686.5 days

Orbital eccentricity: 0.093

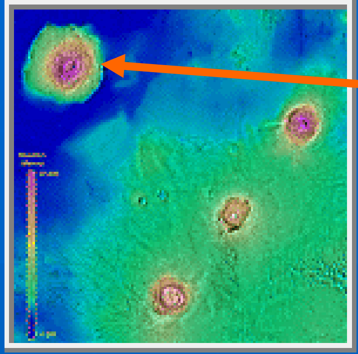
Orbital inclination: 1.9 deg.

Mars is dusty, with fine dust being the main source of its reddish color. Mars' winds redistribute this, resulting in changes of surface color. In Mars' thin air, dust is often shaped into dunes. Interestingly, most of Mars' dust originates in the erosion of a single rock unit.

Mars' atmosphere is mostly CO2, like that of Venus, but is much thinner, 6.3 x 10-3 bars. Its butterscotch color mostly comes from tiny dust grains suspended in it. The only time optical scattering of sunlight colors the sky is at sunset, when sunlight passes through enough air to produce blue sunsets.

Mars' average temperature is 218 K (-55 deg C), however temperatures vary from 140 K (-133 deg. C) in polar winter to 300 K (27 deg. C, 80 deg. F) in equatorial summer. Mars has permanent polar water-ice caps.

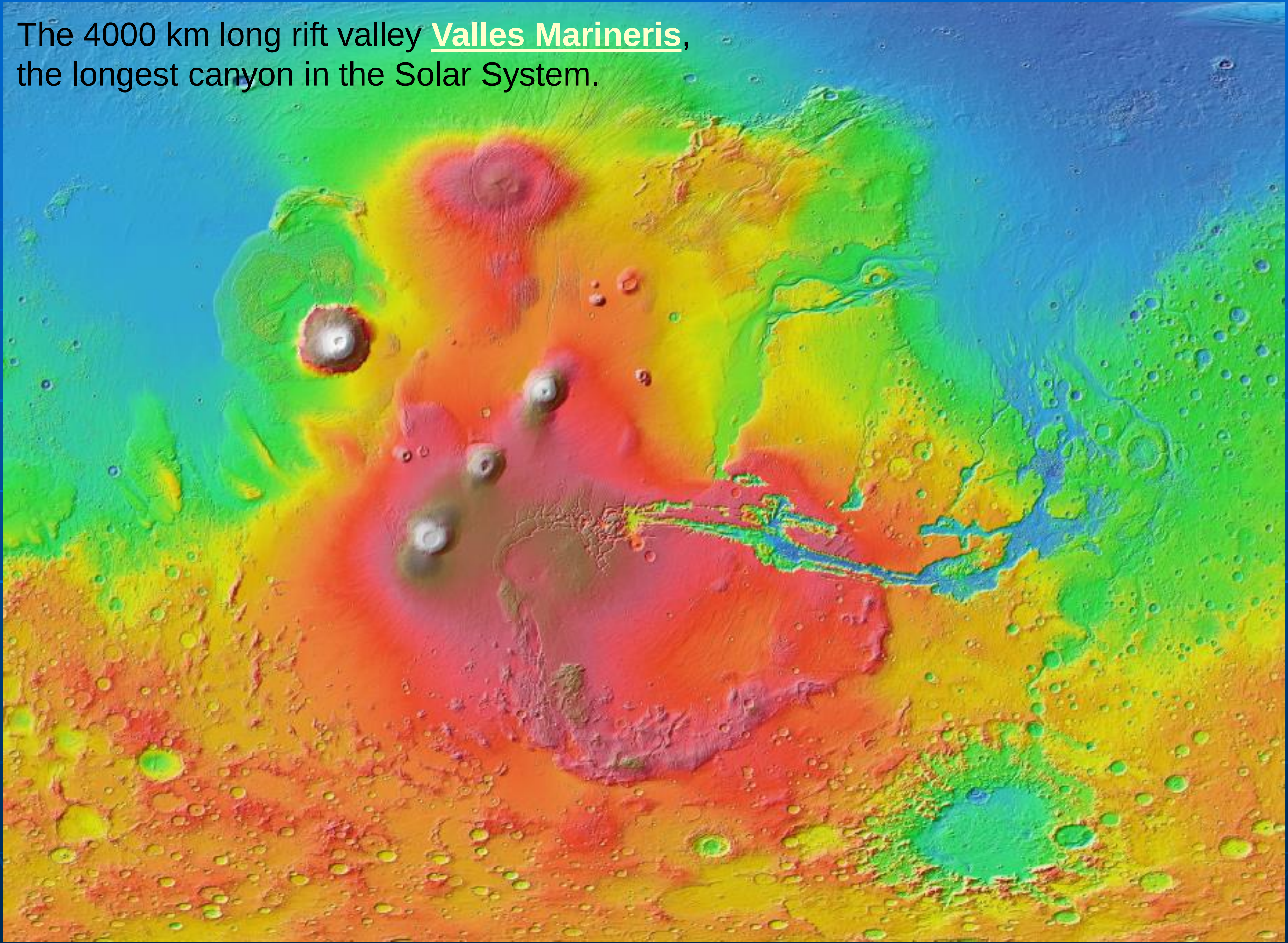
The temperature contrast between these ice caps and adjacent warmer ground drives much of Mars' weather. Recent explorations have revealed that considerably more ice is buried beneath thin layers of soil across much wider regions of the planet, or occasionally pooled on the surface.



- Explored remotely by man
- Thought most likely to have had life
- Evidence of water erosion: Valles Marineris

- Volcanism: largest mountain in the solar system (24x500 KM)
- Polar ice caps of solid water and Carbon dioxide

The 4000 km long rift valley **Valles Marineris**,
the longest canyon in the Solar System.



Comparison to Earth

- When a rocky planet's core cools
  - Magnetic field is lost
  - Tectonic activity ceases
  - Atmosphere is lost

Mars' Moons

Deimos: 7.5 miles across

Phobos

Asteroid like

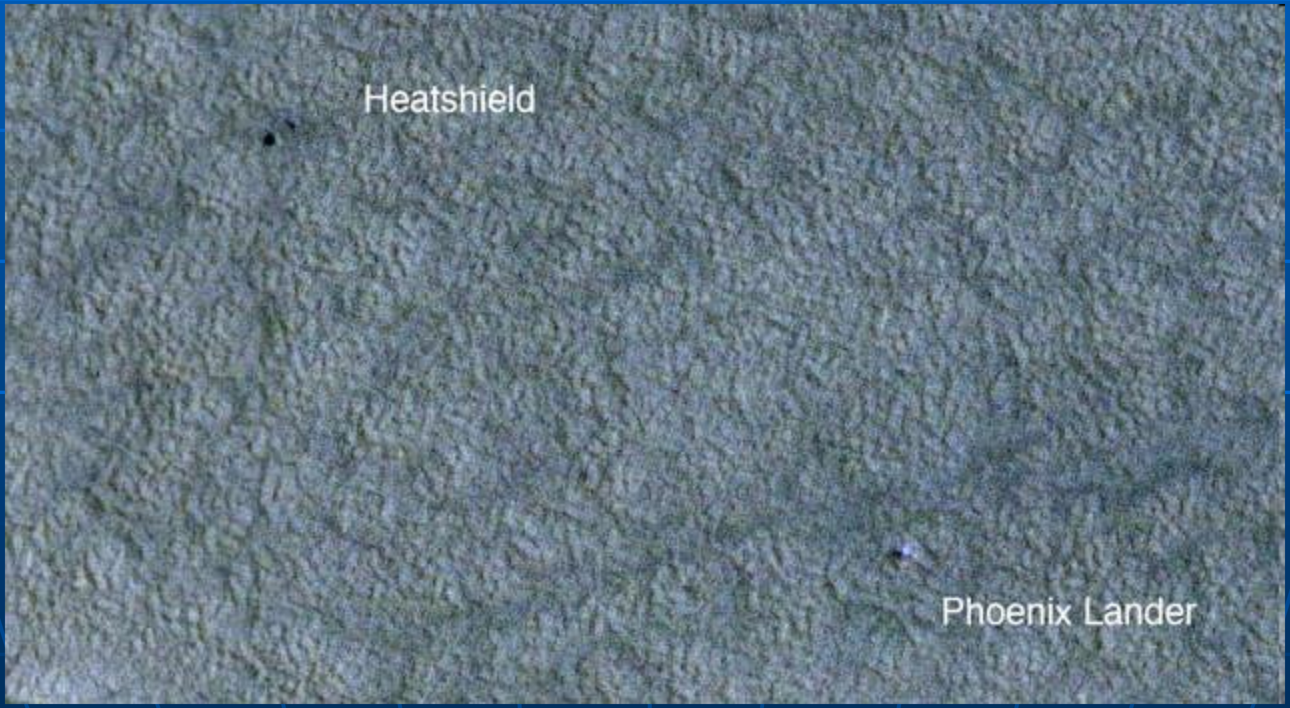
Mars

Sunrise on Mars, August 26, 2008

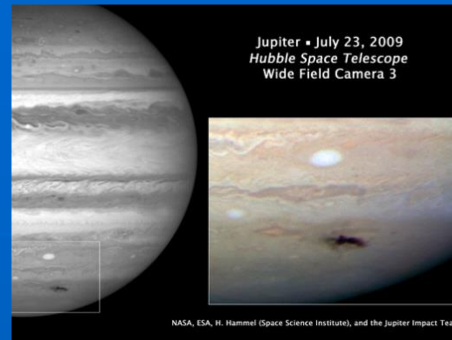
The Phoenix Lander arrived May 25. 2008

- Polar region: explore the possibility of life; characterize climate; the geology
- May , 2010 transmitting data ceased

Picture taken on December 21, 2008 by Mars reconnaissance orbiter (in orbit since 2001)



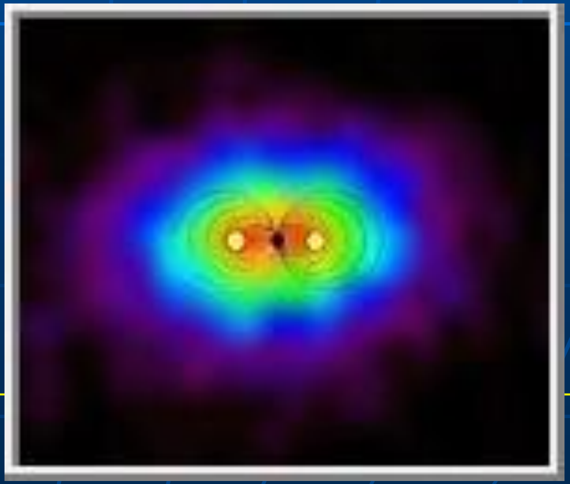
Jupiter



- 1000 Earths could fit inside an empty Jupiter
- Atmosphere: H, He some methane, ammonia
- Surface pressures so great H gas converted to liquid
- Metallic hydrogen core
- 63 Moons
- Orbit around Sun: 12 Earth years
- Rotation: 9 hours, 56 minutes

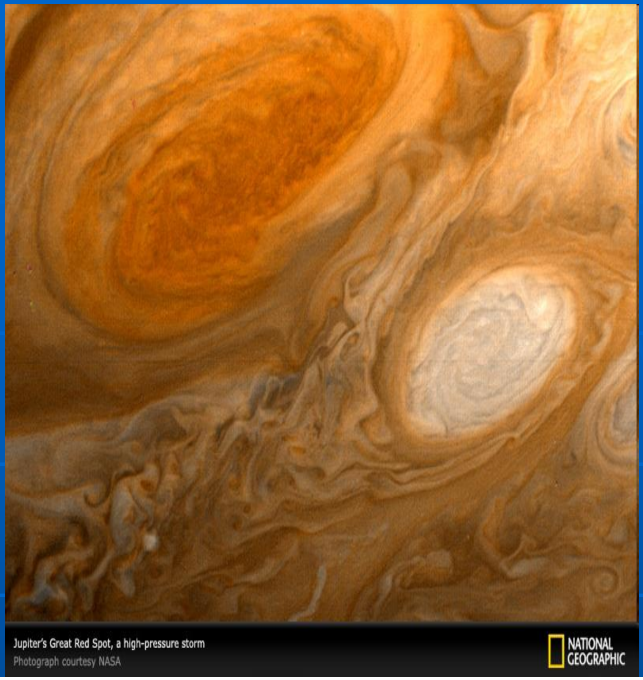
Jupiter

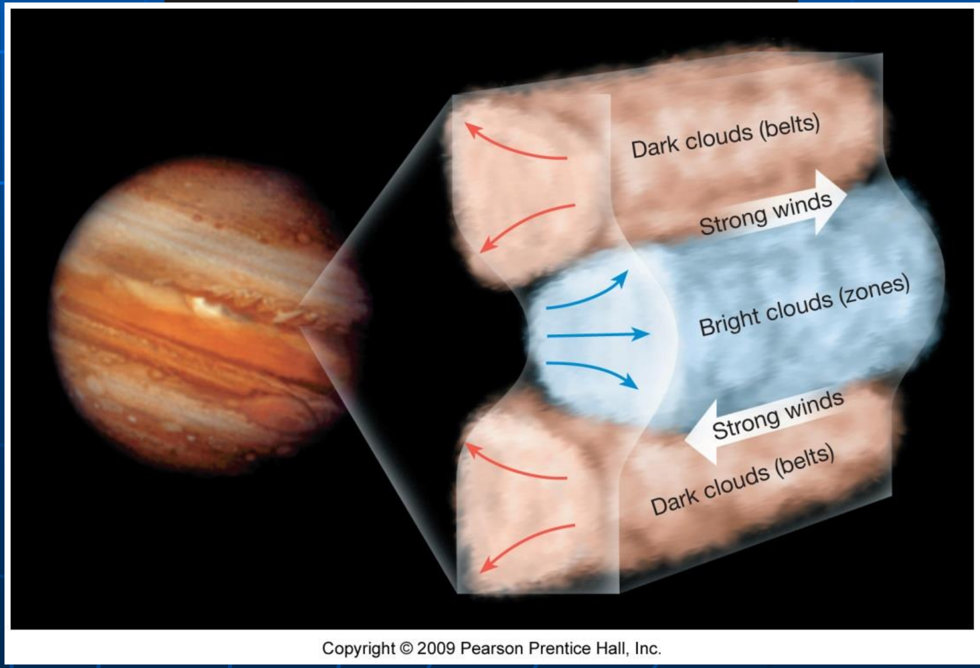
- Pressure breaks up atoms: electrons flow freely, single protons causes **Hydrogen to become metallic**
- **Magnetic field: 10 x stronger than Earth**



Great Red Spot

- 1^{st} photographed by Voyager 1, 1979
- Colors are due to warm air rising and cooler air sinking
- Winds blow counter clockwise around the spot
- Two times larger than Earth
- Migrates east and west



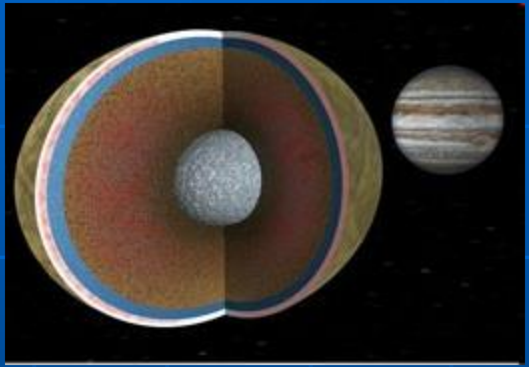


Galileo spacecraft: launched 1989 crashed 2003

- 1st to fly past an asteroid
- Measured Jupiter's atmosphere
- Evidence of salt water on Europa, Ganymede, and Callisto
- Volcanism on Io
- Purposefully crashed into Jupiter to discover temperatures and pressures

Arrived to Jupiter, 1995

Galileo: observed 4 of Jupiter's 63 moons

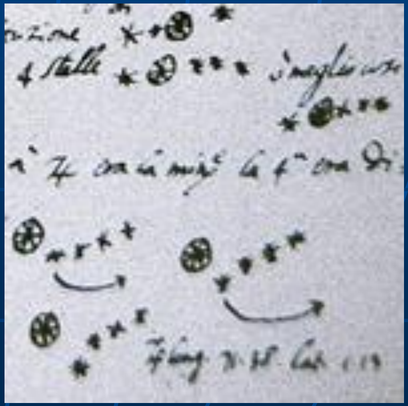
Ganymede

- Europa

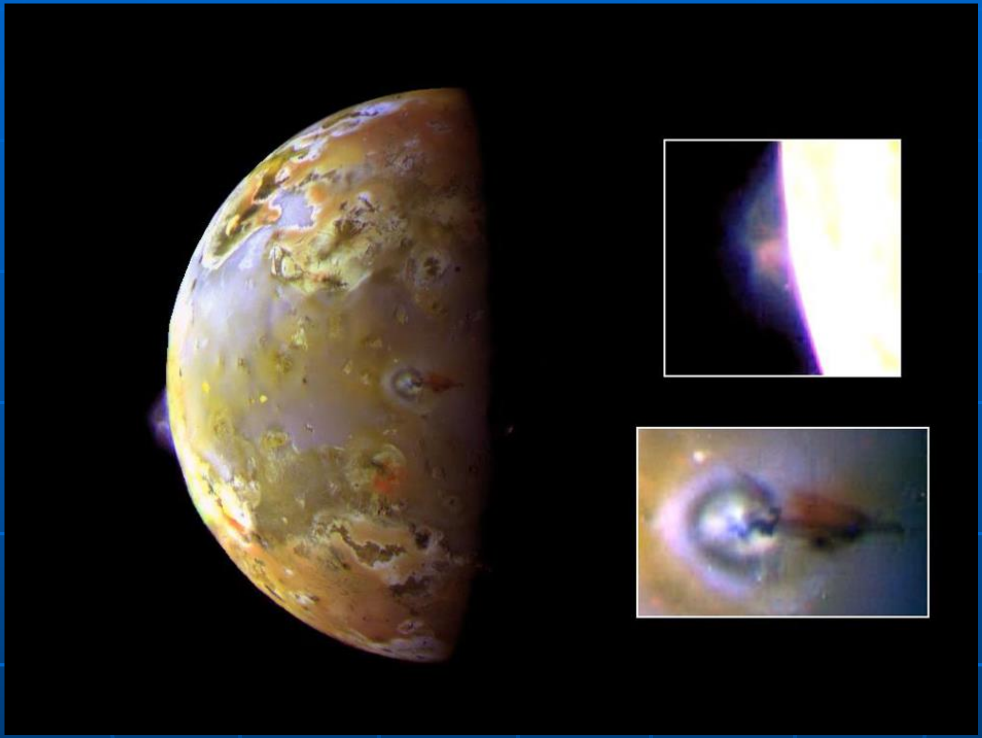
Io

Callisto

6 year mission by the spacecraft Galileo

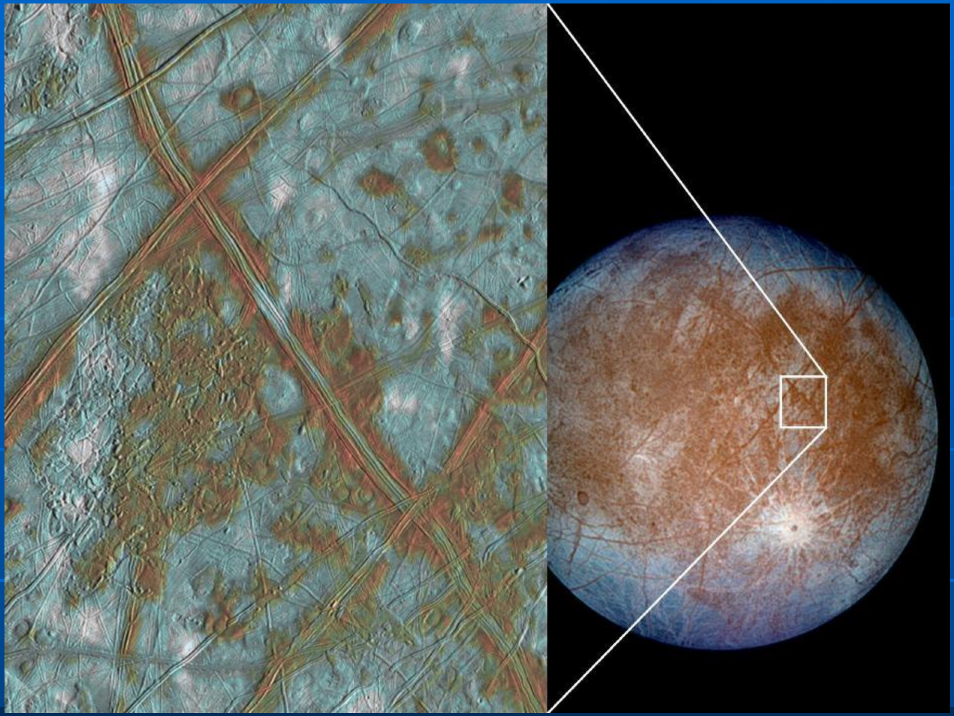



Io



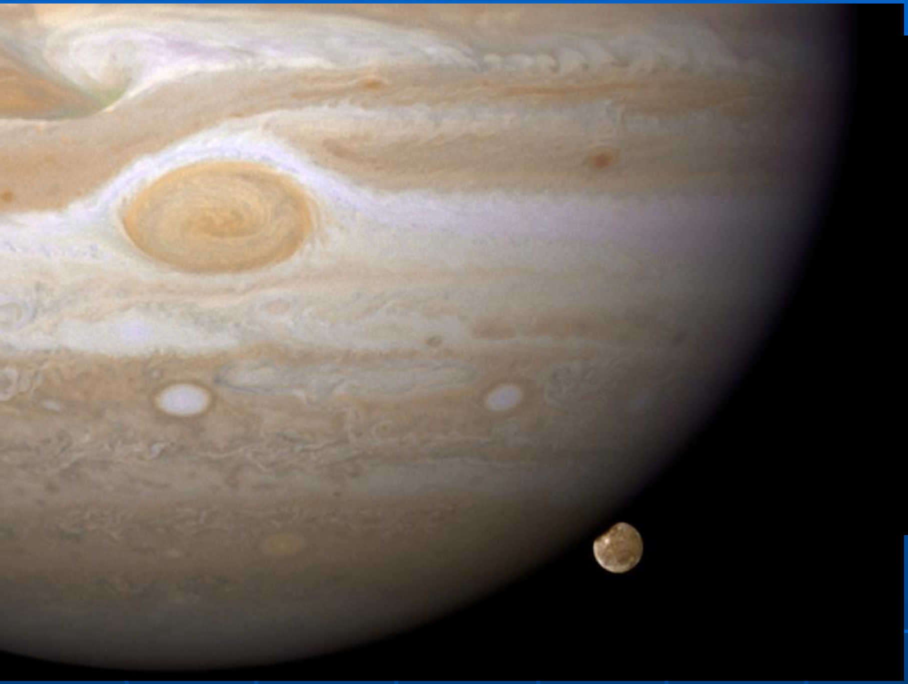
- The most volcanically active in solar system
- Some volcanoes are hotter than on Earth
- 100 foot tidal pull on surface

Europa



- Roughly the size of our moon
- More water than Earth
- Thin oxygen atmosphere
- May have a liquid ocean below icy surface
- Cooled, icy crust, brown = non-ice
- Internal source of heat

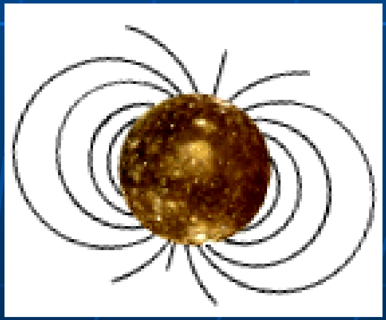
Ganymede



- Largest moon
- Has a magnetic field
- Rocky core
- Icy outer layer

Callisto

- Size of Mercury
- Cratered surface
- Rocky core
- Icy mantle



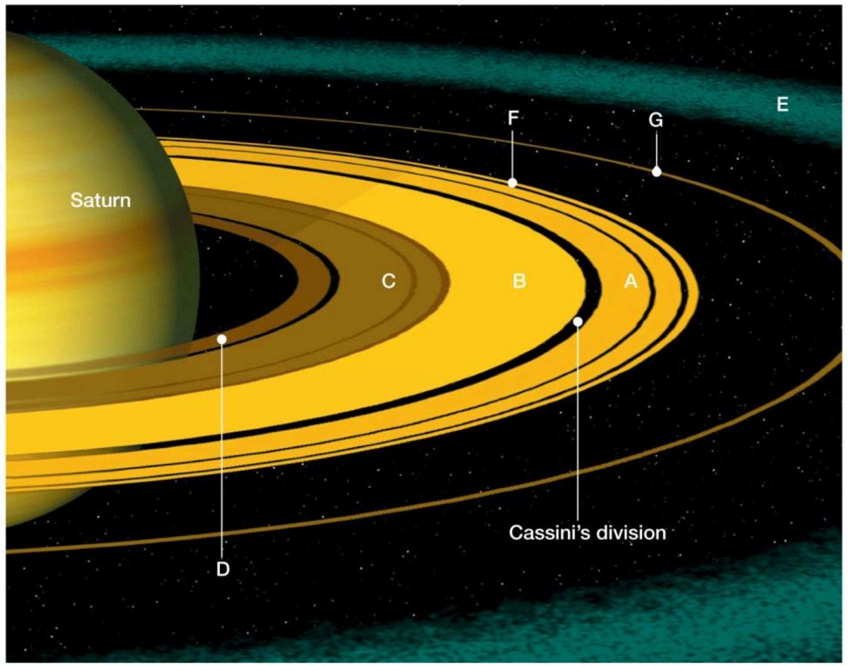
Saturn

- Hubble photograph
- 1996-2000
- Rotates on its axis
- Orbiting around the Sun
- Each season is 7 years
- 30 Earth years to orbit the Sun
- 10.5 hour rotation

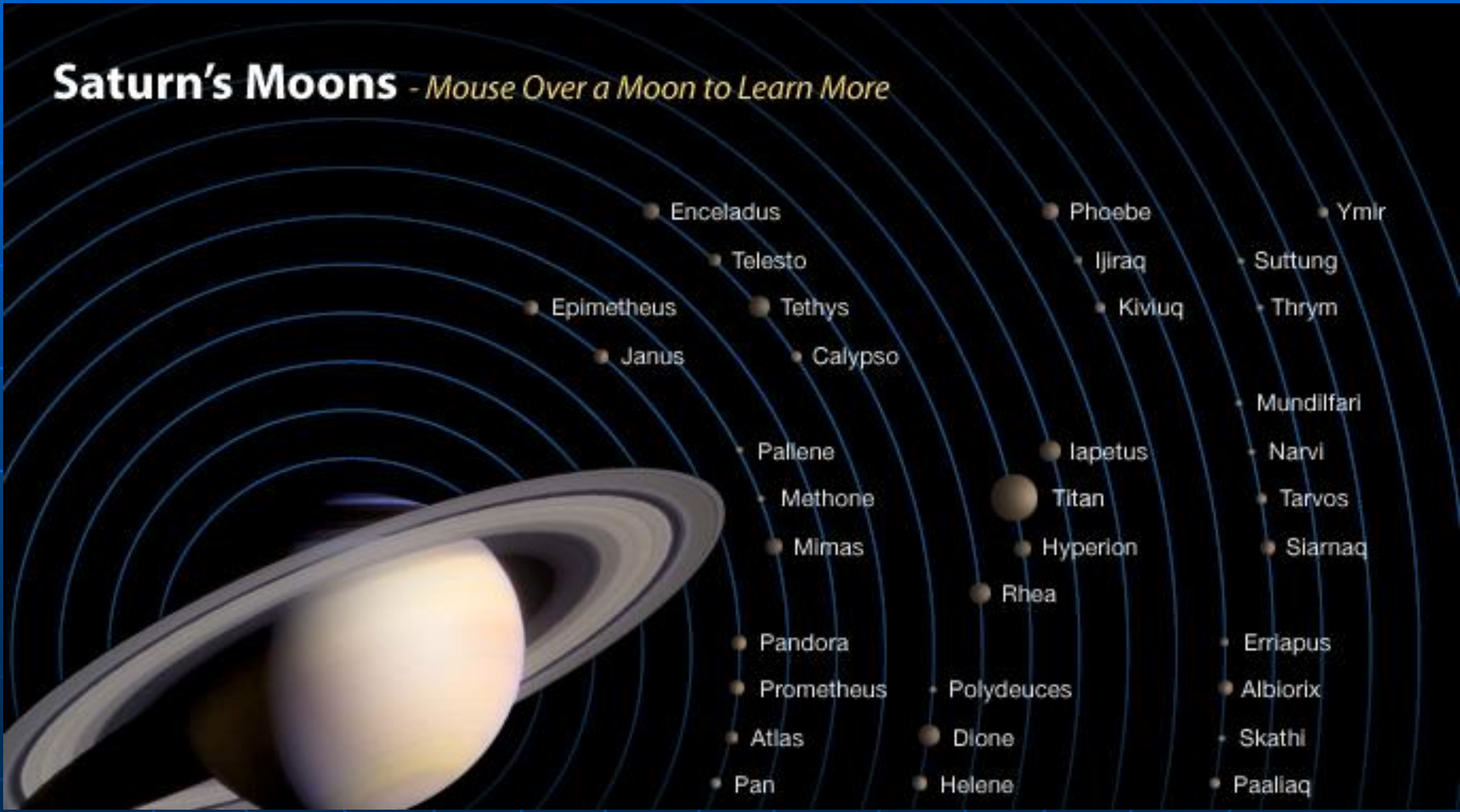
- Second gas giant and second largest planet in Solar System
- Average distance from Sun: 9.582 AU.
- Density: Saturn's radius is about 8.5 times that of Earth and mass is 95.2 times that of Earth. Density, therefore, is 0.69 kg m-3. That is considerably less than liquid water, making Saturn the least dense planetary body.
- Saturn rotates at different rates at different latitudes, but overall roughly once every 10.5 hours.
- Weather: On average, Saturn displays the same general weather patterns as Jupiter, although they are less visibly pronounced.
- Oblateness: Like Jupiter, Saturn rotates fast enough that it is slightly flattened at the poles.
- Composition: Broadly similar to that of Jupiter. Much of its mass takes the form of metallic hydrogen.
- Rings: Saturn has the most extensive ring system, clearly visible from Earth through a small telescope. Consist of small icy particles. Their width is 73,000 km but thickness ranges from tens to a few hundred m. Gaps in the rings are occupied by small shepherd moons.

Saturn's Rings

- Water ice, dust, and gases
- Particles range in size from pebble to house size
- 18,000 miles wide
- .6 mile thick

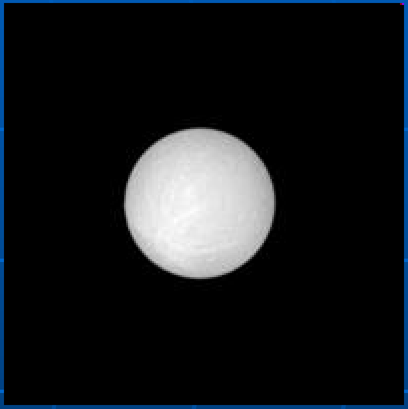


Saturn has 62 Moons



Spacecraft Cassini (artist's interpretation)

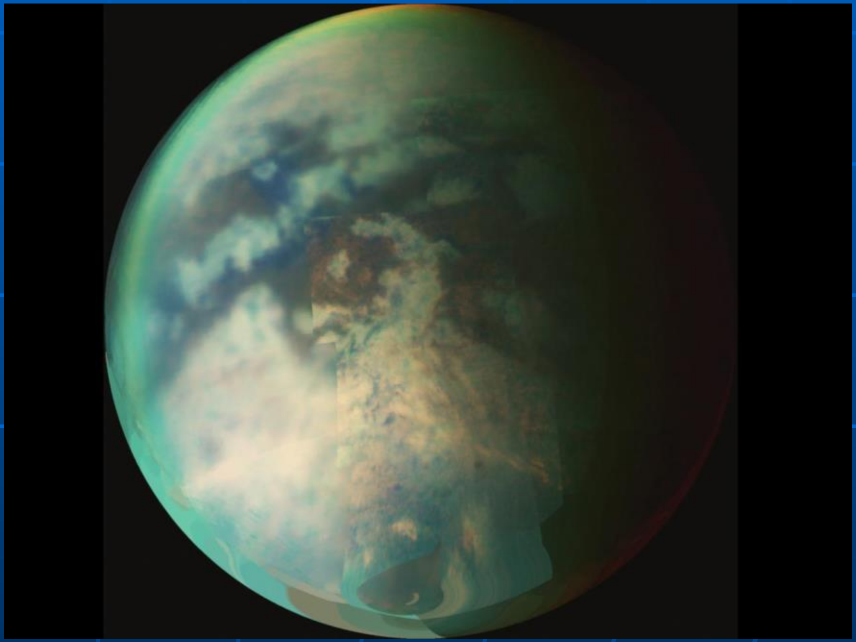
Since 2004, this spacecraft is collecting data from Saturn and several moons



Picture of one moon

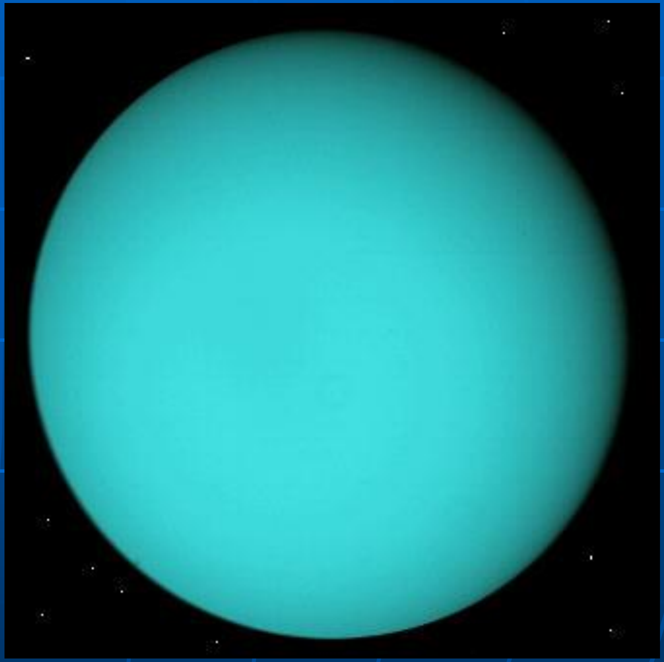
Titan

- Largest satellite of Saturn
- Rocky core, shell of water ice
- Atmosphere: nitrogen and methane



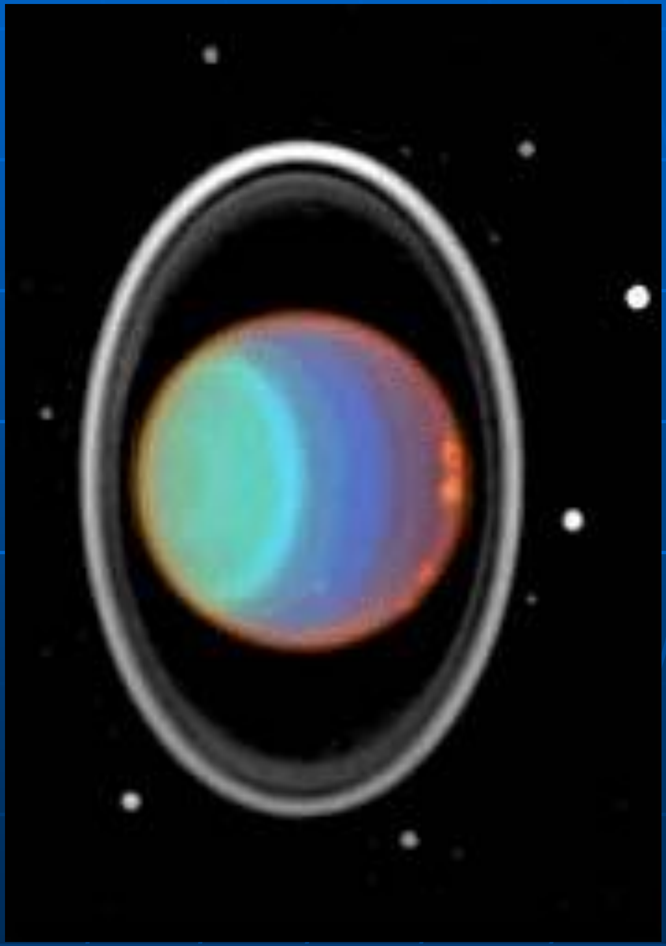
Uranus

- Blue-green color: crystals of methane
- Atmosphere: H and He
- Interiors are composed of methane, ammonia and water
- Core is composed of rock and metal
- 84 Earth year orbit
- 17 hour rotation
- 98 degree tilt on its axis



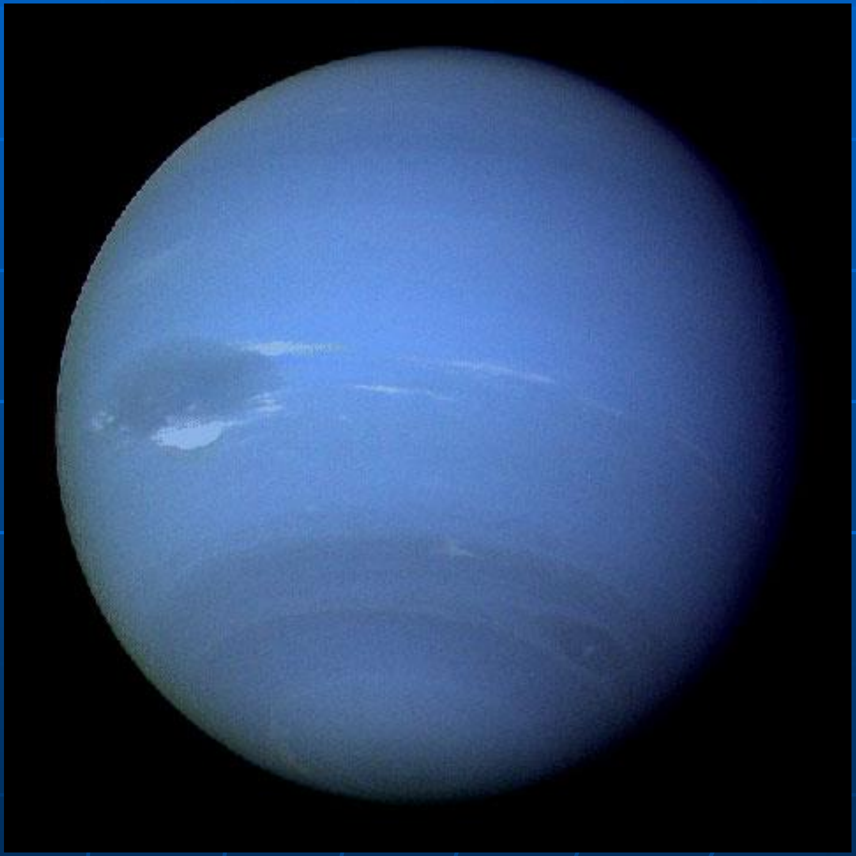
Voyager 2, 1986

- Magnetic field on Uranus is tilted at 58 degrees
- Uranus has a number of rings
- Ranging from3-60 miles thick



Neptune

- Magnetic field is tilted at 50 degree
- 4 X bigger than Earth
- Orbit: 165 Earth years
- H, He, water and silicates
- Solid rocky core
- 11 satellites

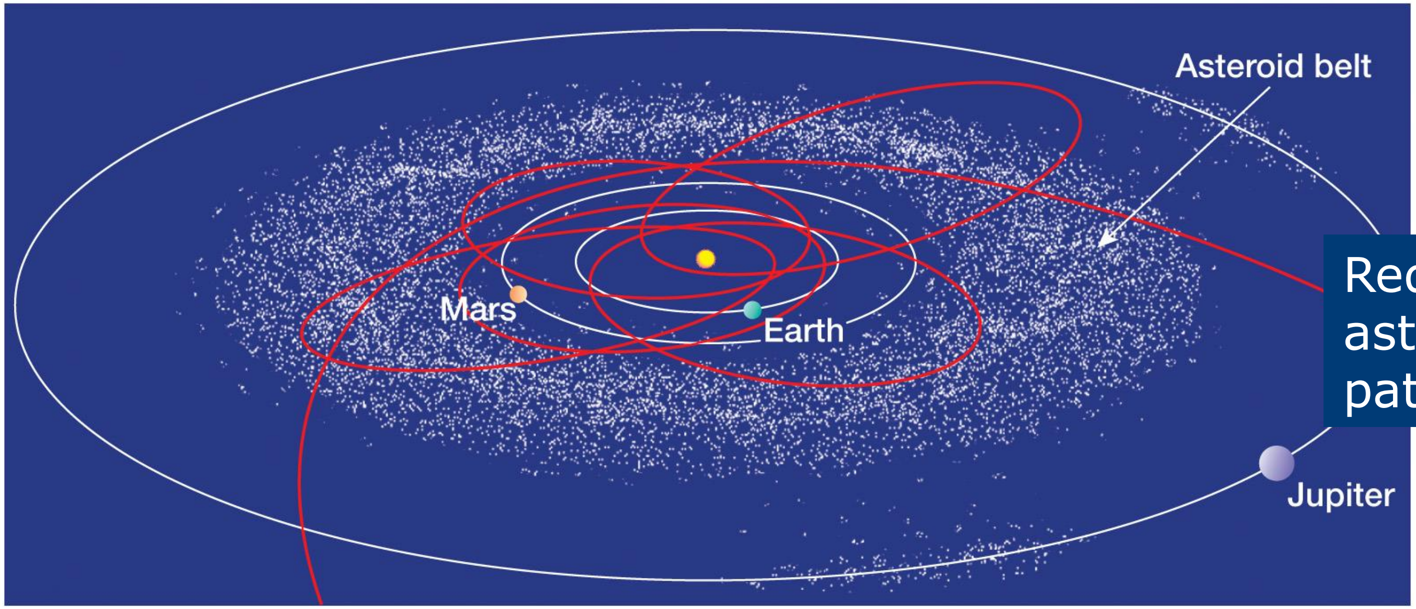


Asteroids

- Small fragments of rock from the solar system's formation

Asteroid Gaspra

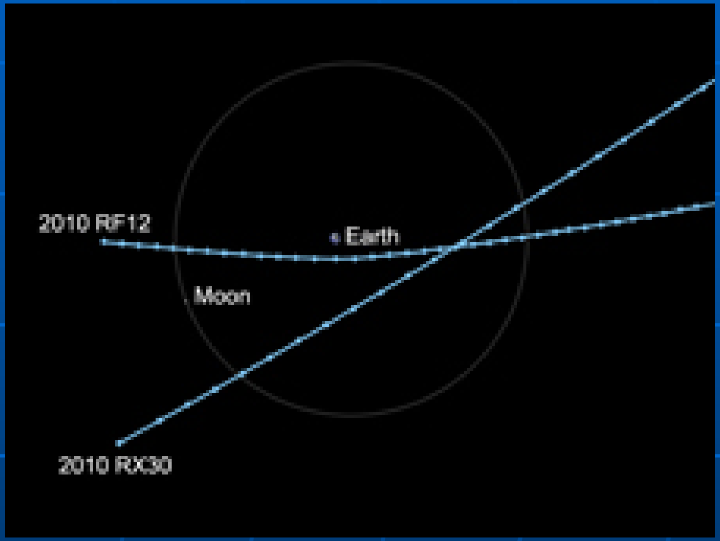
19x12x11 kms



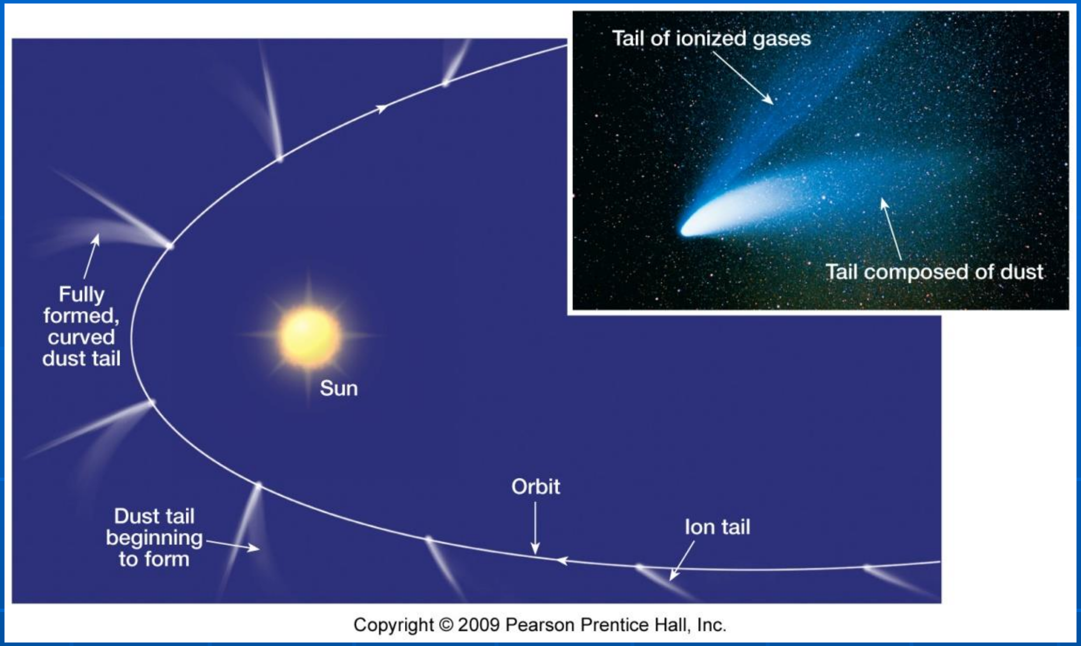
Red indicates asteroid belt path

Asteroids passing Earth

- Two asteroids pass Earth at about the distance of the Moon
- One is 32-65 feet in size
- The other is 20-46 feet in size



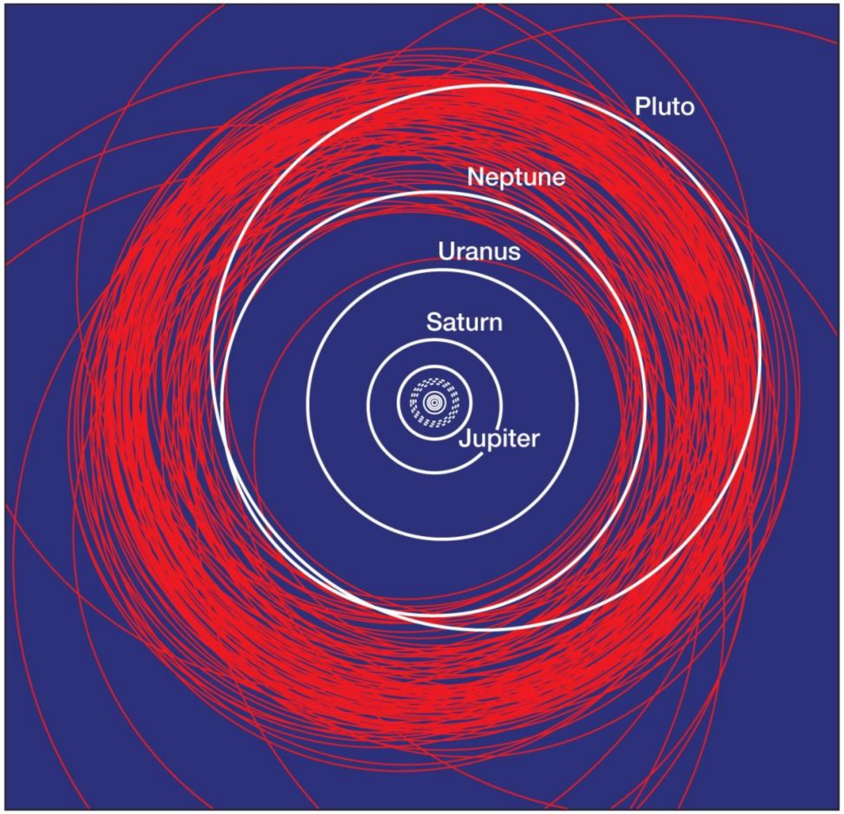
Comets



- Composed of ice (ammonia, methane, carbon dioxide, and carbon monoxide)
- Rocky core
- Tail: solar wind and radiation pressure move ionized gases and dust
- **Sublimation:** the change in state from solid to gas without passing through the liquid stage

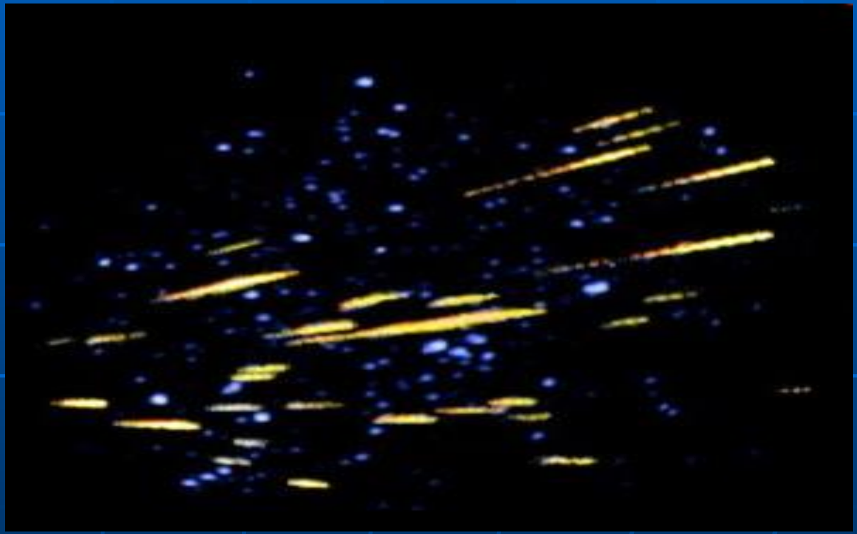
Kuiper Belt

- Comets orbit the Sun in the same plane as the planets



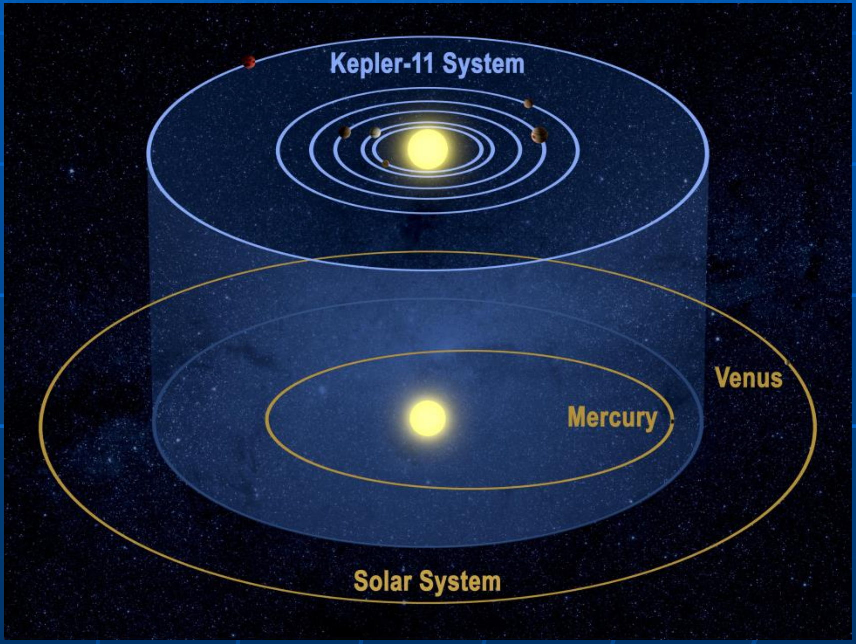
Meteoroids

- Less than a meter
- Debris from asteroid belt, interplanetary material or the moon
- Friction from the meteoroids and air heats both and we see a "shooting star"



New Information

- Kepler-11 star, 2000 light years away
- Appears to have rocky planets
- Most complete planetary system



Remote Sensing Techniques for Planetary Exploration

Measure changes in:

- Electromagnetic fields (spectroscopy)
- Acoustic fields (sonar)
- Potential fields (gravity)

Chemical composition:

- Gamma and neutron spectroscopy
- X-Ray spectroscopy
- VNIR reflectance spectroscopy (limited)

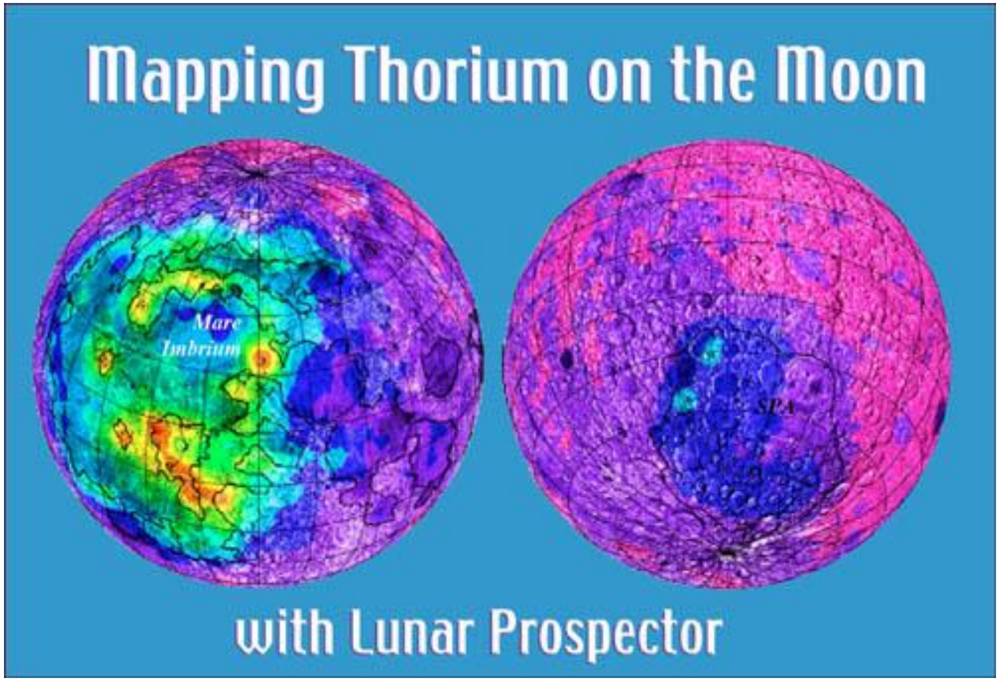
Mineralogical composition:

- VNIR reflectance spectroscopy
- MID NIR emission spectroscopy

Remote Sensing Techniques for Planetary Exploration

- **In general, remote sensing is the only way to determine the surface composition of inaccessible targets**
- **Compositional information is important for constraining the**
- **History of a target. Thus compositional information is the key to understand the origin and evolution of planetary bodies.**
- **Compositional information allows conclusions to be drawn about the processes that are or were acting on a planetary body**
- **Remote Sensing is required to identify potential landing sites and potential recourses for humans.**
- **We can have a closer look on the planetary surface using spectroscopy and color photometry.**.

- Gamma-ray spectrometers have been widely used for the elemental and isotopic analysis of bodies in the Solar System, especially the Moon and Mars.
- These surfaces are subjected to a continual bombardment of high-energy cosmic rays, which excite nuclei in them to emit characteristic gamma-rays which can be detected from orbit.
- Thus an orbiting instrument can map the surface distribution of the elements for an entire planet.



Remote Sensing Tools in Planetary Exploration

METHOD	EM SPECTRUM	INFORMATION	INTERPRETATION	MISSION
Gamma-Ray Spectroscopy	Gamma rays	Gamma spectrum	K, U, Th Abundances	Apollo 15, 16: Venera
X-ray Fluorescence spectrometry	X-rays	Characteristic Wavelengths	Surface mineral/ chemical comp.	Apollo; Viking Landers
Ultraviolet Spectrometry	UV	Spectrum of Reflected sunlight	Atmospheric Composition: H,He,CO_2	Mariner; Pioneer; voyager
Photometry	UV, Visible	Albedo	Nature of Surface; Composition	Earth Telescopes; Pioneer
Multispectral Imagers	UV, Visible, IR	Spectral and Spatial	Surface Features; Composition	On most missions
Reflectance Spectrometers	Visible, IR	Spectral intensities of reflected solar radiation	Surface Chemistry; mineralogy; processes	Telescopes; Apollo
Laser Altimeter	Visible	Time delay between emitted and reflected pulses	Surface Relief	Apollo 15,16,17
Polarimeter	Visible	Surface Polarization	Surface Texture; Composition	Pioneer; Voyager
Infrared Radiometer (includes scanners)	Infrared	Thermal radiant intensities	Surface and atmospheric temperatures; compos.	Apollo; Mariner; Viking; Voyager

Remote Sensing Tools in Planetary Exploration

METHOD	EM SPECTRUM	INFORMATION	INTERPRETATION	MISSION
Infrared Radiometer (includes scanners)	Infrared	Thermal radiant intensities	Surface and atmospheric temperatures; compos.	Apollo; Mariner; Viking; Voyager
Microwave Radiometer	Microwave	Passive microwave emission	Atmosphere/Surface temperatures; structure	Mariner; Pioneer Venus
Bistatic Radar	Microwave	Surface reflection profiles	Surface Heights; roughness	Apollo 14,15,16; Viking
Imaging Radar	Microwave	Reflections from swath	Topography and roughness	Magellan; Earth systems
Lunar Sounder	Radar	Multifrequency Doppler Shifts	Surface Profiling and imaging; conductivity	Apollo 17
S-Band Transponder	Radio	Doppler shift single frequency	Gravity data	Apollo
Radio Occultation	Radio	Frequency and intensity change	Atmospheric density and pressure	Flybys and Orbiters

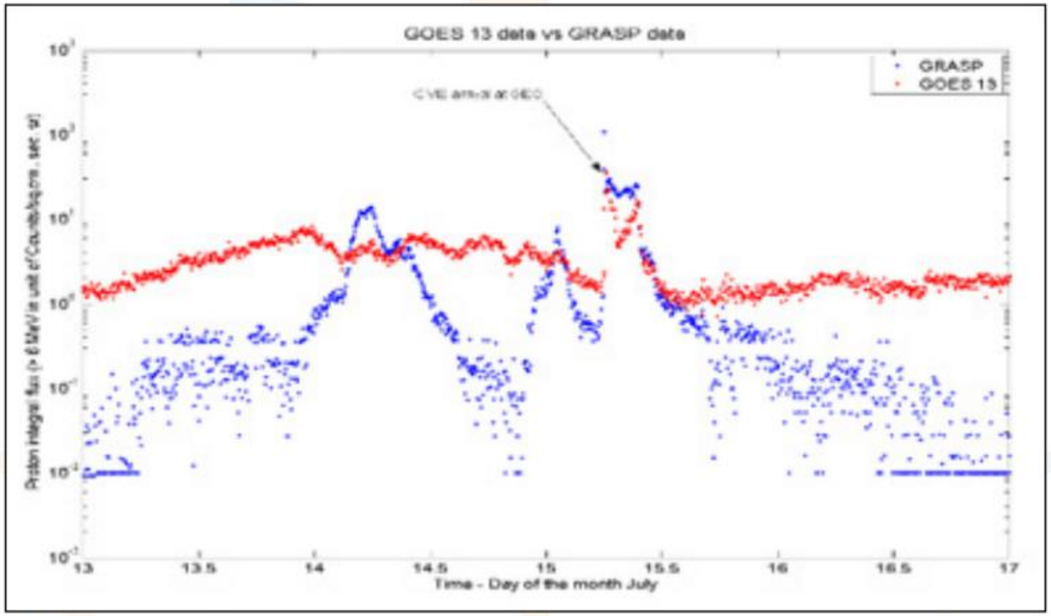
Remote Sensing Techniques for Planetary Exploration

Gamma-Ray Spectroscopy

- Gamma rays
- Gamma spectrum
- K, U, Th Abundances
- Apollo 15, 16: Venera, CH-1, CH-2

A gamma-ray spectrometer (GRS) is an instrument for measuring the distribution of the intensity of gamma radiation versus the energy of each photon. The study and analysis of gamma-ray spectra for scientific and technical use is called gamma spectroscopy, and gamma-ray spectrometers are the instruments which observe and collect such data. Because the energy of each photon of EM radiation is proportional to its frequency, gamma rays have sufficient energy that they are typically observed by counting individual photons.

GRASP on-board GSAT-19 . Geostationary Radiation Spectrometer (GRASP) is a light weight (2.5kg) and compact instrument on-board GSAT-19, designed to detect charged particles in the energy range 500 keV-10MeV, 4-85MeV and 17-85MeV for electrons, protons, and alphaparticles respectively in the geostationary orbit. The initial observations of a Coronal Mass Ejection(CME) event



GRASP (blue) Vs GOES data (red), Showing the passage of a CME event on the 16th July 2017.

Thorium distribution on the Moon: new insights from *Chang'E-2* gamma-ray spectrometer *

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Abstract We present the thorium distribution on the lunar surface derived from observations by the *Chang'E-2* gamma-ray spectrometer (*CE-2* GRS). This new map shows a similar thorium distribution to previous observations. In combination with this new thorium map and impact cratering model, we investigate the origination of thorium on the Moon's highlands, which was previously thought to be contributed from Imbrium ejecta. We found that the Imbrium ejecta has a small contribution (~20%–30%) to the thorium on the lunar highlands but most thorium is likely to be indigenous before the deposition of the Imbrium ejecta. This new thorium map also confirms that the eastern highlands have a relatively higher thorium concentration than the western highlands. We propose that the thin crust and large basins on the eastern highlands are responsible for this difference in thorium.

Key words: Moon — Chang'E-2 Gamma-ray Spectrometer — Thorium distribution

1 INTRODUCTION

Associated with the asymmetric features of elevation and crustal thickness between the Moon's nearside and farside is the radioactive elemental distributions (Prettyman et al. 2006; Kobayashi et al. 2010, 2012; Yamashita et al. 2010; Zhu et al. 2013). The nearside of the Moon, with a thin crust and relatively flat surface that is dominated by volcanic maria, is enriched in radioactive elements sitions are enriched in Th with a concentration larger than 3 ppm (based on a *Lunar Prospector* (*LP*) $5^\circ \times 5^\circ$ Th map, Lawrence et al. 1998). The SPAT has a Th concentration between 1.5 ppm and 3.5 ppm. In contrast, the FHT, constituting over 60% of the Moon's surface, is depleted of Th, with a concentration lower than 1.5 ppm.

The Th contained within the KREEP materials was thought to be last crystallized between the boundary of the

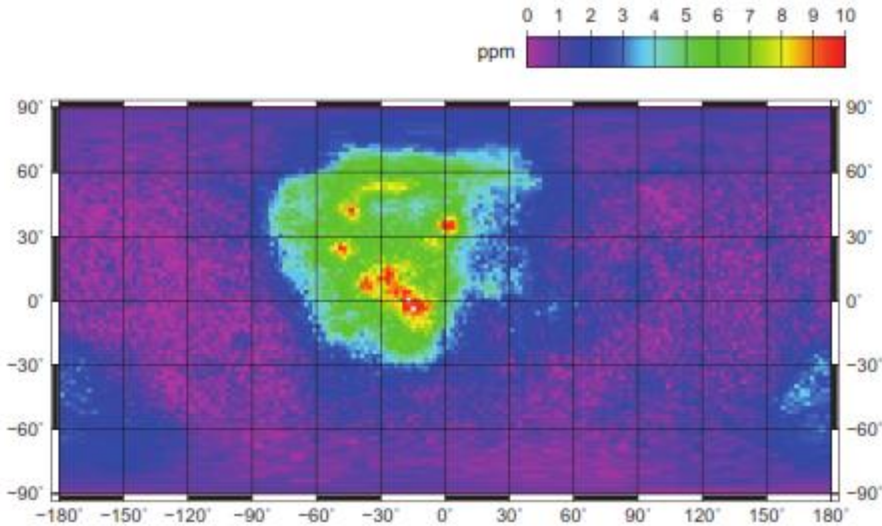
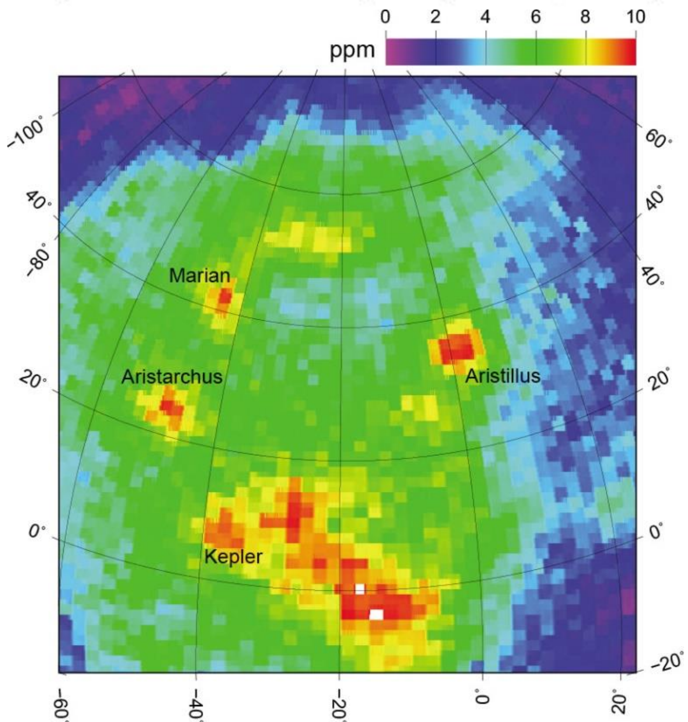


Fig. 2 The global Th distribution on the Moon derived from *CE-2* GRS. The Th gamma rays emitted from the Moon are binned into pixels of 60 km ×60 km quasi-equal area (11 306 pixels). The map is displayed in cylindrical equidistant projection.



The Th distribution in the PKT derived from *CE-2* GRS. The Th gamma rays emitted from the Moon are binned into pixels of 60 km × 60 km quasi-equal area (11 306 pixels). The map is displayed in azimuthal projection.

X-ray Fluorescence spectrometry

- X-rays
- Characteristic Wavelengths
- Surface mineral/ chemical comp.
- Apollo; Viking Landers

X-ray fluorescence (XRF) spectroscopy is one of the most widely used and well-established methods of routine estimation of geochemical composition of rocks, sediments, earth and planetary materials,

XRF spectrometry is used in the determination of geochemical concentrations for a range of major and trace elements at parts per million (ppm) level

XRF spectrometry is ability to rapidly provide a high-resolution assessment of relative variations of most Earth and planetary elemental compositions.

XRF spectrometry is based on the wavelength-dispersive principle, which states that individual atoms emit a relative abundance of X-ray photons of energy or wavelength feature that can be estimated (Weltje & Tjallingii, 2008).

XRF procedure

The incoming X-rays from an XRF instrument knock the electron of an atom out of the inner orbital. This results in the excitation of the atom and the production of high-energy radiation (photons, protons, electrons, etc.). The detection and integration of characterised emitted lines to give varying levels of intensity. The conversion of the detected line intensities to elemental concentrations.

- The Mars path finder spacecraft landed on the surface of Mars on July 4, 1997

- The Sojourner rover rolled down the ramp of the lander and began to explore and measure its surroundings using multi spectral imaging cameras and an Alpha Proton X-ray Spectrometer (APXS). In all, the APXS analyzed a dozen soil samples and rocks. The analyses proved difficult because all of the rocks were covered with loose soil or weathering rinds which interfered with the analyses.

CLASS payload on-board Chandrayaan-2 The Chandrayaan-2 Large Area Soft X-ray Spectrometer (CLASS) experiment aims to map the abundance of the major rock forming elements on the lunar surface using the technique of X-ray Fluorescence (XRF) during solar flare events. This payload has been developed and tested.

Ultraviolet Spectrometry

- UV Spectrum of Reflected sunlight
- Atmospheric Composition: H,He,CO_2
- Mariner; Pioneer; voyager

- Mass spectrometers on a lander allow for the chemical analysis of minor and trace elements, undetectable by remote spectroscopy.

- Also, from a lander the atmosphere surface interaction can be studied. Being located on a fixed geographic location, temporal variations of the atmosphere composition (e.g. condensation/sublimation, chemical interaction with the surface)

- On time scales of diurnal, seasonal, and annual periods, given sufficient operation time of the lander

- Understanding the atmospheric composition is a key element in understanding a planet. The atmospheres of most of the terrestrial planets, of Jupiter, of Saturn and its moons Titan and Enceladus have been investigated with mass spectrometry

- The elemental, isotopic, and chemical composition including all trace species are of great scientific interest by giving clues to the evolution of the planetary object.

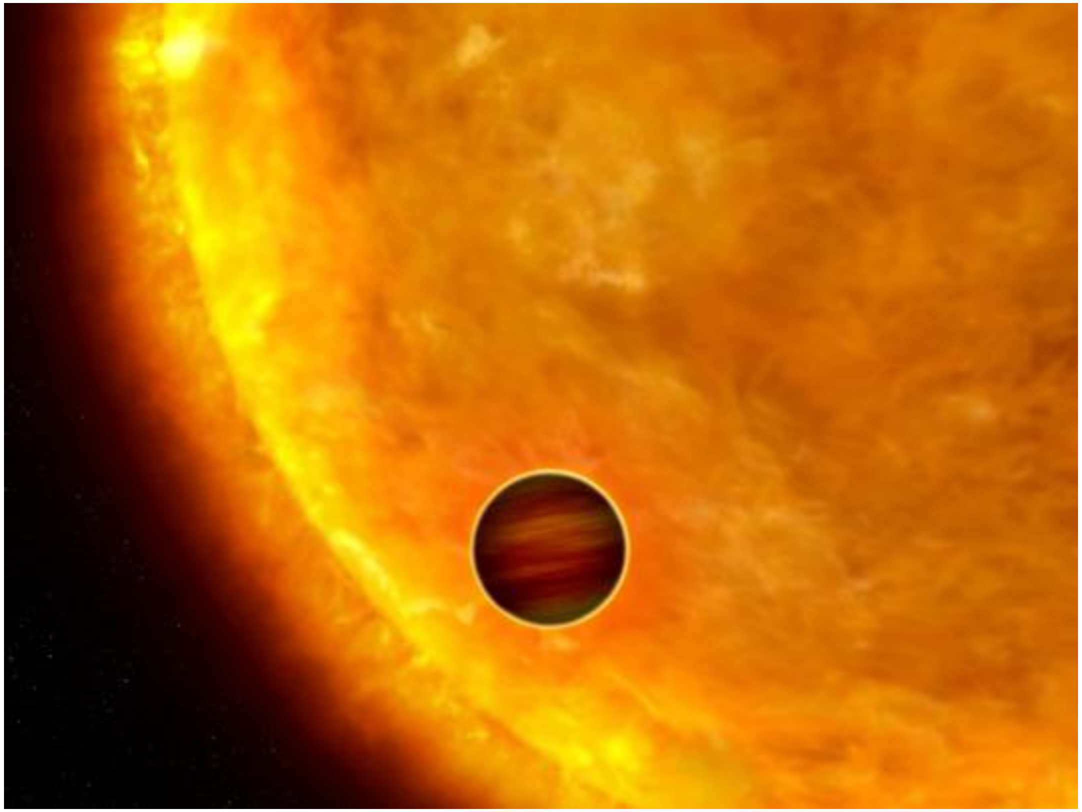
- Mass spectra allowing for element identification at the ppm level, the abundance of trace elements can be determined to provide further information on the nature of planetary differentiation and the geological origin of surface materials

Photometry

- ❖ UV, Visible
- ❖ Albedo
- ❖ Nature of Surface; Composition
- ❖ Earth Telescopes; Pioneer

Photometry, in astronomy, the measurement of the brightness of stars and other celestial objects (nebulae, galaxies, planets, etc.).

Such measurements can yield large amounts of information on the objects’ structure, temperature, distance, age, etc.



A PLANETARY TRANSIT

An artist's impression of a Jupiter size extrasolar planet passing in front of its parent star

This method detects distant planets by measuring the minute dimming of a star as an orbiting planet passes between it and the Earth. The passage of a planet between a star and the Earth is called a "transit."
If such a dimming is detected at regular intervals and lasts a fixed length of time, then it is very probable that a planet is orbiting the star and passing in front of it once every orbital period.

The dimming of a star during transit directly reflects the size ratio between the star and the planet: A small planet transiting a large star will create only a slight dimming, while a large planet transiting a small star will have a more noticeable effect.

The size of the host star can be known with considerable accuracy from its spectrum, and photometry therefore gives astronomers a good estimate of the orbiting planet's size, but not its mass.

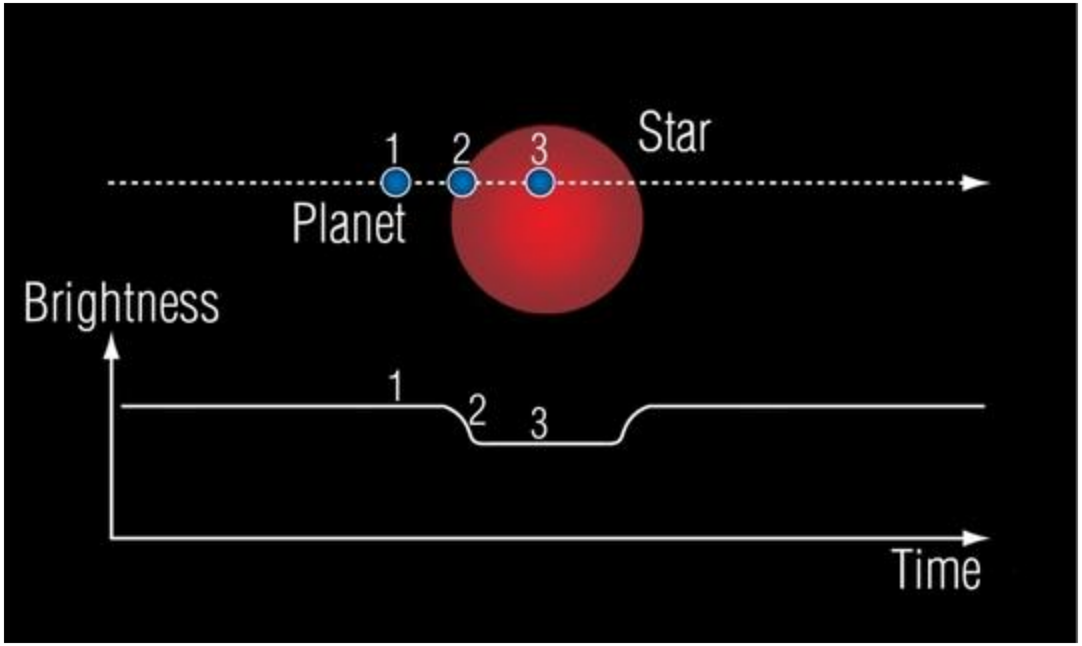
This makes photometry an excellent complement to the spectroscopic method, which provides an estimate of a planet's mass, but not its size. Using both methods, combining mass and size, scientists can calculate the planet's density, an important step towards assessing its composition.

Transit photometry is currently the most effective and sensitive method for detecting extrasolar planets, particularly from an onservatory in space. The Kepler mission, launched in March of 2009, uses photometry to search for extrasolar planets from space.

The spacecraft's sensitivity is such that it has already detected thousands of planetary candidates, including several that are Earth-sized and orbiting in their star's habitable zone. No other method currently proposed can match either the volume of the search or its sensitivity.

Transits can also provide scientists with a great deal of information about the planet that is not otherwise measurable. First and foremost the "dip" in a star's luminosity during transit is directly propotionate to the size of the planet. Since the star's size is known known with a high degree of accuracy, the planet's size can be deduced from the degree to which it dims during transit.

When combined with radial velocity data, a transit can also provide a good estimate of the planet's mass. This is because a transiting planet is necessarily in an "edge-on" position to an observer on Earth. Under these conditions, the minimum mass normally provided by radial velocity measurements is, in fact, the planet's true mass. Taken together, the planet's size and mass provide scientists with a crucial clue as to its composition: the planet's density.



Kepler, a space-based photometry observatory, launched in March 2009 and as of January 2013 has identified over 2,700 candidate exoplanets. The vast majority of these are expected to be confirmed as planets, making Kepler by far the most successful planet humting instrument to date.

The main difficulty with this method is that in order for the photometric effect to be measured, a transit must occur. This means that the distant planet must pass directly between it's star and the Earth. Unfortunately, for most extrasolar planets this simply never happens.

In order for a transit to occur the orbital plane must be almost exactly "edge-on" to the observer, and this is true only of a small minority of distant planets. The rest will never be detected with photometry.

Laser Altimeter

A laser altimeter is a device used aboard planet-orbiting satellites to map a planet's terrain. The elevations of surface features can be calculated by comparing how long it takes a laser pulse to echo back at different locations.

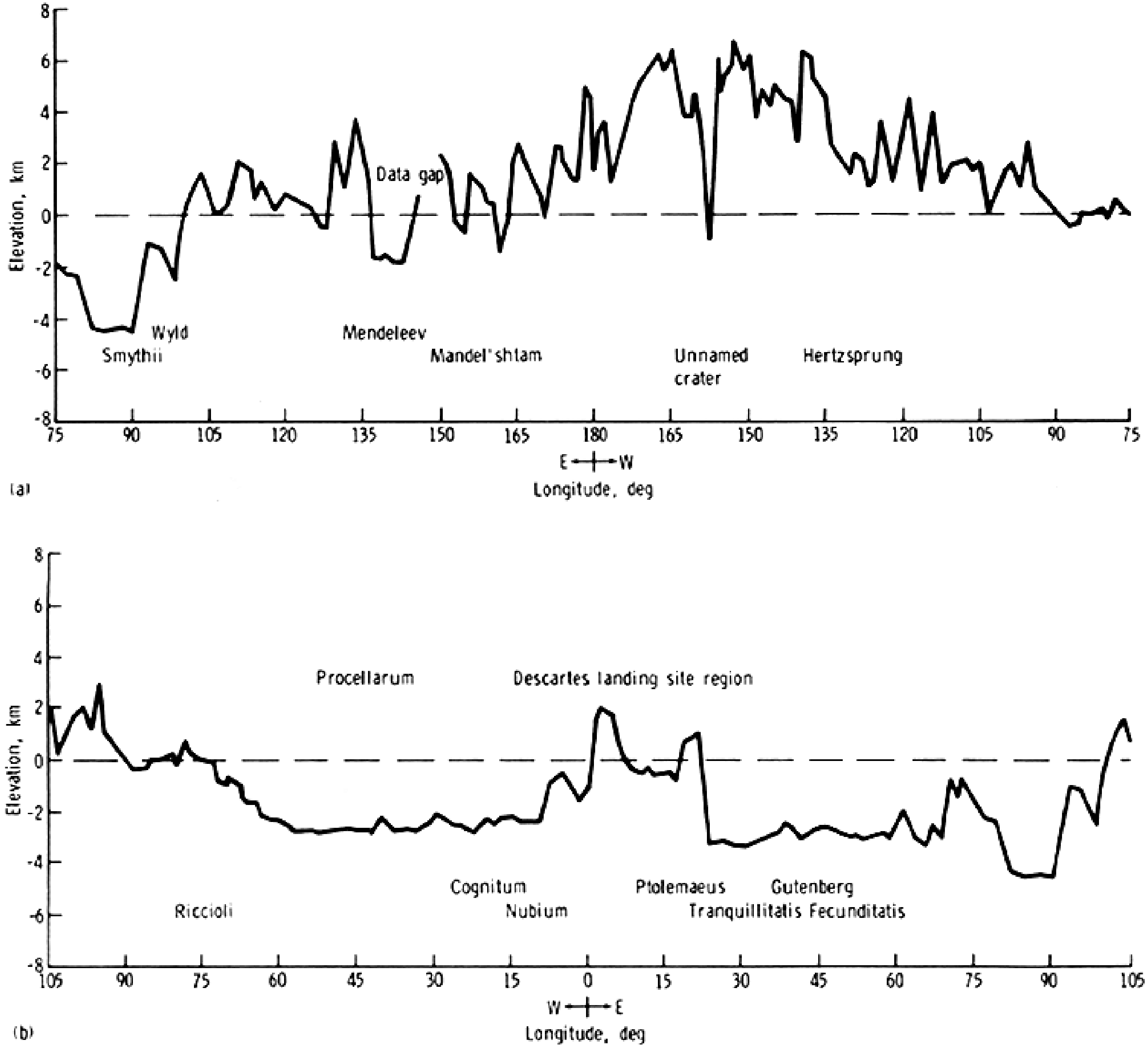
A laser altimeter is an instrument that measures the distance from an orbiting spacecraft to the surface of the planet or asteroid that the spacecraft is orbiting. The distance is determined by measuring the complete round trip time of a laser pulse from the instrument to the body's surface, and back to the instrument.

On NASA's Earth-orbiting ICESat satellite, a laser altimeter (Geoscience Laser Altimeter System) is used to obtain data on the elevation or thickness of ice sheets. This is relevant to understanding global climate change.

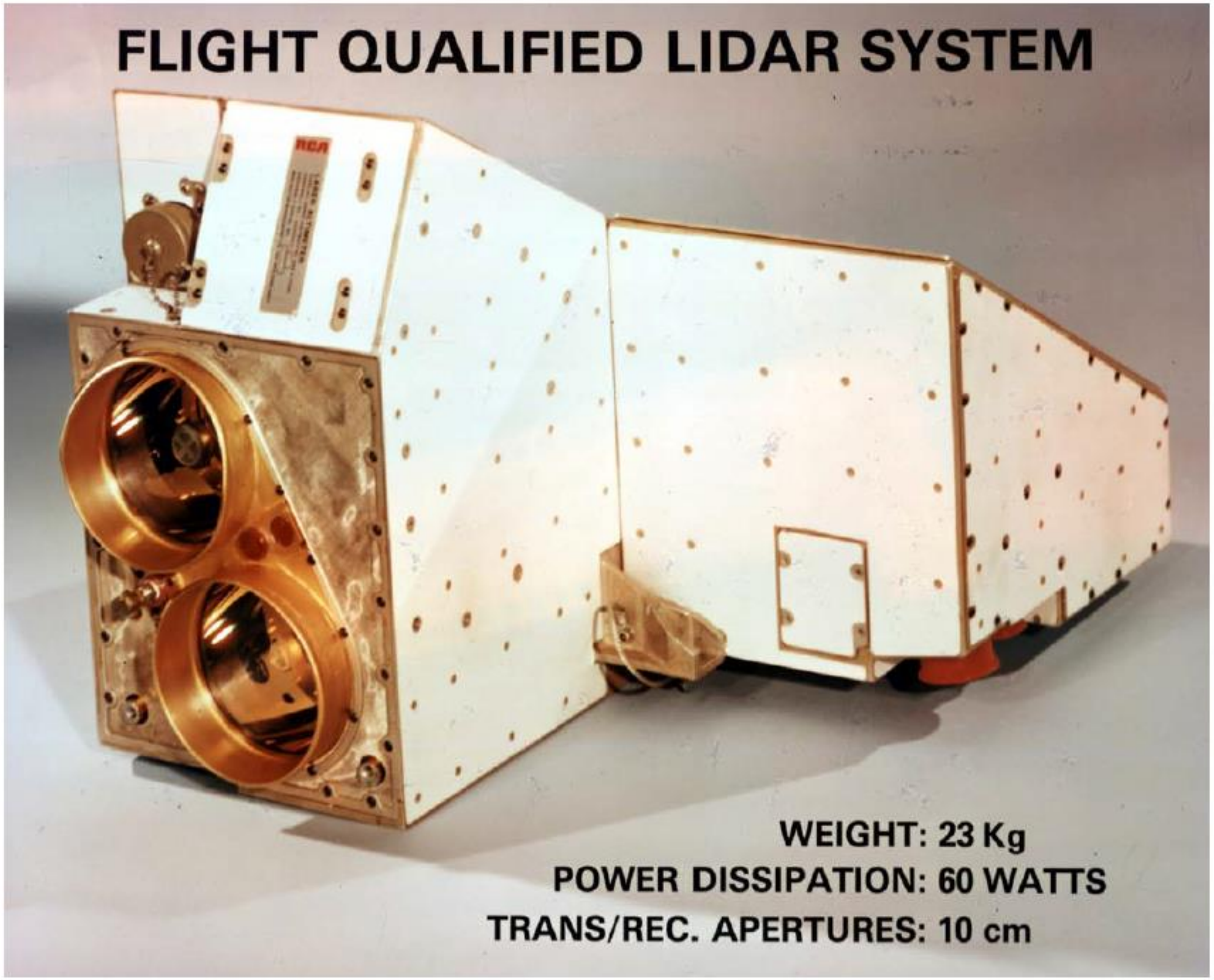
The Laser Altimeter Experiment was performed on *Apollo 15, 16,* and *17.* In this experiment, a pulse from a laser was aimed at the lunar surface.

The reflection of the pulse from the surface was then observed with a small telescope. The length of time the pulse took to travel from the spacecraft to the Moon and back is related to the height of the spacecraft above the surface of the Moon.

Measurements were made roughly every 30 kilometers across the Moon's surface. These measurements are sufficiently accurate to distinguish height variations of 10 meters between adjacent measurement points.



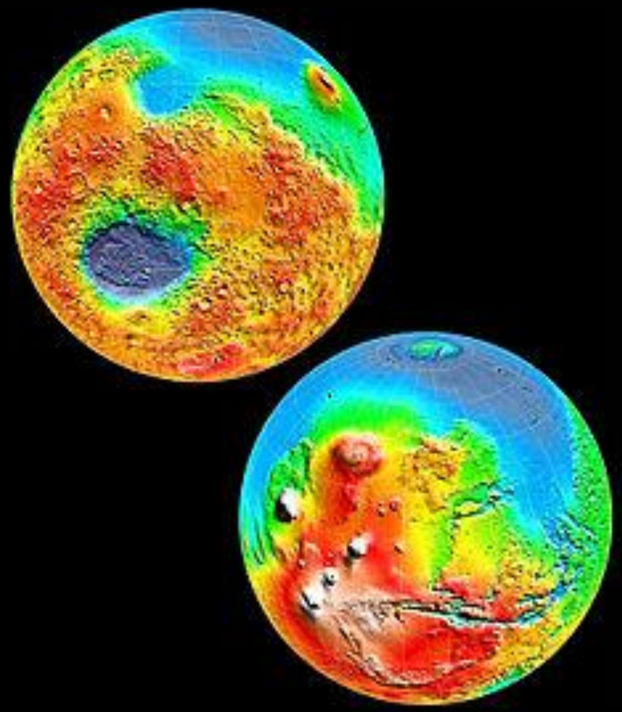
Elevation, km
Data gap
Smythii
Wyld
Mendeleev
Mandel'shtam
Unnamed crater
Hertzsprung
E W
Longitude, deg
(a)
Elevation, km
Procellarum
Descartes landing site region
Riccioli
Cognitum
Nubium
Ptolemaeus
Gutenberg
Tranquillitatis
Fecunditatis
W E
Longitude, deg
(b)



Laser transmitter:

- Mechanically Q- switched ruby laser
- Flashlamp pumped
- Based on mil-qualified rangefinder for tank
- 0.05 Hz laser firing rate
- RCA Astronautics
- Flown on Apollo 15-17

The **Mars Orbiter Laser Altimeter (MOLA)** was one of five instruments on the Mars Global Surveyor (MGS) spacecraft, which operated in Mars orbit from September 1997 to November 2006. However, the MOLA instrument transmitted altimetry data only until June 2001.

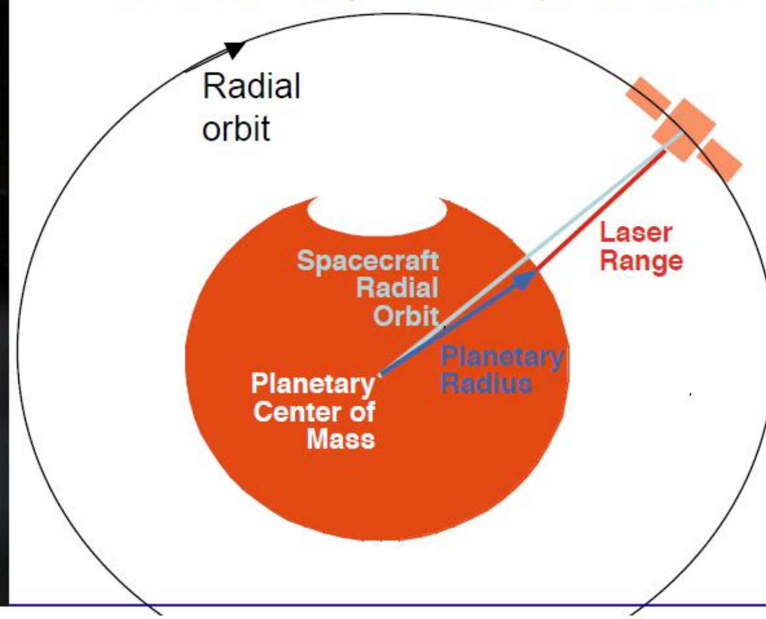


The MOLA instrument transmitted infrared laser pulses towards Mars at a rate of 10 times per second, and measured the time of flight to determine the range (distance) of the MGS spacecraft to the Martian surface. The range measurements resulted in precise topographic maps of Mars.

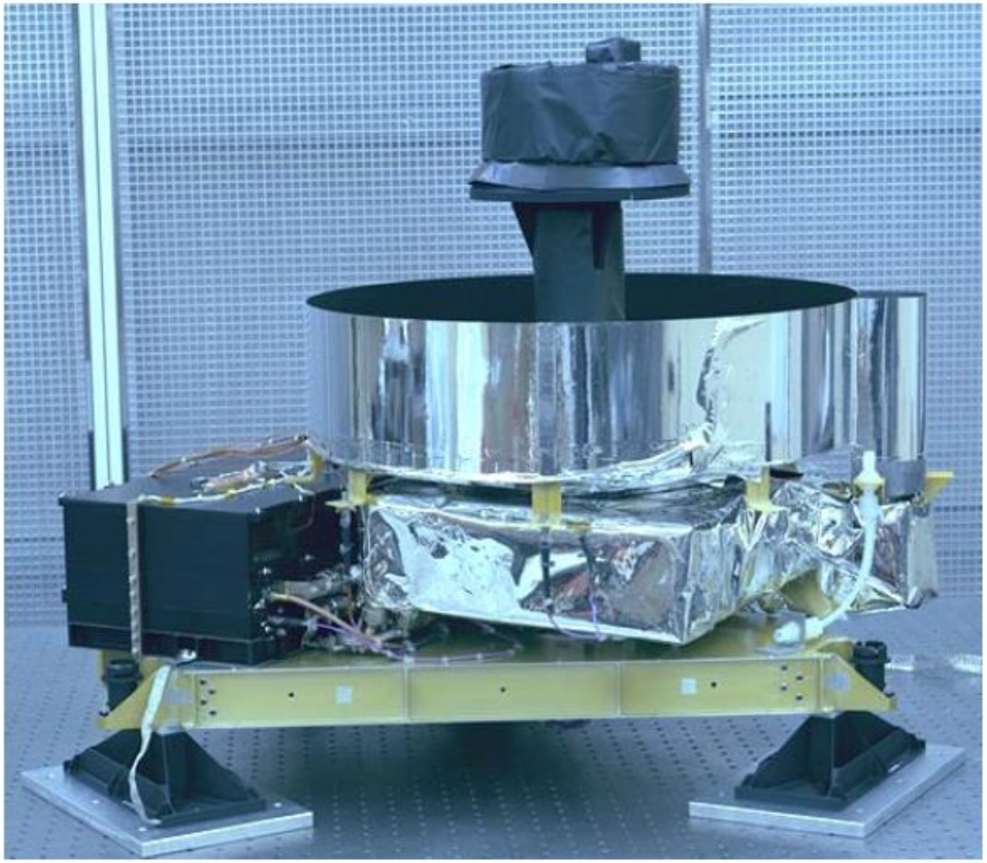
Mars Orbiter Laser Altimeter (1996, GSFC)
(initially on Mars Observer Mission, launched Sept., 1992)

GSFC

- Radial orbit quality depends on gravity field, atmospheric drag, solar radiation pressure, spacecraft maneuvers.
- Range accuracy depends on pulse timing resolution, surface roughness,
off-nadir angle, atmospheric refraction.
- MOLA measured pulse spreading and echo pulse energy; permit estimates of pulse spreading, surface reflectivity and atmospheric extinction



MOLA Instrument & Mapping Parameters



- Laser Wavelength: 1064 ± 0.2 nm
- Laser Pulsewidth: 8 nsec
- Pulse energy (start of mapping): 48 mJ
- Pulse repetition frequency: 10 Hz
- Range resolution: 38 cm
- Return pulses detected: ~99%
- Maximum range (hardware limit): 786 km
- Surface spot size in mapping orbit: ~168 m
- Along-track shot spacing: ~330 m
- Vertical accuracy (radial orbit error): <1 m
- Number of laser firings: 671,121,600
- Operated in lidar & radiometer modes

NEAR Laser Rangefinder (NLR)

On 17 February 1996, NASA's first Discovery mission began as the Delta II rocket rose from complex 17B carrying the Near Earth Asteroid Rendezvous (NEAR) spacecraft.

The overall NEAR mission objective is to provide information about the origin and nature of near-Earth asteroids, whose characteristics are suspected to provide clues about the formation of the inner planets, including the Earth, and whose composition is reflective of material as it existed soon after the "big bang."

The target asteroid is 433 Eros, one of the largest and most intensively studied near-Earth asteroids. Astrophysicists have estimated Eros to be 10–20 km in size, with a rotational period of roughly 5.27 h and an albedo of 0.15. Available Earth-based observations

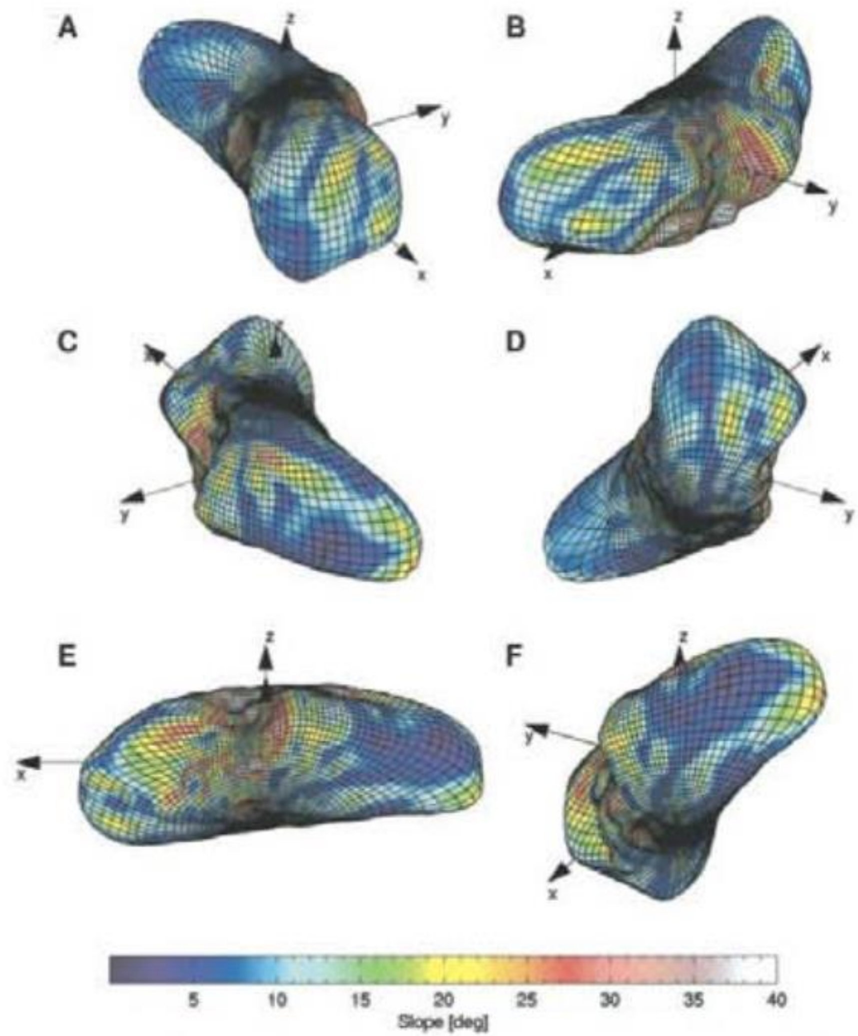


Fig. 3. Six perspective views of a three-dimensional shape model of 433 Eros from the NLR plotted to spherical harmonic degree and order 24. The mesh represents the scaled shape, and the surface facets are color-coded according to the surface slope with respect to a constant-density gravity field derived from the shape model (*32*). The asteroid is viewed at the following (elevation, azimuth) pairs: (**A**) 30°N, 60°E; (**B**) 30°N, 120°E; (**C**) 30°N, 0°E; (**D**) 30°S, 60°E; (**E**) 30°S, 300°E; and (**F**) 30°S, 0°E.

Reflectance spectroscopy

- The field of reflectance spectroscopy as a remote sensing tool applied to the study of solar system objects has blossomed in the past 15 years, resulting in major discoveries about almost all solar system objects.
- Reflectance spectroscopy has become one of the most important investigations on most current and planned Solar System Exploration Program space missions.
- Reflectance spectroscopy has proven to be the most powerful technique for determining surface lithologic composition by remote sensing.
- The reflectance spectroscopy effort encompasses virtually all objects in the solar system, and it involves many disciplines other than spectroscopy, such as geology, geochemistry, geophysics, and atmospheric sciences.

Essentially all the existing reflectance spectra for planetary objects have been obtained using ground-based telescopes.

Laboratory measurement and models of reflectance properties of materials are essential for developing the methods, background information, and the models to interpret planetary data.

Scope and Limitations

Terrestrial remote sensing

The development of reflectance spectroscopy as a remote sensing tool occurred First in the solar system exploration program as applied to other solar system objects using ground-based telescopes.

The terrestrial program is now more advanced in flight measurement technology and available data sets.

Atmospheric studies

The application of reflectance spectroscopy to the study of the composition and physical properties of planetary atmospheres has been extensive and successful.

Here we concentrate on scattering from solid surfaces, but aerosols or clouds contain solid or liquid particles and may show characteristic absorptions; the same physics and theory apply.

Emission spectroscopy

In the mid-infrared spectral region (about 5—50 μ) there are strong and complicated bands in the emission spectrum of many geologically important minerals.

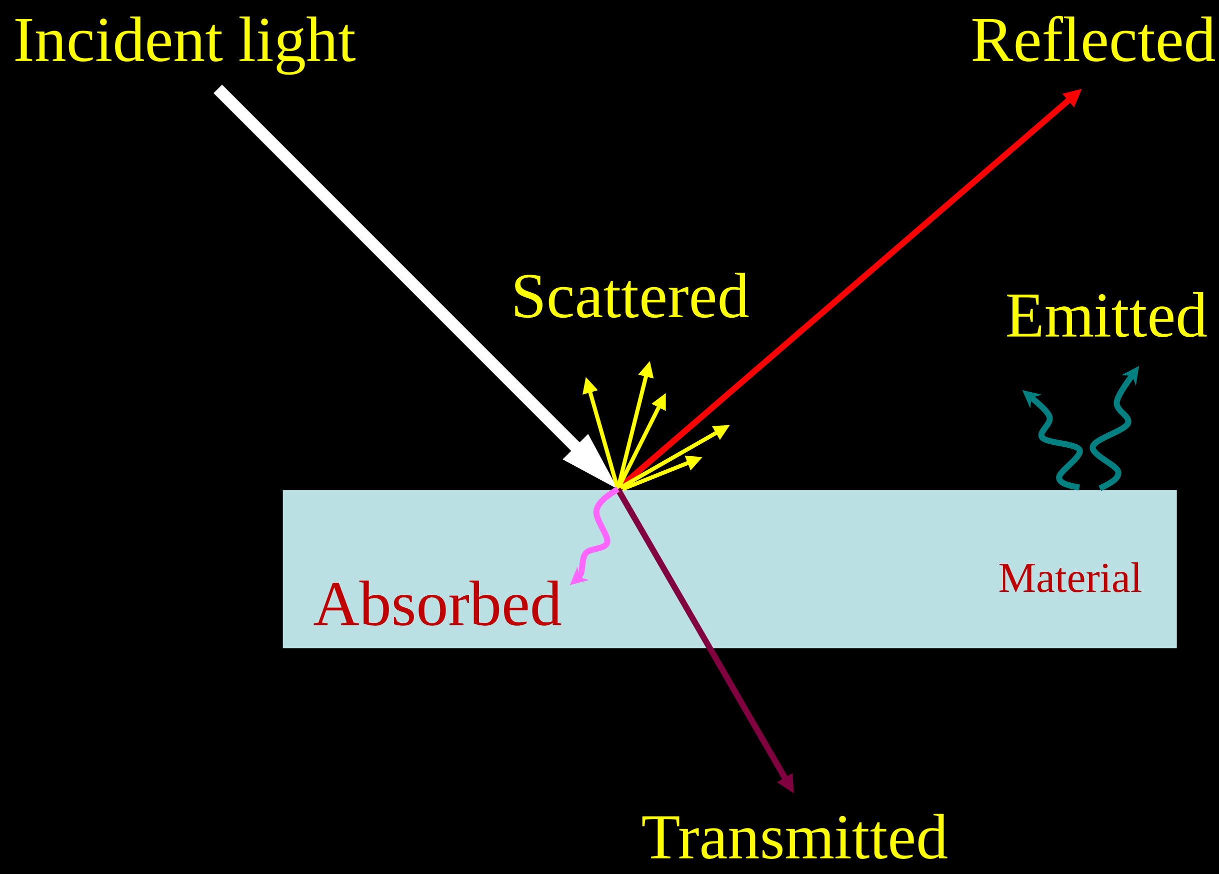
Absorption and emission features in this region of the spectrum arise primarily from molecular and lattice vibrations.

Vacuum ultraviolet spectroscopy

Vacuum ultraviolet spectroscopy is concerned with wavelengths shorter than about 0.2 μ, where common atmospheric gases are strongly absorbing.

For use in planetary science, this spectral region has had to await the development of observational facilities, such as the IUE (International Ultraviolet Explorer spacecraft) or Space Telescope, situated above the obscuring atmosphere.

What happens when light hits a rock?

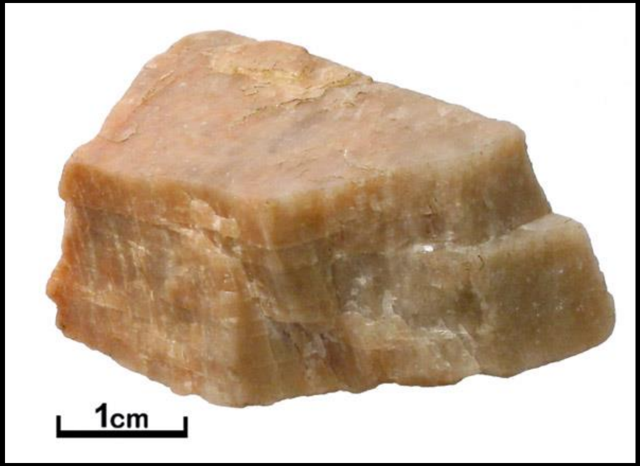


EMR INTERACTION WITH PLANETARY SURFACES

The Originators: Minerals

- Naturally-occurring inorganic substances with a definite and predictable chemical composition and physical properties

- Major groups:
  - Silicates
  - Carbonates

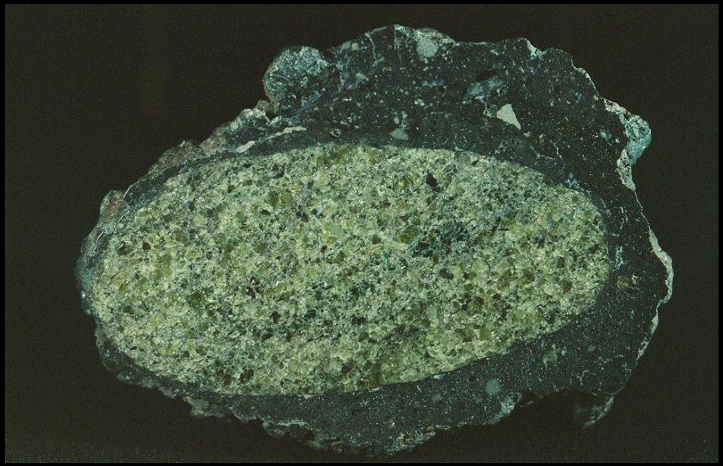


Rocks

- Naturally-occurring aggregates showing similar composition and texture; composed of minerals or their fragments (+ organics on Earth)

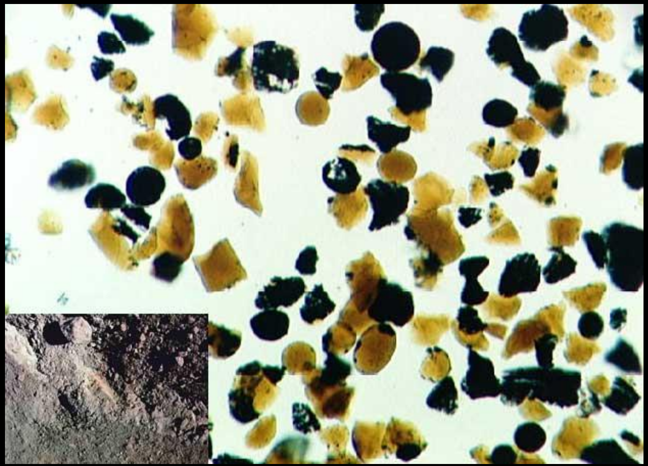
- Groups:

  – igneous rocks (e.g. basalt)
  – sedimentary rocks (e.g. sandstone)
  – metamorphic rocks (e.g. gneiss)



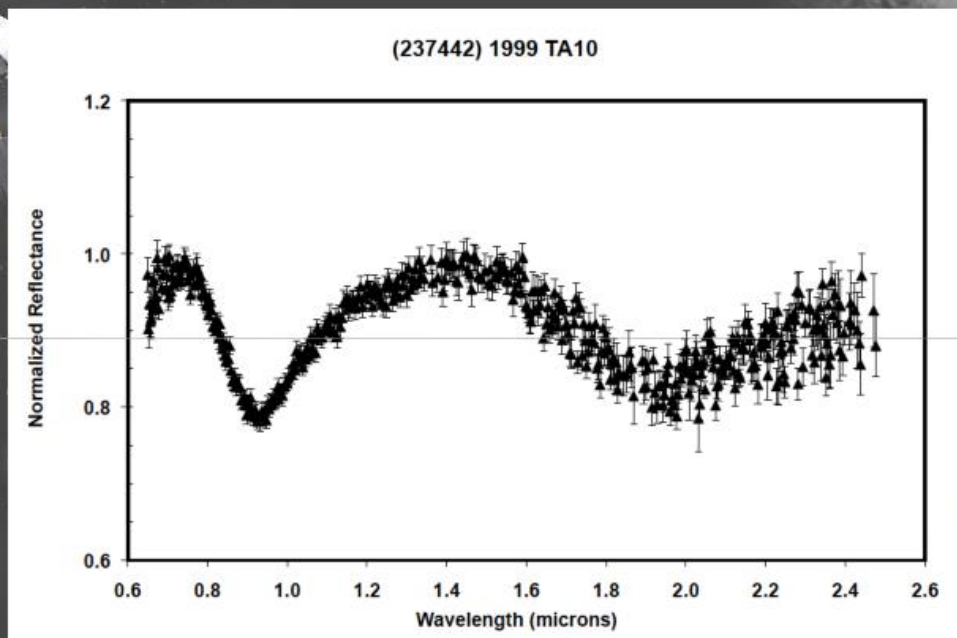
Regolith

- Fragmental incoherent rocky debris that covers the most areas of atmosphere-less bodies like for example the Moon and asteroids



SPECTRUM

- Variation in a quantity as a function of wavelength.
- "Spectral reflectance" is the reflectance measured in a narrow band of wavelength as a function of wavelength.

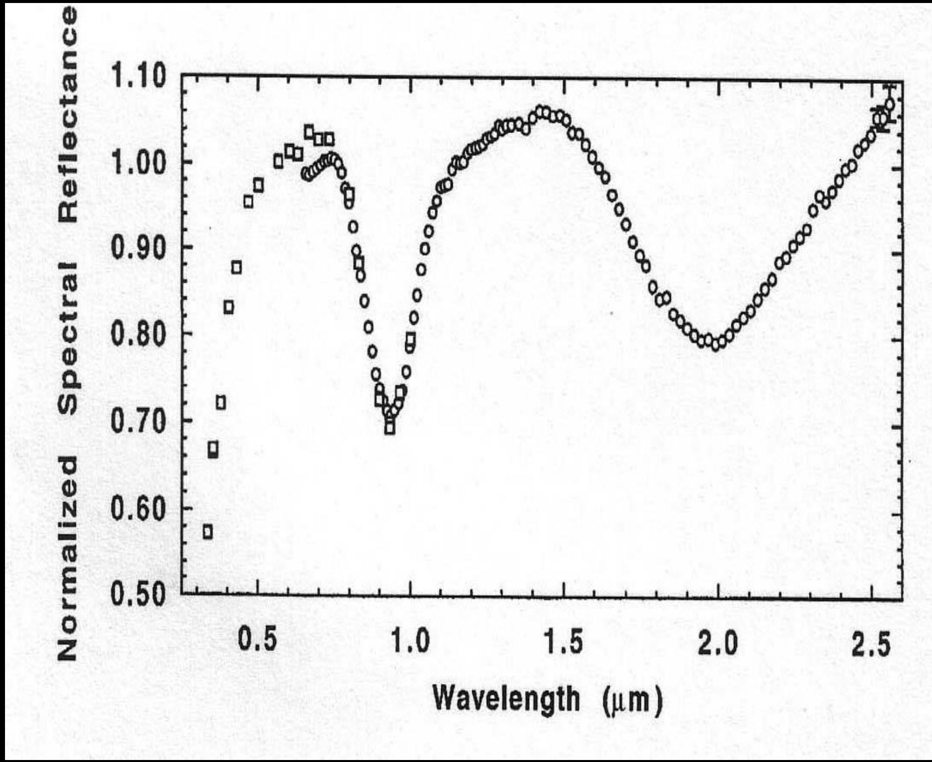


❑ **Differences in absorption and scattering for different wavelengths can be used to identify the minerals.**

SPECTRA

We can measure the light energy at the various wavelengths = a spectrum

We examine the maxima and minima of spectral reflectance curves – minima are caused by molecular absorption, and we call these absorption features or absorption bands.



Differences in absorption and scattering for different wavelengths can be used to identify the minerals.

- Absorption features that occur in reflectance spectra are a sensitive indicator of mineralogy and chemical composition for a wide variety of materials.

- The investigation of the mineralogy and chemical composition of surfaces delivers insights into the origin and evolution of planetary bodies.

    - e.g. Pyroxene mineralogy and chemistry are important for determining the petrogenesis

    - e.g. Iron content crucial for the degree of body differentiation

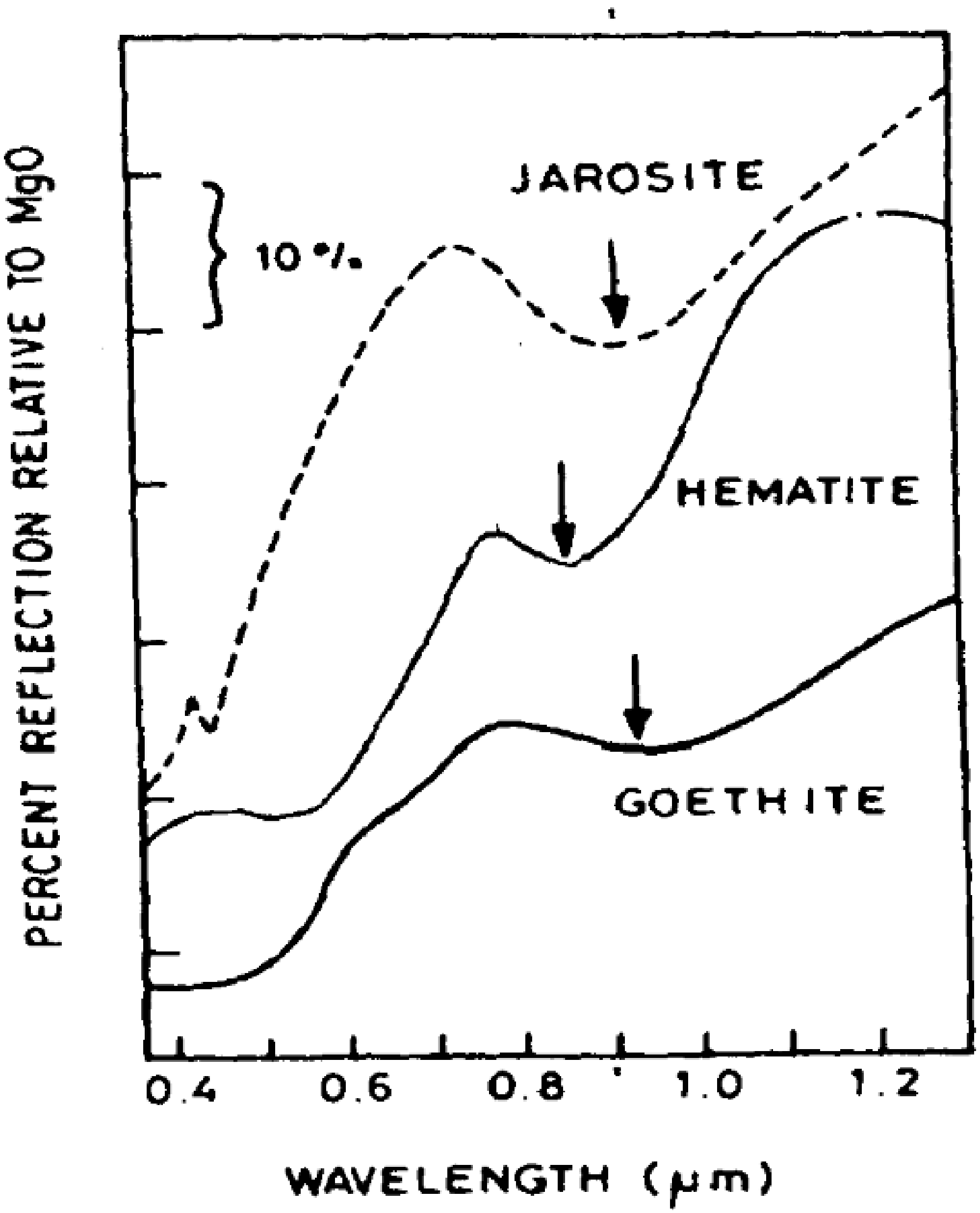
Spectral Ranges (in Planetary Science)

- UV: 100 - 400 nm
- VIS: 400 - 750 nm
- NIR: 0.75 - 3 µm
- Mid-infrared: 3 - 8 µm
- Thermal infrared : 4 50 µm
- Thermal infrared : 4 - 50 µm

Charge transfer effect

Absorption bands can also be caused by charge transfers, or inter-element transitions where the absorption of a photon causes an electron to move between ions or between ions and ligands. The transition can also occur between the same metal in different valence states, such as between Fe^{2+} and Fe^{3+}.

Charge transfer absorptions are the main cause of the red color of iron oxides and hydroxides (Clark, 1999)



Spectral reflectance curves for jarosite, hematite and goethite showing sharp fall of reflectance in the UV-blue region due to the charge- transfer effect. Also note a ferric-ion feature at 0.871im present in all three (Sega11983)

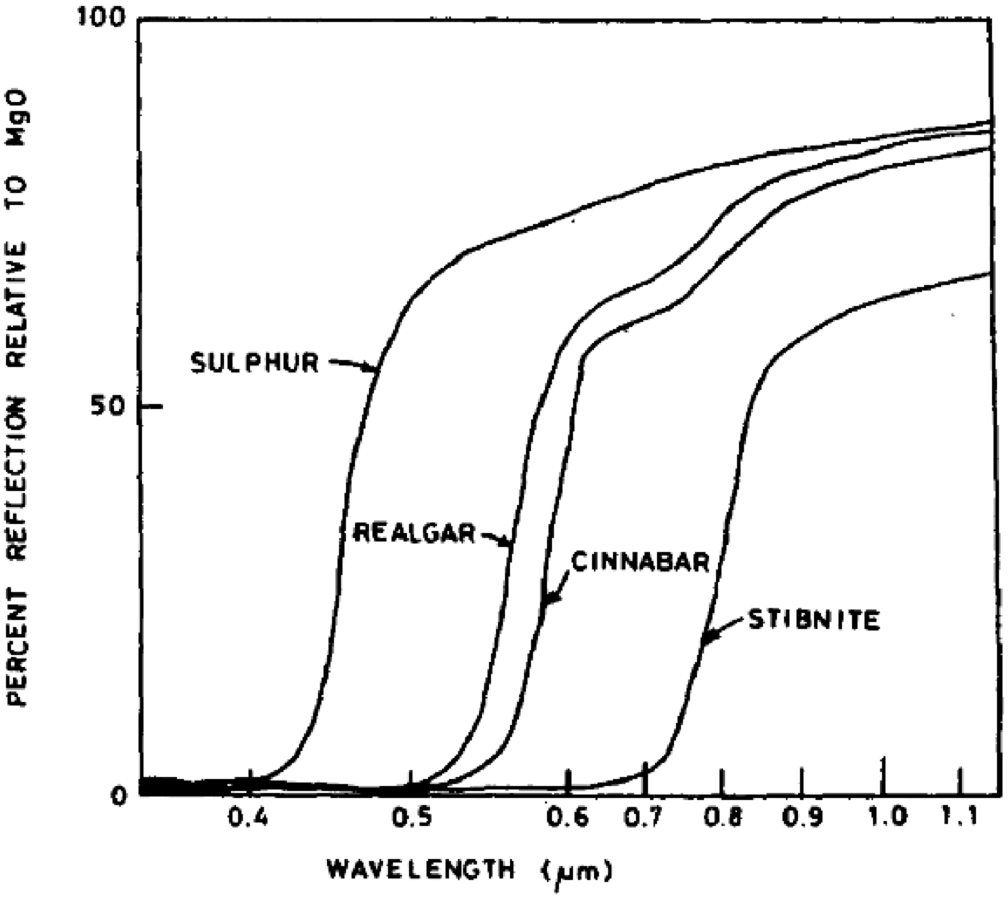
Conduction band absorption effect

In some minerals, there are two energy levels in which electrons may reside: a higher level called the "conduction band," where electrons move freely throughout the lattice, and a lower energy region called the "valence band," where electrons are attached to individual atoms.

The difference between the energy levels is called the band gap. The band gap is typically small or non-existent in metals, and very large in dielectrics. In semiconductors, the band gap corresponds to the energy of visible to near-infrared wavelength photons and the spectrum in these cases is approximately a step function.

The yellow color of sulfur is caused by such a band gap.

Conduction band absorption effect



Reflection spectra of particulate samples of stibnite, cinnabar, realgar and sulphur, displaying sharp conduction-band absorption edge effect. (after Hunt 1980).

Electronic transition in transition metal

Electronic processes frequently occur for the following metals have electronic transition at various part of spectrum. The presence of these elements leads to absorption bands at the appropriate wavelengths

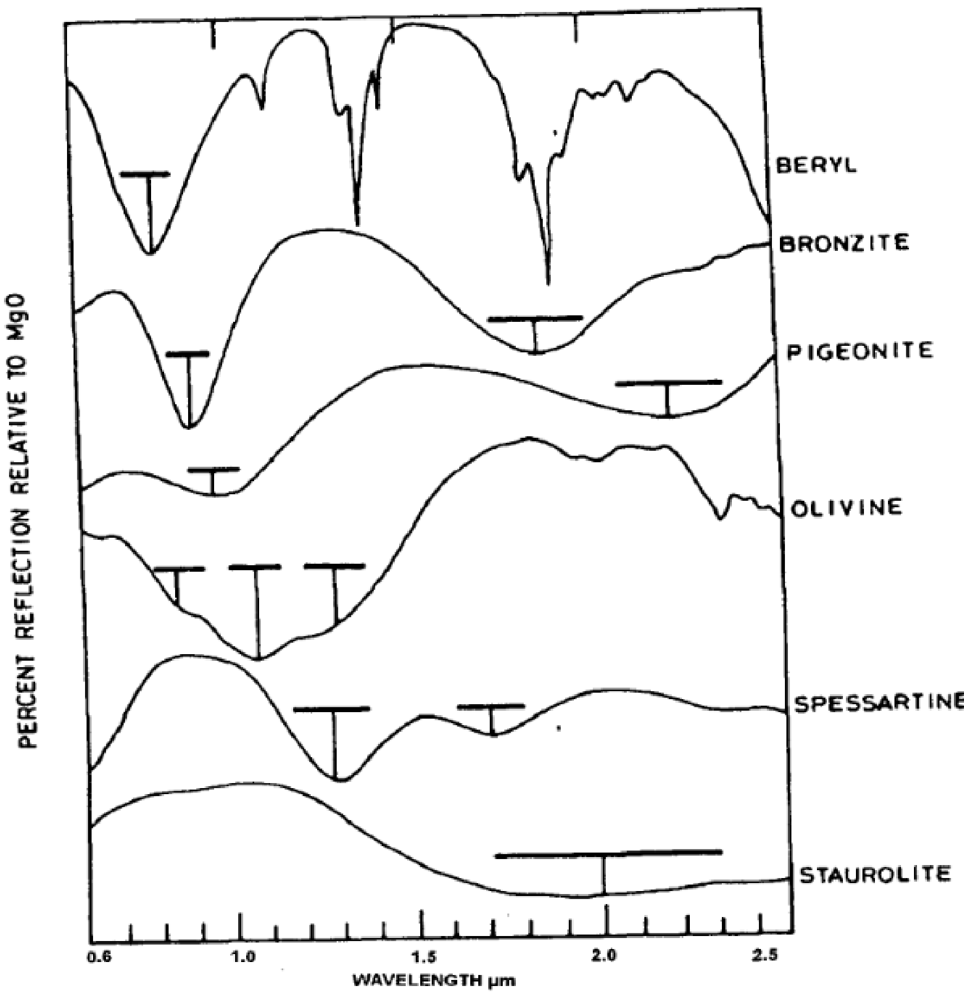
- Ferrous iron: 0.55 - 0.57 µm , 1.0µm and 1.8 - 2.0 µm
- Ferric iron: 0.87µm and 0.35µm ; sub-ordinate bands around 0.5µm
- Manganese: 0.34µm , 0.37 µm , 0.41p.m, 0.45 um and 0.55 µm
- Copper: 0.8µm
- Nickel: 0.4µm , 0.74 µmand 1.25 µm
- Chromium : 0.35 µm , 0.45 µm and 0.55 µm

Crystal field effect

The most common electronic process revealed in the spectra of minerals is due to unfilled electron shells of transition elements (Ni, Cr, Co, Fe, etc.). Iron is the most common transition element in minerals. For all transition elements, d orbitals have identical energies in an isolated ion, but the energy levels split when the atom is located in a crystal field (Burns, 1970, 1993).

This splitting of the orbital energy states enables an electron to be moved from a lower level into a higher one by absorption of a photon

The energy levels are determined by the valence state of the atom (e.g. Fe2+, Fe3+), its coordination number, and the symmetry of the site it occupies.



Crystal field effect. Reflection spectra showing ferrous-ion in selected minerals.

The ferrous ion is located

in an aluminium octahedral six-fold coordinated site in beryl,

in a distorted octahedral six-fold coordinated site in olivine,

in an octahedral eight fold co-ordinated site in spessartine, and

in a tetrahedral site in staurolite (after Hunt 1980).

Vibrational process

The bonds in a molecule or crystal lattice are like springs with attached weights, the whole system can vibrate. The frequency of vibration depends on the strength of each spring (the bond in a molecule) and their masses (the mass of each element in a molecule). For a molecule with N atoms, there are 3N-6 normal modes of vibrations called 'fundamentals'.

Each vibration can also occur at roughly multiples of the original fundamental frequency. The additional vibrations are called overtones when they involve multiples of a single fundamental mode, and combinations when they involve different modes of vibrations.

Spectral features of mineralogical constituents

Hydroxyl ion: Hydroxyl ion is a common constituent of rock forming minerals like clay, mica, chlorite etc. The hydroxyl ion has a single fundamental tone, the position depends upon the ion to which it is attached.

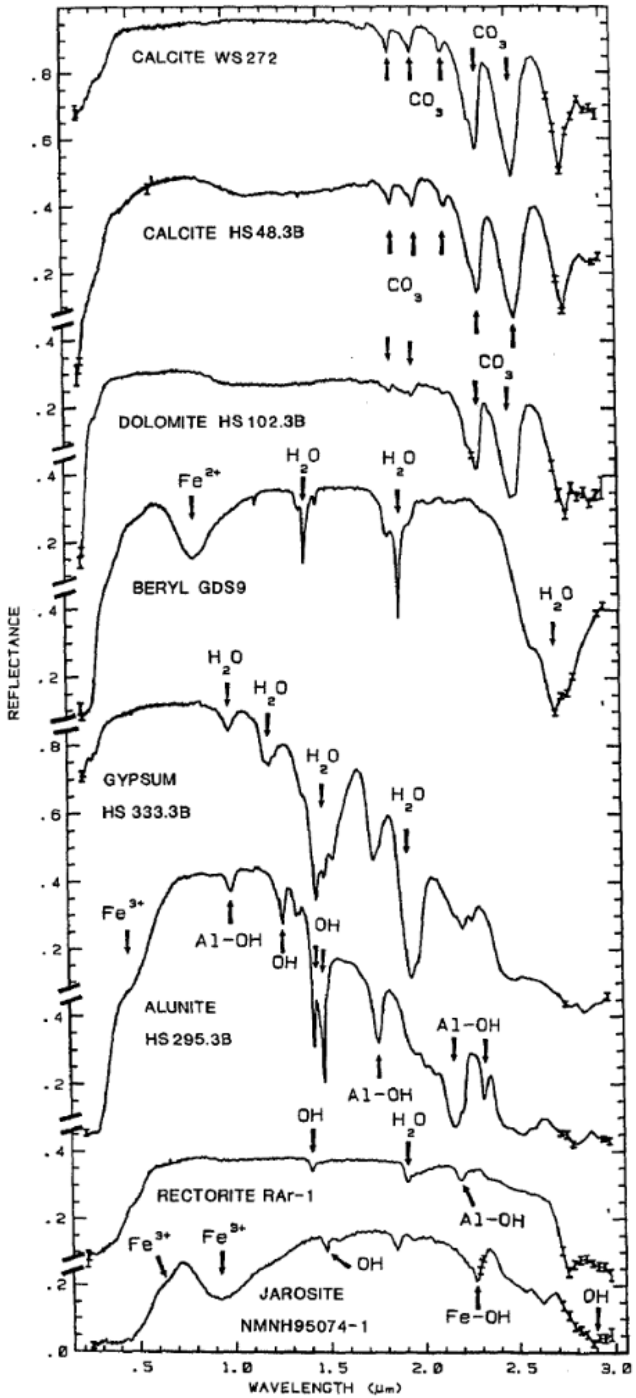
The absorption due to fundamental vibration typically occurs near 2.7 to 2.8μmbut can occur anywhere in the range from 2.67 μm to 3.45μm .

When attached to Al or Mg, OH absorption position occurs between 2.2 to 2.3μm . For Al-OH, the absorption is noted at 2.2μmand for Mg-OH it is noted at 2.3μm . μm

The metal - OH bend and OH stretch near 2.2µm- 2.3µmis very diagnostic feature of mineralogy (Clark et al., 1990). When both Mg and Al are present, then absorption doublets are noted, the stronger band near 2.3µm and weaker band near 2.2µm .

The absorption band due to overtone occurs near 1.4µm .

In middle infrared (MIR) region, metal - OH bend occurs near 10µm .



Fig

Reflectance spectra of Calcite, Dolomite, Beryl, Gypsum, Allunite, Rectorite, Jorosite showing vibrational bands due to OH, CO3 and H20 (after Clark et al., 1990).

Water molecules : Water molecule (vapour) fundamental tones are seen at 2.17µm , 6.27µm , and 2.66µm . In liquid water, the same shifts to 3.106µm , 6.079p.m and 2.903µm .

Overtones occur near 1.4µm and combinations occur near 1.9µm. Thus a mineral whose spectrum has a 1.9µm absorption band contains water. But, a spectrum that contains only 1.4µm band, without 1.9µm contains only OH. Sharp peak indicate that water molecule occupy in well defined site and the broad peak indicate it occupies disorder sites.

Carbonates: Carbonates are one of the commonly occurring rock types like calcite, dolomite, magnesite and siderite. All carbonates show diagnostic vibrational bands. The absorption is due to planar CO3 ion. There are four fundamental bands viz., 7.067pm, 9.407pm, 11.4pm and 14.7pm. In NIR and SVVIR region combination and overtone band occur. Two strongest bands occur at 2.5pm - 2.55pm and 2.3pm - 2.35pm. Three weaker bands occur near 2.12pm - 2.16pm, 1.97p.m - 2.0pm, 1.85p,m -1.87pm

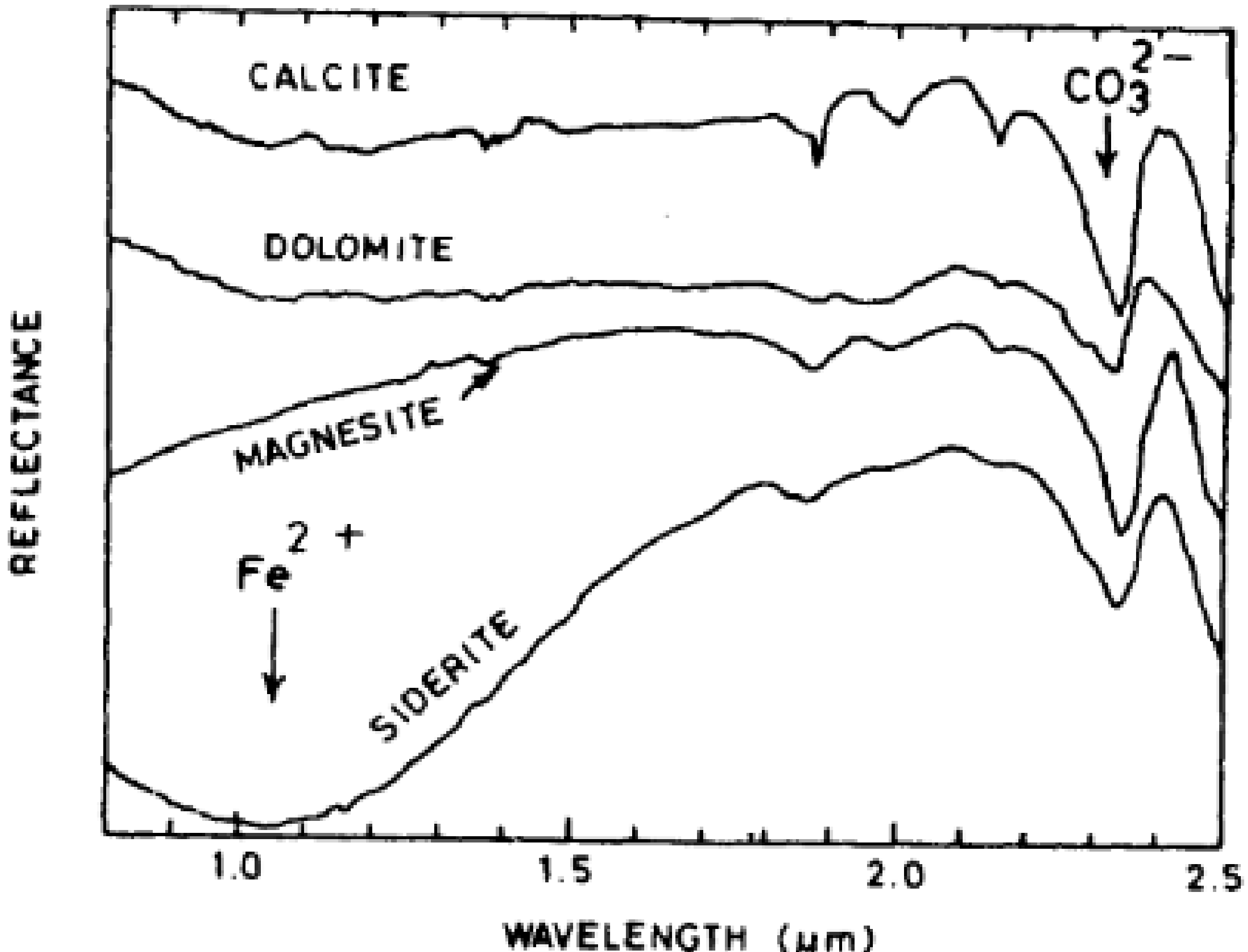


Figure 1.8 Laboratory spectra of carbonate minerals (Whitney et al., 1983)

Spectra of Rock Forming Minerals

- Absorption features that occur in reflectance spectra are a sensitive indicator of mineralogy and chemical composition for a wide variety of materials

- The investigation of the mineralogy and chemical composition of surfaces delivers insights into the origin and evolution of planetary bodies

  - e.g. Pyroxene mineralogy and chemistry are important for determining the petrogenesis

  - e.g. Iron content crucial for the degree of body differentiation

Lab Spectra and Remote Sensing

- Lab spectra of well–characterized minerals and mineral mixtures are the basis for the analysis of ground and space based spectra since only laboratory measurements allow to investigate homogeneous samples in which all parameters can be controlled.

- Tasks

1. Characterization of individual phases (minerals, ices, glasses)
   - mineralogy
   - chemistry
   - particle size
2. Characterization of rocks and mineral mixtures
   - mineralogy
   - chemistry
   - particle sizes
   - packing
3. Characterization of effects caused by the physical environment
   - temperature
   - viewing geometry
   - maturation processes (Space Weathering)

Spectra of Rock Forming Minerals

1) Silicates
   - Olivine: strong absorption at ~ 1 µm due to three overlapping bands
   - Pyroxene:
     - Opx displays strong absorptions around 0.9 µm and 1.9 µm
     - Cpx displays strong absorptions around 0.9 µm and sometimes around 2.2 µm
   - Feldspars: often faint absorption bands
     - Plagioclase for example displays absorption around 1.3 µm
   - Phyllosilicates: partly very sharp and narrow absorptions!
2) Carbonates
   - show a number of narrow, sharp absorption features for wavelengths > 1.6 µm
3) Oxides
   - e.g. spinel (lunar rocks) display strong absorptions near 2 µm
   - iron oxides show strong absorptions in UV
4) Sulfides and Sulfur are less important and barely investigated

Spectra of Rock Forming Minerals

1) Hydrates (H_2O) and hydroxides (OH^-)
   - bands located often > 3 μm

2) Metals
   - no absorption features, but reddish spectra, identification via suppressed absorption bands

Most Relevant Minerals for Remote Sensing

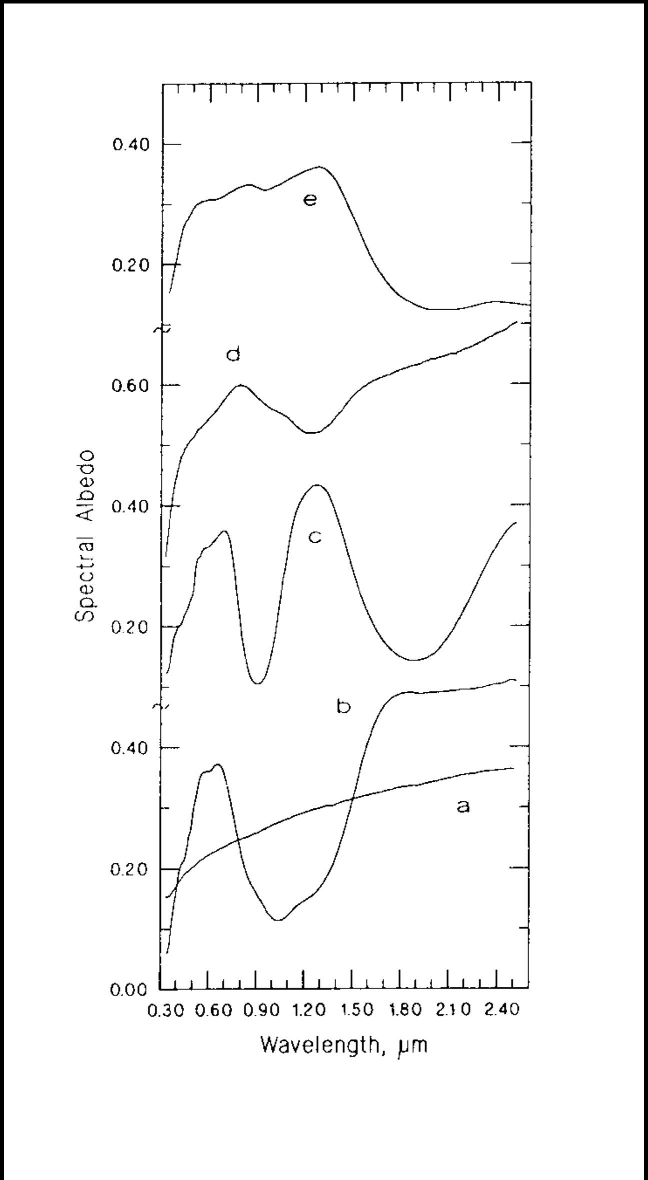
a) Ni-Fe metal

b) Olivine

c) Pyroxene, here Orthopyroxene (offset)

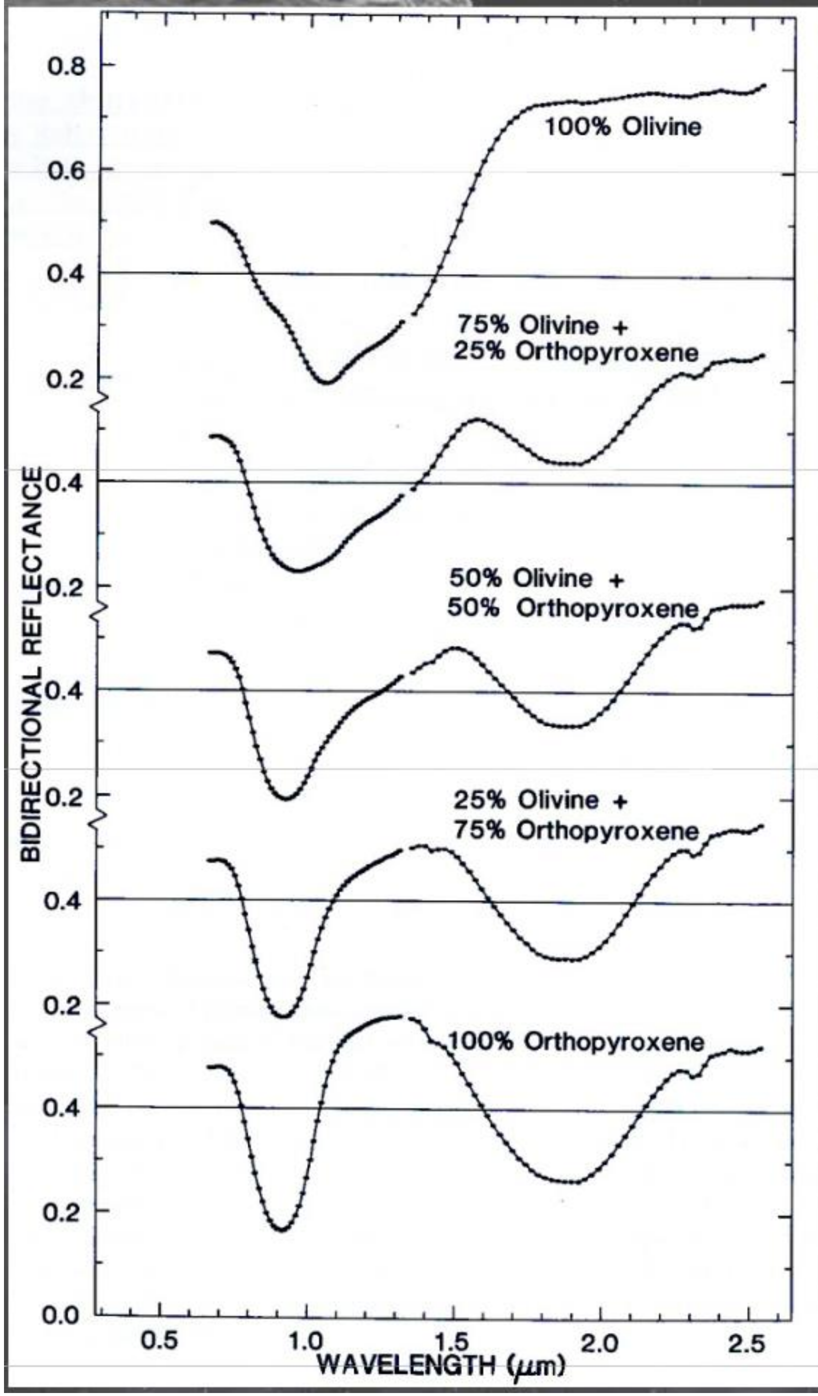
d) Plagioclas (offset)

e) Spinel (offset)



Probable Mineral Mixtures in Terrestrial Planetary Surfaces and Remote Sensing

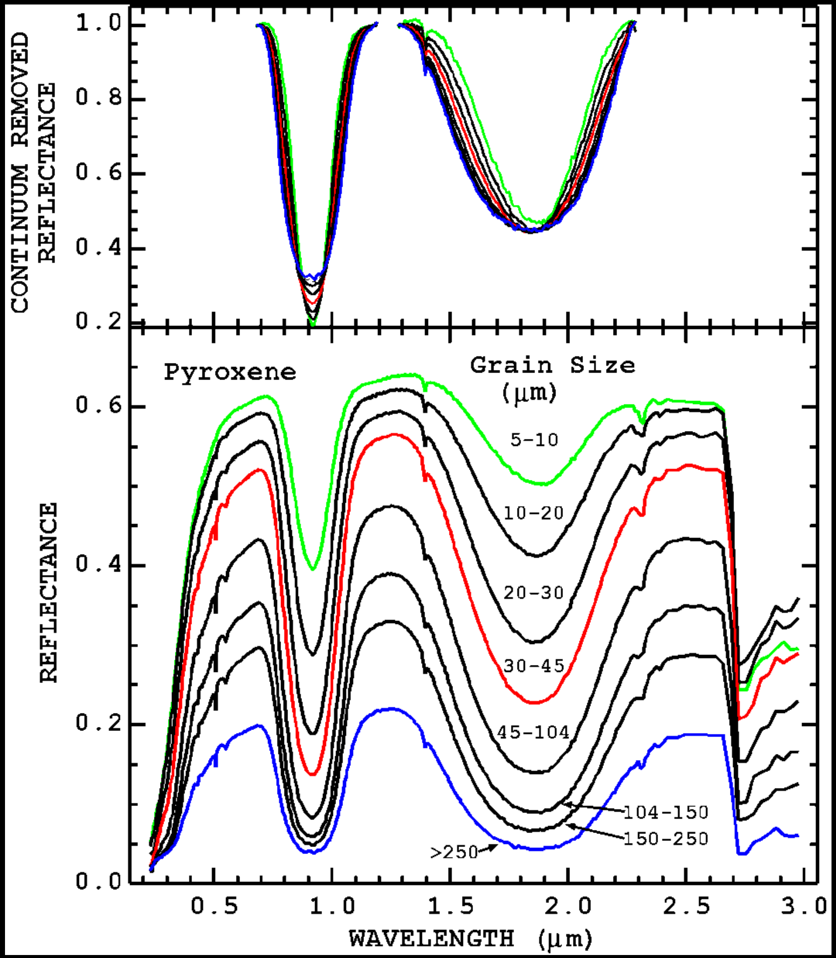
- Almost all by remote sensing investigated solid surfaces consist of polymict rocks / mineral mixtures show a wide range of grain sizes.
- It's often not possible to uniquely define the contributions of each parameter without independent constraints
- Ground reference sample helpful for remote sensing.
- Most regoliths need nonlinear mixing models for composition determination, purely empirical and more quantitative methods including "Gaussian fitting" have been developed



Physical Effects (1)
Grain Size and Albedo

- Particle size and albedo
  - The albedo of weakly absorbing minerals increases with decreasing particle size
  - The albedo of very strongly absorbing minerals decreases with decreasing particle size
- Particle size and contrast
  - Absorption band contrast varies with particle size but does not affect positions of absorption features

Grain size needs to be considered

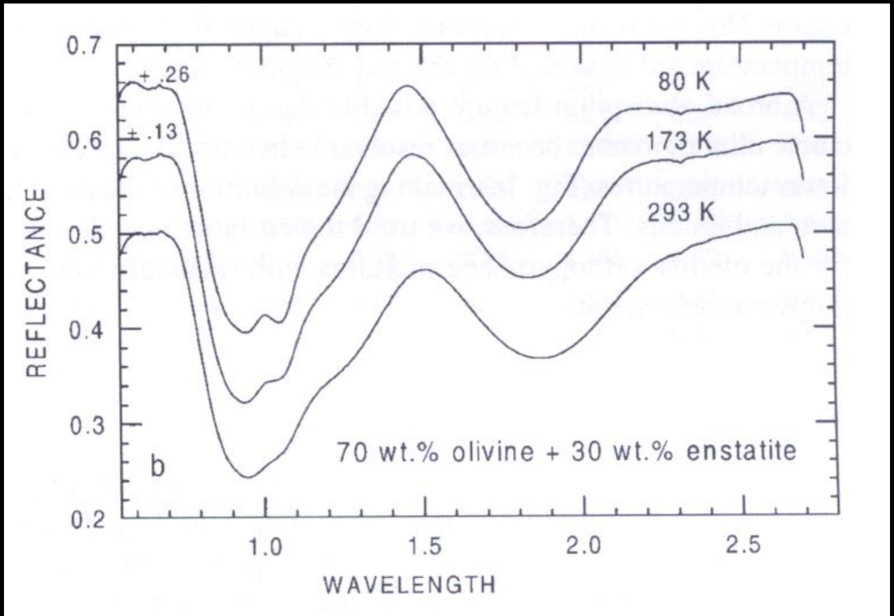


Physical Effects (2)
Temperature

- Lowering of sample temperature can lead to:

  1) Slight negative shifts of absorption band positions

  2) Splitting of absorption bands



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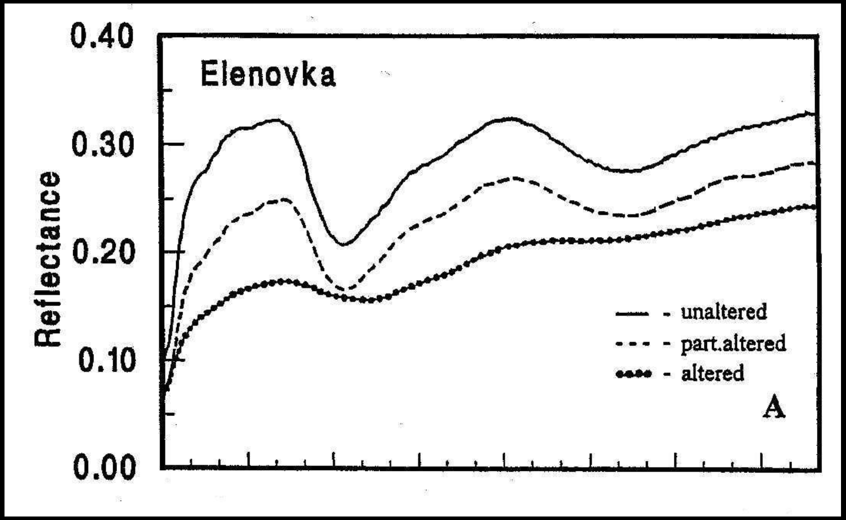
For detailed investigations: T difference between observed surface and lab sample to be considered

Physical Effects (3)
Maturation – Space Weathering

Solar and cosmic radiation + micrometeoritic bombardment



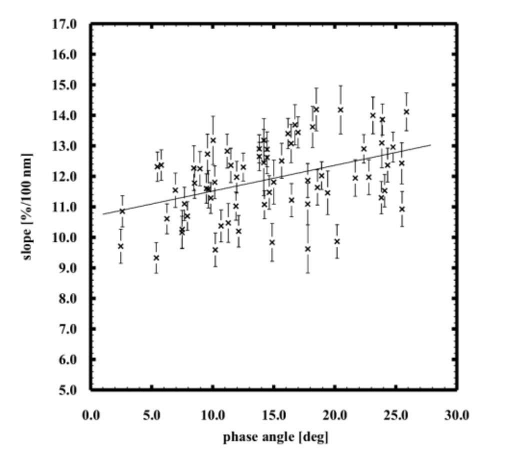
- Lowering of albedo
- Reddening of spectral slopes
- Weakening of absorption bands

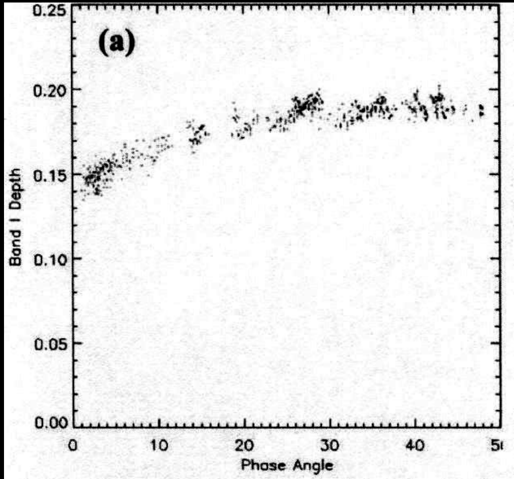
Physical Effects (4)
Geometry Effects

- Phase angle increase leads to:

  1) phase reddening, i.e. the steepness of the spectral slope outside of absorption features increases

  2) Absorption band depth increase





Photometric correction necessary

Color Photometry + Spectroscopy

- Color photometry (filter):

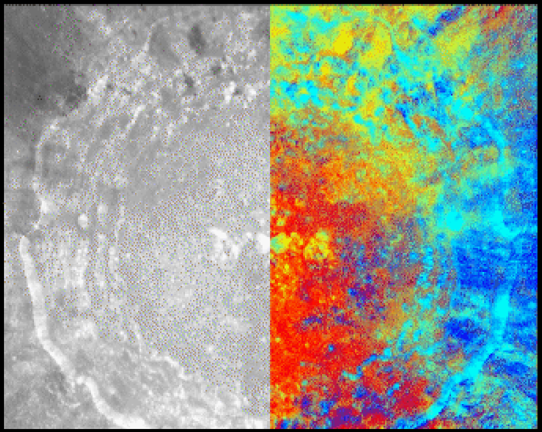
  Advantages:
  - Large surface area coverable in one exposure
  - Morphological information

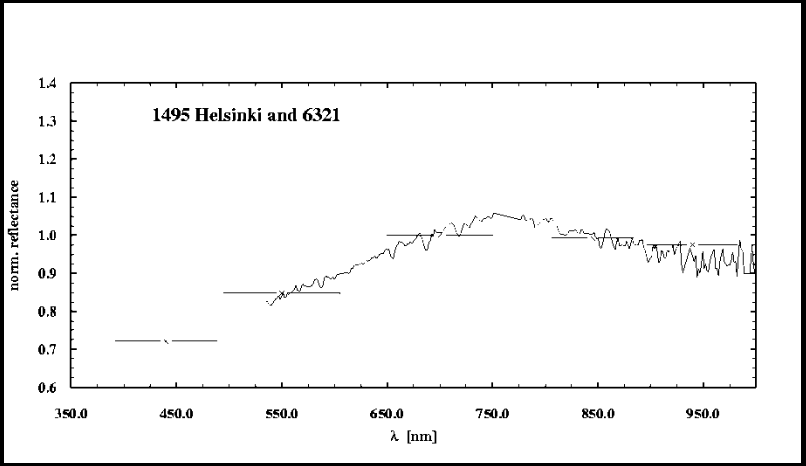
  Disadvantages:
  - Often low spectral resolution ➔ raw mineralogical analysis
  - Colors not measured simultaneously ➔ further tricky corrections needed

- Spectroscopy:

  Advantage:
  - High Spectral resolution and simultaneous measurements ➔ best possible composition analysis

  Disadvantage:
  - No morphological information





Resources of Spectra

Ground-based Telescopes

- Low costs
- Large number of targets
- Low spatial resolution

- Invisibility of surface areas (e.g. lunar poles and far-side)
- Disturbances by Earth atmosphere (except Hubble)
- Time slots for observations to be watched

Spacecrafts

- High spatial resolution
- Visibility of the whole surface

- High risk
- High costs
- Low number of targets

Minor bodies such as asteroids, comets, meteor, meteoroid and meteorites

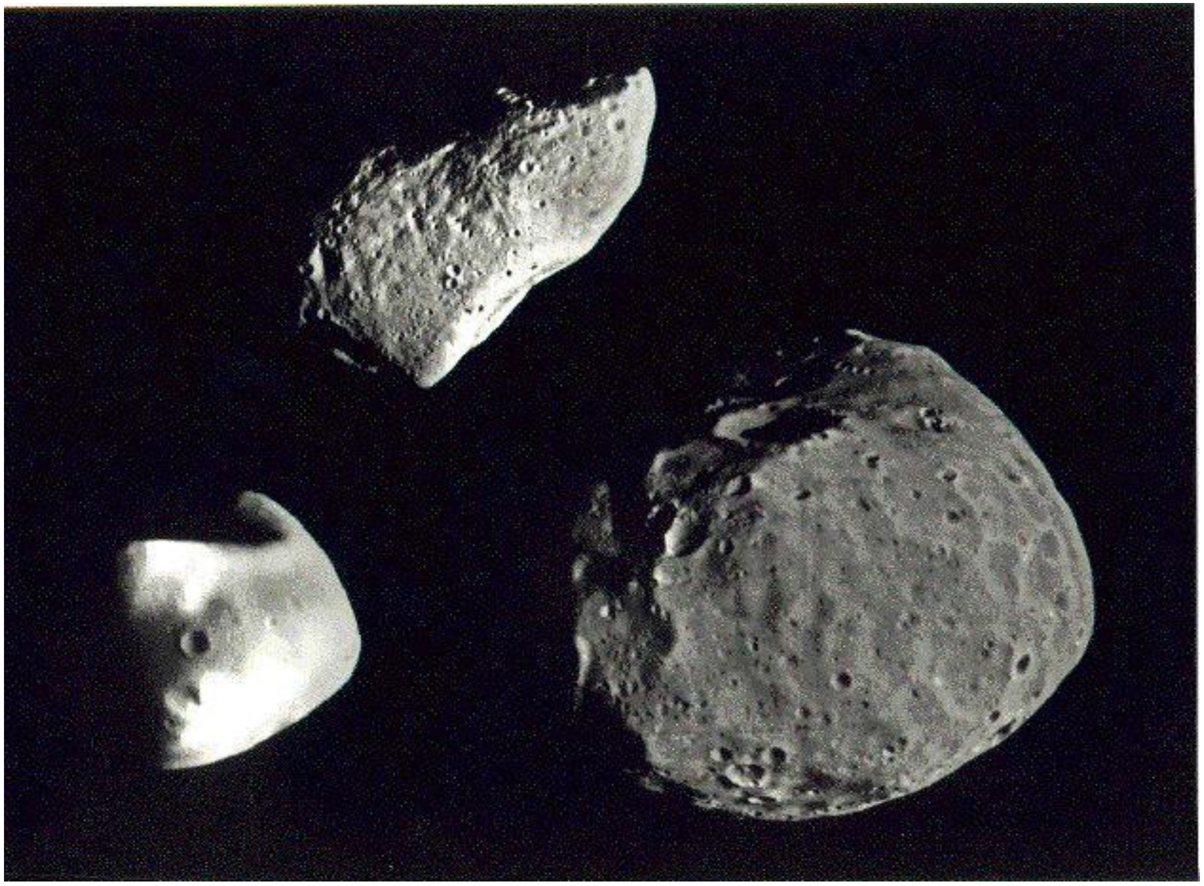
Minor Bodies of Solar System

- »Asteroids
- »Pluto and Charon
- »Comets
- »Meteorites
- »Cosmic Collisions

- **Asteroid: a rocky leftover planetesimal orbiting the Sun**
- **Comet: an icy leftover planetesimal orbiting the Sun (regardless of whether it has a tail!)**
- **Meteor: a flash of light in the sky caused by a particle or chunk of rock entering the atmosphere. May come from comet or asteroid.**
- **Meteorite: any piece of rock that fell to the ground from space, whether from an asteroid, comet, or even from another planet**

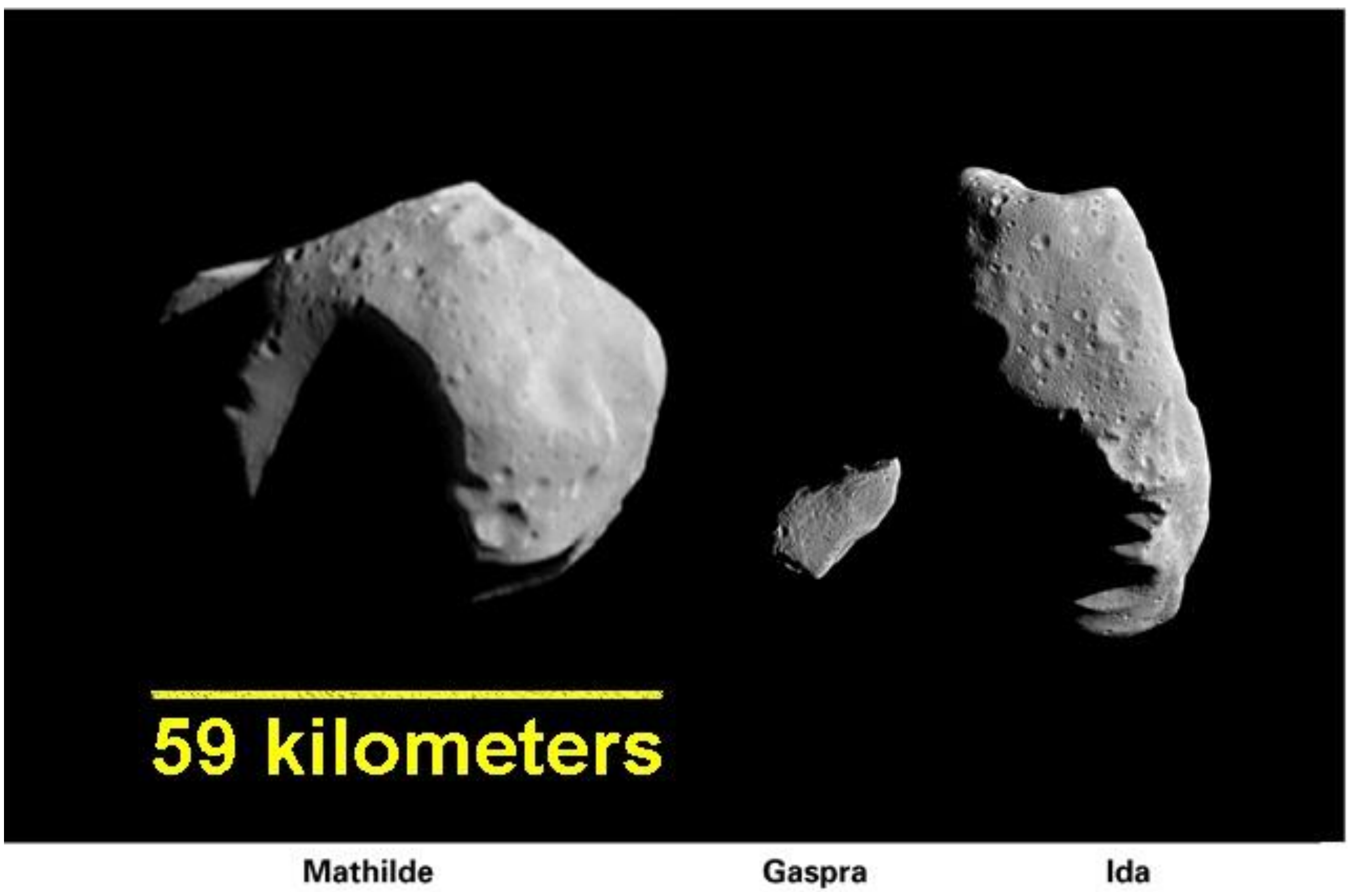
Asteroids

Asteroids are believed to be left over from the beginning of the solar system 4.6 billion years ago.



Asteroids

- Rocky and metallic objects too small to be considered planets.
- Range in size from Ceres (diameter of ~1000 km), down to objects a few centimeters or less across.
- Name asteroids, meaning "star-like", derives from the fact that they are more star-like in appearance than comets.



Asteroids: Discovery

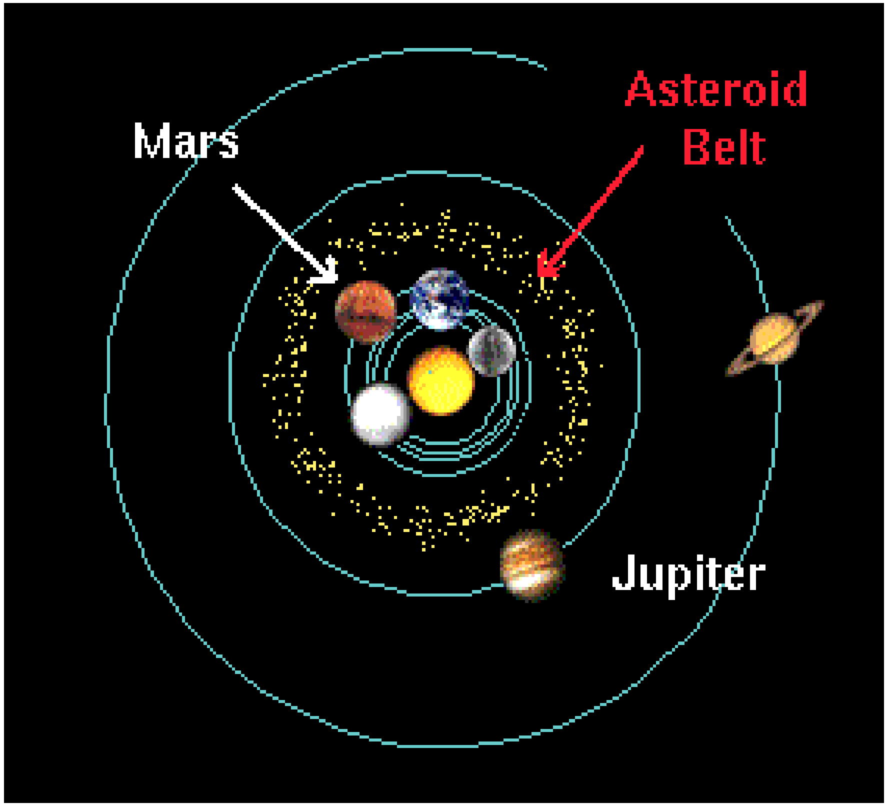
- **Too small be seen without a telescope.**
- **Ceres, largest of asteroids, orbiting Sun at 2.8 AU was discovered first by Giovanni Piazzi in 1801.**
  - **He was searching for the missing planet predicted to be between Mars and Jupiter by Titius-Bode law.**
  - **In next 6 years, three more objects found in region.**
- **Currently, more that 10,000 asteroids have well-determined orbits.**
  - **Each given a number for order of discovery & a name.**
- **Most orbits lie between those of Mars and Jupiter**

Asteroids: Formation

- Believed to represent material left over from formation of solar system.
- Although sometimes suggested that asteroids are remains of a planet that was destroyed in a massive collision, it is more likely that they represent material that never coalesced into a planet.

- Highest concentration of asteroids in asteroid belt, the region lying between orbits of Mars and Jupiter.

- Likely that origin of the asteroid belt is linked to gravitational perturbation by Jupiter, which kept these planetisimals from coalescing into larger bodies.



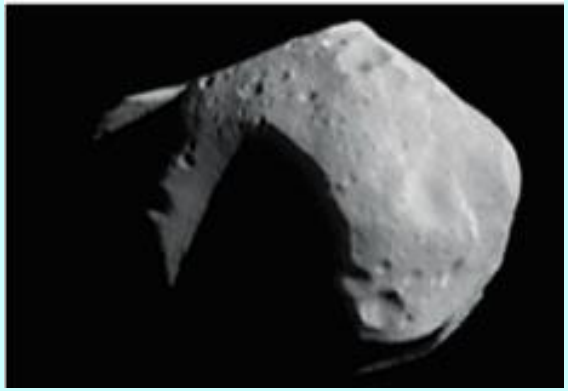
Asteroids: Orbits about the Sun

- Asteroids orbit the Sun in many regions at different distances.
- They are often grouped by characteristics of their orbits.
  - Asteroid Belt: between Mars and Jupiter
  - Trojan asteroids: co-orbital with Jupiter
  - Apollo and Aten asteroids: Earth-crossing asteroids
  - Amor asteroids: Mars-crossing asteroids
  - Other asteroids

Asteroids: Classes Compared

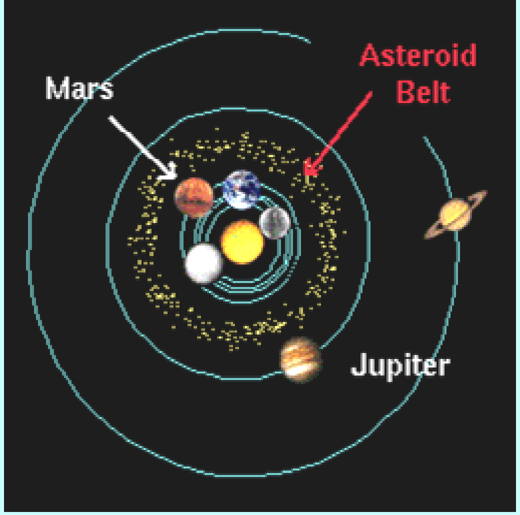
- **S-type**
  - Appear bright (reflectivity 15-20%)
  - Predominately silicate materials
- **C-type** (e.g., Ceres and Pallas)
  - Appear very dark (reflectivity 3-4%)
  - Carbon–rich silicate materials
    - composition thought to be similar to the Sun, depleted in hydrogen, helium, and other volatiles.
- **M-type** (e.g., Psyche)
  - Relatively bright (reflectivity 10-18%)
  - Metals like iron and nickel
  - Rare

Gaspra: S-type asteroid



Mathilde: C-type asteroid

The Asteroid Belt

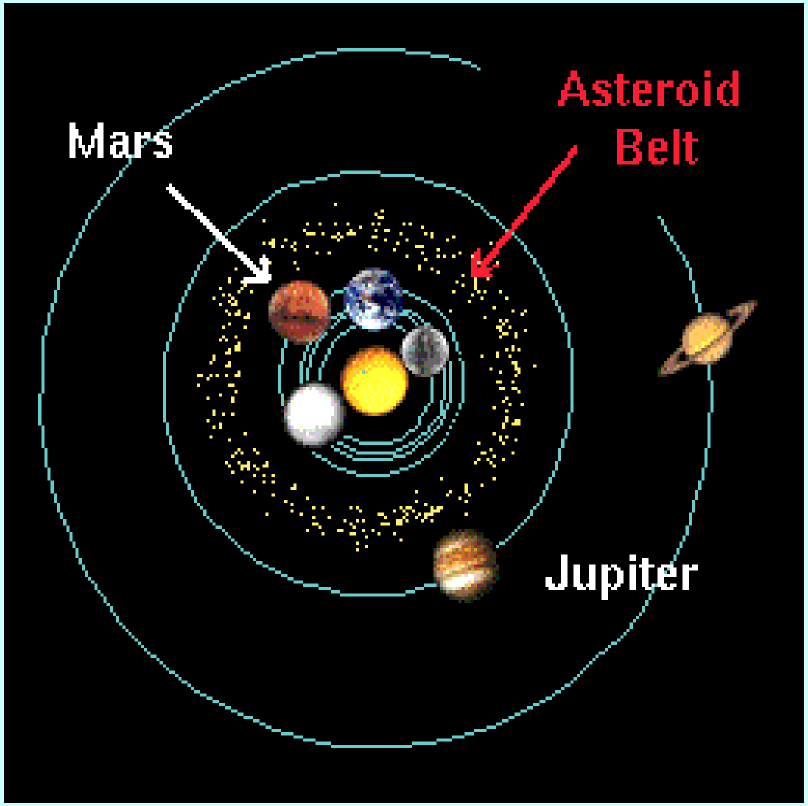


- All orbit Sun in west-to-east direction (same as planets).
- Most orbits lie near plane of ecliptic.
- The asteroid belt defined as region containing asteroids with semi-major axes in the range of 2.2-3.3 AU.
  - Asteroids in belt take 3.3-6 years to orbit Sun.
  - Contains 75% of known asteroids.
  - Spacing of asteroids in belt ~ several million km.
  - Many classified into families - groups with similar orbital and physical characteristics .

Asteroids: Size and Location

- > 100,000 asteroids lie in the asteroid belt.
- Asteroids differ from planets in both their orbits and their size.
  - generally move on quite eccentric trajectories,
  - few are >300 km in diameter, and most are far smaller (as small as 1/10 km across).
- Taken together, mass of known asteroids amounts to

  < 1/10 mass of Moon.



Asteroids: Orbital Characteristics

The Asteroid Belt

- Most asteroids orbit in a zone between the orbits of Mars and Jupiter called the Asteroid Belt
- Ranges 2 - 3.5 A.U. from the Sun.
- About 5,000 orbits have been calculated, but 100,000 asteroids may exist.
- Orbits are elliptical but nearly circular and near the plane of the ecliptic.
- Their orbits are very similar to the planets' orbits.
- The Kirkwood gaps are found in the orbits of belt asteroids and are formed by Jupiter's strong gravitational influence.

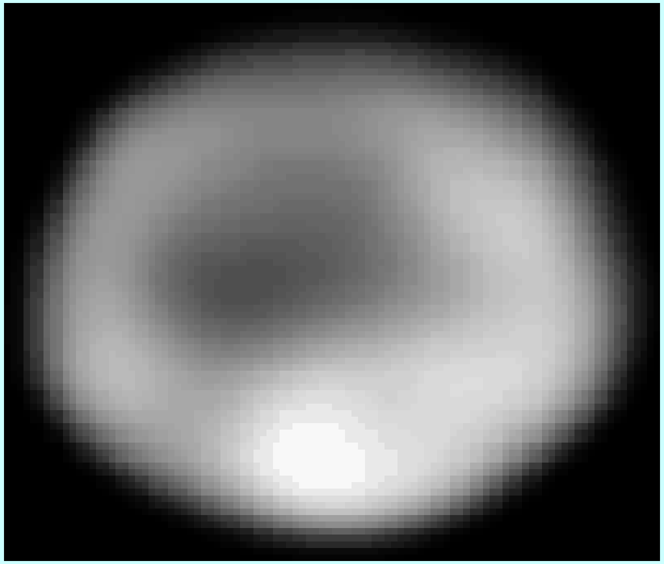
Asteroids: Orbital Characteristics

- **Trojan Asteroids**
  - **Found in the same orbit with Jupiter, but are 60^o ahead and behind the planet.**
  - **They are stable positions in Jupiter's orbit where the gravity of the Sun and Jupiter cancel.**
  - **Such positions called Lagrange points.**
- **Apollo Asteroids**
  - **Orbits cross Earth's orbit.**
  - **About 50 known Apollo asteroids, but may be as many as 1,000.**
  - **All potential "Earth-colliders".**
  - **Eros is an example. It is about 30 kilometers across.**

Asteroids: Orbital Characteristics

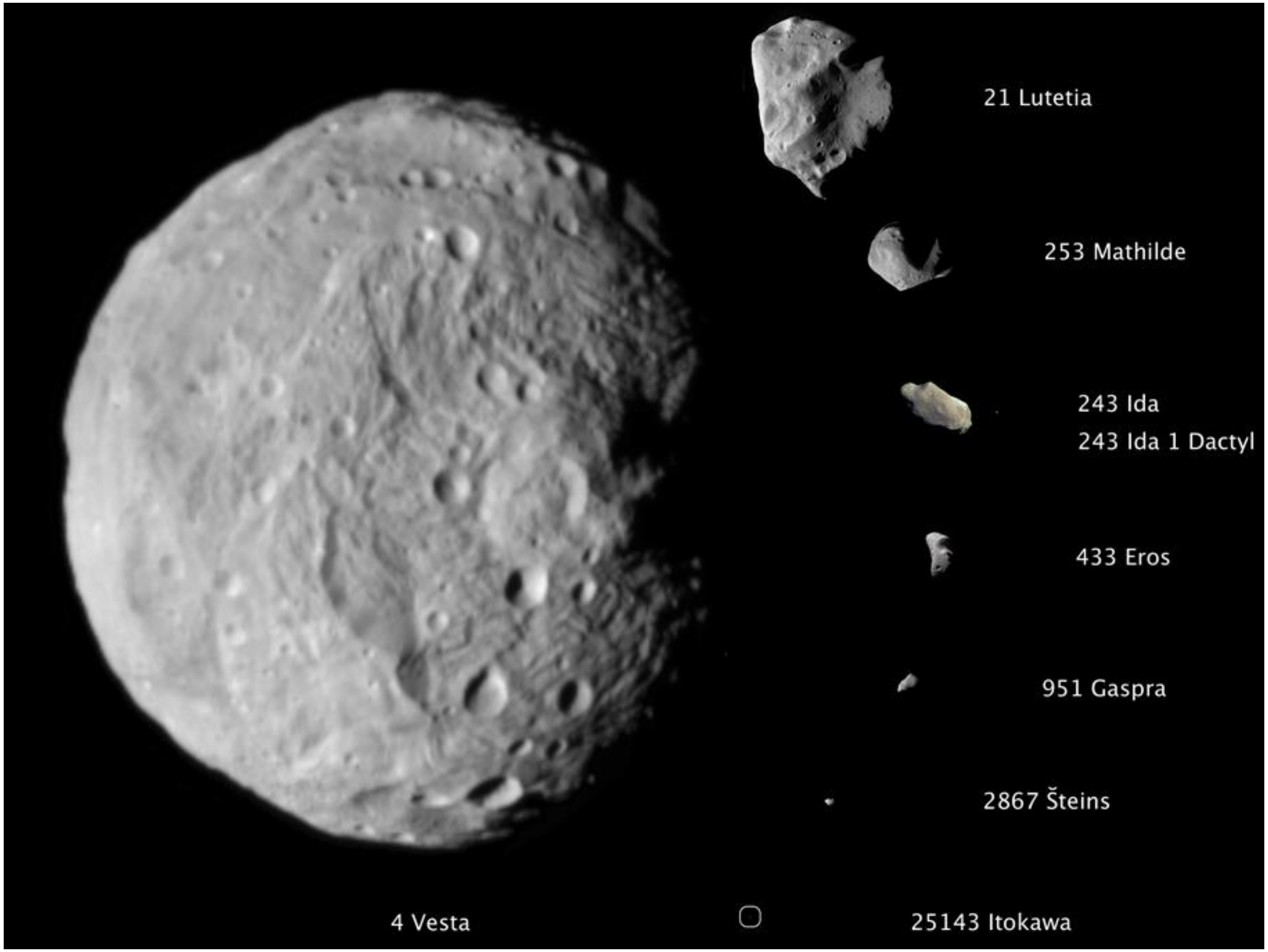
- **Other asteroid groups**
  - **A few stray asteroids have been found that lie completely outside of the asteroid belt.**
  - **Chiron is the most famous example.**
  - **Its orbit carries it between Saturn and Uranus.**
  - **Chiron may actually be a dormant comet that has lost most of its volatiles.**
  - **When it is closest to the Sun, a very diffuse atmosphere forms around it.**
  - **If Chiron is a comet, it is the largest one known with a diameter of about 180 kilometers.**

Vesta: An Unusual Asteroid

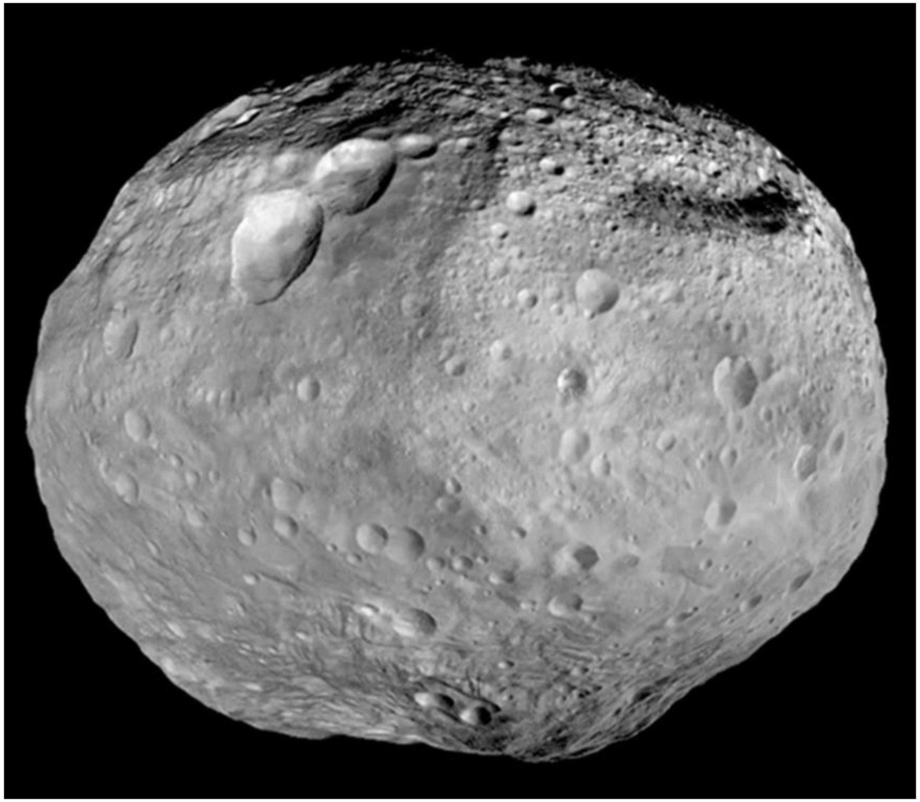


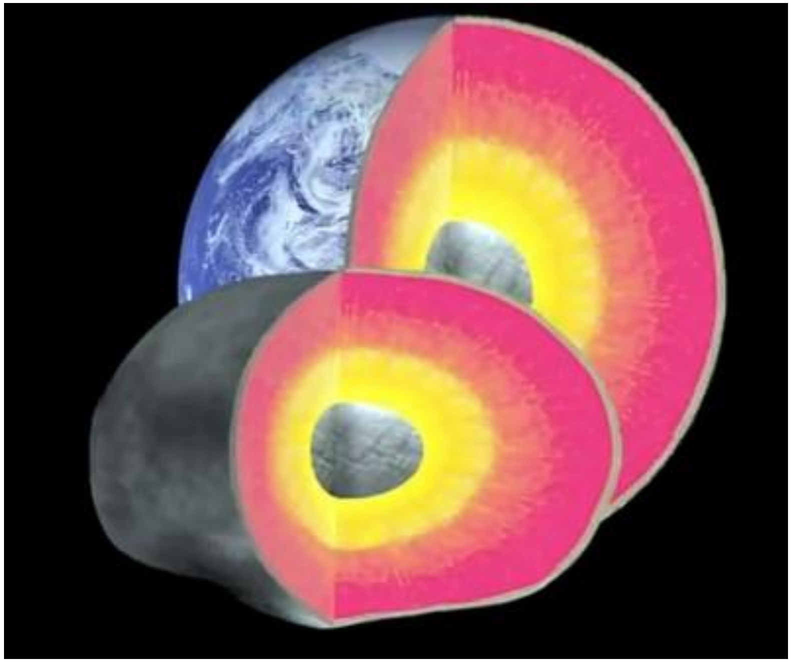
- HST resolves features as small as 50 miles across, allowing astronomers to map Vesta's geologically diverse terrain.
- The surface is a complex record of Vesta's four billion-year history.
- Features include ancient lava flows, and a gigantic impact basin that is so deep, it exposes the asteroid's subsurface, or mantle.

Vesta was reclassified as a "dwarf planet"



Vesta has differentiated interior





Asteroids: View from Space

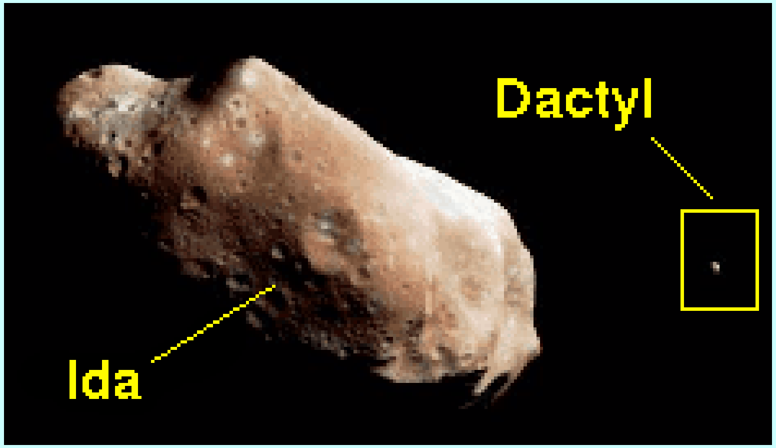
- *Galileo* flew by main-belt asteroids.

Gaspra

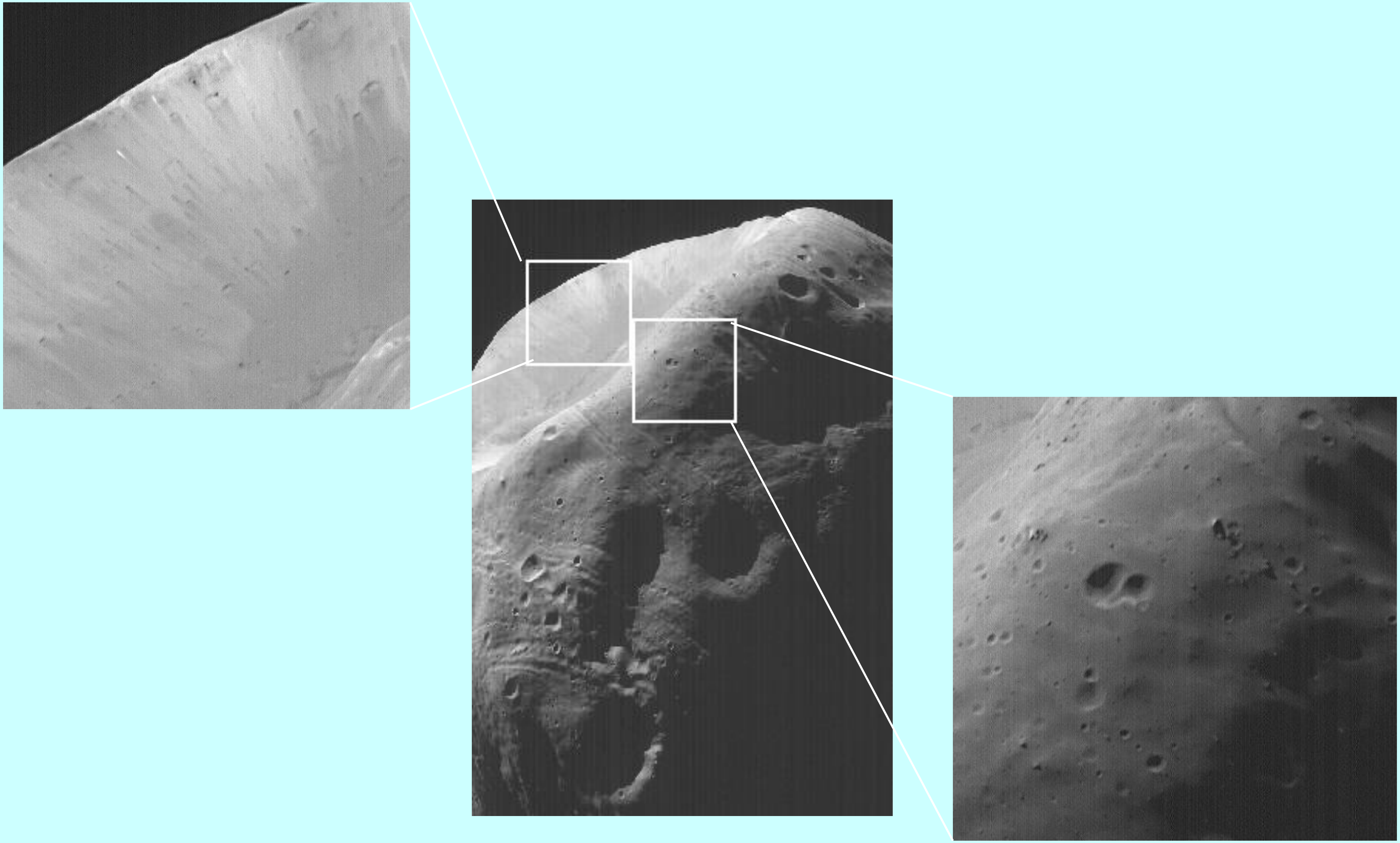
- S-type
- 7 hour rotation period
- 16 x 11 x 10 km, irregular shape
- sparse crater count implies 200 million years old

Ida

- larger S-type
- more heavily cratered, ~1 billion years old
- satellite, Dactyl, 1.5 km diameter
  - period = 24 hours;
  - orbital distance = 100 km
  - Ida's density ~ 2.5 g/cm^3



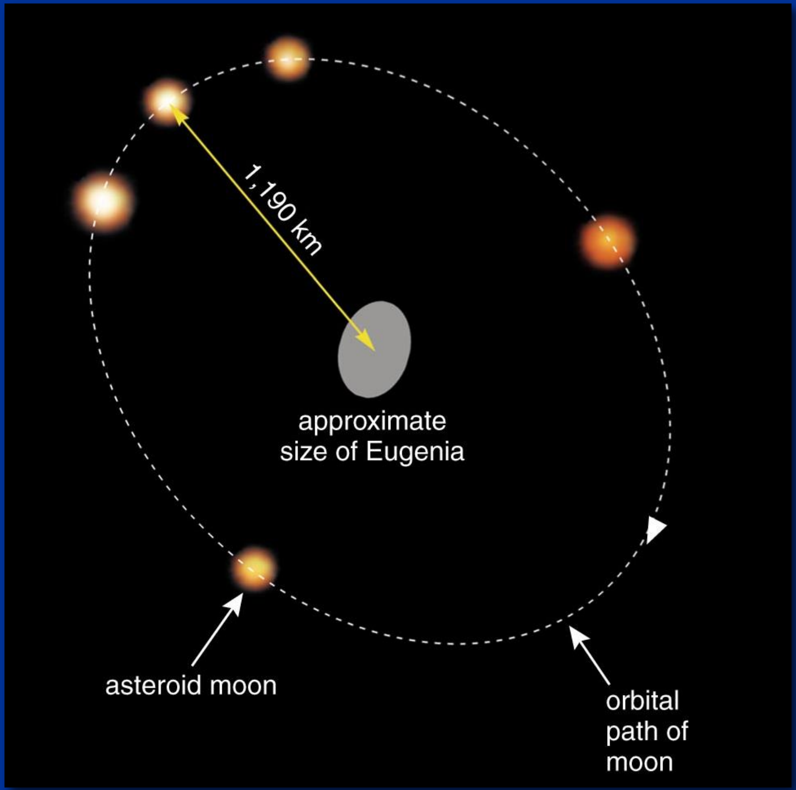
Phobos



***Mars Global Surveyor* images of Phobos**

The few asteroid binaries analyzed so far are not very dense

- Example: Eugenia
  - Made of carbonaceous material, should have high density
  - Yet measured density is only a bit higher than that of water!
  - Conclusion: Eugenia is a loosely bound pile of individual pieces, with cracks ("voids") in between



Asteroids: solid bodies vs. rubble piles?

Mathilde: solid

Itokawa: rubble pile

Centaurs

- **Chiron was the first of four bodies discovered so far with similar orbits and properties.**
- **These bodies have been designated Centaurs, after the race of half-man/half-horse beings from Greek mythology, in recognition of their dual comet/asteroid nature.**
- **It is believed that the Centaurs may be objects which have escaped from the Kuiper belt.**

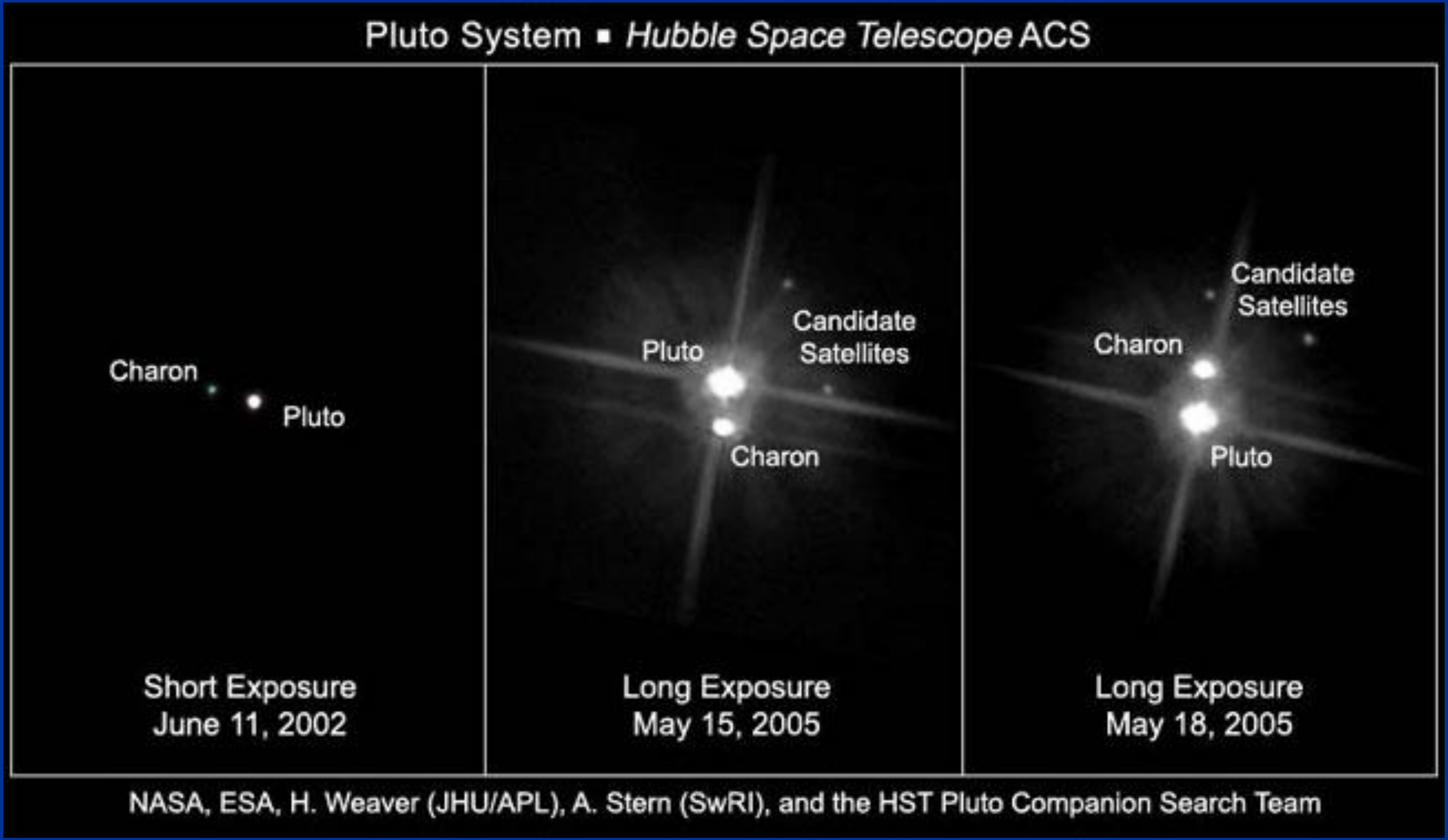
Pluto and Charon

- Pluto's avg density ~ 2 g/ cm^3.
  - Pluto is 50% to 75% rock mixed with ices.
- Charon's density is ~1.6 g/cm^3, indicating it contains little rock.
- Differences in density tell us that Pluto and Charon formed independently

Is Pluto just the largest Kuiper Belt Object?

- **Orbits in same vicinity as Kuiper Belt comets**
- **Comet-like composition**
- **Stable orbital resonance with Neptune, like many comets**
- **But: Pluto is much more highly reflective**
  - **Perhaps ices that sublime when Pluto is closer to Sun stay with Pluto, and re-freeze on surface, whereas they are lost to less-massive comets.**
- **One theory is that Charon was formed from Pluto in same way our Moon was formed from Earth mantle material**

Hubble's view of Pluto & its Moons



Other Kuiper Belt Objects

- **Most have been discovered very recently so little is known about them.**
- **NASA's *New Horizons* mission will study Pluto and a few other Kuiper belt object in a planned flyby.**

Is Pluto a Planet?

- **By far the smallest planet**
  - **Pluto's size was overestimated after its discovery in 1930**
- **Not a gas giant like other outer planets**
- **Has an icy composition like a comet**
- **Has a very elliptical, inclined orbit**
- **Pluto has more in common with comets than with the eight major planets**

What is Pluto? IAU decision, cont'd

- **Defined new class of objects called "dwarf planets"**
- **"Planets" and "dwarf planets" are two distinct classes**
- **First members of the "dwarf planet" category are Ceres, Pluto, Haumea, Makemake, and Eris**
- **More "dwarf planets" are expected to be announced by the IAU in the coming years**
  - **Currently a dozen candidate "dwarf planets" are on IAU's "dwarf planet" watch list**
  - **Keeps changing as new objects are found**
- **"Dwarf planet" Pluto is recognized as an important proto-type of a new class of trans-Neptunian objects**

Slide credit: John Wilson, Georgia State U.

Meteoroids, Meteors, & Meteorites

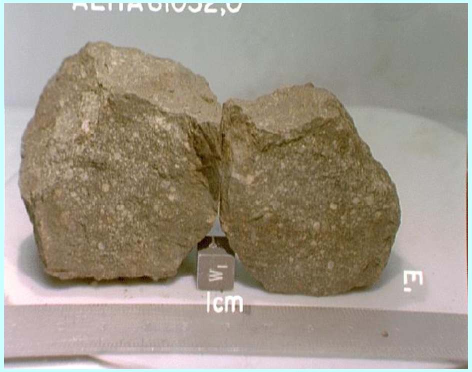
- **Meteoroids are simply smaller versions of asteroids.**
  - **may be chunks that have been broken off asteroids by impacts.**
- **Meteors are streaks of light across the sky caused by a meteoroid entering the Earth's upper atmosphere and burning up in the process.**
  - **Sometimes called "shooting" or "falling stars".**
  - **Typically, 5 or 6 meteors are visible per hour across the sky (sporadic meteors).**
- **Sometimes a portion of a large meteoroid may survive its passage through the atmosphere and reach the Earth's surface. This rock is called a meteorite.**
  - **Meteorites provided astronomers with the first good estimate of the age of the Solar System. Radiometric dating of meteorites gives them an age of about 4.5 billion years.**

Meteorites

- Meteorites are bits of the solar system that have fallen to the Earth.
  - most come from asteroids, including few are believed to have come specifically from Vesta;
  - a few probably come from comets
  - a small number of meteorites have been shown to be of lunar (23 finds) or Martian origin (22).

Types of Meteorites

- **Iron**
  - Primarily iron and nickel; similar to type M asteroids
- **Stony Iron**
  - Mixtures of iron and stony material like type S asteroids
- **Chondrite**
  - by far the largest number of meteorites fall into this class;
  - similar in composition to the mantles and crusts of the terrestrial planets
- **Carbonaceous Chondrite**
  - similar to type C asteroids
- **Achondrite**
  - similar to terrestrial basalts; the meteorites believed to have originated on the Moon and Mars are achondrites

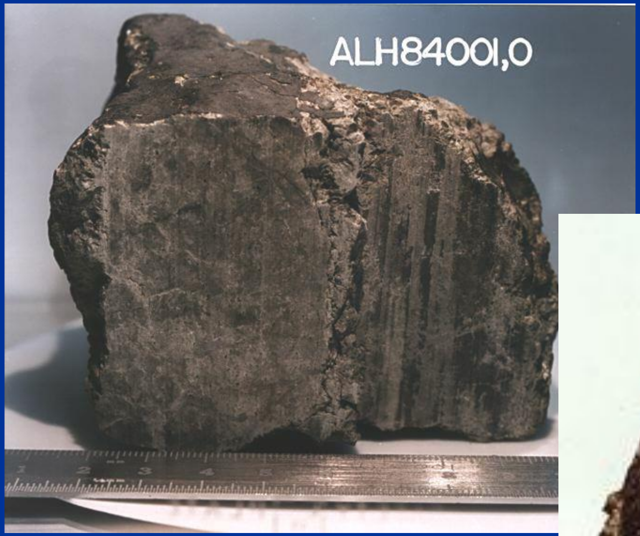


Chondrite

Iron

C. Chondrite

What do meteorites look like?



Mars meteorite

Allen Hills (Moon)

Vesta

Chondrites

- Rocky, inhomogeneous, contain round "chondrules"

Carbonaceous Chondrites contain complex organic molecules

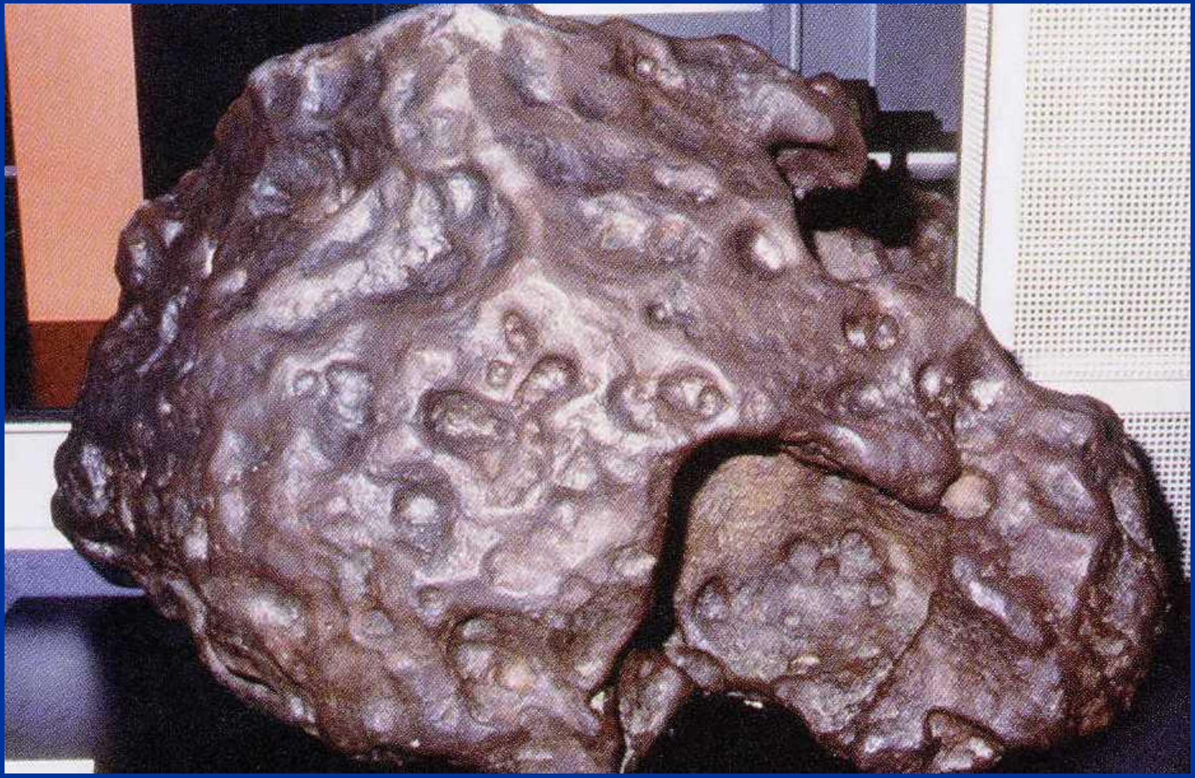
- **Amino acids, fatty acids, other so-called "building blocks of life"**
- **Did building blocks of life come to Earth from space?**
- **Did life itself come to Earth from space?**
  - **"Panspermia" theory**

Carbonaceous Chondrites: Insights into Planet Formation?

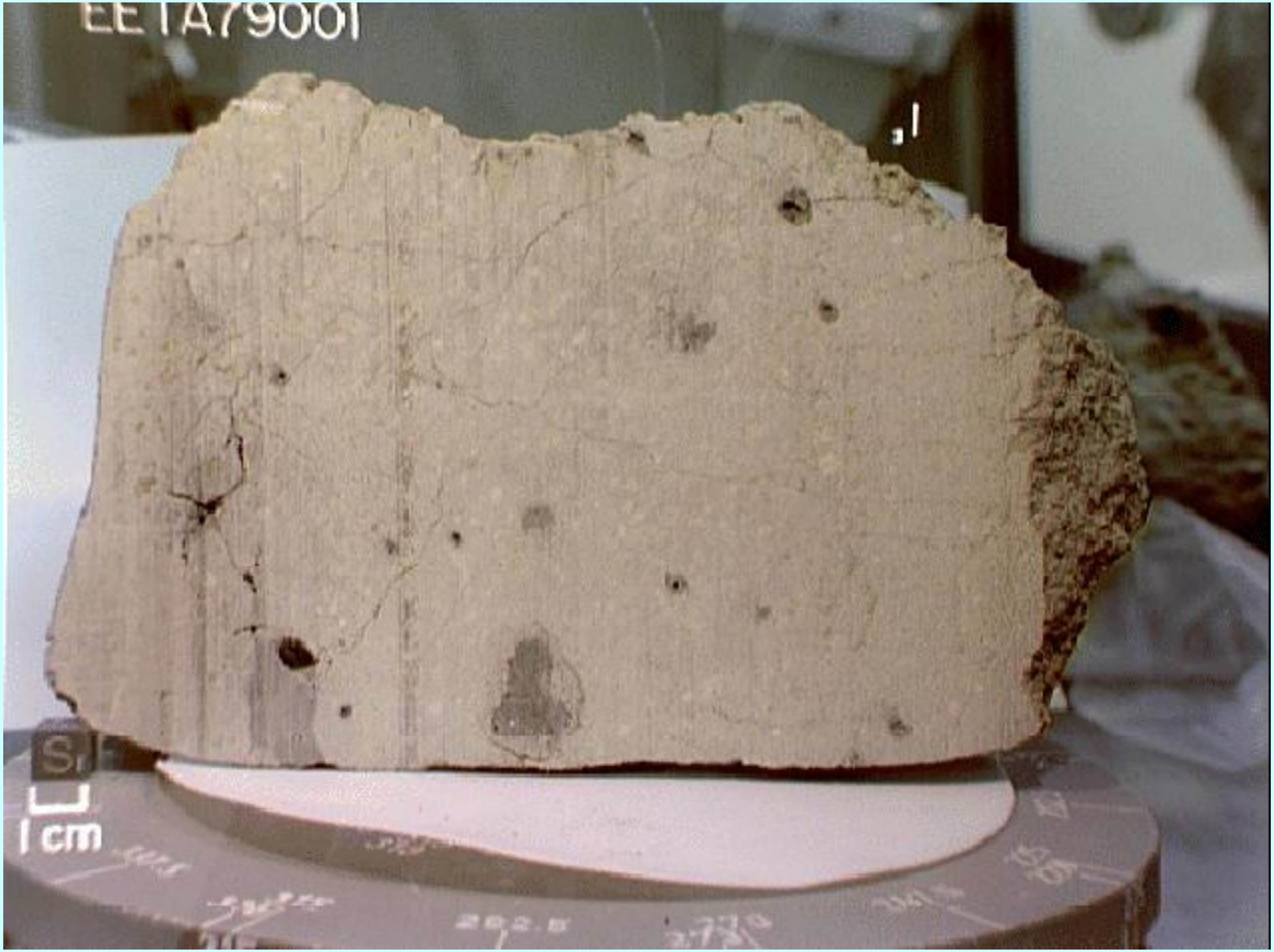
- The oldest meteorites; quite rare
- Chondrules (round): primitive chunks of early Solar System
- Calcium aluminum inclusions (Cal's): isotope ratios (26 Al and 26 Mg) suggest that a supernova explosion went off right next to the early Solar Nebula
  - Did the supernova stimulate formation of our Solar System?

Iron meteorites

- Made of iron and nickel
- Pits made during atmospheric entry (hot!)

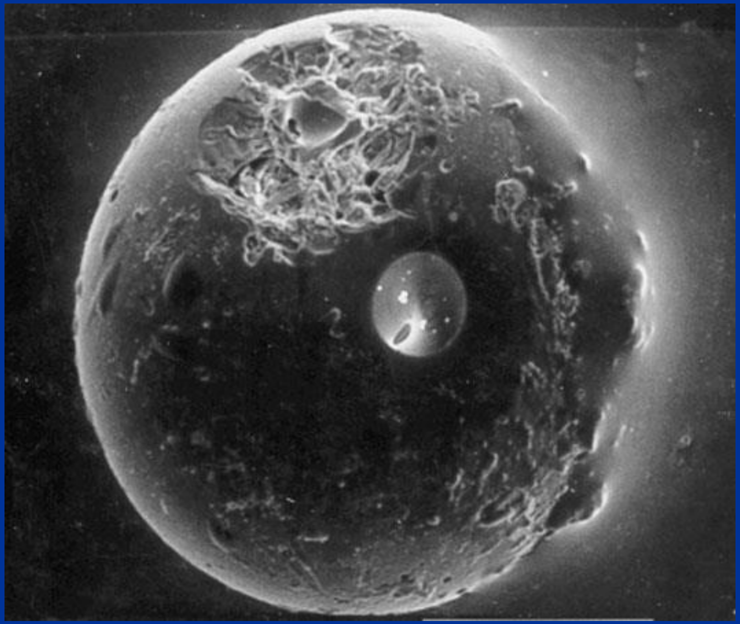


Martian Meteor

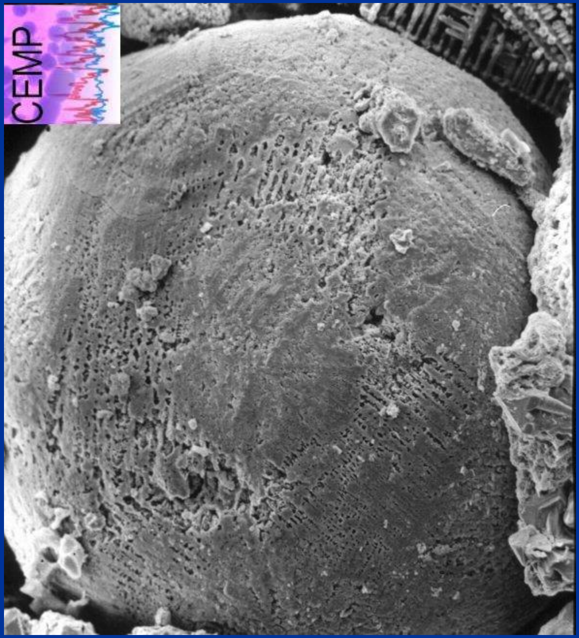


Small particles: spherules

- Tiny droplets from space
- Formed by melting and re-solidification after impacts



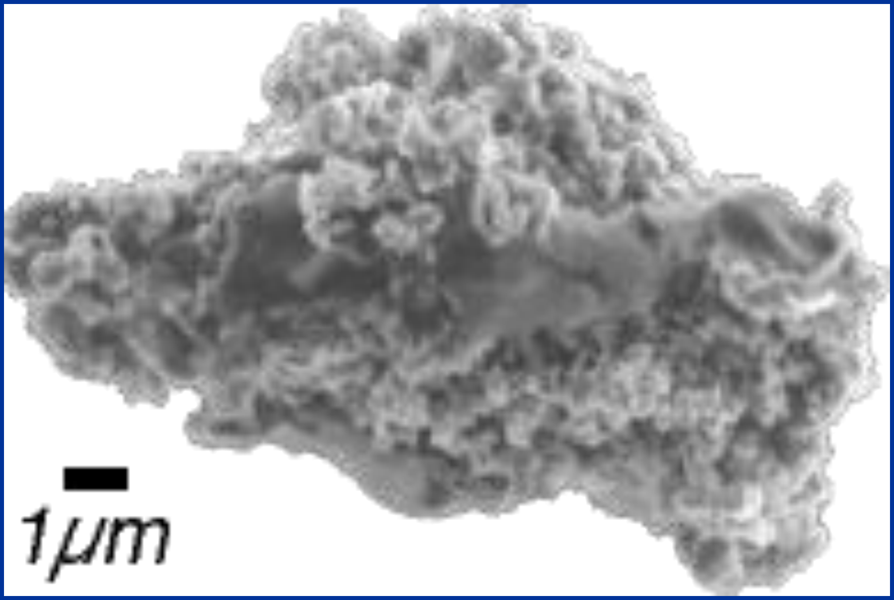
Spherule from Moon
Collected by Apollo 11 astronauts

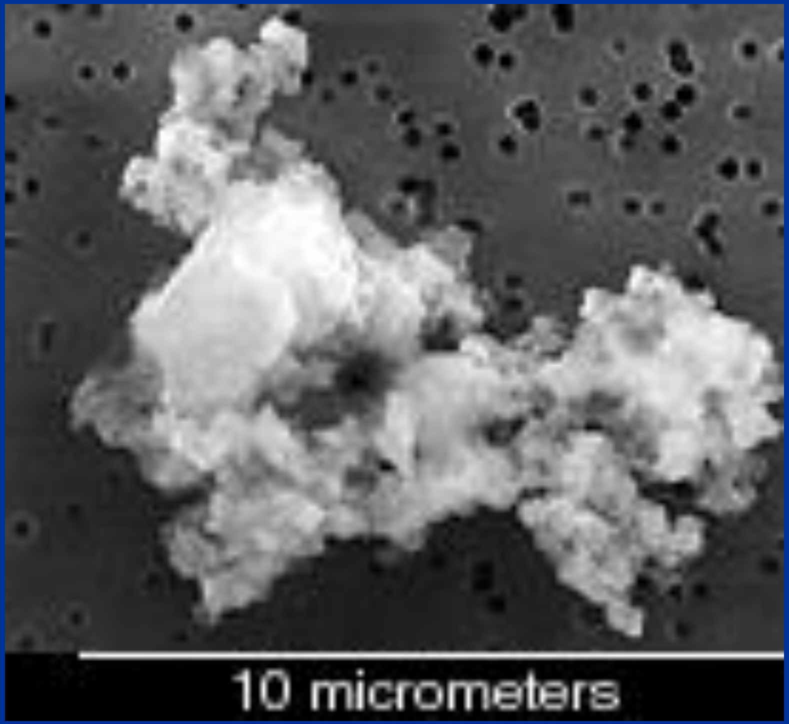


Spherule
from bottom of the Indian Ocean

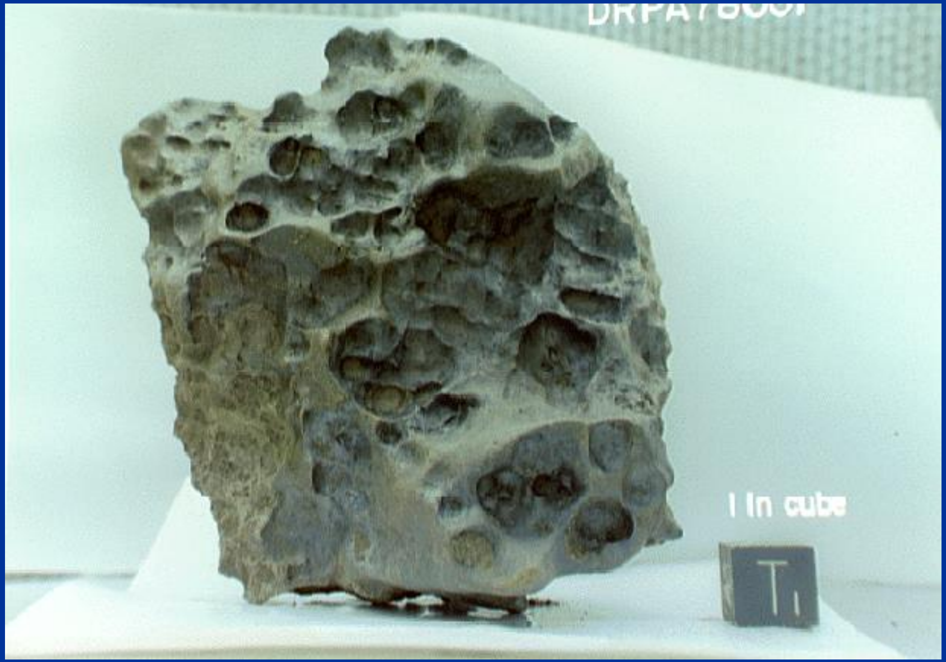
Small particles: cosmic dust

- **Sometimes from comets, sometimes left over from the cosmic dust cloud from which the Solar System formed**





Single small chunks of rock



Iron-nickel meteorite
A few inches across

Allende
Carbonaceous chondrite

Several-ton boulders

Hoba Meteorite, Namibia

Meteor Showers

- At certain times of the year, many more meteors are observed to be radiating from a particular point in space.
- These so-called meteor showers are now known to be associated with comet orbits.
- When the Earth crosses the "dusty" trail of a comet, many more meteors per hour can be observed.
- There are several major meteor showers each year.

Comets

- Comets: small bodies made out of dust and ices ("dirty snowballs").
- The term "comet" derives from the Greek aster kometes, which means "long-haired star"---a reference to the tail.
- Since the observations of Tycho Brahe, comets are known to be members of the Solar System well beyond Earth's atmosphere.
- Most are on long elliptical orbits (perhaps parabolic in some cases) that take them from the outer reaches of the Solar System to the vicinity of the Sun.
- When they come near the Sun they are heated and emit gases and dust that are swept by the Solar Wind into the characteristic tail that always points away from the Sun.

Comets

- Dirty snowballs
- Long term comets
  - most in Oort cloud (up to 50,000 AU from Sun)
  - normally orbit far from the Sun, very few enter planetary region of solar system
  - highly elongated orbits
  - not confined to ecliptic, all orbital inclinations
  - prograde and retrograde orbits
  - roughly uniform distribution
- Short term comets (periods < 200 years)
  - most originate in region beyond Neptune called Kupier belt
  - approximately circular, prograde orbits 30-100 AU
  - normally orbit outside jovian planets, occasionally kicked into inner solar system

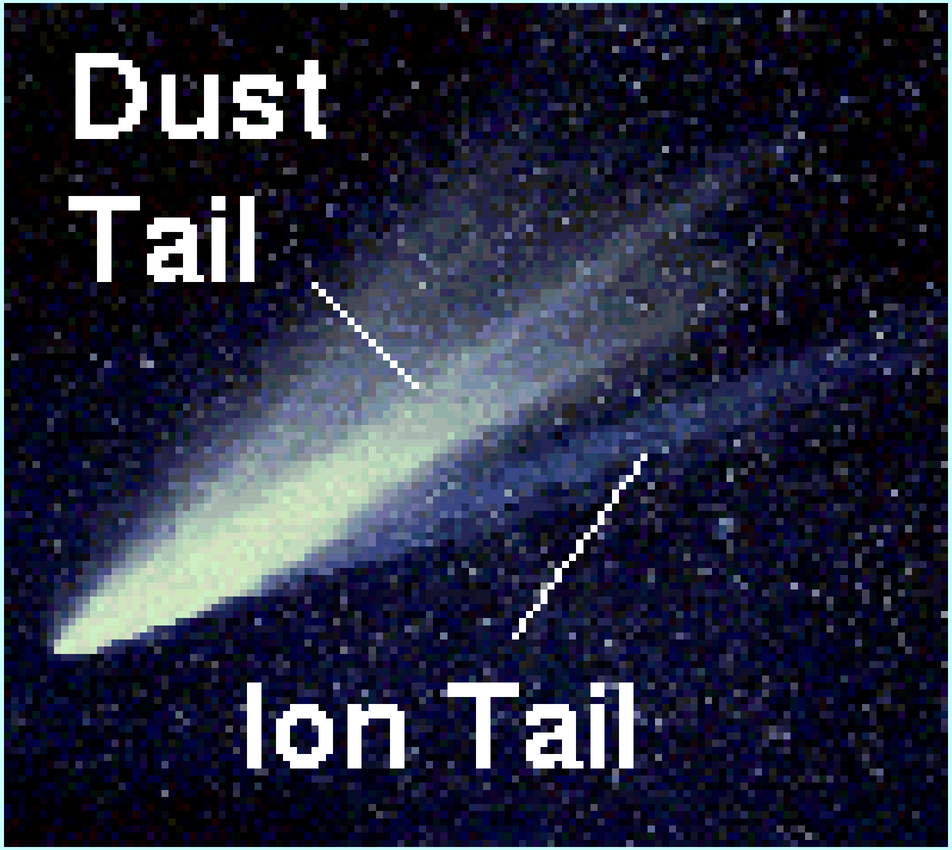
Parts of a Comet

Comets have several distinct parts when near the Sun and active:

- **nucleus**
  - relatively solid and stable, mostly ice and gas with a small amount of dust and other solids
- **coma**
  - dense cloud of water, carbon dioxide and other neutral gases sublimed from the nucleus
- **hydrogen cloud**
  - huge (millions of km in diameter) but very sparse envelope of neutral hydrogen
- **dust tail**
  - up to 10 million km long composed of smoke-sized dust particles driven off the nucleus by escaping gases;
  - most prominent part of a comet to the unaided eye
- **ion tail**
  - as much as several hundred million km long
  - composed of plasma; laced with rays and streamers caused by interactions with the solar wind.

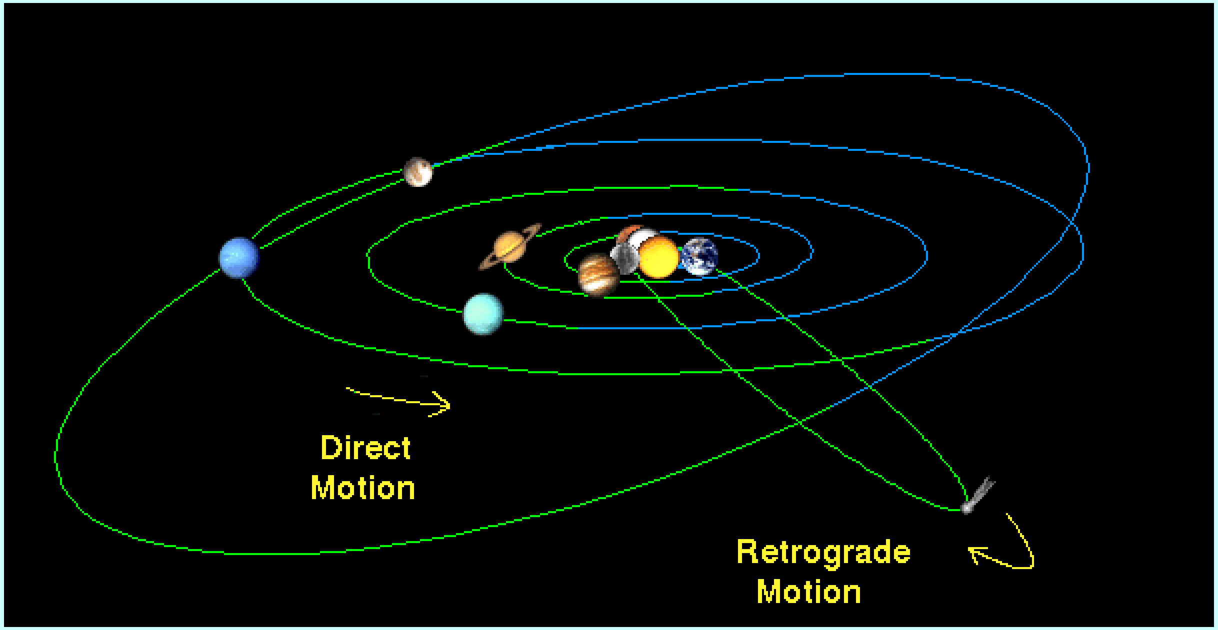
Comet Tails

- **Tails of bright comets can be 150 million kilometers (1 AU) in length, making them the "largest" objects in the Solar System.**
- **Many comets have two tails:**
  - **gas tail (or ion tail) composed of ions blown out of the comet away from the Sun by the solar wind, and**
  - **dust tail composed of dust particles liberated from the nucleus as the ices are vaporized.**



Comet Orbits

- Comets interact gravitationally with the Sun and other objects.
- Their motion is also influenced to some degree by gases jetting out of them, so their orbits are not completely determined by gravity.
- Most comets' orbits appear to be elliptical, or in some cases parabolic.
- The most common comets are called *short-period* comets that have only mildly elliptical orbits that carry them out to a region lying from Jupiter to beyond the orbit of Neptune. These are normally seen only with telescopes.
- Comets visible to the naked eye are rare and are thought to come from a great spherical cloud of cometary material surrounding the Solar System called the Oort Cloud.



Comet Halley

- **English astronomer Edmund Halley used Newton's new theory of gravitation to determine the orbits of comets from their recorded positions in the sky as a function of time.**
- **He found that the bright comets of 1531, 1607, and 1682 had the same orbits, and concluded that these were different appearances of the same comet.**
- **He used his calculations to predict the return of this comet in 1758.**
- **If one traces back in the historical records for recordings of bright comets and their positions in the sky, it can be concluded that Comet Halley has been observed periodically as far back as 240 B.C.**

Halley in 1910

Halley in 1986

Comet Shoemaker-Levy 9

In July of 1994, fragments of Comet Shoemaker-Levy 9 impacted the planet Jupiter. The points of impact could be observed by the Galileo spacecraft.