Cosmic Calendar

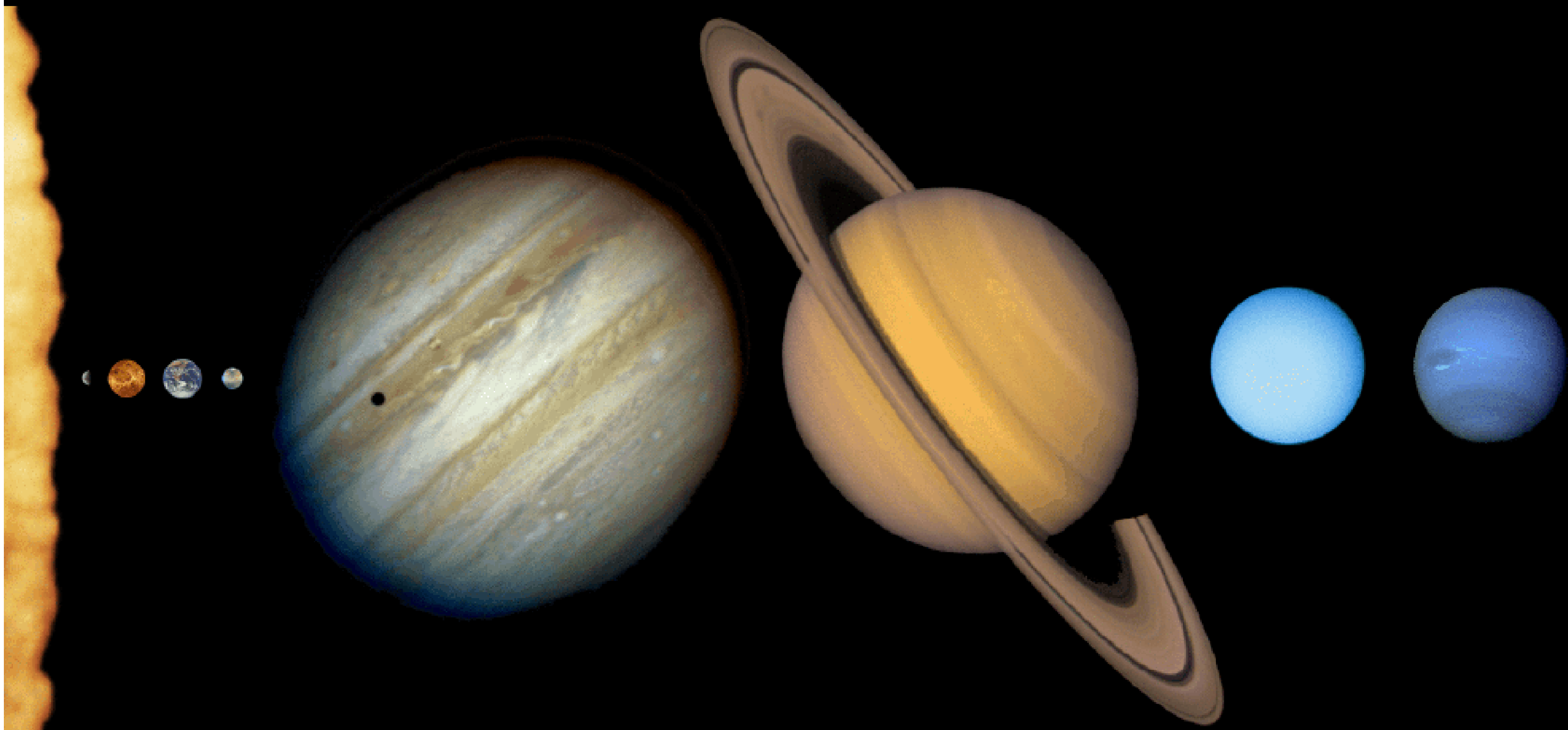
History of the universe is compressed into one year

- January 1 - Big Bang (13.4 G years)
- April 1 - Origin of Milky Way Galaxy
- May 1 - Origin of the Pre-Sun
- September 1 - Origin of the solar system
- September 14 - Formation of the Earth
- September 25 - Origin of life on Earth
- October 9 - Date of oldest fossils (bacteria and blue-green algae)
- December 1- Significant oxygen atmosphere begins to develop on Earth.

Cosmic Calendar (December)

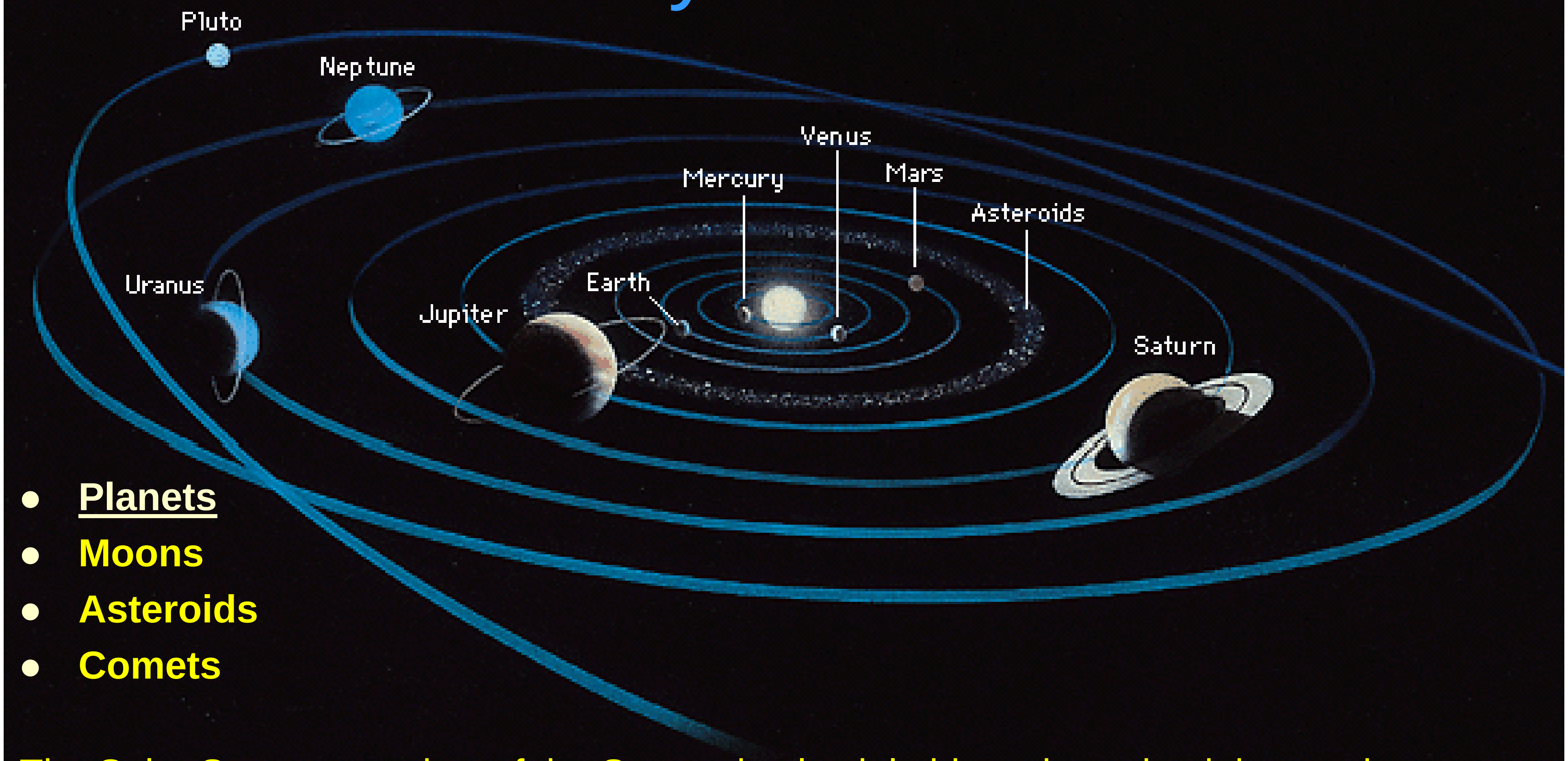
- 24^{th} - First dinosaurs.
- 25th - First Mammals
- 28^{th} - First Flower. Dinosaurs become extinct.
- 31^{st}
  - **10:30 p.m. - First humans**
  - 11:59 p.m. - Extensive cave painting in Europe
  - 11:59:20 p.m. - Invention of agriculture
  - 11:59:35 p.m. - Neolithic civilization; first cities
  - **11:59:45 p.m. - Invention of writing**
  - 11:59:50 p.m. - First dynasties in Sumer, Ebla and Egypt; development of astronomy
  - **11:59:59 p.m. - Voyage of Vasco da Gama**
  - Widespread development of science and technology; emergence of global culture; acquisition of the means of self-destruction of the human species; first steps in spacecraft planetary exploration and the search of extraterrestrial intelligence
  - **The first second of New Year's Day: 4th School of Astrophysics (IST Lisbon 2008)**

The Planets of the Solar System



IST Summer 2008

The Solar System consists of:

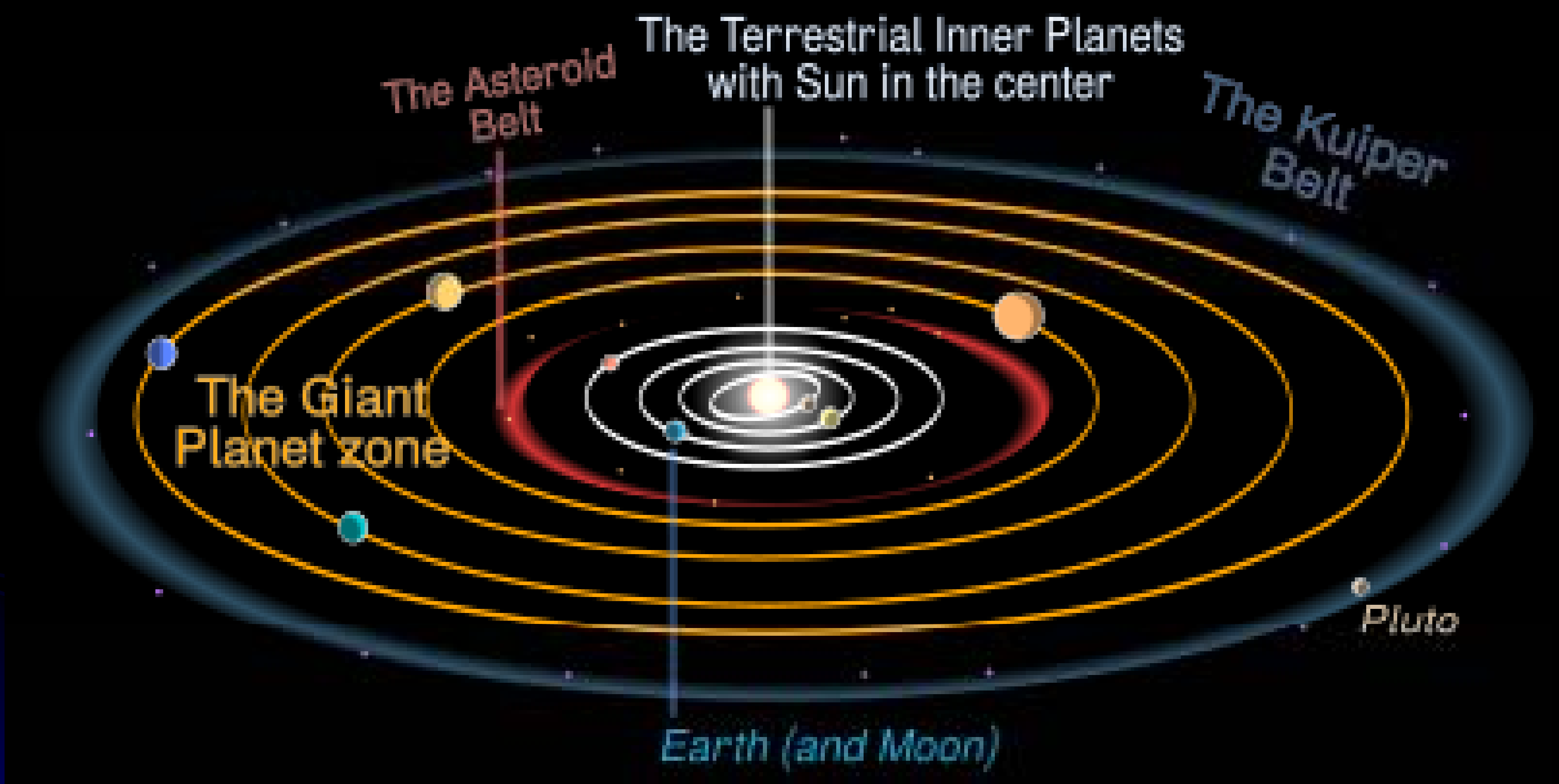


- **<u>Planets</u>**
- **Moons**
- **Asteroids**
- **Comets**

The Solar System consists of the Sun and celestial objects bound to it by gravity.

Celestial objects are the eight planets and their 166 known moons, four dwarf planets and billions of small bodies, including asteroids, icy Kuiper belt objects, comets, meteoroids, and interplanetary dust.

The Solar System consists of:



The regions of the Solar system: the *inner solar system*, the *asteroid belt*, the *giant planets* (Jovians) and the *Kuiper belt*. Sizes and orbits not to scale.

Planets

The International Astronomical Union (IAU, 2003) defines a planet a celestial object that incorporated the following working definition (mostly focused upon the boundary between planets and brown dwarves):

(i) Objects with true masses below the limiting mass for thermonuclear fusion of deuterium (currently calculated to be 13 times the mass of Jupiter for objects with the same isotopic abundance as the Sun) that orbit stars or stellar remnants are "planets" (no matter how they formed). The minimum mass and size required for an extrasolar object to be considered a planet should be the same as that used in our Solar System.

(ii) Substellar objects with true masses above the limiting mass for thermonuclear fusion of deuterium are "brown dwarfs", no matter how they formed or where they are located.

(iii) Free-floating objects in young star clusters with masses below the limiting mass for thermonuclear fusion of deuterium are not "planets", but are "sub-brown dwarfs" (or whatever name is most appropriate).

A planet, as defined by the International Astronomical Union (IAU), is a celestial body orbiting a star or stellar remnant that is massive enough to be rounded by its own gravity, is not massive enough to cause thermonuclear fusion, (and has cleared its neighbouring region of planetesimals).

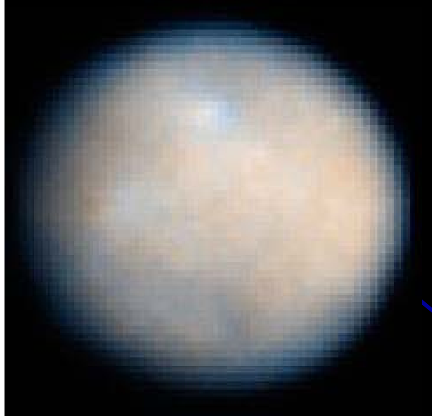
Dwarf Planets

A dwarf planet (IAU), is a celestial body orbiting the Sun that is massive enough to be rounded by its own gravity but which has not cleared its neighbouring region of planetesimals and is not a satellite.

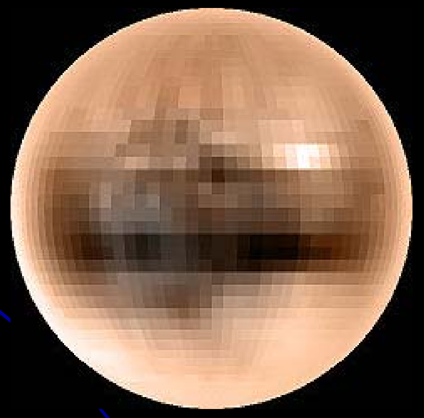
More explicitly, it has to have sufficient mass for its self-gravity to overcome rigid body forces in order to assume a hydrostatic equilibrium and acquire a near-spherical shape.

The term *dwarf planet* was adopted in 2006

The IAU currently recognizes only four dwarf planets—Ceres, Pluto, Makemake, and Eris but it is suspected that at least another 41 discovered objects in the Solar System might belong in this category.



Ceres as seen by Hubble Space Telescope (1801).



Pluto based on Charon eclipses, highest resolution currently possible (1930).

Artist's conception of Makemake, (2005)

Eris (centre) and Dysnomia (left of centre). Hubble Space Telescope (2003).

Dwarf Planets II

Ceres is the smallest identified dwarf planet in the Solar System and the only one in the asteroid belt. With a diameter of about 950 km, Ceres is by far the largest and most massive body in the asteroid belt, and contains approximately a third of the belt's total mass. Recent observations have revealed that it is spherical, unlike the irregular shapes of smaller bodies with lower gravity.

Pluto is the second-largest known dwarf planet in the Solar System (after Eris) and the tenth-largest body observed directly orbiting the Sun. Pluto is now considered the largest member of a distinct region called the Kuiper belt.

Makemake is the third-largest known dwarf planet in the Solar System and one of the two largest Kuiper belt objects (KBO). Its diameter is roughly three-quarters that of Pluto.

Eris is the largest known dwarf planet in the Solar System and the ninth largest body known to orbit the Sun directly. It is approximately 2,500 kilometres in diameter and 27% more massive than Pluto.

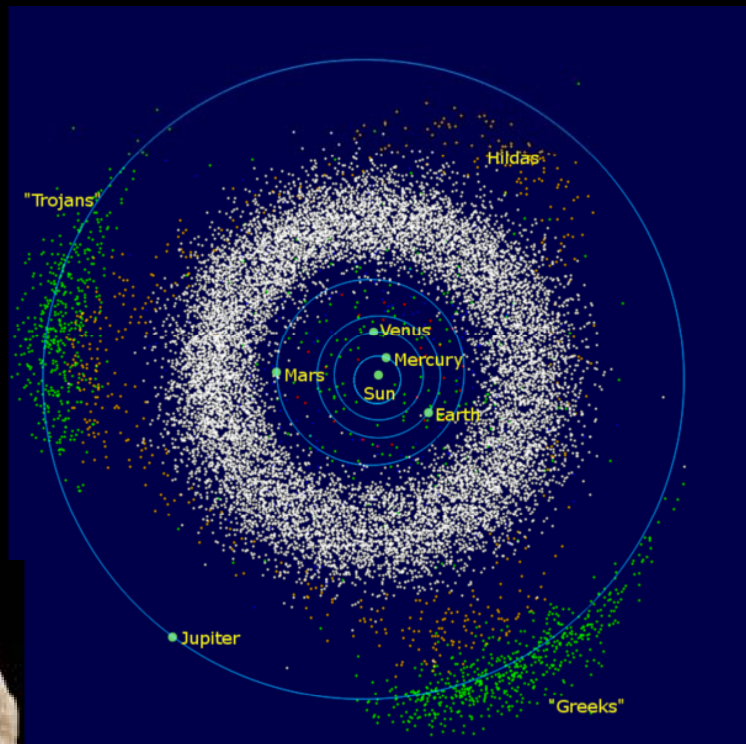
ASTEROID BELT

Most asteroids can be found in the Asteroid Belt, which is located between Mars and Jupiter. Asteroids are rocky and metallic objects that orbit the Sun, but are too small to be considered planets. Asteroids range in size from **Ceres,** which has a **diameter of about 1000 km**, down to the size of pebbles.

More than half the mass within the main belt is contained in the four largest objects: Ceres, Vesta, Pallas, and Hygiea. All of these have mean diameters of more than 400 km, while Ceres, the main belt's only dwarf planet, is about 950 km in diameter.
The remaining bodies range down to the size of a dust particle.

Vesta

Pallas

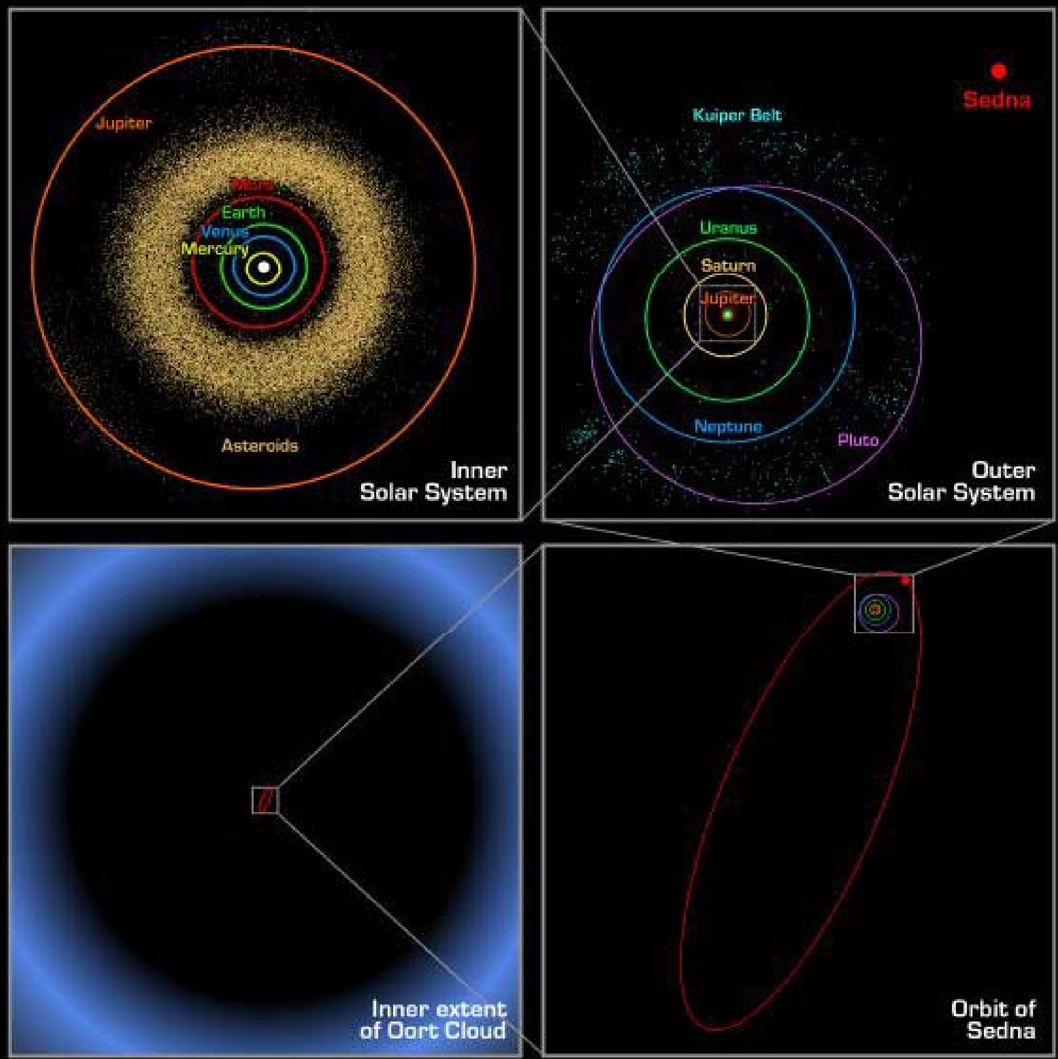


Asteroid belt (shown in white)

What does the solar system look like?

NASA Figure

- Sun, 0 AU
- Inner Planets (Mercury, Venus, Earth, Mars) ~ 1 AU
- Asteroid Belt, ~ 3 AU
- Outer Planets (Jupiter, Saturn, Neptune, Uranus), ~ 5-40 AU
- Keiper Belt, ~ 30 to 50 AU
- Oort Cloud, ~ 50,000 AU



Astronomical Unit (AU)
=149,597,870.7 km

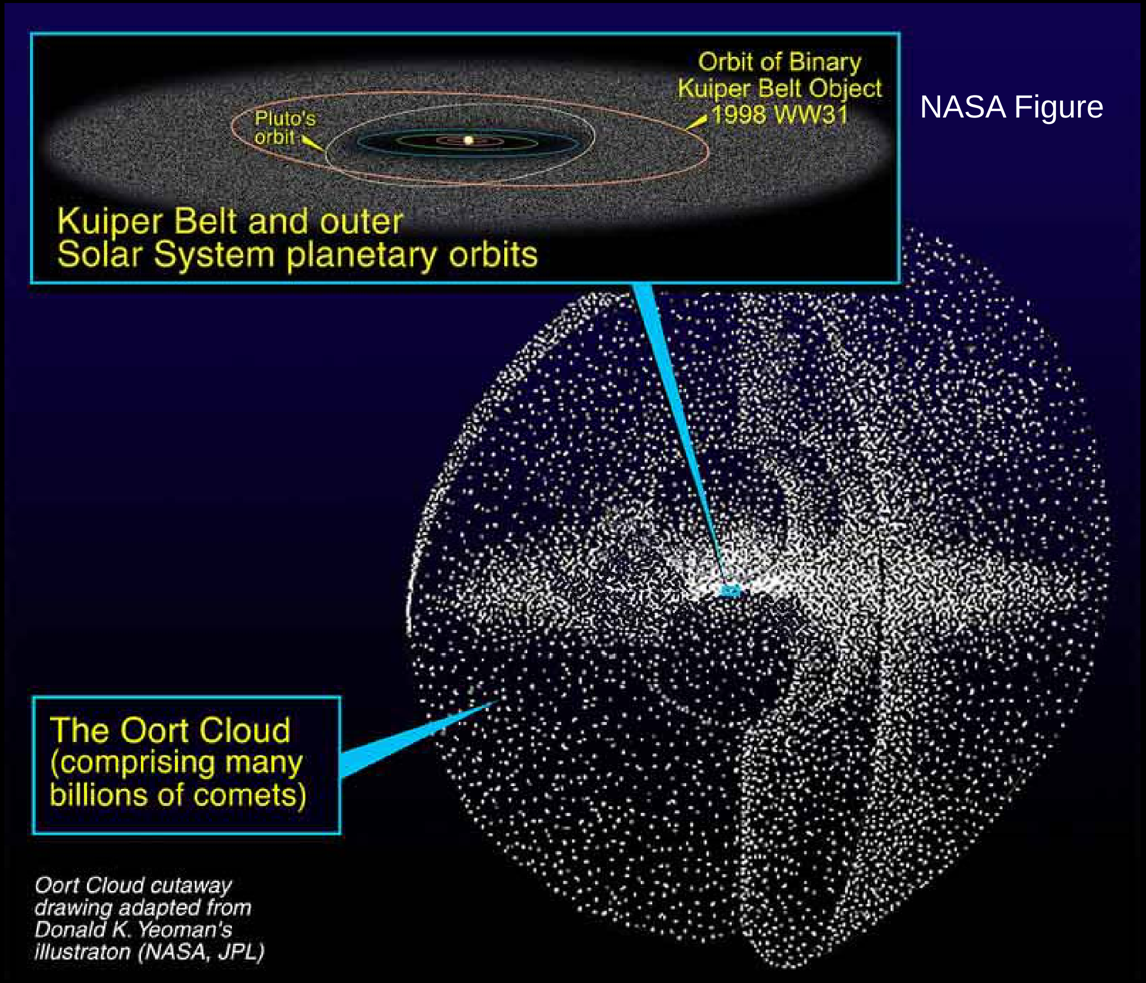
The Kuiper Belt and the Oort Cloud

Kuiper Belt

A large body of small objects orbiting (the short period comets) the Sun in a radial zone extending outward from the orbit of Neptune (30 AU) to about 50 AU.

Oort Cloud

Long Period Comets (period > 200 years) seems to come mostly from a spherical region at about 50,000 AU from the Sun.



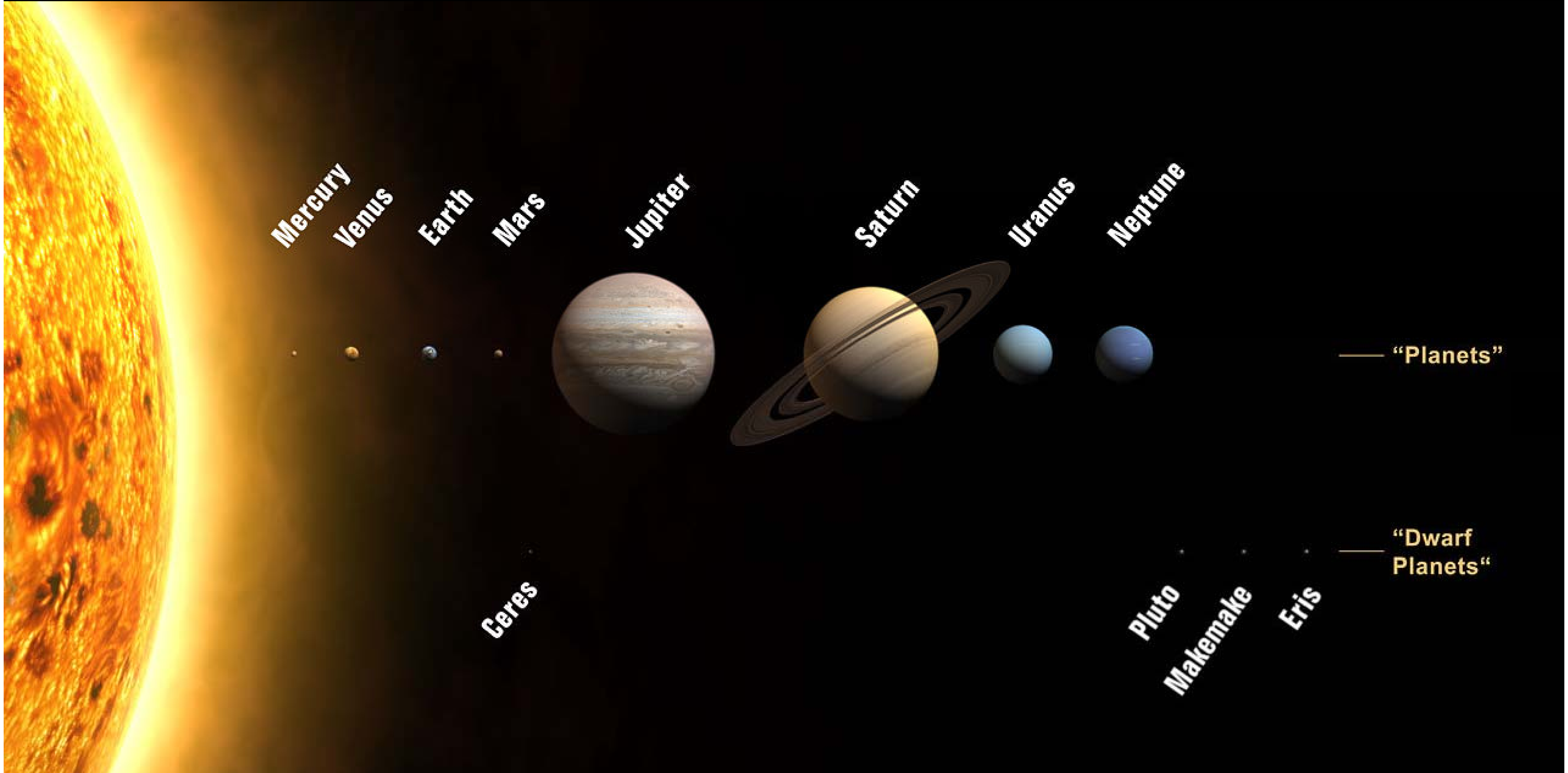
NASA Figure

Astronomical Unit (AU)
=149,597,870.7 km

The solar system constituents

- The Sun: a middle-aged, average sized star
- The Terrestrial Planets:
  - Rocky Planets: Mercury, Venus, Earth & Mars
- The Jovian Planets:
  - Gas Giants: Jupiter, Saturn, Uranus & Neptune
- The Dwarf Planets:
  - Rocky Objects: Ceres, Pluto, Makemake & Eris
- Small Icy & Rocky Bodies:
  - Icy: Icy Moons, Kuiper Belt Objects, & Comets
  - Rocky: Giant Moons, Asteroids & Meteoroids

The Planets of the Solar System (Dynamics)



- the sizes are to scale,
- the relative distances from the Sun are not.

Planet's basic dynamical properties

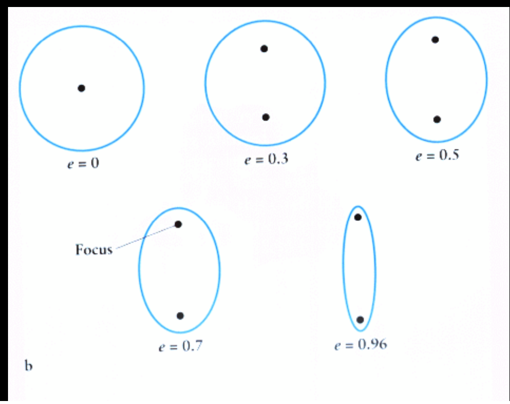
The properties characterizing planets are:

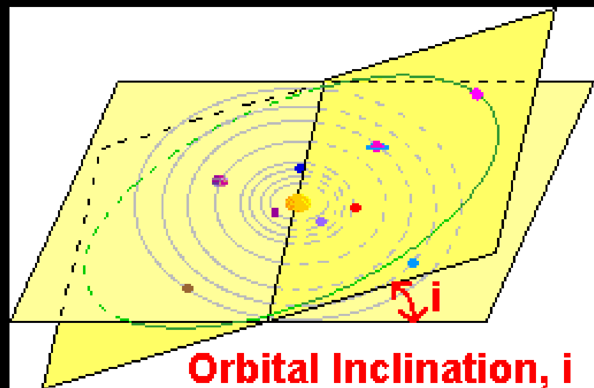
Distance from the Sun
Orbital period
Mass
Radius
Rotational period

These quantities are what determine the physical conditions on a planets, like presence of atmosphere, volcanic activity, magnetic field, ……

Orbits of the Planets

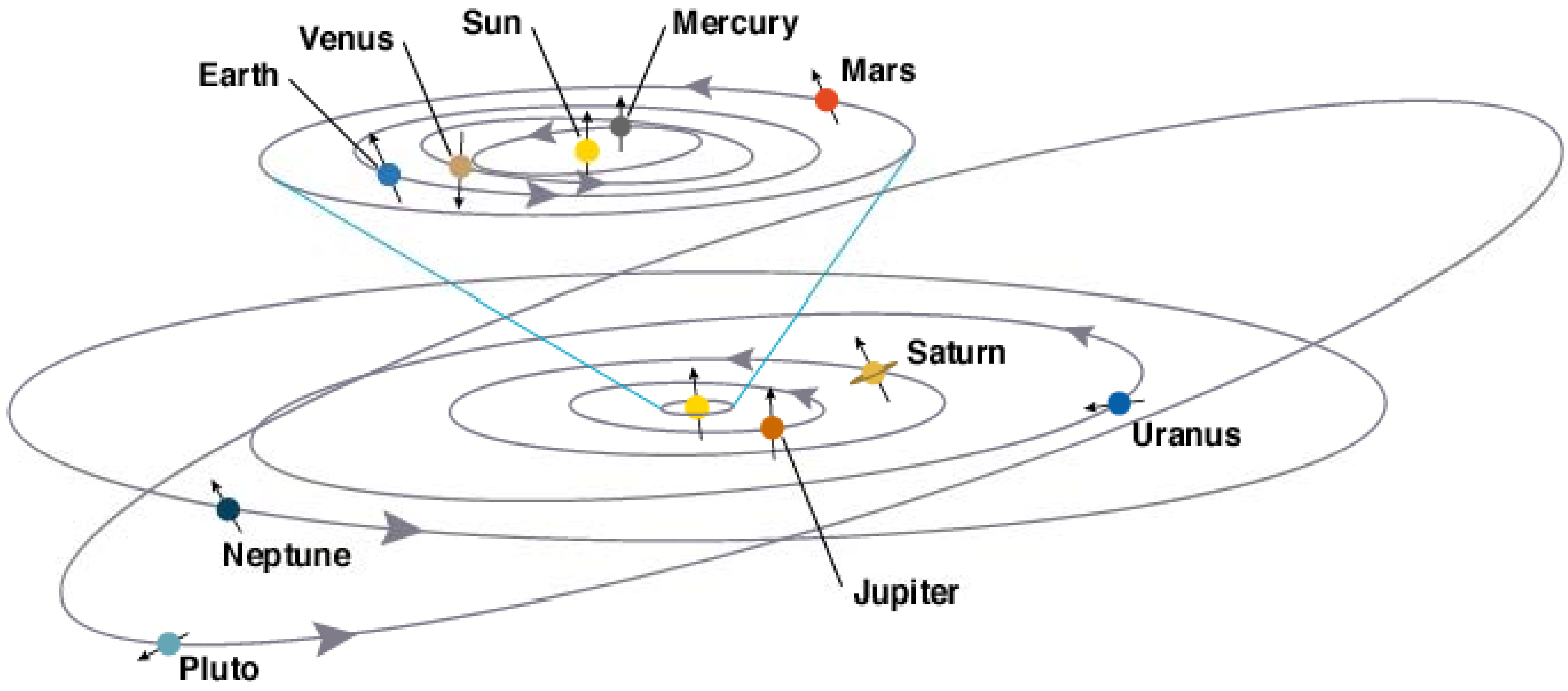
Planet	Semi-major Axis (A.U.)	Eccentricity	Inclination (degrees)
Mercury	0.387	0.205	7.005
Venus	0.723	0.007	3.395
Earth	1	0.017	0
Mars	1.523	0.093	1.851
Jupiter	5.203	0.048	1.305
Saturn	9.537	0.054	2.484
Uranus	19.191	0.047	0.77
Neptune	30.069	0.008	1.769
Pluto	39.481	0.248	17.141





The Orbits of the Planets

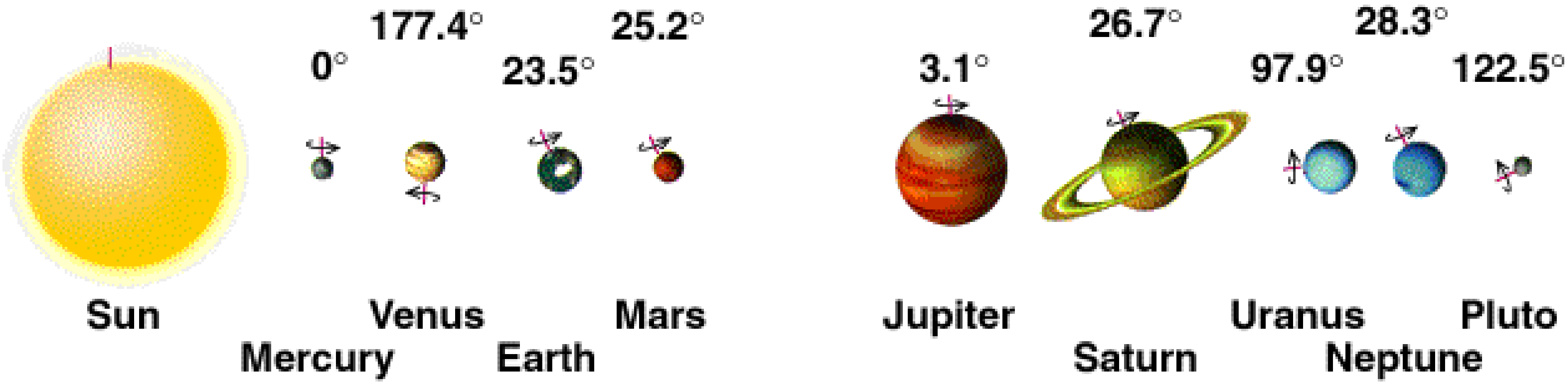
- All the planets orbit the Sun in the same direction
- The rotation axes of most of the planets and the Sun are roughly aligned with the rotation axes of their orbits.
- Orientation of Venus, Uranus, and Pluto’s spin axes are not similar to that of the Sun and other planets.



Rotation of the Planets

Planet	Rotation Period (days)	Axis Tilt (degrees)
Mercury	58.646	0
Venus	-243.0187	177.3
Earth	0.997	23.45
Mars	1.026	25.19
Jupiter	0.413	3.12
Saturn	0.444	26.73
Uranus	-0.718	97.86
Neptune	0.671	29.58
Pluto	-6.387	119.61

Side View of the Solar System



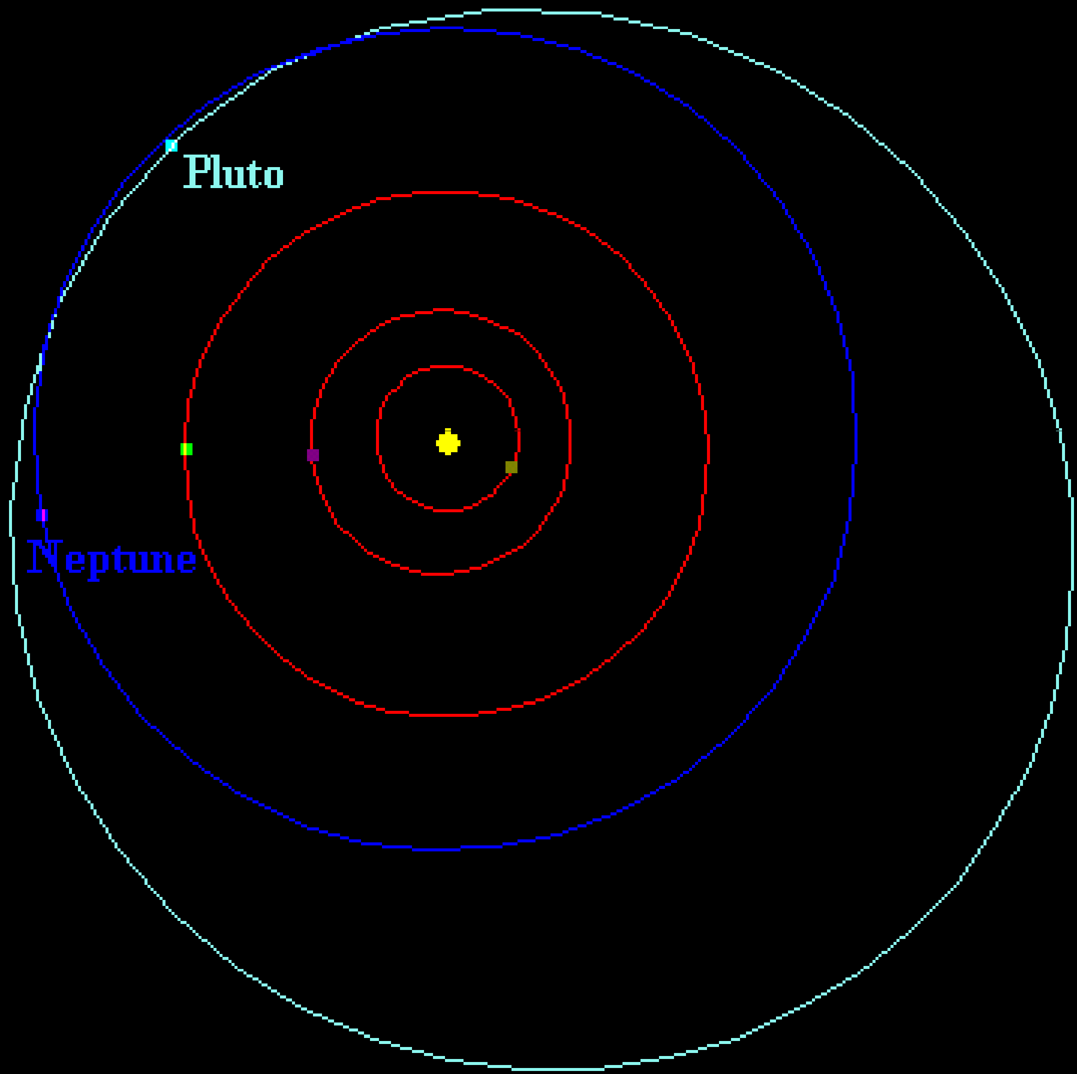
Summary of Orbital Characteristics

- Planets orbit in nearly the same plane (the ecliptic plane), inclinations are small.
- Planets orbit in the same direction with small eccentricities. The direction is that which the sun rotates.
- Most of the planets spin in the same direction that they orbit. Venus, Uranus and Pluto are exceptions.

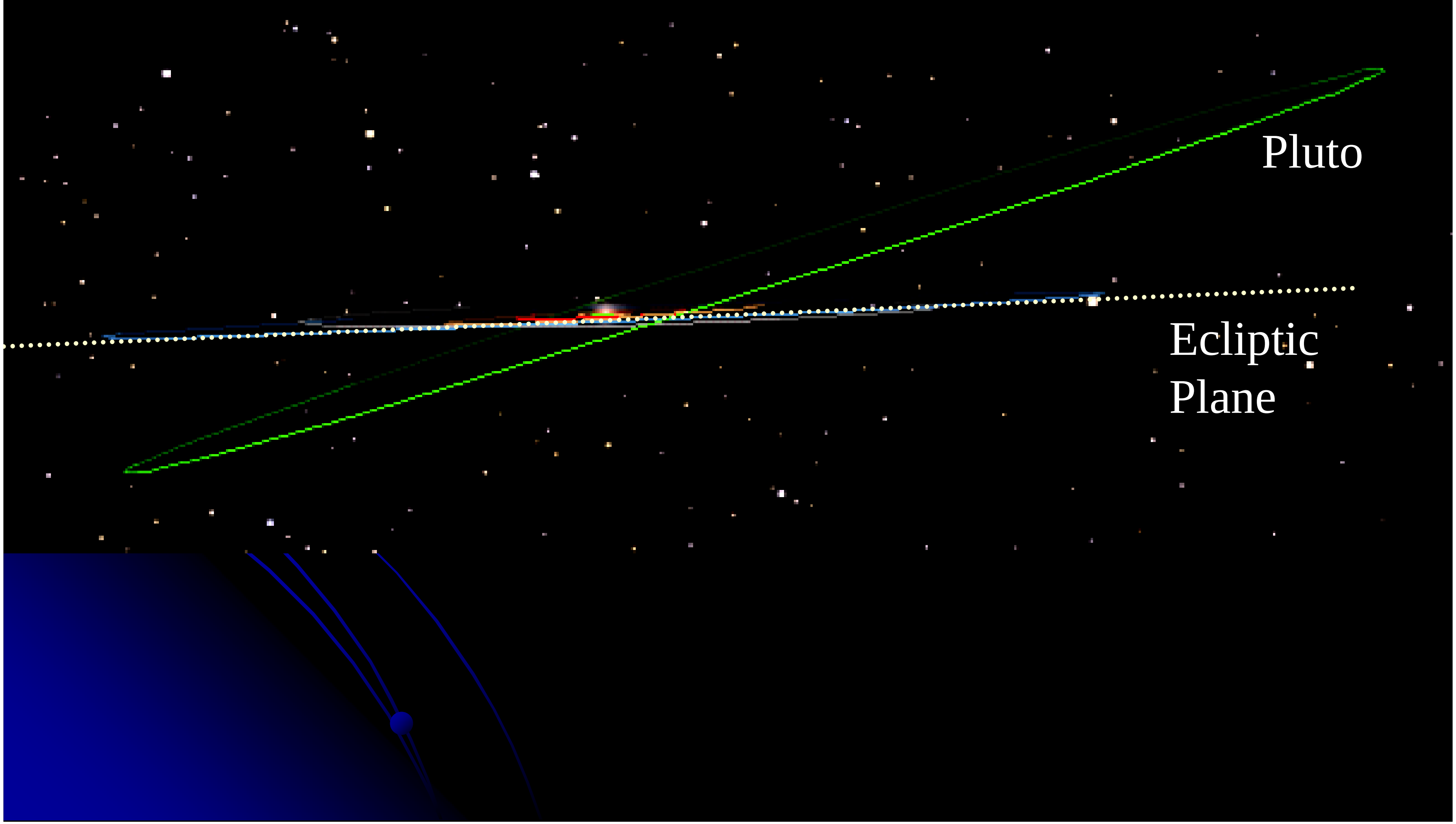
Basic Properties of the Planets

- Locations:
  - **Terrestrial planets** in the inner solar system: 0.4-1.5AU
  - **Jovian planets** in the outer solar system: 5-30 AU
- All orbit in the same direction & same plane:
  - Orbit counterclockwise, in the same sense as the rotation of the Sun.
  - All except Pluto orbit very near the Ecliptic plane.
- Provides clues to Solar System formation.

What’s wrong with Pluto?



Pluto…. Planet ? No



Why Pluto is not a Planet

- Pluto is neither a Terrestrial nor Jovian Planet.
  - Smallest of the planets
  - Intermediate Density: 1.8 g/cc (mostly icy)
- Pluto’s orbit is also odd:
  - The most elliptical orbit of all the planets
  - The most highly inclined: ~17º from the Ecliptic.
- Largest of a distinct class of objects, but still a “planet”.

Planet Stat Sheet

H_2O has a density of 1 gram/cc

Silicate rocks ~ 3-4 grams/cc

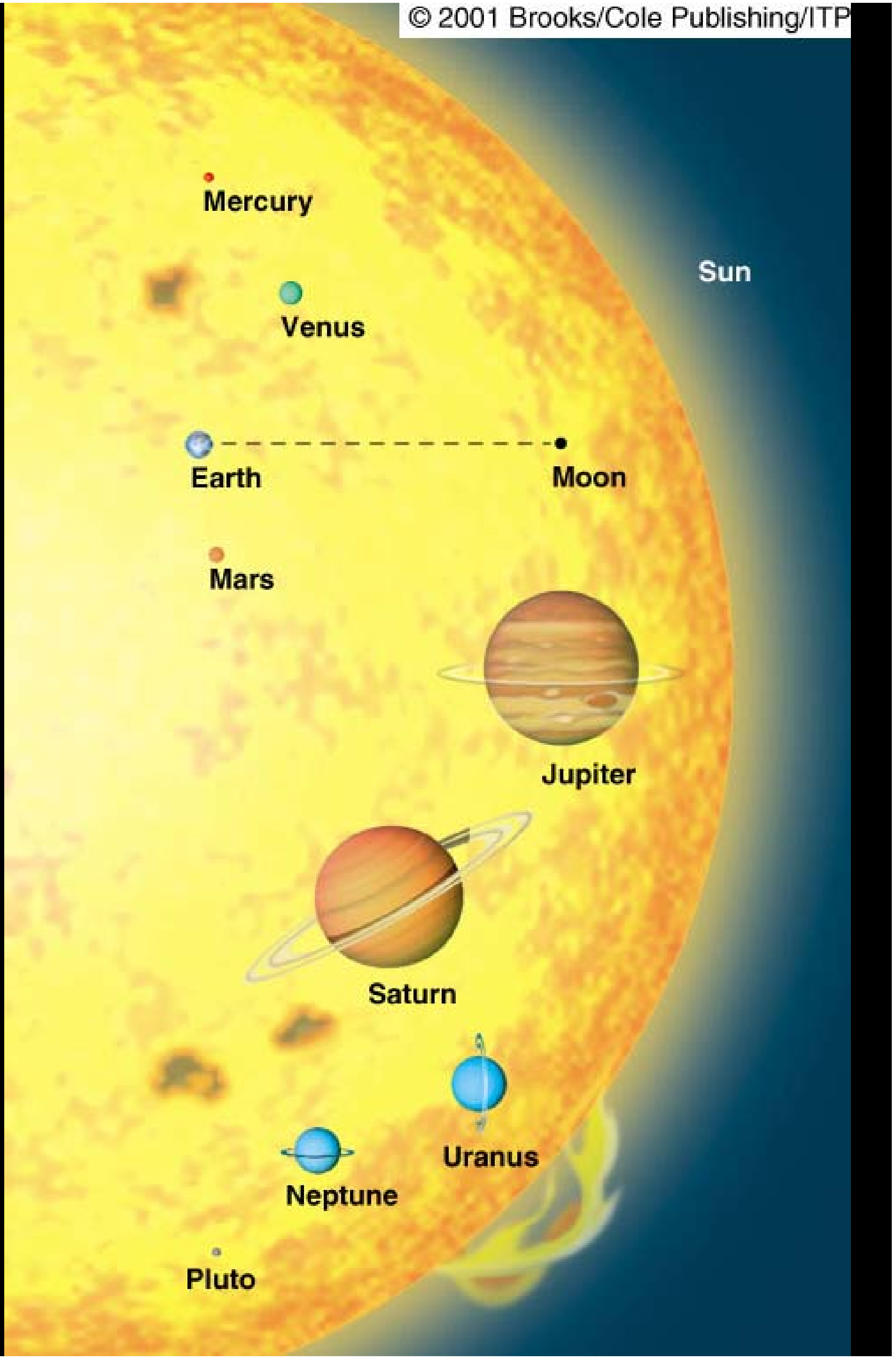
Metals ~5-7 grams/cc

Name	Dist. from Sun (AU)	Revolution Period (years)	Diameter(km)	Mass (10^{23} kg)	Density (g/cm^3)
Mercury	0.39	0.24	4,878	3.3	5.4
Venus	0.72	0.62	12,102	48.7	5.3
Earth	1.00	1.00	12,756	59.8	5.5
Mars	1.52	1.88	6,787	6.4	3.9
Jupiter	**5.20**	11.86	142,984	18,991	**1.3**
Saturn	**9.54**	29.46	120,536	5,686	**0.7**
Uranus	**19.18**	84.07	51,118	866	**1.2**
Neptune	**30.06**	164.82	49,660	1,030	**1.6**
Pluto	39.44	248.60	2,200	0.01	2.1

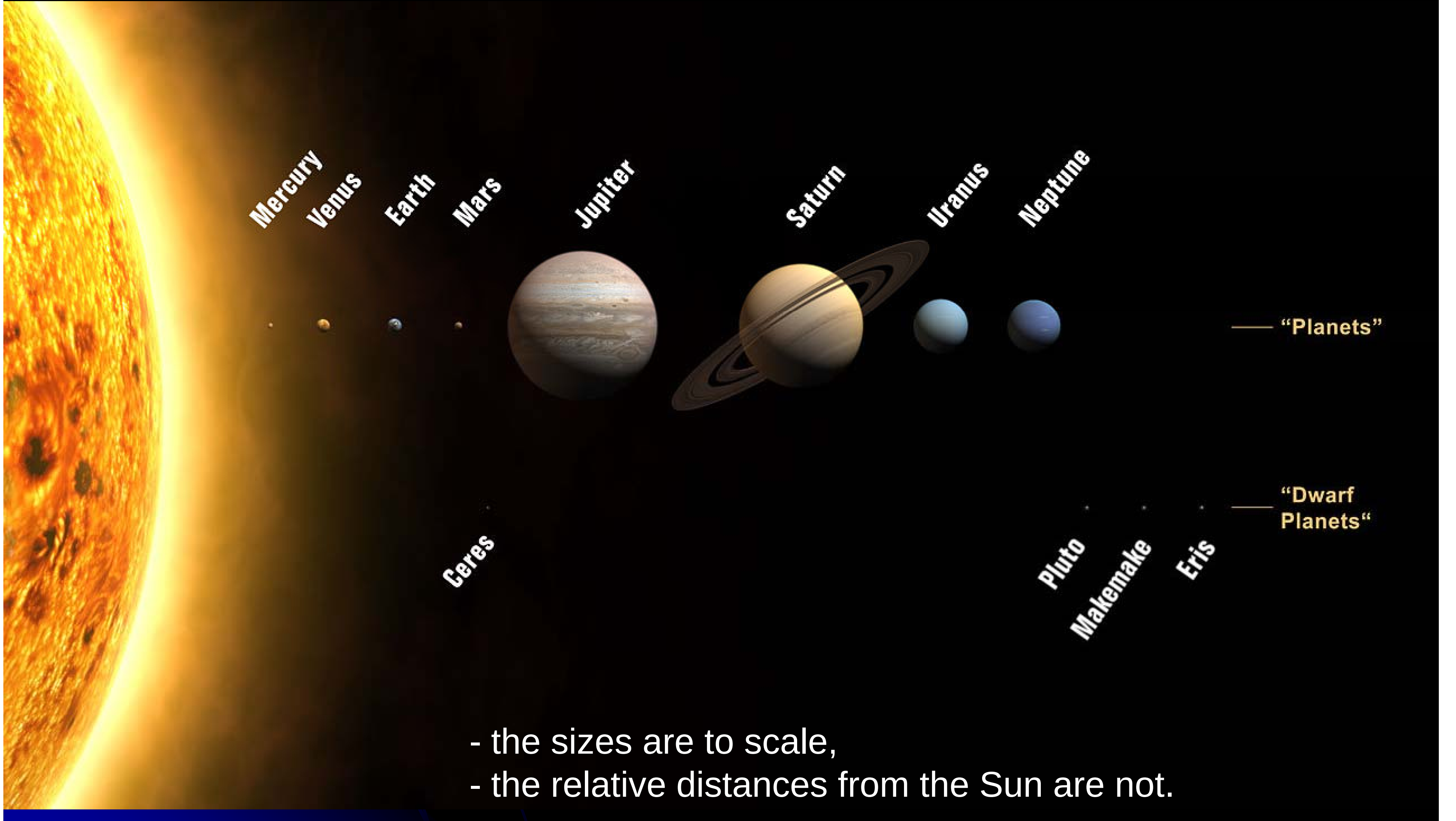
Relative sizes of the planets as compared to the Sun

SUN: 99% of the total mass

- The Sun is a middle-aged, average-sized star.
  - Mostly Hydrogen & Helium
  - Contains 99.8% the mass of the Solar System
  - about 4.6 Gyr old
- The Sun shines because it is hot:
  - Surface (photosphere) is ~6000 K
  - Radiates mostly Visible light plus UV & IR
- Kept hot by nuclear fusion in its core:
  - Builds Helium from Hydrogen fusion.



The Planets of the Solar System (Chemical Composition)



- the sizes are to scale,
- the relative distances from the Sun are not.

Groups of Planets

Terrestrial Planets: Mercury, Venus, Earth, Mars

Mostly rock, radii of several thousand kilometers, densities of ~5 grams/cc. These are the first 4 planets out from the Sun.

Jovian Planets: Jupiter, Saturn, Uranus, Neptune

Radii of tens of thousands of kilometers, densities of 0.7-1.76 grams/cc composition similar to the Sun but with extra "heavy" elements (carbon, oxygen, nitrogen, etc.).

The Leftovers of Solar System:

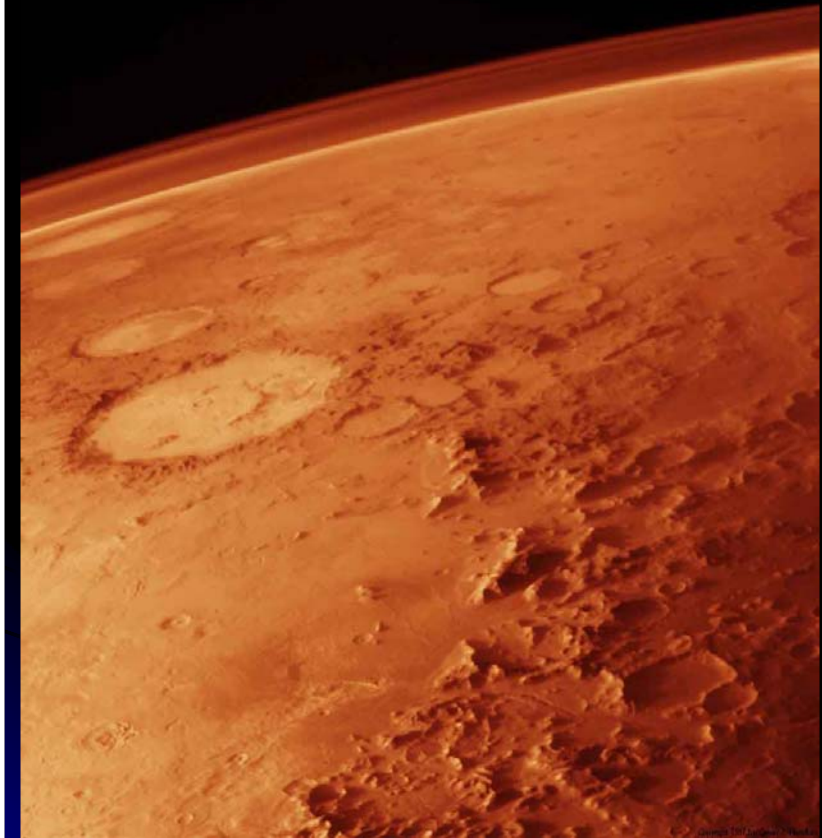
Comets, Asteroids, Kuiper Belt Objects, dwarf planets.

Radii from tens (or smaller) to hundreds of kilometers. Density ~ 0.5-2 grams/cc (with exceptions). Composed of ice and rock.

Composition Trends

Body	Rocky(%)	Icy(%)	Gaseous(%)
Sun			98.5 (100%)
Terrestrial Planets	70	30	0
Jupiter	2	5	93
Saturn	6	14	80
Uranus	25	58	17
Neptune	27	62	11

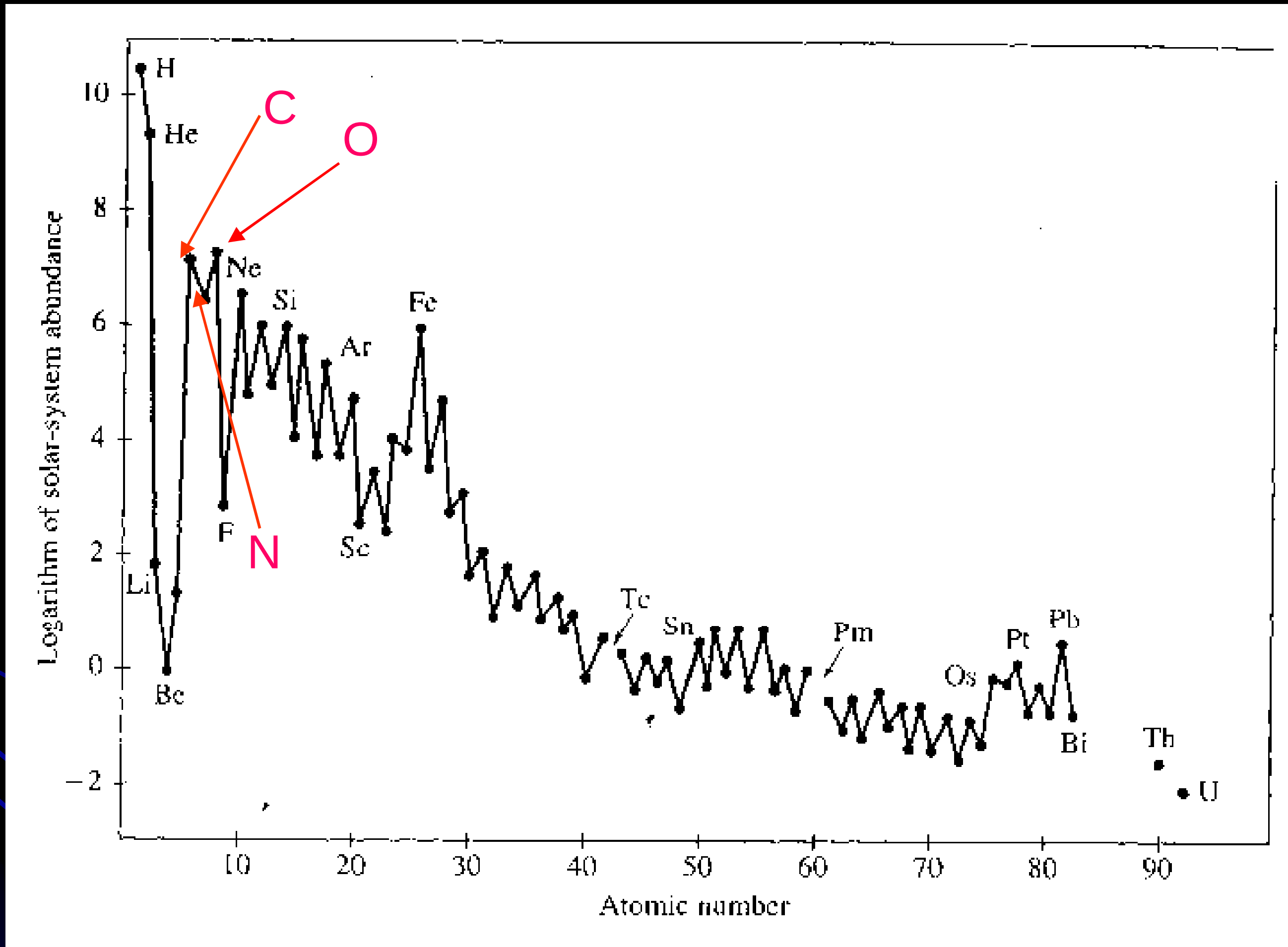
Inner vs Outer Planets



Mars

Jupiter

Composition of the Solar System

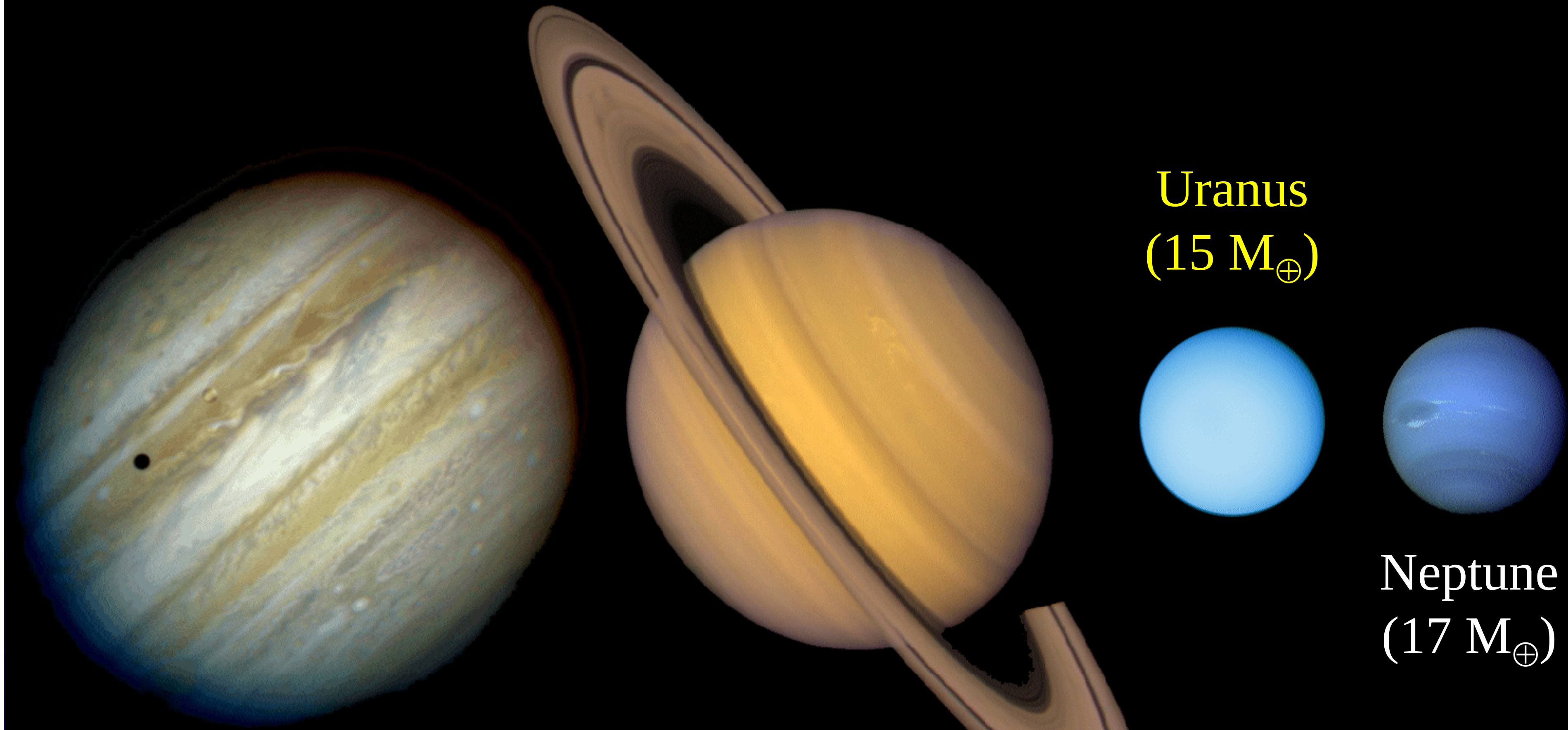


Composition of the Solar System

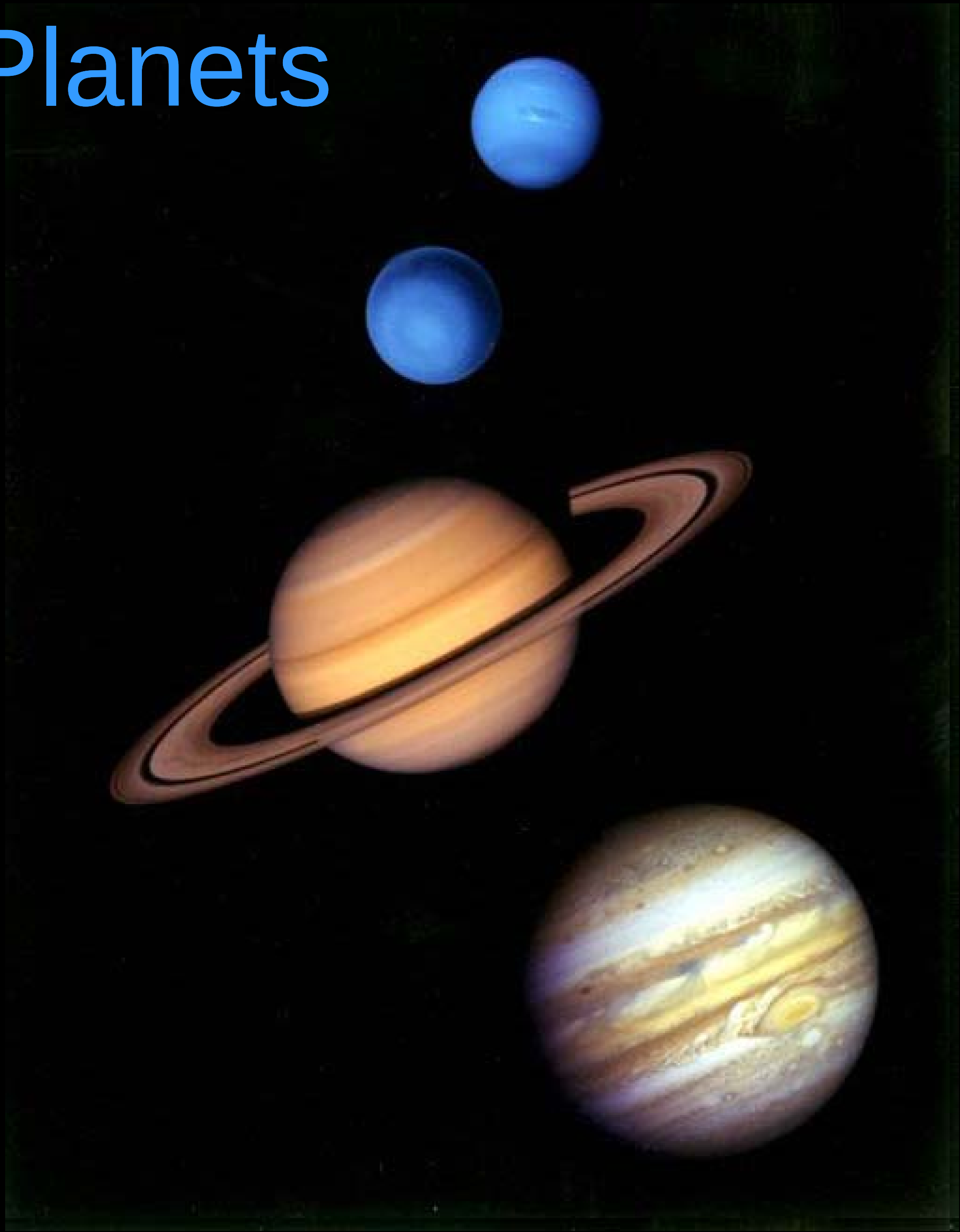
Astronomers classify materials according to their tendency to exist as gases, ices, or rocks at Earth-like temperatures and pressures.

- Gases: Elements - H, He, Ar, Ne, noble gases.
  Molecules - H_2, He, Ar, Ne, …
- Ices: Elements – O, C, N.
  Molecules – H_2O, CH_4, NH_3, CO, CO_2, …
- Rocks: Elements, Fe, Si, O, Mg, Ni, …
  Minerals – Silicates, Sulfides, Metals, …

The Jovian Planets

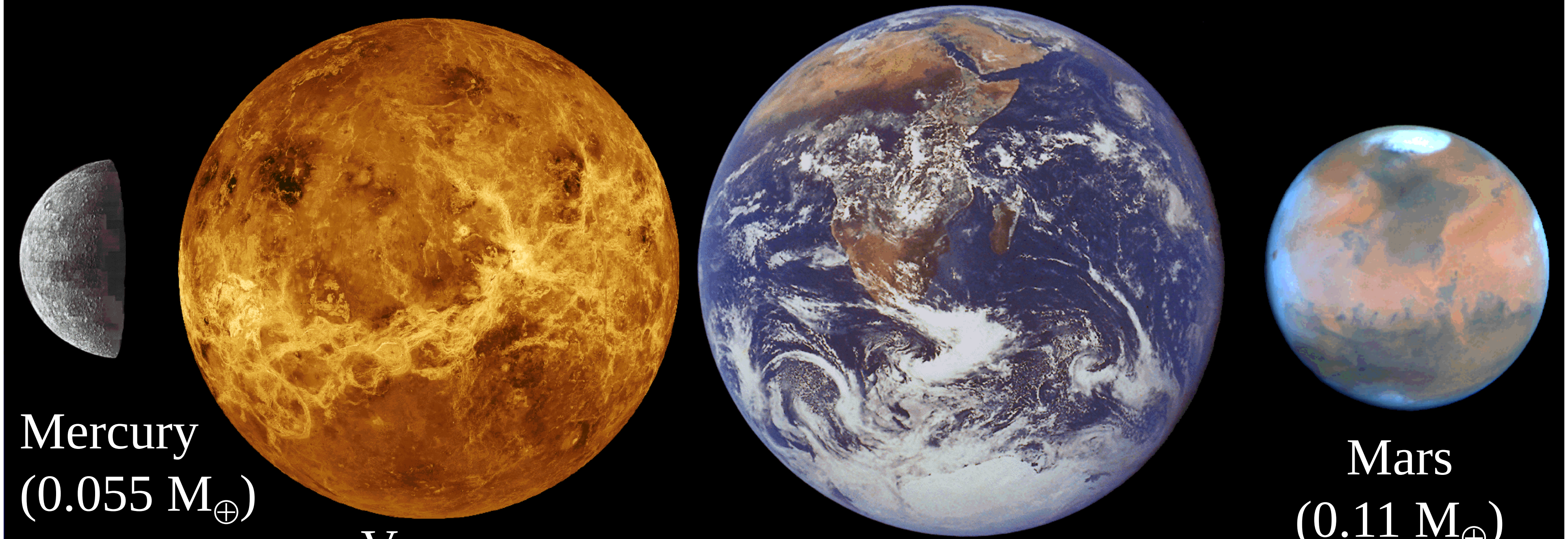


The Jovian Planets



- *Jupiter, Saturn, Uranus & Neptune*
  - Large Mass, Large Radius
  - Largest Planets: at least 15 times mass of Earth.
  - Jupiter, largest, is 318 Earth Masses
  - Only in the outer solar system (5 to 30 AU)
- <u>Gas Giants</u> ("Jupiter-like"):
  - Gaseous composition, low density
  - No Solid Surfaces (mostly atmosphere)
  - Atmospheres (clouds): H, He, + molecules (H_2O, CH_4, NH_3)
  - Mostly Hydrogen & Helium
  - Rocky/icy inner cores
  - Low density: 0.7 to 1.7 g/cc (water is 1 g/cc)

The Terrestrial Planets



Mercury
(0.055 $M_\oplus$)

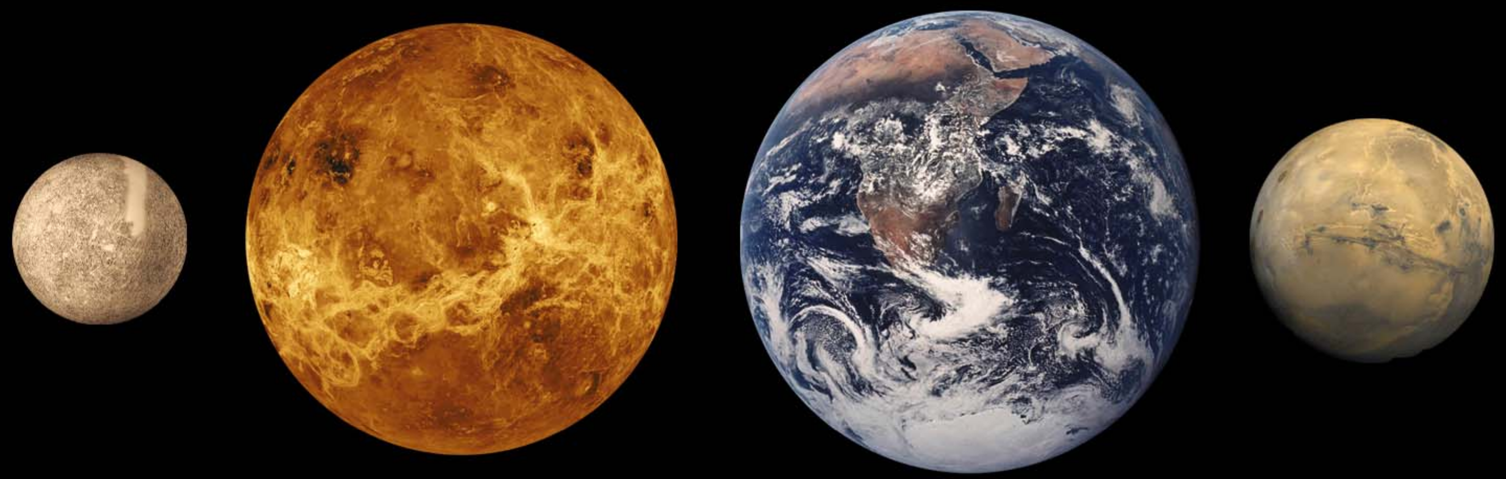
Venus
(0.82 $M_\oplus$)

Earth
(1 $M_\oplus$)

Mars
(0.11 $M_\oplus$)

Terrestrial Planets I

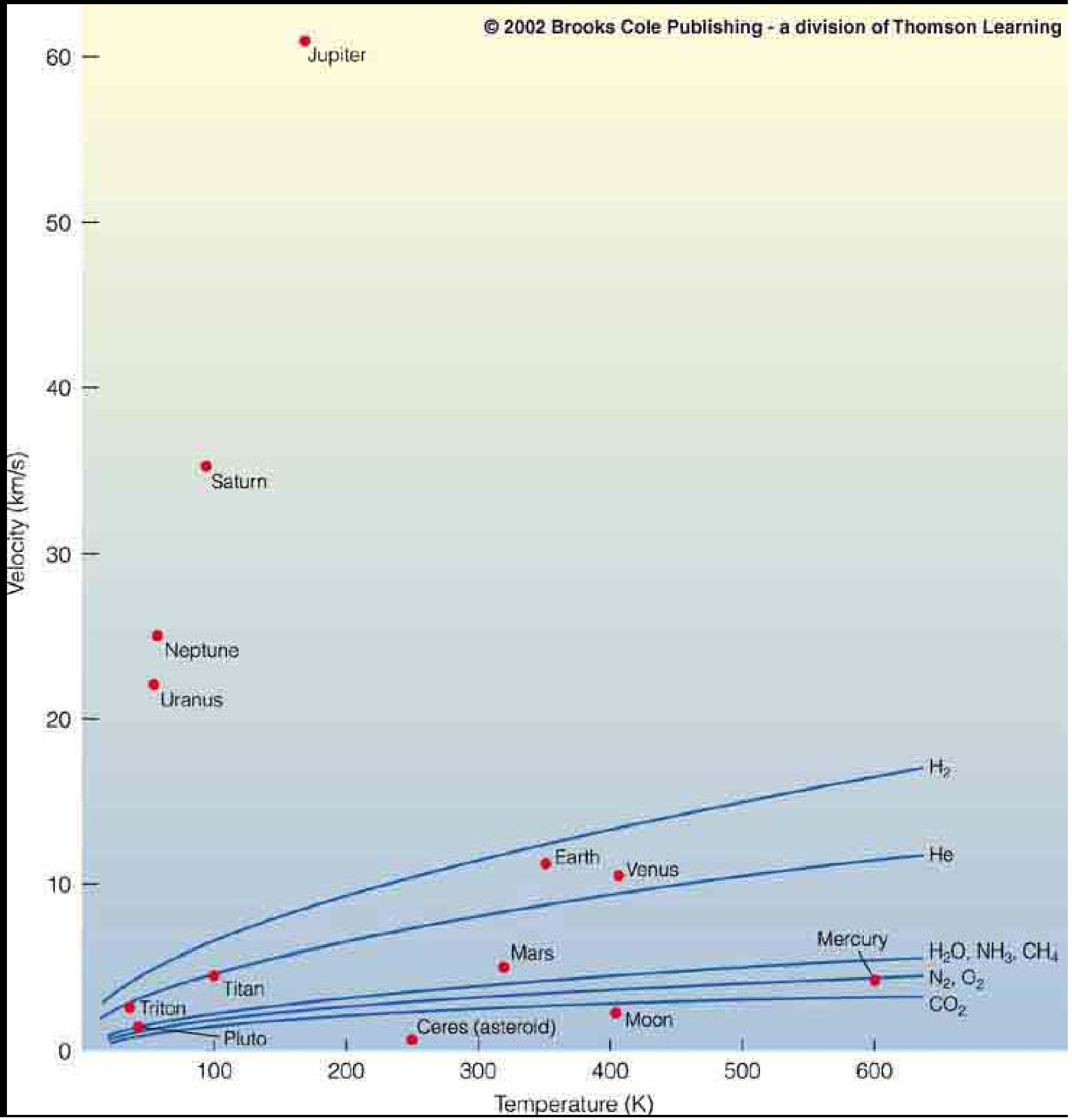
- *Mercury, Venus, Earth & Mars*
  - Small Mass, Small Radius
  - “Earth-Like” Rocky Planets
  - Largest is Earth
  - Only in the inner solar system (0.4 to 1.5 AU)
- Rocky Planets:
  - Solid Surfaces
  - Mostly silicates and iron
  - High Density: 3.9-5.5 g/cc (rock & metal)
  - Earth, Venus, & Mars have atmospheres
  - Atmospheres - large molecules - CO_2, H_2O, O_2, N_2



Planet Atmospheres

Escape velocity of the planets
vs.
Highest velocities of molecules

- Average energy (½mv2) of molecules ~ temp
- lighter molecules therefore move faster
- In a gas there is a wide range of molecular speeds (Maxwell distribution)
- a significant number of molecules travel at more than10 times the average speed
- if they reach the escape velocity without colliding any more, they will escape
- The Earth has lost its primitive H2 and He

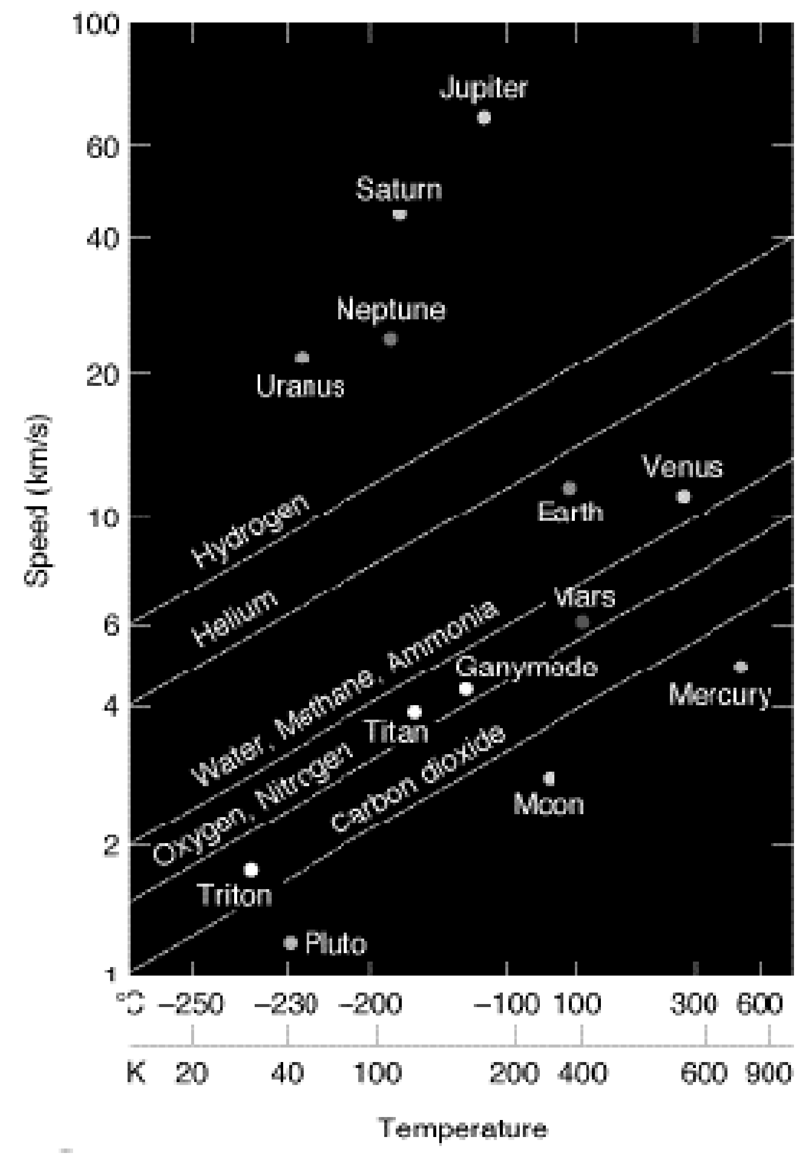


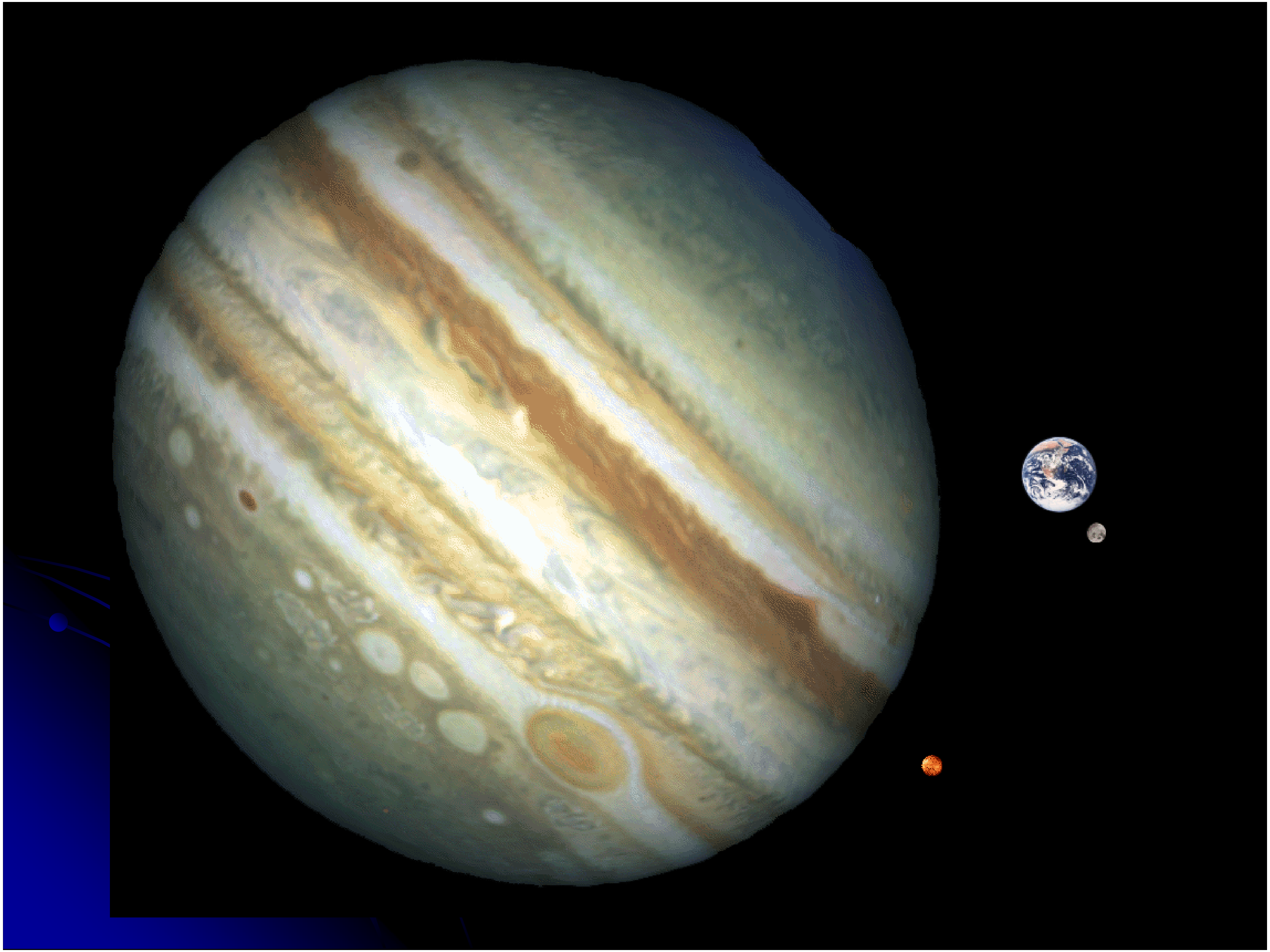
Planet Atmospheres

Escape velocity of the planets
vs.
Highest velocities of molecules

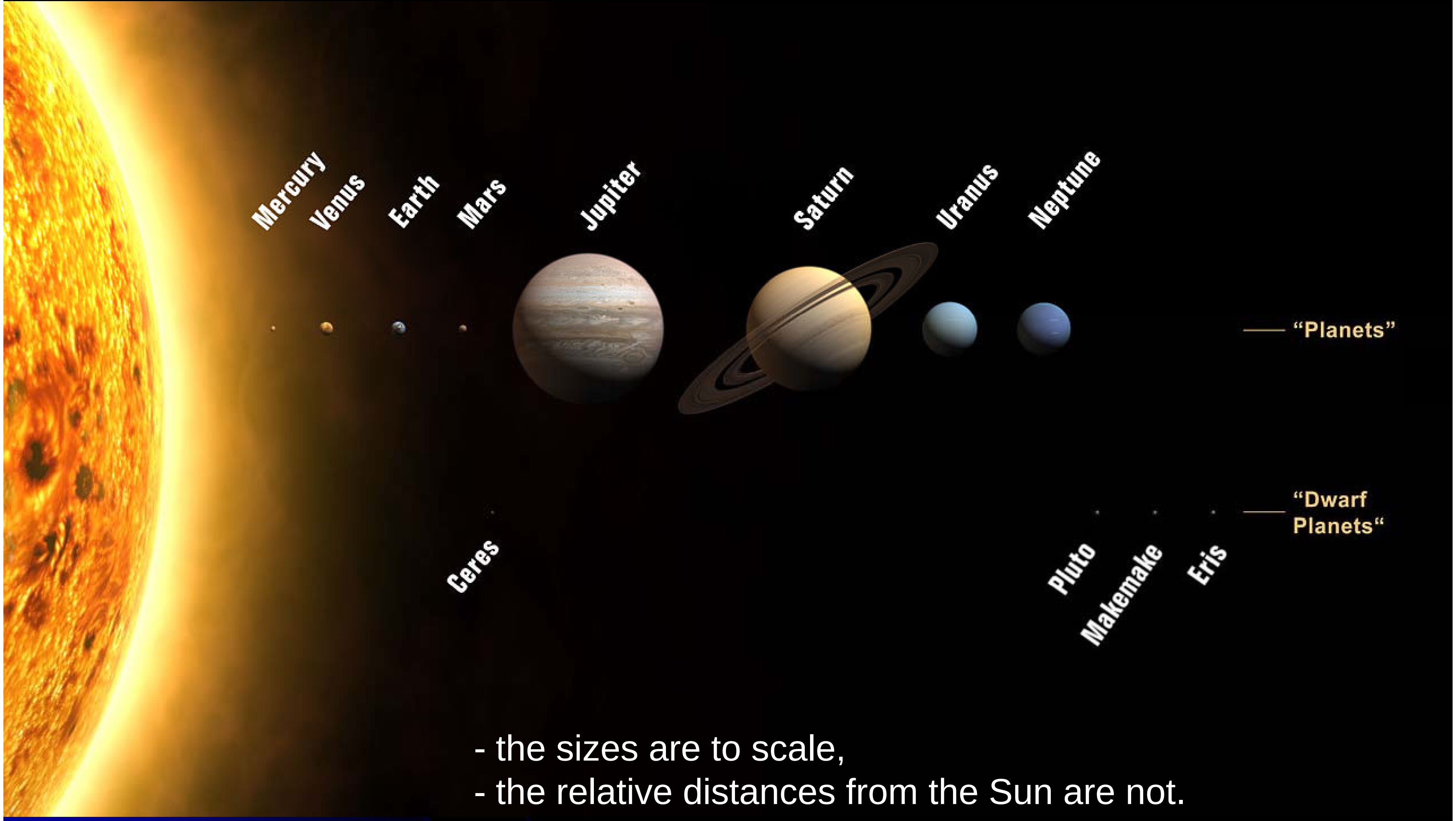
How Molecular Speeds Depend on Temperature

Each planet is plotted at its atmospheric temperature and escape velocity





The Planets of the Solar System (Internal Structure)



- the sizes are to scale,
- the relative distances from the Sun are not.

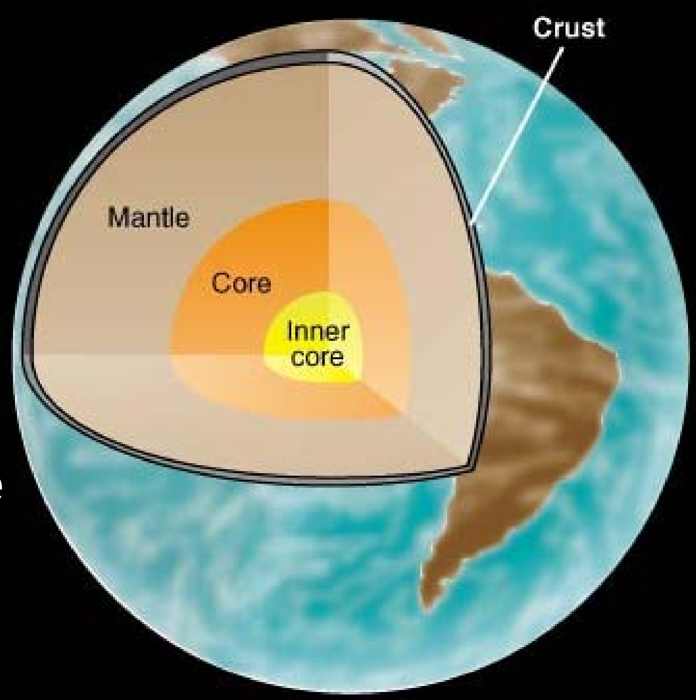
The Terrestrial Planets

- Terrestrial planets (Mercury, Venus, Earth, and Mars) seem to have experienced a similar early history, with extensive volcanism, cratering, and internal differentiation
- Each has a metallic core and a silicate mantle crust, and shows evidence of continuing lava flows and meteorite impact
- Outgassing produced an atmosphere as light gases from the interior rose to the surface during volcanism

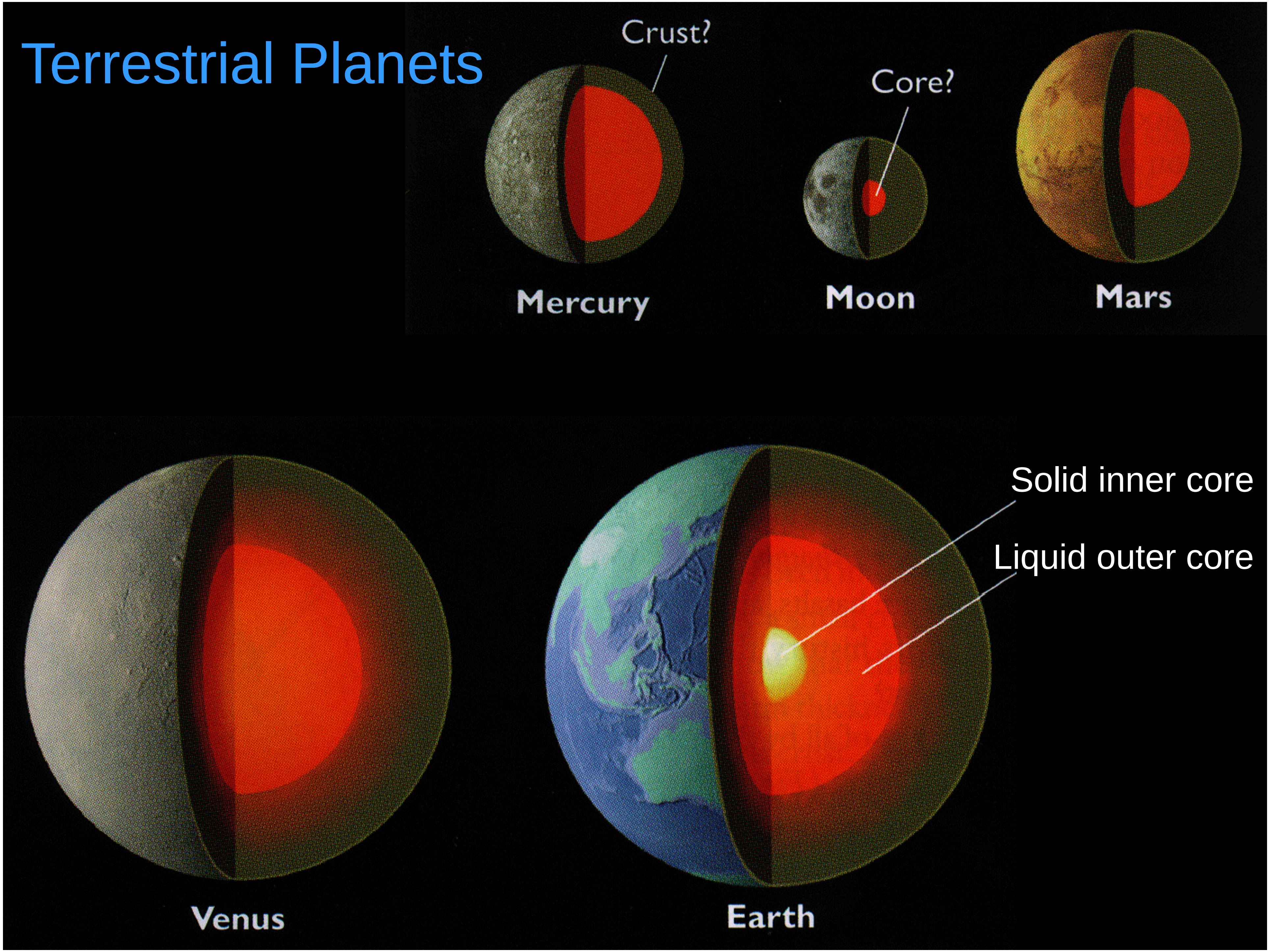
Composition of the Earth Interior

Fraknoi/Morrison/Wolff, Voyages Through the Universe, 2/e
Figure 7.2 The Interior Structure of the Earth

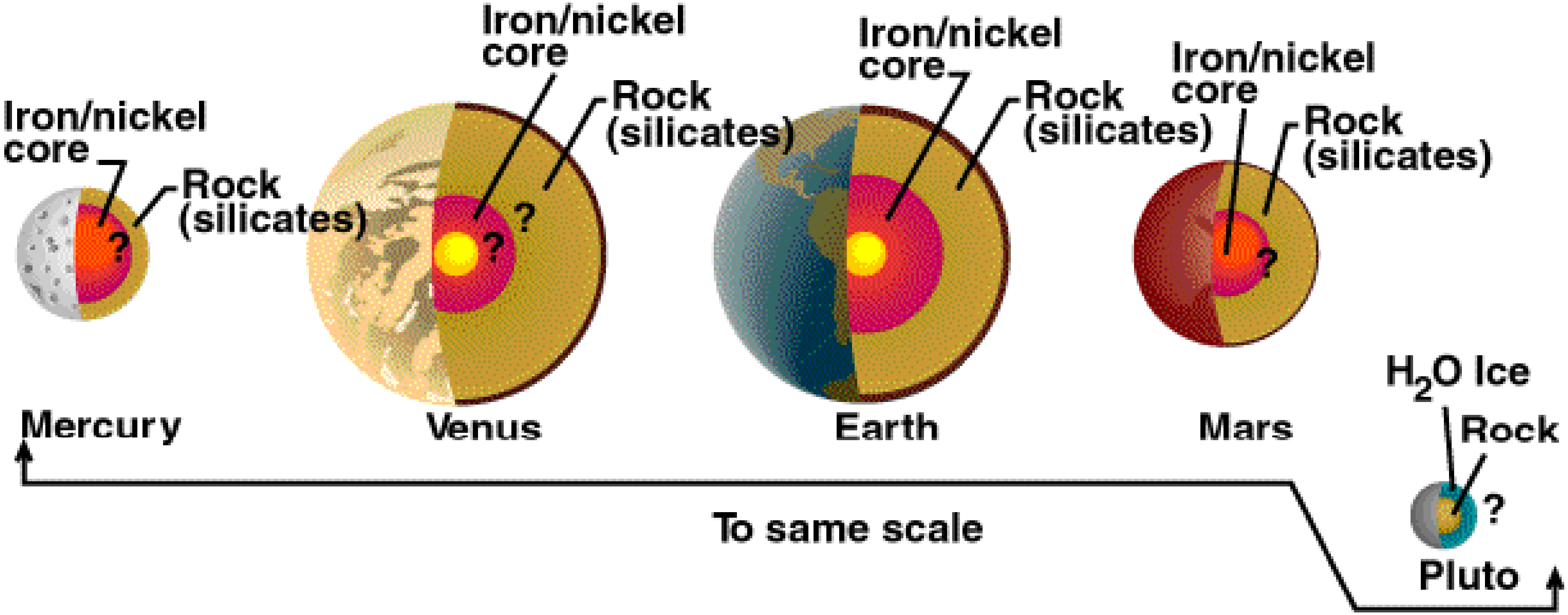
- Crust (5-50 km)– composed of basalts and granites
- Mantle 3500<R<6400 km– mostly solid though deformation of mantle occurs due to increasing temperature and pressure with depth (magma,plastic)
- Outer Core 1300<R<3500km – made of liquid iron and responsible for the Earth's magnetic field
- Inner Core R<1300 km – probably solid due to higher pressures



Terrestrial Planets

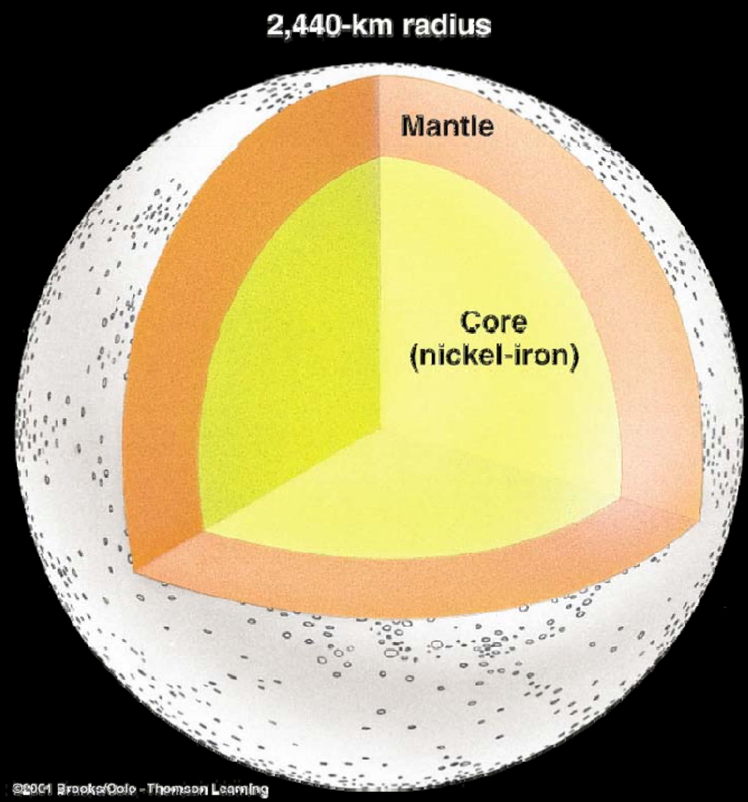


Cut Aways of Planets



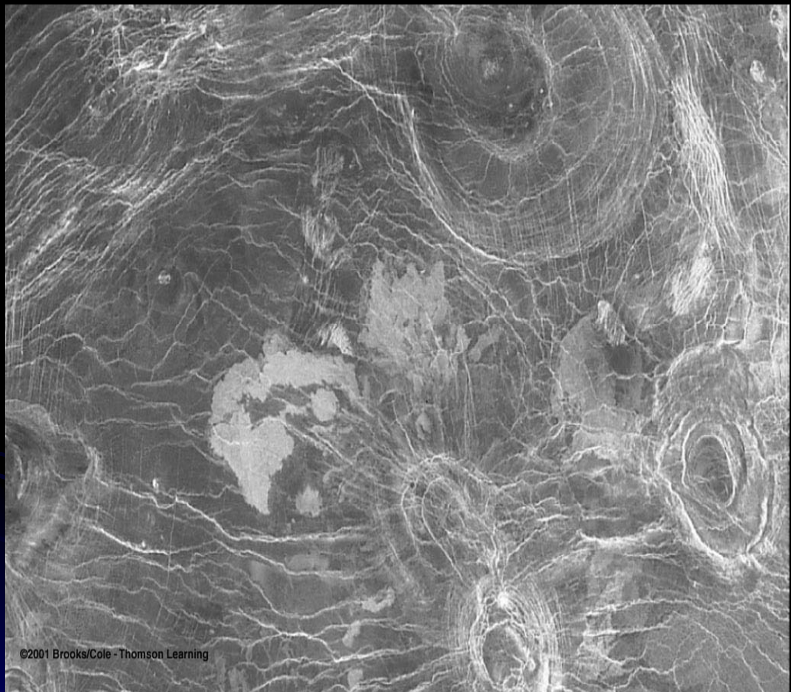
The Terrestrial Planets

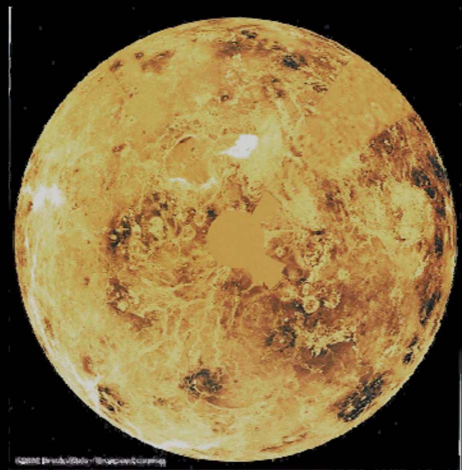
- Mercury
  - heavily cratered
  - large metallic core
  - little tectonic activity
  - no atmosphere



The Terrestrial Planets

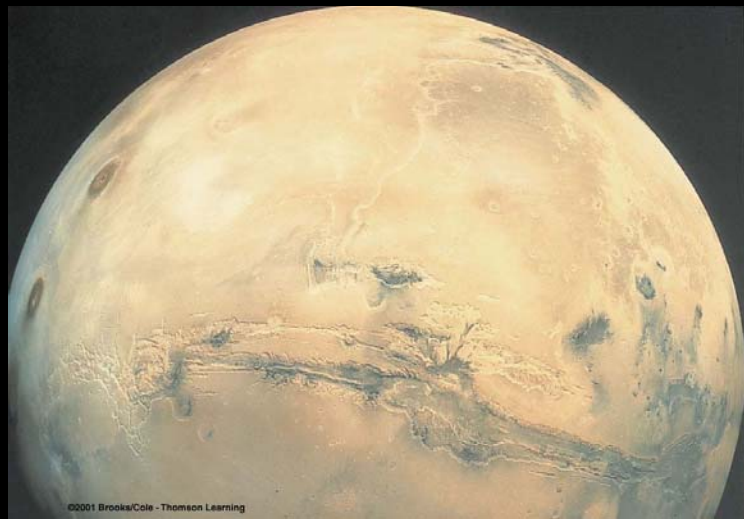
- Venus
  - similar in size and mass to Earth
  - extremely hot surface
  - 96% CO_2 atmosphere
  - sulfuric acid cloud layers
  - lava flows and folded mountain ranges have been observed





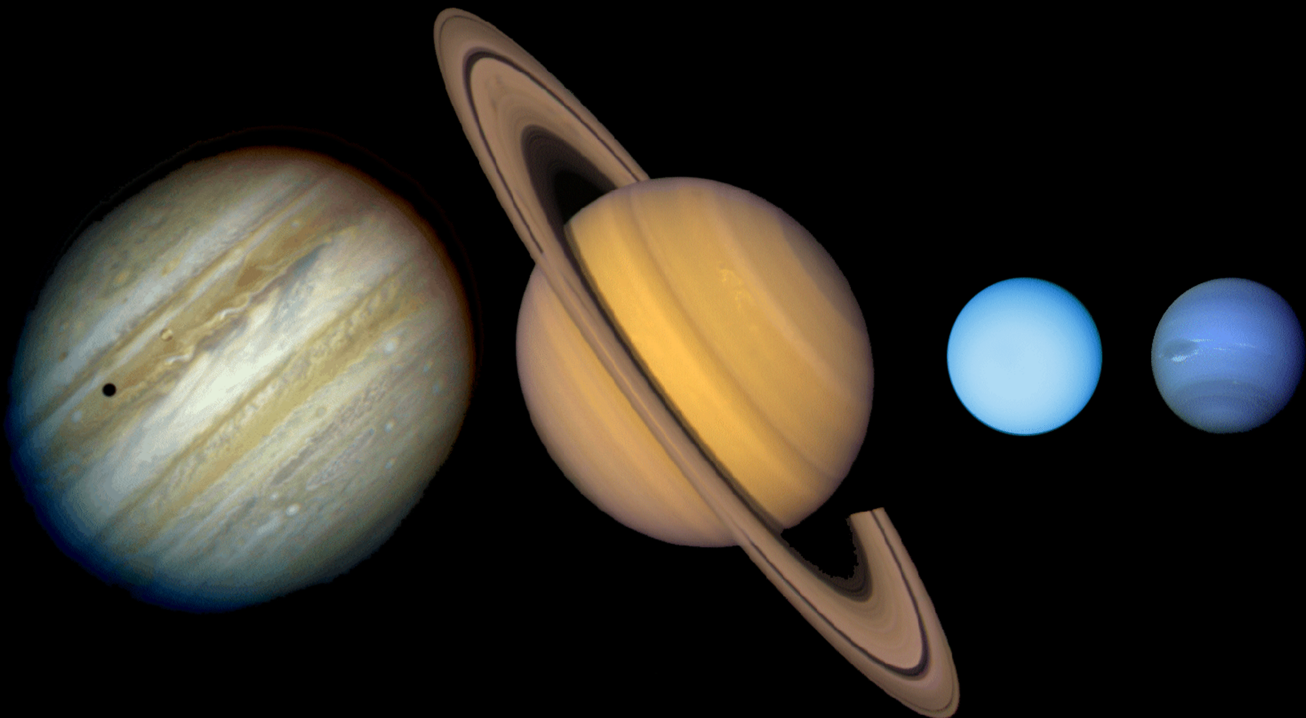
The Terrestrial Planets

- Mars
  - thin atmosphere of mostly CO_2
  - polar ice caps
  - evidence of extensive volcanism, cratering, and water movement
  - largest crater, volcano, and canyon in the solar system



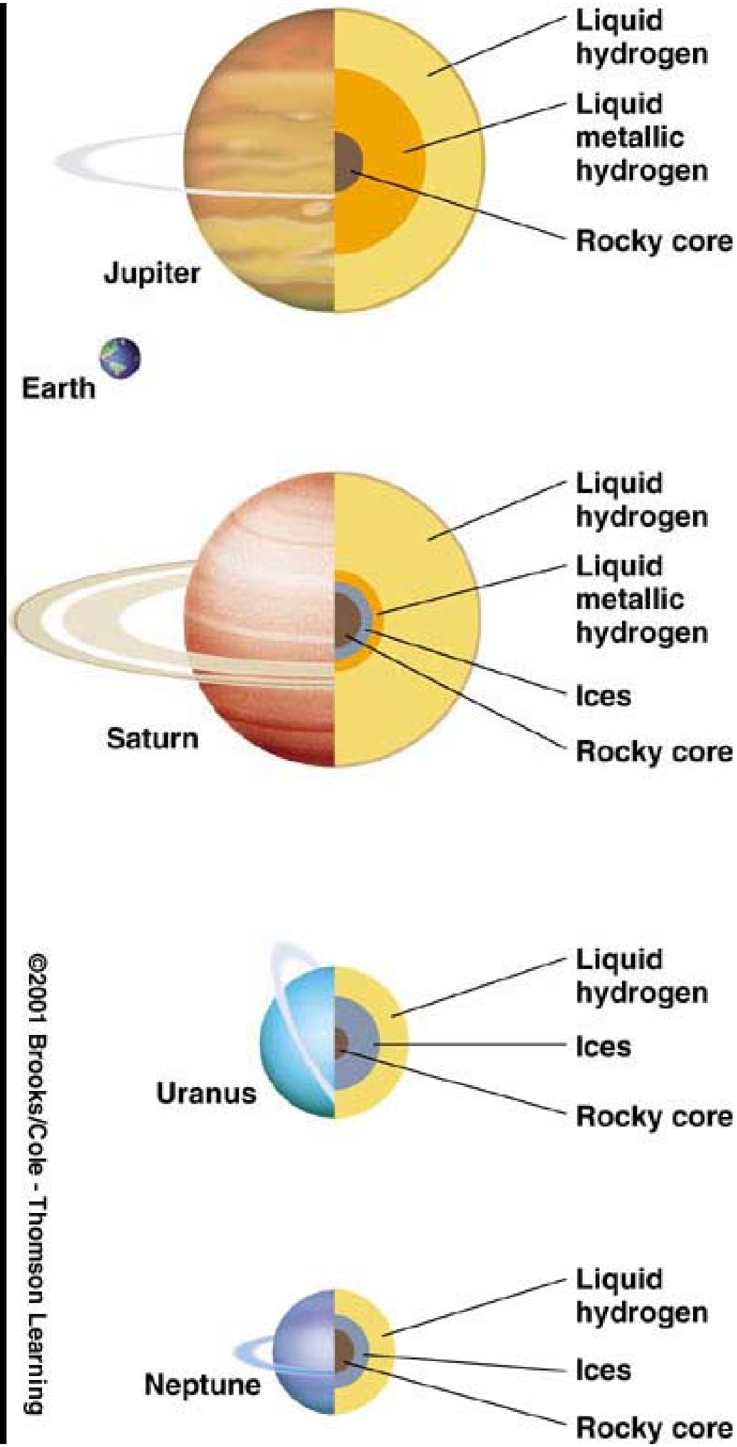
The Jovian Planets

- The four outer planets, or gas giants (sometimes called Jovian planets), collectively make up 99 percent of the mass known to orbit the Sun.
- Jupiter and Saturn consist overwhelmingly of hydrogen and helium;
- Uranus and Neptune possess a greater proportion of ices in their makeup.
- Some astronomers suggest they belong in their own category, “ice giants”.
- All four gas giants have rings, although only Saturn's ring system is easily observed from Earth.

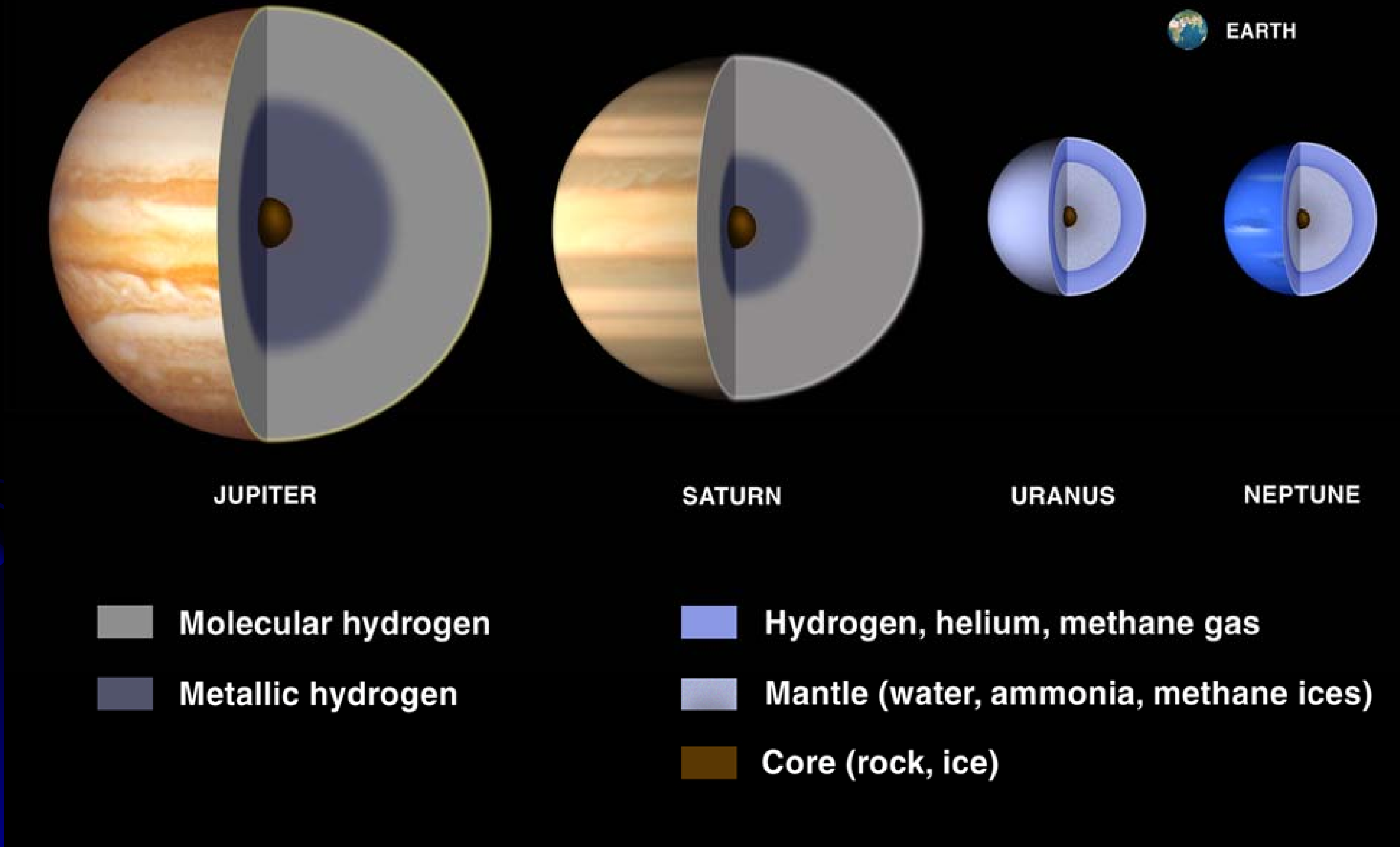


The Jovian Planets

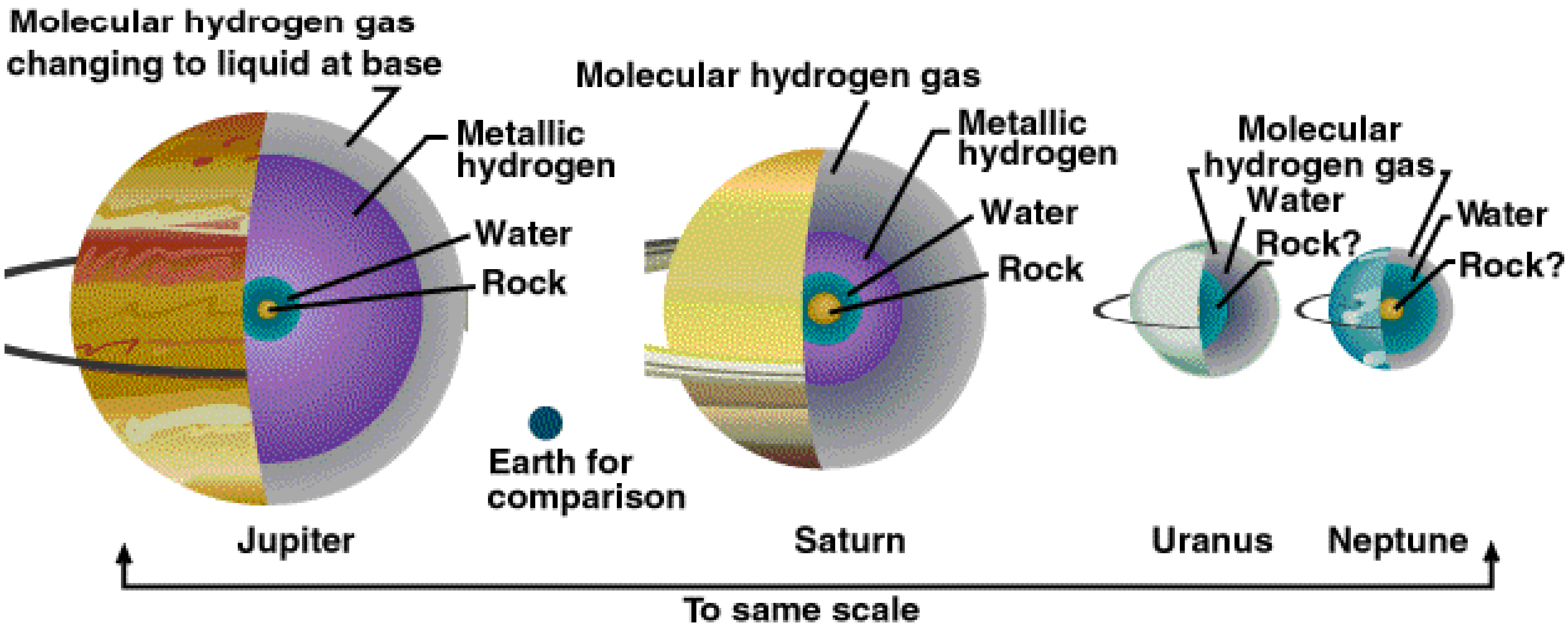
- Jupiter
  - largest of the Jovian planets, most complex of all
  - dense, hot atmosphere of H, He, and other gases
  - 16 moons
- Saturn
  - smaller than Jupiter, but similar internal structure and atmosphere
  - ring system consisting of thousands of spiraling bands of countless particles
  - 18 known moons
- Uranus
  - much smaller than Jupiter, but densities are about the same
  - lies on its side - rotational axis is nearly parallel to the ecliptic
  - faint rings and 18 small moons
- Neptune
  - similar atmosphere as other Jovians, with zonal winds and storm systems
  - three faint rings, 8 moons



Interiors of Jovian Planets: cross-cuts



Cut Aways of Planets



The Giant Moons

- Natural satellites orbiting planets.
- Giant Moons:
  - Earth: The Moon
  - Jupiter: Io, Europa, Ganymede, & Callisto (the Galilean moons)
  - Saturn: Titan
  - Neptune: Triton
- Many smaller moons, both rocky & icy.
- Only Mercury & Venus have no moons.

The Giant Moons

Medium & large moons

Moons (Satellites):

- Large R> 1500 Km
- Small R< 400 Km
- Medium others
- Formed in orbit around jovian planets.
- Circular, equatorial orbits in same direction as planet rotation.
- Terrestrial Planets: small number of moons
- Mercury and Venus: no moons
- Mars: two asteroids - Phoebes and Deisms

Small Icy Bodies

- Pluto is the largest of a class of icy bodies:
  - Found only in the outer solar system
  - Densities of 1.2 to 2 g/cc (like ices)
- Examples:
  - Triton, large moon of Neptune
  - Charon, Pluto's large moon
  - Trans-Neptunian Objects (Kuiper Belt Objects & Plutinos)

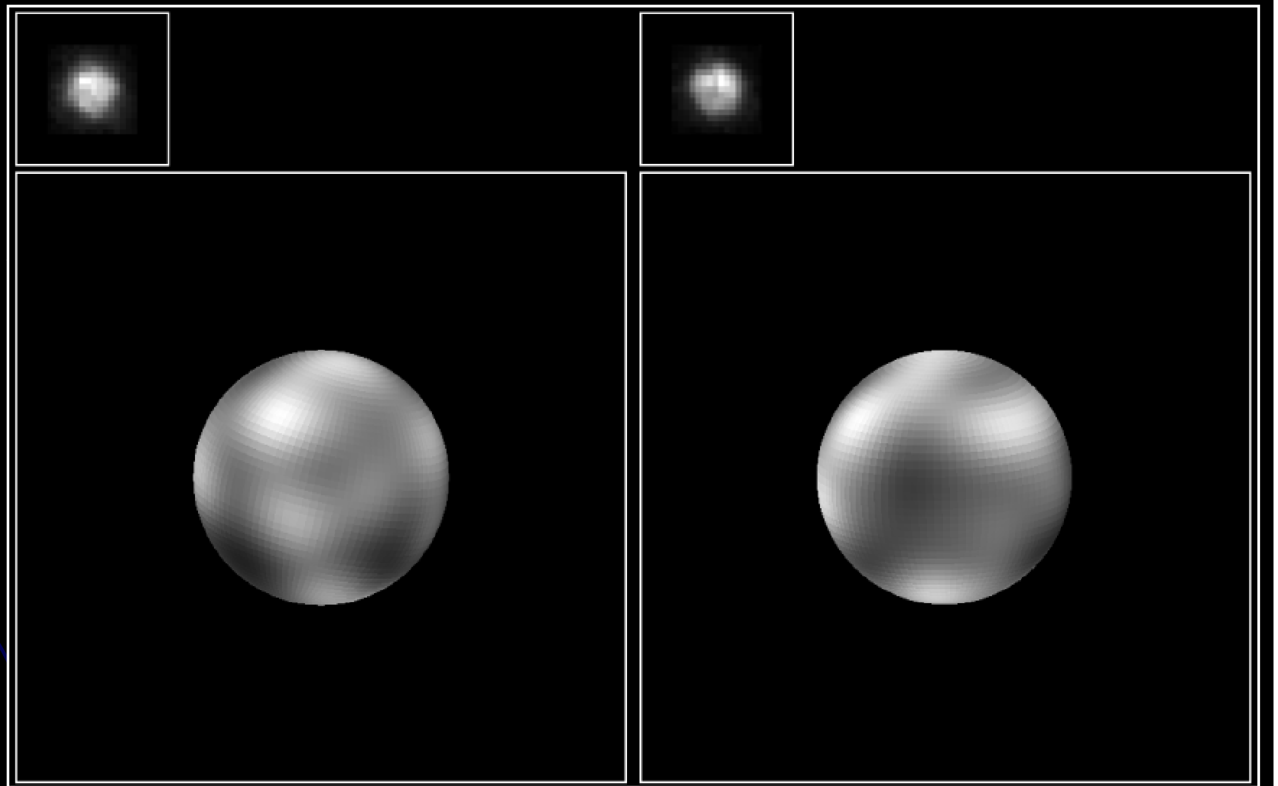
Distant Pluto

Charon

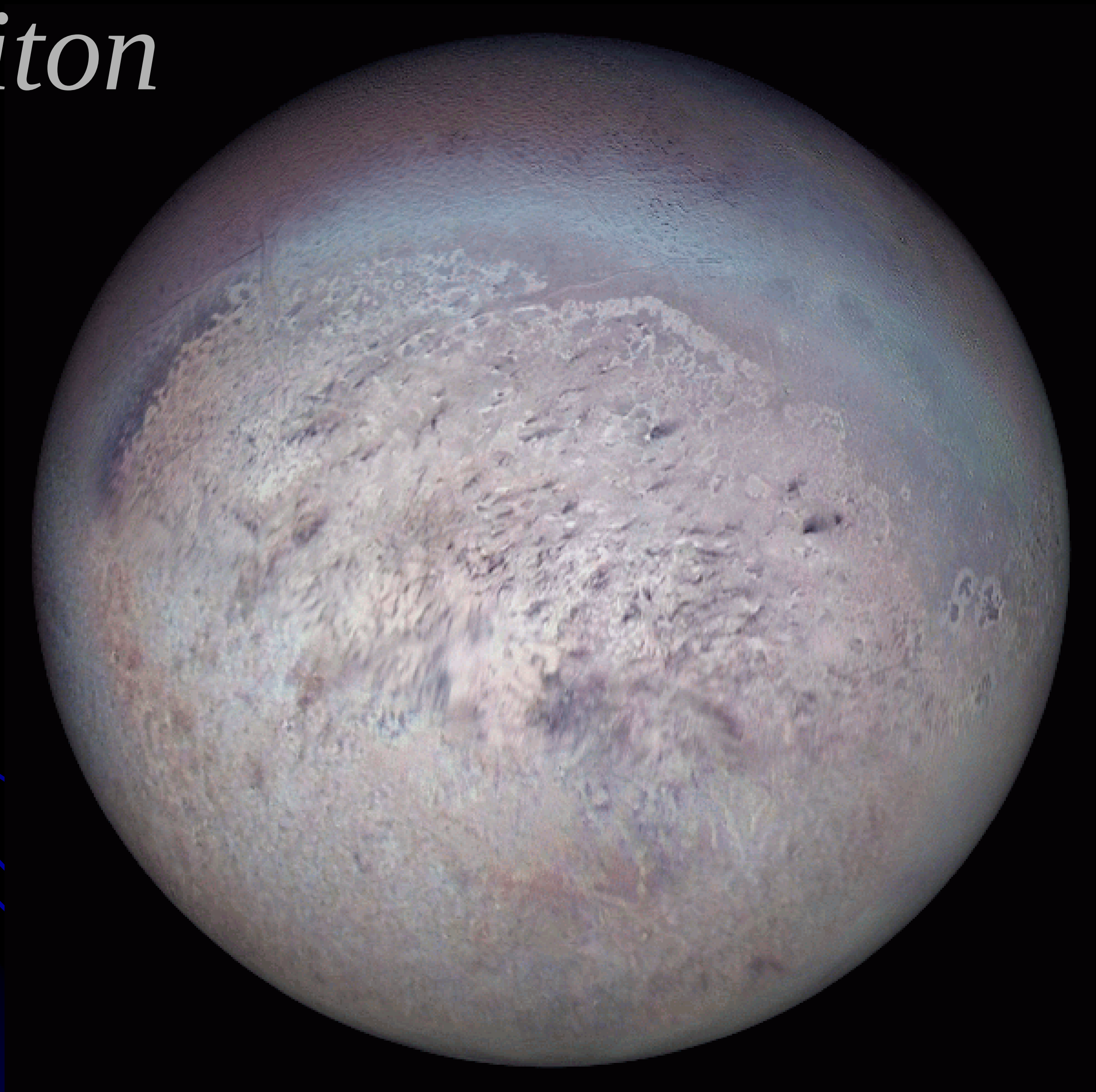
Pluto's Moon

Pluto

Hubble Reconstruction of Pluto



Triton



Minor Bodies (The Leftovers)

- Asteroids (Asteroid Belt):
  - Range from 500km (Ceres) to large boulders
  - Made of rock (density 2-3 g/cc)
- Comets (Oort Cloud & Kuiper Belt):
  - Composite rock & ice “dirty snowballs”
  - Longs tails of gas & dust are swept off them when they pass near the Sun.

Asteroids

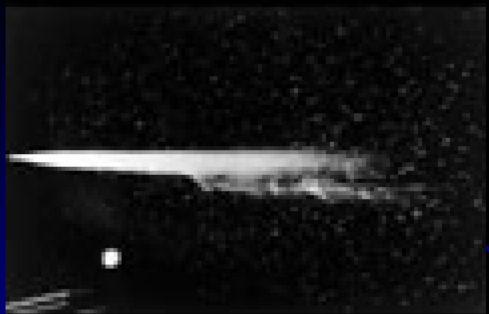
951 Gaspra

253 Mathilde

243 Ida

COMETS

Comets are sometimes called **dirty snowballs** or "icy mudballs".
They are a mixture of ices (both water and frozen gases) and dust that for some reason didn't get incorporated into planets when the solar system was formed. This makes them very interesting as samples of the early history of the solar system.



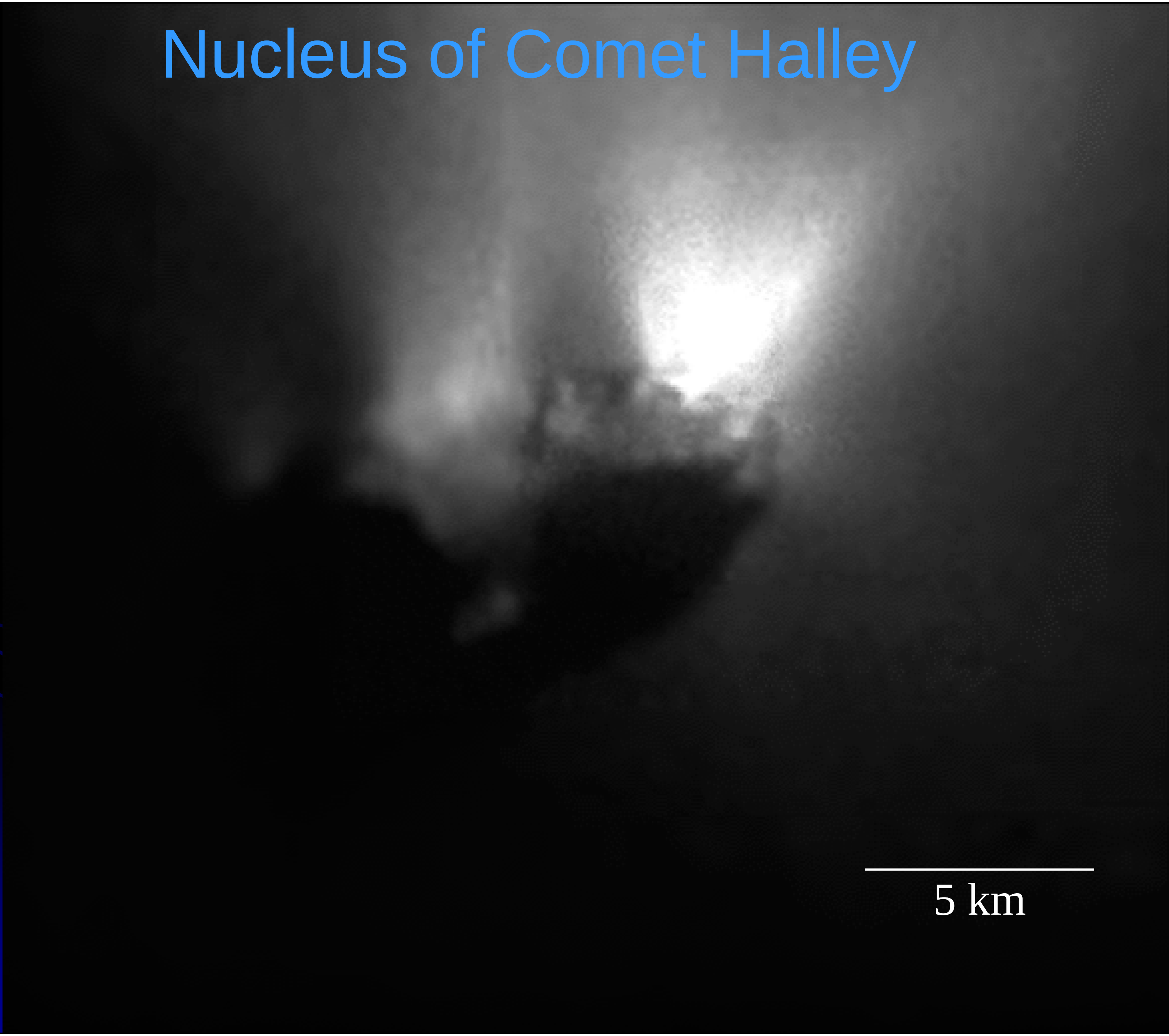
Comet Halley in 1910

Comets have elliptical orbits.

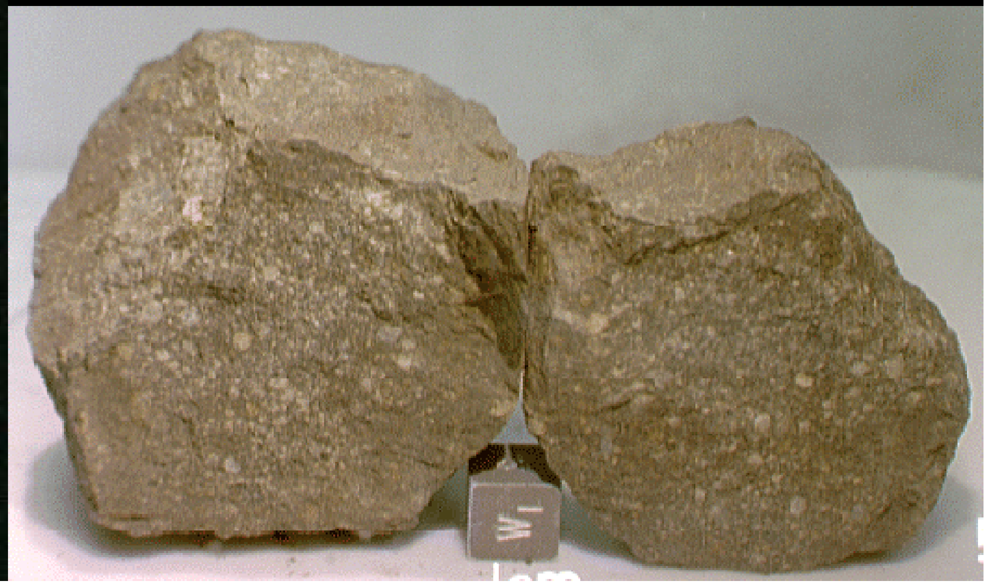
When we see a comet, we are seeing the tail of the comet as comes close to the Sun.

Comet Hale-Bopp

Nucleus of Comet Halley



Meteor burning up in the atmosphere.



Dynamics of the Solar System

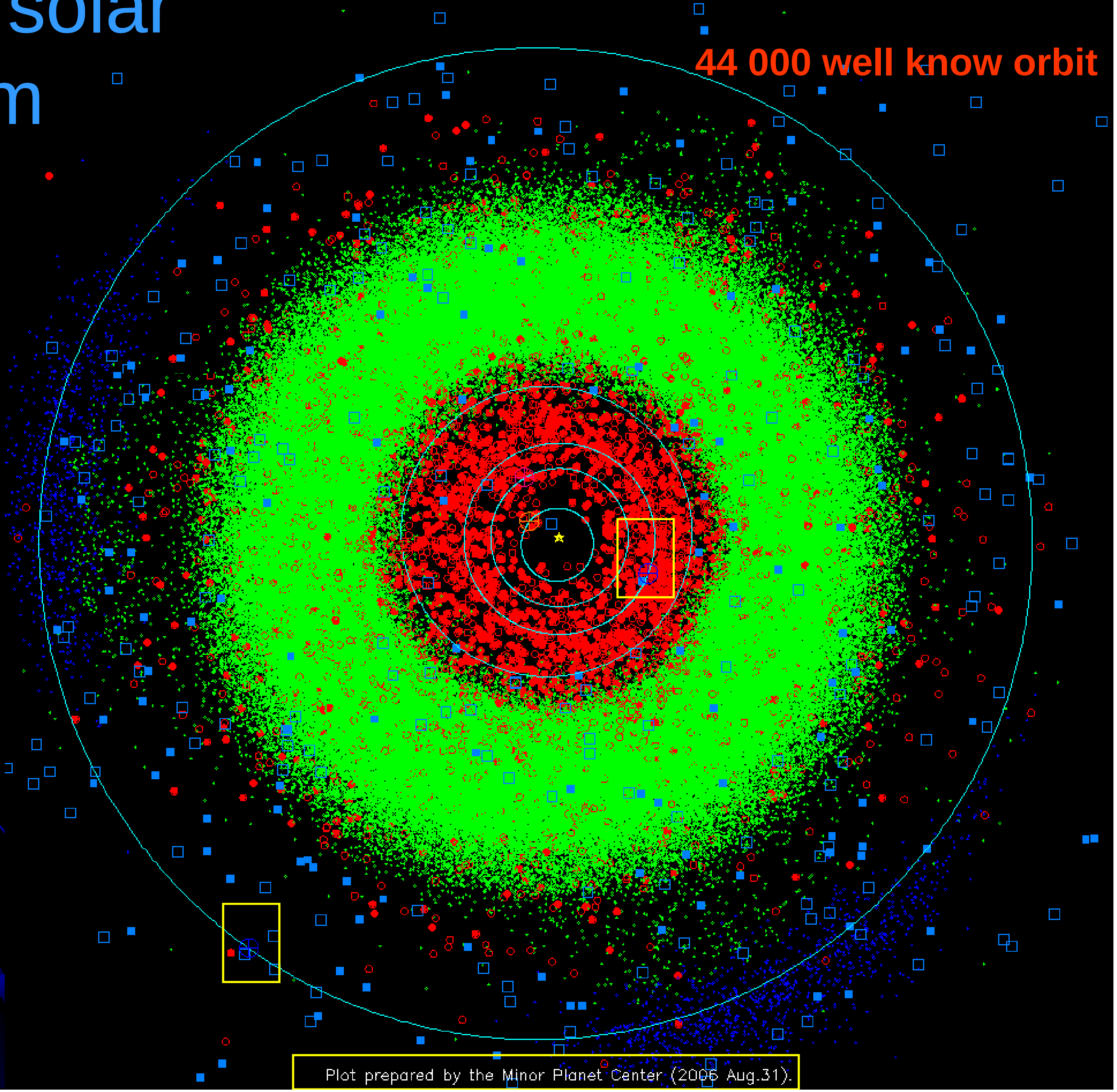
- Sun, containing 99.9% of mass
- 8 planets
- 15 moons over 1000 km in diameter
- ~ 200 smaller moons
- ~100,000 asteroids
- billions of potential comets
- billions of meteorites, meteoroids and debris
- solar wind
- magnetic field

The Inner solar System

http://cfa-www.harvard.edu/iau/lists/InnerPlot.html

Location of the minor planets that are in the inner region of the solar system.

- •Unnumbered objects: green circles.
- •Objects with perihelia within 1.3 AU: red circles.
- •Jupiter Trojans: deep blue - two "clouds" at 60° ahead and behind Jupiter (and at or near Jupiter's distance from the sun).
- •Numbered periodic comets: filled light-blue squares.
- •Other comets: unfilled light-blue squares.



The Inner solar System

http://cfa-www.harvard.edu/iau/lists/InnerPlot.html

- motion of objects in the inner- to mid-region of the solar system over a two-year period.
- objects out to the orbit of Jupiter and a little beyond.
- Jupiter and its orbit are now shown and the Jupiter Trojans, which orbit in the same orbit as Jupiter but roughly 60 degrees ahead or behind the planet, are colored blue.

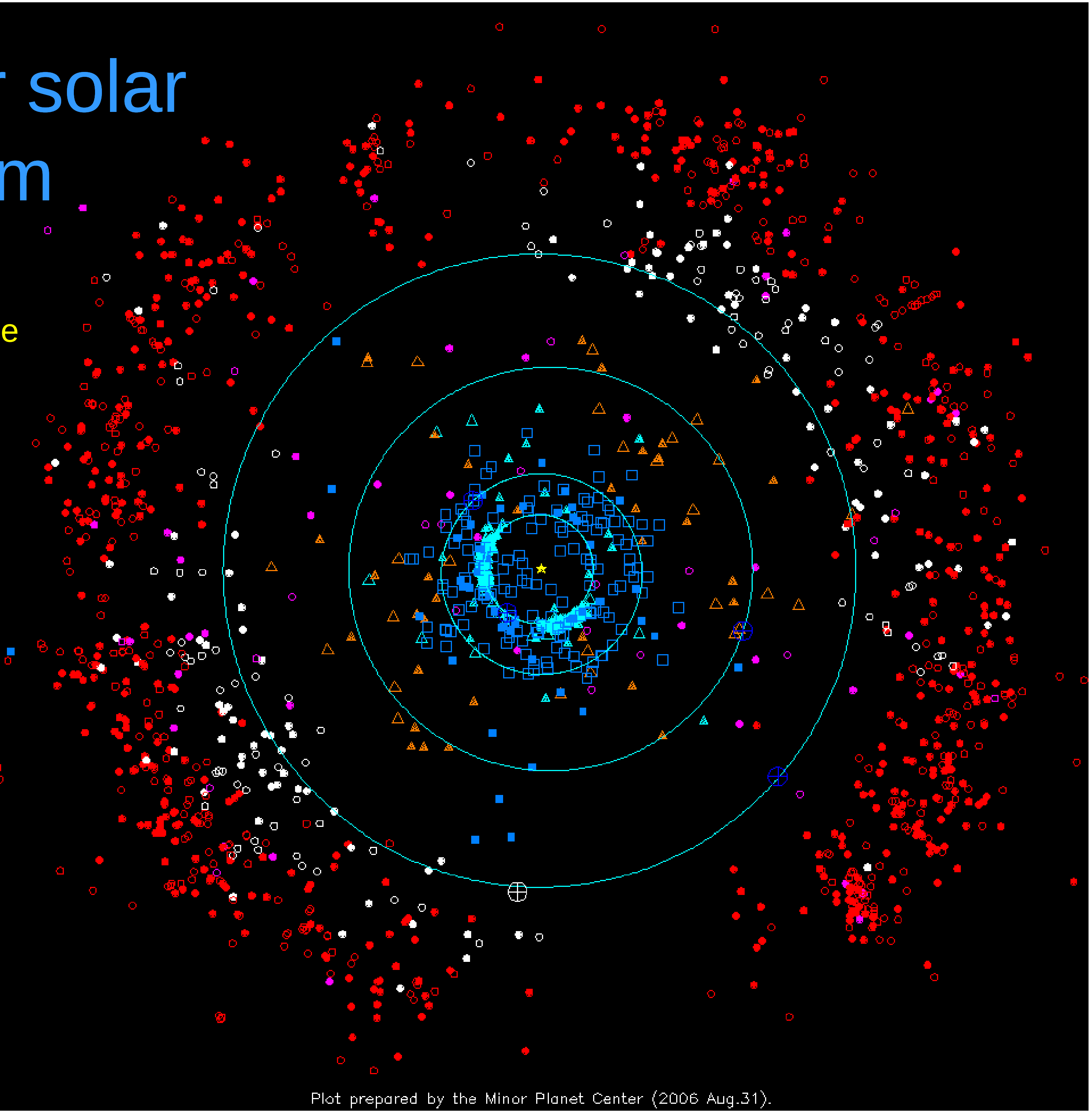
THE MIDDLE SOLAR SYSTEM

This animation shows the motion of the middle part of the solar system over a two-year time period. The sun is at the center and the orbits of the planets Mercury, Venus, Earth Mars and Jupiter are shown in light blue (the locations of each planet are shown as large crossed circles). Comets are shown as blue squares (numbered periodic comets are filled squares, other comets are outline squares). Main-belt minor planets are displayed as green circles, near-Earth minor planets are shown as red circles.

The individual frames were generated on an OpenVMS system, using the PGPLOT graphics library. The animation was put together on a RISC OS 4.03 system using !InterGif.

The Outer solar System

- The current location of the minor bodies:
- Unusual high-e objects: cyan triangles
- <u>Centaur objects</u>: orange triangles,
- Plutinos (resonance with Neptune): white circles
- Pluto: large white
- scattered-disk objects: magenta circles
- "classical" or "main-belt" objects: red circles.
- Numbered periodic comets: filled light-blue squares.
- Other comets: unfilled light-blue squares.



The Outer solar System

- motions of objects in the outer solar system beyond the orbit of Jupiter:
- The orbits and current locations of the Jovian planets.
- The current location of Pluto: large white crossed circle.
- High-eccentricity objects : cyan triangles
- Centaurs: orange triangles
- Plutinos :white circles,
- "Classical" TNOs: red circles
- Scattered-Disk Objects: magenta circles.

THE OUTER SOLAR SYSTEM

This animation shows the motion of the outer part of the solar system over a 100-year time period. The sun is at the center and the orbits of the planets Jupiter, Saturn Uranus and Neptune are shown in light blue (the locations of each planet are shown as large crossed circles).

Comets: blue squares (filled for numbered periodic comets,
outline for other comets)
High-e objects: cyan triangles
Centaurs: orange triangles
Plutinos: white circles (Pluto itself is the large white crossed
circle)
"Classical" TNOs: red circles
Scattered Disk Objects: magenta circles

The individual frames were generated on an OpenVMS system, using the PGPLOT graphics library. The animation was put together on a RISC OS 4.03 system using !InterGif.

The strange behavior exhibited by the comets (heading inwards - mid 1990s then heading outwards post 2000):
a consequence of plotting only those comets currently observable (as of mid 2002).

If the full cometary catalogue had been plotted, this effect would not be so noticeable as there would be inbound and outbound comets visible on each pre-2002 frame.

The Near-Earth Environment 2002

No objects are displayed that are more than 20 million km from the earth:
- Objects within one-third of this distance are colored red, objects within two-thirds are colored orange, other objects are green.
-Objects below the ecliptic plane are shown as outline circles, objects above as filled circles.

A Ride With the Earth

An animation centered on Earth showing the known objects that have approached to within 20 million km during 2002.
See the Animations Page on the MPC website for a description of the symbols used in this animation.

END