Comets, Asteroids, and Meteorites

Clues to the Origin of the Solar System

Is Pluto a Planet?

Introduction

- There is evidence that the small amounts of debris that we observe in our Solar System is a remnant of a previous era of intense bombardment that produced frequent impacts on all of the planets – the **Late Heavy Bombardment** (~4.1 billion years ago)
- Moon and Mercury for example, testify to this episode of intense cratering.
- Such bombardment was universal and hammered the Earth as well, later to be disguised by erosion and plate tectonics.
- The survivors of this original space debris, still exist today, in the form of asteroids, comets, and meteoroids.

The Tunguska Event was accompanied by an intense fireball, a series of deafening explosions heard up to 1000 km away, and trees felled radially within 30 km.

The 1908 Tunguska Event

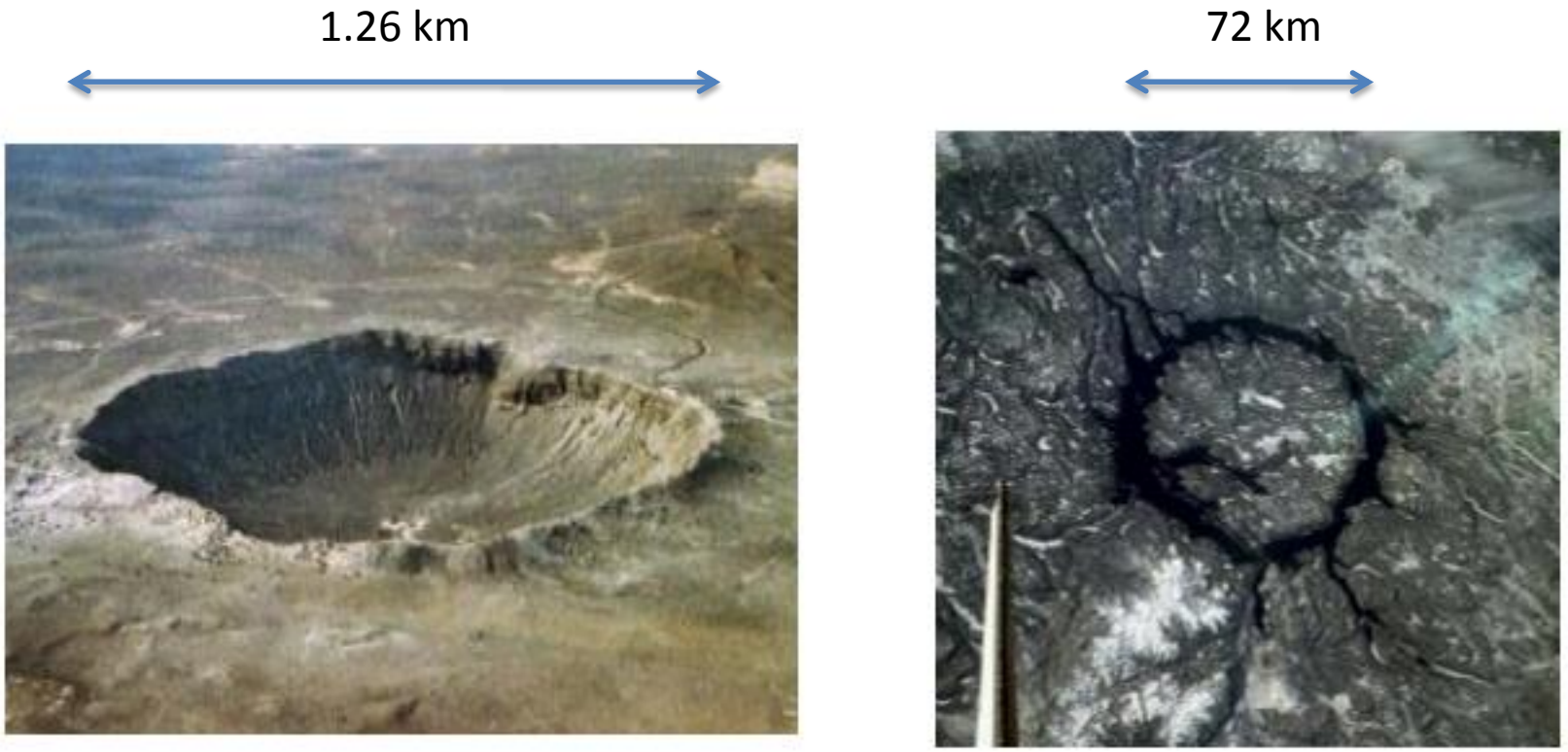
- First proposed that the Tunguska event was caused by the **collision between the Earth and a small comet**.
- **not a reasonable explanation** because an icy comet would have exploded too high in the atmosphere to produce the damage seen from the Tunguska event.
- consistent with the Earth **colliding with an 80-meter diameter, rocky meteoroid traveling at hypersonic speed, about 79,000 km/h.**
- Some **particles consistent in composition with meteoritic dust** were found embedded in tree resin at the impact site.
- **modeled the impact and found it consistent with the impact of a 70-meter diameter stony meteorite that exploded in the atmosphere.**

1969 Chihuahua Mexico Event

- **In 1969 hundreds of people watched while an intense blue-white light crossed the night sky near Chihuahua, Mexico**.
- punctuated by an explosion that showered the ground with hundreds of rocks, **carbonaceous chondrites,** all fragments of what is now known as the **Allende meteorite**.
- Analysis found a short-lived isotope of aluminum that indicates **that radioactive isotopes were deposited in the neighborhood of the Sun by an exploding star, or supernova**, at the time that this meteorite was formed, and by inference, that the Solar System was formed.
- this **supernova may have triggered the formation of our Solar System.**

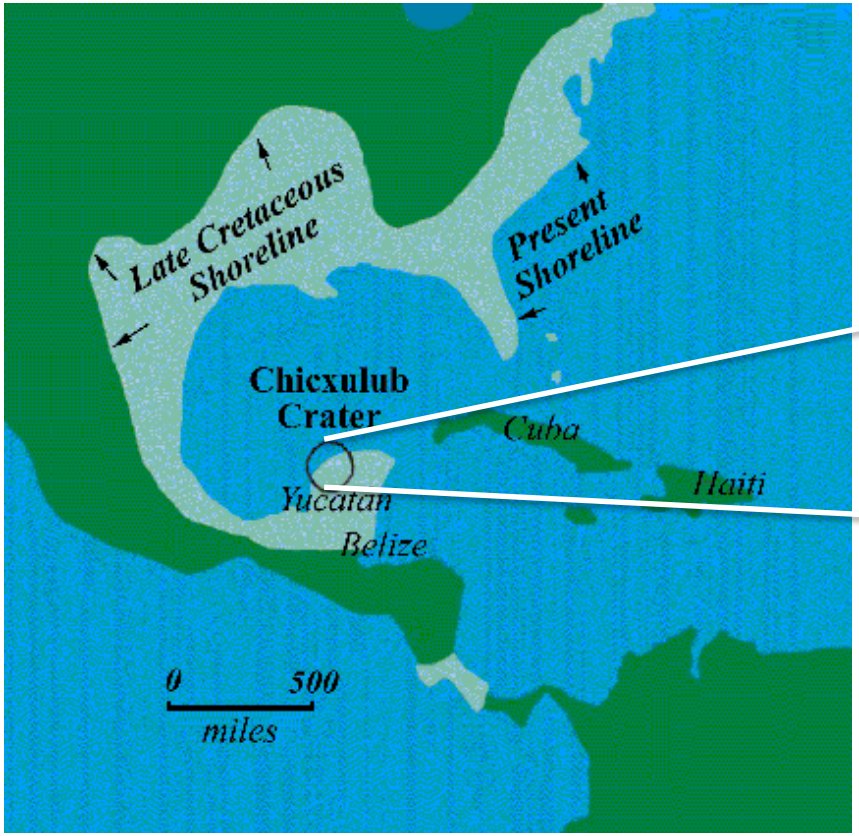
Barringer Crater, Arizona

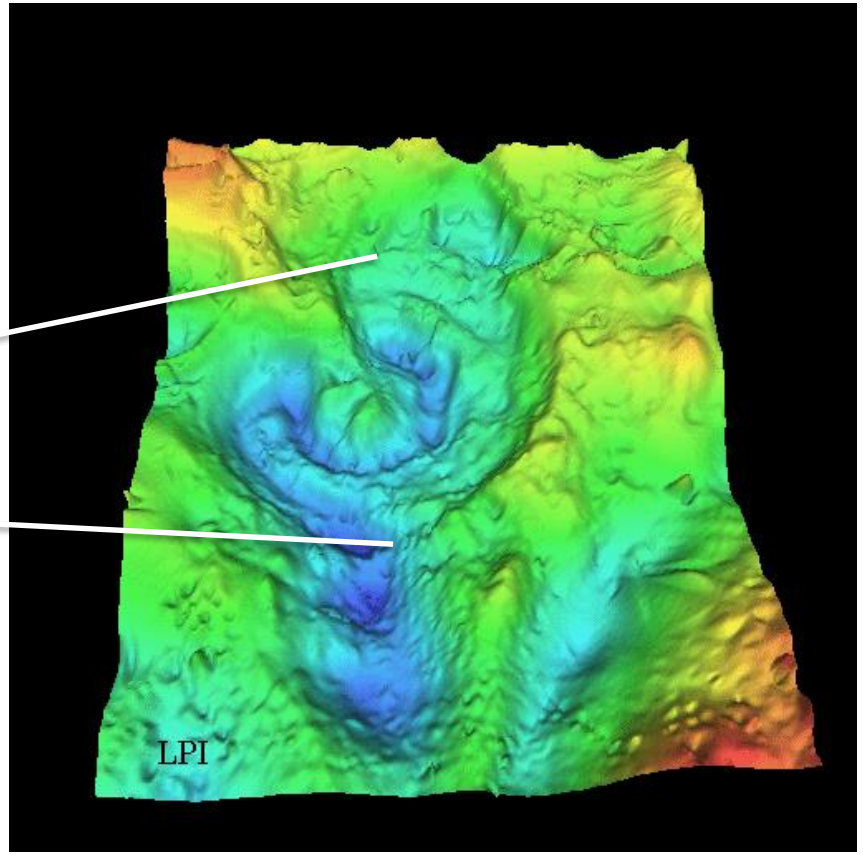
- **Barringer Crater** near **Winslow Arizona**
- formed from a meteoroid impact about 25,000 years ago.
- crater is **170 m deep, 1260 m in diameter, and has an elevated rim 50 m above the surrounding desert.**
- **Nickel-iron fragments** discovered in the area indicate that Barringer Crater was excavated by the impact of **a 60,000 ton, 25 meter diameter nickel-iron meteoroid striking the desert floor at a velocity of about 15 km/s.**



Barringer Crater (left) and Manicouagan Crater (right).

Chicxulub Crater, Yucatan

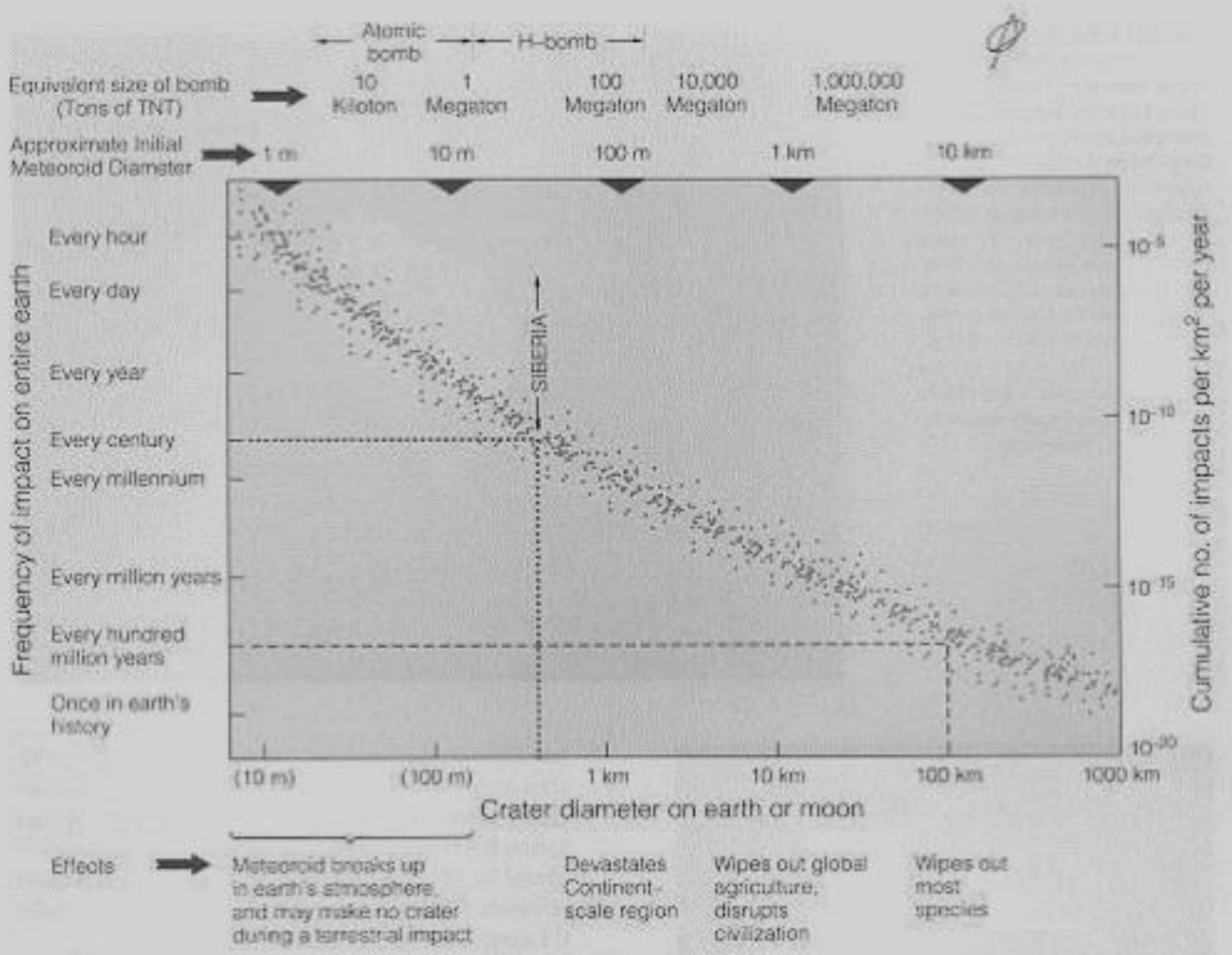




These events, show range of meteorite impacts on the Earth caused by the collision of Earth with space debris.

- **Three kinds of cosmic debris: comets**, **asteroids**, and **meteoroids. All orbit the Sun**.
- **Comets are solid icy bodies typically a few kilometers in diameter.**
- **Asteroids are rock/metallic objects up to 1,000 kilometers in diameter.**
- **Meteoroids are smaller debris, probably fragments or asteroids, having circular or elliptical orbits, usually out of the ecliptic plane.**
- **If a meteoroid collides with the Earth it can produce either a meteor or meteorite.**
- **It is likely that much of these objects are material that is left over from the formation of the Solar System.**

What Is Pluto?



Frequency of cratering events on the Earth.

Asteroids

- **Asteroids are any large interplanetary bodies that don't emit gas**. Asteroids are larger than meteoroids.
- Asteroids are **typically made of rocky materials and embedded metals**.
- The **spectra (colors) of asteroids are similar to those of meteorites that have been collected on Earth**.
- Analysis of spectra indicates that asteroids fall into **three groups according to composition: basalt-like lavas, rocks containing a high percentage of nickel-iron, and water-rich clays.**

Bode's Rule (not a law) popularized by Johann Bode 1772

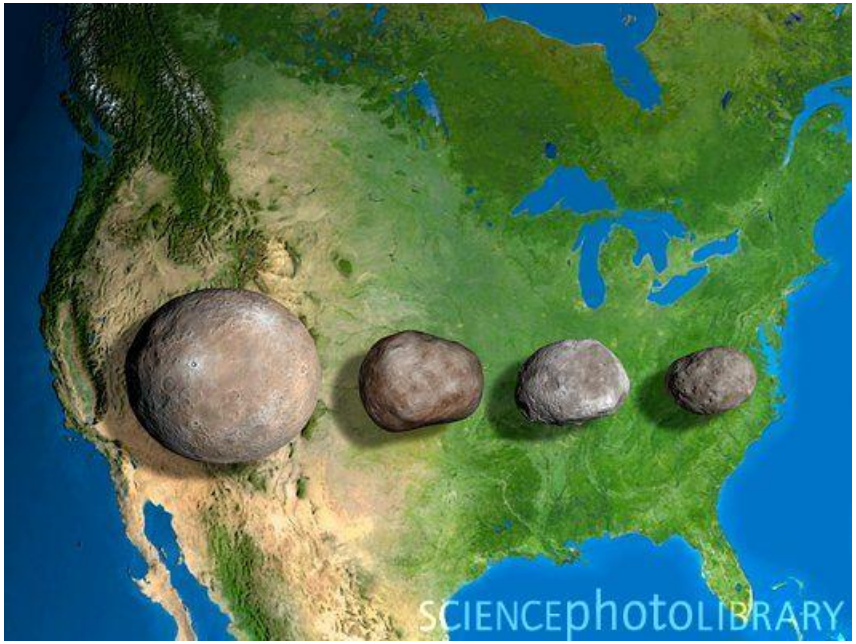
Planet	Mercury	Venus	Earth	Mars	Ceres	Jupiter	Saturn	Uranus	Pluto
1st Series of Nos.	0	3	6	12	24	48	96	192	384
Add 4	4	7	10	16	28	52	100	196	388
÷ by 10	0.4	0.7	1	1.6	2.8	5.2	10	20	39
Actual Distance (in AU)	0.4	0.7	1	1.5	2.8	5.2	9.5	19	39

Note: to make this work, Neptune is ignored, Ceres & Pluto included.

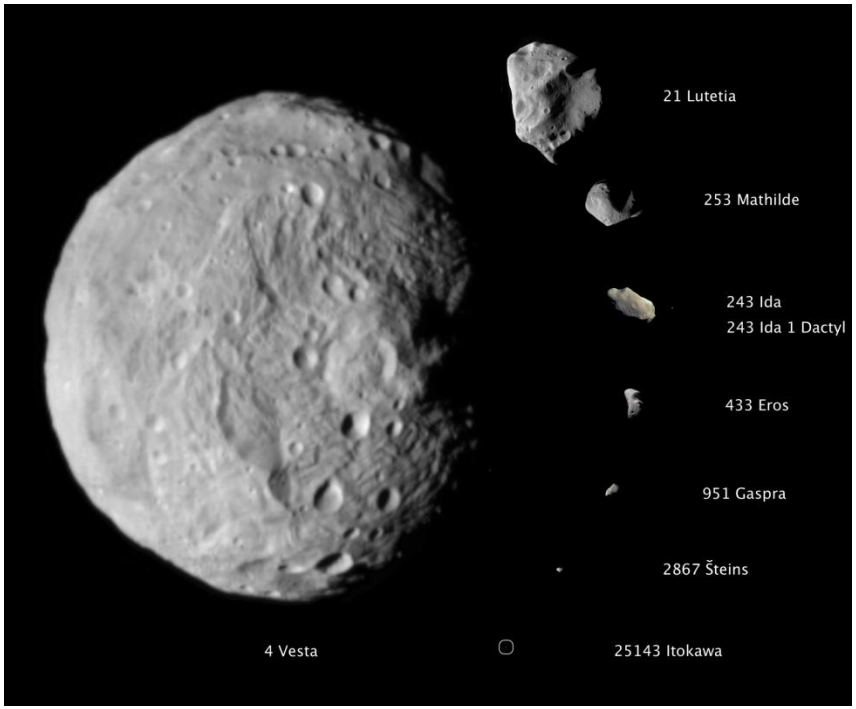
Bode’s Rule

- **discovery of Uranus in 1781 seemed to confirm Bode's Rule**
- many astronomers were determined to search for **the missing planet at 2.8 AU.**
- On the first day of the 19th century, New Years Day 1801, Ceres was discovered
- **Ceres is the largest asteroid, with a diameter of about 940 km and a distance of about 2.8 AU from the Sun.**
- 1802 **Pallas** discovered, also between the orbits of Mars and Jupiter.
- **Since then over 6,000 asteroids have been discovered, most in the ecliptic between 2 and 3.5 AU, known as the asteroid belt**.
- Ceres is only 1000 kilometers in diameter, far too small to be a planet. **All of the subsequently discovered asteroids in the asteroid belt only sum to a mass of about 10% of the Earth's mass.**

Ceres, Vesta, Pallas, and Hygiea



Vesta, et al.

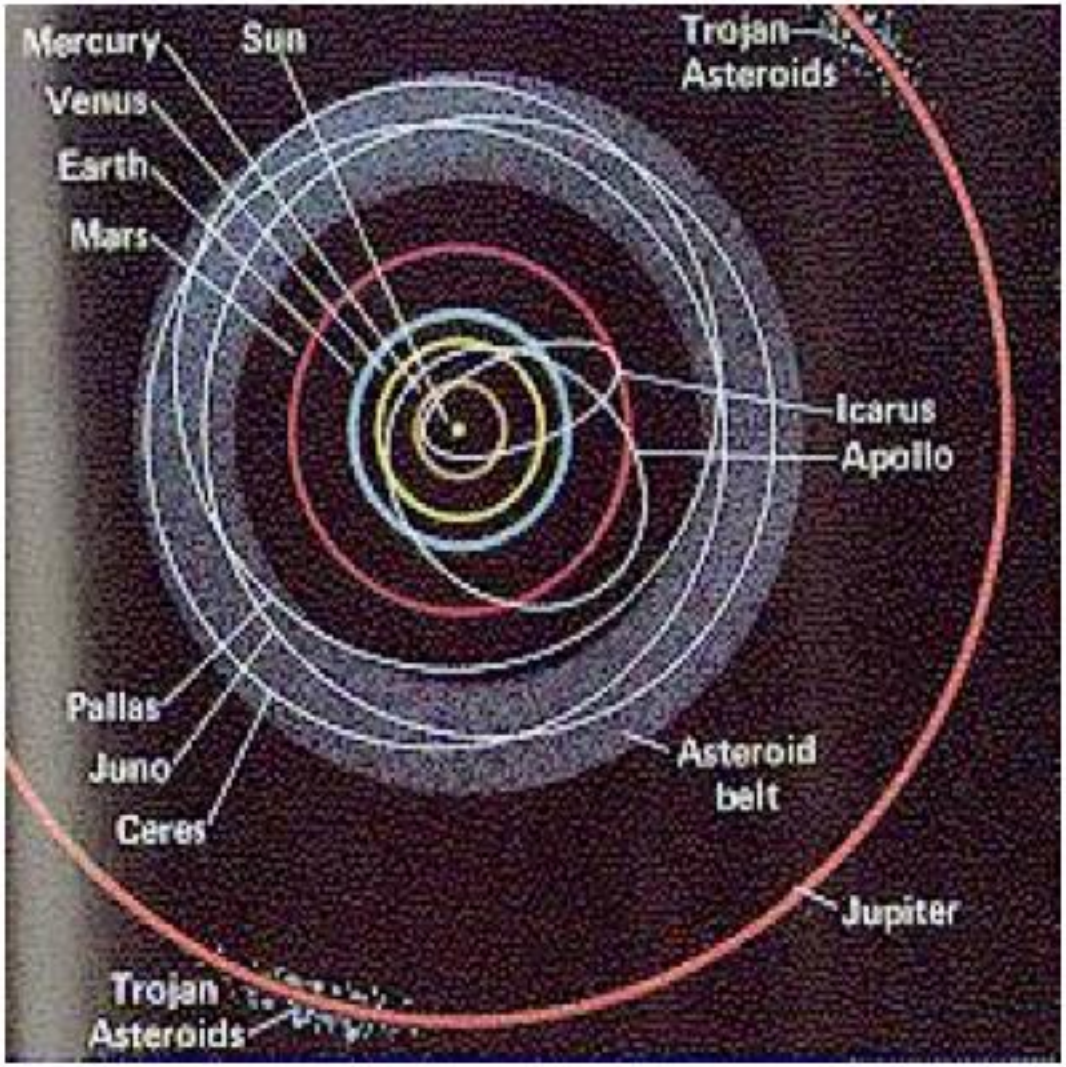


Is Pluto a Planet?

Why is there a difference in the shape of large and small planetary objects.

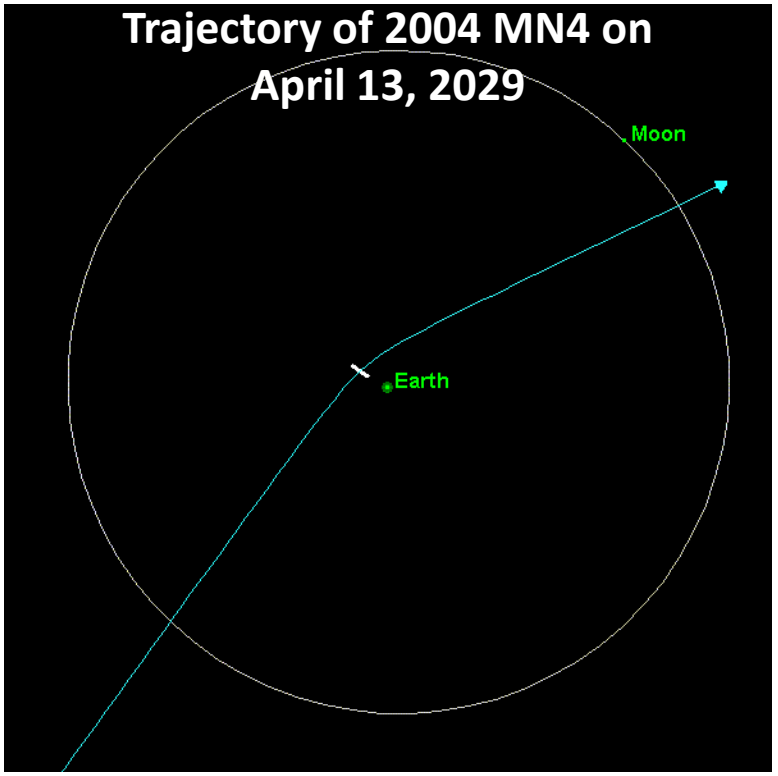
- The largest bodies in the Solar System, planets and the larger moons, are all nearly spherical.
- Moons and asteroids larger than 500 kilometers in diameter tend to be spherical.
- Moons and satellites smaller than 500 kilometers in diameter are typically irregularly shaped.
- The reason is the stronger pull of gravity among high-mass objects. Gravity tends to pull massive objects together into the smallest, most compact volume.

Asteroid Belt



Asteroids Cont'd

- **number of asteroids outside the main asteroid belt. Some cross inside the orbit of Mars; others, the Apollo asteroids cross the Earth's orbit** and some will eventually collide with it. probably the source of meteorites that are found on Earth.
- 1994, the 10-meter diameter asteroid 1994 XM1 passed within 105,000 kilometers of the Earth (less than 9 Earth diameters).
- In 2029, the 320-meter asteroid 2004 MN4 will pass within 36,350 km (3 Earth diameters)



Near Earth Asteroids

- Most Apollo asteroids will eventually strike a planet or moon.
- **Chances of a major collision between the Earth and an asteroid in our lifetimes, or even in the next 1,000 years, is insignificant.**
- Any Apollo asteroid or comet in an Earth-crossing orbit will be swept up by the Earth or other planet in about 10 million years. Because asteroids and comets are continually being thrown our way from the asteroid belt and the cloud of comets in our outer Solar System, this will occur steadily.

Meteorites

- **Meteorites are space rocks that have been discovered on the surface of the Earth.**
- **velocities between 11 and 60 kilometers/second** (24,000 to 134,000 mph). **dust and gravel-sized debris burns up from air friction, and can sometimes be seen as meteors of shooting stars**.
- **300 tons of meteorites fall to Earth each day**. large meteorites are very infrequent.
- **1972 a 1,000-ton object was observed by a US Air Force reconnaissance satellite to skip off the upper atmosphere over northwestern Wyoming**. Such a large meteorite probably impacts the Earth at most a few times a century.
- **10,000-ton Tunguska-class meteorite hits Earth every few centuries.**
- **Arizona meteor crater impact every 20,000 years.**
- **The largest impact crater known on the Earth's surface is the Canadian shield crater, some 70 km in diameter.**

Meteorite Composition

- **three composition classes**: **stony meteorites**, **iron meteorites**, and **stony-iron meteorites**. Stones look like **ordinary volcanic rocks**, although some have distinctive darks crusts, caused by surface melting from air friction as the meteorite passed through the atmosphere.
- **Iron meteorites have an unusually high iron content that makes them easy to distinguish.** Iron meteorites show nickel-iron crystals up to several centimeters long. These crystals are only found in meteorites because they cooled slowly over millions of years.
- Because of appearance, most meteorites that have been identified and put on display in museums are iron meteorites, but stony meteorites represent 95% of the meteorites that strike the ground.
- **Stony-iron meteorites have equal amounts of rock and iron-nickel.**
- **One rare stony meteorite is the carbonaceous chondrite, a primitive type of meteorite that never experienced differentiation.**

Carbonaceous Chrondrites

- Carbonaceous chondrites do not contain more carbon than other chondrites.
- **They do contain complex organic compounds and up to 20% water**.
- These organic compounds include **amino acids**, a basic component of proteins, conceivably a terrestrial contaminant. Meteorites could have introduced one of the basic building blocks of life to the Earth?
- **In carbonaceous chondrites water is chemically bound and is expelled only by heating to 100s of K.**
- **This means that they could not have been part of a larger body that underwent differentiation.** They contain pristine primordial material from the beginning of the Solar System
- **Also means that they were formed in the asteroid belt or beyond, where volatiles could condense.**

Meteorites Cont'd

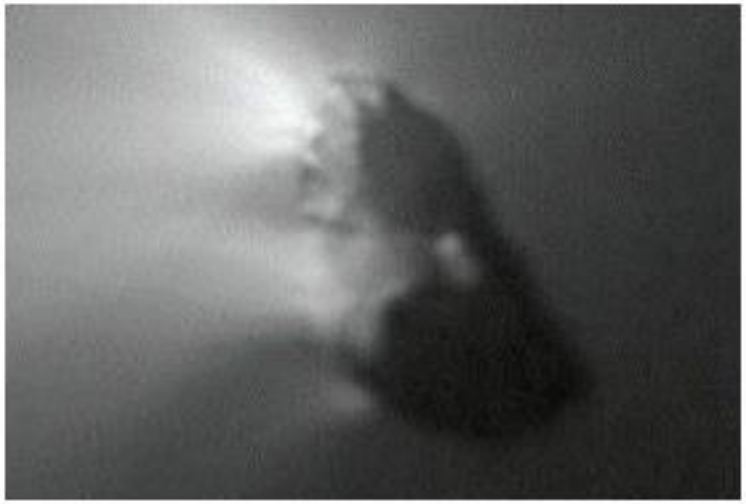
- **meteorites commonly exhibit partial melting, welding of individual grains together (like lunar breccia), and a network of fractures.**
- **Radioactive dating of meteorites indicates that almost all of them formed over a 20 million-year interval approximately 4.6 billion years ago.**
- **simply explained if they came from 4 to 30 parent objects, or parent bodies, perhaps 100s of kilometers across that were shattered in a collision with other objects**.
- **similar to the asteroids that we see today.** visible light spectra of sunlight reflected from asteroids are similar to the laboratory spectra of meteorites, indicating similarities in composition.
- **three meteorite classes (stony, iron, and clay-like) are similar to the asteroid classes (basalt-like lavas, rocks containing a high percentage of nickel-iron and water-rich clays).**
- **In addition, some of the unique features of meteorites can be explained by them having once been incorporated in a larger planetary body that was shattered in a collision**.

Meteorites III

- **meteorites show evidence of differentiation. Stony, stony-iron, and iron meteorites would correspond to parent body fragments from the crust, mantle, and core, respectively. Undifferentiated bodies would show no such evidence of differentiation, but would be primitive chunks of intermediate density and composition. This is exactly what we find in our meteorite collections on Earth: the ordinary basaltic, or stony, meteorites, nickel-iron meteorites, and the primitive carbonaceous chondrites.** The later contain a large amount of water, which would be expelled by heating only to few 100s of K.
- **Brecciated meteorites, showing individual grains of differing composition that have been welded together by impact may have resulted from breccia formed in a layer of regolith, by small impacts, later ejected into space by a large, moon-shattering collision.**
- **Meteorites show evidence of a high-energy collision between their parent body and another object.** Many meteorites show evidence of being shocked in a high-speed impact

Comets

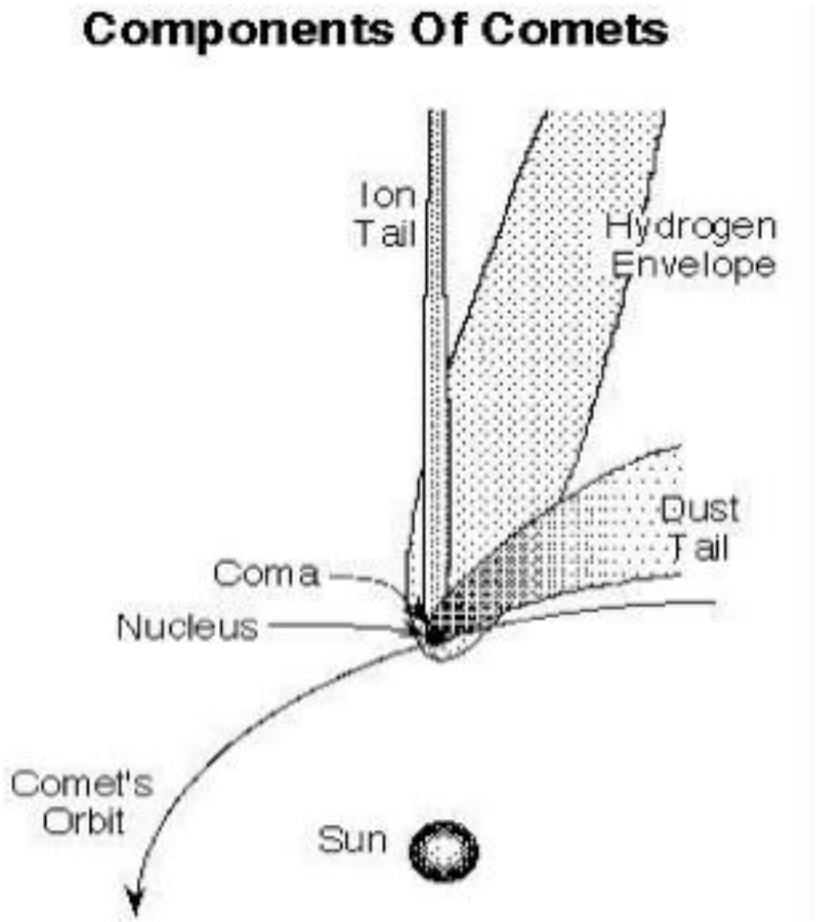
- **Comets are the small icy bodies in our Solar System that swarm around the Sun** small (**roughly one to ten kilometers in diameter**) chunks of ice and dust, without noticeable structure.
- generally have long **elliptical orbits around the Sun, so large that we only see the comet over an infinitesimally small fraction of its orbit.**
- **When they approach the Sun, sunlight striking a comet will boil off gas, giving a comet its signature appearance: an enormous tail.**
- **comet nucleus is the solid part of the comet and the only part of a comet when it is far from the Sun. As a comet approaches 6 AU from the Sun it begins to form a thick fog, the coma.** The coma can eventually become as large as the Sun, some 1 million kilometers in diameter.



Comet Halley: head and nucleus.

Comet Tails

- **Solar wind particles eventually push the coma gas into a tail of tenuous gas, stretching up to tens of millions of kilometers in length – Type 1 tail**
- **A separate dust tail is pushed away from the coma in those comets having dusty nuclei –Type 2 tail.** The dust tail is arched because the dust is pulled into a curved orbit by the Sun's gravity, the dust particles being too massive to be blown into a straight line by the solar wind**. For this reason, comet tails always point away from the Sun no matter what their direction of motion.**



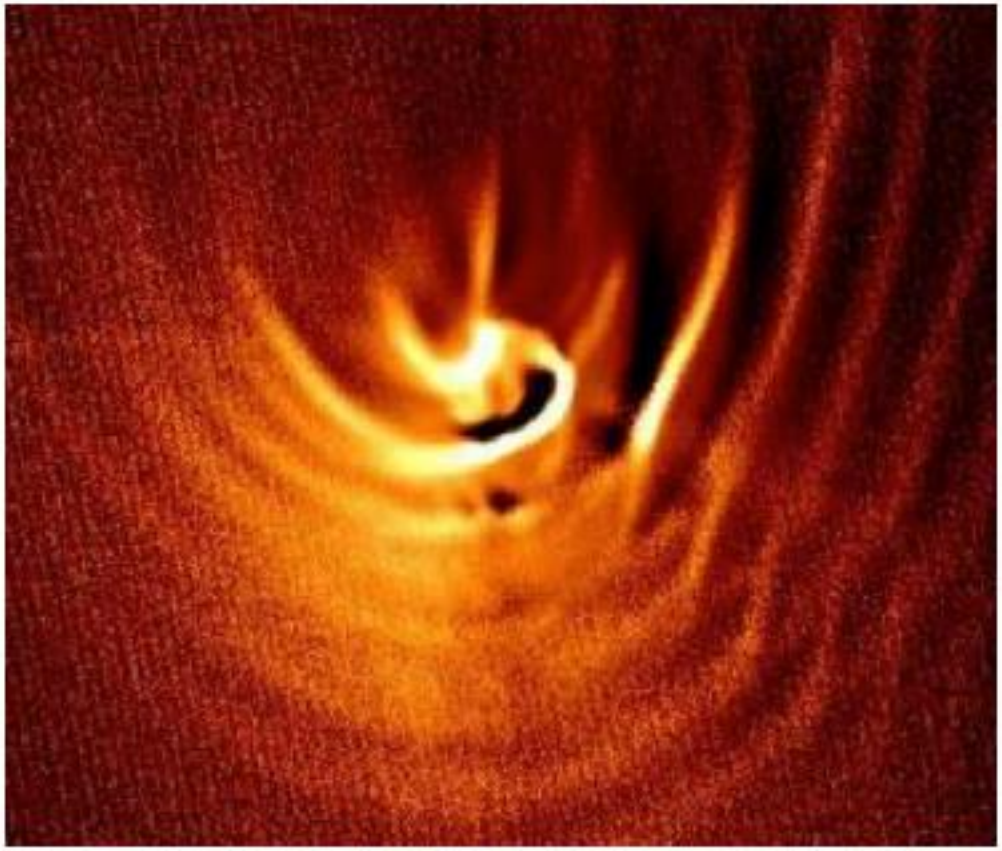
The solar wind and sunlight push the gas and dust away from the sun. Dust particles move in an orbit around the sun.

Comet Hale Bopp (1997), the 3rd most luminous comet on record

Comets cont'd

- **Ices and rocky debris are thought to have condensed in roughly equal amounts into small bodies in the early Solar System.** Ices include the carbon dioxide, methane, ammonia and water ices that we have seen on solid-surfaced planets and moons.
- **Comets formed in the outer solar system where these ices could condense. Gravitation from the gas giants subsequently randomly scattered them into space in all directions.**

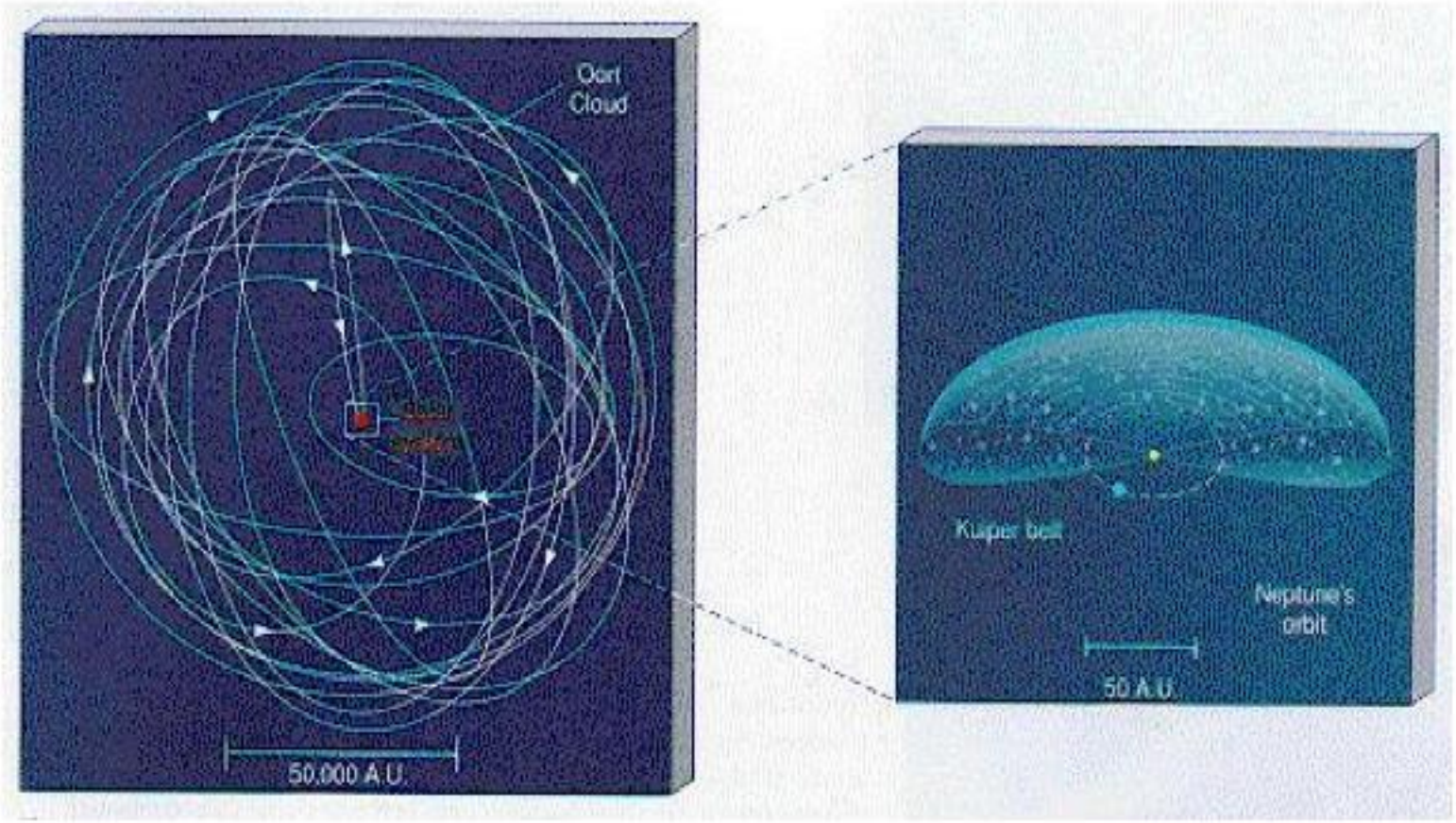
The head of comet Hale Bopp, showing jets of gas/dust



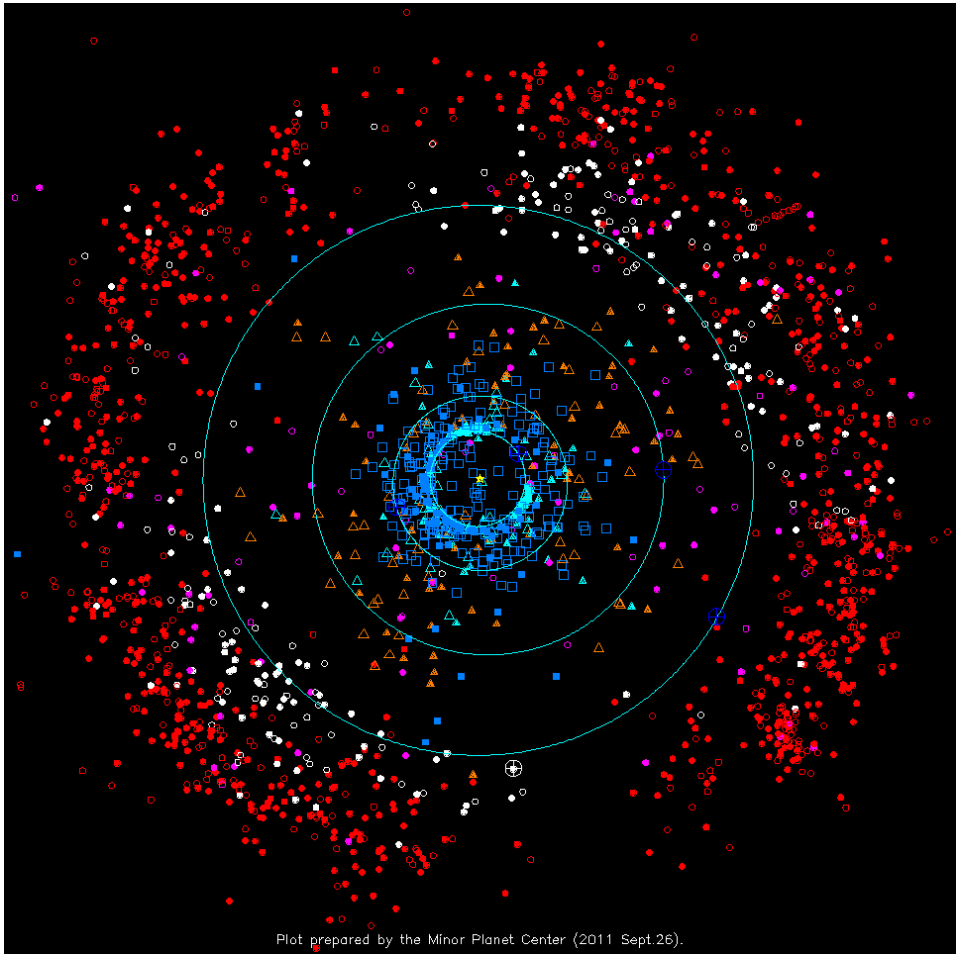
Comets III

- two families of comets, residing in the **Kuiper belt** and **Oort cloud**
- **Kuiper belt of comets lies in a disk beyond Pluto to 500 AU**. Nearly 50 comets are observed here; but there may be a reservoir of a billion comet nuclei in the Kuiper belt. **Short-period comets, having periods from a few decades to a few centuries to orbit the Sun, are found in the Kuiper belt.**
- In the 1950s **Jans Oort proposed that several billion comets exist far from Sun, in what is now known as the Oort cloud, a spherical swarm of comets extending out to the limits of the gravitational reach of the Sun, 50,000 AU or one-third the distance to the nearest star.**
- Most Oort-cloud comets have orbits that never get close enough to the Sun to be detected. **A passing star can exert enough gravitational influence to perturb one of the Oort comets into an orbit that takes it close to the Sun**.
- **These long (orbital) period comets thrown into the inner Solar System from the Oort cloud are seen to pass the Sun once and can have orbital periods from one to 30 million years**.

Kuiper and Oort Clouds



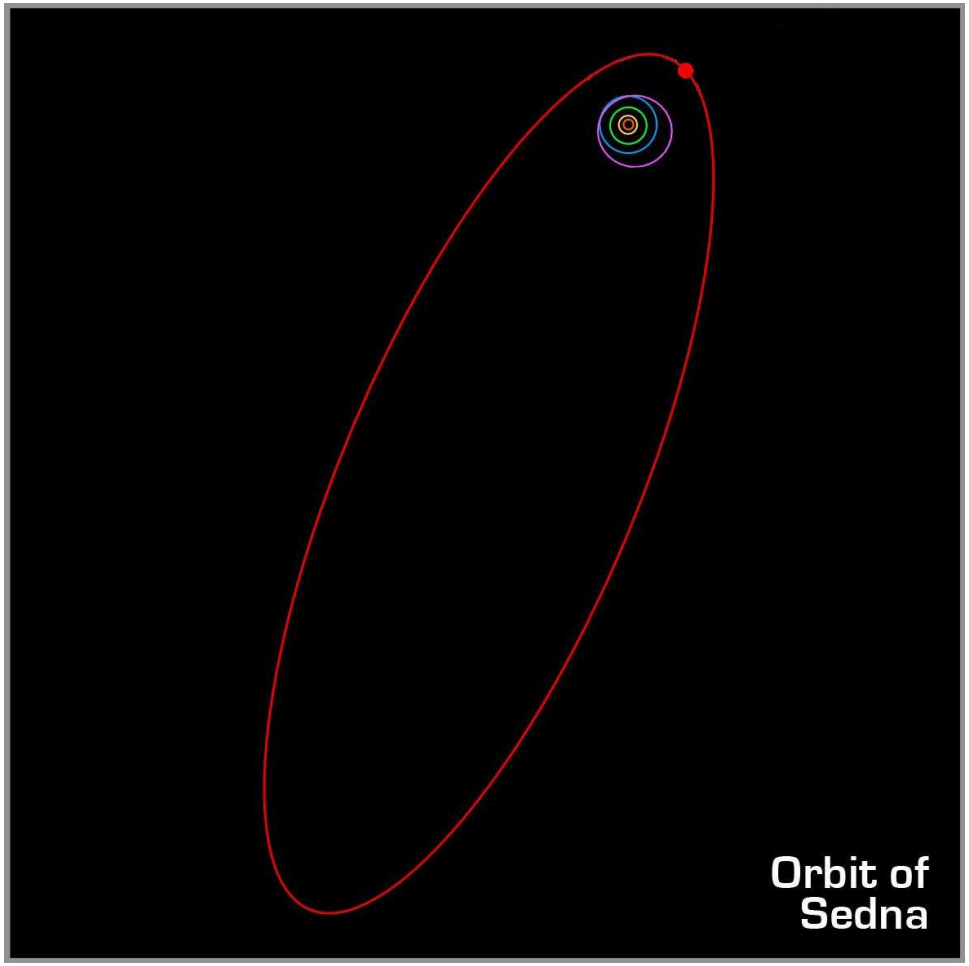
The Kuiper Belt




Largest known Kuiper Belt objects
Dysnomia
Charon
Eris
Pluto
Makemake
Haumea
Sedna
Quaoar

Is Pluto a planet?

Sedna

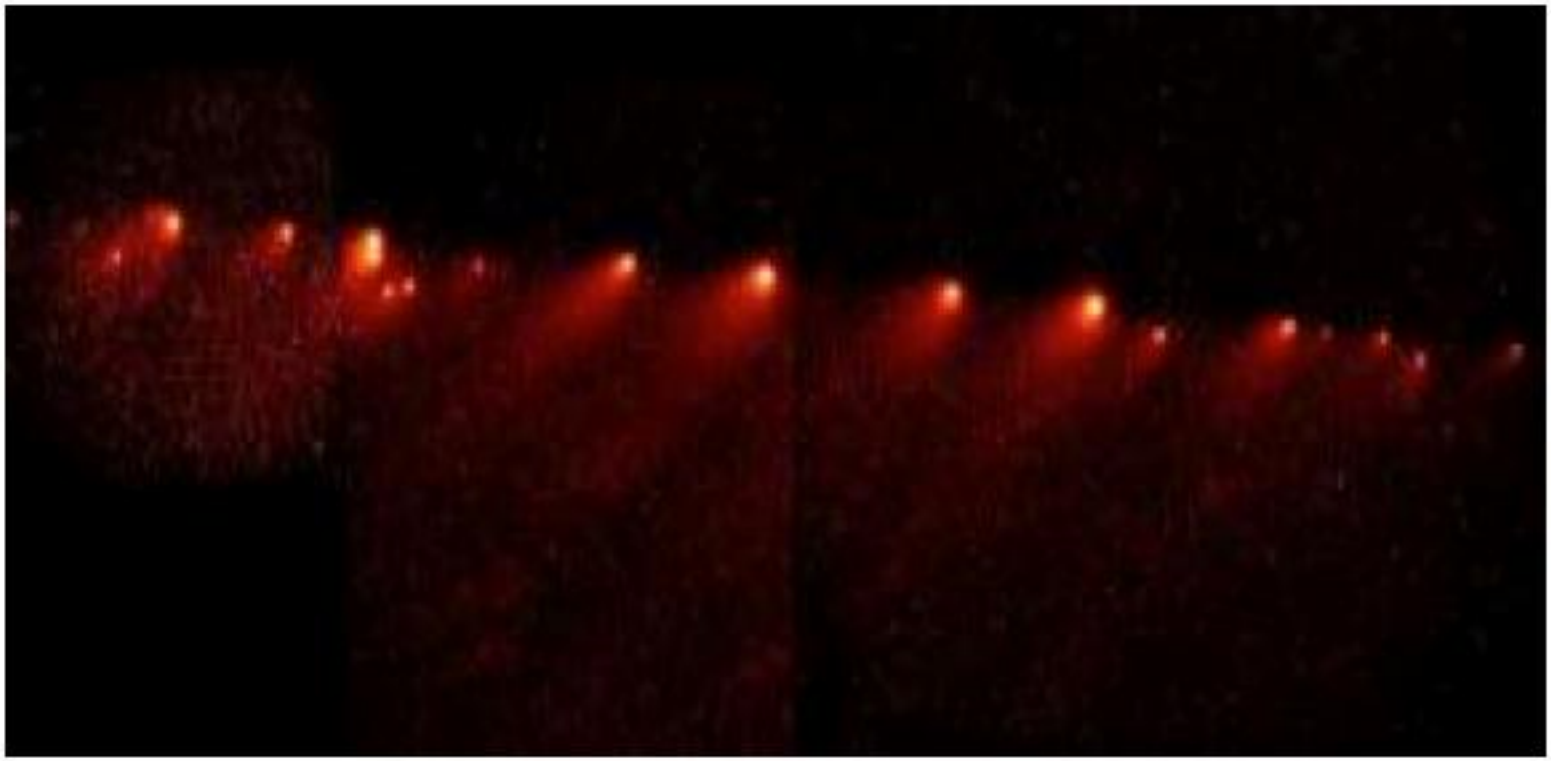


- Perihelion (closest approach to Sun) of 76 AU
- Aphelion (farthest approach) of 937 AU
- Kuiper Belt or Oort Cloud?

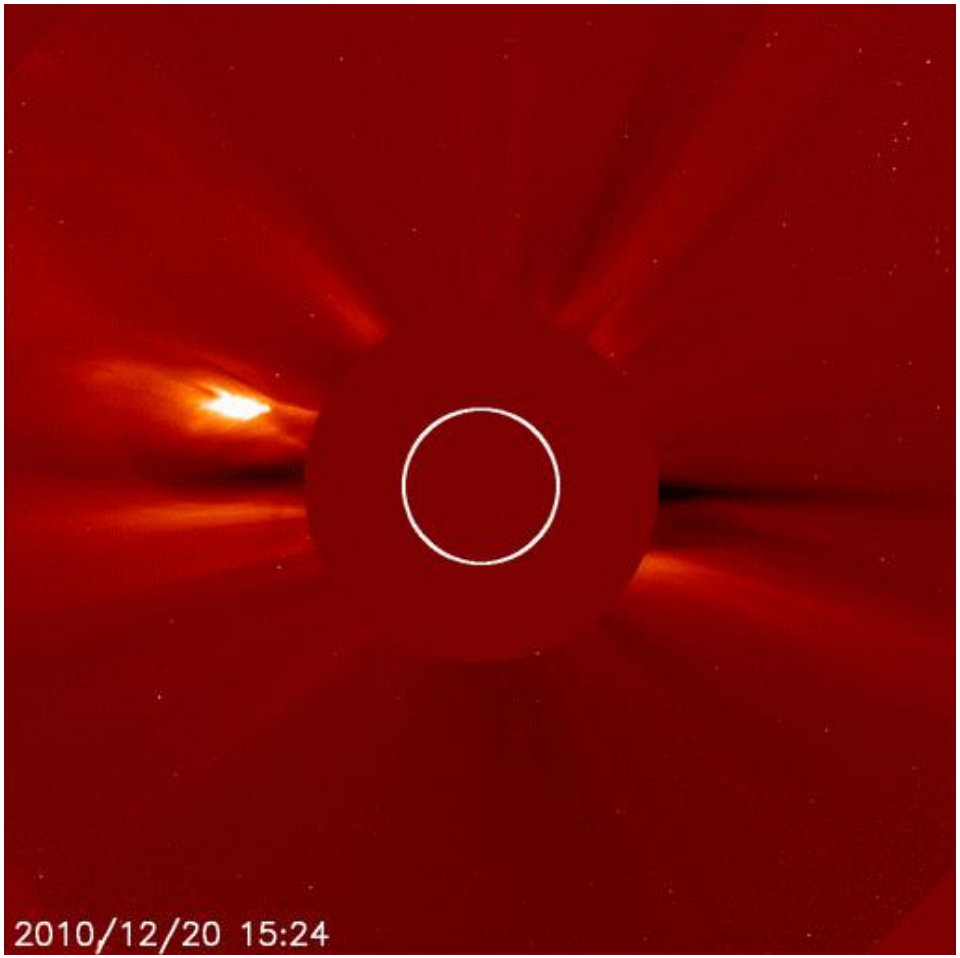
Comets IV

- **A comet can't survive large number of close passages to the Sun, because it typically loses about 1% of its mass at each solar encounter.**
- **A comet can be destroyed when it is disrupted tidally by a planet or collides with it**. A prime example was **Comet Shoemaker Levy 9**
- **Spectroscopic analysis of sunlight reflected from comets has generated a number of common ions, in comet comae which come from solid carbon dioxide, ammonia, water, and methane.**
- **Astronomers currently think of comets as dirty snowballs.** The materials that form ices in the outer Solar System, **water, ammonia, and methane, are commonly seen in comet spectra**. Combined with the dust seen in some comets, these ices would produce a dirty snow. This can breakup when comets pass close to the Sun.
- **rich in many of organic compounds on which life is based. Some suspect that comets seeded organic molecules to the planets in their formative stage, creating the initial conditions on Earth for the later evolution of life.**

Pieces of Comet Shoemaker Levy 9 prior to its collision with Jupiter, 1994



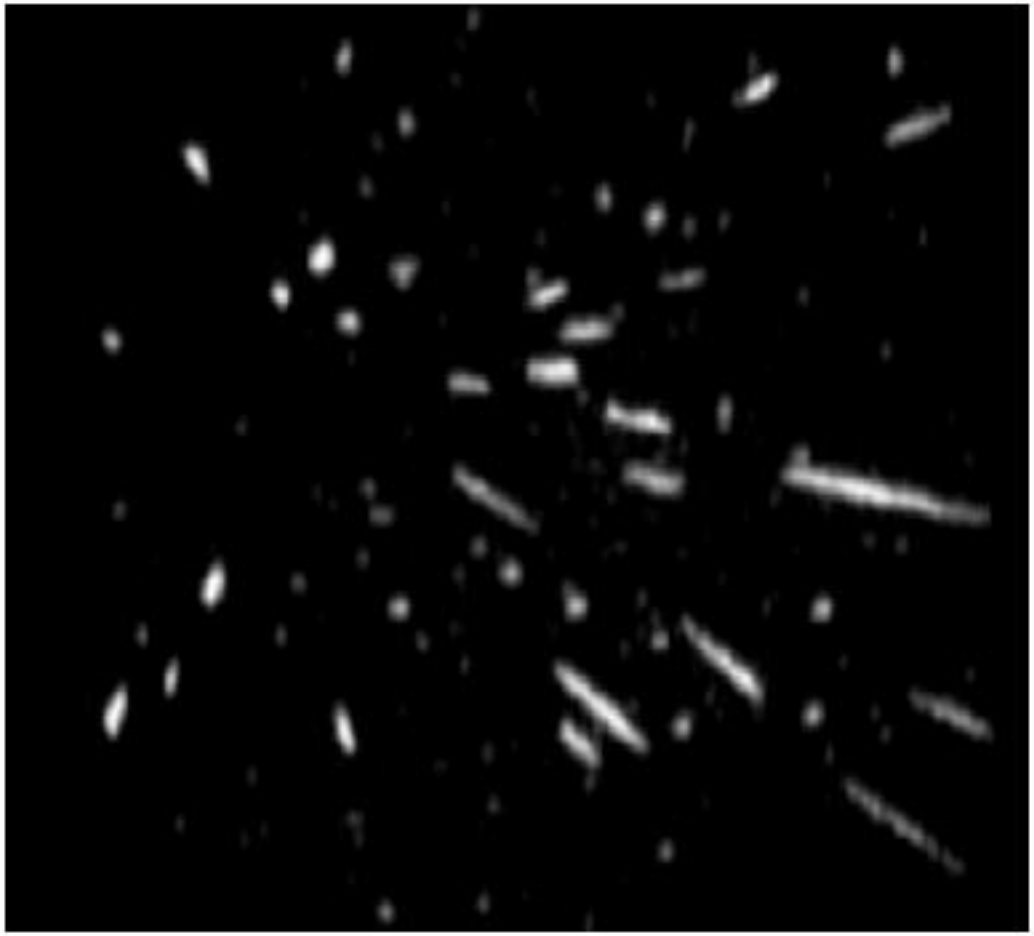
A sun-grazing comet seen by SOHO



Meteors

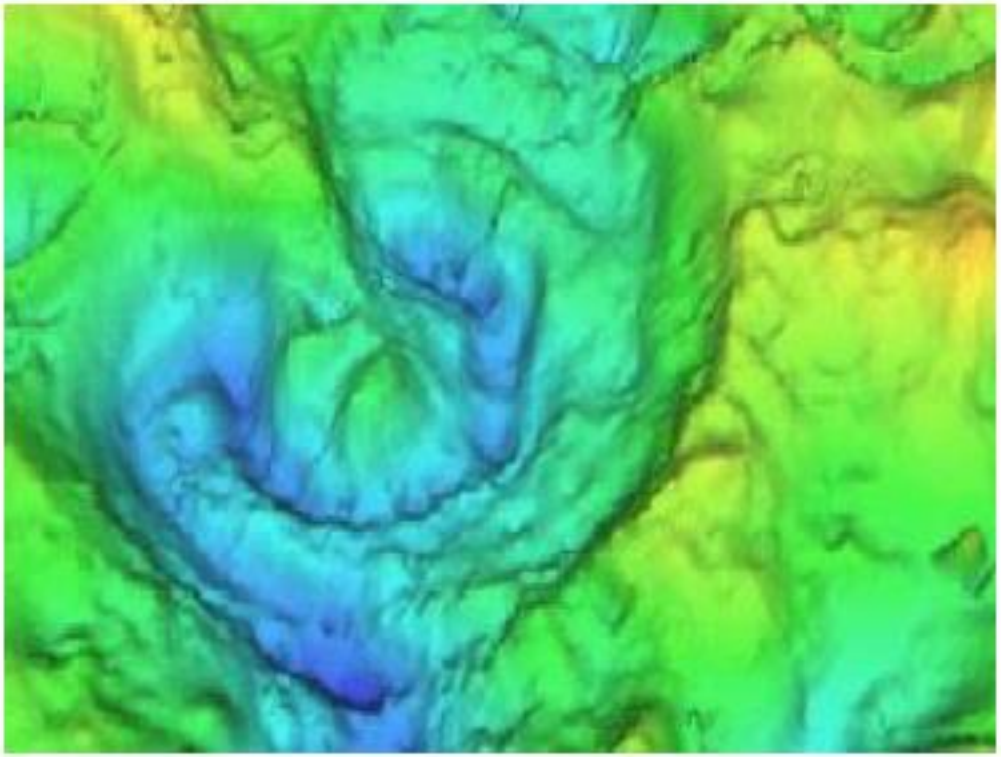
- **Meteors, or shooting stars, are the manifestation of some meteoroids that collide with the Earth's atmosphere and burn up from the intense friction with air when they enter the atmosphere at 10 to 40 kilometers/second (22,000 to 135,000 mph)**.
- Far from bright city lights on a dark night one can typically see 3 to 15 meteors in a one-hour period. There are times when the rate of observed meteors is significantly larger. These meteor **showers can have from sixty to 2,000 shooting stars**, all apparently radiating from the same direction in the sky. Some showers are even more dramatic. The Leonid meteor shower of **November 17, 1966 produced more than 2,000 meteors per minute**.
- the **Perseid shower, like other periodic showers, named for the constellation from which they appear to come, Perseus in this case. In 1866 the Italian astronomer Schiaparelli discovered that the Perseids occurred when the Earth crossed the orbit of Comet 1862 III. Comet 1862 III broke up and disappeared after its near-Sun passage in 1862.**
- **Schiaparelli proposed that major meteor showers occur whenever the Earth crosses a deceased comet's orbit and sweeps up a significant amount of debris that has been spread out along its orbit**.
- Cometary ices are more fragile than the rocky/metallic meteorites that impact the Earth, and are more likely to vaporize on impact with the atmosphere, producing a visible shooting star.
- In 1986, the Infrared Astronomical Satellite, discovered dust spread out along the orbital paths of active comets. It is thought that most meteors form this way. Meteors are produced whenever the Earth crosses such a path in its orbit.

Time lapse photo of the Quadrantid meteor shower



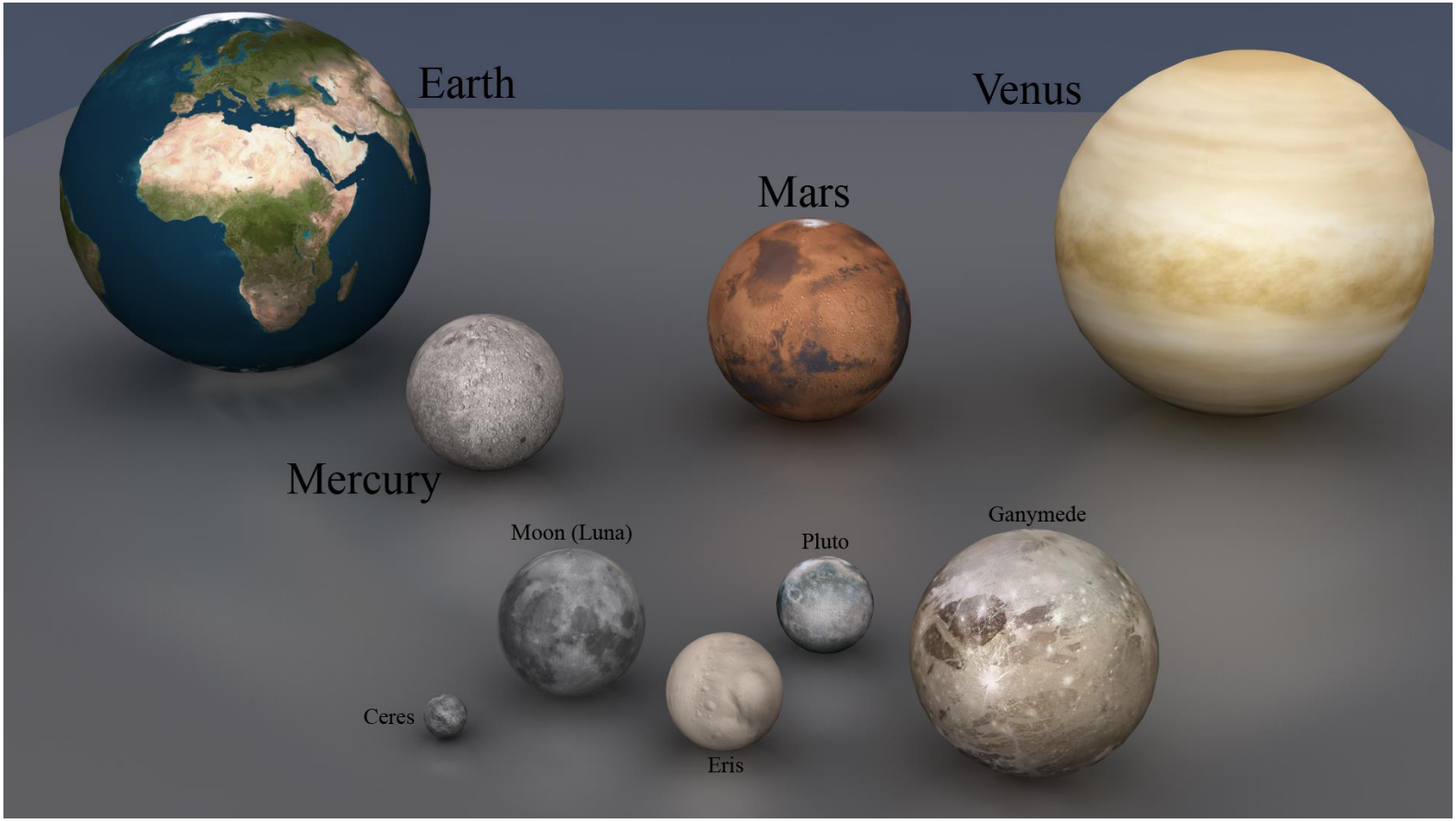
Dinosaur Extinction

- In the 1970s Walter Alvarez and his father Luis Alvarez, of the University of California at Berkeley were studying a **65 million-year-old layer of exposed marine limestone in Italy**. This layer is unusual because it has **an unusually high abundance of the element iridium in a layer between two limestone layers**. Iridium is **common in meteorites** but extremely rare in the Earth's crust . Such an iridium-rich layer has been seen worldwide. In every case it is in clay dated at 65 million years. Coincidentally, it was **65 million years ago that dinosaurs became extinct along with two-thirds of all species.**
- **The Alvarezs proposed that some 65 million years ago an asteroid, approximately 10 kilometers in diameter, struck the Earth**. Such a collision would have been catastrophic for life on Earth, blasting enough dust high into the atmosphere to block sunlight from the Earth's surface for several years, and dropping the Earth's temperature dramatically. **Plants died first, then plant-eating dinosaurs and other vegetarians, and finally meat-eating predators. When dust enriched in iridium from the impacting asteroid finally settled to Earth, it formed an iridium-rich layer of rock-forming sediment.**
- **Later, in 1992, geologists identified the 180-kilometer diameter Chicxulub crater embedded in the Yucatan peninsula as the crater formed from this impact.** Glassy debris and shocked grains of rock found in the crater suggest a high-energy impact origin. Radioactive dating of these rocks indicates that this crater was formed 64.98 million years ago.
- This theory is still controversial. Large objects strike Earth with megatons of destructive capability, but very infrequently. **The time between species-threatening collisions of this kind is about 100 million years.**



Chicxulub Crater on the Yucatan Peninsula. This 3D image was created from gravity and magnetic data. Some have speculated that this event could have caused the dinosaur extinction some 65 million years ago.

Dwarf Planets



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