# Chapter 11

## Meteors, Asteroids and Comets



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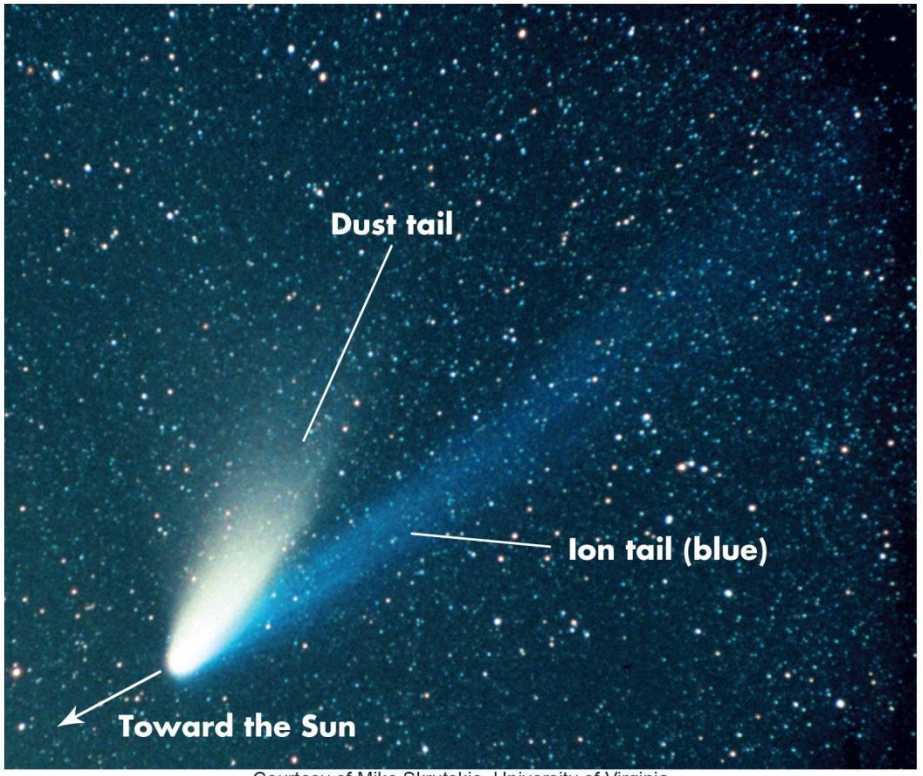
# Asteroids and Comets

- Orbiting the Sun are numerous small bodies – the asteroids and comets
  - Asteroids are generally rocky objects in the inner Solar System
  - Comets are icy bodies and spend most of their time in the outer Solar System



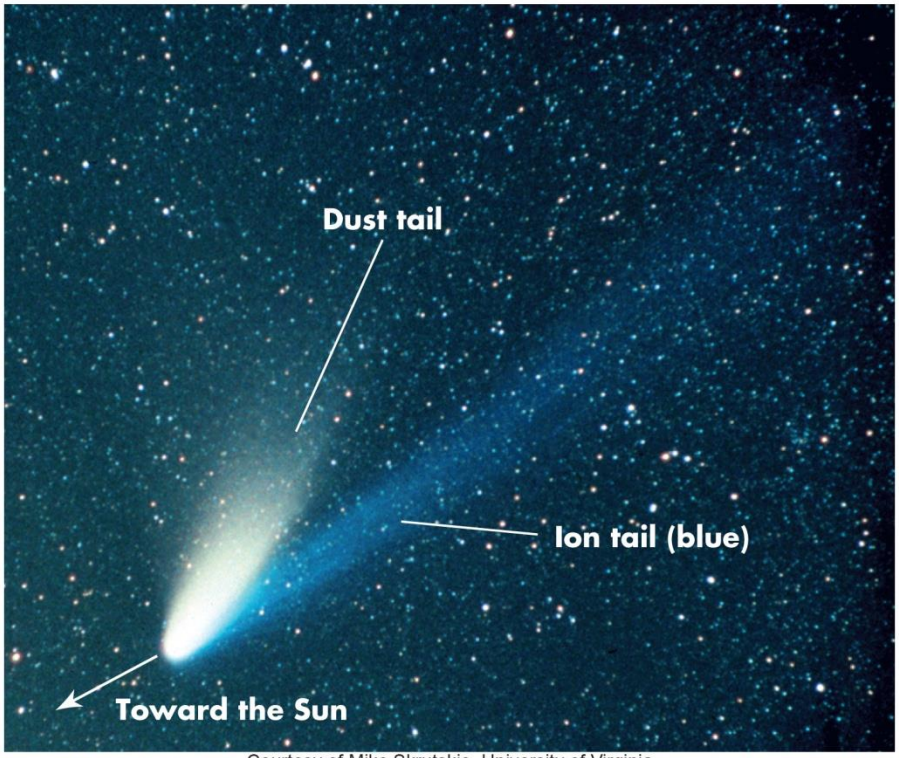



Courtesy of Mike Skrutskie, University of Virginia

# Leftovers of the Solar System

- Asteroids and comets are remnants of the formation of the Solar System
  - Some may be planetesimals
  - Best source of information about the Solar System's early years
- Asteroids and comets play a central role in planetary impact and in particular can have a large influence on Earth's biological life






Courtesy of Mike Skrutskie, University of Virginia

# Meteors and Meteorites



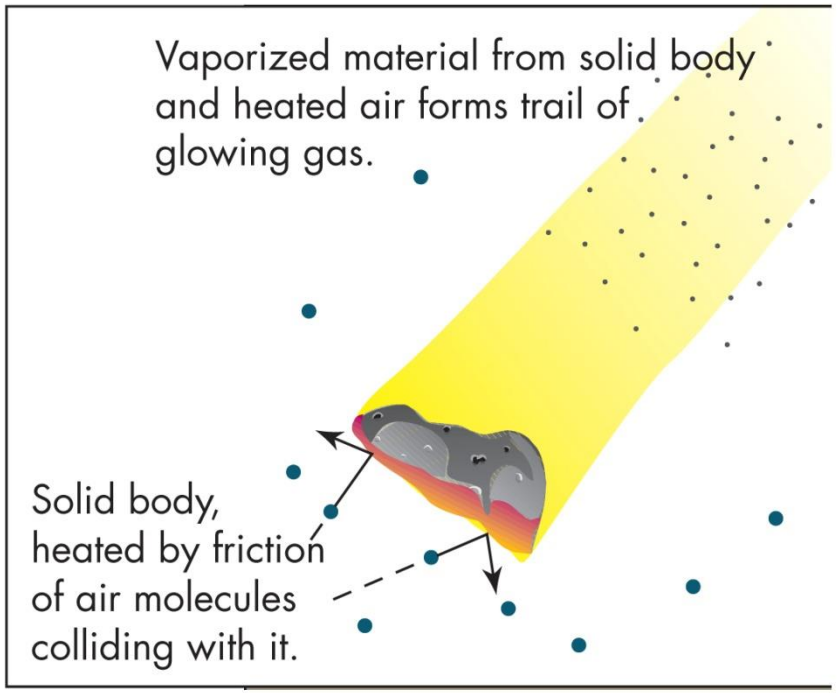
Courtesy of Ronald A. Oriti, Santa Rosa Junior College, Santa Rosa, Calif.

- A “shooting star”, that streak of light that appears in the night sky for a fraction of a second, is a ***meteor***
- A meteor is the glowing trail of hot gas and vaporized debris left by a solid object heated by friction at it moves through the Earth’s atmosphere (generally, at the upper fringes)
- If the solid body is in space, it is called a ***meteoroid***

# Heating of Meteors

- Heated to thousands of degrees Kelvin, meteors convert their kinetic energy into heating the meteor and air molecules
- Meteoroids larger than a few centimeters sometimes are visible in daylight as "fireballs"





# Meteorites

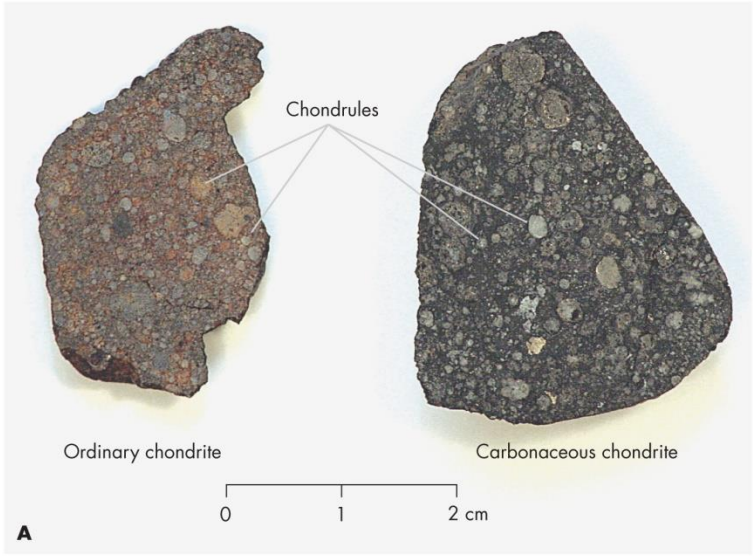


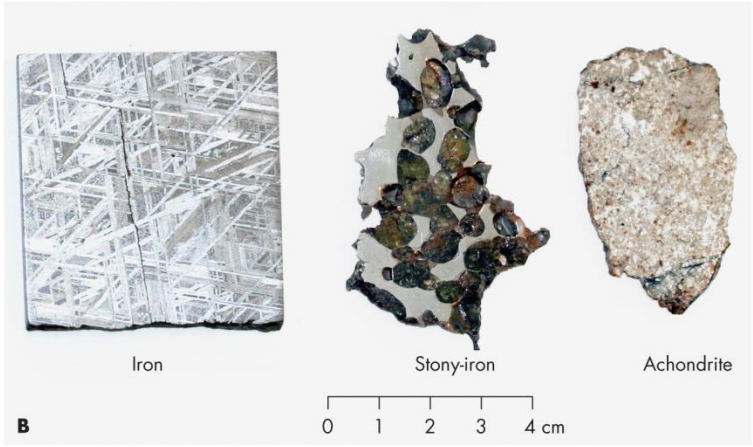

- Hundreds of tons of meteoritic material hit Earth each day
- Best time to observe meteors is midnight to dawn
- Most meteors are too small to reach the Earth's surface – those that do are called ***meteorites***
- Comets and asteroids are the primary source, some come from Moon or Mars

# Three “flavors” of meteorite

- Meteorites are classified into three broad categories based on their composition: iron, stony, and stony-iron
  - Stony meteorites are composed mainly of silicate compounds
  - Iron meteorites are mostly metals





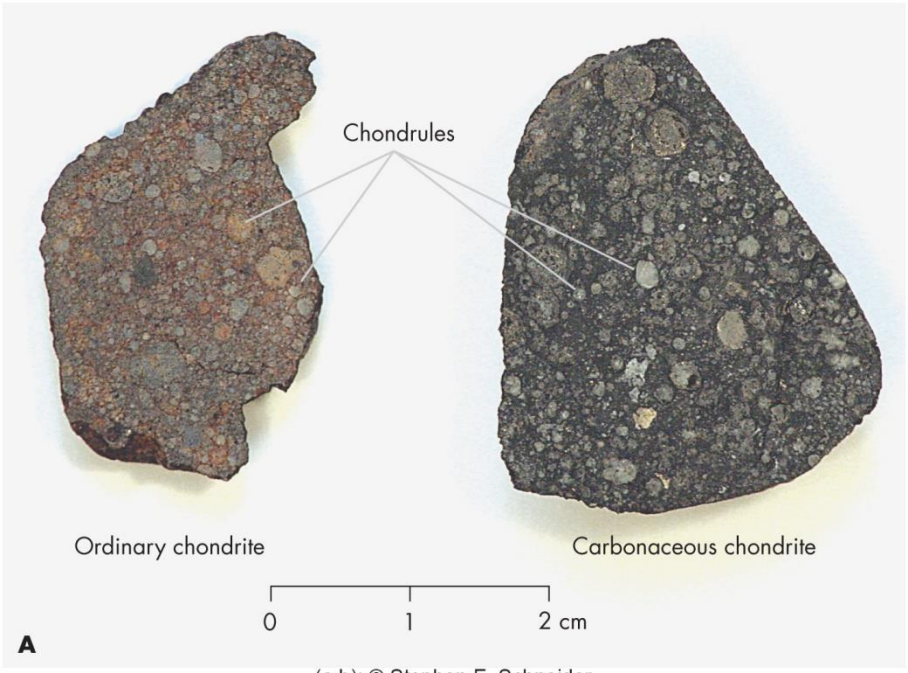




(a,b): © Stephen E. Schneider

# Classification

- Most stony meteorites include smaller rounded chunks of rocky material called ***chondrules*** – these meteorites are called ***chondritic meteorites***
- In some chondritic meteorites, the chondrules are embedded in a black, carbon-rich, coal-like substance and are called ***carbonaceous chondrites***

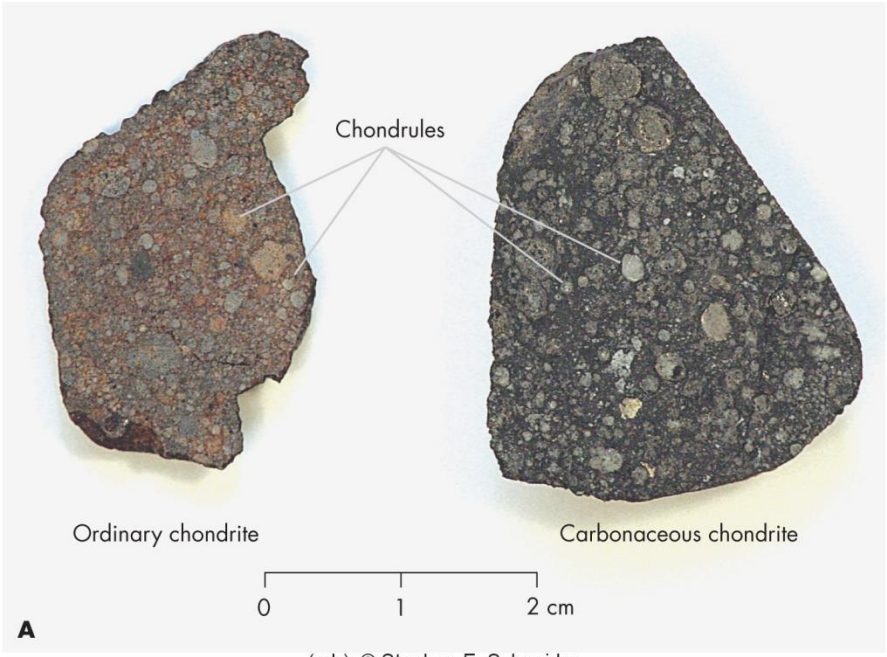




# Chondrules

- Chondrules appear to have been rapidly melted and cooled in the solar nebula
- Radioactive material in chondrules allows dating back to when they first condensed from the solar nebula
- Some chondrules contain ancient dust grains that have survived from before the Solar System's birth!

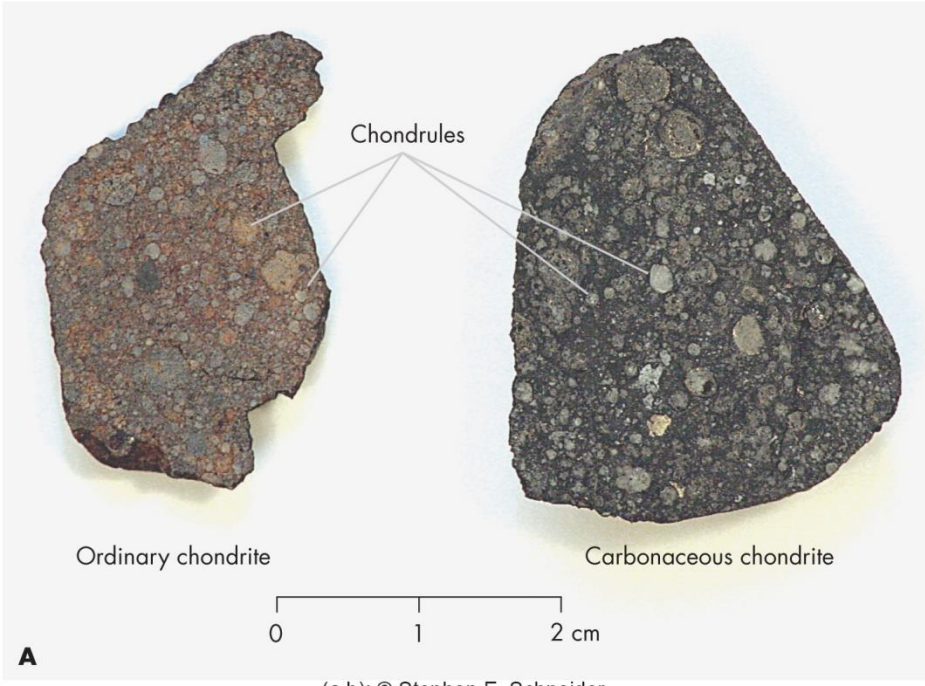




# Carbonaceous Chondrites

- The carbonaceous matter contains organic compounds, including amino acids
- Raw material of life can form in space and was available from the start of the Solar System



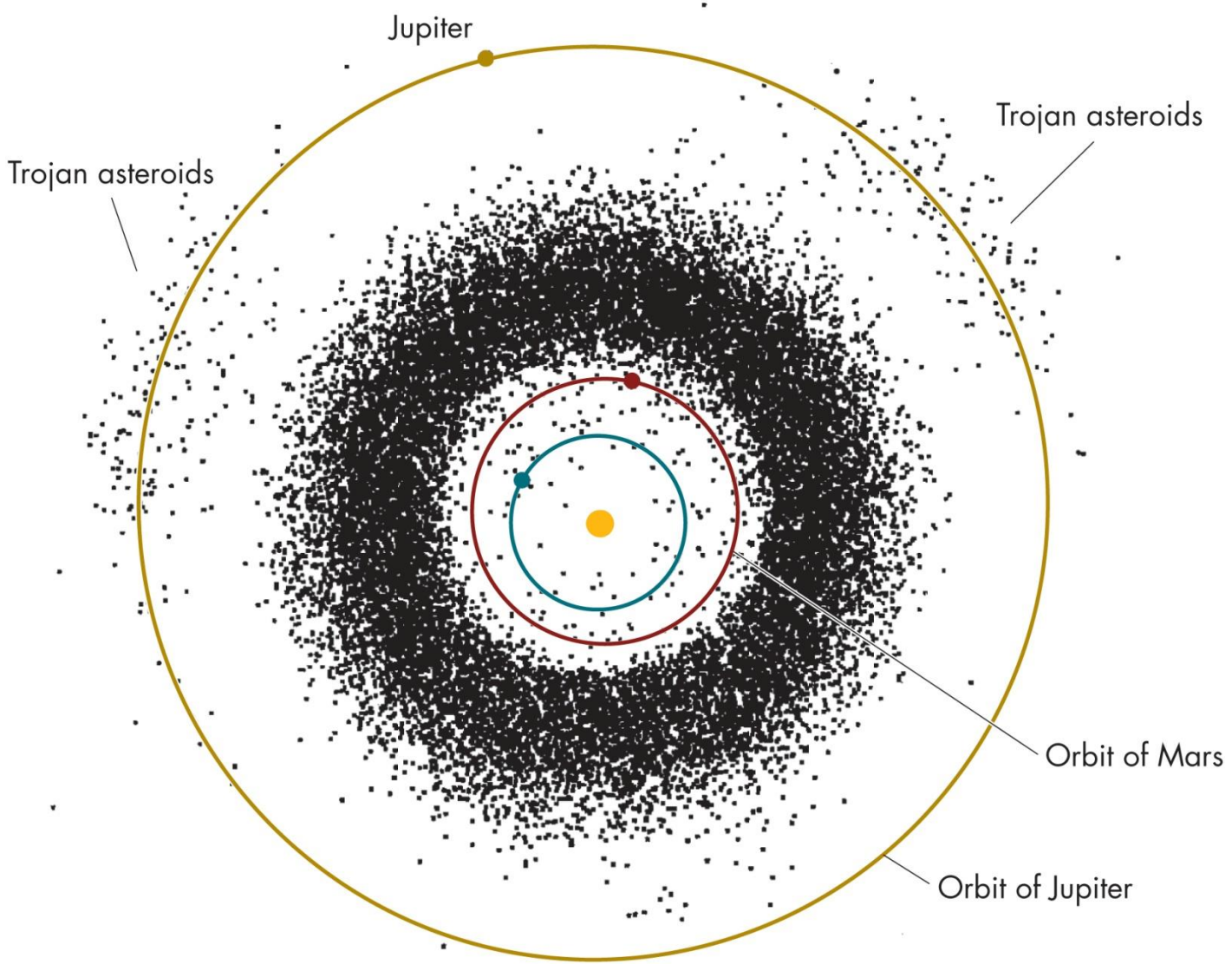


# Asteroids

- Asteroids are small, generally rocky bodies that orbit Sun
- Most asteroids (thousands) lie in the asteroid belt, a region between the orbits of Mars and Jupiter
- The first asteroid (Ceres) of this asteroid belt swarm was discovered as a result of a search for the “missing planet” of Bode’s law
- The combined mass of all the asteroids is probably less than 1/1000 the mass of the Earth

# The Asteroid Belt



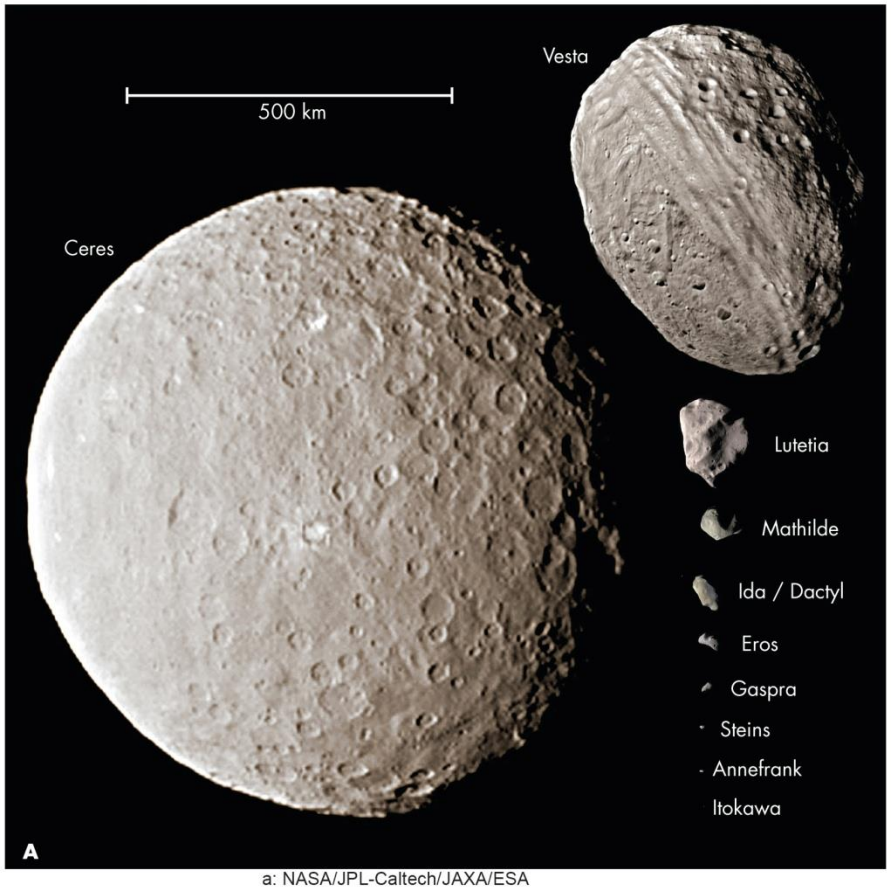



Courtesy of E.L.G. Bowell, Lowell Observatory

# Size of Asteroids

- Asteroids are small, so their sizes are best determined from infrared measurements: bigger bodies emit more IR than smaller ones at the same temperature
- Asteroids range in size from 1000 km across (Ceres) down to kilometer-sized objects and even smaller



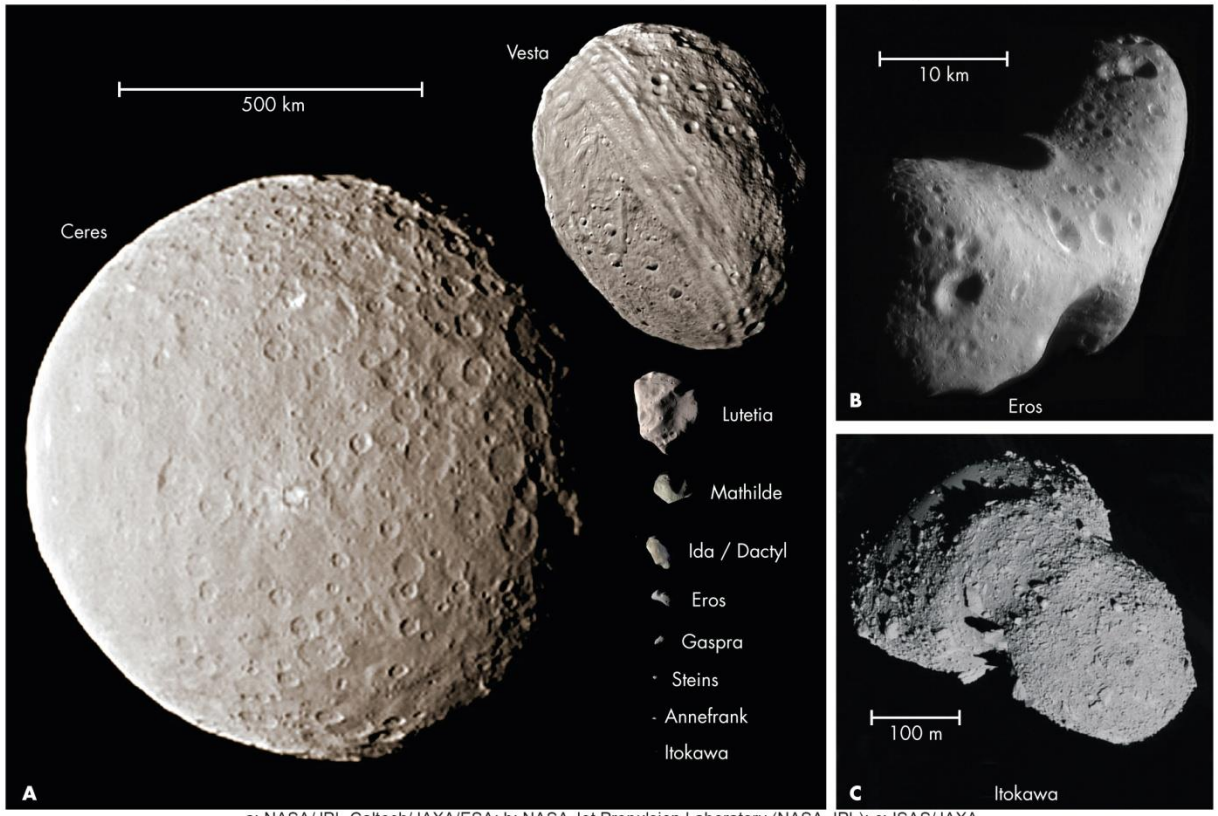



a: NASA/JPL-Caltech/JAXA/ESA

# Shape of Asteroids

- Most asteroids are irregularly shaped as determined from spacecraft images and their brightness fluctuations seen in telescopes



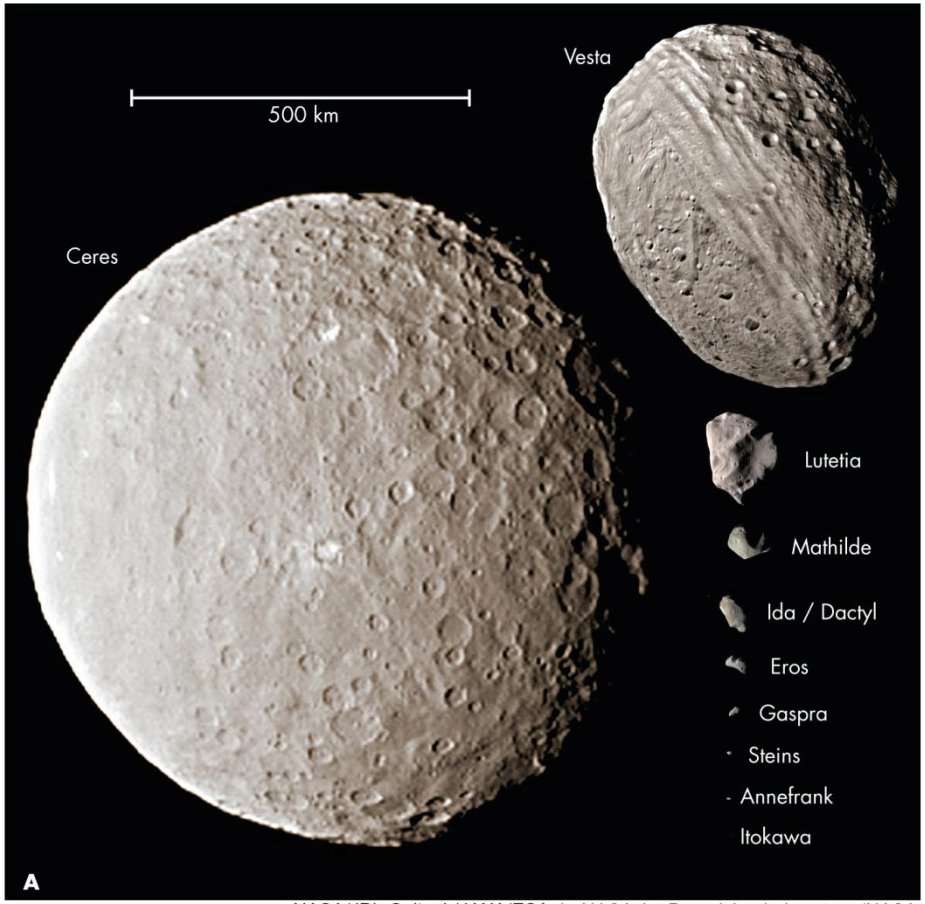



a: NASA/JPL-Caltech/JAXA/ESA; b: NASA Jet Propulsion Laboratory (NASA-JPL); c: ISAS/JAXA

# Ceres

- Ceres is the largest object in the asteroid belt.
- Now classified as a dwarf planet
- Ceres has a density of 2.1 g/cm$^3$, suggesting it contains a significant proportion of ice.

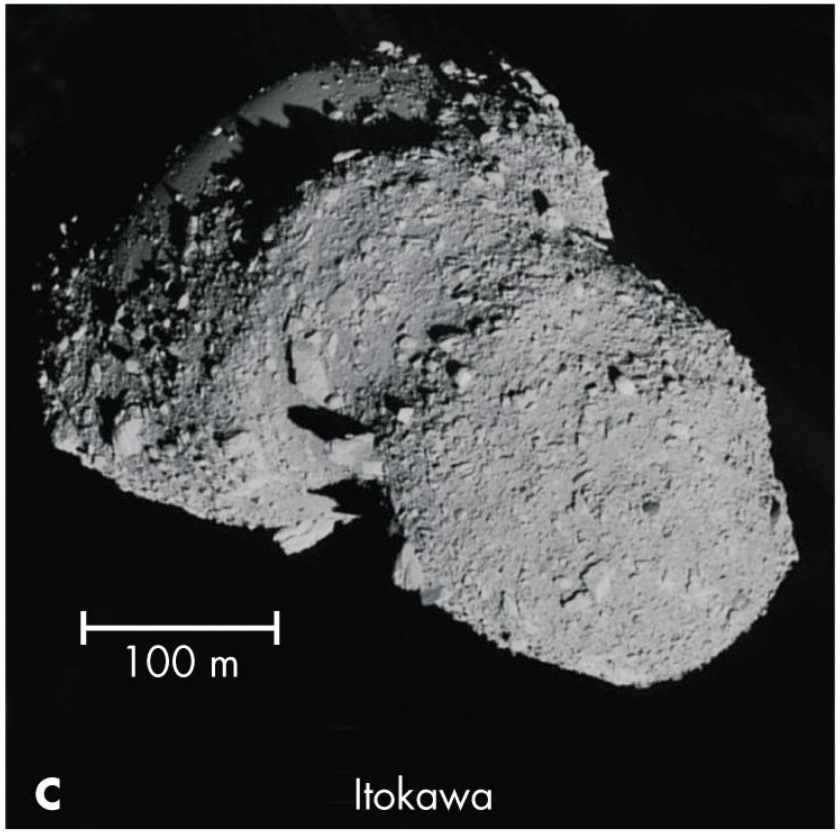





a: NASA/JPL-Caltech/JAXA/ESA

# Asteroid Composition






c: ISAS/JAXA

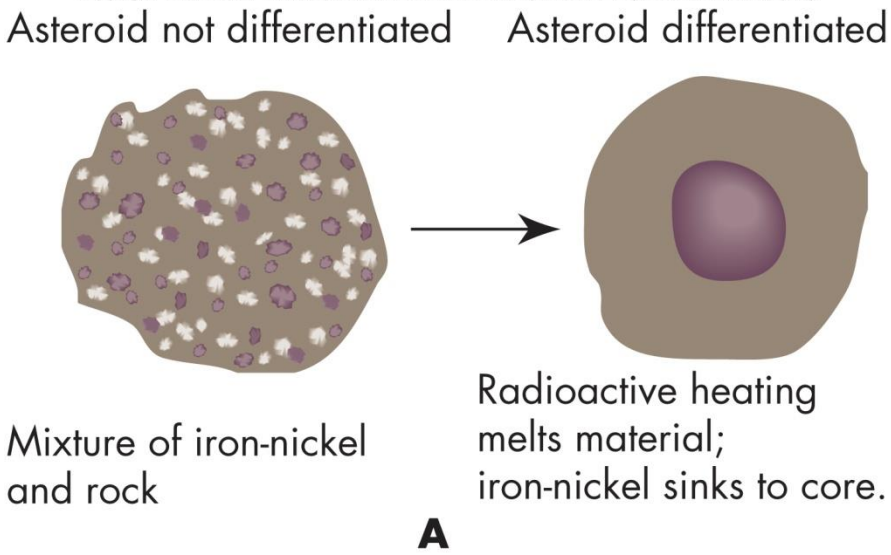
- Reflection spectra show that asteroids belong to three main compositional groups: carbonaceous bodies, silicate bodies, and metallic iron-nickel bodies
- Inner-belt asteroids tend to be silicate-rich and outer-belt asteroids tend to be carbon-rich
- Some asteroids are loose lumps of material held together by gravity

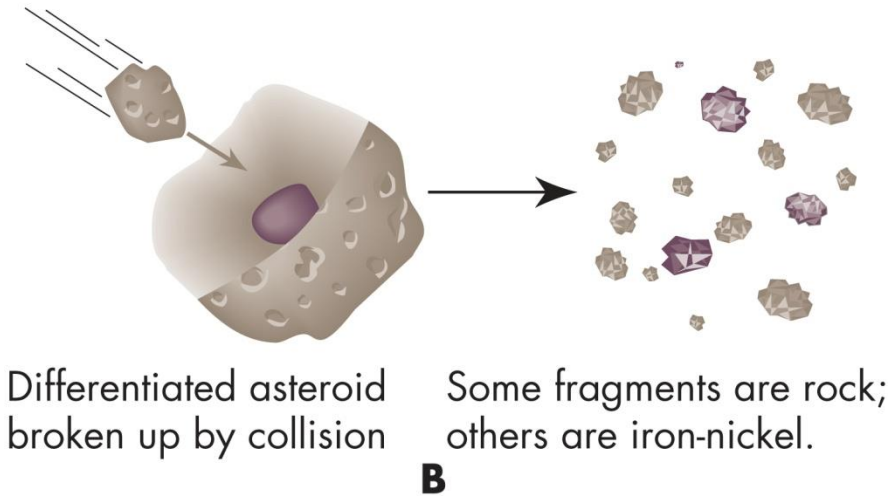
# Origin of the Asteroids

- From their composition, size, and location, asteroids support the solar nebula hypothesis and are thought to be fragments of planetesimals
- For this connection to be established, differentiation needed to occur in large asteroids
- Fragmentation of these early large asteroids (planetesimals) through collisions created the stony and iron asteroids we see today
- Asteroid belt is the result of Jupiter disturbing the accretion process in that zone and preventing a planet from forming

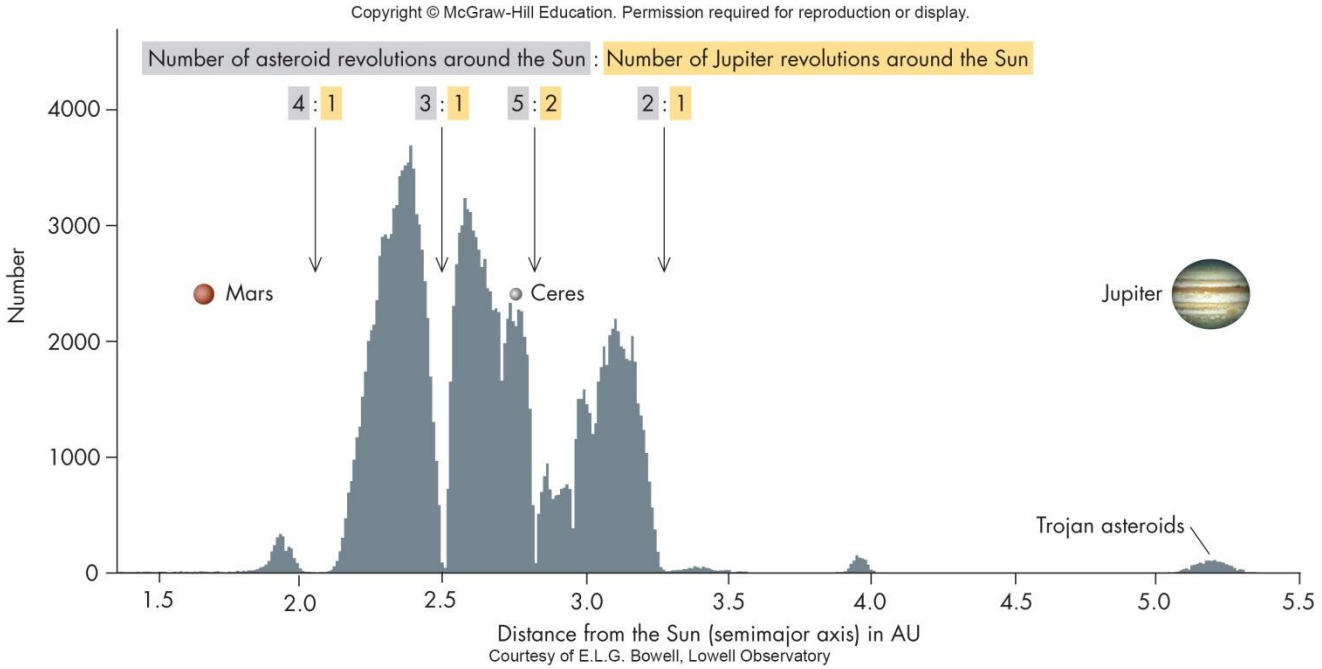
# Origin of Asteroids and Meteoroids





# Asteroid Belt Structure




- Regions of the asteroid belt seemingly empty of asteroids are called ***Kirkwood Gaps***
  - The gaps are caused by the same resonance process that causes the gaps in Saturn's rings
- Trojan asteroids are two loose swarms located along Jupiter's orbit, 60° ahead and 60° behind

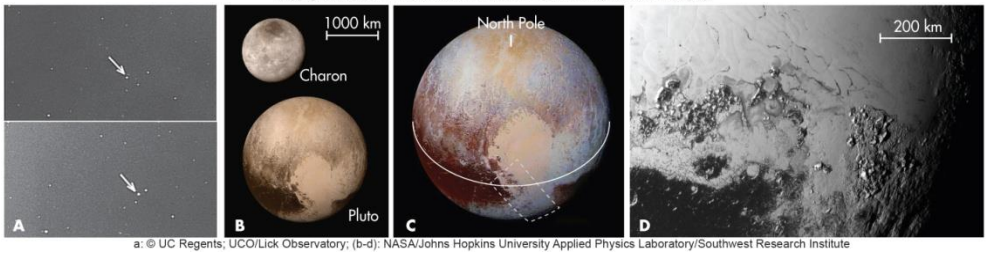
# Near-Earth Objects

- Orbits of ***Near-Earth Objects (NEOs)*** carry them into the inner Solar System and across the Earth's orbit
  - More than 5000 have been found, which represents an Earth collision probability of once every 10,000 years
  - They may be "dead" comets, shifted into their orbits by Jupiter and devoid of surface ice from repeated close trips around the Sun

# Pluto

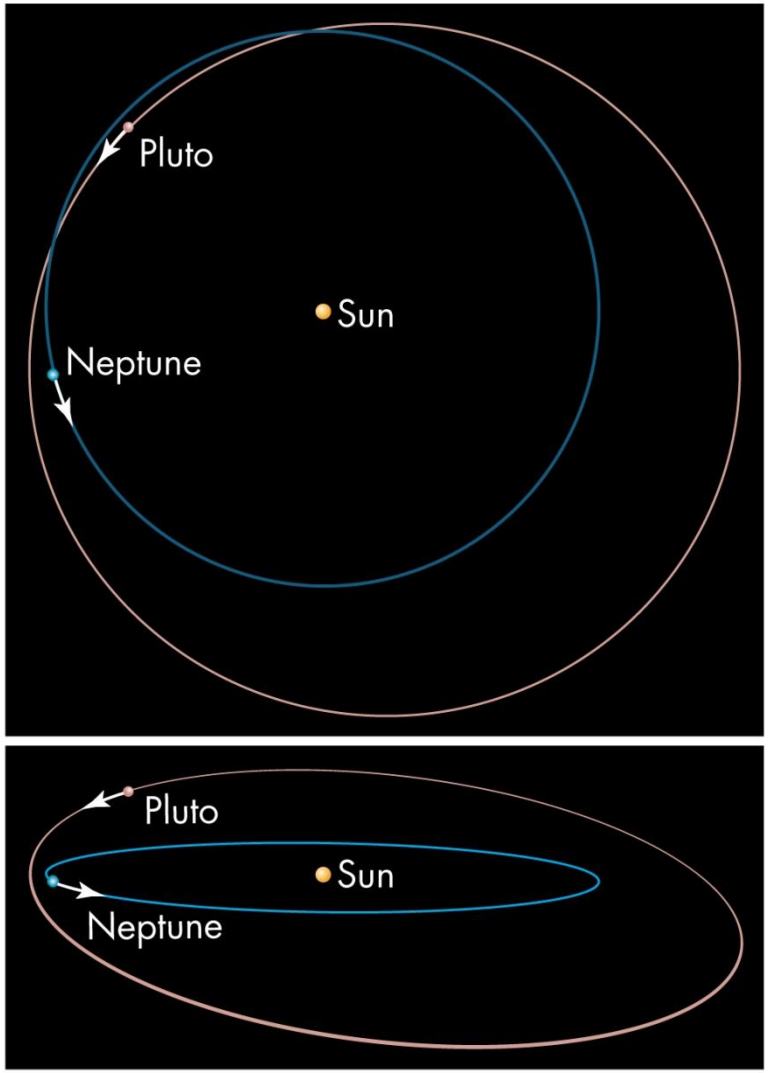
- Discovered by Clyde Tombaugh in 1930 by scanning millions of star images over the course of a year
- Pluto's large distance and very small size make it difficult to study, even in the largest telescopes
- In 1978, James Christy discovered Charon, Pluto's moon
- In 2006, Pluto was classified as a dwarf planet





# Orbit of Pluto

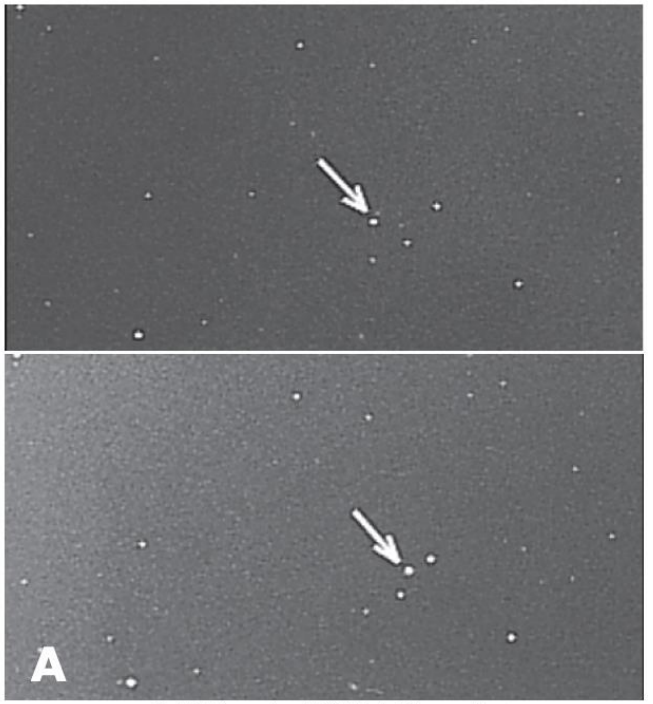




# Pluto and Charon

- The orbiting combination of Pluto and Charon allows an accurate measurement of their masses – Pluto is less massive than any of the planets.
- Charon's steeply tilted orbit implies that Pluto is highly tilted as well
  - Charon takes 6.4 days to orbit Pluto once
  - Pluto rotates with the same period of 6.4 days



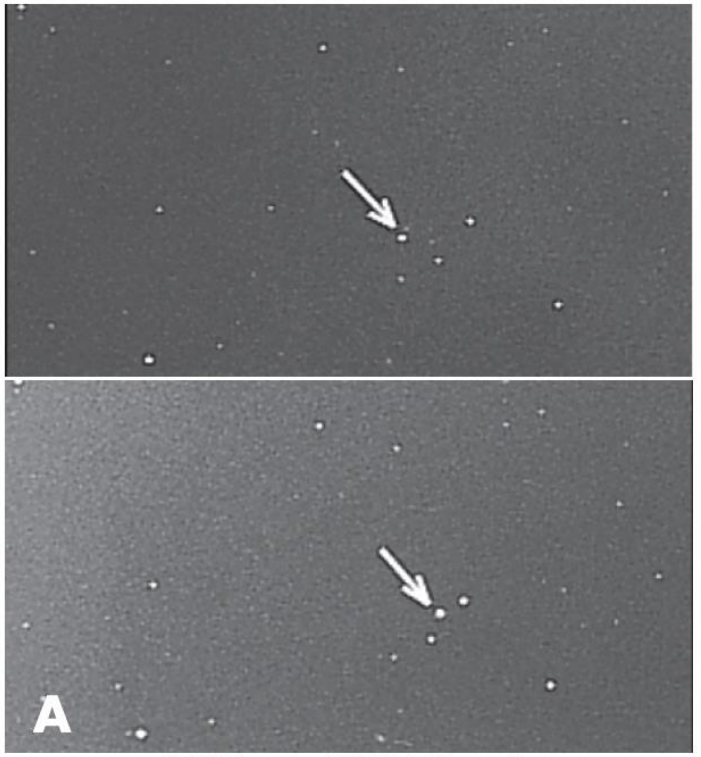



a: © UC Regents; UCO/Lick Observatory

# Size of Pluto and Charon

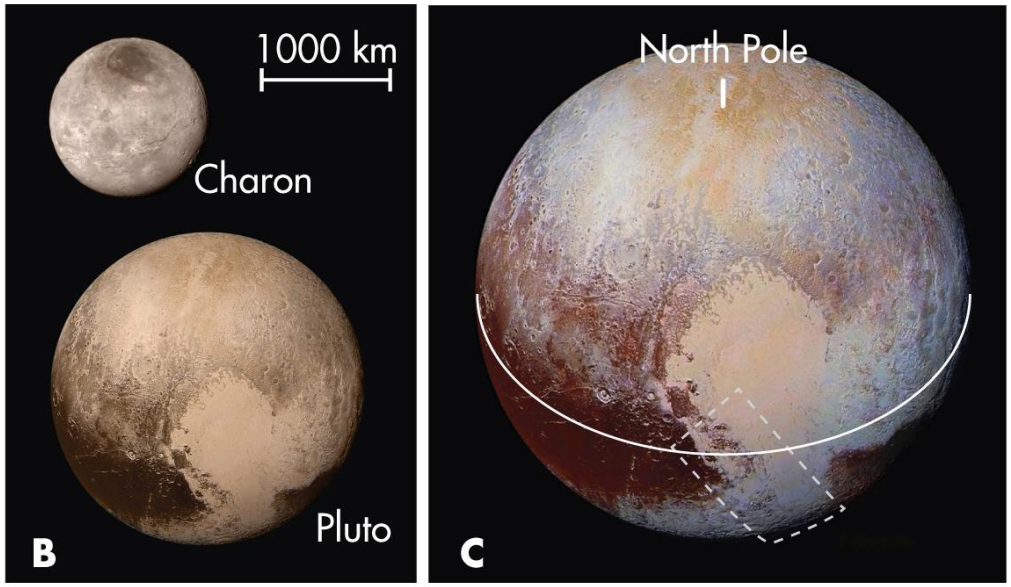
- The recent eclipses of Pluto with Charon have allowed the radii of both objects to be determined
  - Pluto is 1/5 the diameter of Earth
  - Charon is relatively large being about 1/2 Pluto's diameter
- From these masses and diameters, Pluto's density is 2.1 g/cm$^3$, suggesting an object of water, ice, and rock





# New Horizons



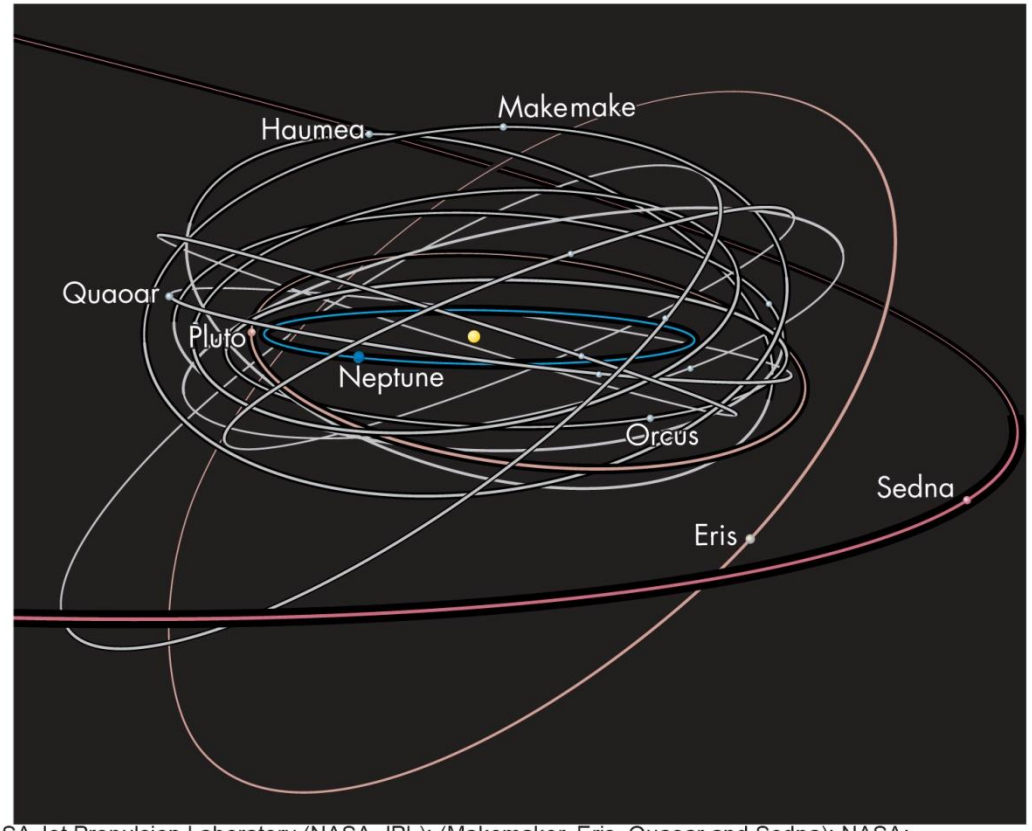



NASA/Johns Hopkins University Applied Physics Laboratory/Southwest Research Institute

- The New Horizons spacecraft flew past Pluto and Charon in the summer of 2015.
- Pluto also has a tenuous atmosphere of $N_2$, CO, and traces of $CH_4$
- New Horizons data will be studied for many, many years to come.
- Insert New Horizons findings as they arrive!

# The Dwarf Planets




(Triton): National Space Science Data Center; (Orcus, Haumea): NASA Jet Propulsion Laboratory (NASA-JPL); (Makemaker, Eris, Quaoar and Sedna): NASA; (Pluto, Charon): Images courtesy of Marc W. Buie/Lowell Observatory

# Comets

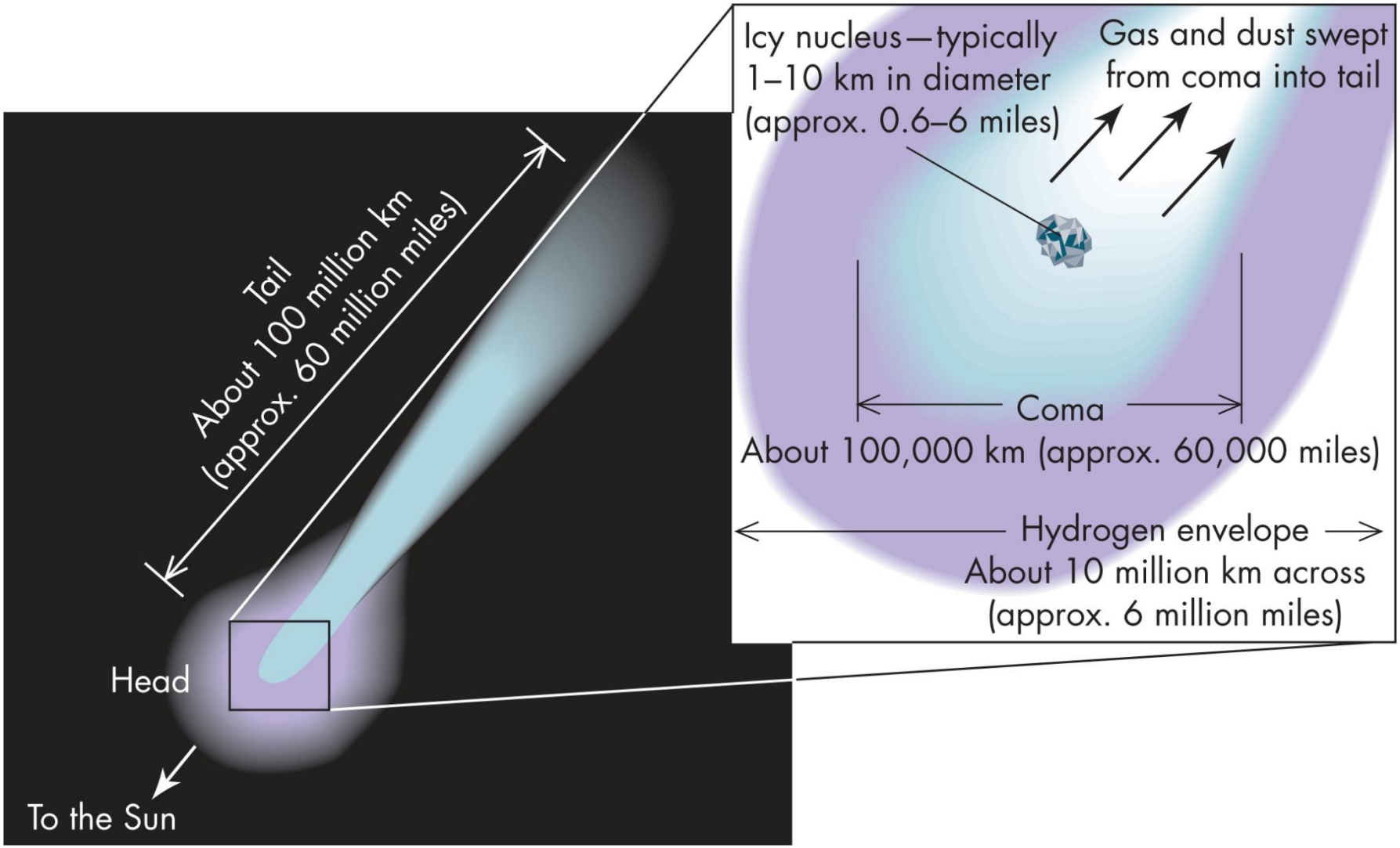
- Comets offer a stunning sight
- Light pollution from cities distracts this view
- Historically, comets held in fear and reverence

# Parts of a Comet

- ***Tail*** **-** Narrow column of gas and dust, it may stretch over 100 million kilometers
- ***Coma*** – Extremely rarified gaseous atmosphere that may reach a diameter of 100,000 km
- ***Nucleus*** – A "dirty snowball" roughly 10 km across and containing most of the comet's mass
  - *Giotto* spacecraft to Comet Halley determined a nucleus density of about 0.2 g/cm$^3$ indicating that comets are "fluffy" as opposed to compacted icy material

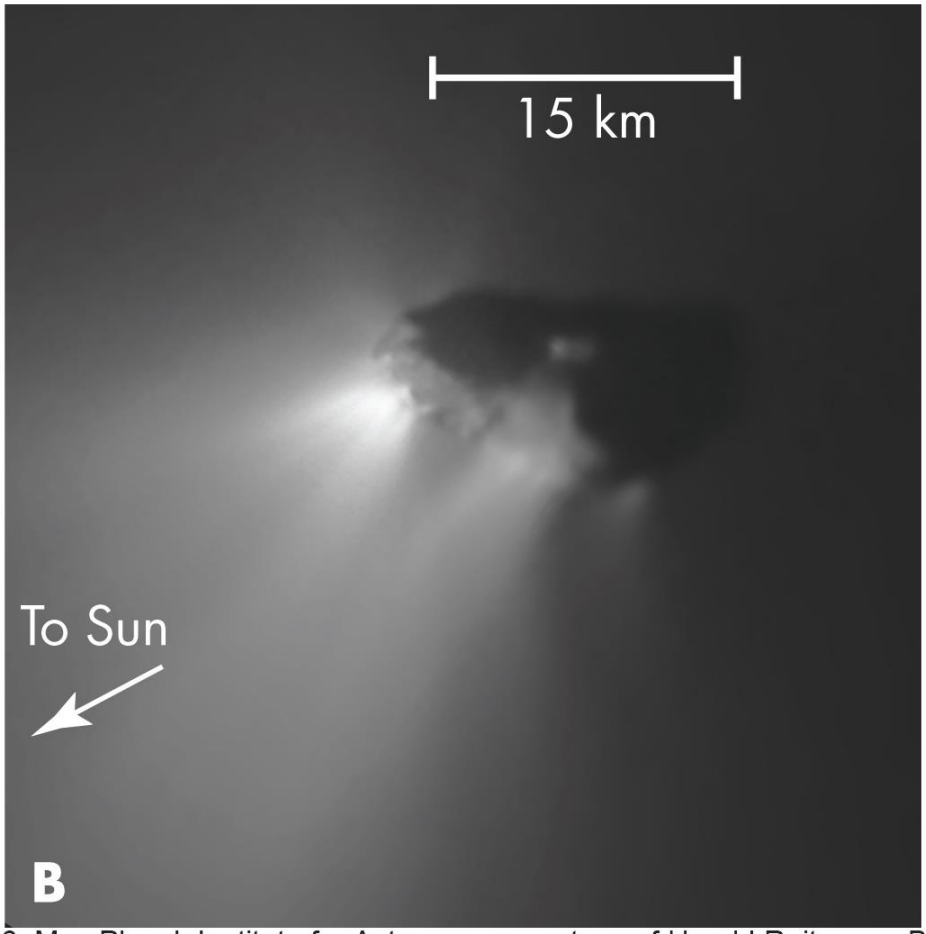
# Structure of Comets





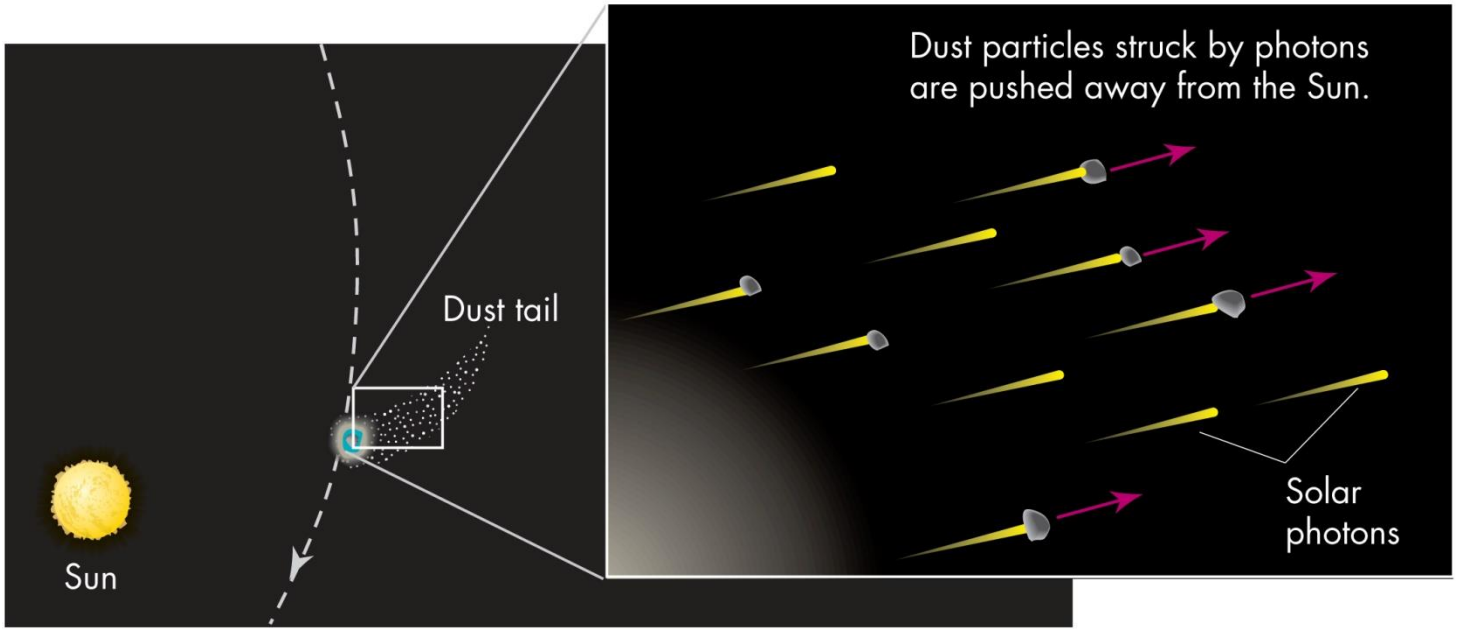
# Nucleus of Comet Halley





# The Comet's Tail

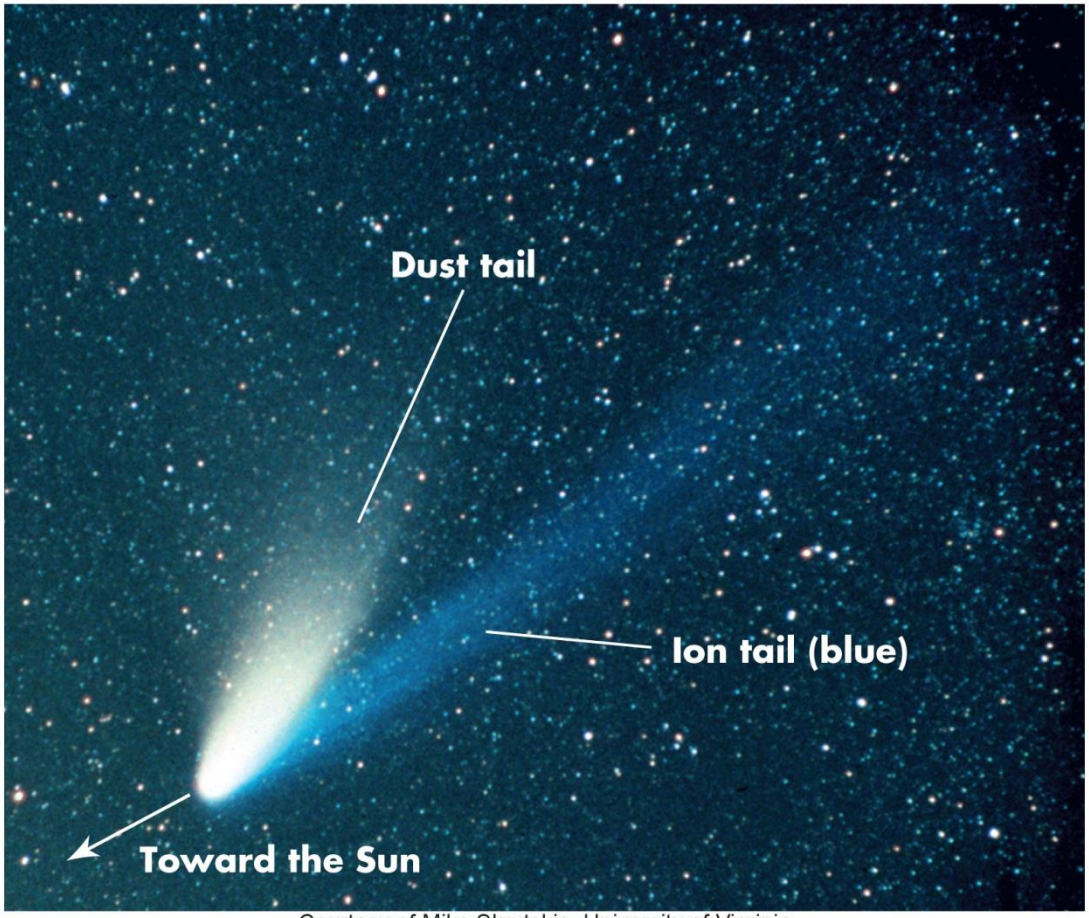





- ***Radiation pressure*** drives emitted cometary dust into a dust tail
- A second tail, a gas tail, is created by the interaction of the comet's emitted gas and the ***solar wind***

# Two Tails



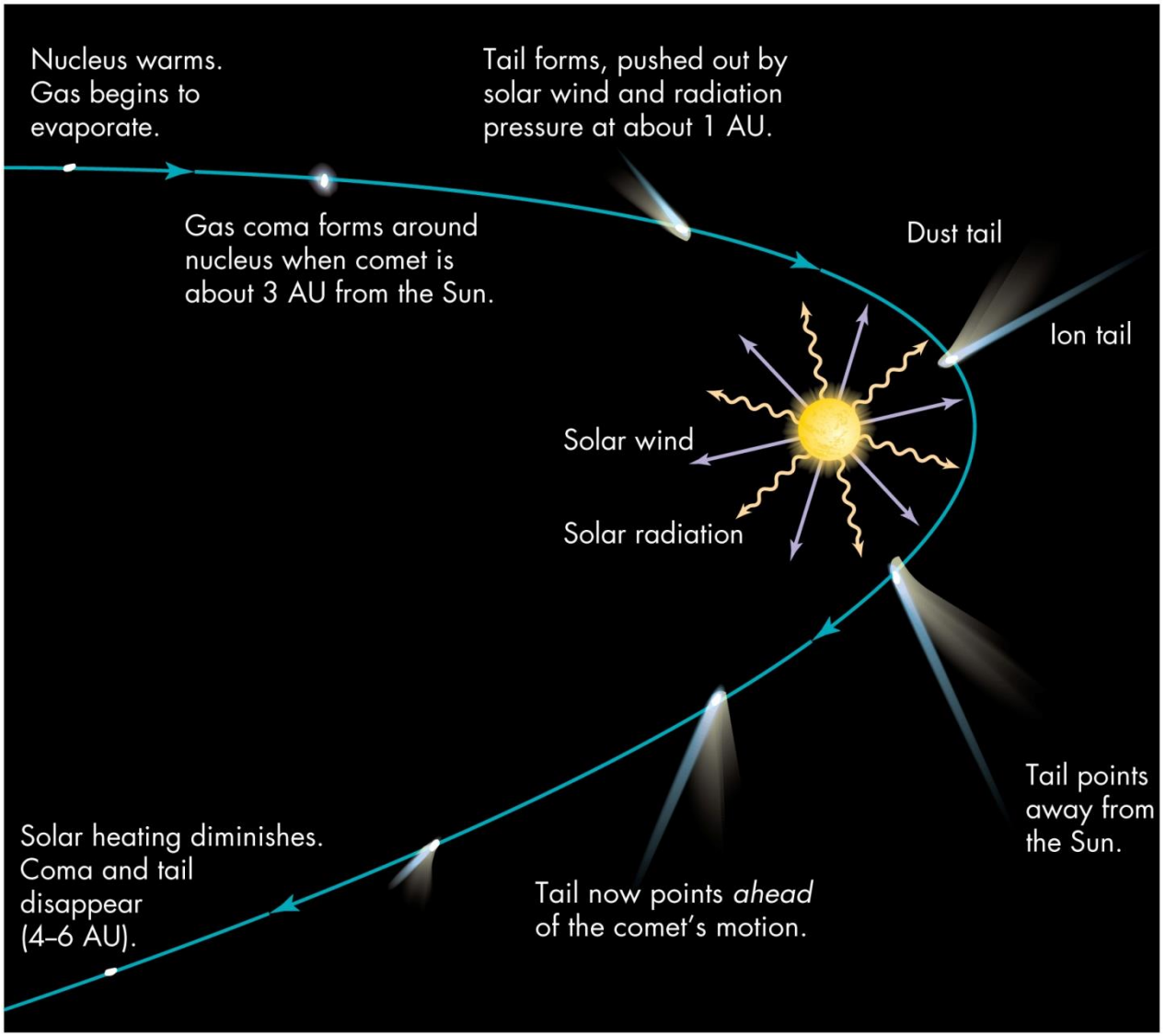



Courtesy of Mike Skrutskie, University of Virginia

- Since both the solar wind and solar radiation move away from the Sun, comet tails always point away from the Sun

# Tail Evolution



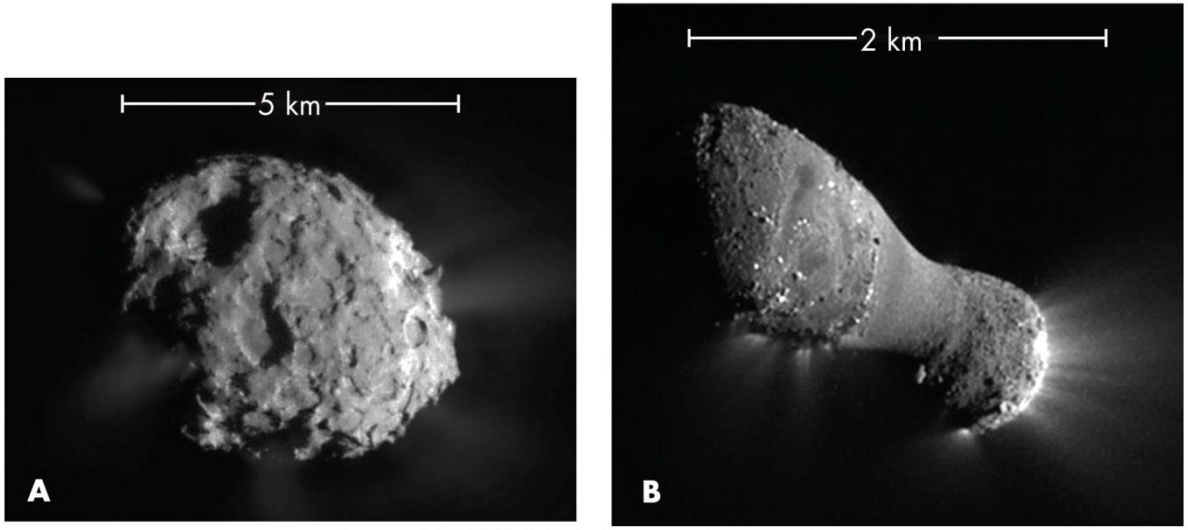


# Composition of Comets

- Spectra of coma and tail shows comets are rich in water, $CO_2$, CO, and small amounts of other gases
- Evaporating $H_2O$ is dissociated by solar ultraviolet radiation creating a large hydrogen cloud around the comet
- *Fluorescence* is the source of a large portion of the comet's light
- Repeated passage by Sun eventually erodes a comet's gas production ability

# Spacecraft Exploration of Comets



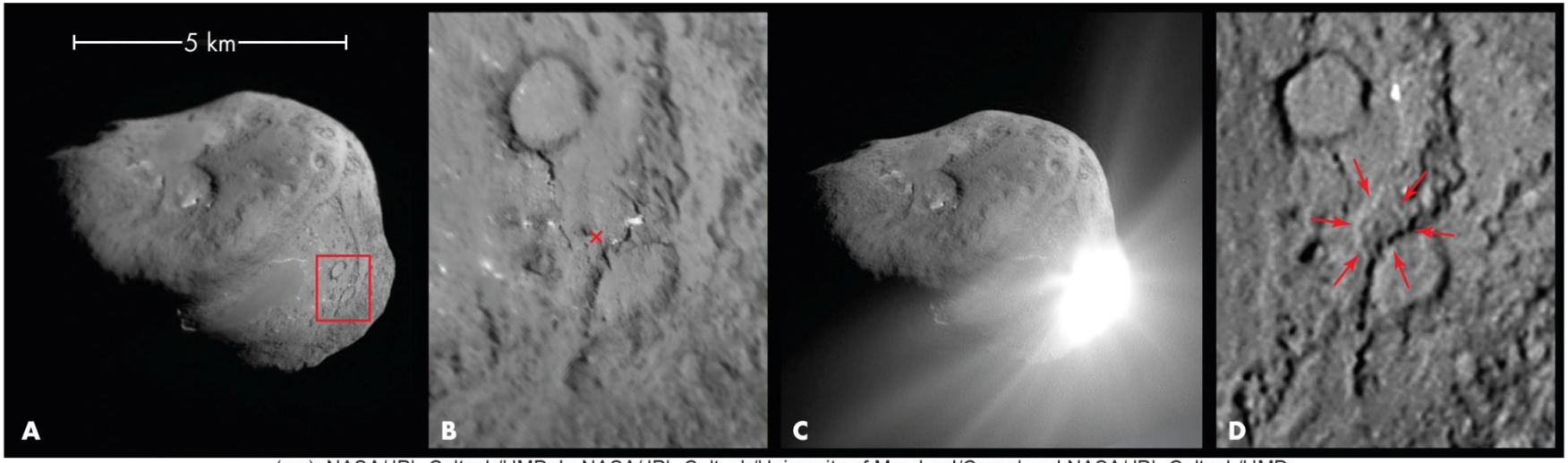



a: Courtesy NASA/JPL-Caltech.; b: NASA/ JPL-Caltech/UMD

- NASA's Stardust and Deep Impact missions have contributed to our understanding of a comet's composition
- Silicates, clays and other water-based crystals were discovered!

# Comet Tempel 1



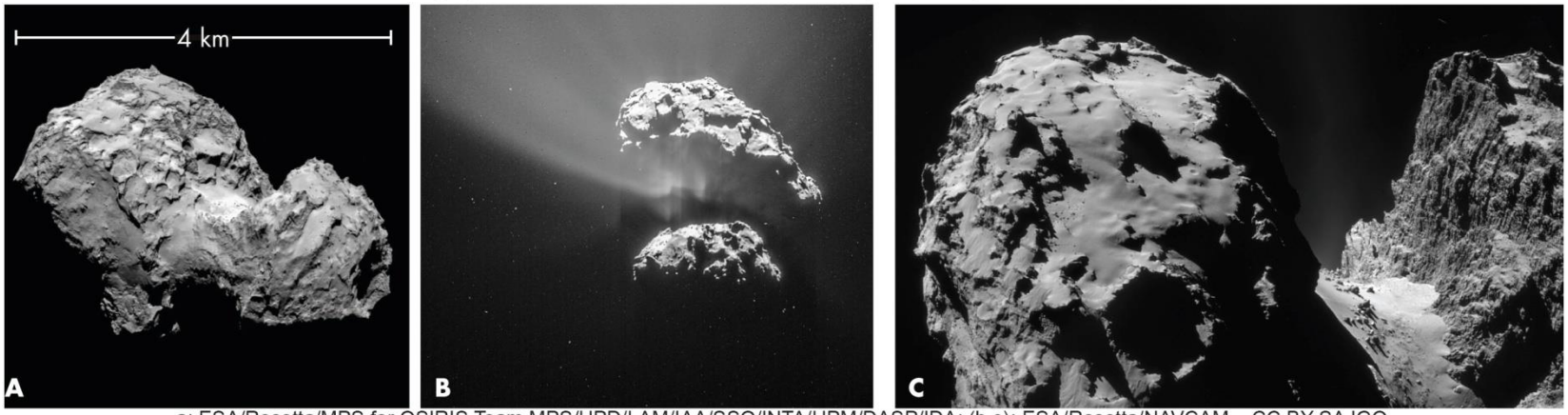



(a,c): NASA/JPL-Caltech/UMD; b: NASA/JPL-Caltech/University of Maryland/Cornel and NASA/JPL-Caltech/UMD;
d: NASA/JPL-Caltech/Cornell

- NASA's Deep Impact mission, smashed a 370-kilogram probe into Comet Tempel 1 at a relative speed of just over 10 kilometers per second (about 23,000 mph).
- The impact was designed to break through the comet's outer crust and stir up and release dust and gas.

# Comet Churyumov-Gerasimenko





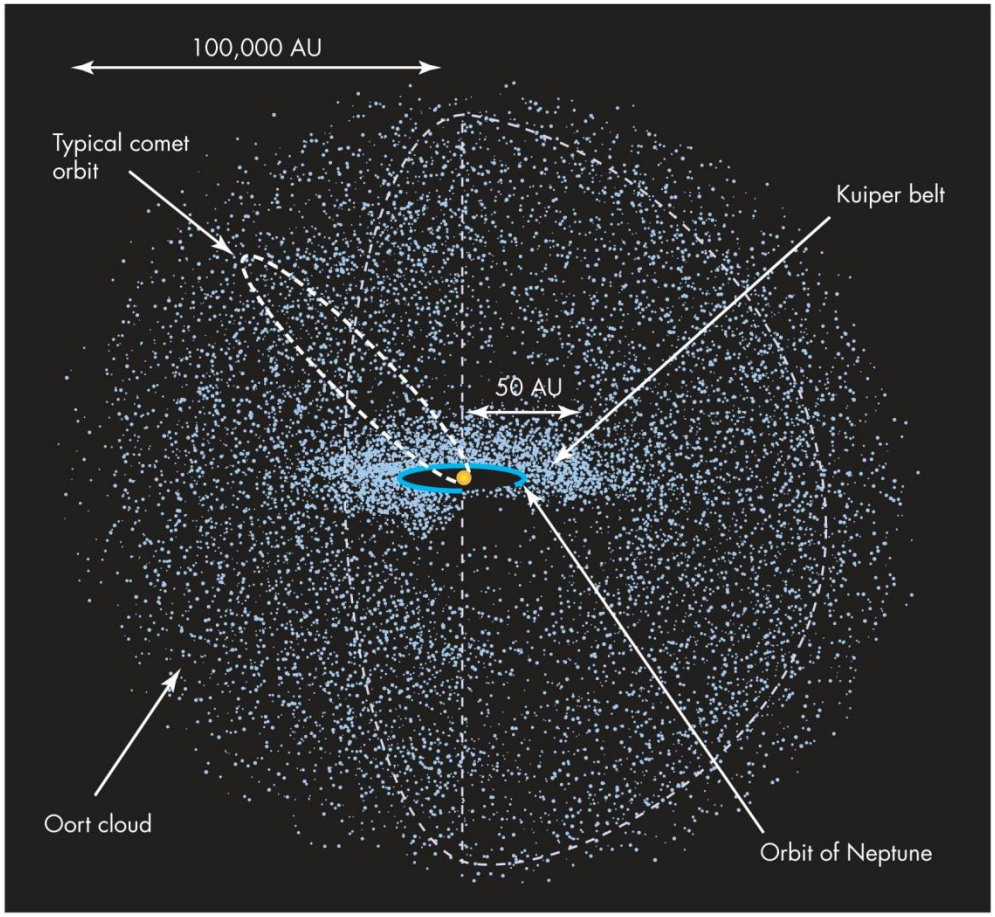

a: ESA/Rosetta/MPS for OSIRIS Team MPS/UPD/LAM/IAA/SSO/INTA/UPM/DASP/IDA; (b,c): ESA/Rosetta/NAVCAM – CC BY-SA IGO

- Rosetta spacecraft put a probe on the comet's surface.
- Water sampled on the surface is very different from Earth's oceans.

# Origin of Comets

- Most comets come from the ***Oort Cloud,*** the spherical shell of trillions of icy bodies believed to lie far beyond Pluto's orbit to a distance of about 150,000 AU



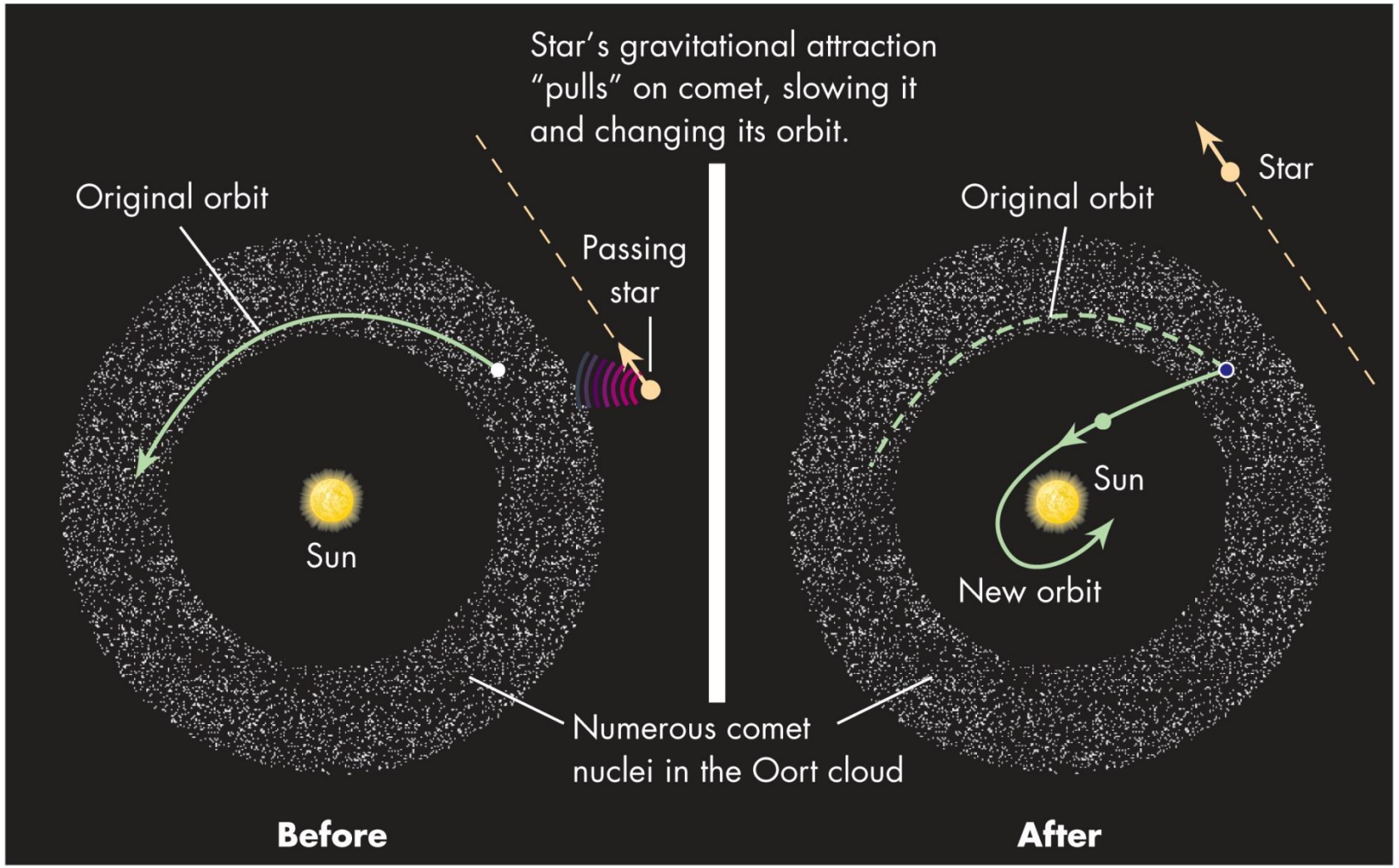


# The Oort Cloud

- Originally orbiting among the giant planets as planetesimals, comets were tossed into the Oort cloud by those planets
- The shape of the Oort cloud is determined from observations of comet orbits
  - Some comet orbits seem to come from a flatter, less remote region – the ***Kuiper belt,*** which extends from Neptune's orbit out to some unknown distance
- Comets in the Oort cloud are a frigid 3 K and only warm up enough to emit gas when they enter Solar System, especially as they pass Jupiter

# Incoming Comet!



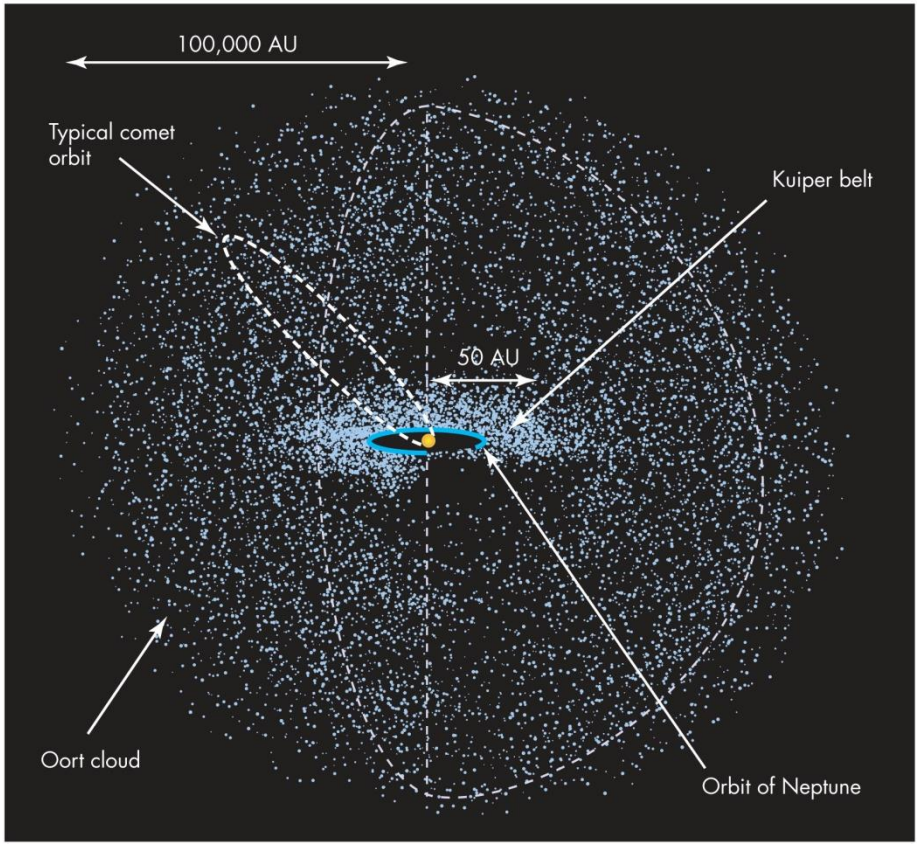


# Short Period Comets

- Most comets seen on Earth are “one-time” visitors, having periods of thousands and millions of years
- A small number of comets have periods of less than 200 years – these are the ***short-period comets***
- Repeated passages around the Sun eventually deplete the comet of its icy material

# Origin of Short-Period Comets






- Short-period comets are now believed to be icy nuclei from the Kuiper belt
  - Support for this comes from the detection of over 800 small, presumably icy, bodies orbiting near and somewhat beyond Pluto
  - Statistical analysis indicates that the Kuiper belt may have an total mass far greater than that found in the asteroid belt

# Shooting Stars

- Typically one can see a meteor in a clear dark sky once every 15 minutes – most of these are stray fragments of asteroids that arrive at Earth randomly

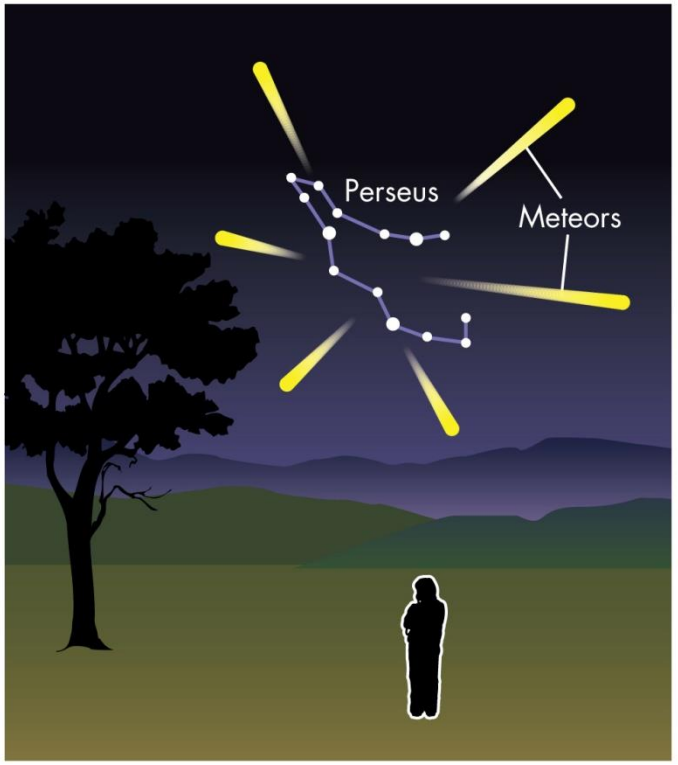


Courtesy of Ronald A. Oriti, Santa Rosa Junior College, Santa Rosa, Calif.

# Comets and Meteor Showers

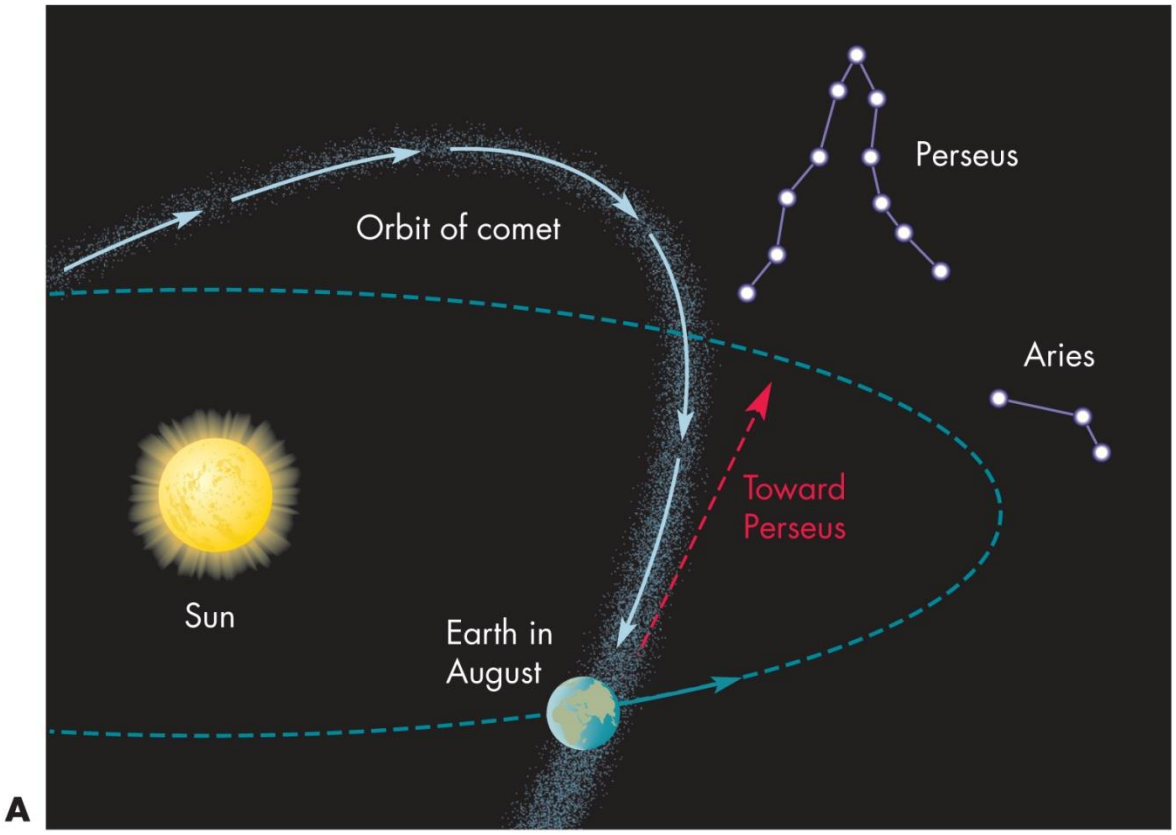
- Meteors seen at a faster rate (one every few minutes or less) and from the same general direction in the sky are called ***meteor showers***
- The point in the sky from which the meteors seem to emerge is called the ***radiant***





# Debris from Comets



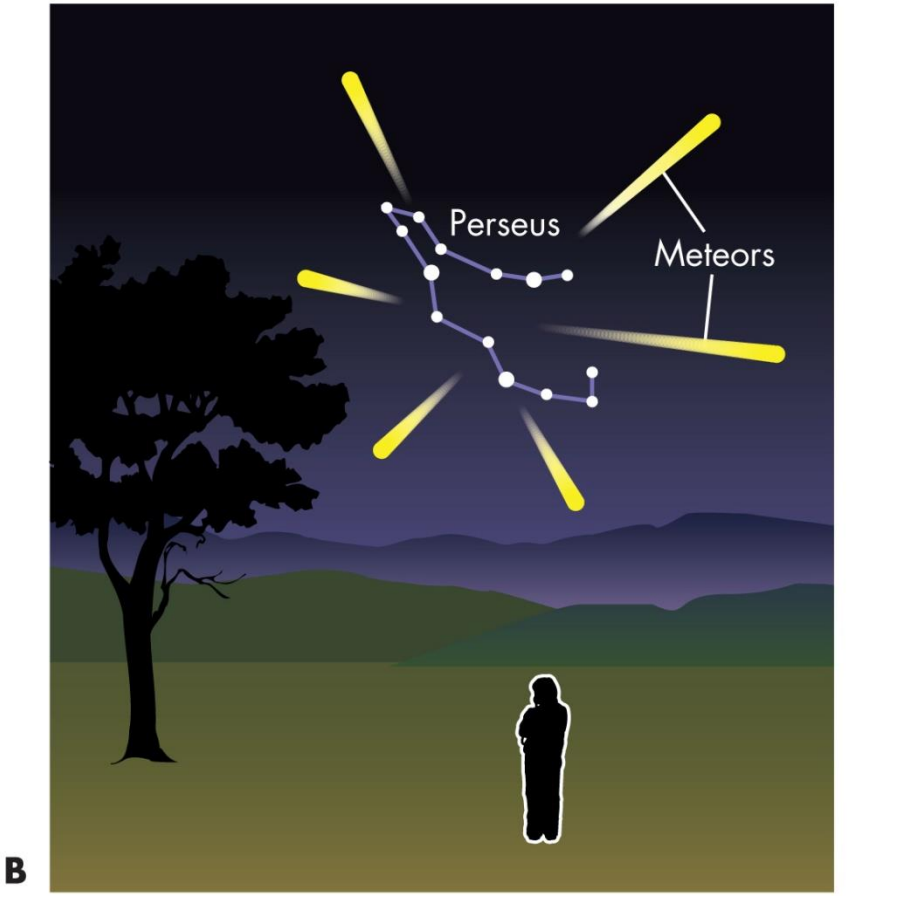



- A meteor shower is the result of a comet filling its orbit with emitted dust and the Earth passing through the dust-filled orbit

# Names of Meteor Showers

- Meteor showers are typically named after the constellation where the radiant is located – the Perseid meteor shower has its radiant in Perseus

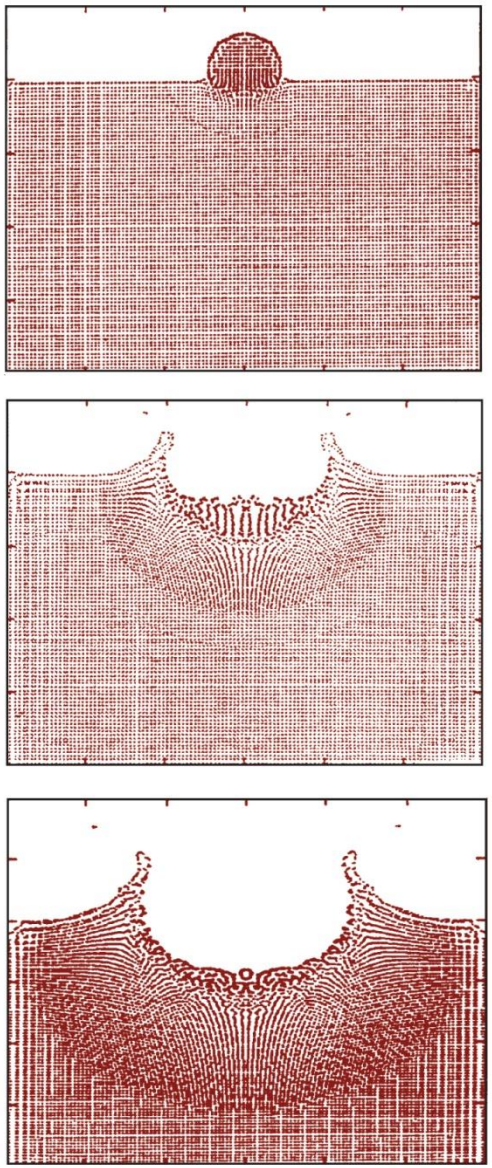




# Giant Impacts

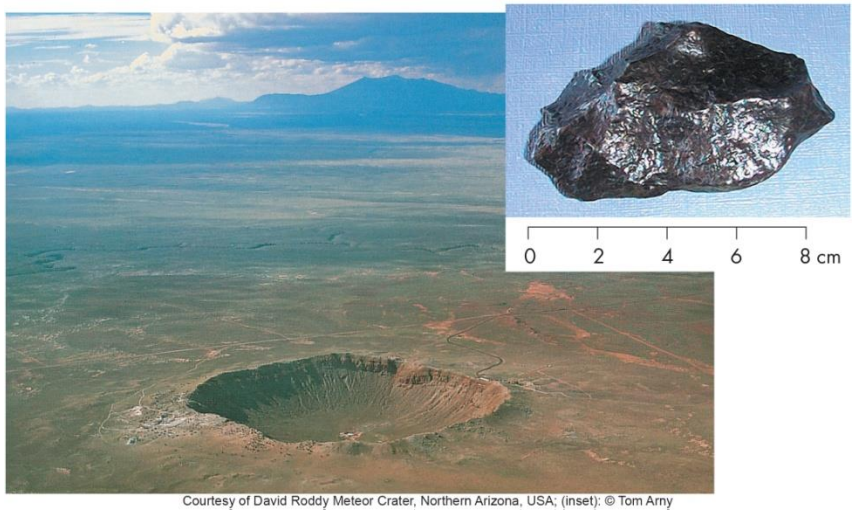


- Every few thousand years, Earth is hit by a huge meteoroid, a body tens of meters or more in size
- A typical 100 kg meteoroid has the kinetic energy equivalent of 100 tons of dynamite, which would make a crater 30 meters across
- A 10-meter meteoroid has the explosive power of a thermonuclear bomb and would leave a kilometer-wide crater



# Giant Meteor Craters






Courtesy of David Roddy Meteor Crater, Northern Arizona, USA; (inset): © Tom Arny

- The giant crater in northern Arizona is 1.2 km across and 200 m deep, and was probably created 50,000 years ago by a 50-meter meteoroid
- In 1908, an asteroid broke up in the atmosphere in a remote region of Siberia, the Tunguska event, flattening trees out to 30 km

# Meteor Explosion over Russia



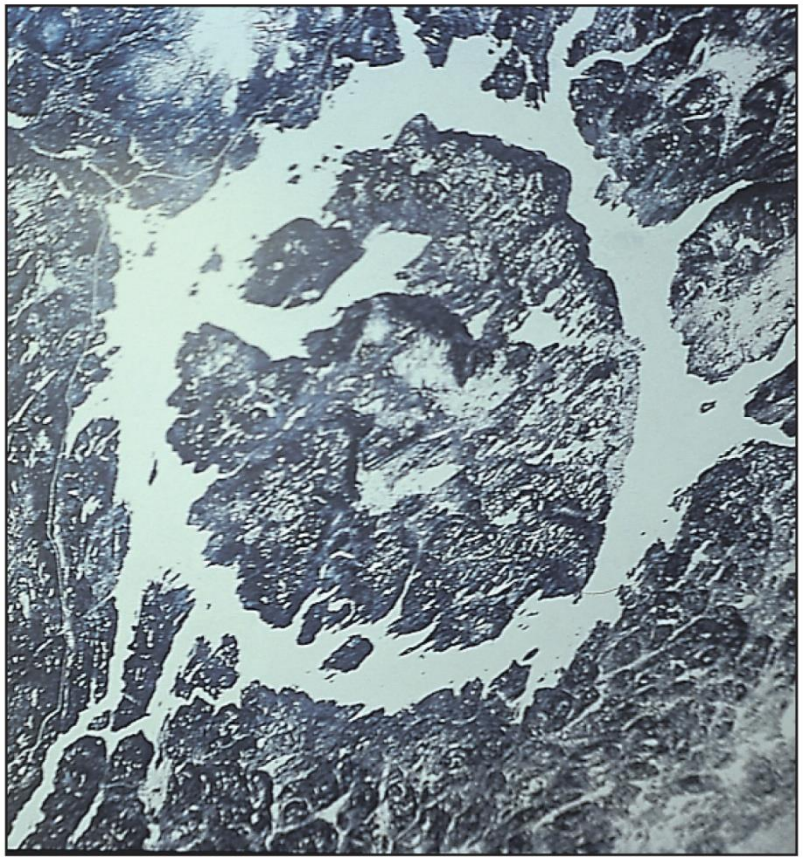



- A large meteor exploded over Russia in 2013.
- The shock wave from the blast blew in windows, injuring more than a thousand people.
- The original asteroid may have been about 17 meters in diameter.

# Other Meteor Craters

- Other impacts sites exist
  - Ring-shaped Manicouagan Lake in Quebec with a diameter of 70 km
  - Vast arc on east edge of Hudson Bay (500 km)
  - A basin in central Europe (300 km)






Courtesy of Landsat/ESO

# Mass Extinction and Impacts

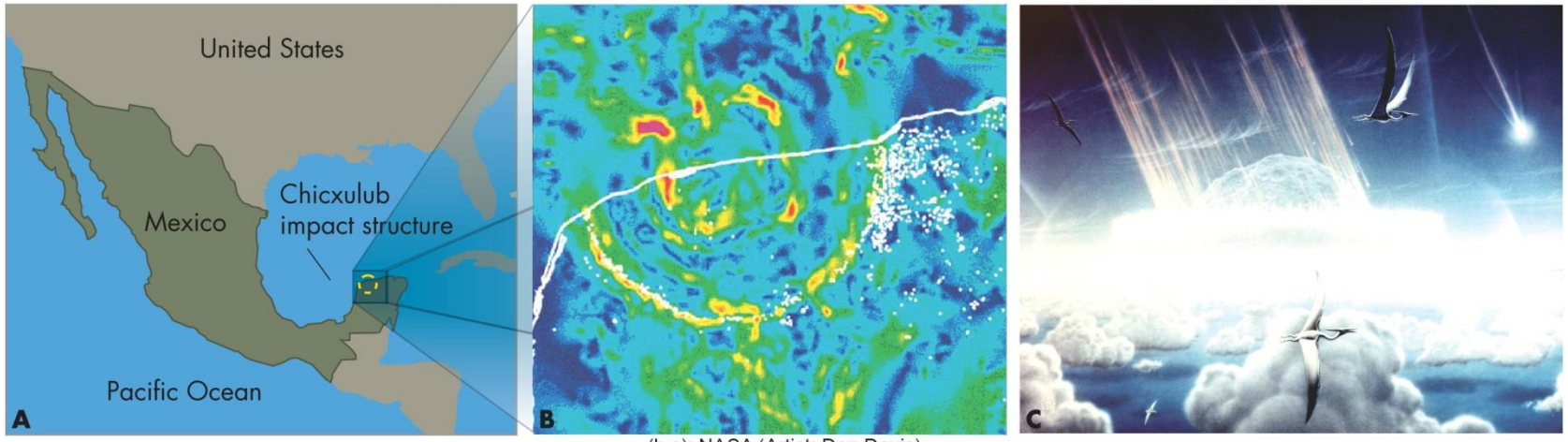
- About 65 million years ago, at the end of the Cretaceous period, an asteroid or comet hit the Earth exterminating the dinosaurs and many other life forms
- Evidence for an extraterrestrial cause of the extinction is the high abundance of the otherwise rare element iridium in the sediments of the time
- The amount of iridium found suggests a 10-km asteroid hit the Earth

# An Extinction-level Impact

- A 10-km asteroid would produce the explosion equivalent of several billion nuclear bombs
- Initial destruction by high temperatures, blast, and acid rain would be followed by months of darkness and intense cold as the Sun's light is blotted out by clouds of dust
- Further evidence of the impact is a layer of soot, tiny quartz pellets, and a circular depression near Chicxulub in the Yucatán region of Mexico
- Cretaceous mass extinction led to rise of mammals
- Other mass extinctions have occurred before and after, but may be related to massive volcanic eruptions or drastic changes in sea level

# The Chicxulub Impact Structure






(b,c): NASA (Artist: Don Davis)