Lecture 15: Small Solar System Bodies

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Astro 18: Planets and Planetary Systems

UC Santa Cruz

Outline of lecture

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

First, some definitions

- **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**

The Main Points, part 1

- Asteroids
  - Failed planetesimals in outer Solar System
  - Fairly circular orbits
  - Mostly in “Kuiper Belt” beyond Neptune
- Pluto and Charon
  - Similar to Kuiper Belt asteroids in many ways
- Comets
  - Highly elliptical orbits
  - “Dirty snowballs” - agglomerations of rock and ice
  - Born in “Oort Cloud” that surrounds Solar System

The Main Points, part 2

- **Meteorites**
  - **Some are identifiable pieces of the Moon, Mars, or Vesta; most are pieces of asteroids**
  - **Broken off their parent bodies 10's to 100's of million years ago ("recently")**
  - **Oldest meteorites contain unprocessed material from when the Solar System formed**

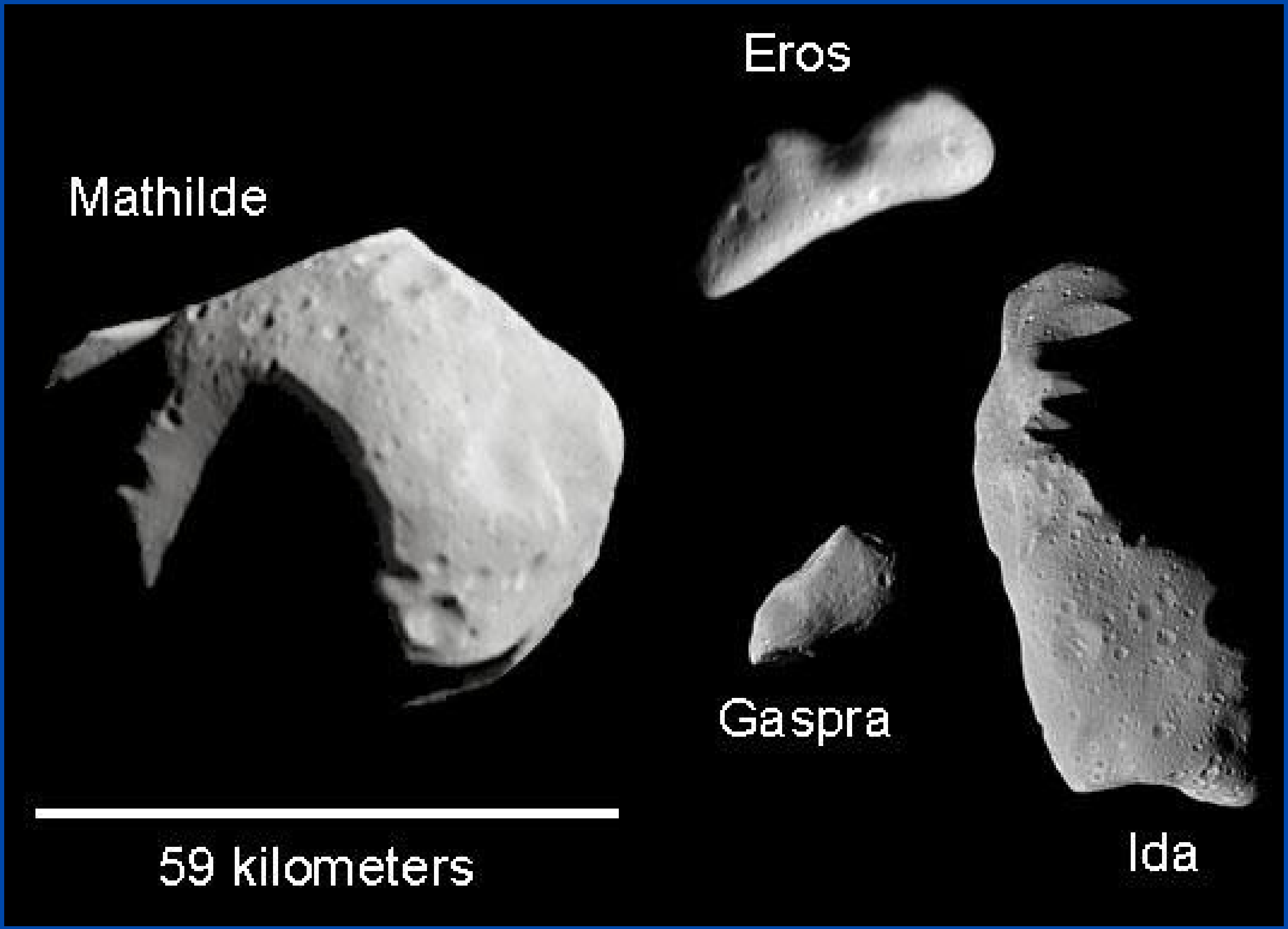
- **Cosmic Collisions**
  - **Major role in evolution of Solar System, Earth**
  - **Significant collision with s Near Earth Objects is not improbable today**

Asteroids as seen from Earth

Vesta (525 km)
Keck Tel. Adaptive Optics.
Movie in spectral line of pyroxene.

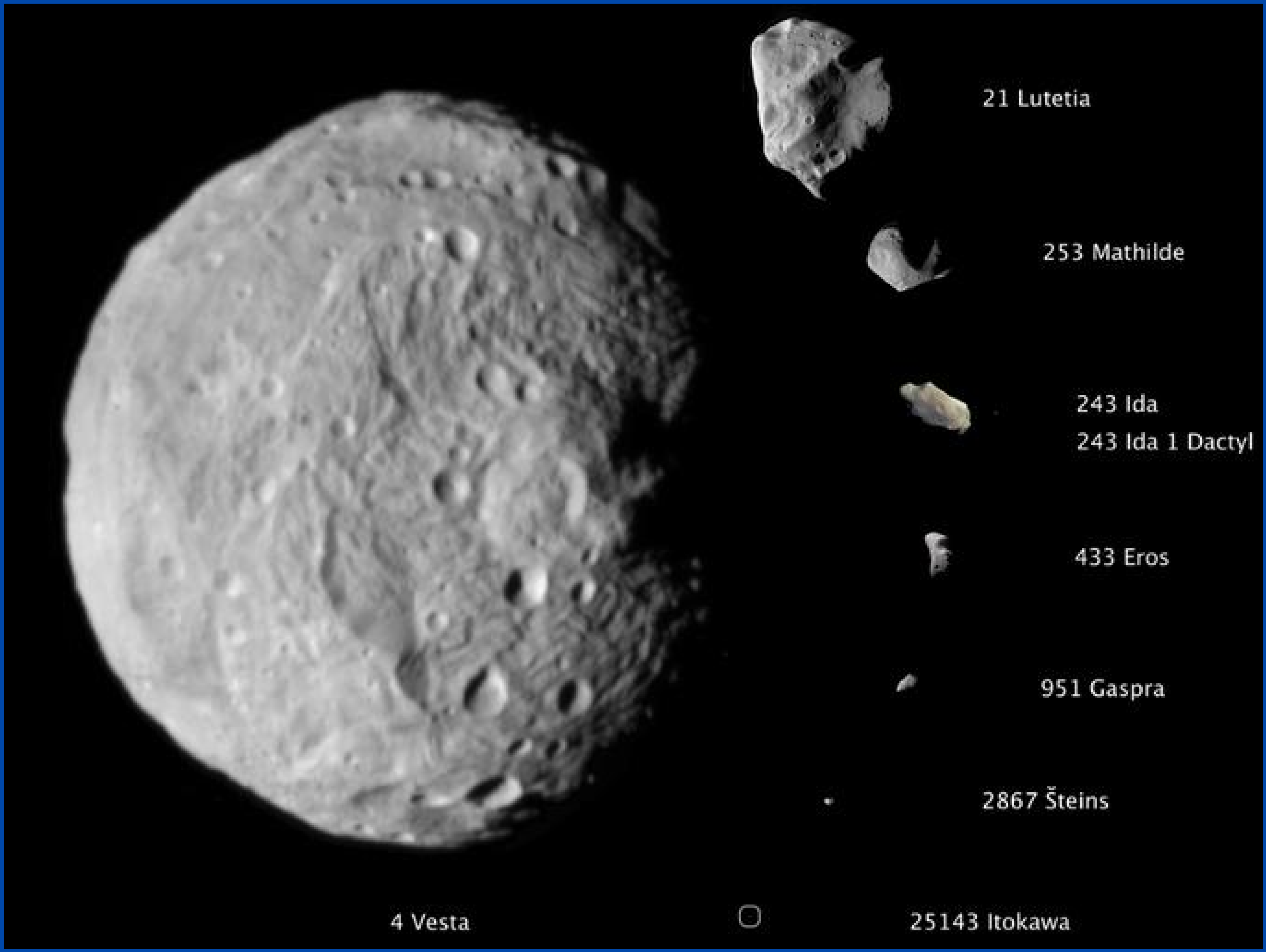
A piece of Vesta landed on Earth as a meteorite!
Made almost entirely of pyroxene.

Some asteroids photographed by spacecraft (up close)

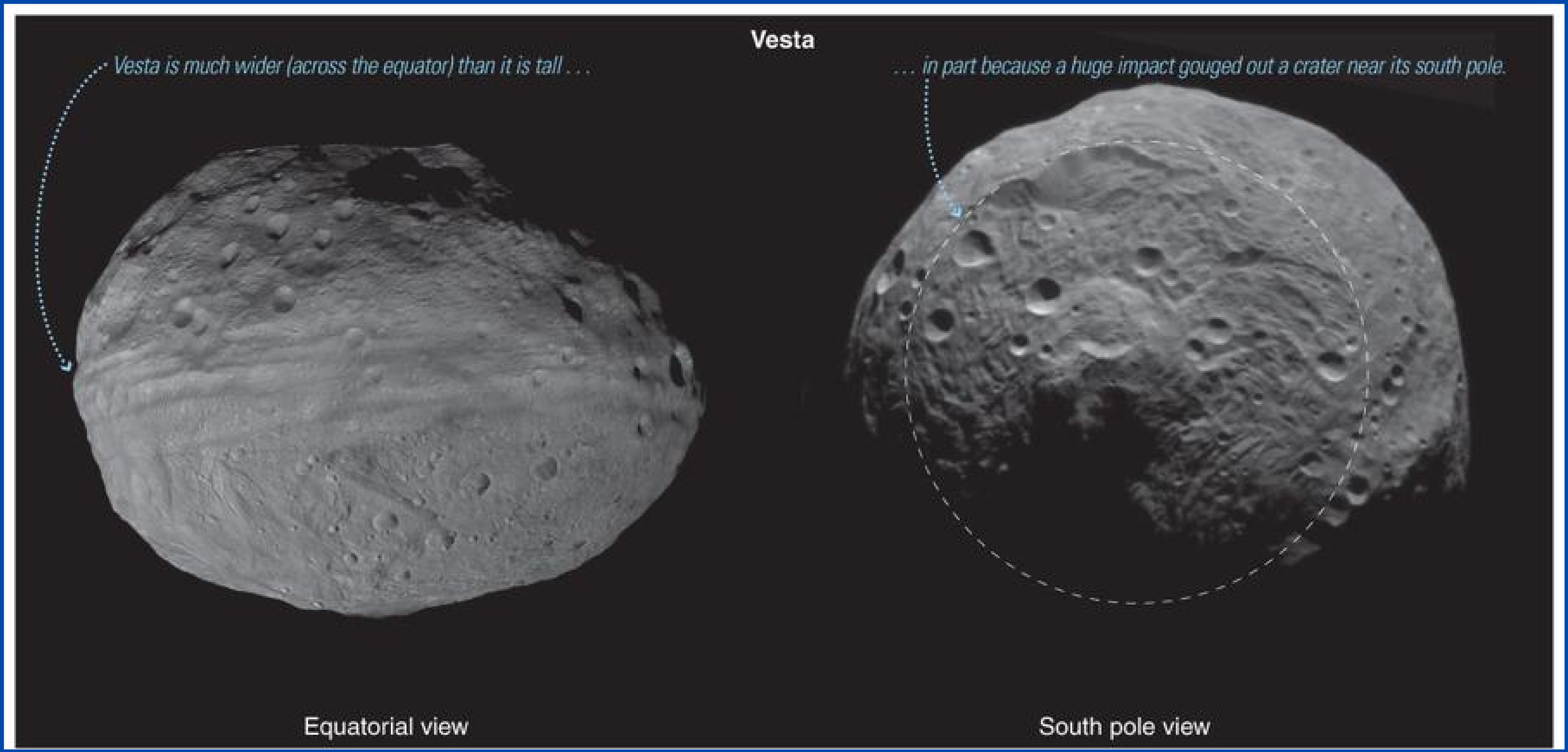


Asteroids as seen from space

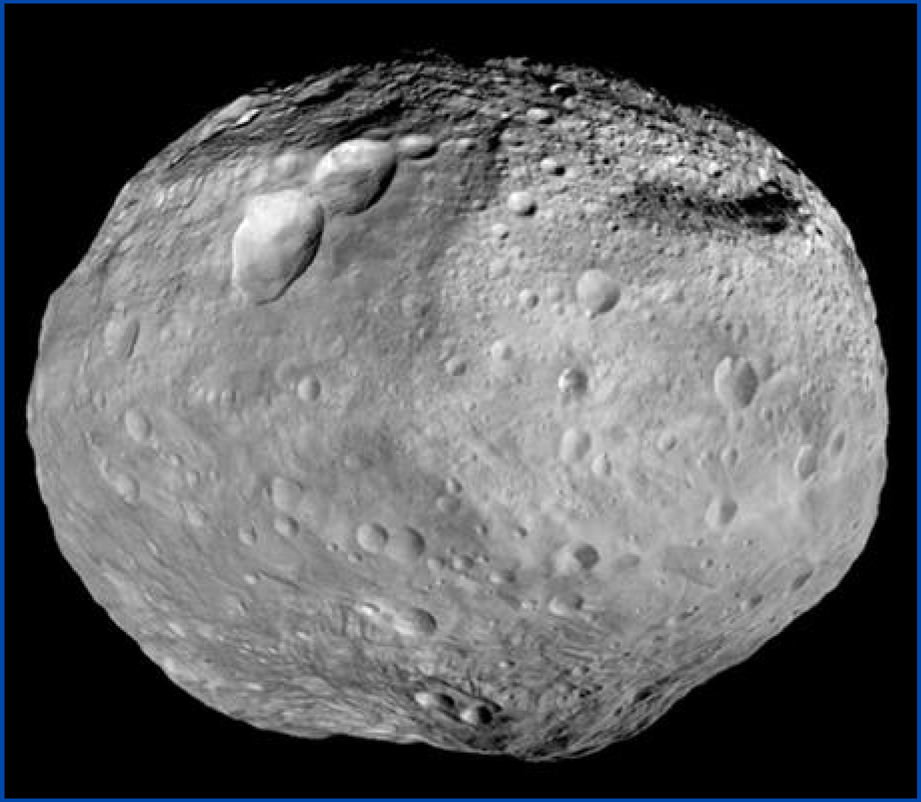
Vesta was reclassified as a “dwarf planet”

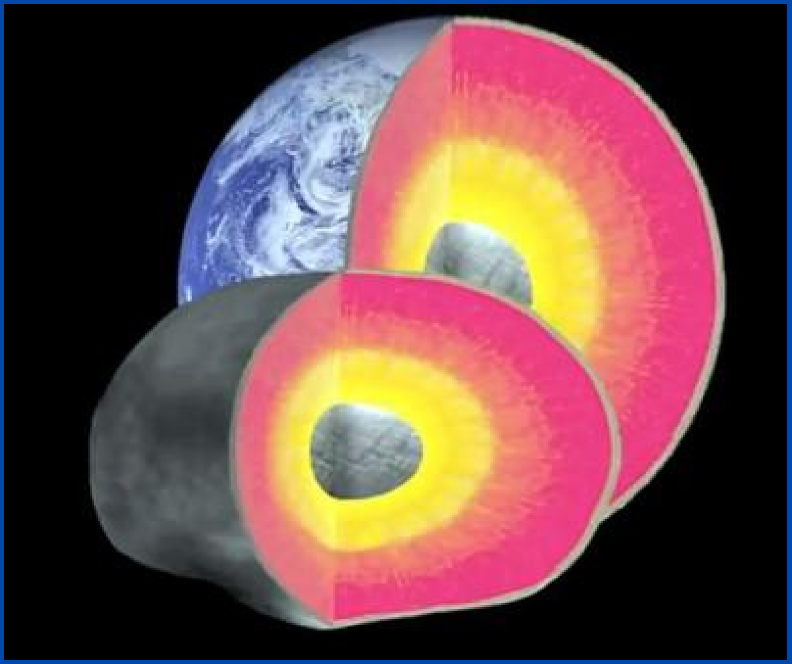


Vesta as seen by the Dawn Spacecraft



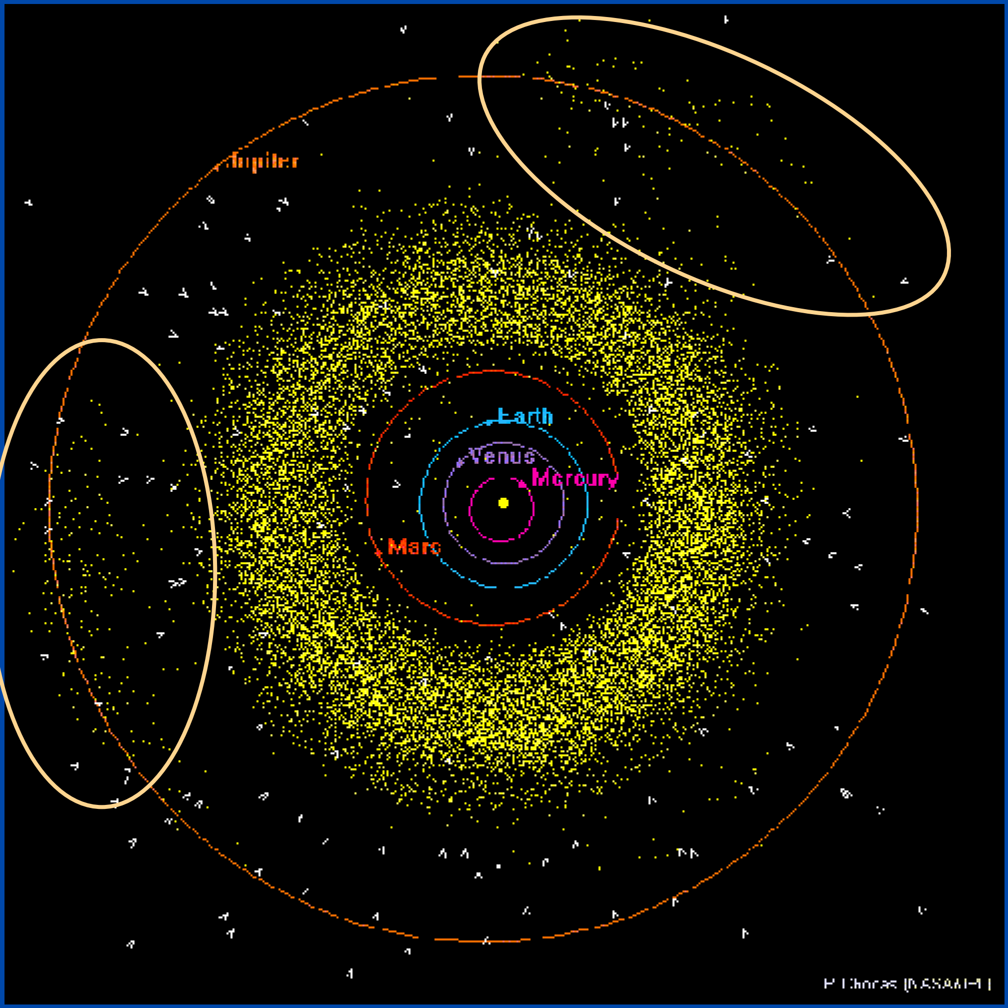
Vesta has differentiated interior



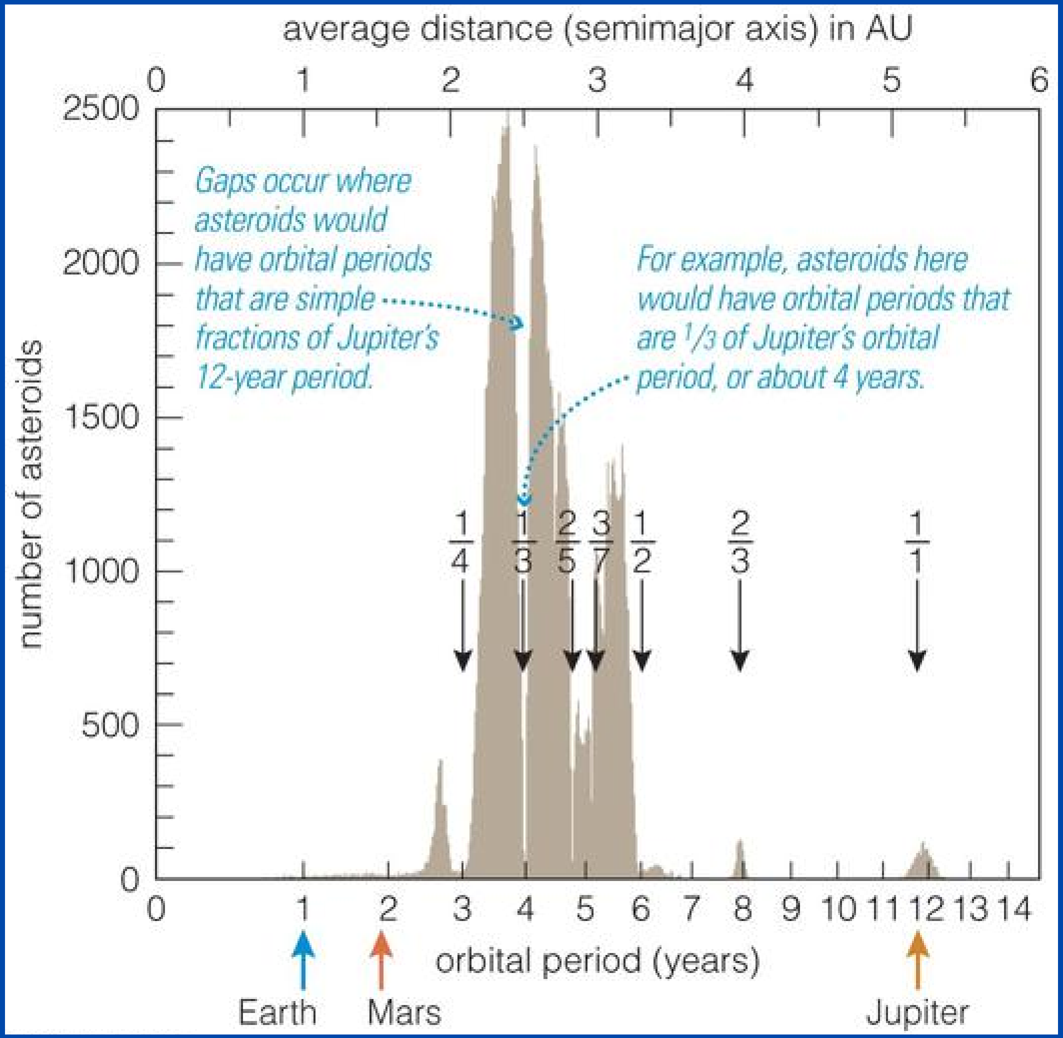


The asteroid belt: actual positions

- Between Mars and Jupiter orbits
- "Should" be a planet there
- Jupiter's gravity perturbations probably prevented coalescence
- Also "Trojan Asteroids" 60 deg ahead of and behind Jupiter



Orbital Resonances



- **Asteroids in orbital resonance with Jupiter experience periodic nudges.**
- **Eventually, those nudges move asteroids out of resonant orbits, leaving gaps in the asteroid belt.**

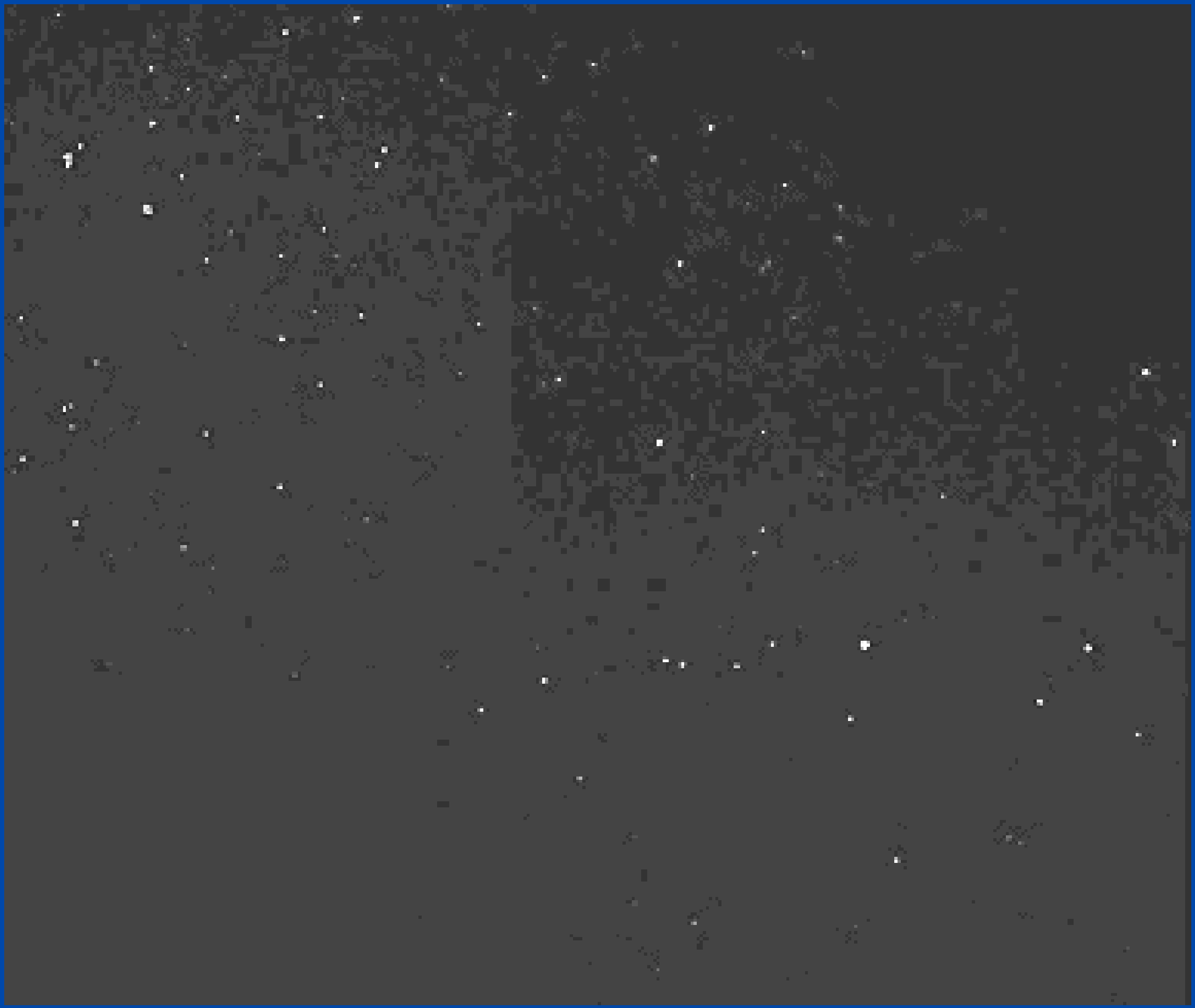
How did asteroid belt get there in the first place?

- Current asteroid belt has total mass 5×10^{-4} x mass of Earth
- Several lines of evidence suggest that the original asteroid belt was 100 - 1000 times more massive
- But once Jupiter fully formed (after ~ 10 million years), its gravity strongly perturbed the orbits of almost all the asteroids
- Most of them got nudged into highly eccentric orbits, from which they either leave the Solar System or head inwards toward the Sun
- A fraction of the asteroids headed inwards may have hit the early Earth!

Asteroids are quite far apart (not like in Star Wars)

- **About 100,000 asteroids larger than 1 km**
- **Not much mass: if gathered in a sphere, they would make a body less than 1000 km in diameter**
- **Mean distance between asteroids is several million km!**
- **If you were on an asteroid and looked up, you would see at most one other asteroid with your naked eye**

Finding asteroids: they move fast with respect to the stars

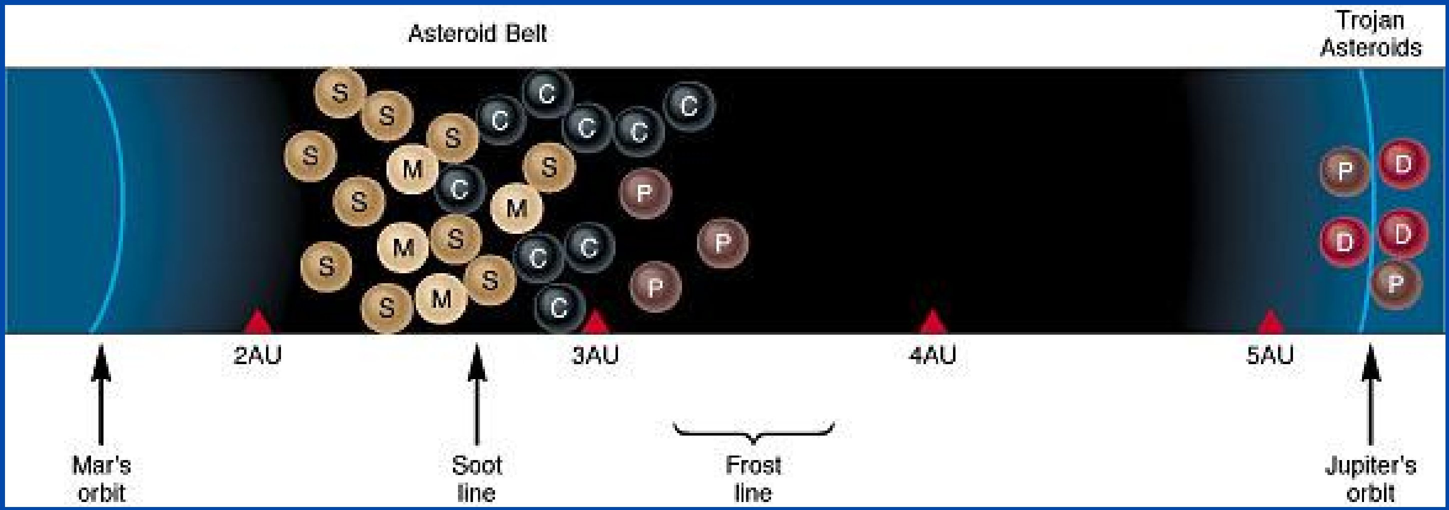


ConcepTest

- We've seen that many asteroids look like lumpy potatoes (very irregular shapes).
- But some, such as Vesta, are pretty round.
- What physical properties could cause some asteroids to be lumpy and some to be round?

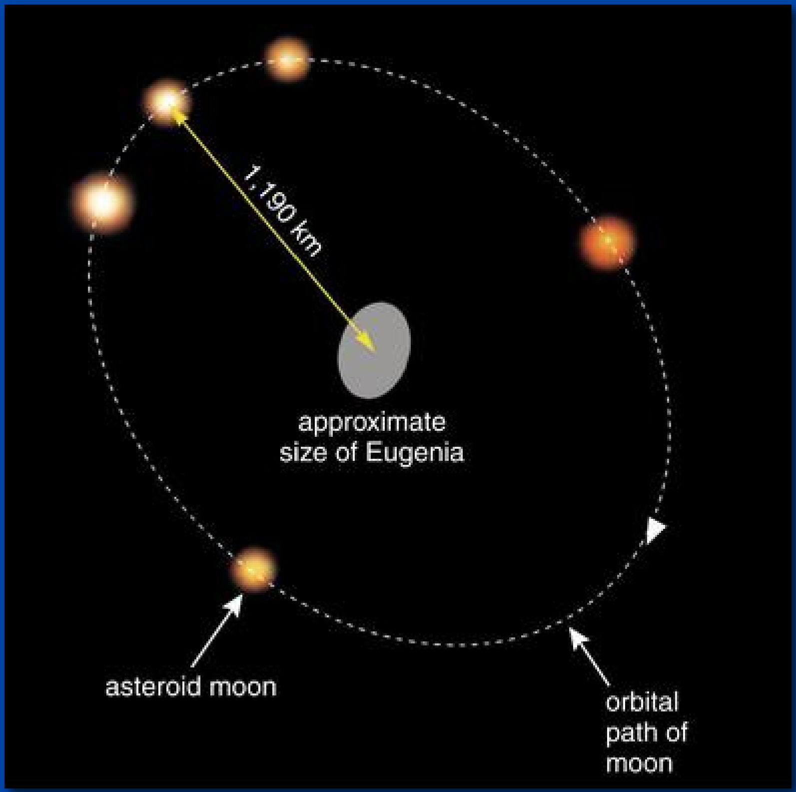
Asteroid categories and characteristics

- Can categorize asteroids by albedo (reflectance)
  - Dark (low reflectance): C (carbon)
  - Medium reflectance: M (metallic)
  - High reflectance: S (silicates, rock)
  - Meteorites hitting Earth have same categories!
- Categories correlate with distance from Sun

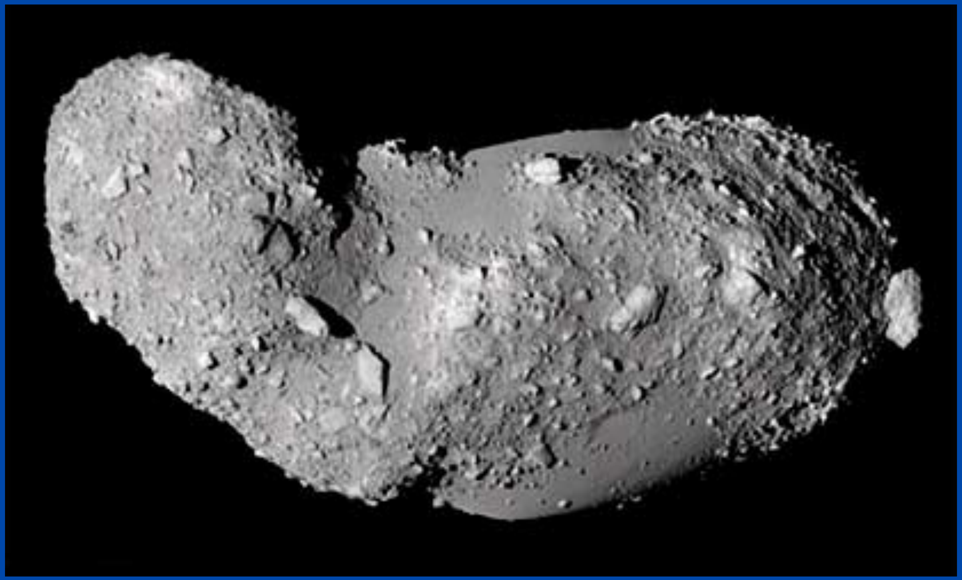


The few asteroid binaries analyzed so far are not very dense

- **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

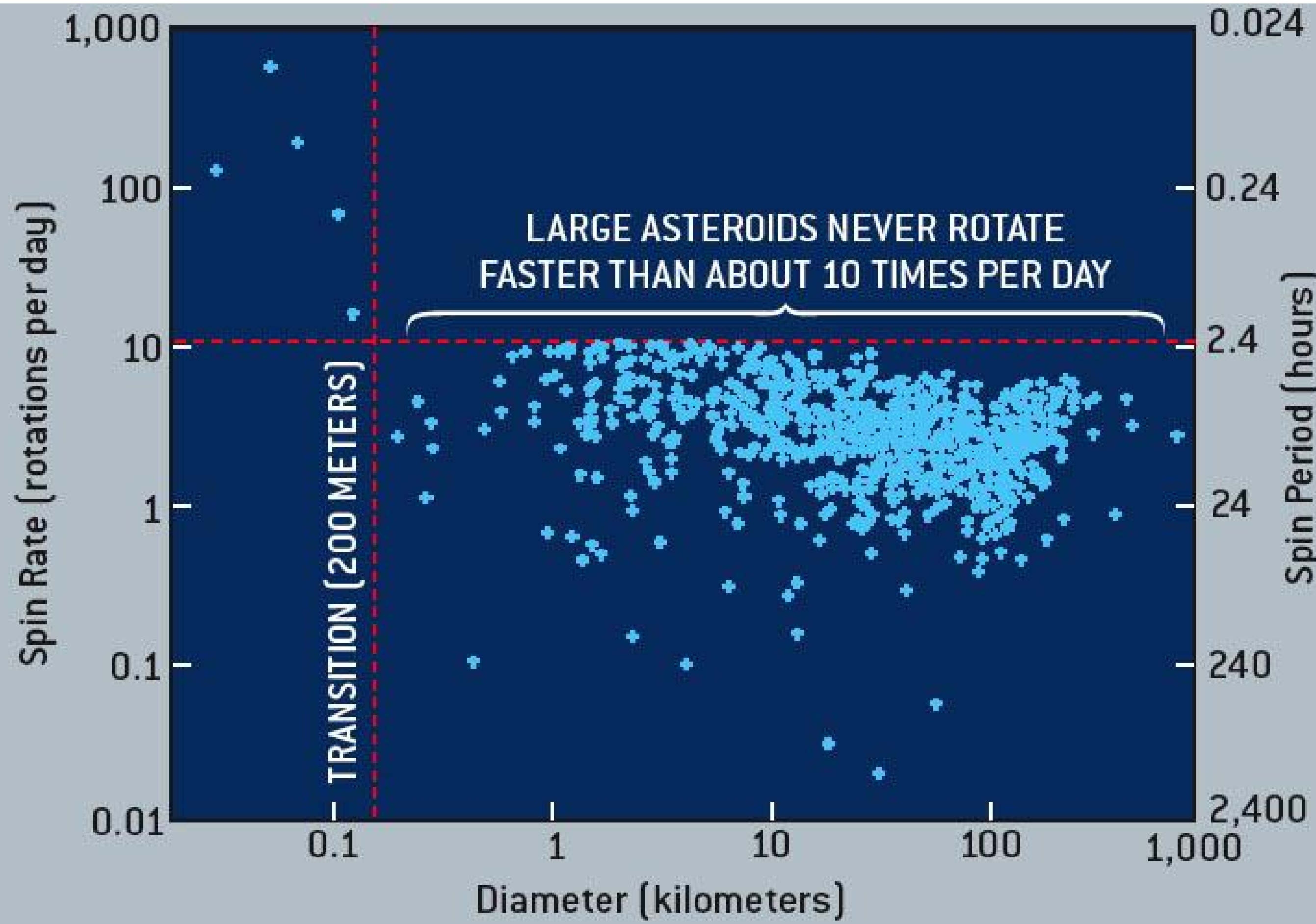


Asteroids: solid bodies vs. rubble piles?



Mathilde: solid

Itokawa: rubble pile



TWO GROUPS OF ASTEROIDS emerge on a plot of their rotation rates (*vertical axis*) versus size (*horizontal axis*). No known asteroid larger than 200 meters across rotates faster than once every 2.2 hours. The cutoff is easy to explain if these asteroids are piles of rubble that fly apart if spun too fast. Smaller asteroids, which can turn once every few minutes, must be solid rocks. The transition probably arose because of collisions.

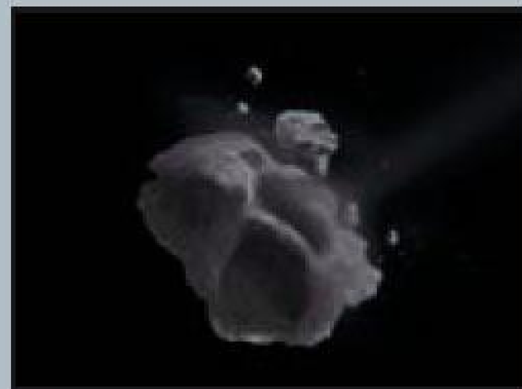
Source: E. Asphaug, Scientific American

Flintstone or Rubble?

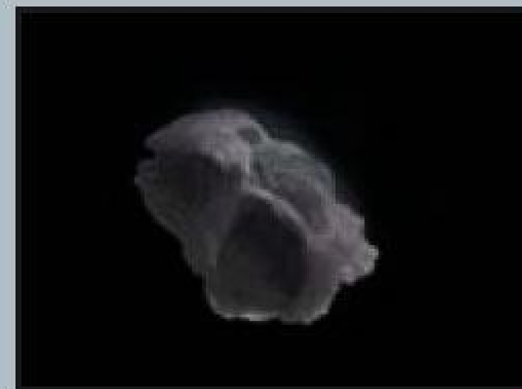
Really Deep Impacts

Source: E. Asphaug, Scientific American

RUBBLE-PILE ASTEROID, whose fragmented structure bears the scars of collisions, is struck again by a smaller asteroid at high speed. Such bang-ups are common.



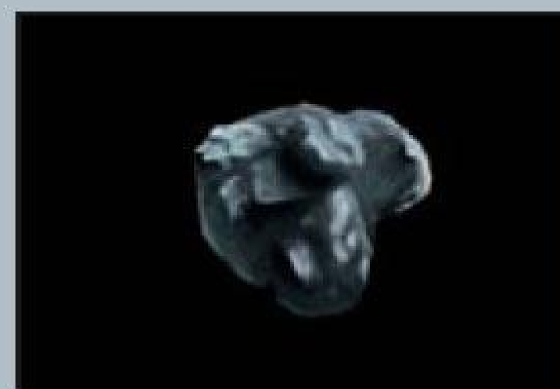
In the aggregate body the blast remains confined to the local area. Within a few minutes, the smallest, fastest debris has escaped. Larger fragments drift outward.



Some large pieces escape; some return. A few days later things settle. Over time the wound will be covered in debris from bombardment and other processes.

SOLID ASTEROID responds very differently to a collision than the rubble pile does—just as a log responds differently to the blow of an ax than a mound of wood chips does.

The shock wave propagates deep, blasting apart the body. The fastest ejecta are soon gone, leaving larger fragments to undergo a gentle gravitational dance for hours.



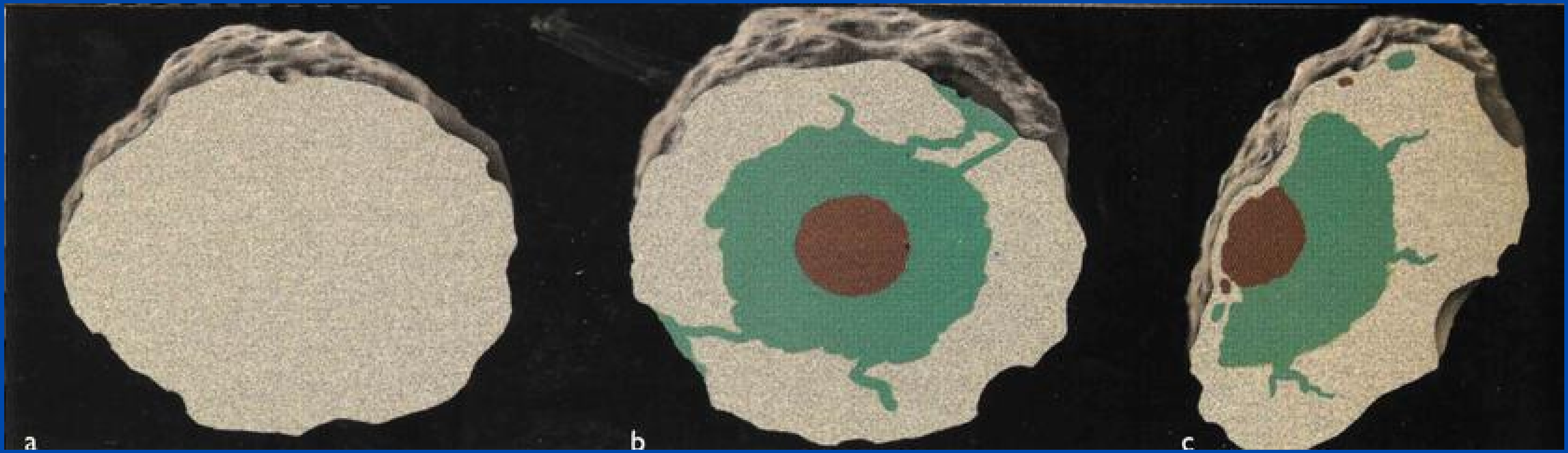
Many of these pieces come to rest in a pile of rubble. Because it is so easy to turn a rock into a rubble pile, few asteroids larger than a few hundred meters across are still solid.

Is this an asteroid-asteroid collision?

Direction of Solar Wind

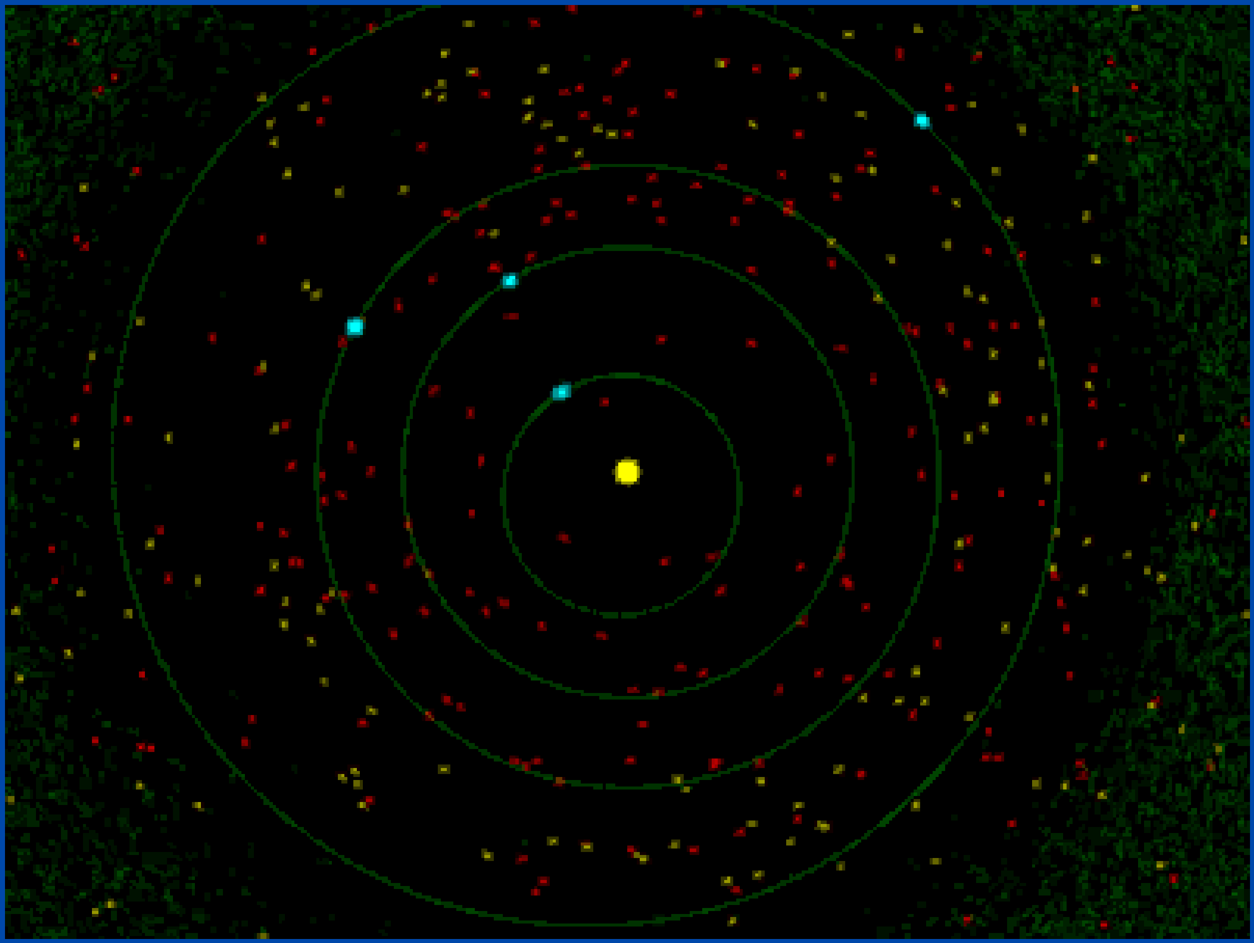
Differentiation in asteroids

Primitive, undifferentiated	Iron separates, sinks. Core forms.	Collisions expose iron core

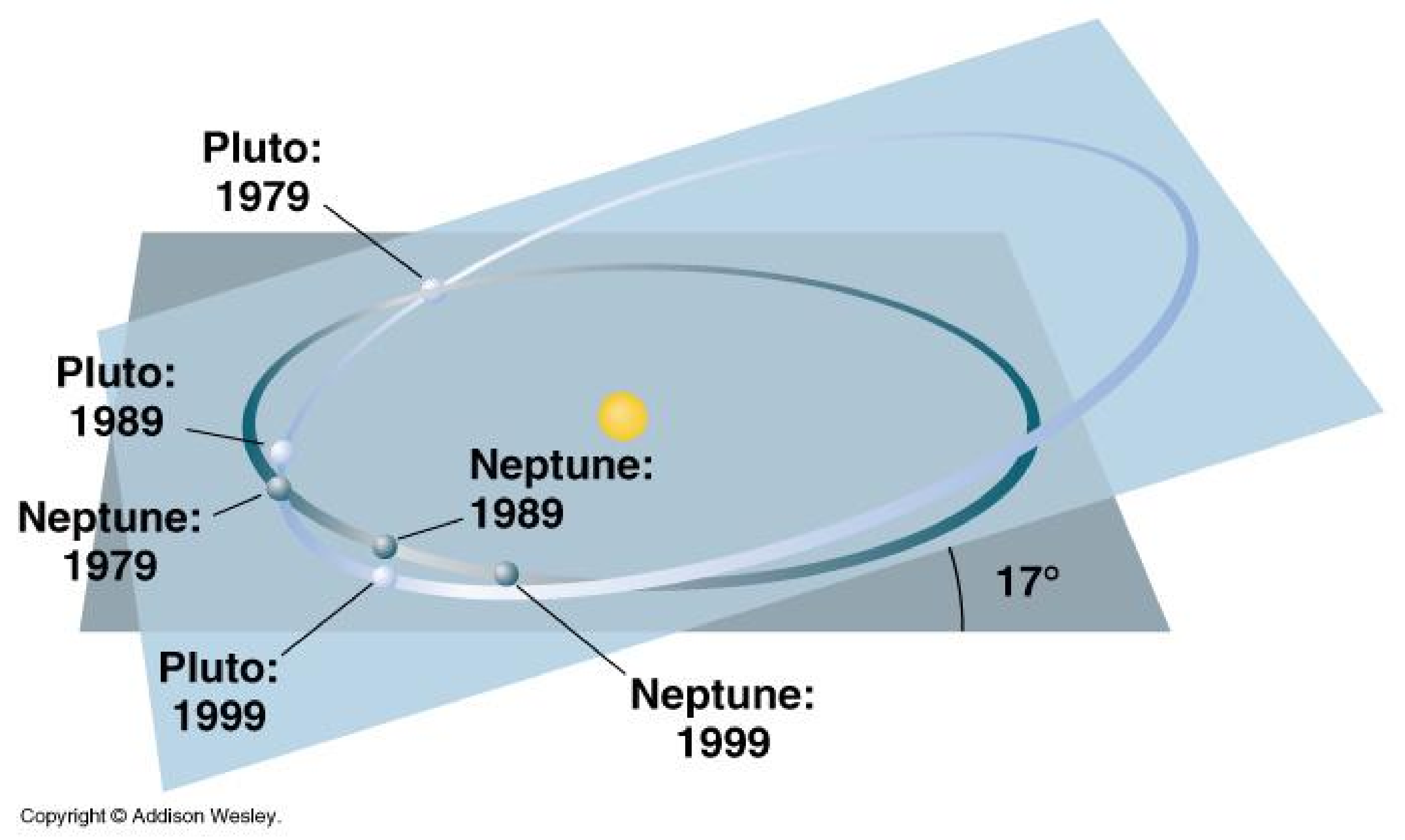


- Most asteroids were not heated beyond stage a)
- Vesta reached stage b)
- M and S type asteroids c) (M = metal)

Near Earth Asteroids: perturbed out of asteroid belt by Jupiter



Pluto and Charon: orbit is elliptical, out of plane of rest of Solar System



- **Pluto wasn't discovered till 1930!**

Other Pluto is not alone

- **There are many icy objects like Pluto on elliptical, inclined orbits beyond Neptune.**
- **The largest of these, Eris, was discovered in summer 2005, and is even larger than Pluto.**

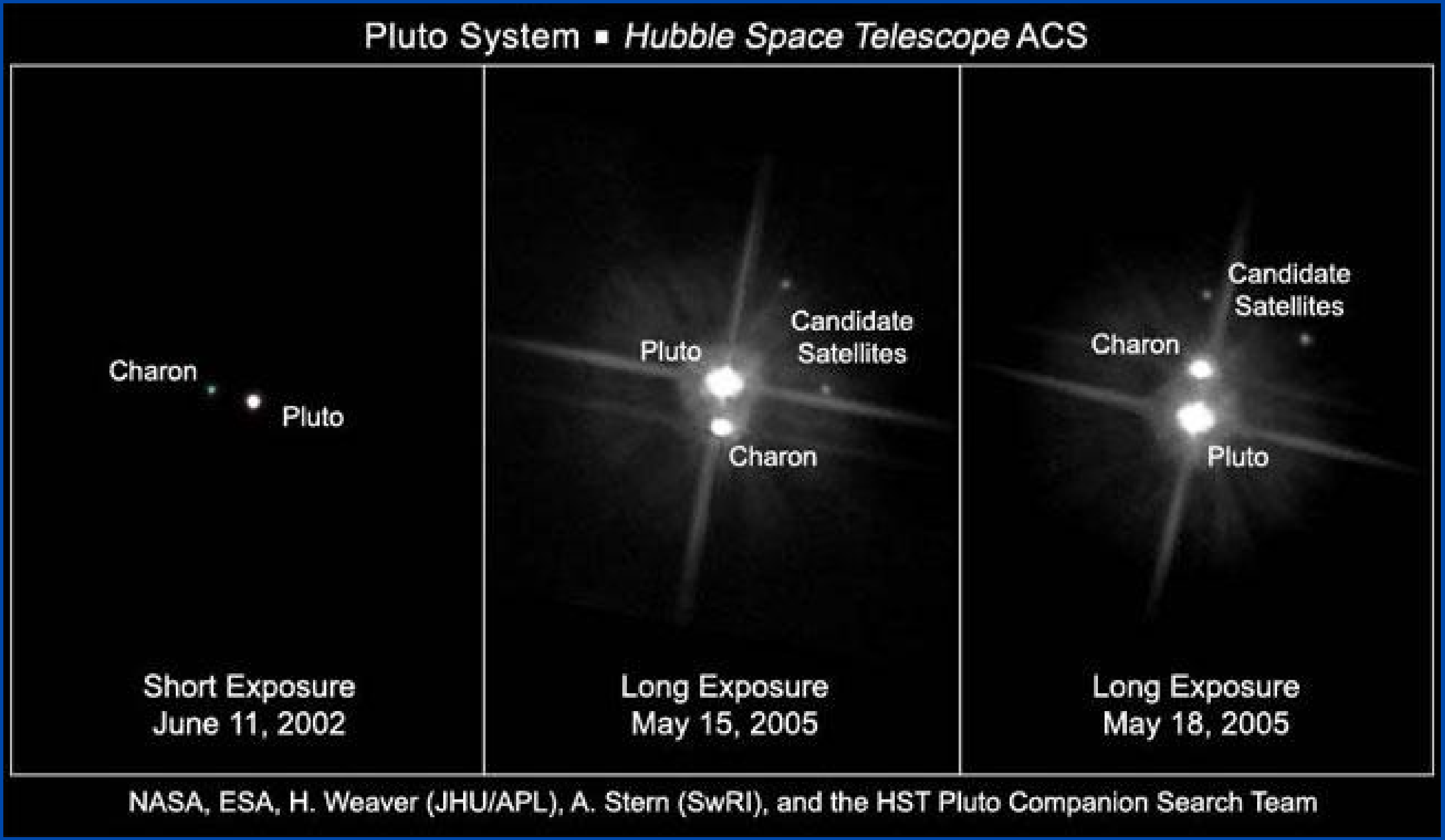
Pluto and Charon

- 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?

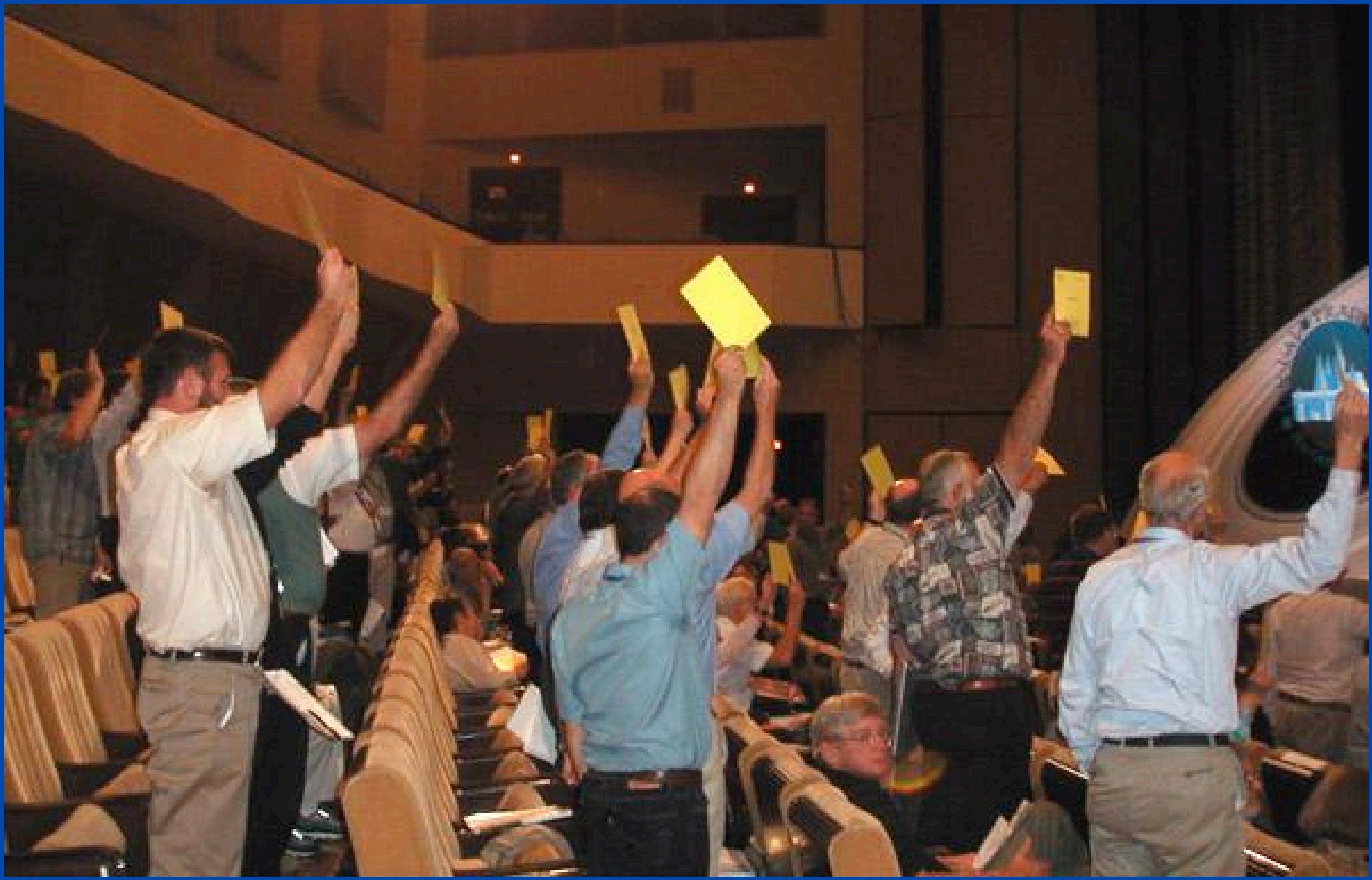
- By far the smallest planet
  - Pluto's size was overestimated after its discovery in 1930
- Not a gas giant like other outer planets
- Has an icy composition like a comet
- Has a very elliptical, inclined orbit
- Pluto has more in common with comets than with the eight major planets

What is a planet?

- **International Astronomical Union meeting in Prague in 2006**
- **Agreed that a "planet" is defined as a celestial body that**
  - **(a) is in orbit around the Sun**
  - **(b) has sufficient mass for its self-gravity to overcome rigid body forces so that it assumes a hydrostatic equilibrium (nearly round) shape, and**
  - **(c) has cleared the neighborhood around its orbit.**

Slide credit: John Wilson, Georgia State U.

What is a planet?



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.

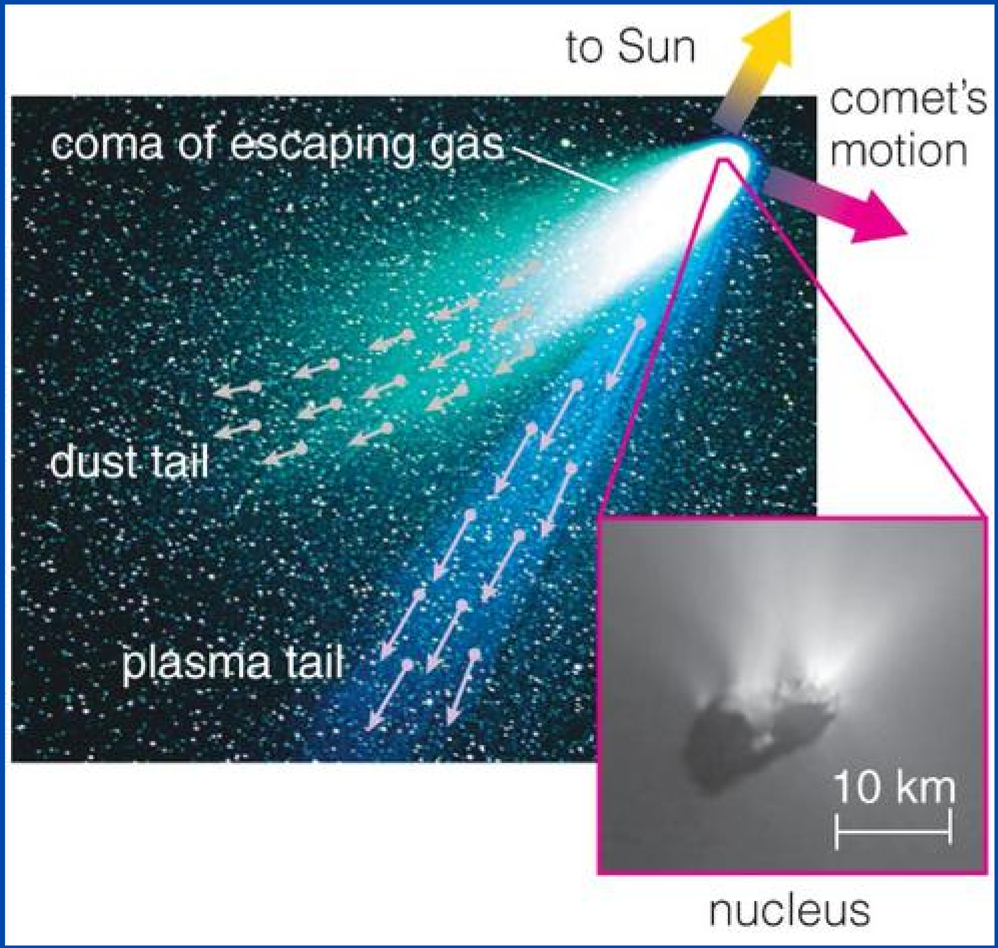
What are comets like?

Comet Facts

- Nucleus of comet is a "dirty snowball" (ice mixed with with rock)
- Most comets do not have tails
- Most comets remain perpetually frozen in the outer solar system
- Only comets that enter the inner solar system grow tails

Sun-grazing Comet

Anatomy of a Comet

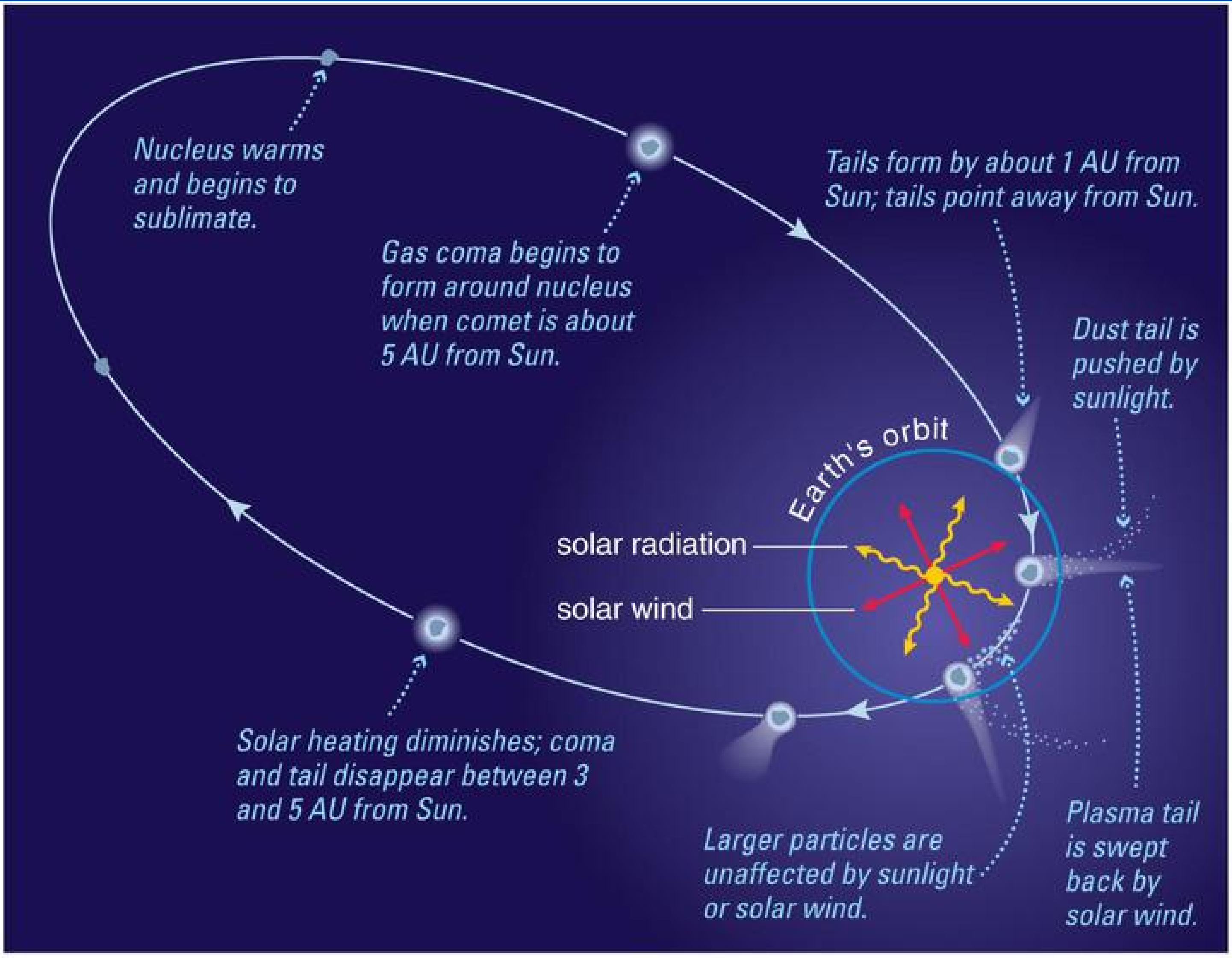


- **Gas "coma"** is atmosphere that comes from heated nucleus
- **Plasma tail** is gas escaping from coma, pushed by solar wind
- **Dust tail** is pushed by photons from the Sun

Length of comet tail is huge

- Tail size many millions of km
- By comparison, Jupiter is about 150,000 km in diameter

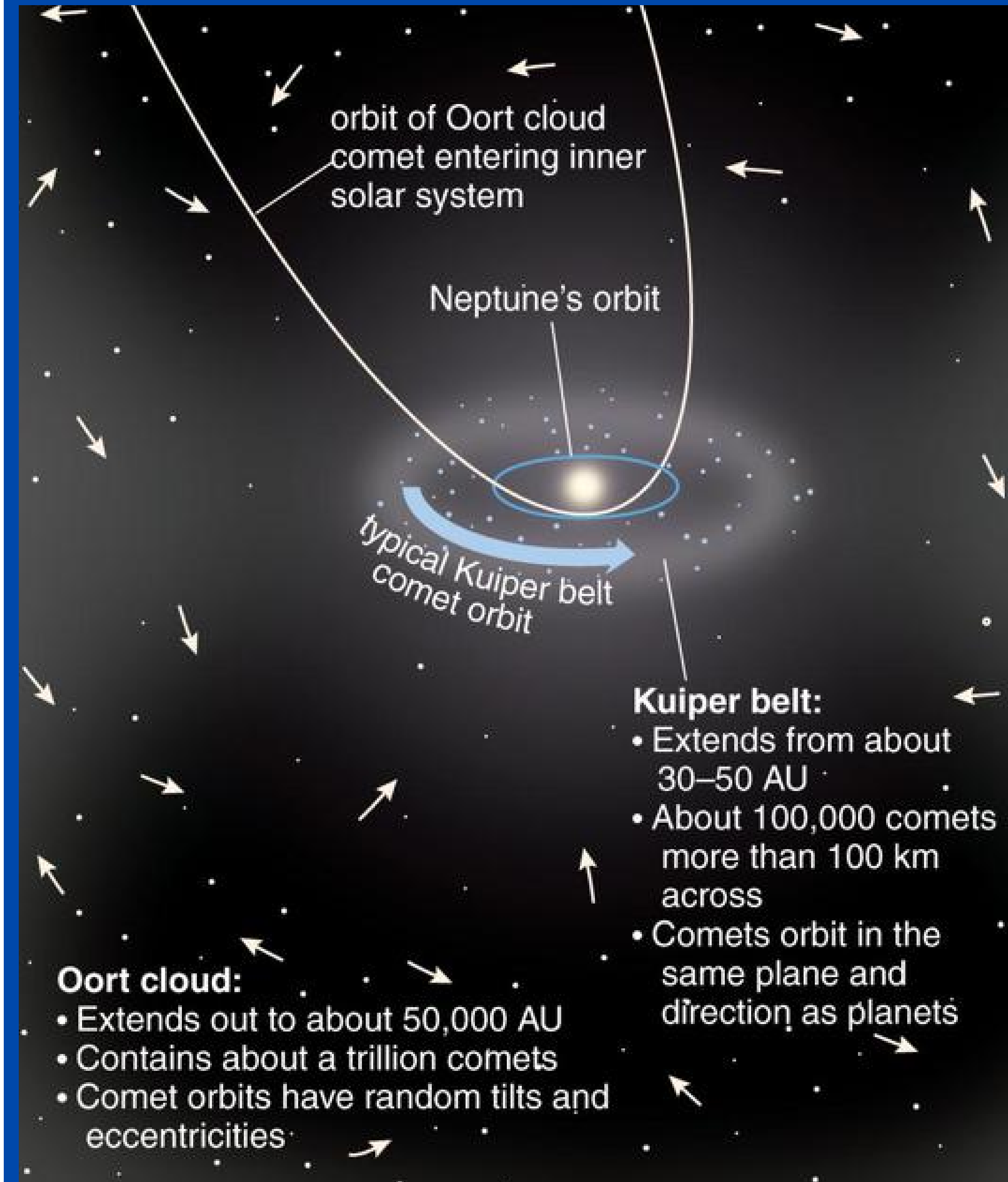
Tail grows as comet comes closer to Sun



Deep Impact Spacecraft sent projectile into Comet Tempel 1

- Mission to study nucleus of Comet Tempel 1
- Projectile hit surface on July 4, 2005
- Recorded by the "mother ship"
- Many telescopes from Earth studied aftermath of impact

Where do comets come from?



Few comets enter inner solar system

Oort cloud:
On random orbits extending to about 50,000 AU

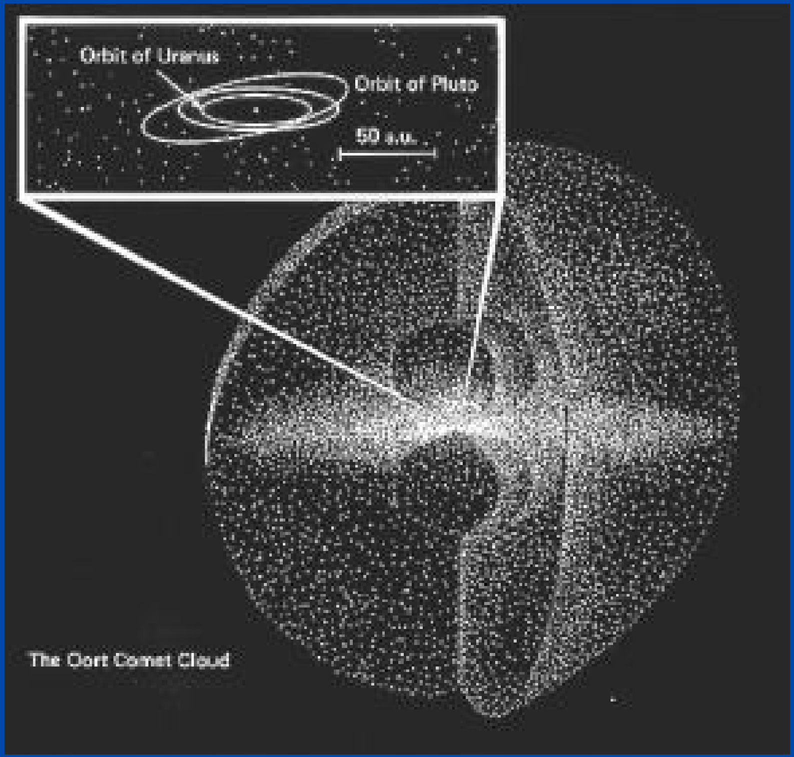
Kuiper belt:
On orderly orbits from 30-100 AU in disk of solar system

How did they get there?

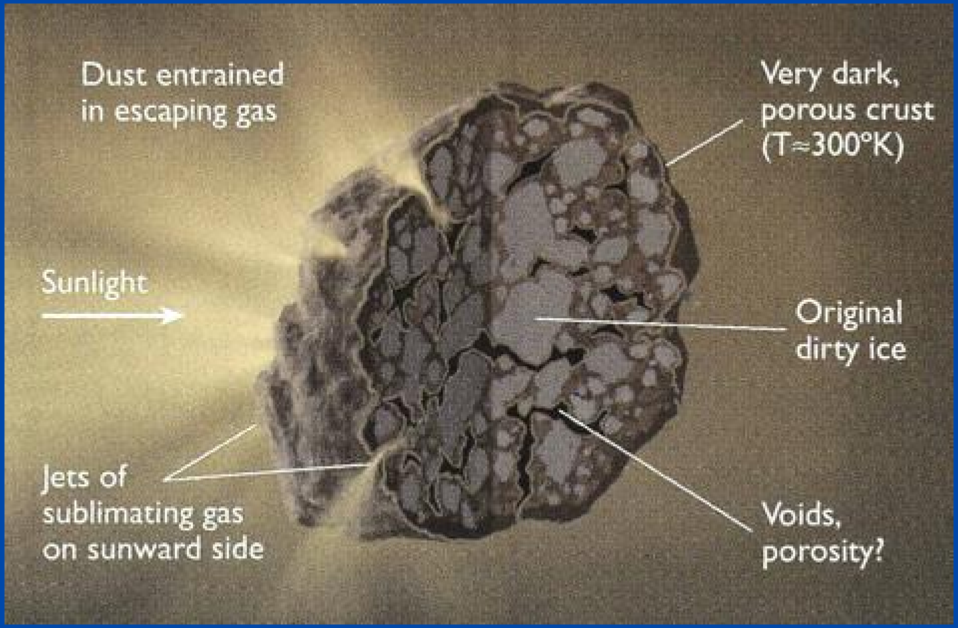
- **Kuiper belt comets** formed in the Kuiper belt: flat plane, aligned with plane of Solar System, orbiting in same direction as the planets.
- **Oort cloud comets** were once closer to the Sun, but they were kicked out there by gravitational interactions with jovian planets: spherical distribution, orbits in any direction.

The Oort Cloud is almost spherical, well beyond orbit of Pluto

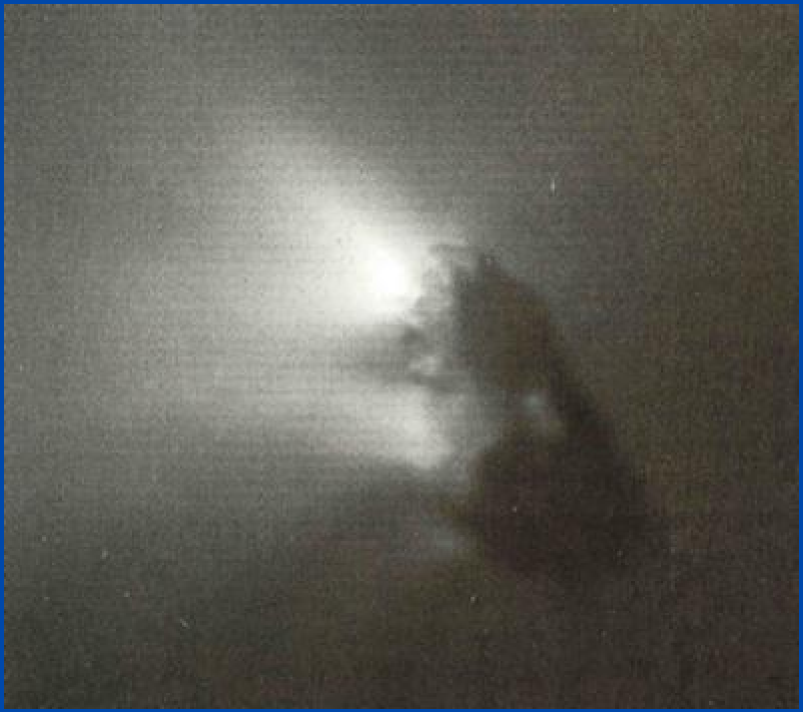
- In 1950 Jan Oort noticed that
  - no comet orbit observed suggesting it came from interstellar space
  - strong tendency for aphelia of long period comet orbits to lie at distance ~ 50,000 AU
  - there is no preferential direction from which comets come.
- He proposed that comets reside in a vast cloud at the outer reaches of the solar system
- Up to a trillion comets in Oort cloud!



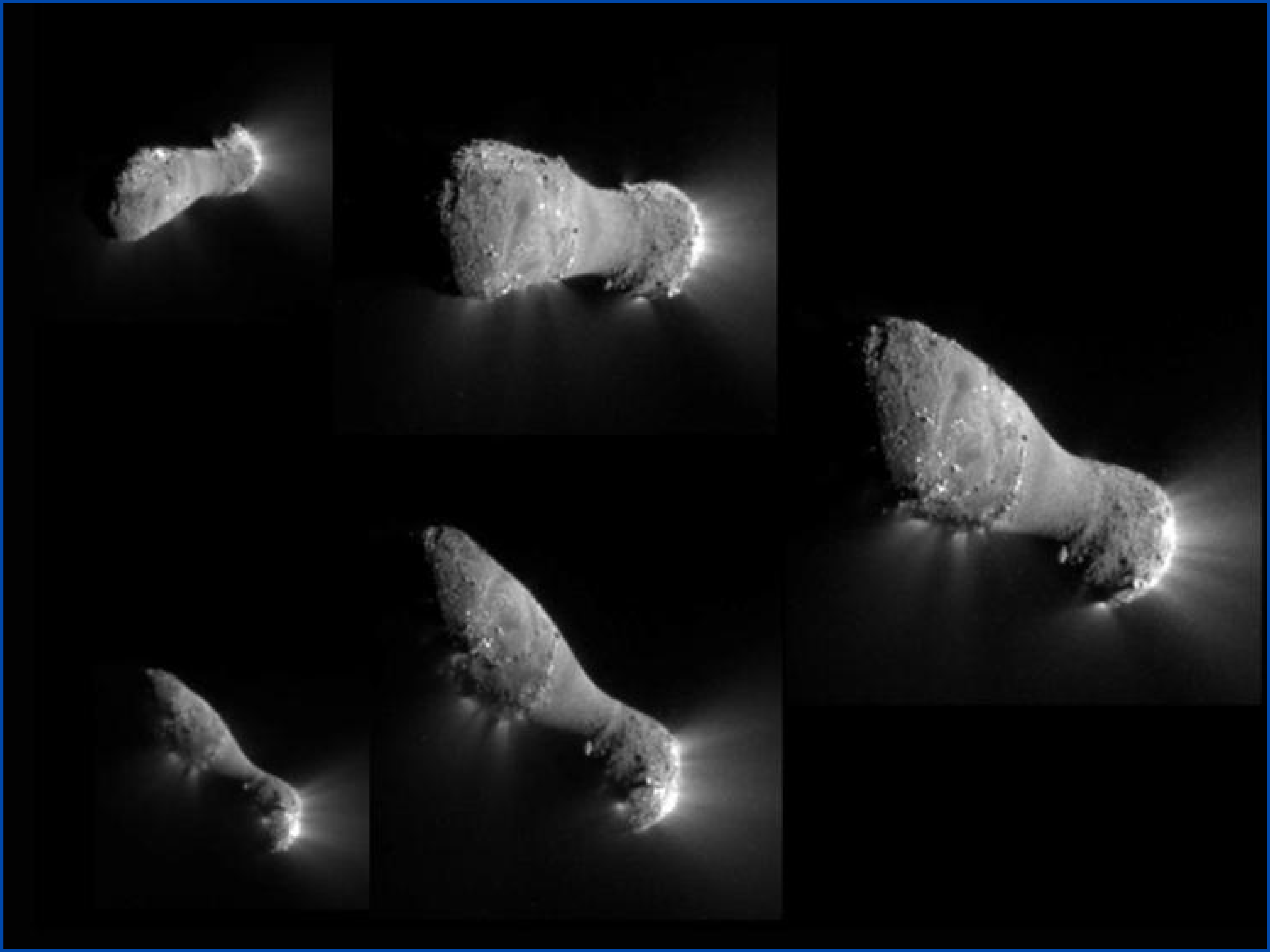
Comet nucleus



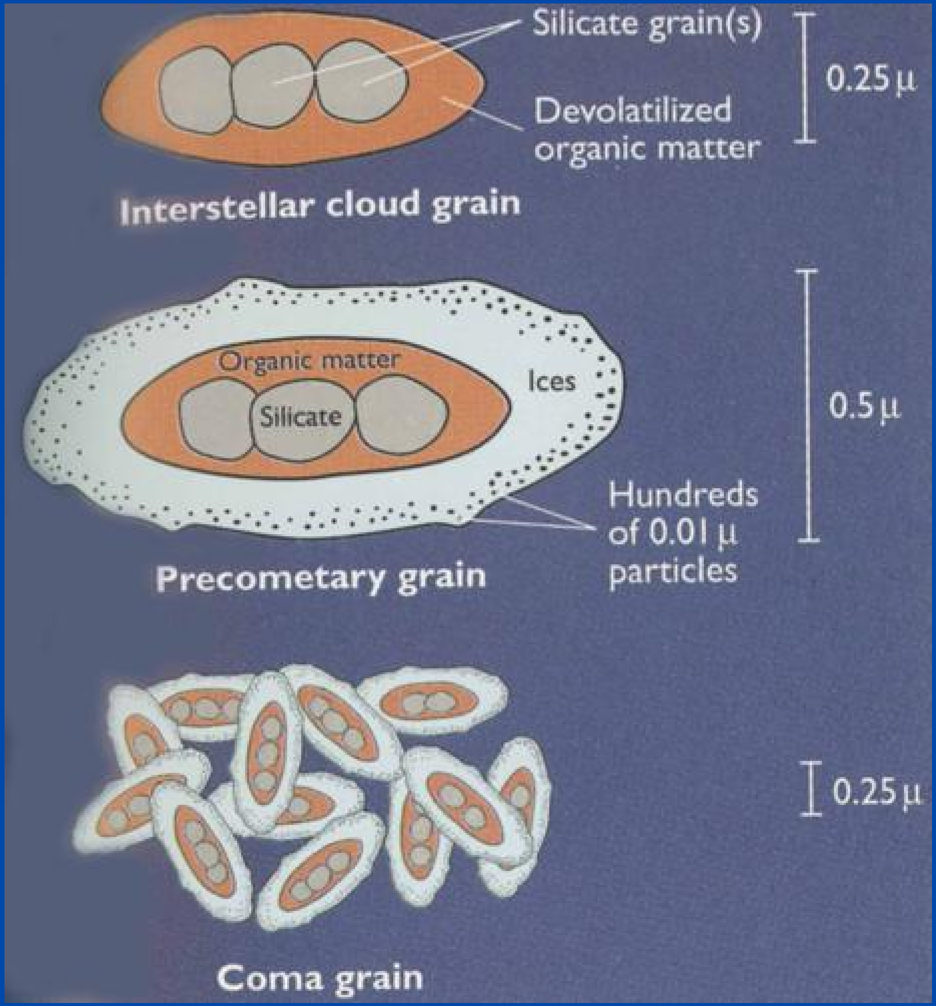
Nucleus of Halley's Comet



Comet Hartley 1 seen from the EPOXI spacecraft



Dust is ejected from nucleus as it heats up, makes comet tail

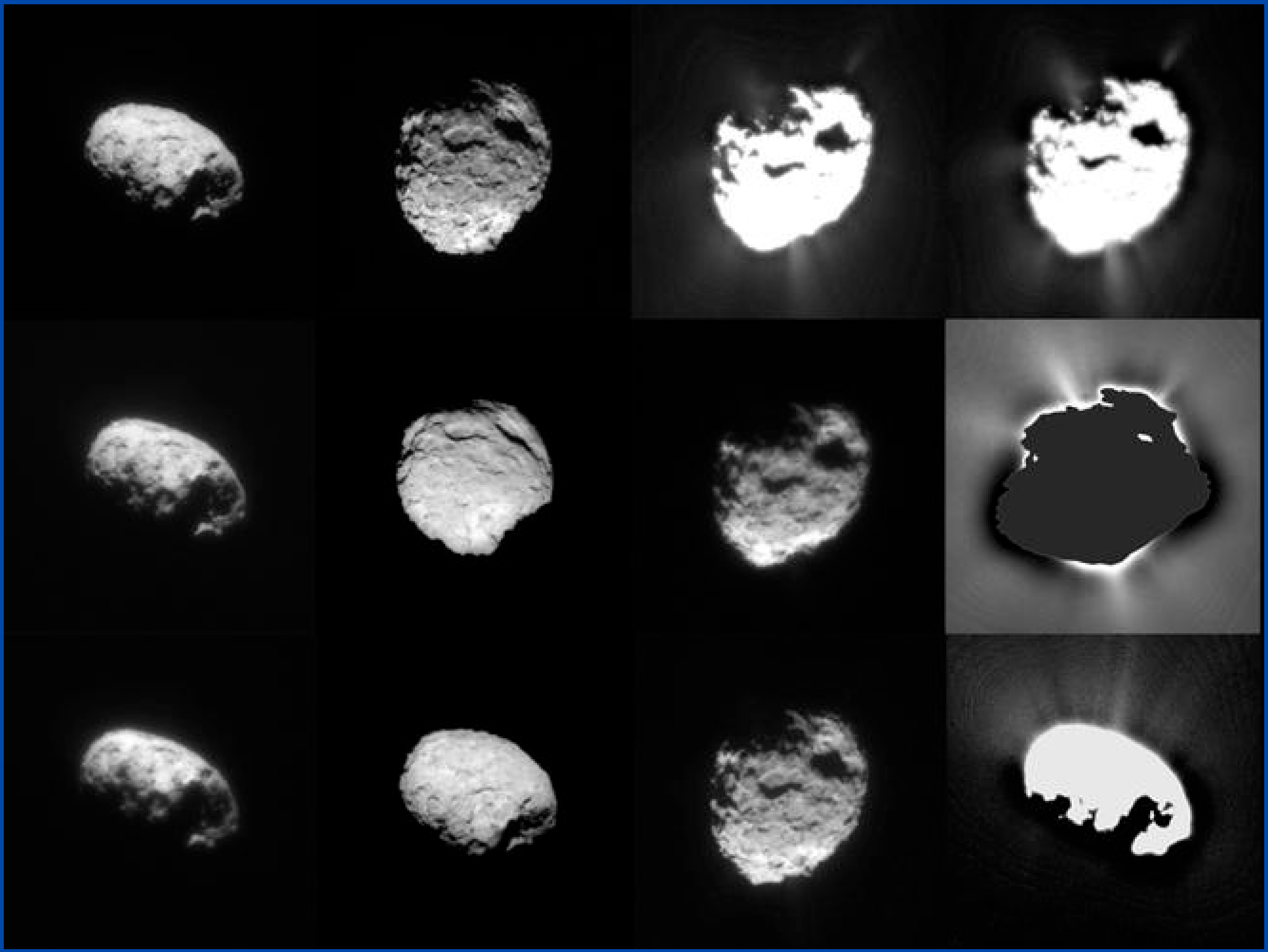


Electron microscope image of dust

Concept Question

- Remembering the division between the inner Solar System's rocky "terrestrial planets" and the outer Solar System's icy satellites, where in the Solar System might comets have originally formed?

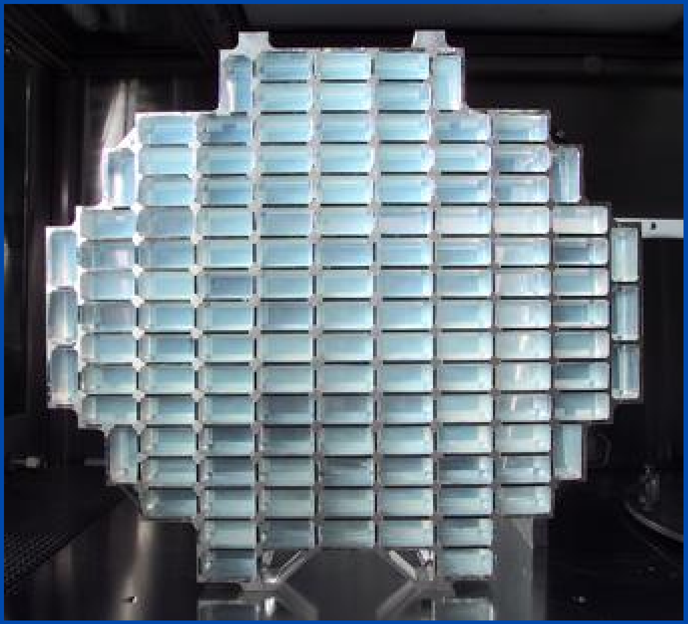
Stardust spacecraft flew to a comet, brought dust back to Earth



Stardust images of the nucleus

Stardust spacecraft, continued

- Gathered cometary dust using aerogel targets
  – The least dense substance that is still solid
- Brought back to Earth
- Found that dust had been reprocessed in inner Solar System; identified Glycine (a building block of life)



The main points: Meteorites

- Each year Earth sweeps up ~80,000 tons of extraterrestrial matter, from microscopic dust particles to large rocks
- Some are identifiable pieces of the Moon, Mars, or Vesta; most are pieces of asteroids
- Meteorites were broken off their parent bodies 10's to 100's of million years ago (recently compared to 4 Billion Years)
- Oldest meteorites (chondrites) contain bits of interstellar dust, tiny diamonds made in supernova explosions, organic molecules and amino acids (building blocks of life), tiny spherules left over from the very early Solar System
- Direct insight into solar system formation

Meteor showers

- Time exposure image, tracking stellar motion
- Stars stay still, meteorites make trails

Table 12.1 Major Annual Meteor Showers

Shower Name	*Approximate Date*	*Associated Comet*
Quadrantids	January 3	?
Lyrids	April 22	Thatcher
Eta Aquarids	May 5	Halley
Delta Aquarids	July 28	?
Perseids	August 12	Swift-Tuttle
Orionids	October 22	Halley
Taurids	November 3	Encke
Leonids	November 17	Tempel-Tuttle
Geminids	December 14	Phaeton
Ursids	December 23	Tuttle

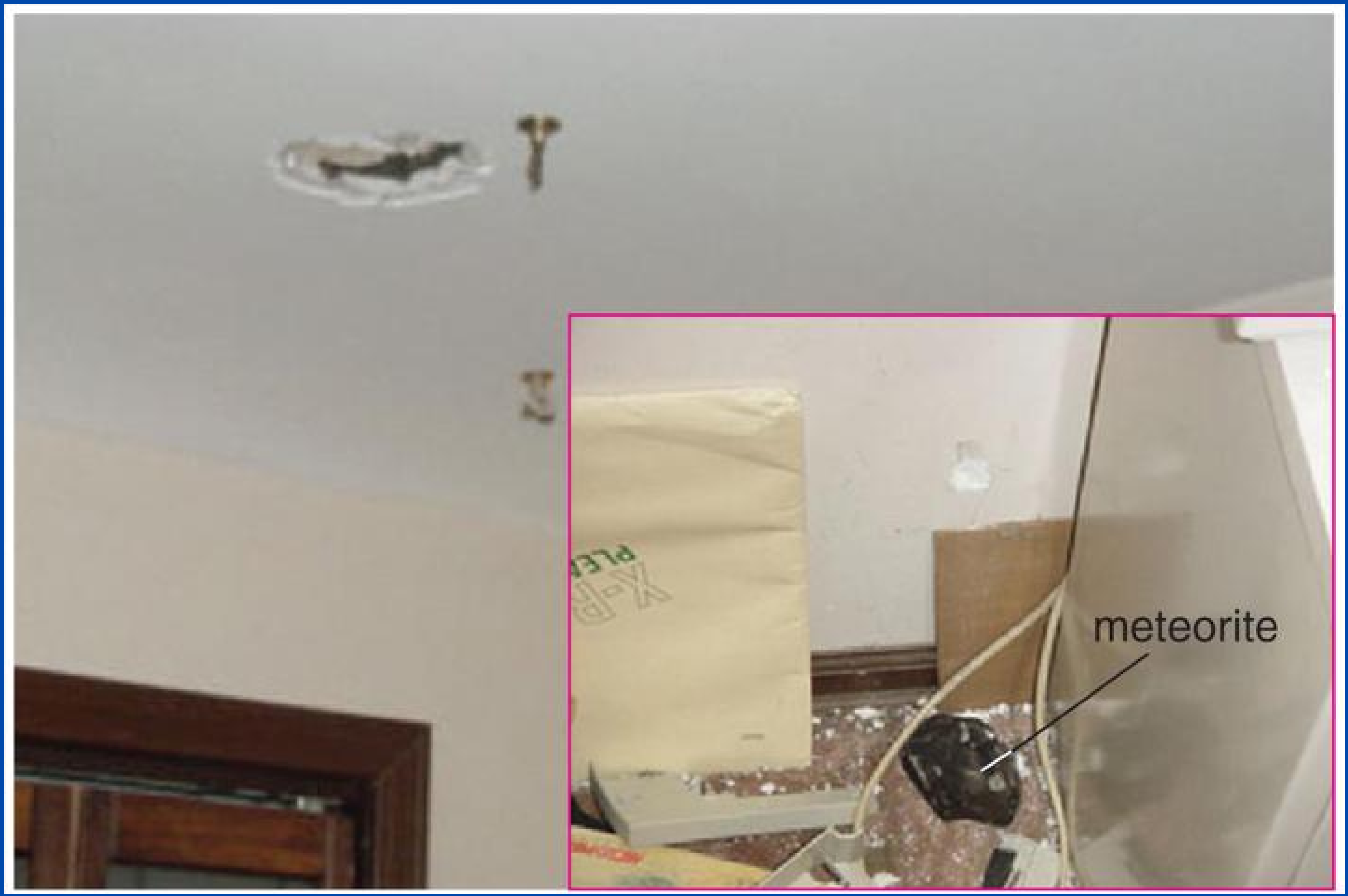
Rocks Falling from the Sky

- meteor – a flash of light caused by a particle which enters Earth's atmosphere.
  - most of these particles are the size of a pea or smaller
  - they completely burn up in Earth's atmosphere
- meteorite – a rock which is large enough to have survived its fall to Earth
  - they caused a brighter meteor…sometimes a *fireball*
- How can you tell that you have a meteorite?
  – they have a higher metal content than terrestrial rocks
  – they contain Iridium and other isotopes not found in terrestrial rocks

What are meteorites?

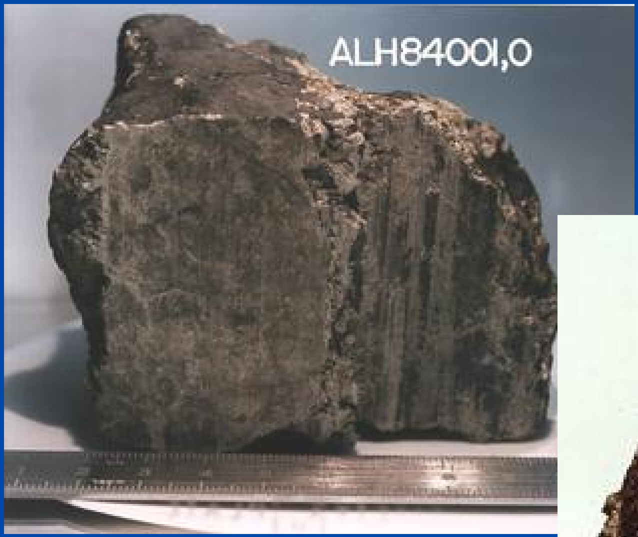
- Chunks of rock or iron-nickel that fall to Earth from space
- Pieces of asteroids, comets, Moon, Mars, interstellar dust
  – Can weigh from < 1 ounce to a few tons (!)
- "The Poor Man's Space Probe"
  – From parts of the Solar System astronauts may never explore
- Usually named after the place where they fall
  – Examples: Prairie Dog Creek (US), Zagora (Morocco), Campo del Cielo (Argentina), Mundrabilla (Australia)

Meteorite Impact!



Chicago, March 26, 2003

What do meteorites look like?



Mars meteorite

Allen Hills (Moon)

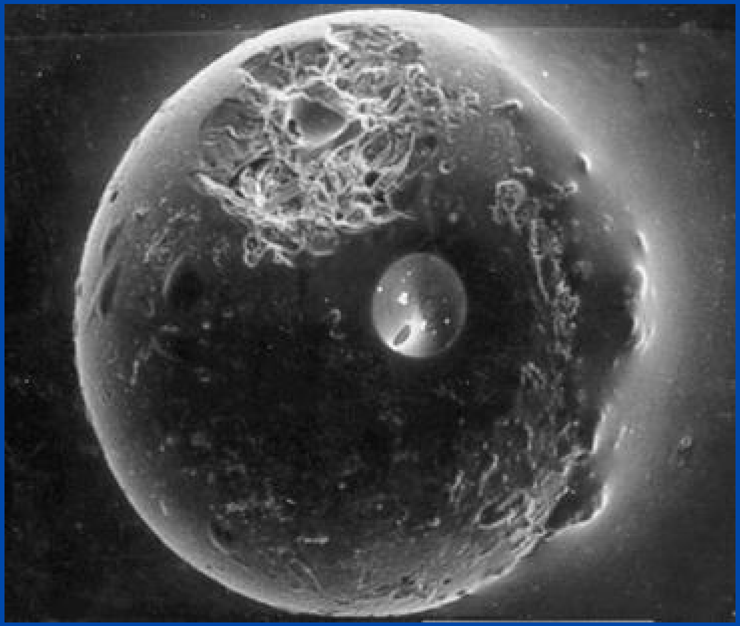
Vesta

Variety of meteorite "falls"

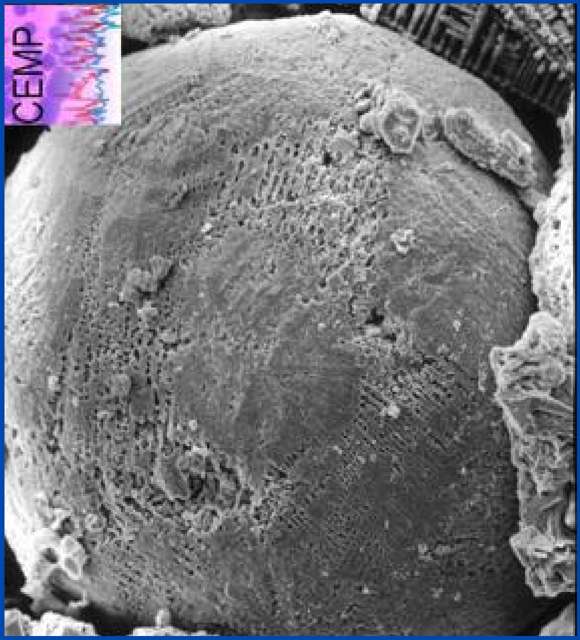
- Tiny pieces of cosmic dust
  - Collected by special airplanes, in clay under the oceans, or in Antarctic ice
- Find single small chunks of rock
  - Sometimes at random, sometimes by following trajectory of a "fireball" or meteor trail
- A several-ton meteorite breaks up during descent, falls as separate pieces
  - Biggest pieces can make large craters if they hit land

Small particles: spherules

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



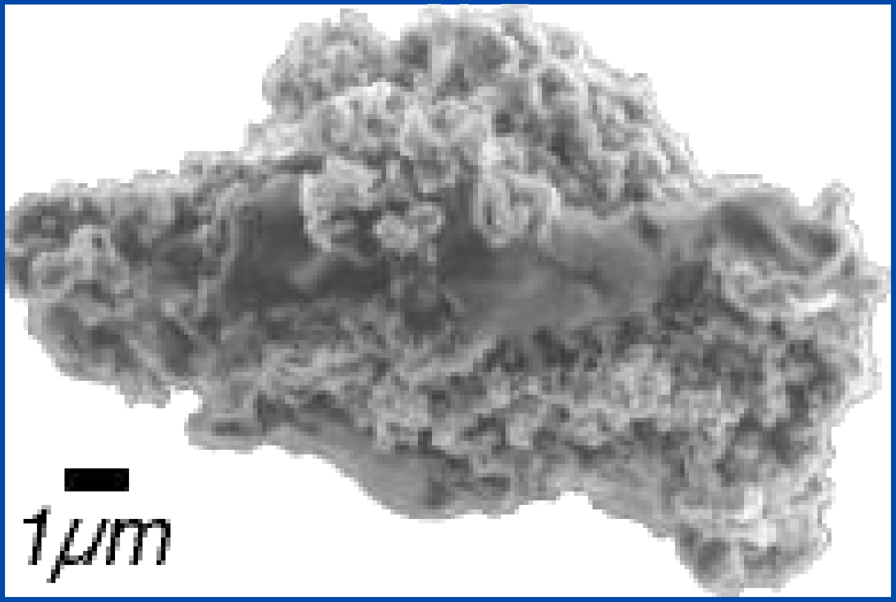
Spherule from Moon
Collected by Apollo 11 astronauts

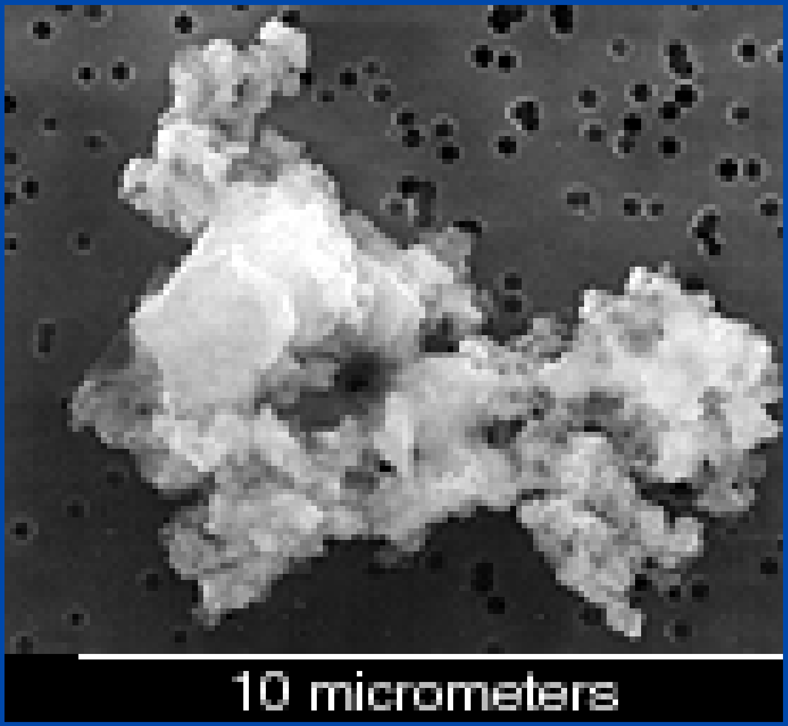


Spherule
from bottom of the Indian Ocean

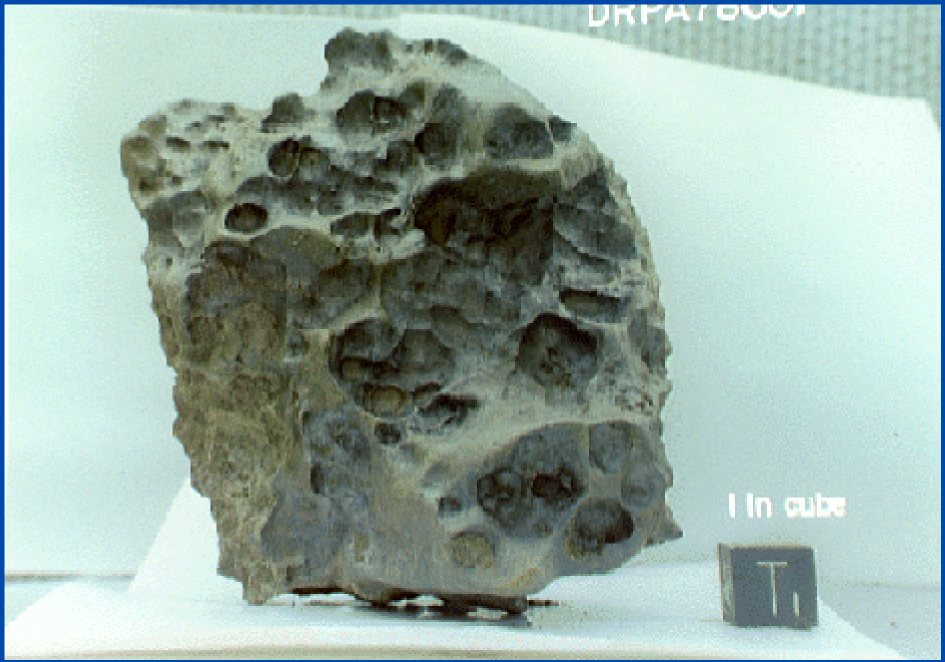
Small particles: cosmic dust

- **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

How dangerous are meteorites?

Worldwide frequency of meteorites as function of size

	Impact Frequency	
Size	**Frequency**	**Destruction Area**
Pea	10/ hour	
Walnut	1/ hour	
Grapefruit	1/ 10 hours	
Basketball	1/ month	
50 meters	1/ century	New York City
1 kilometer	1/ 100,000 years	Virginia
2 kilometers	1/ 500,000 years	France
10 kilometers	1/ 100 million years	World-Wide?

Tonguska meteorite in Siberia caused widespread devastation

- **Fortunately it hit in an unpopulated area!**

How meteorites are found

- Random “finds” lying on ground
- Fragments around meteor craters
- Follow glowing trail of meteor or fireball
- Systematic searches in Antarctica
- Special high-flying airplanes (for dust)

Random "finds"

- **Rare: a big meteorite in desert of Oman**
- **Pretty rare: random "finds" of smaller chunks**

Fragments around meteor craters

- **Very large meteorites vaporize when they hit ground, form big craters**
- **Sometimes small pieces are found around crater**

The Peekskill (NY) Fireball

This year in Sudan....

ScientificAmerican.com > News > Space

March 25, 2009 | 1 comments

Rock Science: First Meteorites Recovered on Earth from an Asteroid Tracked in Space

Fragments in the Sudanese desert make up an "asteroid trifecta": discovery, prediction and recovery

By John Matson

- **Link to Scientific American article**

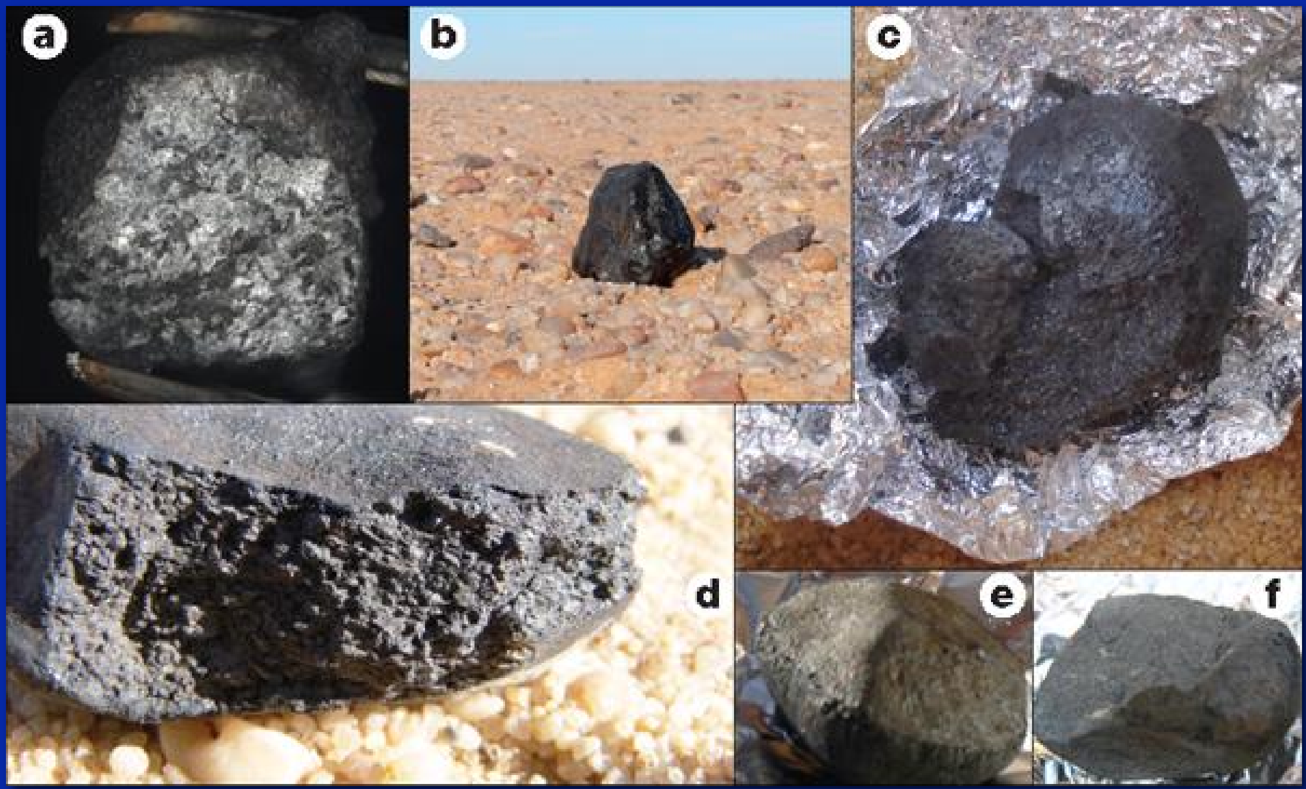
University of Khartoum students did systematic search

- **45 students and staff of the University of Khartoum rode buses out to desert, searched in lines. Found more than 280 pieces**

University of Khartoum students did systematic search

- 45 students and staff of the University of Khartoum rode buses out to desert, searched in long lines. Found more than 280 pieces.

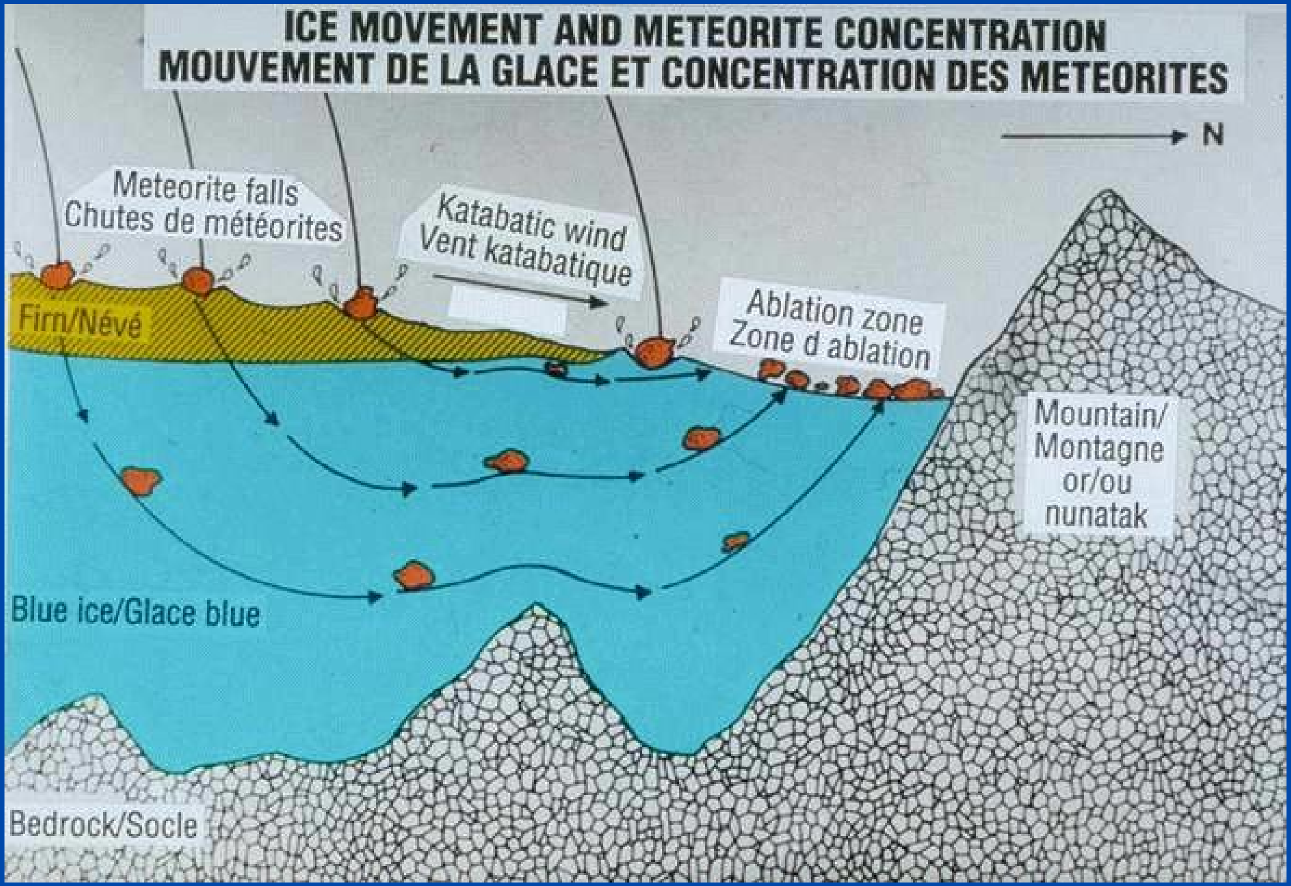
Macroscopic features of the Almahata Sitta meteorite.



P Jenniskens *et al*. *Nature* **458**, 485-488 (2009)

Systematic searches in Antarctica

Systematic searches in Antarctica

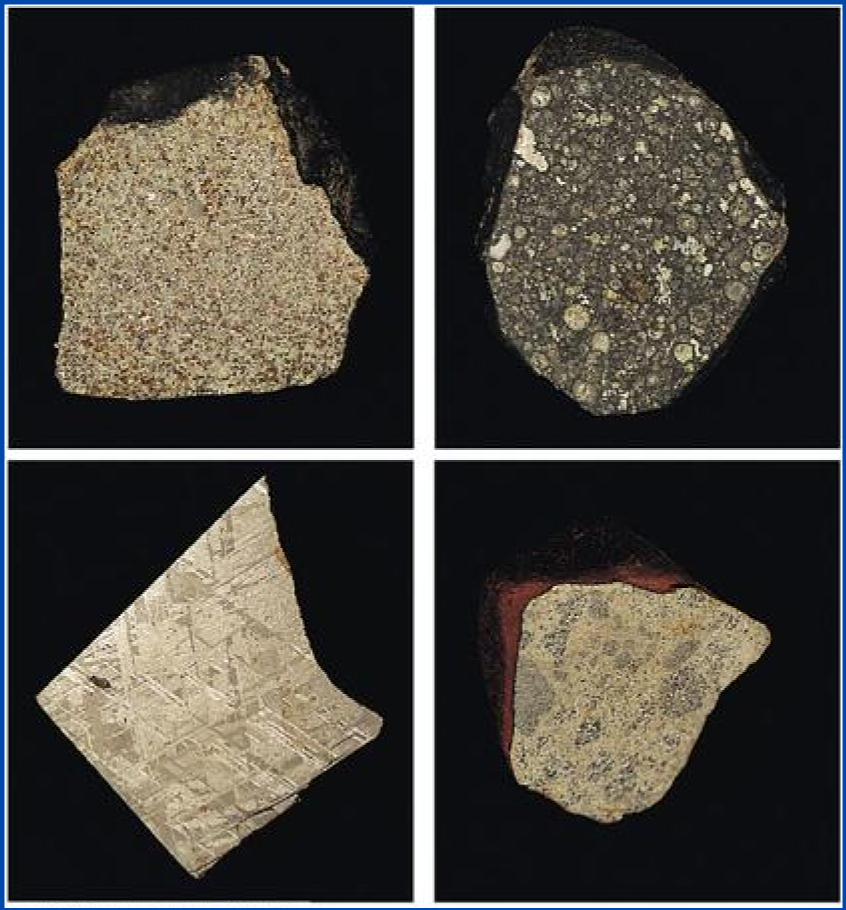


Searching for rare meteorites amidst thousands of Earth-rocks

Primitive vs. processed meteorites

Based on composition, meteorites fall into two basic categories:

- primitive
  - **about 4.6 billion years old**
  - **accreted in the Solar nebula**
- processed
  - **younger than 4.6 billion years**
  - **matter has differentiated**
  - **fragments of a larger object which processed the original Solar nebula material**



Origin of Meteorites

- **Primitive meteorites condensed and accreted directly from the Solar nebula.**
  - **the stony ones formed closer than 3 AU from the Sun**
  - **the Carbon-rich ones formed beyond 3 AU from the Sun, where it was cold enough for Carbon compounds to condense**

- **Processed meteorites come from large objects in the inner Solar System.**
  - **the metallic ones are fragments of the cores of asteroids which were shattered in collisions**
  - **the rocky ones were chipped off the surfaces of asteroids, Mars, and the Moon by impacts**

Main types of meteorites

- Chondrites
  - Carbonaceous
  - Non-carbonaceous
- Achondrites
- Iron
- Stony-Iron

Chondrites

- **Rocky, inhomogeneous, contain round "chondrules"**

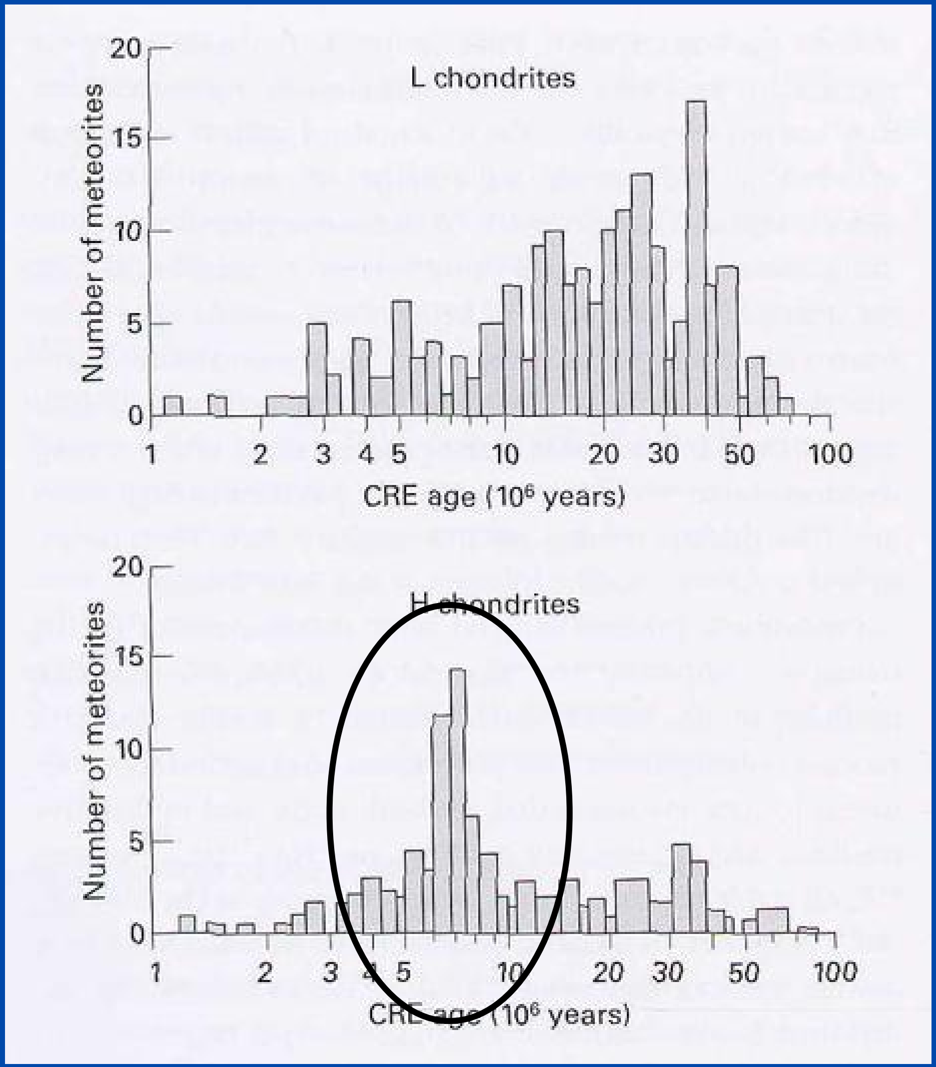
Carbonaceous Chondrites contain complex organic molecules

- 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?

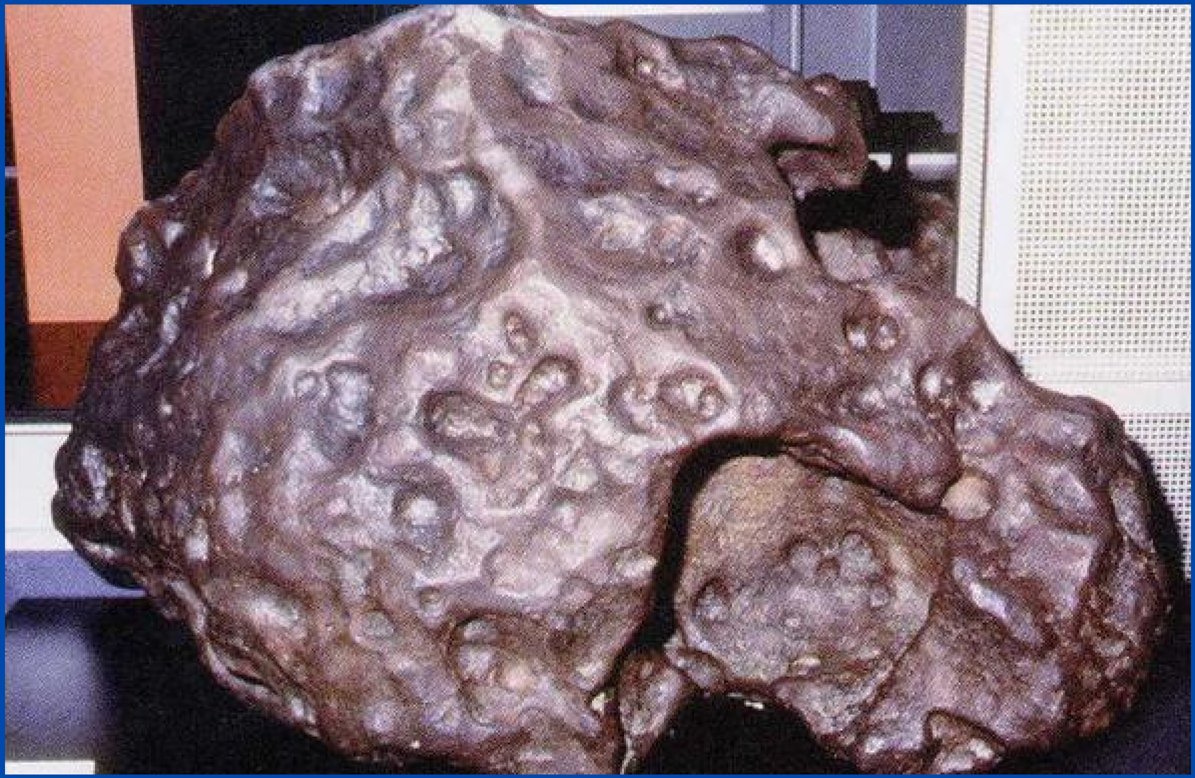
- The oldest meteorites; quite rare
- Chondrules (round): primitive chunks of early Solar System
- Calcium aluminum inclusions (CaI's): isotope ratios (26 Al and 26 Mg) suggest that a supernova explosion went off right next to the early Solar Nebula
  - Did the supernova stimulate formation of our Solar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

Some types of Chondrites were formed all at once: from one asteroid

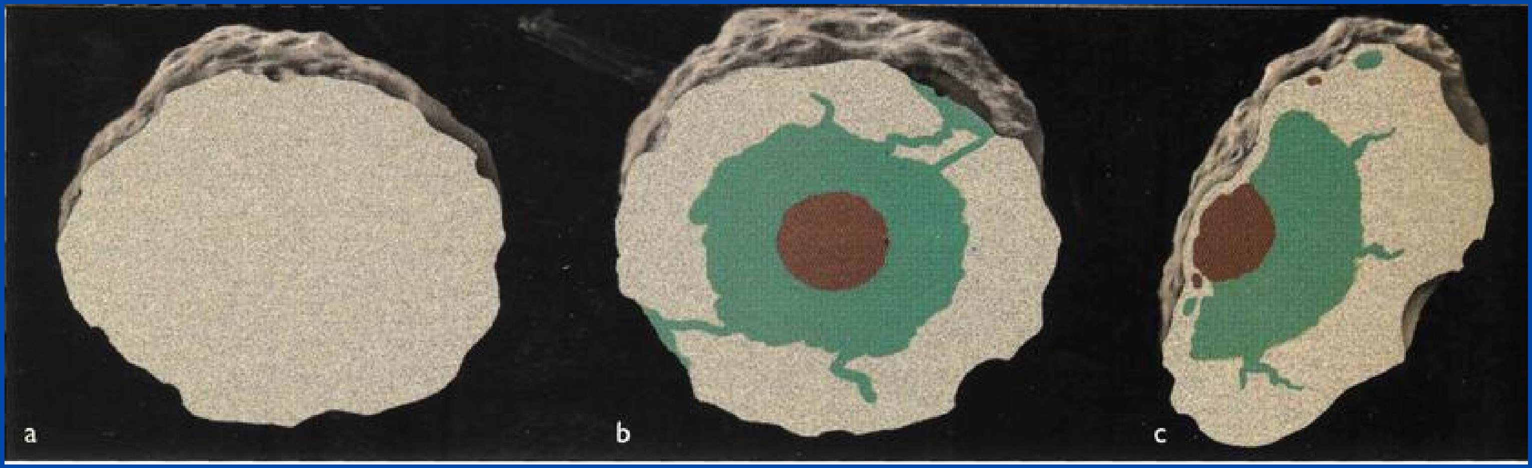


Iron meteorites

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



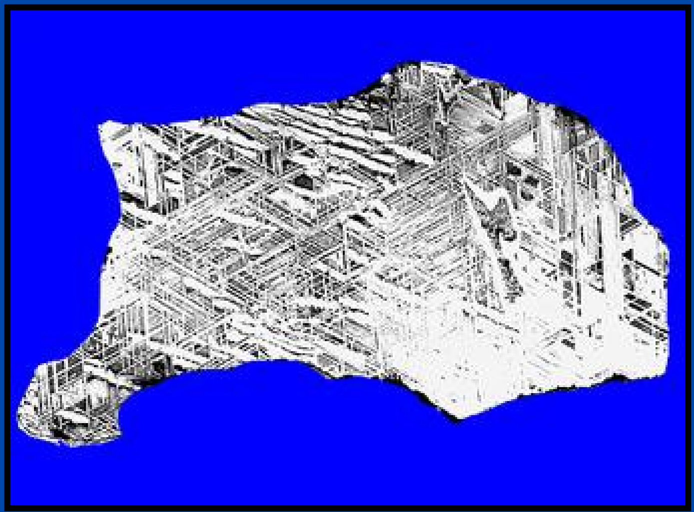
Iron meteorites: from core of differentiated asteroids



The making of future meteorites!

Crystalization pattern of the iron is unique

- **Characteristic of very slow cooling of iron within an asteroid core**
- **Due to diffusion of nickel atoms into solid iron as core cools**
- **Says original asteroid must have been large enough to be differentiated**



Stony-Iron meteorites - the prettiest

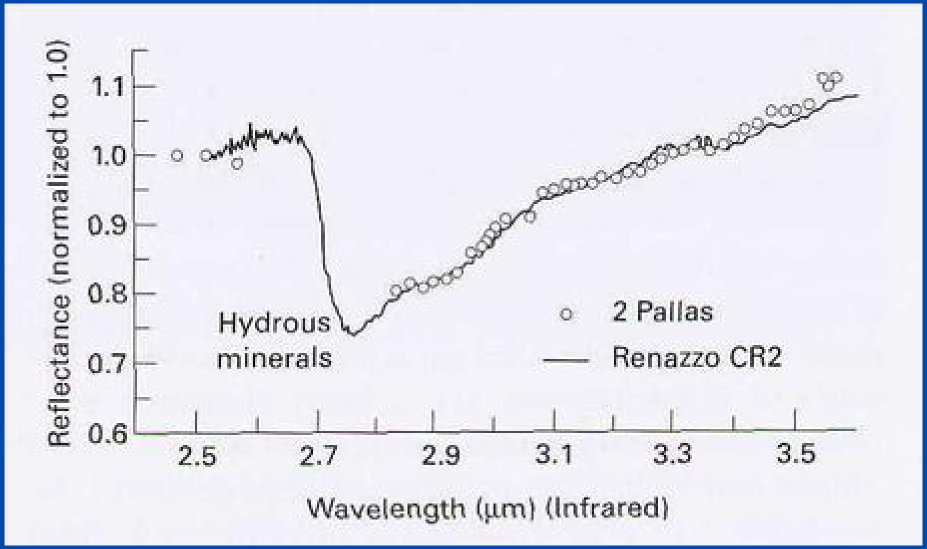
- Crystals of olivene (a rock mineral) embedded in iron
- From boundary between core and mantel of large asteroids?

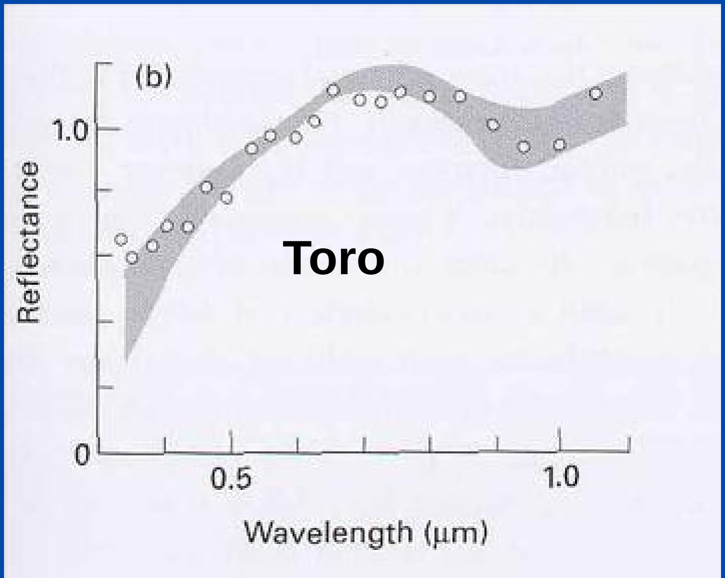
Achondrites: from Mars and Moon

- **From Mars:**
  - **Tiny inclusions have same elements and isotope ratios as Martian atmosphere (measured by spacecraft on Mars)**
- **From the Moon:**
  - **Astronauts brought back rocks from several regions on the Moon**
  - **Some achondrites match these rock types exactly**

Where do meteorites come from, and how do we know?

- **Spectra: reflection of sunlight as function of wavelength of light**
- **Spectra of some meteorites and asteroids can be identical**
- **Implies asteroid was parent body**





The main points: Meteorites

- Each year the Earth sweeps up ~80,000 tons of extraterrestrial matter
- Some are identifiable pieces of the Moon, Mars, or Vesta; most are pieces of asteroids
- Meteorites were broken off their parent bodies 10's to 100's of million years ago (recently compared to age of Solar System)
- Oldest meteorites (chondrites) contain interstellar dust, tiny diamonds made in supernova explosions, organic molecules and amino acids (building blocks of life)
- Direct insight into pre-solar system matter, solar system formation

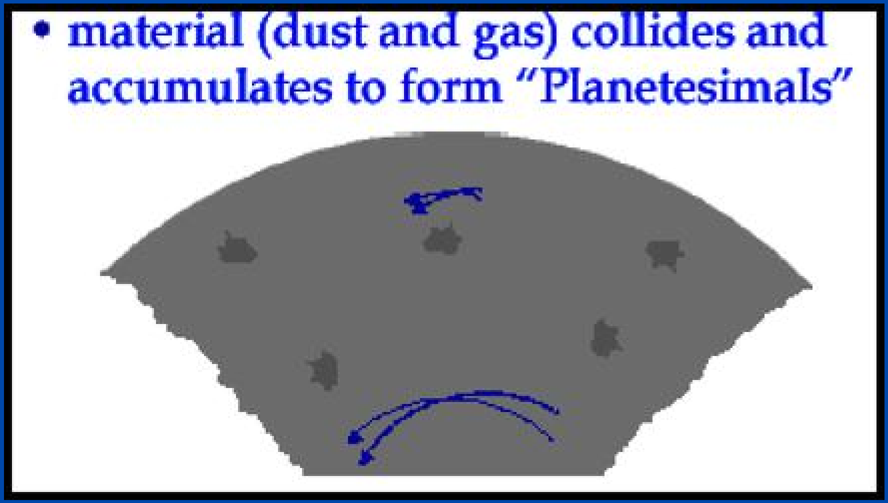
The main points: Cosmic Collisions

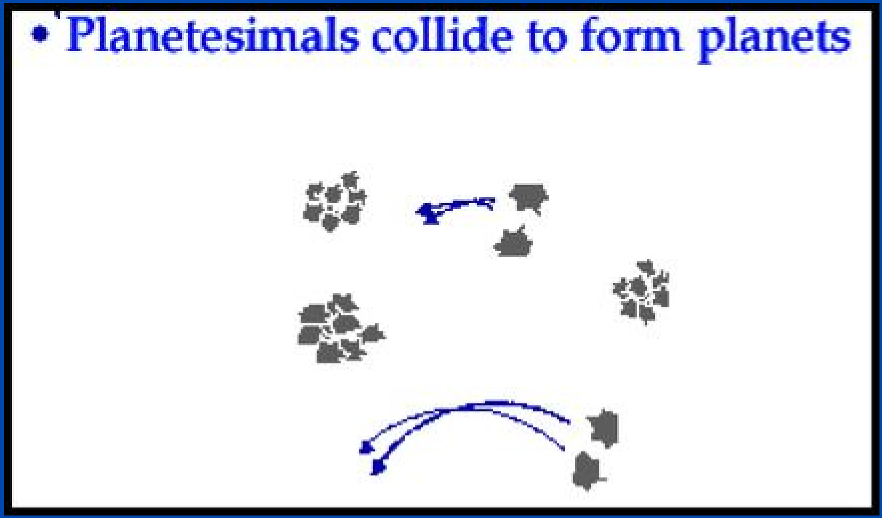
- Cosmic collisions played major role in Solar System evolution
  - Aggregation of planets from planetesimals
  - Formation of Moon, tilt of Venus' and Uranus' rotation axes, composition of Mercury
- Also played a major role in Earth's evolution
  - Tilt of axis
  - Mass extinctions (dinosaurs, others)
- Collision history derived from crater patterns, isotope ratios
- Probability of global catastrophic impact event once every 100 million years
- Strong interest in tracking all Near-Earth Objects (NEO's) that might hit the Earth in the future

Role of cosmic collisions in evolution of Solar System

- Early phase (4.5 billion yrs ago): planet formation
  - Planetesimals collided or accreted to form larger pieces
- Formation of Moon by glancing collision with Earth
- Removal of most of Mercury's crust by collision
- Collision made Venus rotate backwards
- Collision tipped Uranus onto its side (now rotates at 90 deg to rotation axes of all other planets)
- "Late Heavy Bombardment" (~3.9 billion years ago) from Lunar record
  - First signs of life on Earth immediately followed "Late Heavy Bombardment" period. Is there some sort of causal connection?

Early phase (4.5 billion yrs ago): planet formation relies on collisions

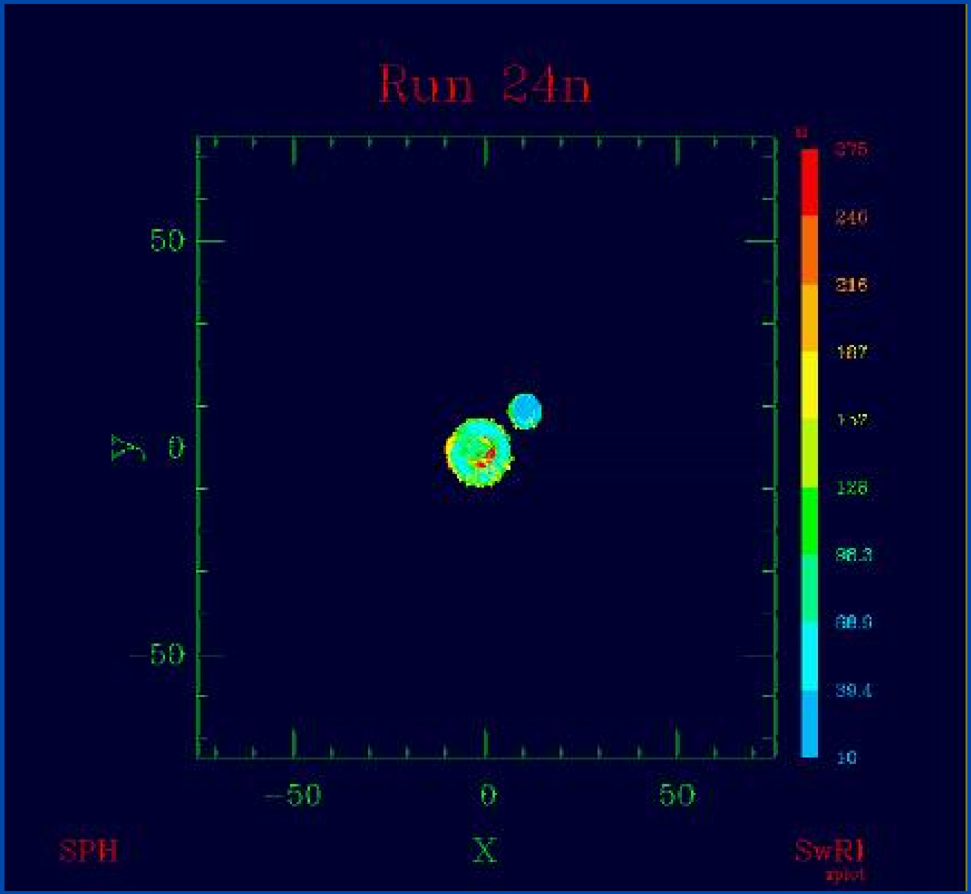




Evidence that Moon formed as result of a collision

- Earth has large iron core, but the moon does not
  - Earth's iron had already drained into the core by the time of the giant impact that formed the moon
- Debris blown out of both Earth and the impactor came from their iron-depleted, rocky mantles
- Explains why mean density of Moon (3.3 grams/cm^3) is much less than Earth (5.5 grams/cm^3)
- Moon has same oxygen isotope composition as the Earth
  - Mars and meteorites from outer Solar System have different oxygen isotope compositions
  - Moon formed form material formed in Earth's neighborhood.

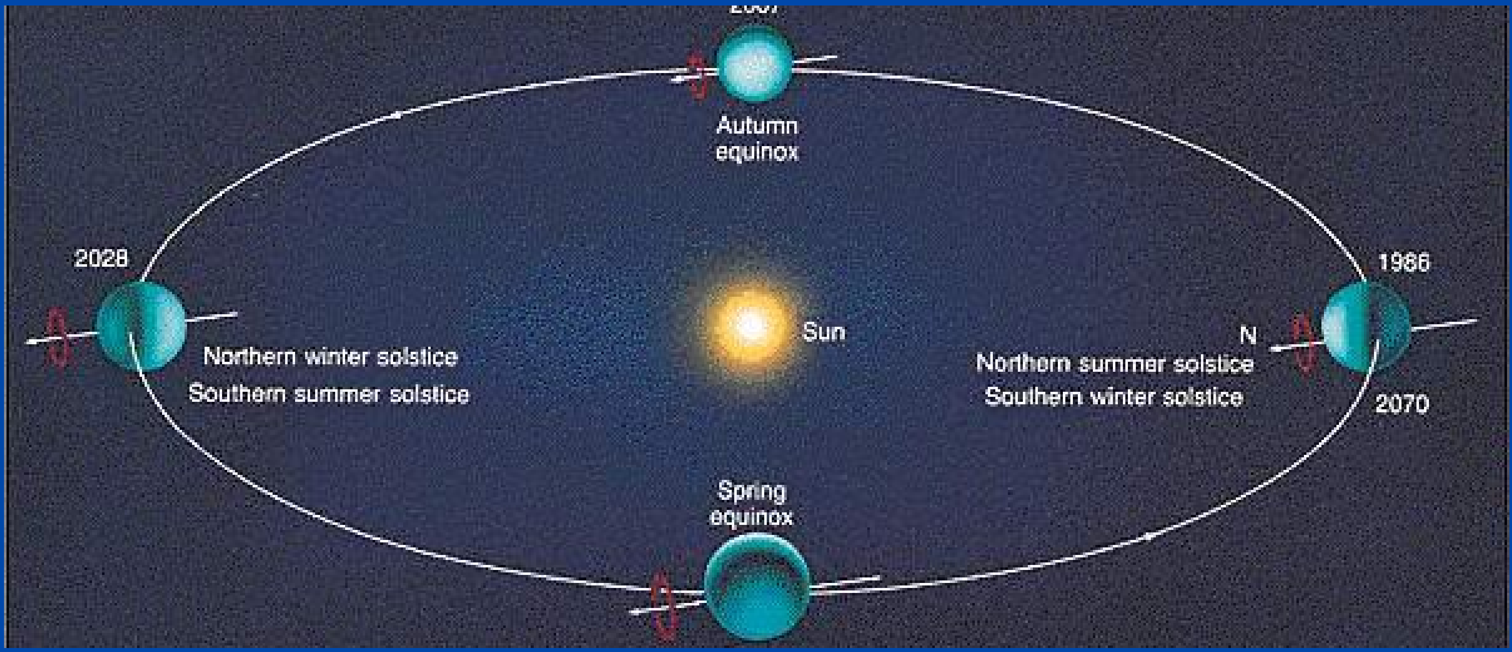
Formation of the Moon….



– **Large planetesimal collides w/ Earth at glancing angle**
– **Removed material is from mantle of Earth**

Uranus' rotation axis lies in plane of its orbit

- **Unique in Solar System**
- **All other planets' rotation axes point out of the plane of their orbits**



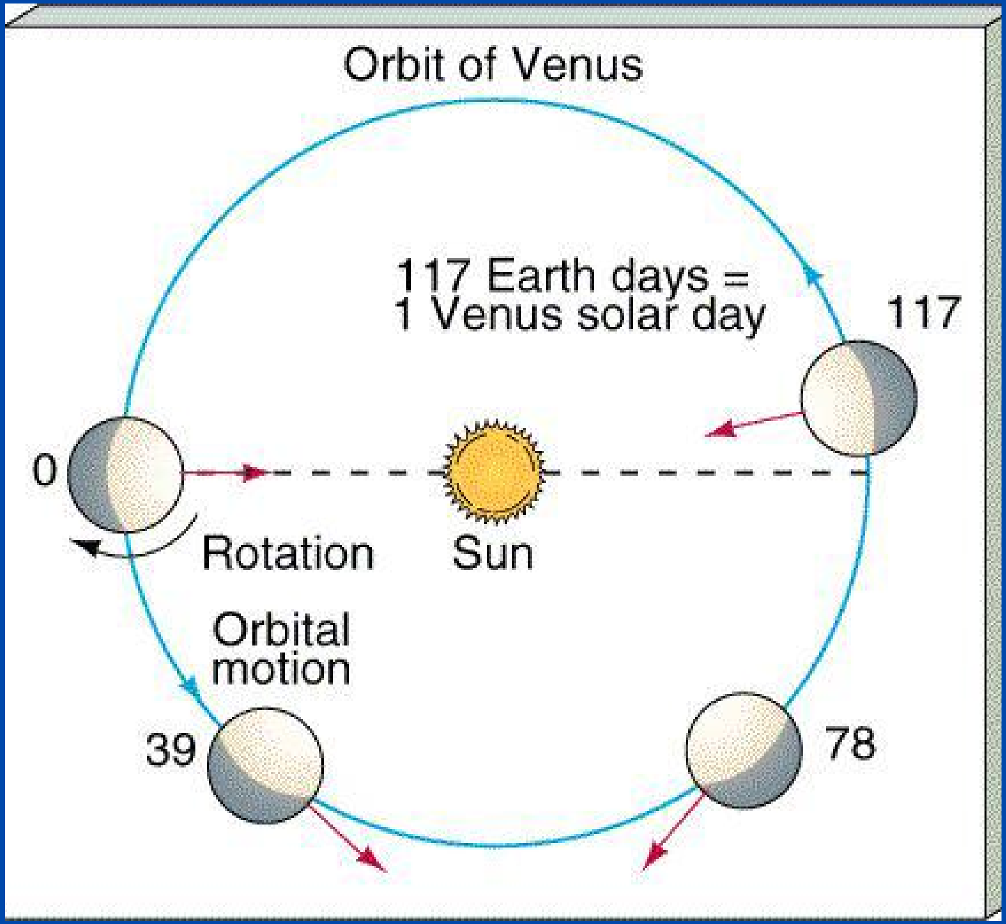
Collision with a massive body is best way to explain this

- Would have to have collided with a body at least as big as the Earth
- Approached Uranus at a large angle to the plane of the Solar System

Theories suggest young outer solar system was very unstable place

- **Many tens of Uranus and Neptune-mass planets initially**
- **Unstable orbits: most of them were ejected from solar system**
- **Perhaps on the way out, one of them hit Uranus**

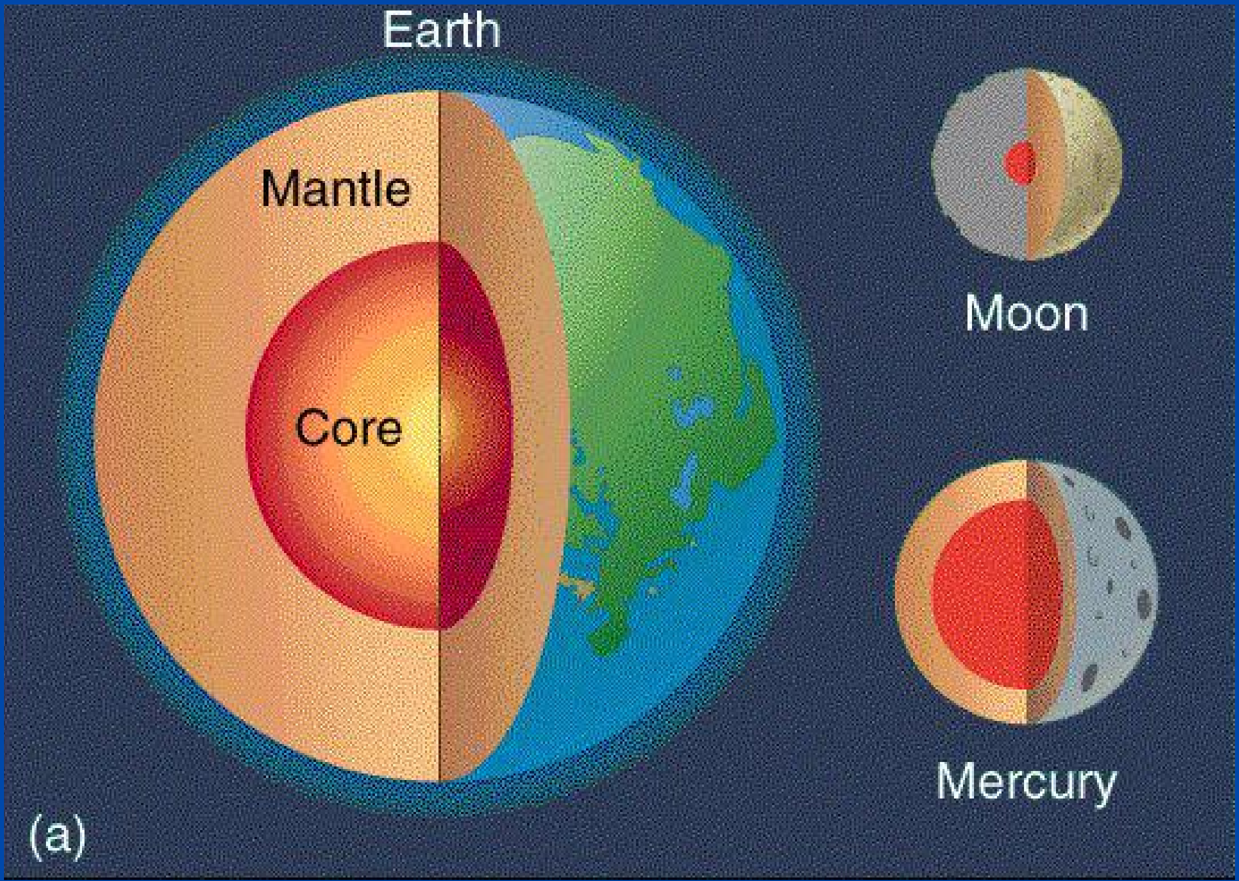
Venus rotates "backwards" compared with all other planets



- **Did two roughly equal-mass bodies merge to form Venus? Was early Venus hit by another planetary object?**

Removal of most of Mercury's crust by collision

- **Theory developed to explain why Mercury has so little lithosphere compared with its core**



The Moon

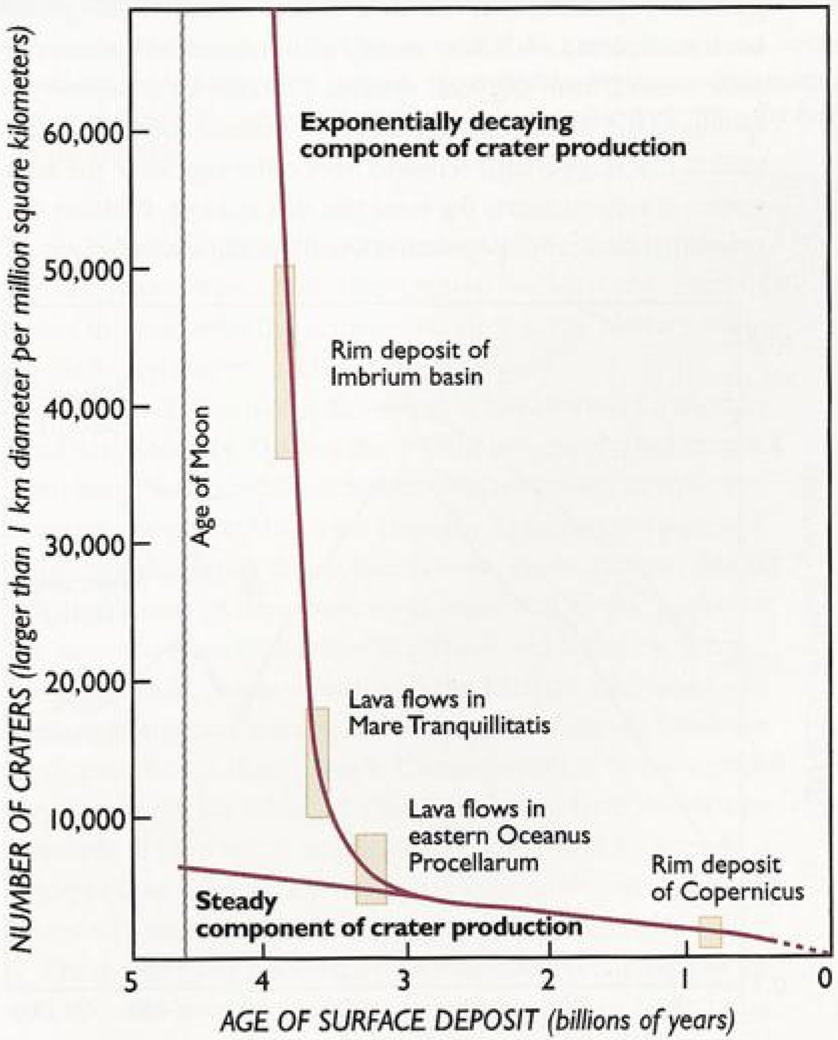


Figure 12. Lunar surfaces of different ages exhibit different crater densities. The rapid cratering rate during the late heavy bombardment fell off dramatically between 3.9 and 3.3 billion years ago, giving way to a slower, steady rate of crater production. This dramatic falloff is reflected in the varying ages and crater densities determined at Apollo landing sites (small rectangles, whose dimensions correspond to uncertainties).

"Late Heavy Bombardment" of Moon

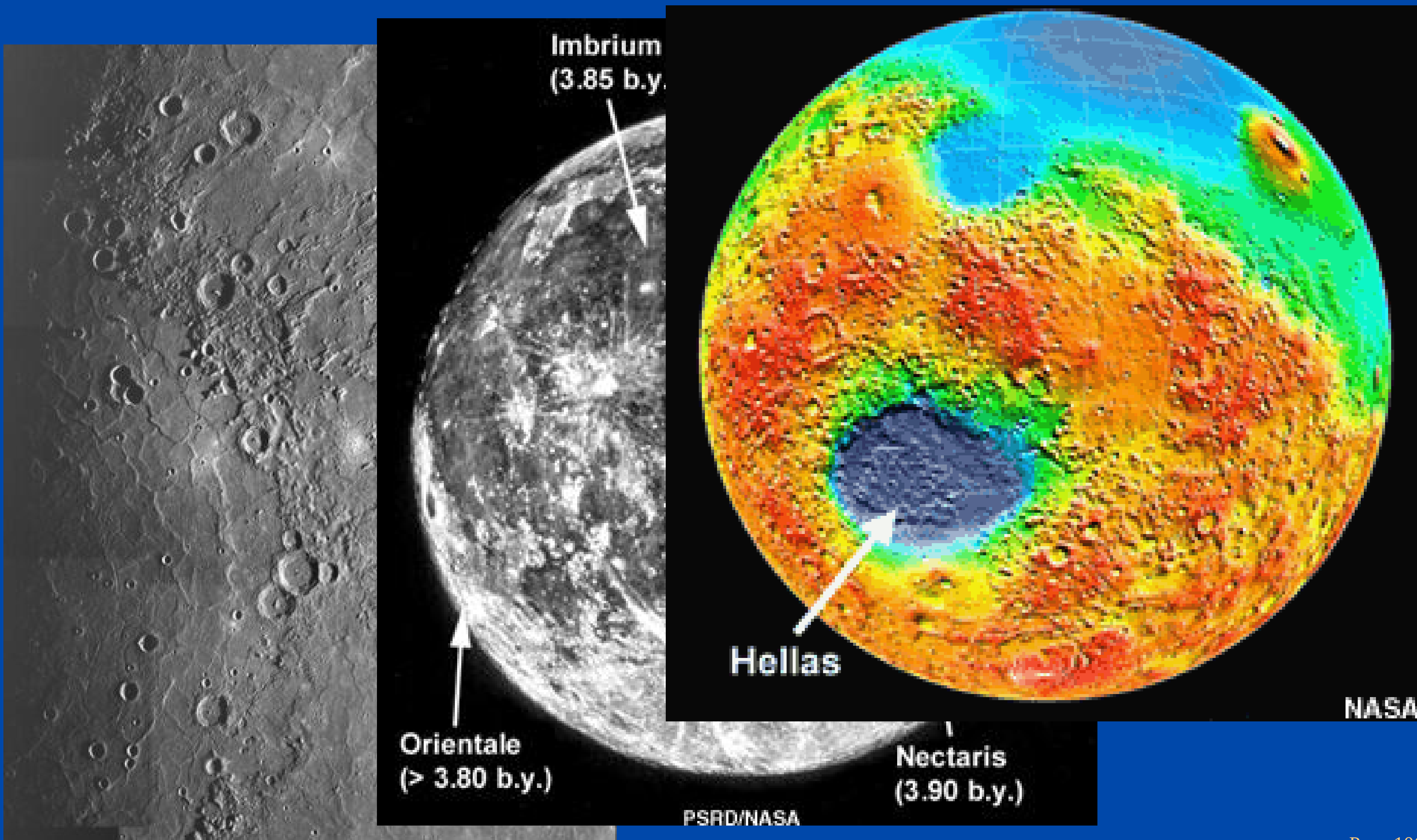
- Evidence from Moon suggests impact rate was 1000 times higher 4 billion years ago than 3.8 billion years ago
- Heavy bombardment of Moon slowed down about 3.8 billion years ago
- Similar evidence from Mercury, Mars

Evolution of the Moon's Appearance

"Mare" are huge lava flows that came from fissures in Moon's crust 3.2-3.9 billion years ago. There are similar flows on Earth (Siberia, India).

Even during heavy bombardment, a major impact only occurred every few thousand years. Now they only occur over tens or hundreds of millions of years (so the lunar surface hasn't changed too much).

Basins on Mercury, Moon, Mars



How general was the "late heavy bombardment" ?

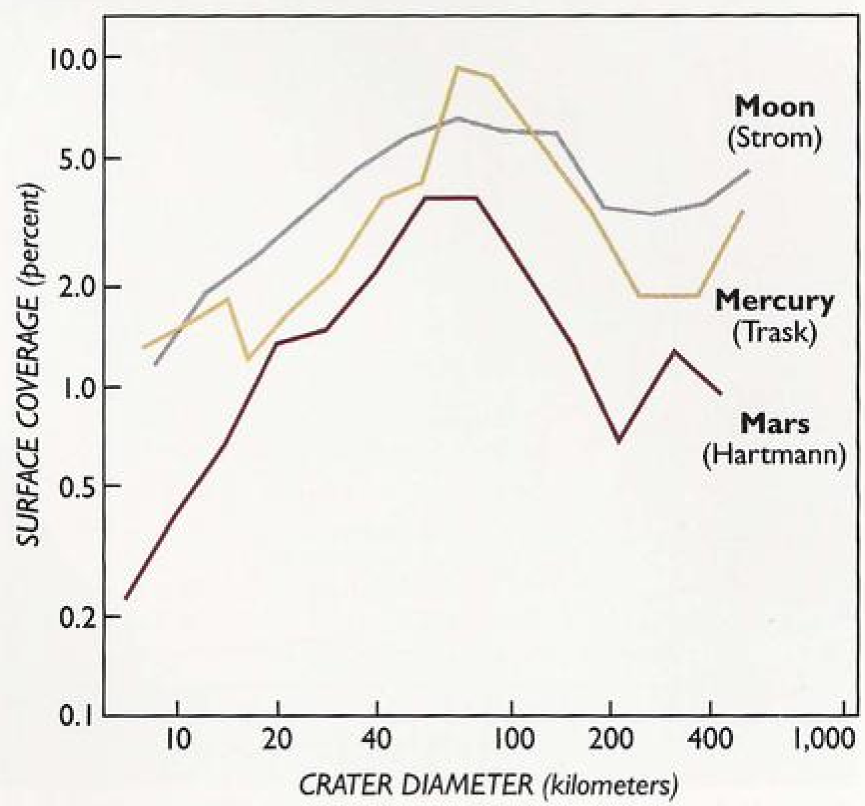


Figure 13. Crater size distributions on the highlands of the Moon, Mercury, and Mars (authors whose data have been used are named by each curve). The coverage on all three bodies peaks for craters with diameters of 40 to 100 km, and the distributions' similar shapes suggest that the same population of impacting projectiles produced most of the craters on the ancient highlands of all three planets.

- **If Moon, Mars, Mercury all were hit, probably the Earth was too**
- **Was it the "last gasp" of planetary accretion? Or a real spike in impact rate?**

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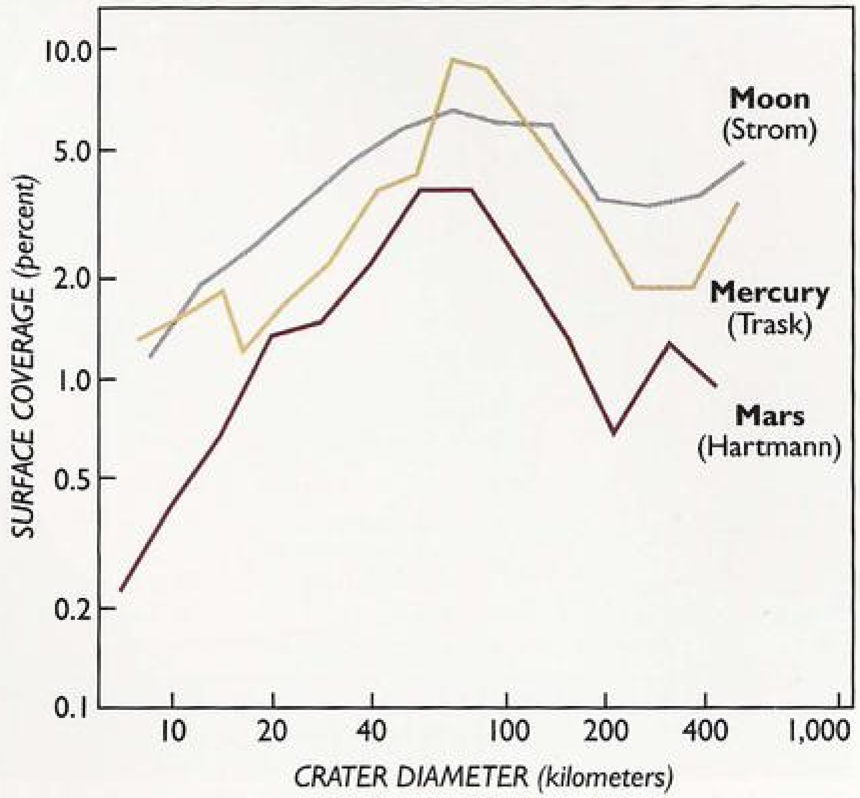

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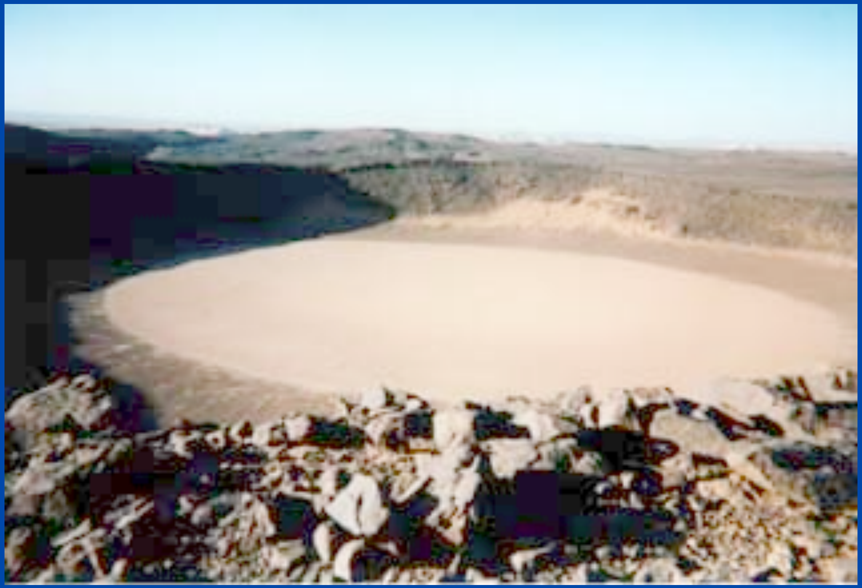
- **If Moon, Mars, Mercury all were hit, probably the Earth was too**
- **Was it the "last gasp" of planetary accretion? Or a real spike in impact rate?**

One theory: a real spike in impacts

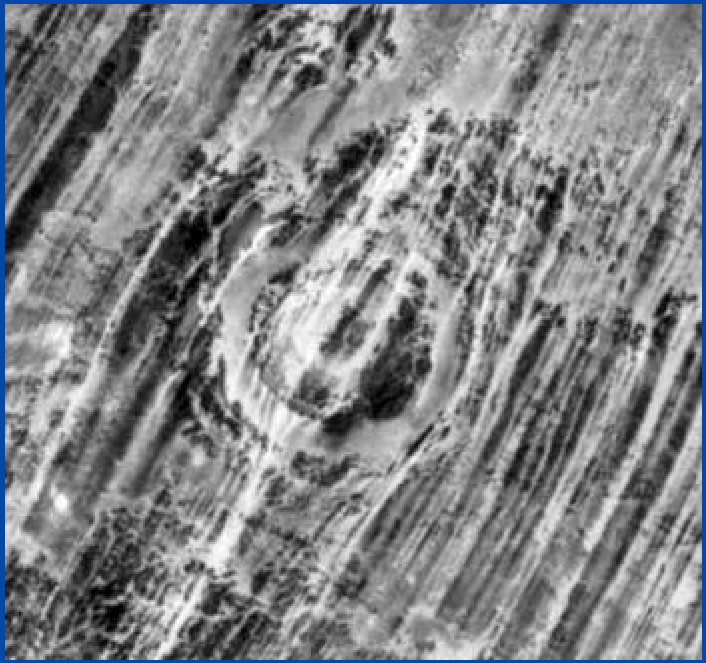
- Initially Solar System had large population of icy objects beyond Saturn
- In stable orbits around Sun for several hundred million years until Neptune and Uranus began to form
- As these planets grew, their gravitational attraction began to scatter the remaining planetesimals into the inner Solar System
- A small fraction crashed into the Moon and rocky planets, making immense craters
- Calculations suggest that the bombardment would have lasted less than 100 million years
- Consistent with ages of craters and impact basins in Lunar highlands

Earth experienced major collisions as well

- **But most craters got eroded away, subducted, or drowned**
- **A tour of craters on Earth:**



Algeria



Chad (Africa) from airplane

Earth's craters

Clearwater, Canada **Henbury, Australia**

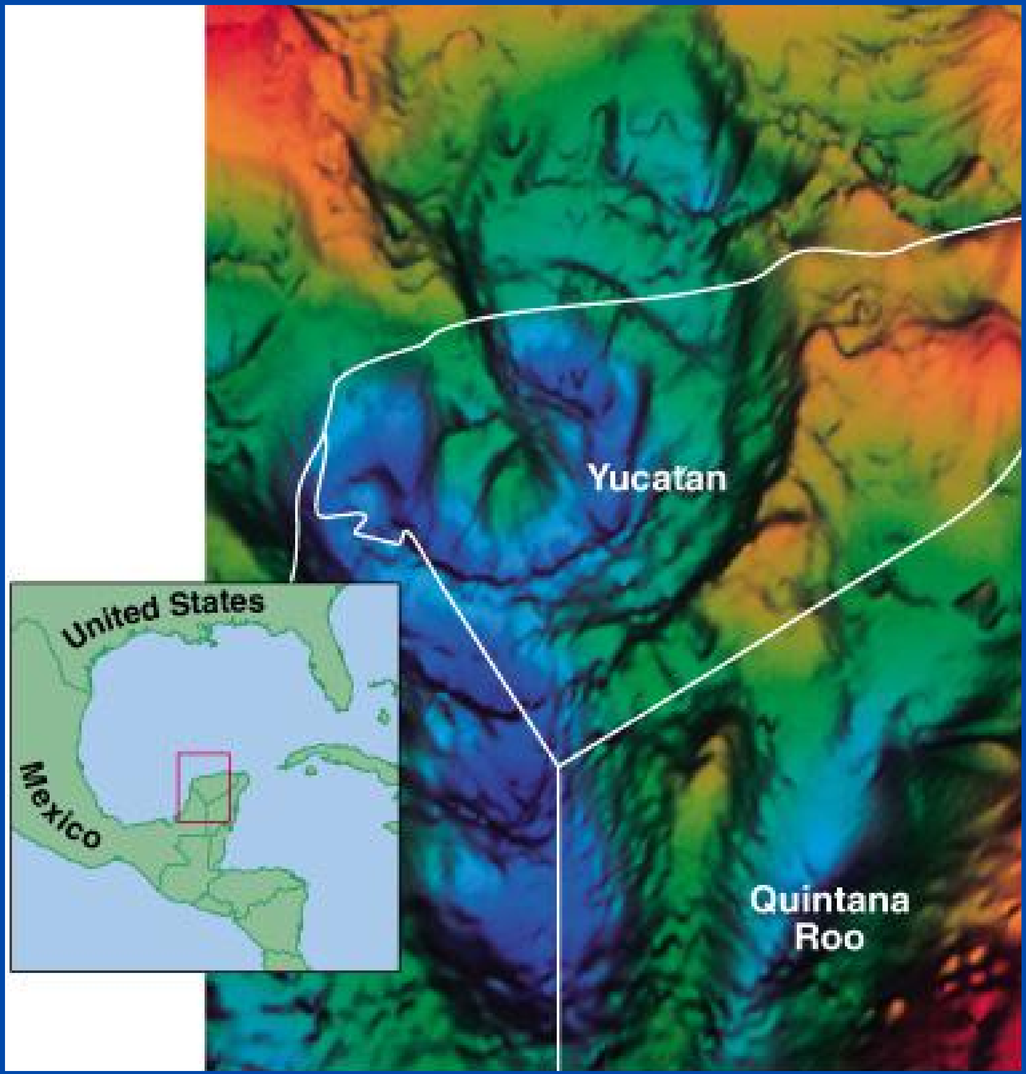
Earth's craters, continued

Tswaing, South Africa

New Quebec, Canada

Arizona's Meteor Crater, the most famous example

Giant impact 64 million years ago: best idea for dinosaur extinction



- Chicxulub crater north of Yucatan peninsula, Mexico
- 180 km wide
- Dated to same period as extinctions at Cretacious-Tertiary boundary

Corroborating evidence: Iridium layer

- Layer of enhanced abundance of Iridium found worldwide
- Dated to same time as dinosaur impact
- Asteroids contain high concentration of Iridium, relative to Earth
- Ash on top of Iridium (huge fires)

Impact energies are very large!

Kinetic energy $= \frac{1}{2}MV^2$ where V is velocity of impactor

V is very large (estimate orbital speed around Earth): 30 km/sec = 66,000 mph

$$M = density \times volume \cong 5\frac{gm}{cm^3} \times volume$$

Volume of sphere $= \frac{4}{3}\pi r^3 = \frac{1}{6}\pi d^3$ where d is diameter

Combine:

$$\text{Kinetic energy} = \frac{1}{2}MV^2 = \left(\frac{d}{1\text{ meter}}\right)^3 \times 10^{19}\text{ gm cm}^2/\text{sec}^2 = 250\left(\frac{d}{1\text{ meter}}\right)^3\text{ tons of TNT}$$

If diameter d = 200 meters, Kinetic Energy = 2 billion tons of TNT!

Note VERY strong dependence on size of impactor, d (Energy $\propto d^3$)

Credit: Bob O'Connell, U Virginia

BBC News, 2002: Evidence for Late Heavy Bombardment on Earth

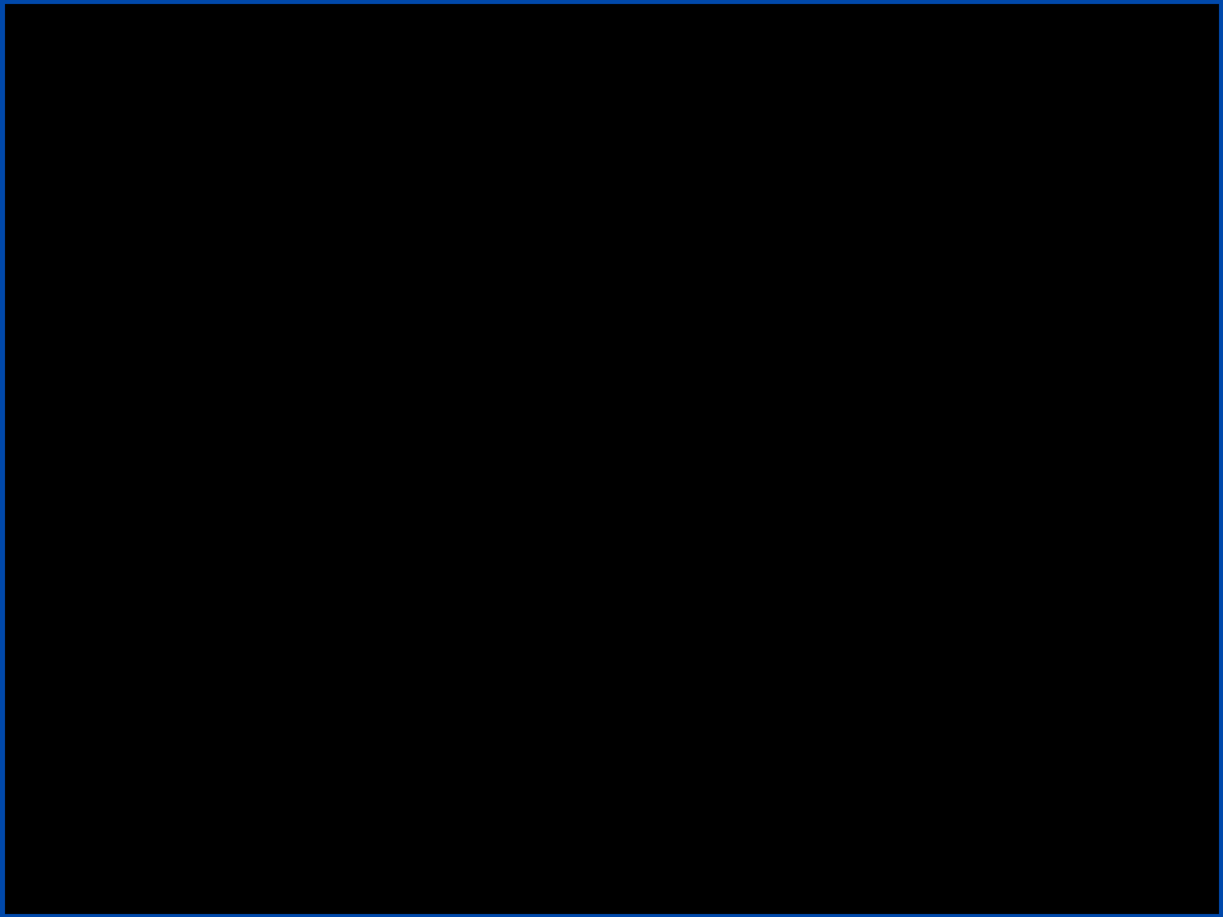
OUR PLANET WAS BEATEN UP

- The first convincing evidence that the Earth was bombarded by a devastating storm of meteoroids and asteroids four billion years ago has been found in Earth's oldest rocks.
- Scientists have looked for clues in sedimentary rocks from Greenland and Canada - the oldest on Earth - that date from the waning phases of the Late Heavy Bombardment.
- Researchers from the University of Queensland, Australia, and the University of Oxford, UK, say they have detected in these rocks the chemical fingerprints of the meteorites left over from the Late Heavy Bombardment - various types of tungsten atoms (tungsten isotopes) that must be extraterrestrial.

Collision of Comet Shoemaker-Levy 9 with Jupiter, 1994

- Comet discovered March 1993, after it was captured into orbit around Jupiter
- In 21 separate pieces! Broke up due to Jupiter's tidal forces
- All 21 fragments hit Jupiter in one week in July 1994

Tidal breakup of a comet when it passes too close to Jupiter



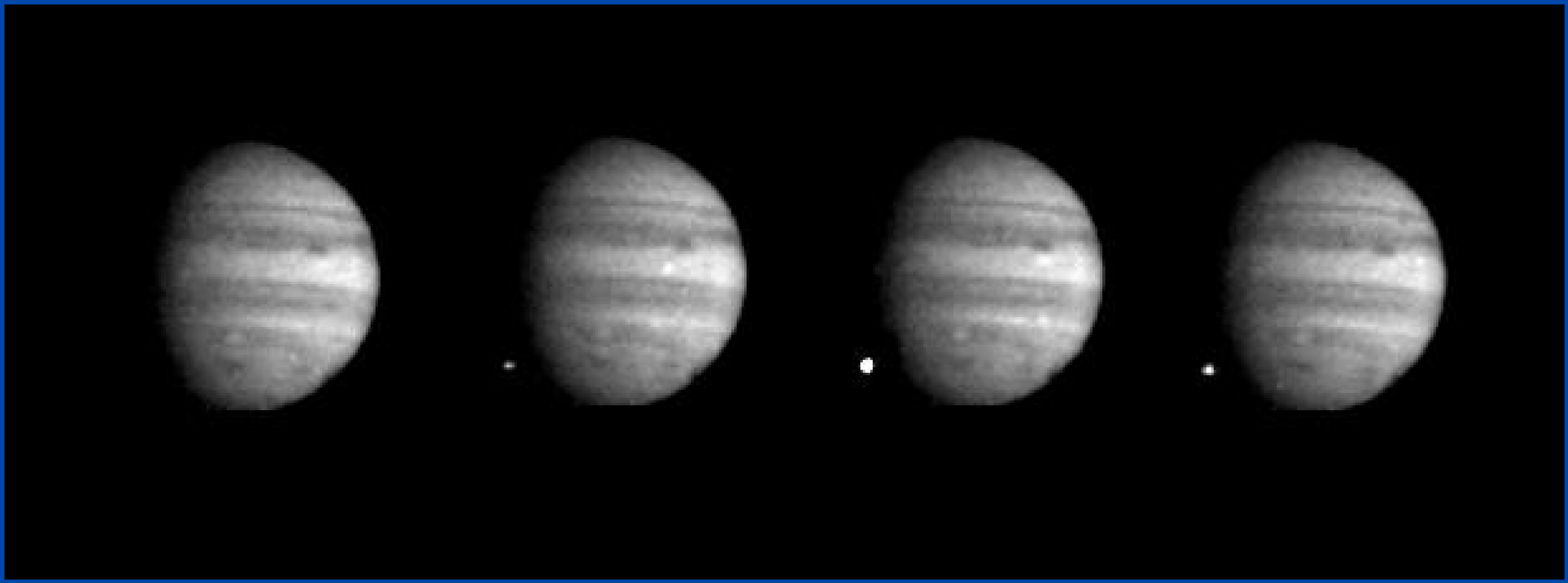
Worldwide network of astronomers observed collisions over one week

- I was at Lick Observatory on Mt Hamilton
- As Earth turned, e-mails flew around the planet to tell people what to look for
  - As Jupiter was setting at one place on Earth, scientists sent e-mails to places where Jupiter was just rising
- Examples: "Impact B is a dud"
  "Impact G is spectacular"

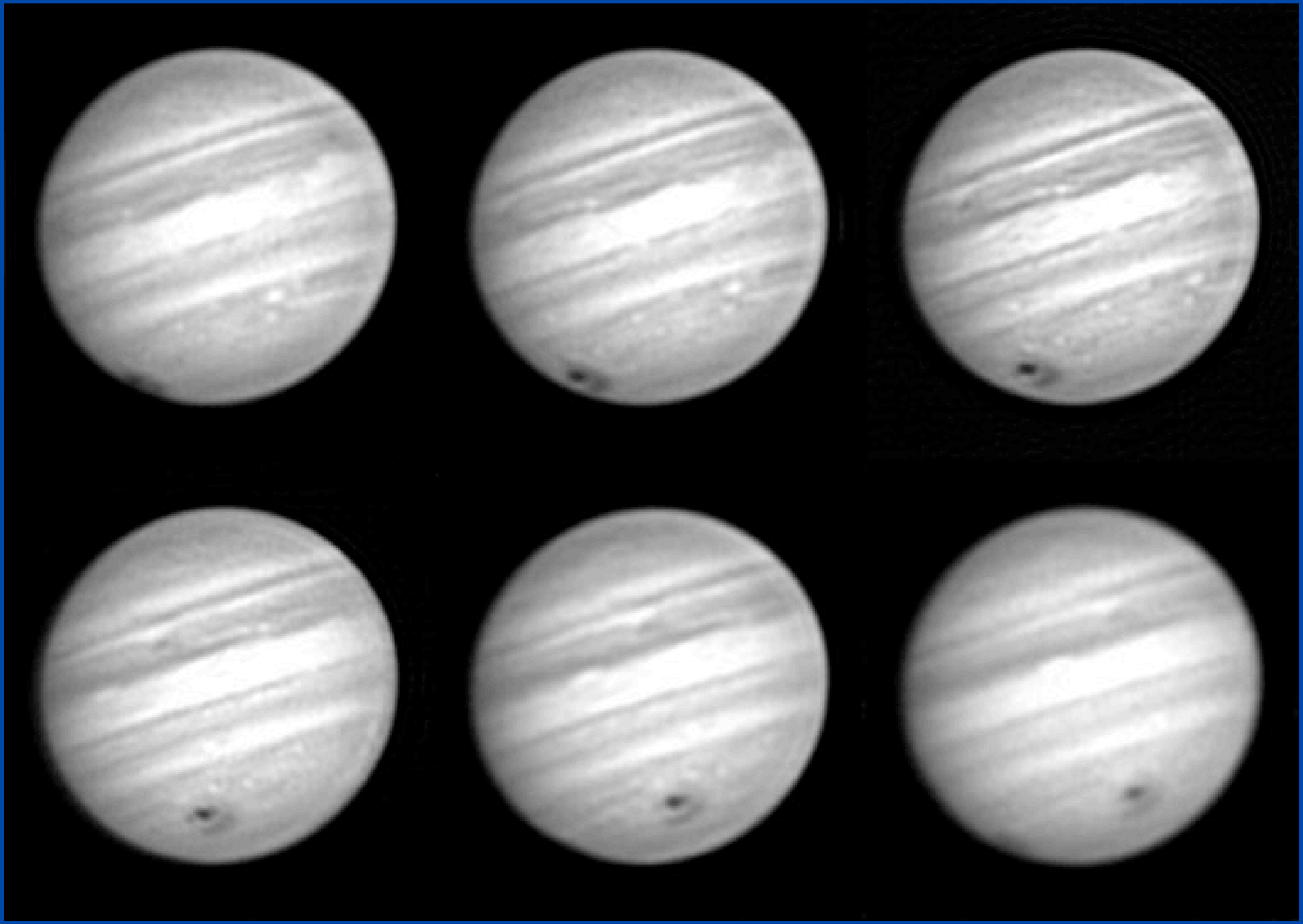
Initial impact with atmosphere on night side, seen by Galileo spacecraft

- Time sequence

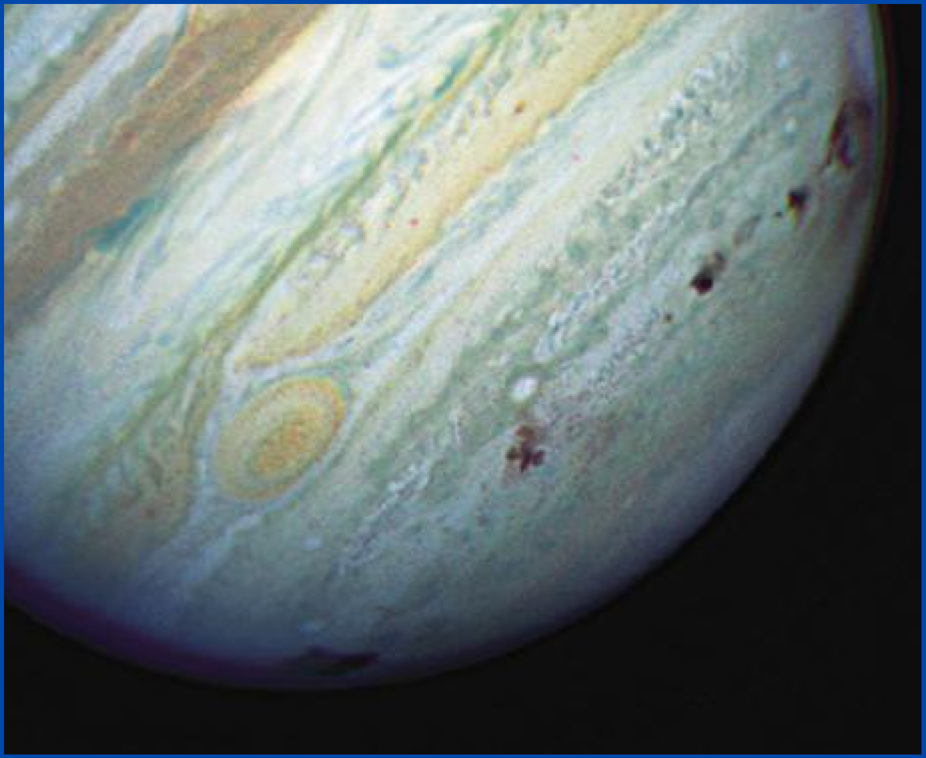
- White dots are hot gases exploding out of Jupiter's atmosphere on night side



G impact spot as Jupiter rotated (Lick Observatory)



Multiple fragments of Shoemaker-Levy 9 hit Jupiter in sequence



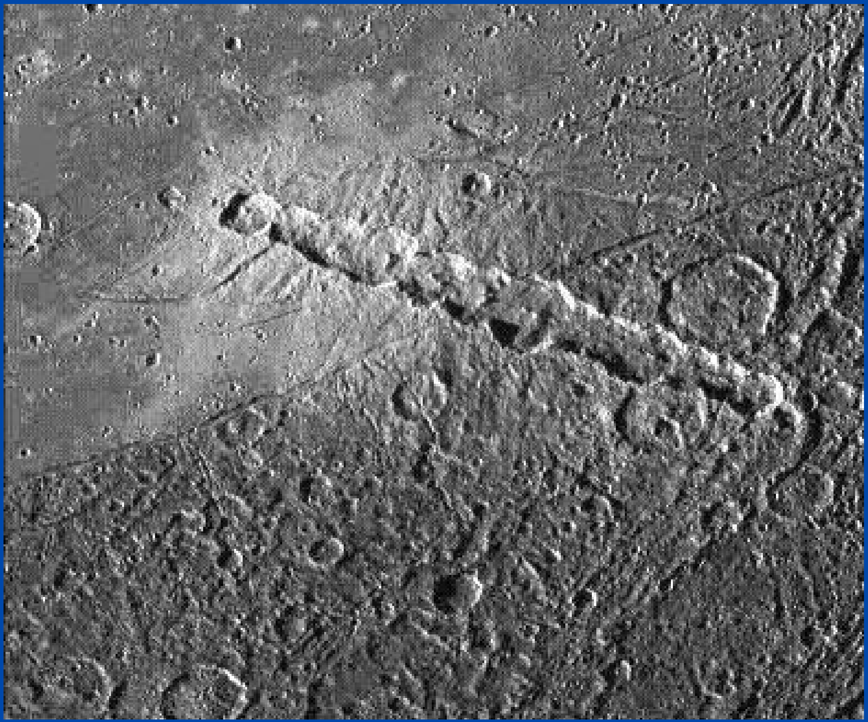
Infrared image of multiple impact points

(Keck Telescope)

Hubble Space Telescope visible-light image

Lessons learned from Comet Shoemaker-Levy 9

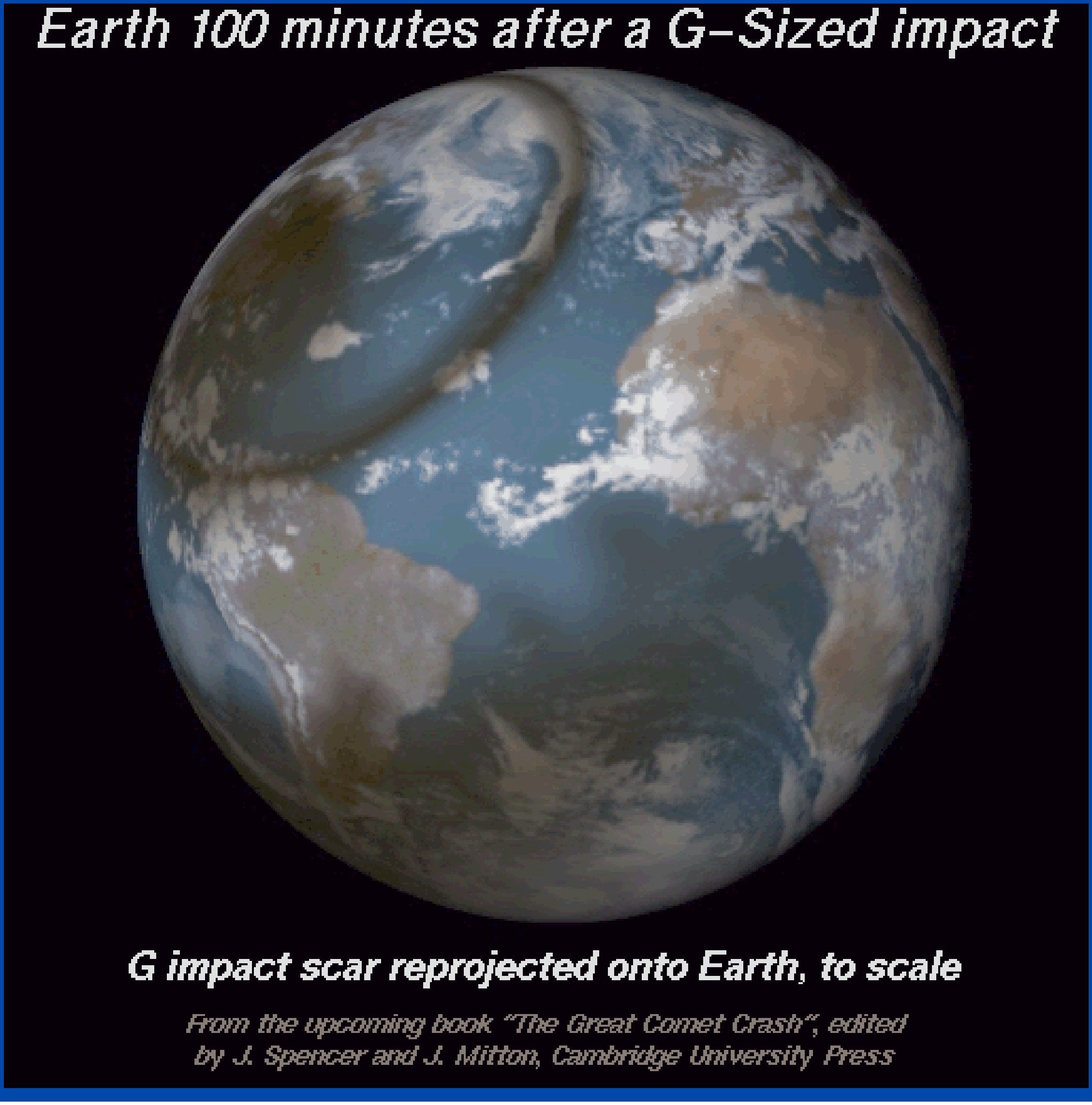
- Made us realize that "impacts happen" !
- Many comets must break up into pieces the way SL-9 did: Ganymede craters



The asteroid with our name on it

- We haven't seen it yet.
- Deflection is more probable with years of advance warning.
- Control is critical: Breaking a big asteroid into a bunch of little asteroids is unlikely to help.
- We get less advance warning of a killer comet….

What if a Shoemaker-Levy 9 size comet were to hit the Earth?

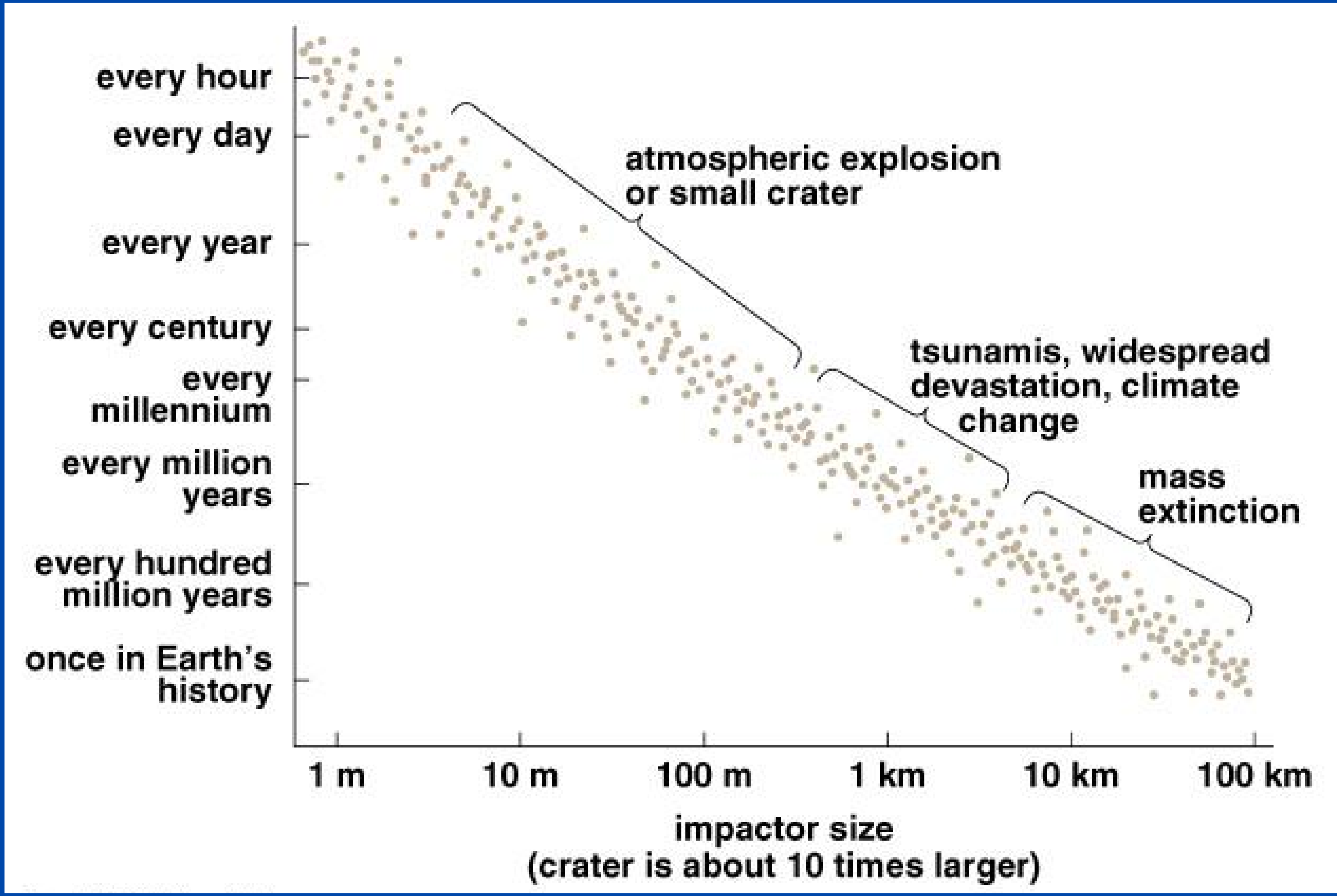


Drastic effects of impact on a terrestrial planet

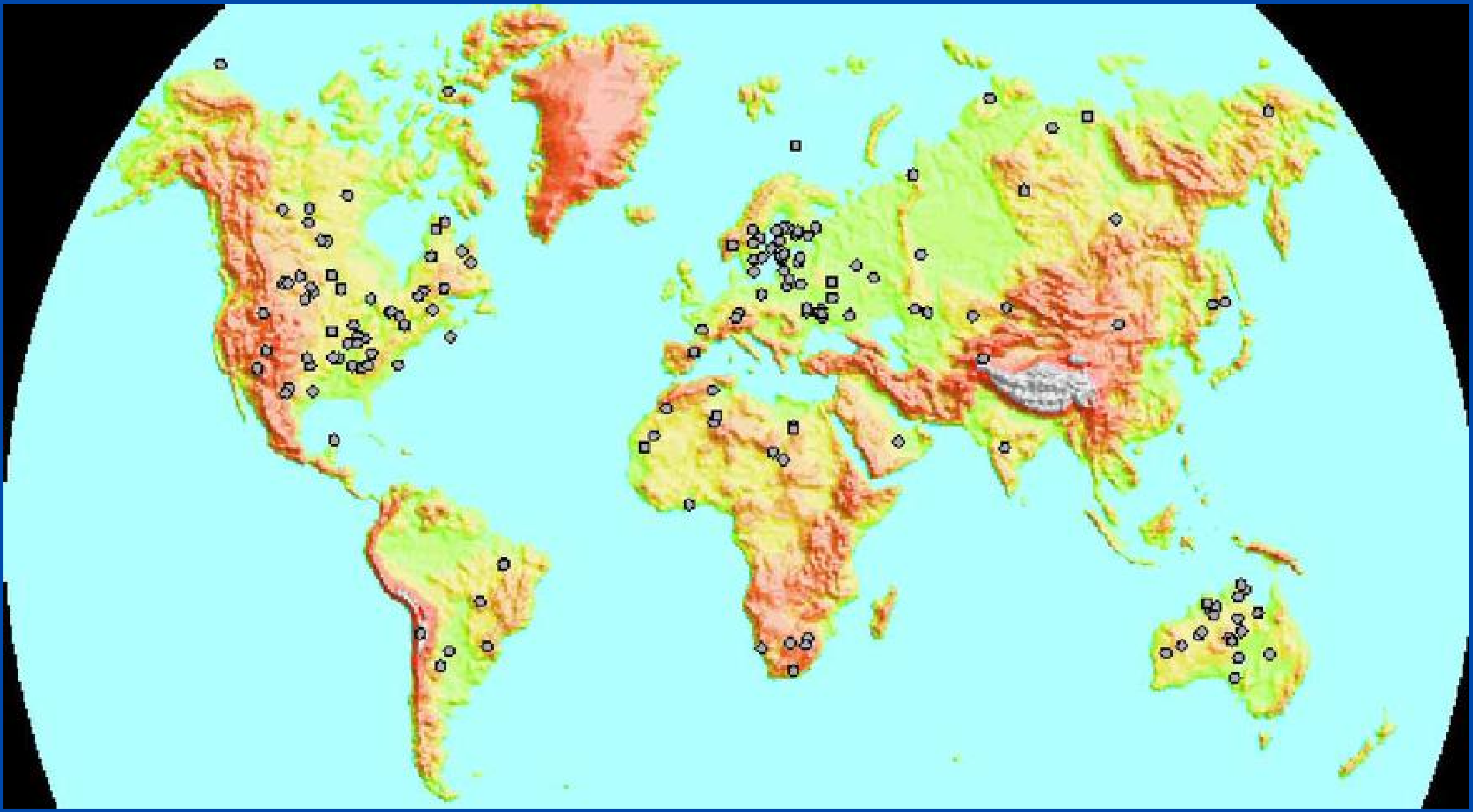
- At "ground zero" rock, water, biomass are vaporized or melted
- Deeper rock is shock recrystallized (ultra high pressures) and fractured
- Series of deep fractures form, may allow lava from the interior to erupt
- Shockwaves obliterate life just outside of "ground zero"
- Earthquakes (and impact itself, if in ocean) generate giant waves in oceans, wipe out coastal areas
- Friction in atmospheric dust generates widespread lightening
- Thick dust in atmosphere blots out sun for months or years
- Aerosols caused by eruptions and vaporization remain in atmosphere for decades

Future extinctions might not be limited to dinosaurs

Near Earth Objects: will Earth have another collision soon?



There have been many impacts in the past



What can be done?

1) Vigorous program to detect objects that are aiming near Earth
   - Several are under way; not as vigorous as they might be
   - Also need better orbit prediction methods

2) Characterize mechanical properties of the main types of asteroids, comets
   - Are they solid? Rubble piles? Makes a difference.

3) Work on conceptual ways to divert an incoming object
   - Gentle (ion thruster for 50 yrs)
   - Not so gentle (e.g. nuclear blast, ….)
   - Solar radiation pressure? (paint one side white!)

There are several projects to find near Earth asteroids and comets

- **It is thought that there are about 1600 Earth crossing asteroids larger than 1 km in diameter.**
- **Only about 100 are known.**
- **Programs to find most of them are under way**
- **Still somewhat of a hard sell to funding agencies**

Question

- If one of the Near Earth Object programs finds an incoming asteroid that will likely hit the Earth, should they announce it to the public?

THE TORINO SCALE

Assessing Asteroid and Comet Impact Hazard Predictions in the 21st Century

Events Having No Likely Consequences	0	The likelihood of a collision is zero, or well below the chance that a random object of the same size will strike the Earth within the next few decades. This designation also applies to any small object that, in the event of a collision, is unlikely to reach the Earth's surface intact.
Events Meriting Careful Monitoring	1	The chance of collision is extremely unlikely, about the same as a random object of the same size striking the Earth within the next few decades.
Events Meriting Concern	2	A somewhat close, but not unusual encounter. Collision is very unlikely.
	3	A close encounter, with 1% or greater chance of a collision capable of causing localized destruction.
	4	A close encounter, with 1% or greater chance of a collision capable of causing regional devastation.
Threatening Events	5	A close encounter, with a significant threat of a collision capable of causing regional devastation.
	6	A close encounter, with a significant threat of a collision capable of causing a global catastrophe.
	7	A close encounter, with an extremely significant threat of a collision capable of causing a global catastrophe.
Certain Collisions	8	A collision capable of causing localized destruction. Such events occur somewhere on Earth between once per 50 years and once per 1000 years.
	9	A collision capable of causing regional devastation. Such events occur between once per 1000 years and once per 100,000 years.
	10	A collision capable of causing a global climatic catastrophe. Such events occur once per 100,000 years, or less often.

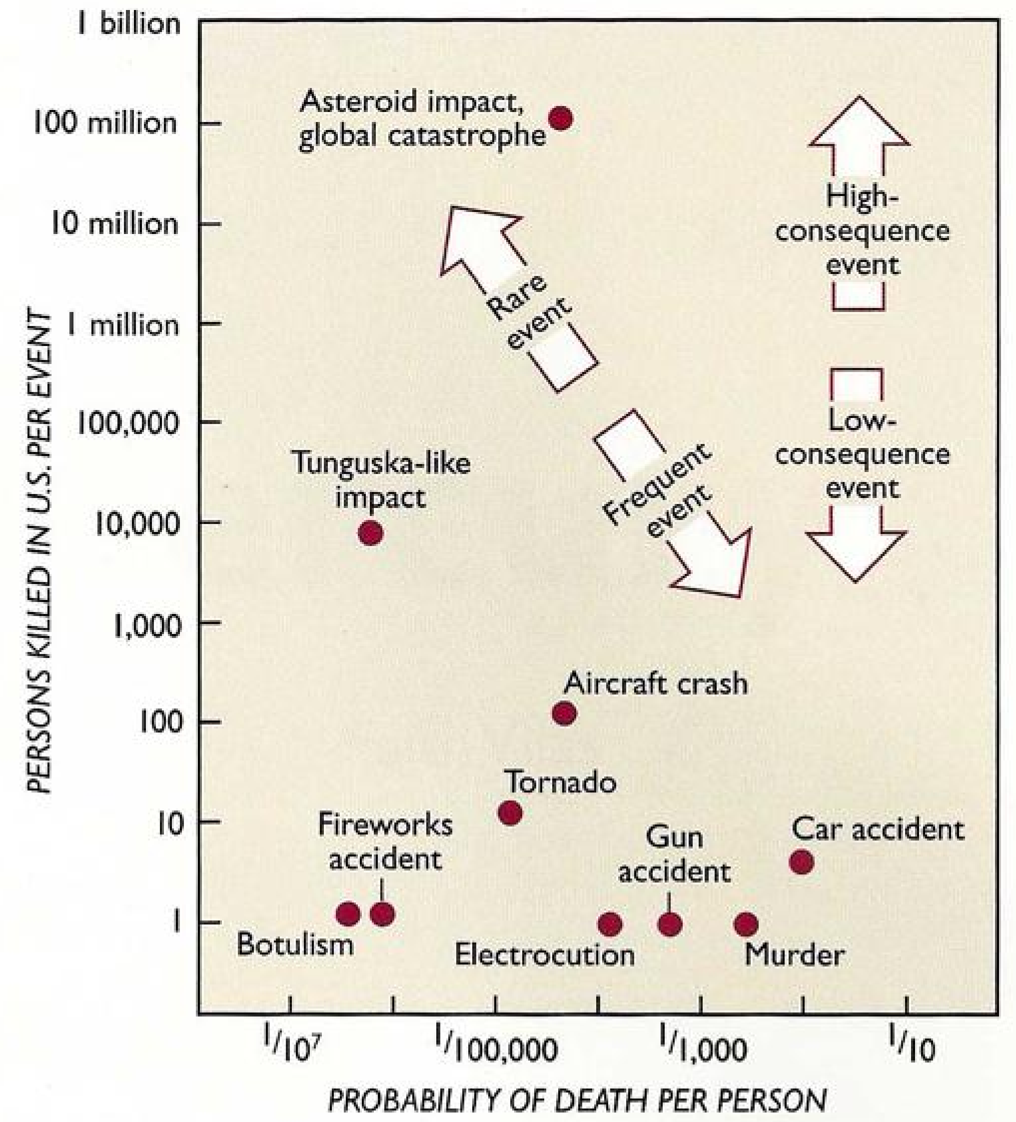


Figure 19. Averaged over a human lifetime, the chance of being killed by an asteroid or comet impact is about the same as dying in a plane crash. Impacts are much rarer than aircraft accidents, but orders of magnitude more persons would be killed if even a small asteroid stuck Earth.

- **Low probability of a rare but high-consequence event**

Cosmic Collisions: The main points

- Cosmic collisions played major role in Solar System evolution
  - Aggregation of planets from planetesimals
  - Formation of Moon, tilt of Uranus' axis, composition of Mercury
- Also played a major role in Earth's evolution
  - Tilt of axis
  - Mass extinctions (dinosaurs, others)
- Collision history derived from crater patterns, isotope ratios
- Probability of global catastrophic impact once every 100 million years; regional catastrophic events more frequent
- Recent advances in tracking all Near-Earth Objects (NEO's)
  - Very active field of research!
  - Probability is 100% that a Near Earth Object will hit us. The big questions are "how soon?" and "what can we do about it?"