Lecture 14:
Meteorites and Cosmic Collisions

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November 16, 2010

Astro 18: Planets and Planetary Systems

UC Santa Cruz

Practicalities

- **Thursday November 18th:**
  - **DIFFERENT CLASSROOM: Interdisciplinary Sci 102**
  - **Lab on Transiting Planets**
- **Tuesday November 23rd:**
  - **Last actual lecture: Life in the Universe**
- **During Break:**
  - **Take a look at our meteorites**

Outline of lecture

- **Meteorites:**
  - – How are meteorites found?
  - – Main types
  - – Where do they come from?
  - – Meteorites as time capsules

Please remind me to take a break at 12:45 pm

- **Cosmic Collisions**
  - – Role of cosmic collisions in evolution of Solar System
  - – History of collisions
  - – Collision of Comet Shoemaker-Levy 9 with Jupiter
  - – Effects of impacts
  - – Prospects for future giant collisions with Earth

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

- **Wikipedia**

  Meteoroid: chunk of debris in the Solar System.

  Meteor: The visible path of a meteoroid that enters Earth's (or another body's) atmosphere.

  Meteorite: A meteoroid that reaches the ground and survives impact

  Meteor Shower: Many meteors appearing seconds or minutes apart.

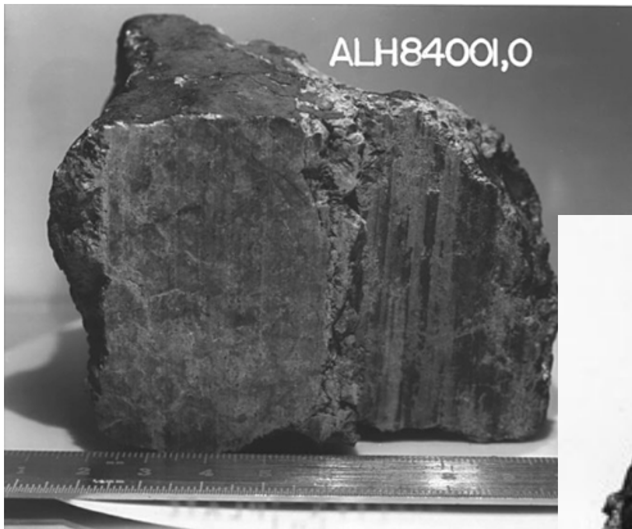
  Origin: Comes from Greek meteōros, meaning "high in the air”.

- **How can you tell that you have a meteorite?**
  - Higher metal content than terrestrial rocks
  - Contain Iridium and other isotopes not 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)**

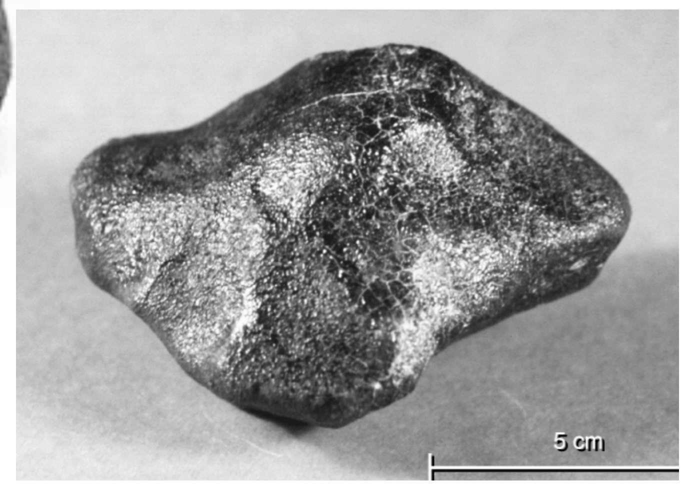
What do meteorites look like?



Meteorite
from Mars

Allen Hills
(Moon)

Vesta

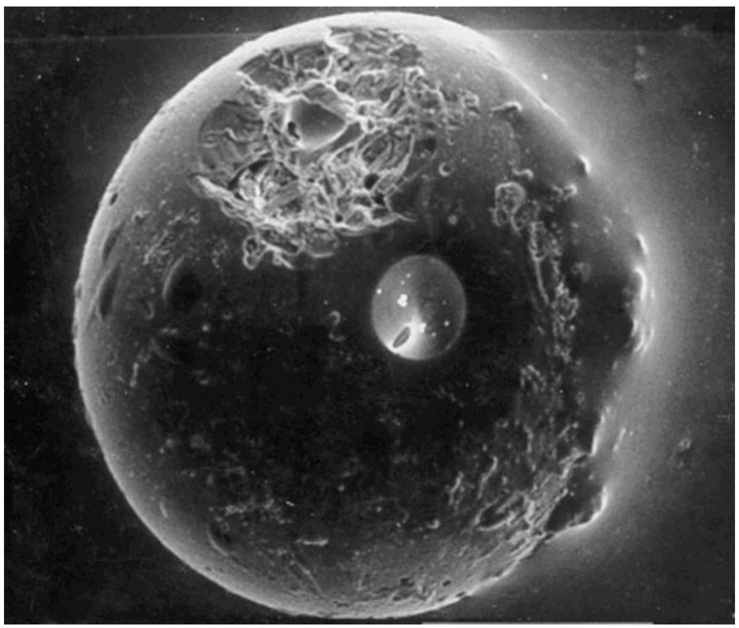


Variety of meteorite "falls"

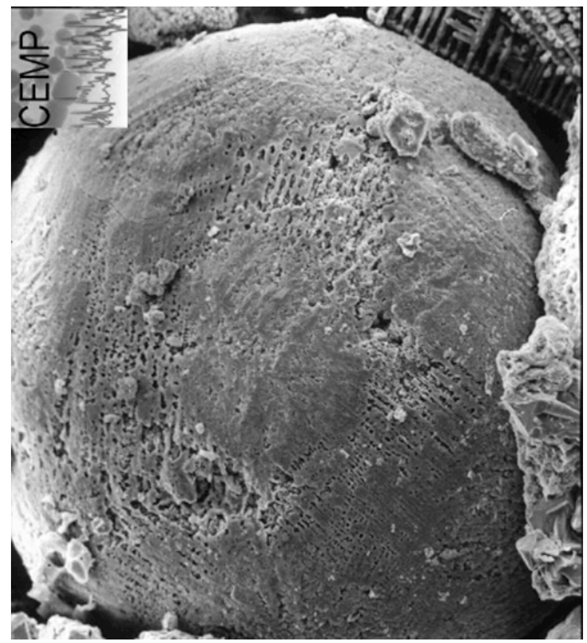
- Tiny pieces of cosmic dust
  - Collected by special airplanes, in clay under the oceans, or in Antarctic ice
- Find single small chunks of rock
  - Sometimes at random, sometimes by following trajectory of a "fireball" or meteor trail
- A several-ton meteorite breaks up during descent, falls as separate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



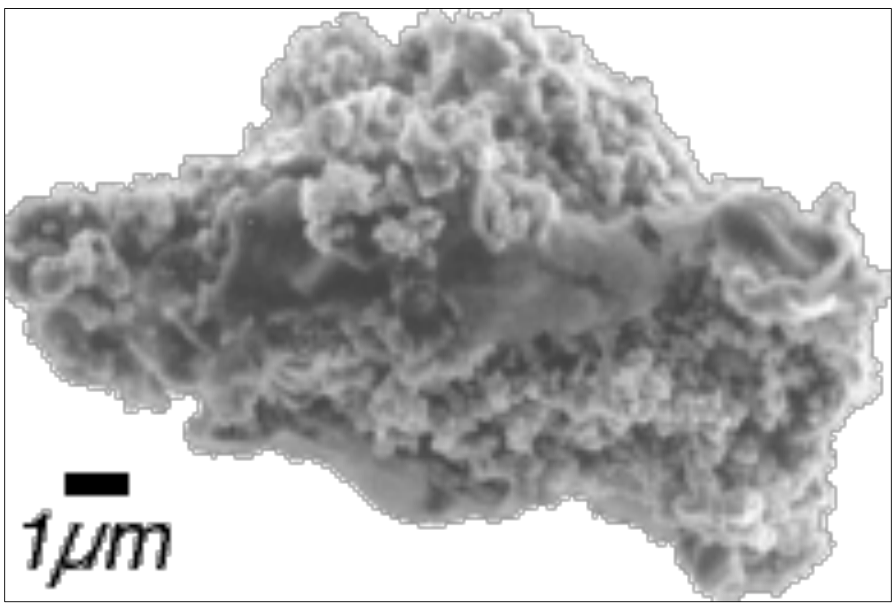
Spherule from Moon
Collected by Apollo 11 astronauts

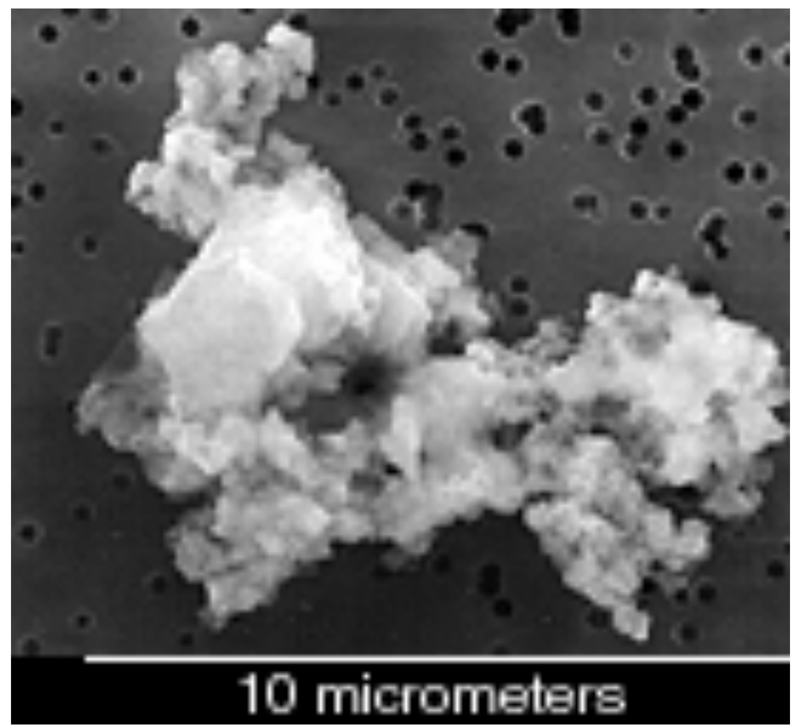


Spherule
from bottom of the Indian Ocean

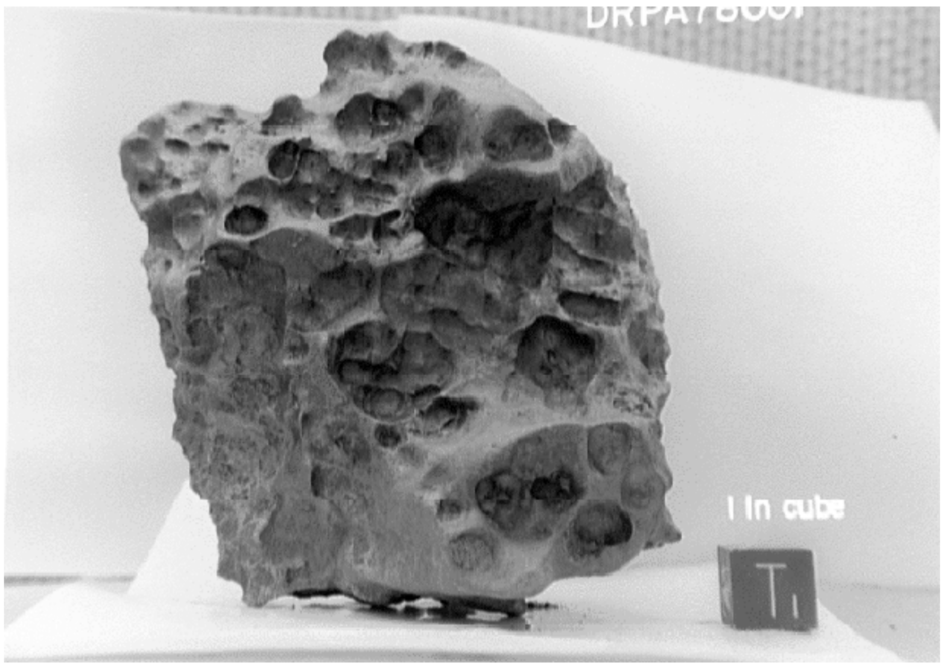
Small particles: cosmic dust

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

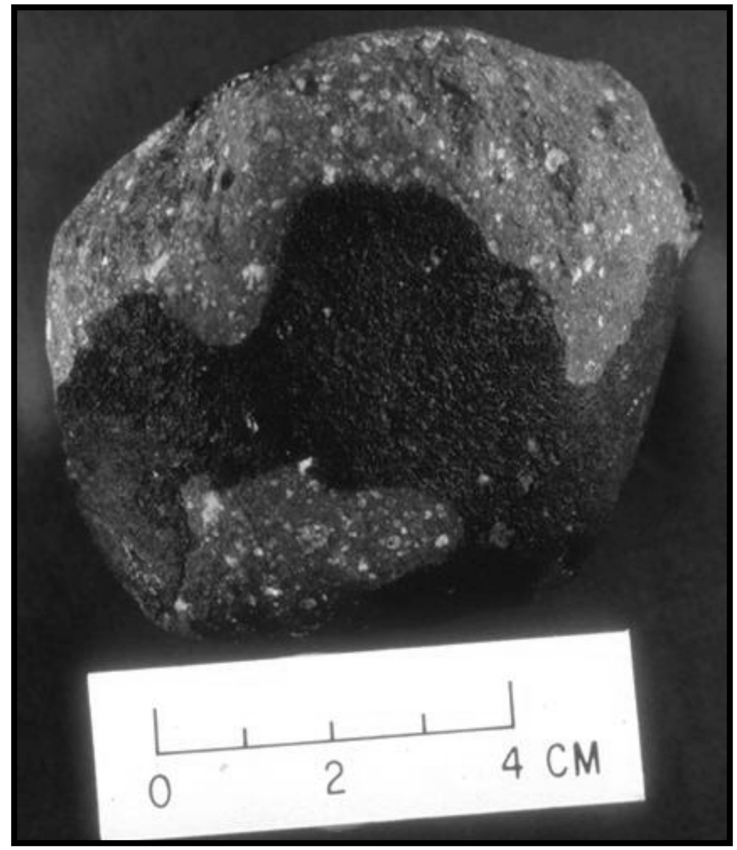




Single small chunks of rock



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?

The Great Daylight Fireball of 1972

- Skipped thru Earth's atmosphere at shallow angle, then exited again into space
- About 10-m diameter, moving at 15 km/sec (33,000 MPH).
- If it had hit the surface of the Earth, it would have had H-bomb equivalent impact energy.
- http://www.youtube.com/watch?v=dKiwzLFzQfc&feature=related

1908 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

Last 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

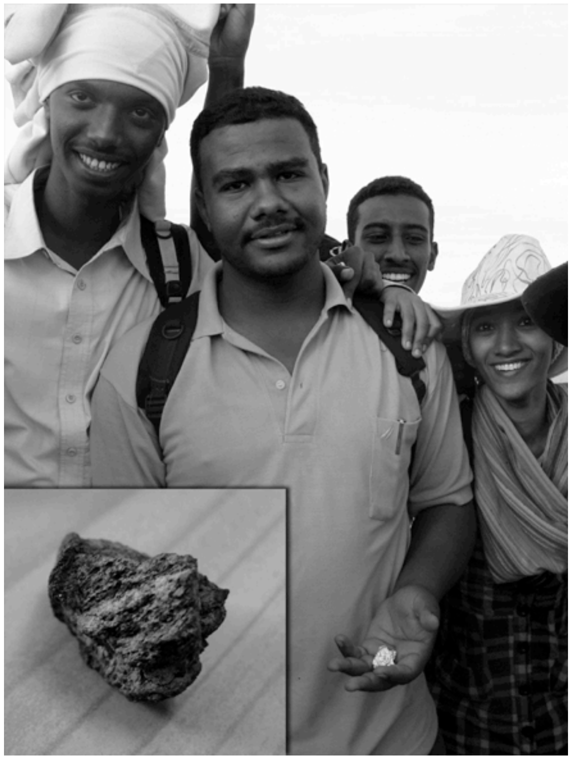
Fragments in the Sudanese desert make up an "asteroid trifecta": discovery, prediction and recovery

By John Matson

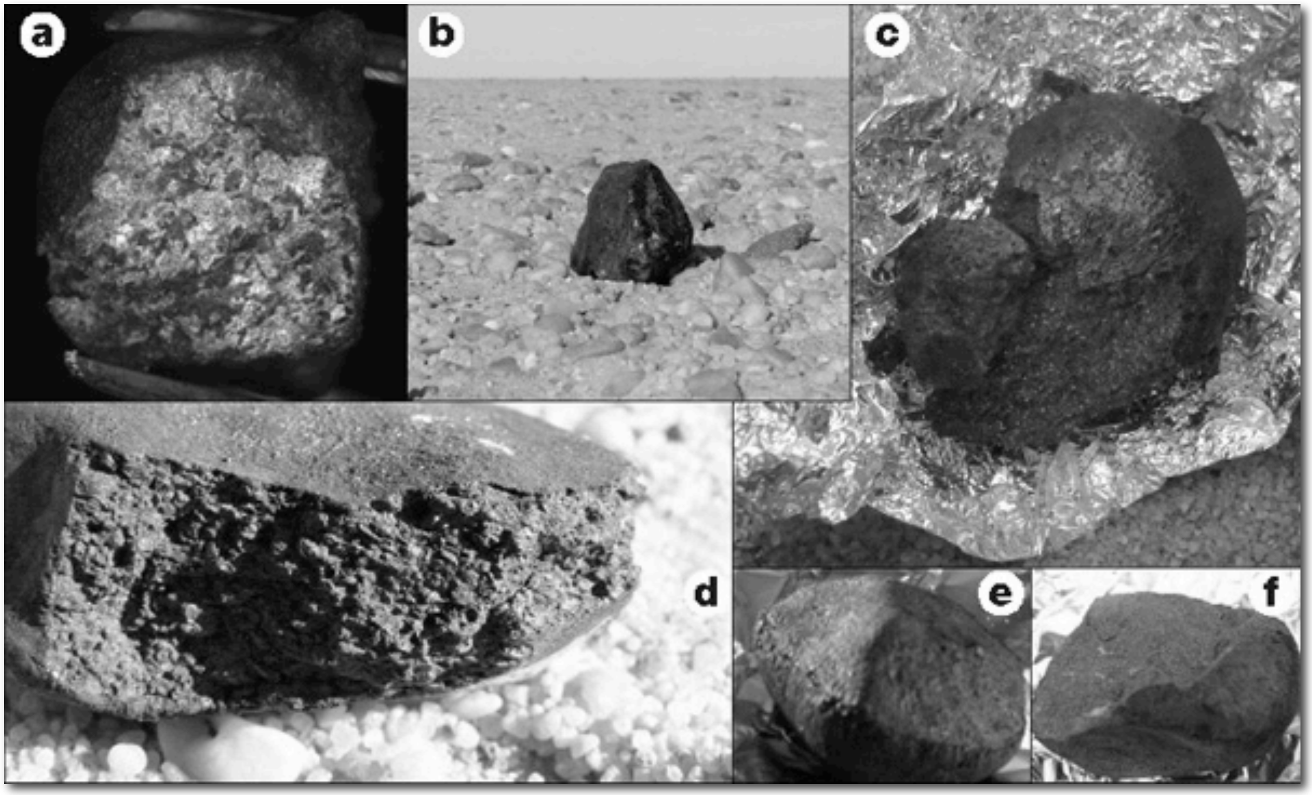
- **Link to Scientific American article**

University of Khartoum students did systematic search

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



Macroscopic features of the Almahata Sitta meteorite.

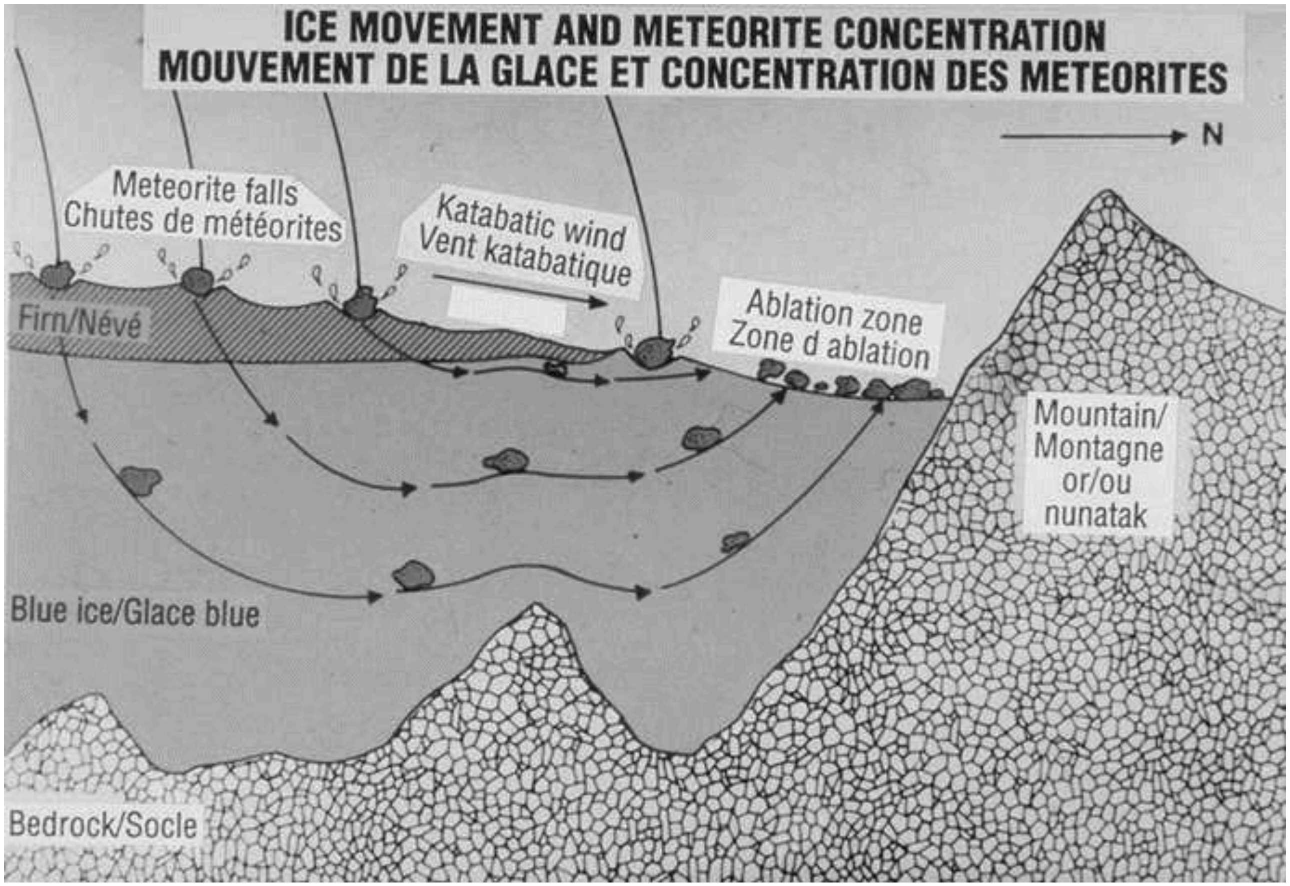


P Jenniskens *et al*. *Nature* **458**, 485-488 (2009)

nature

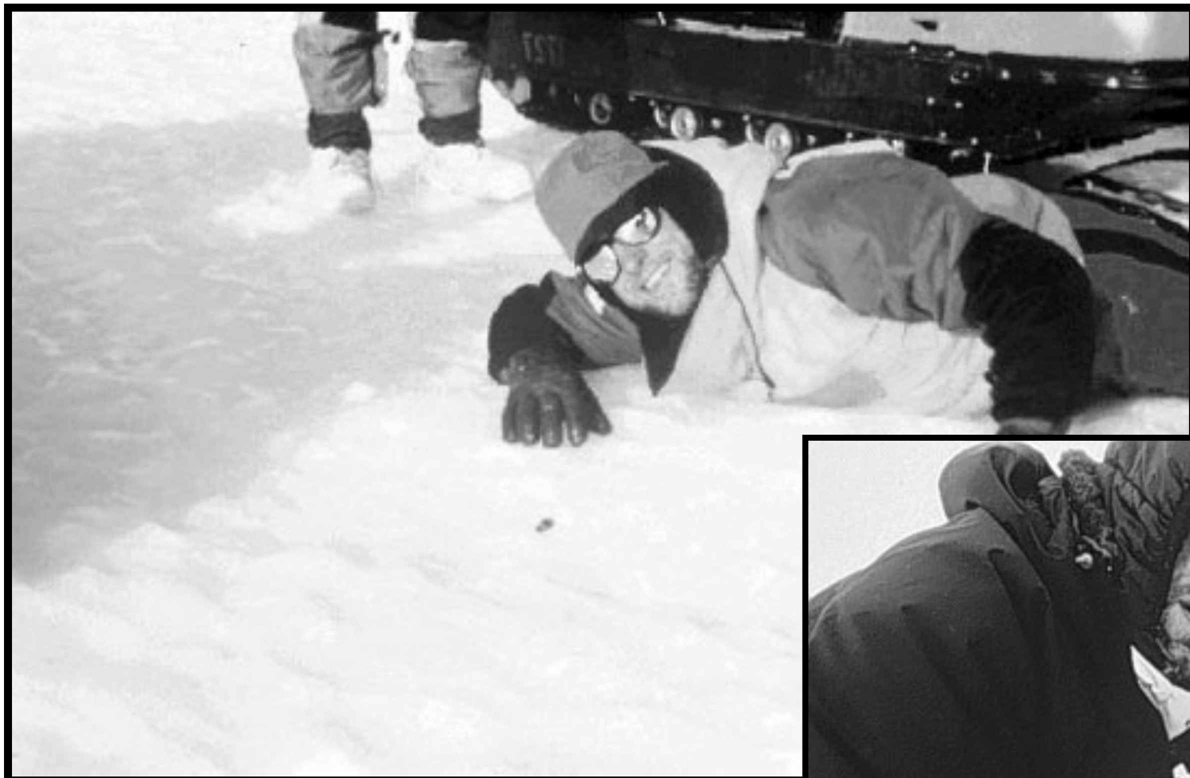
Systematic searches in Antarctica

Systematic searches in Antarctica



Searching for rare meteorites amidst thousands of Earth-rocks

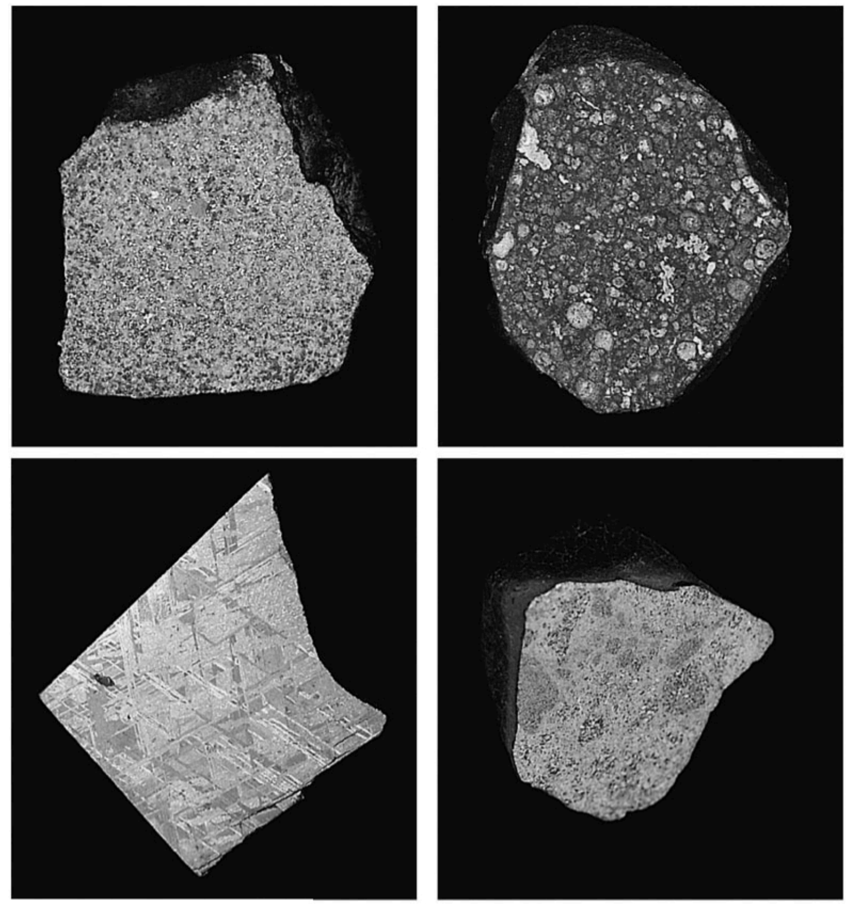
Victory!



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"

Microscope image

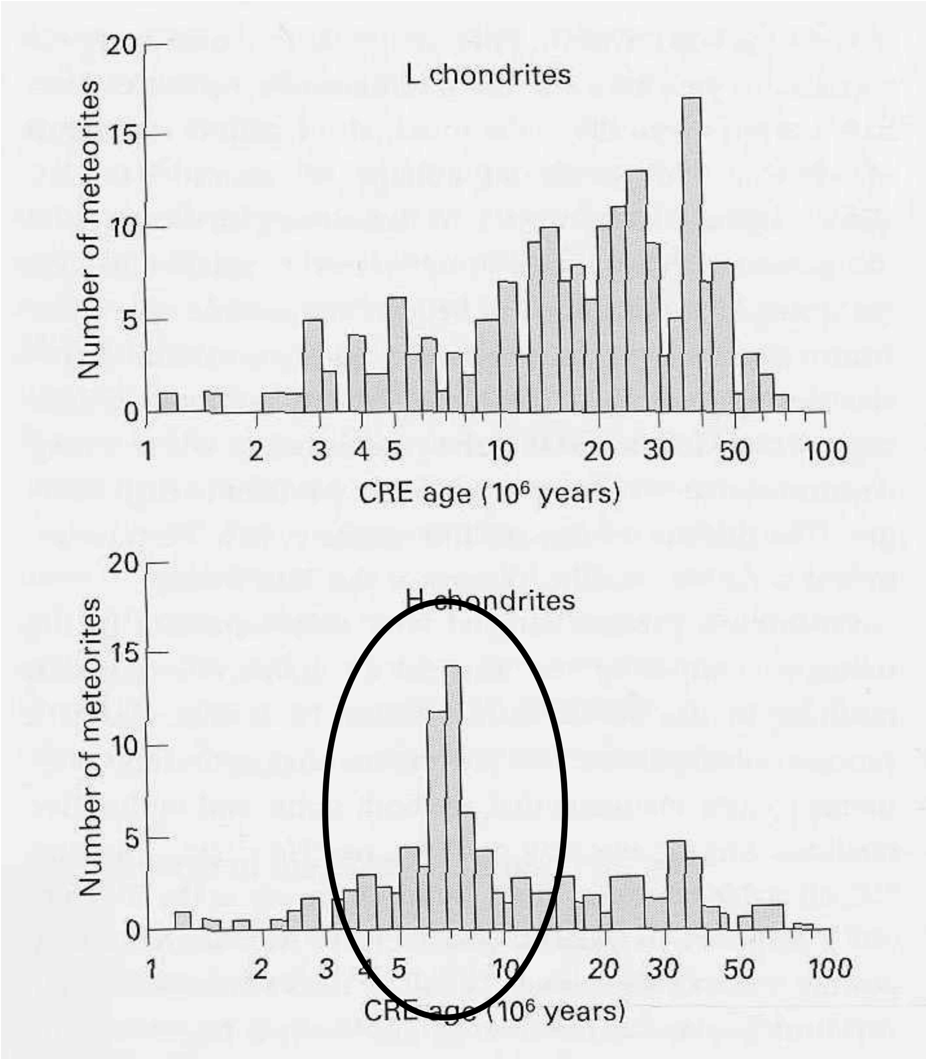
Carbonaceous Chondrites contain complex organic molecules

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

Carbonaceous Chondrites: Insights into Planet Formation?

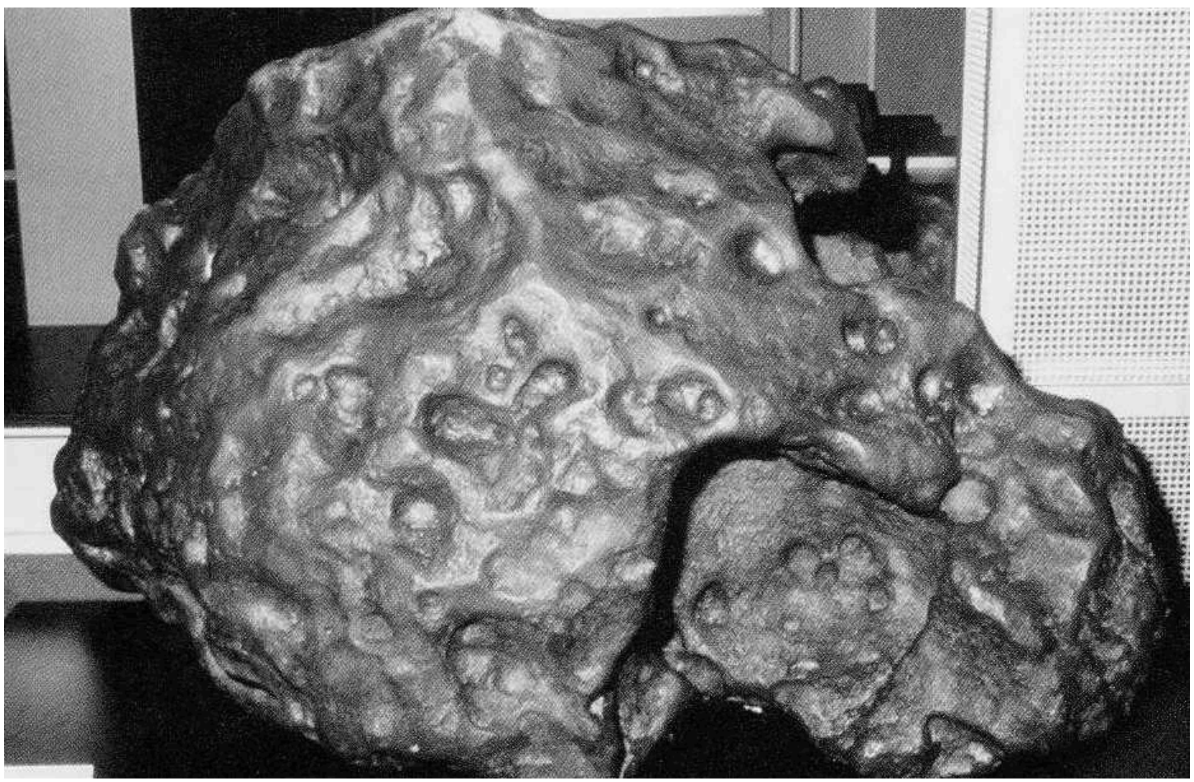
- **The oldest meteorites; quite rare**
- **Chondrules (round): primitive chunks of early Solar System**
- **Calcium aluminum inclusions (Cal's): isotope ratios (26 Al and 26 Mg) suggest that a supernova explosion went off right next to the early Solar Nebula**
  - **Did the supernova stimulate formation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

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

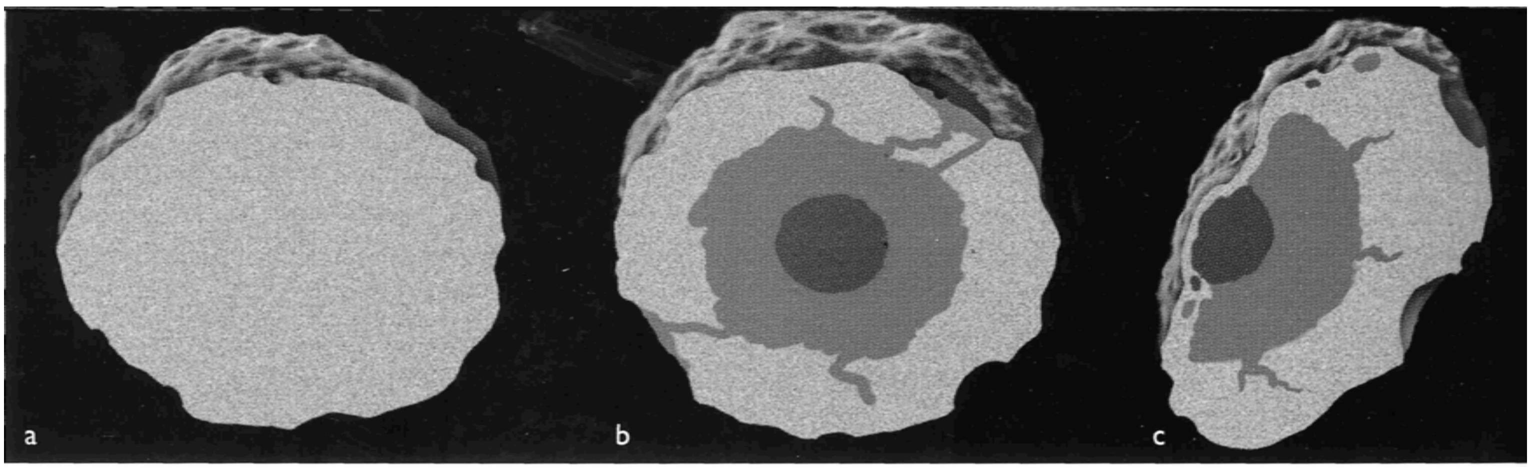


Iron meteorites

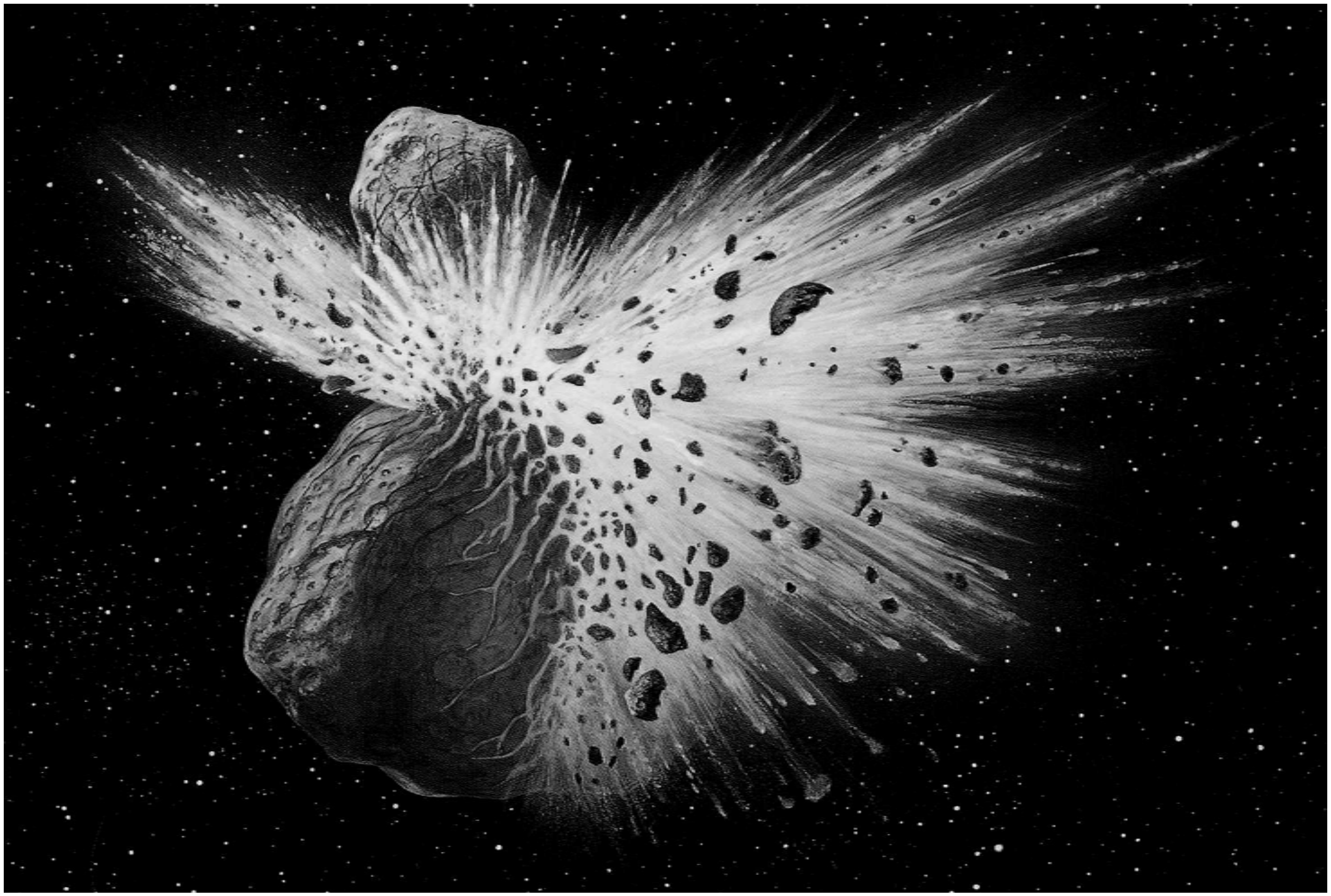
- **Made of iron and nickel**
- **Pits made during atmospheric entry (hot!)**



Iron meteorites: from core of differentiated asteroids

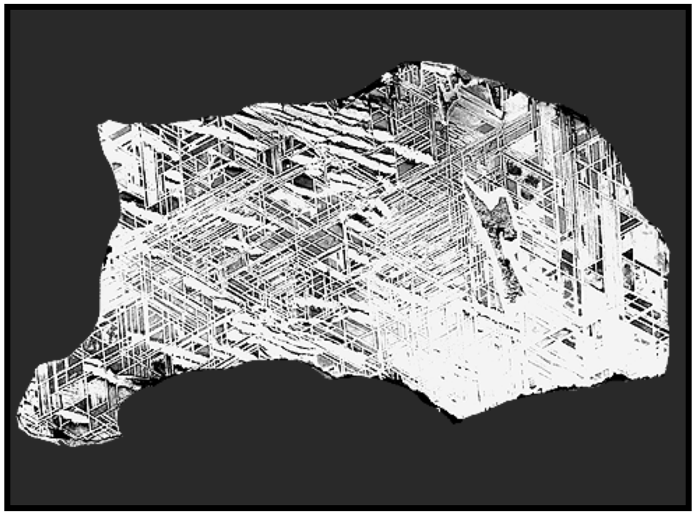


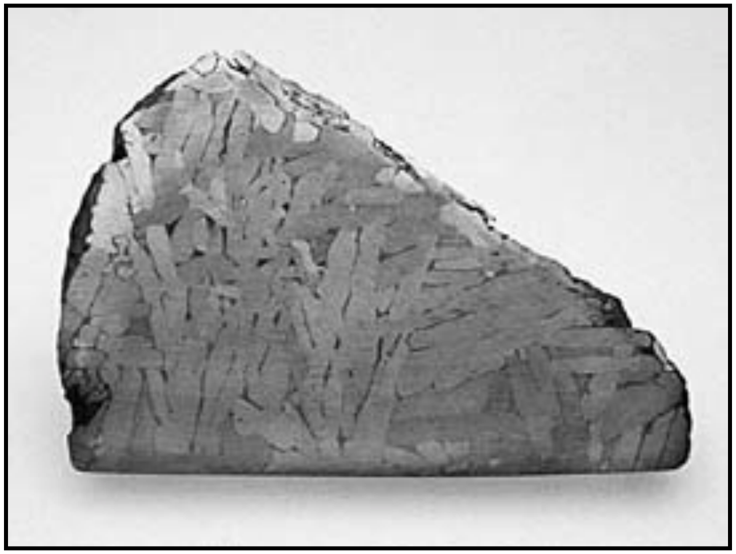
The making of future meteorites!



Crystalization pattern of the iron is unique

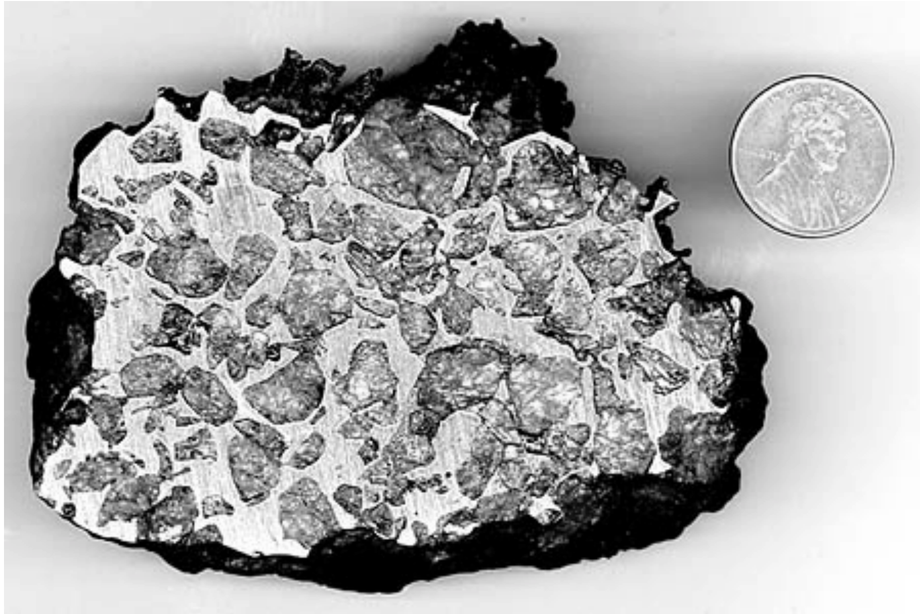
- Characteristic of very slow cooling of iron within an asteroid core
- Due to diffusion of nickel atoms into solid iron as core cools
- Says original asteroid must have been large enough to be differentiated





Stony-Iron meteorites - the prettiest

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

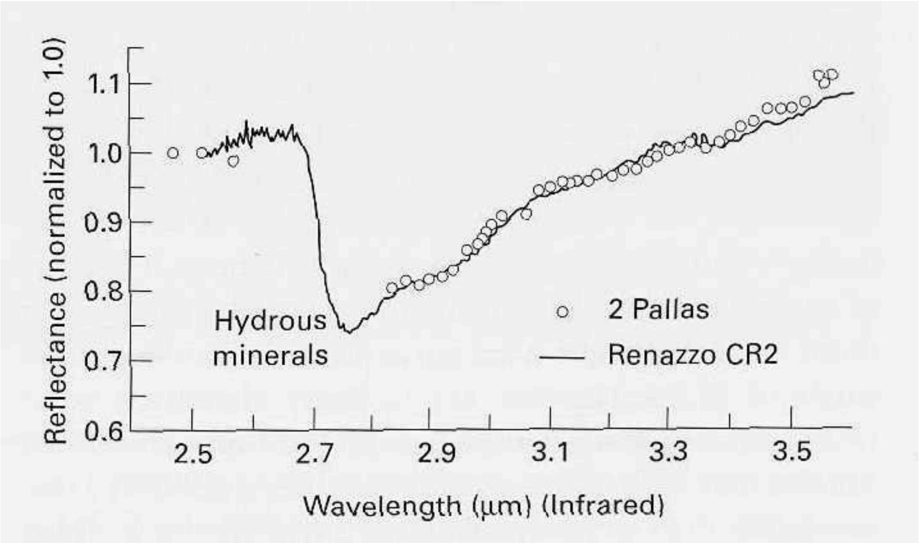


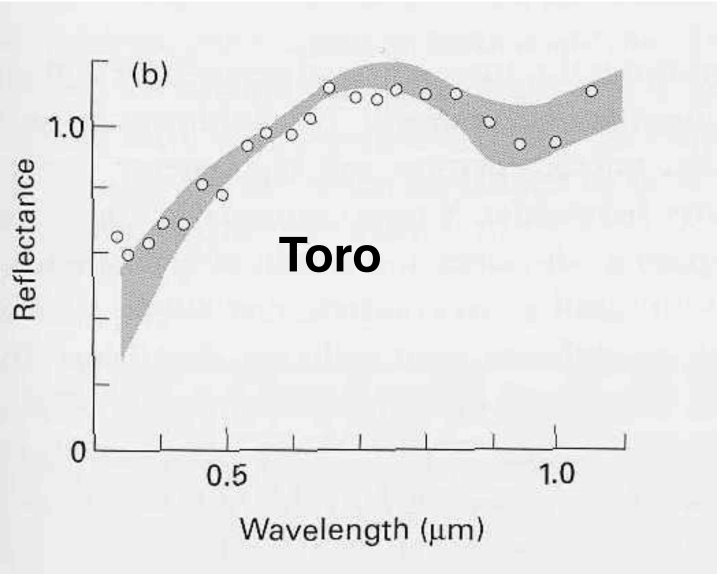
Achondrites: from Mars and Moon

- **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 identical to some asteroids**
- **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

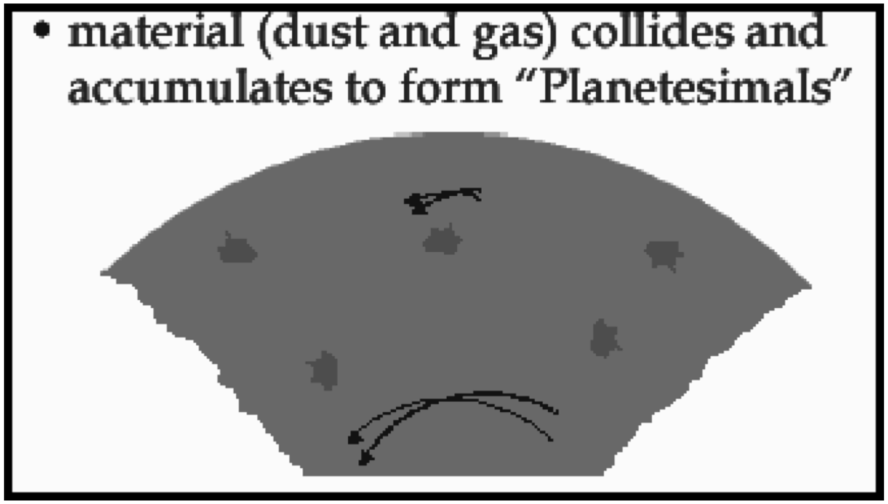
The main points: Cosmic Collisions

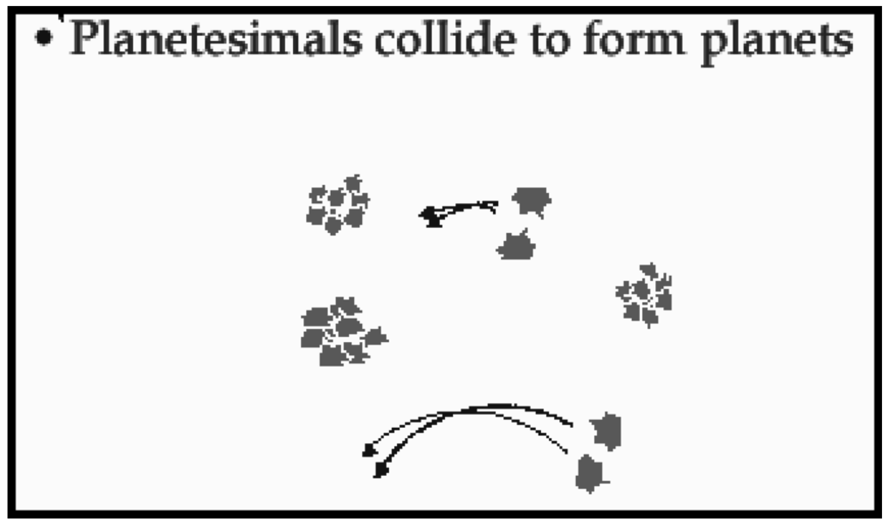
- Cosmic collisions played major role in Solar System evolution
  - Aggregation of planets from planetesimals
  - Formation of Moon, tilt of Venus' and Uranus' rotation axes, composition of Mercury
- Also played a major role in Earth's evolution
  - Tilt of axis
  - Mass extinctions (dinosaurs, others)
- 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

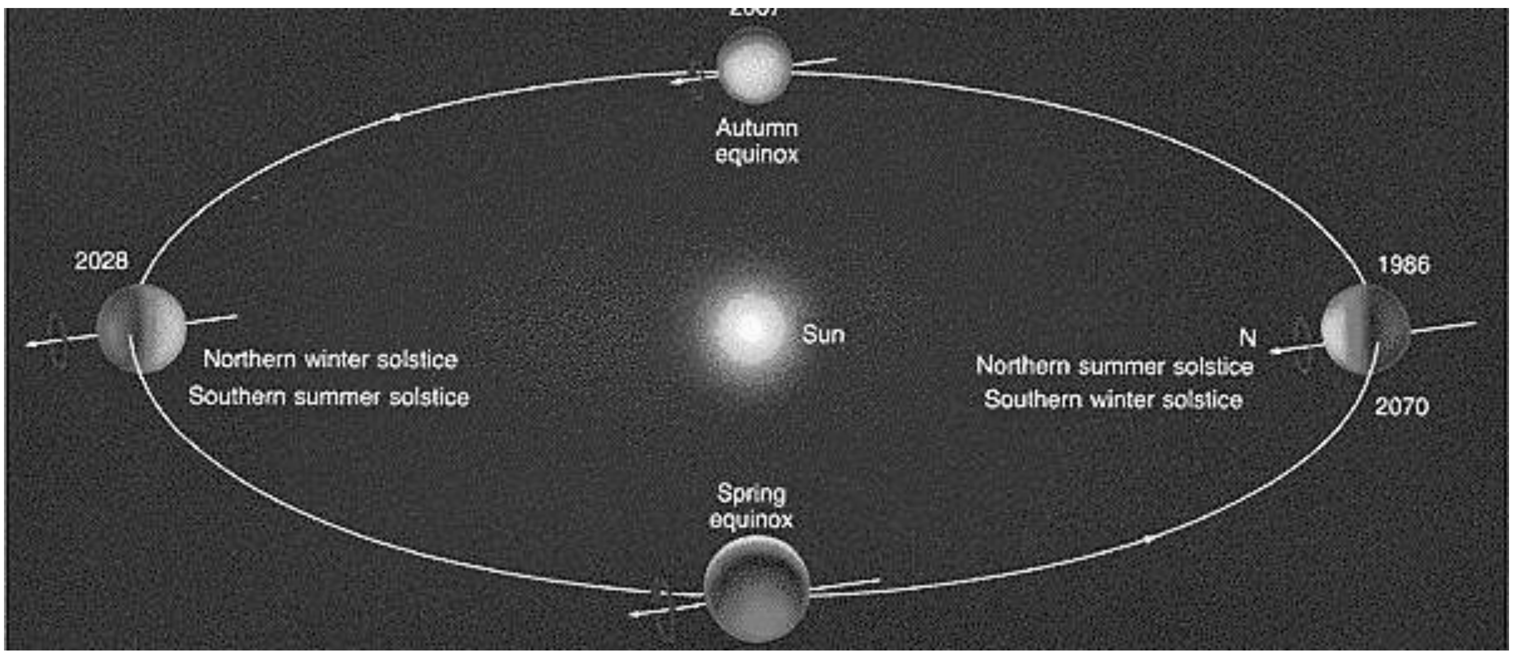
- **Earth has large iron core, but the moon does not**
  - **Earth's iron had already drained into the core by the time of the giant impact that formed the moon**
- **Debris blown out of both Earth and the impactor came from their iron-depleted, rocky mantles**
- **Explains why mean density of Moon (3.3 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**



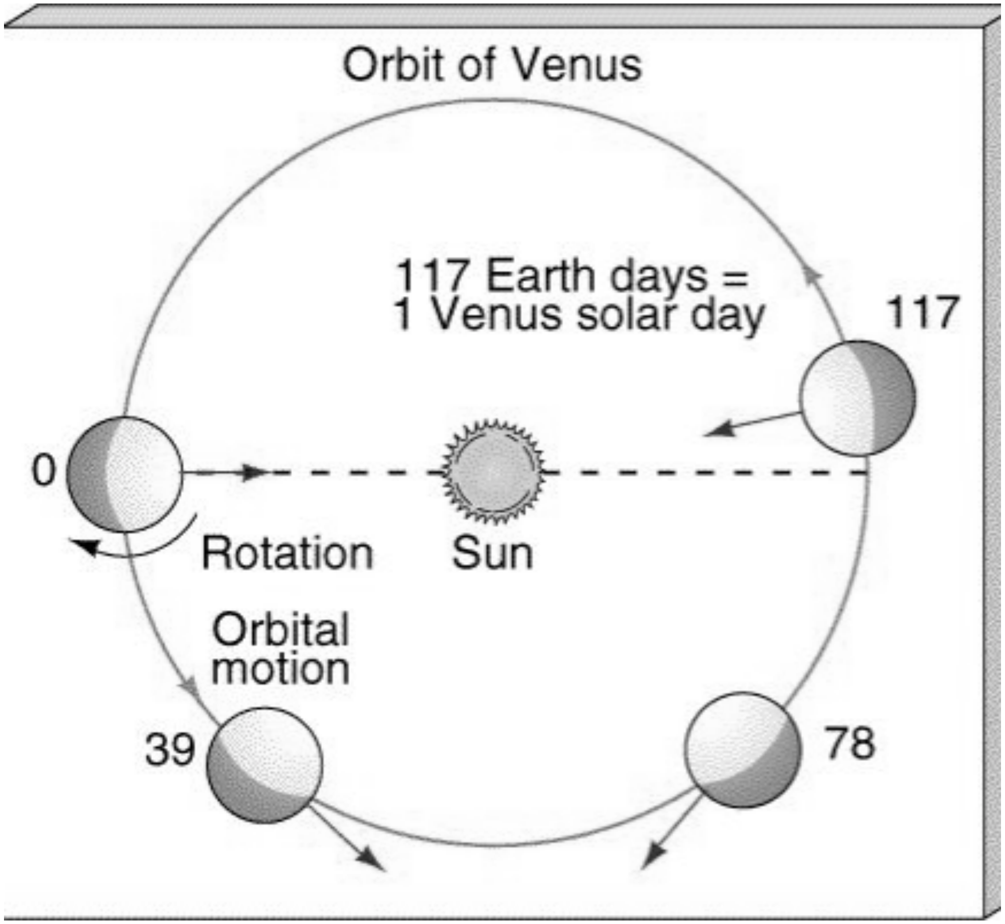
Collision with a massive body is best way to explain this

- **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**

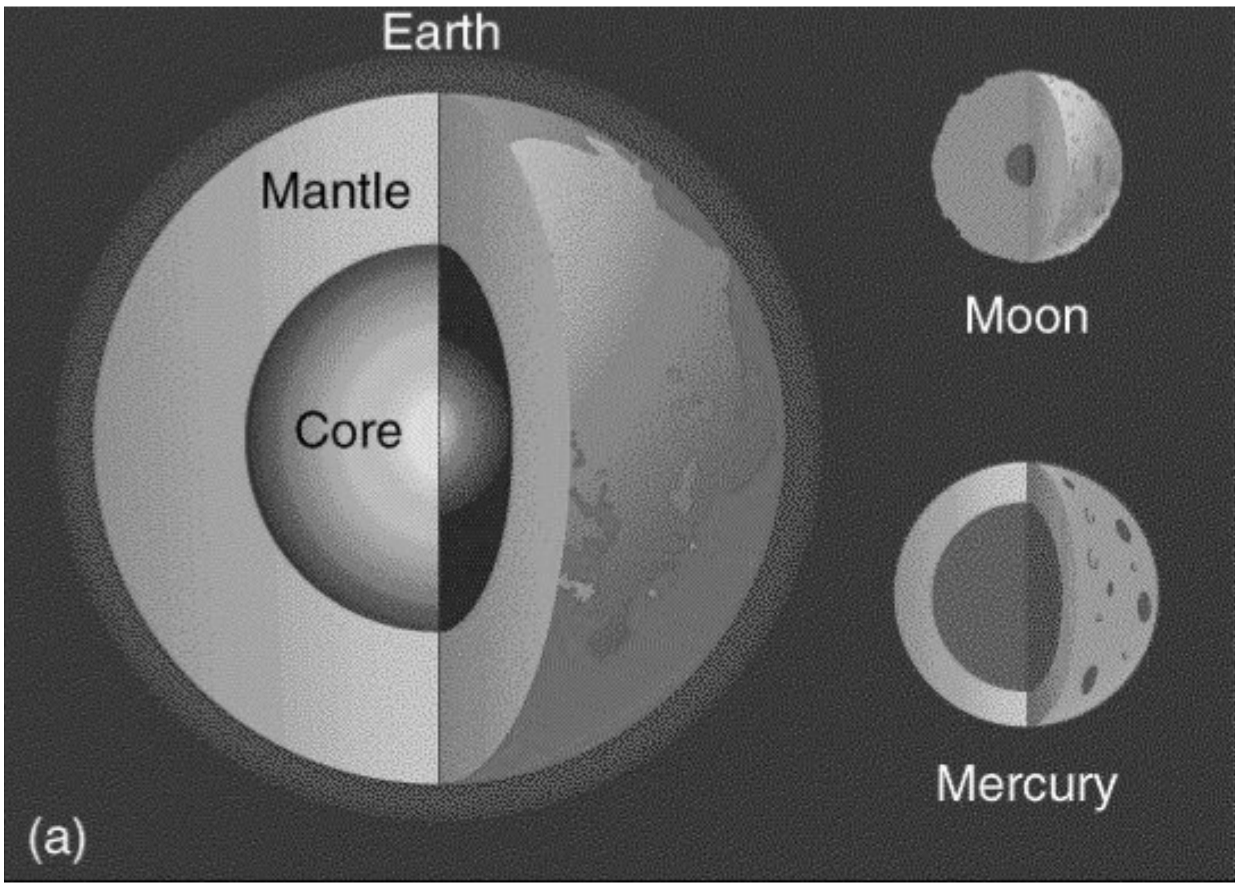
Venus rotates "backwards" compared with all other planets



- **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

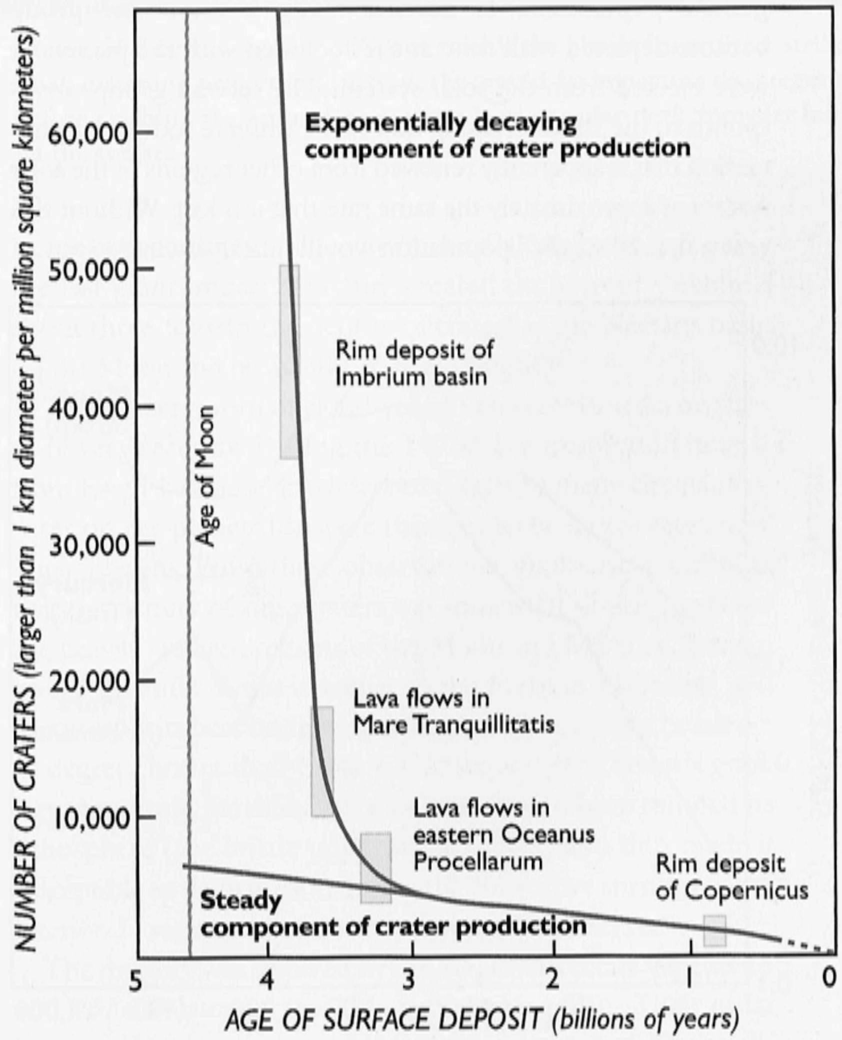


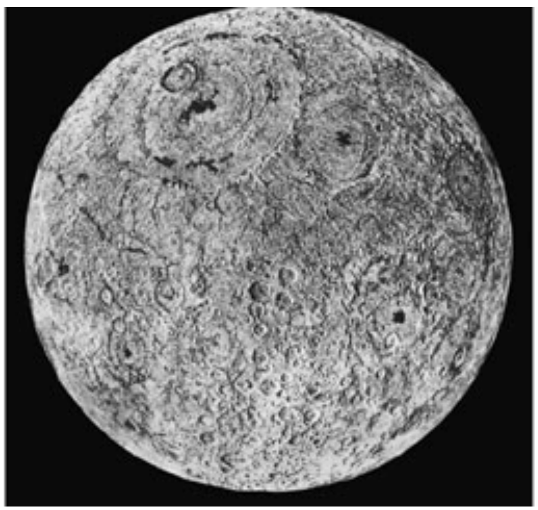
Figure 12. Lunar surfaces of different ages exhibit different crater densities. The rapid cratering rate during the late heavy bombardment fell off dramatically between 3.9 and 3.3 billion years ago, giving way to a slower, steady rate of crater production. This dramatic falloff is reflected in the varying 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**

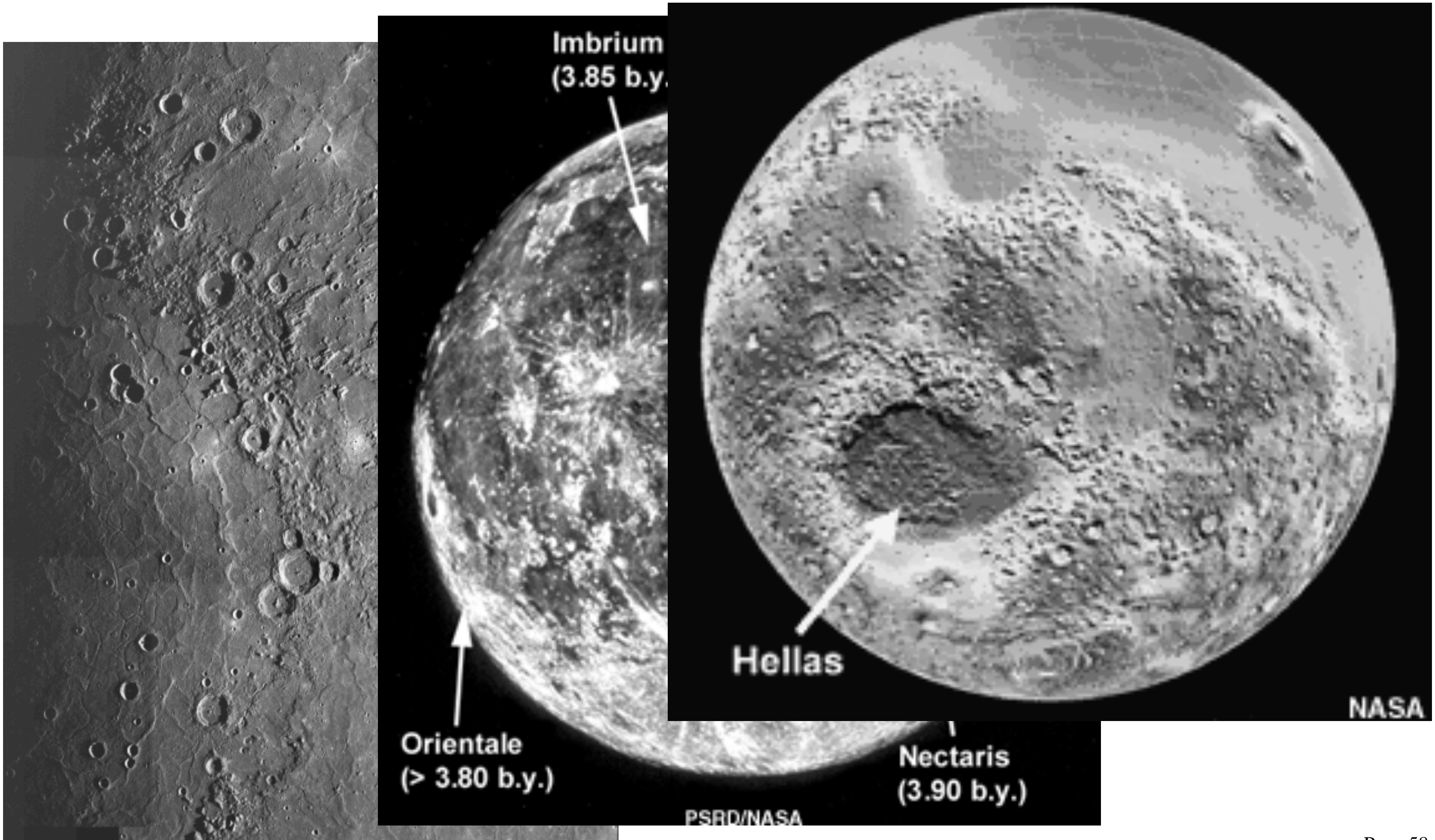
Evolution of the Moon’s Appearance

"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" ?

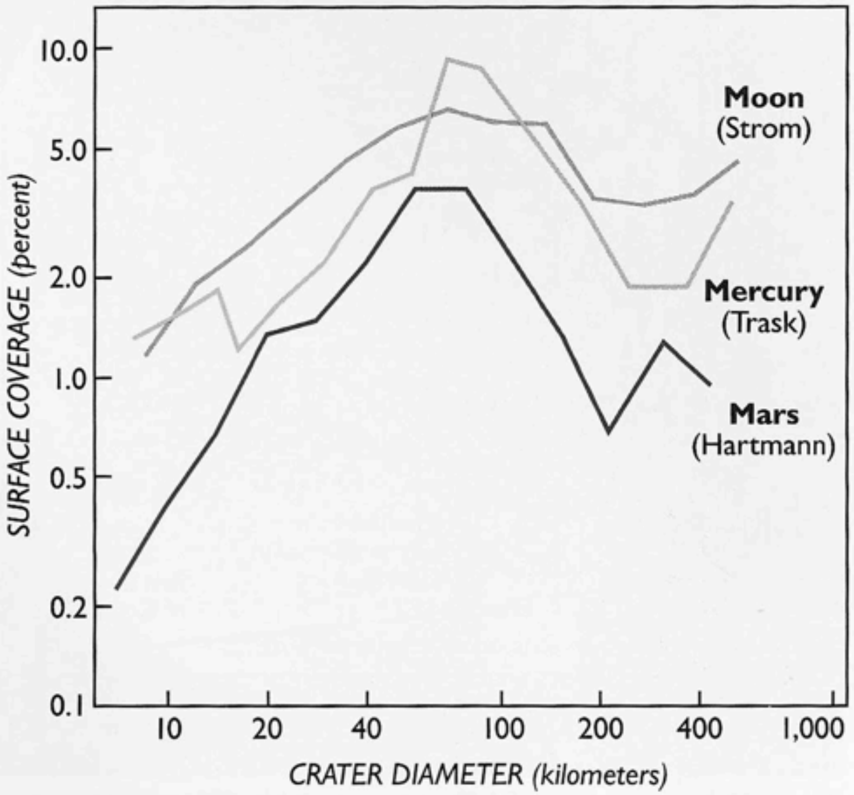


Figure 13. Crater size distributions on the highlands of the Moon, Mercury, and Mars (authors whose data have been used are named by each curve). The coverage on all three bodies peaks for craters with diameters of 40 to 100 km, and the distributions' similar shapes suggest that the same population of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

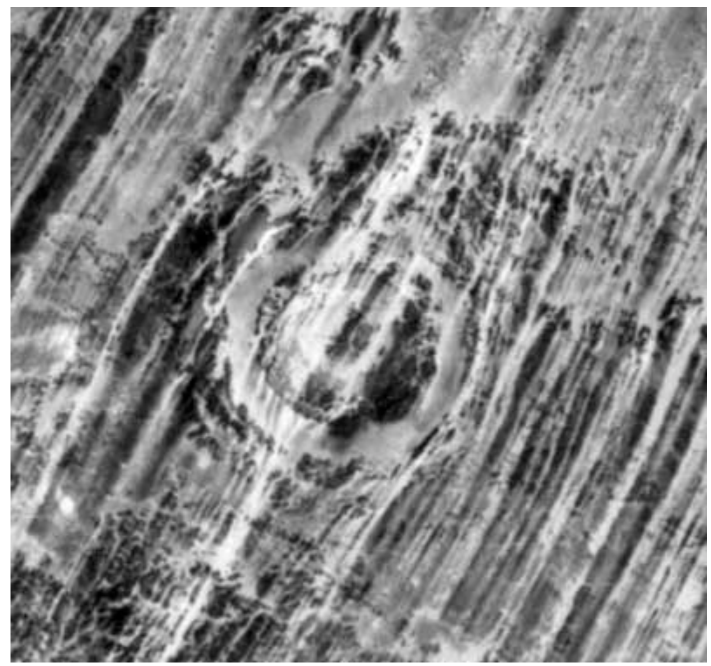
One theory: a real spike in impacts

- 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

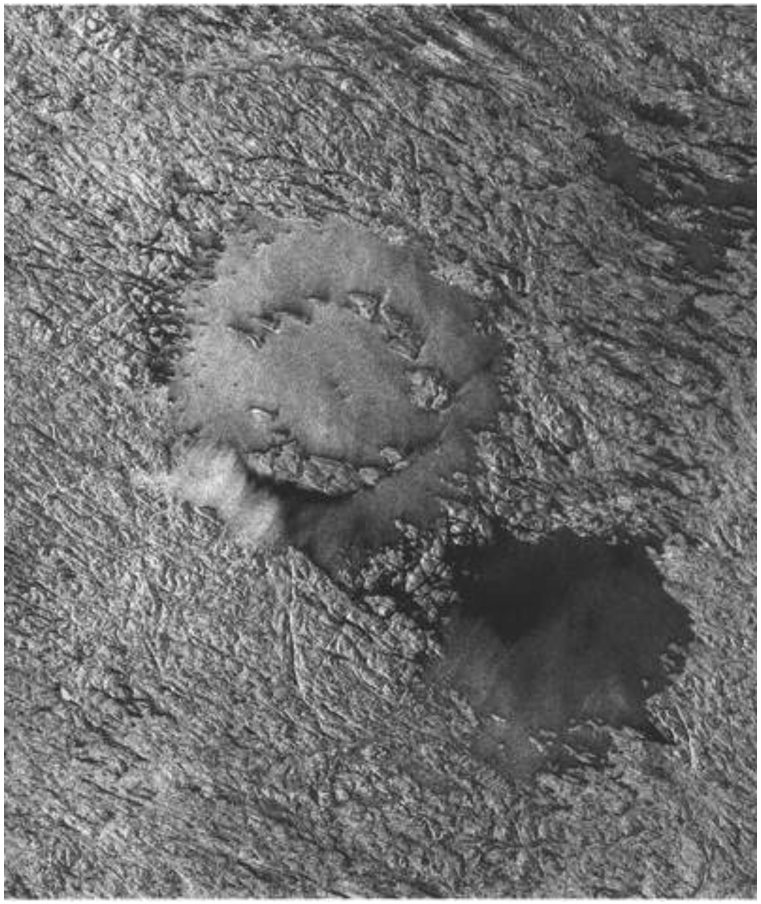
- But most craters got eroded away, subducted, or drowned
- A tour of craters on Earth:

Algeria



Chad (Africa) from airplane

Earth's craters



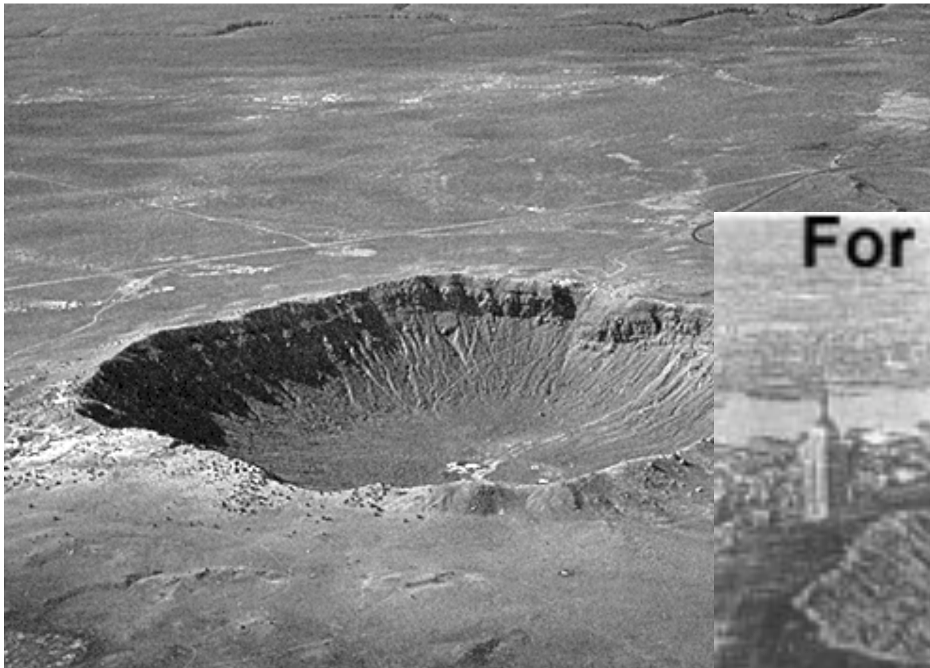
Clearwater, Canada **Henbury, Australia**

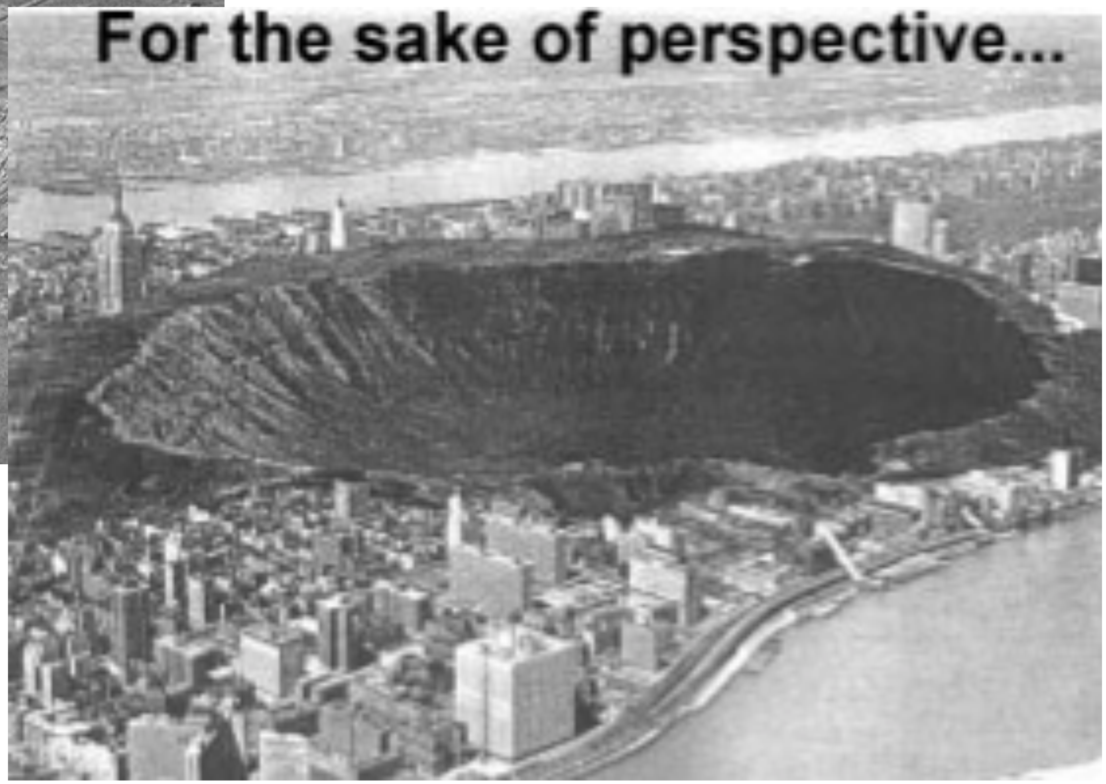
Earth's craters, continued

Tswaing, South Africa

New Quebec, Canada

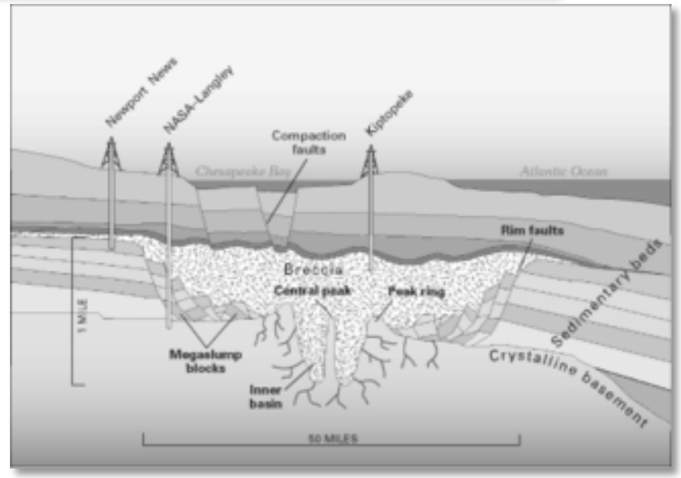
Arizona's Meteor Crater, the most famous example





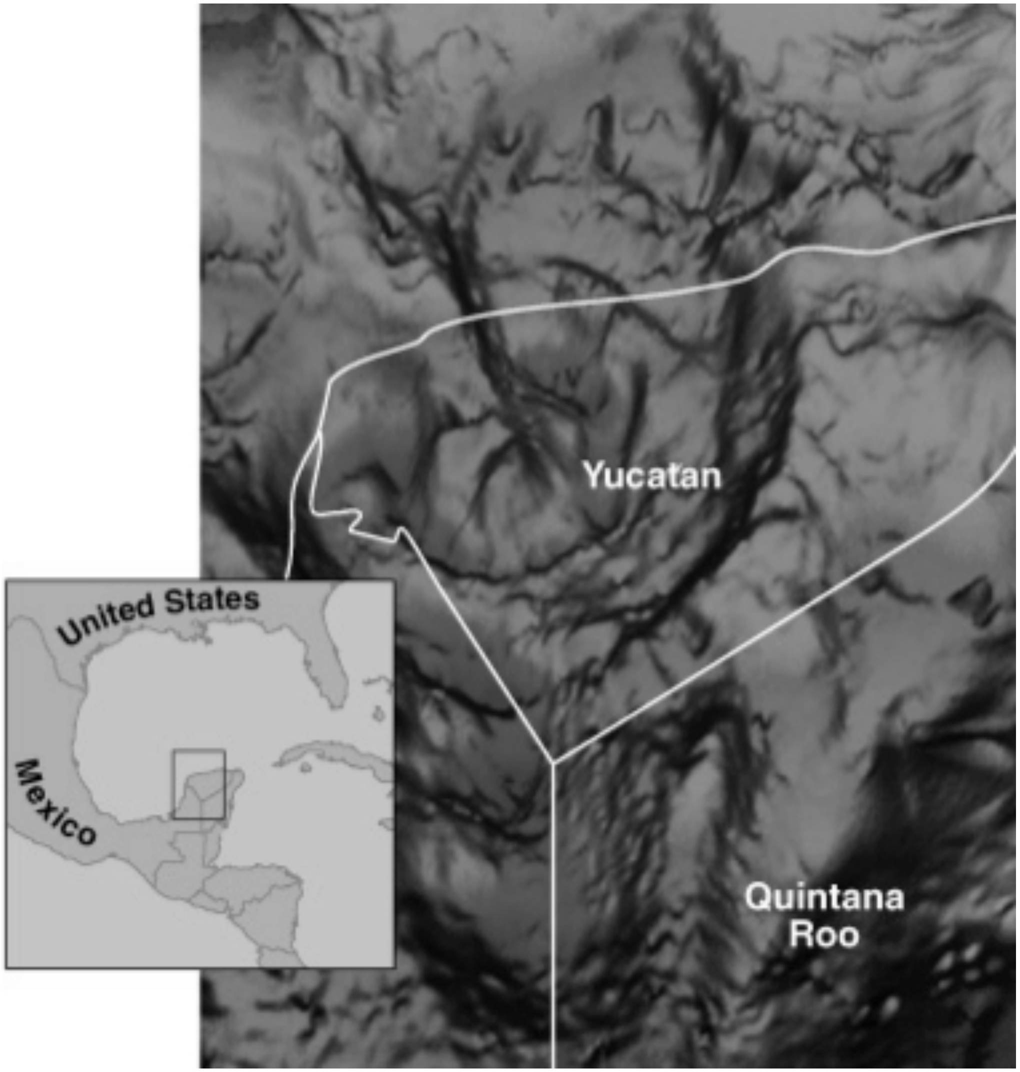
Impact event created opening of Chesapeake Bay

- 35 million yrs ago, 2 mi wide
- 56 mile-wide crater
- Drilling → mixed bits of crystalline and melted rock that can be dated, as well as marine deposits, brine, etc
- Tidal waves 1000 ft high



Inundated area (in blue)

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)

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.

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

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

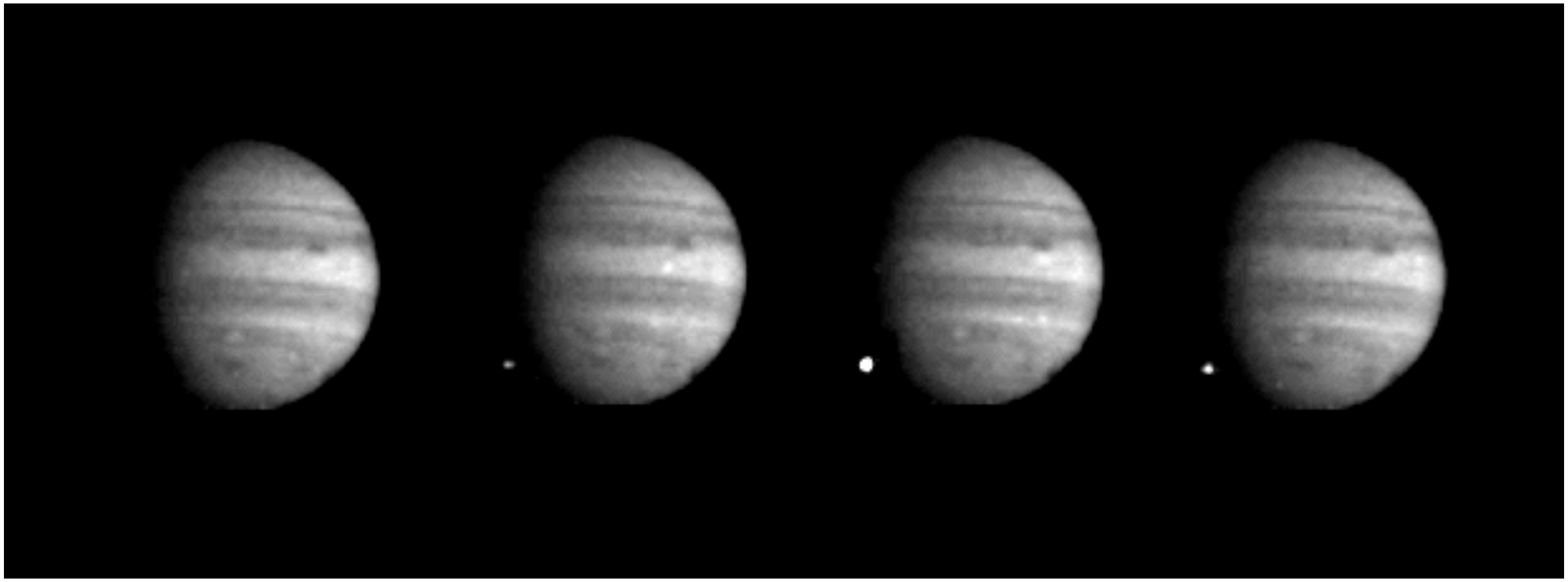
Tidal breakup of a comet when it passes too close to Jupiter

Worldwide network of astronomers observed collisions over one week

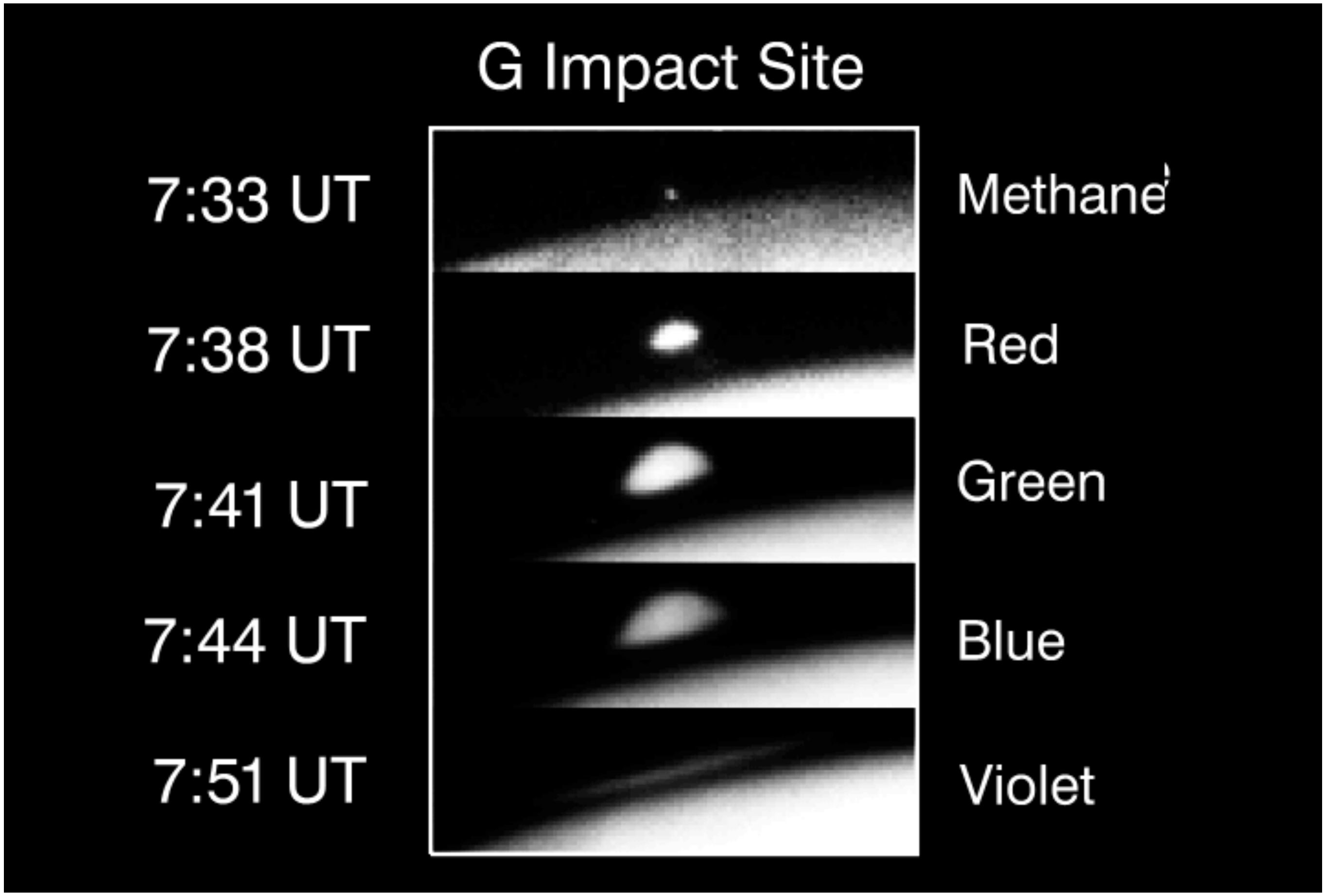
- **I was at Lick Observatory on Mt Hamilton**
- **As Earth turned, e-mails flew around the planet to tell people what to look for**
  - **As Jupiter was setting at one place on Earth, scientists sent e-mails to places where Jupiter was just rising**
- **Examples: "Impact B is a dud" "Impact G is spectacular"**

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

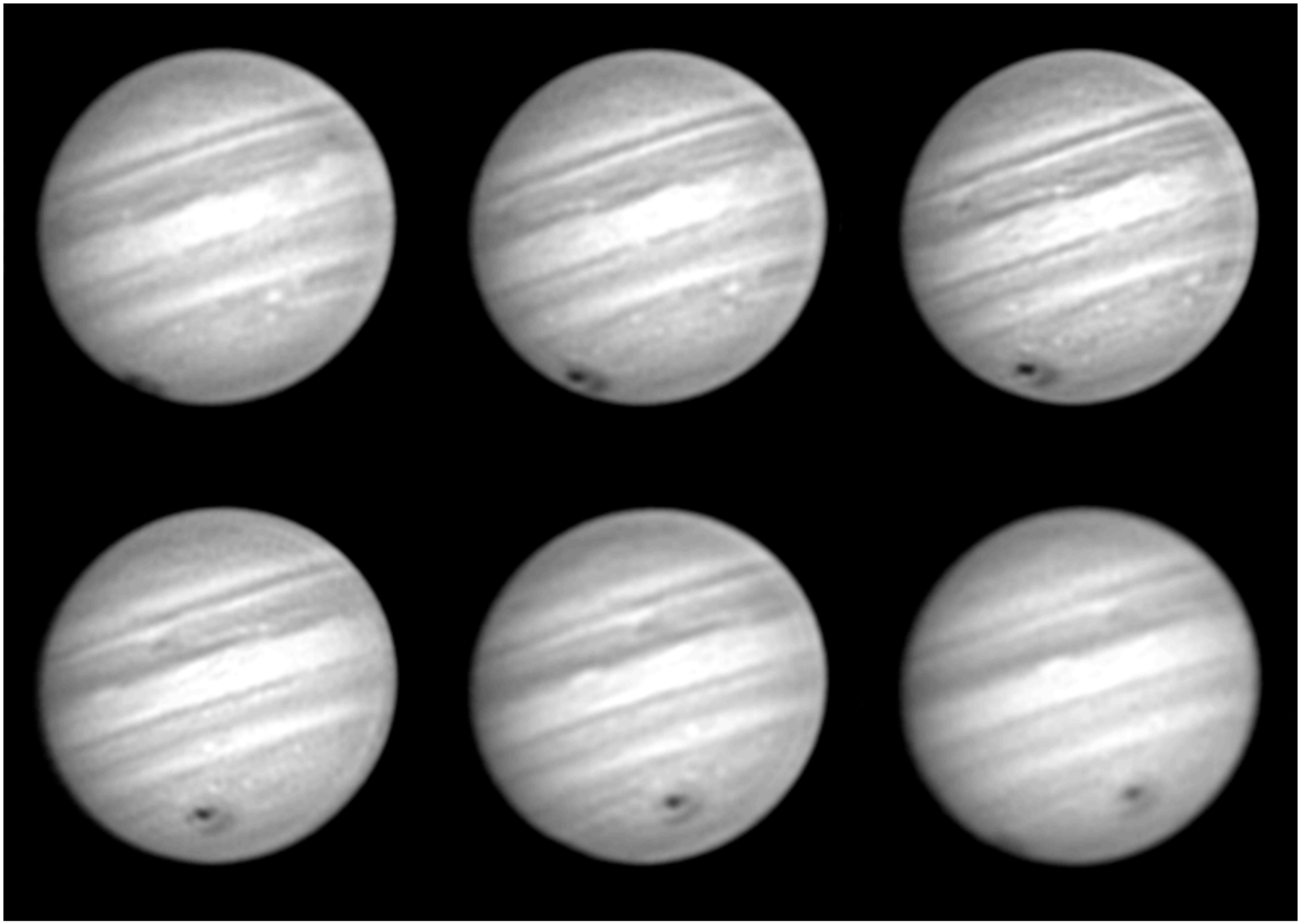
- **Time sequence**
- **White dots are hot gases exploding out of Jupiter's atmosphere on night side**



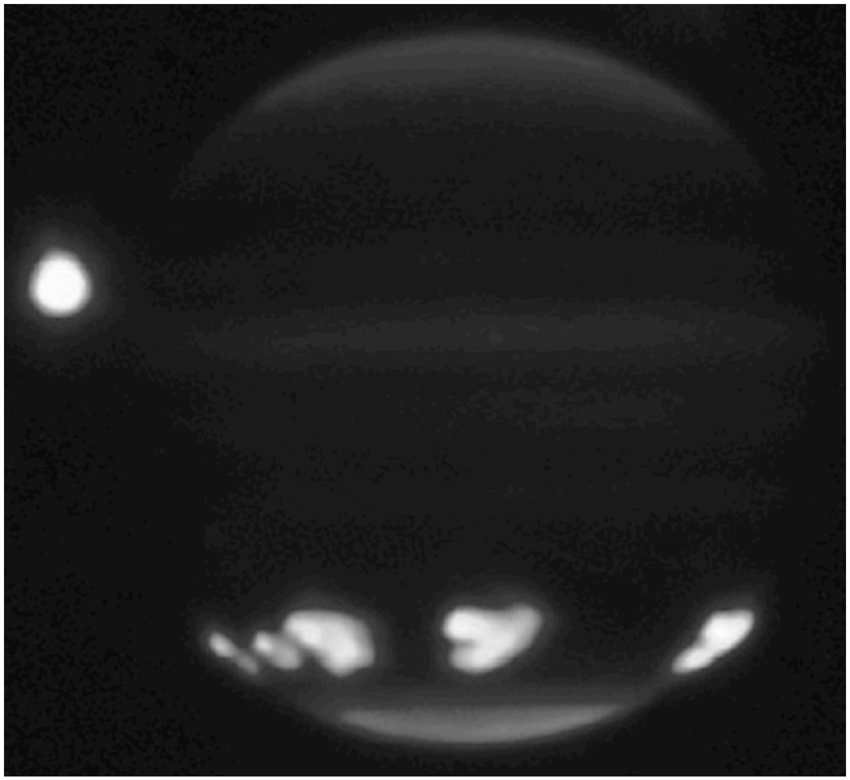
Hubble Space Telescope was next to see impacts

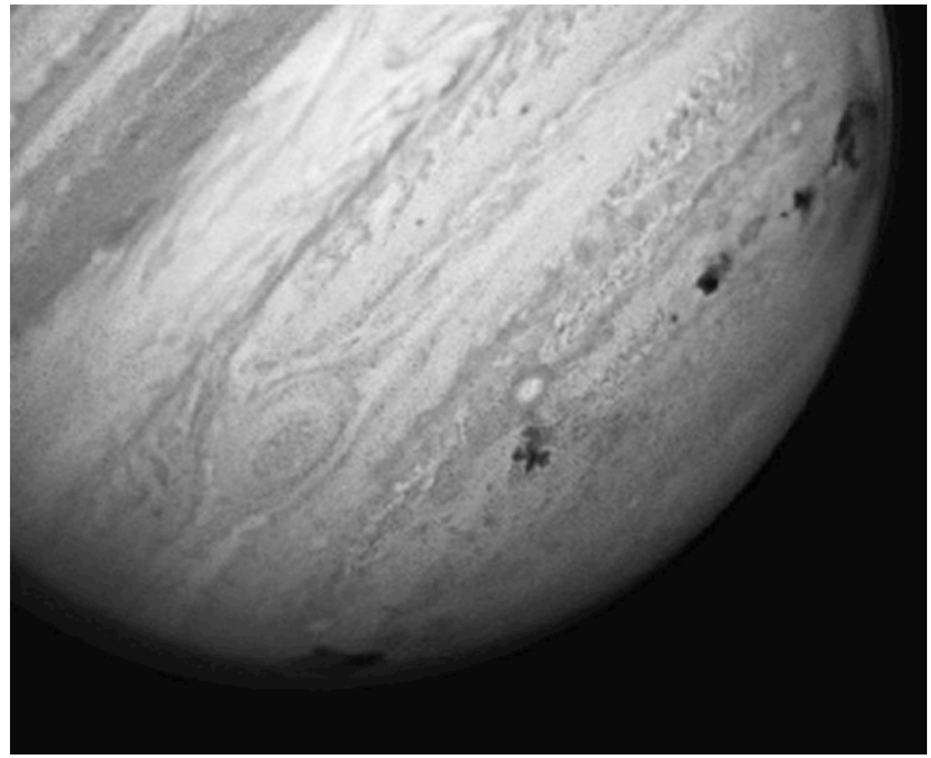


G impact spot as Jupiter rotated (our group at Lick Observatory)



Multiple fragments of Shoemaker-Levy 9 hit Jupiter in sequence





Infrared image of multiple impact points

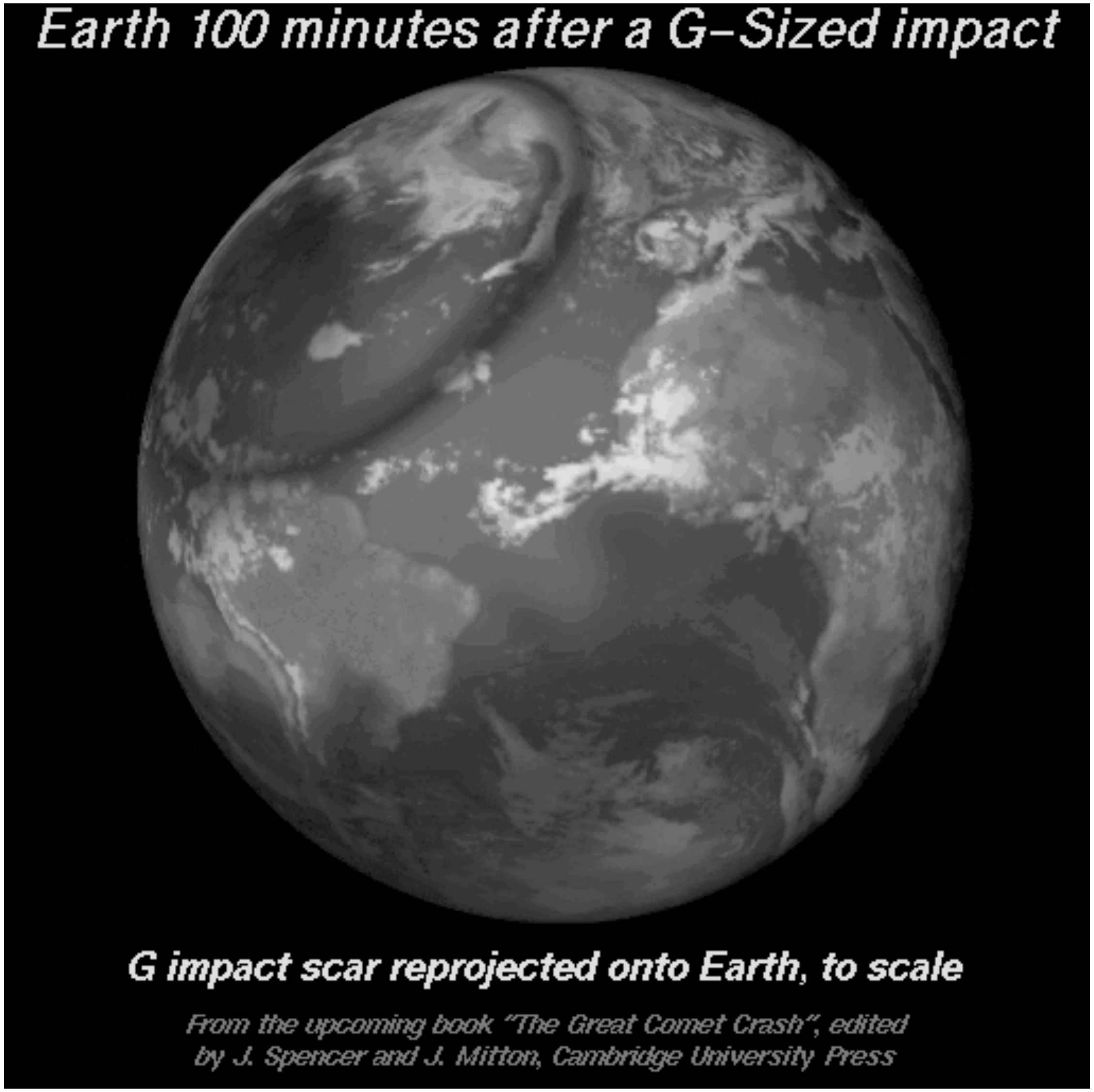
(Keck Telescope)

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: linear crater patterns on Ganymede**

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

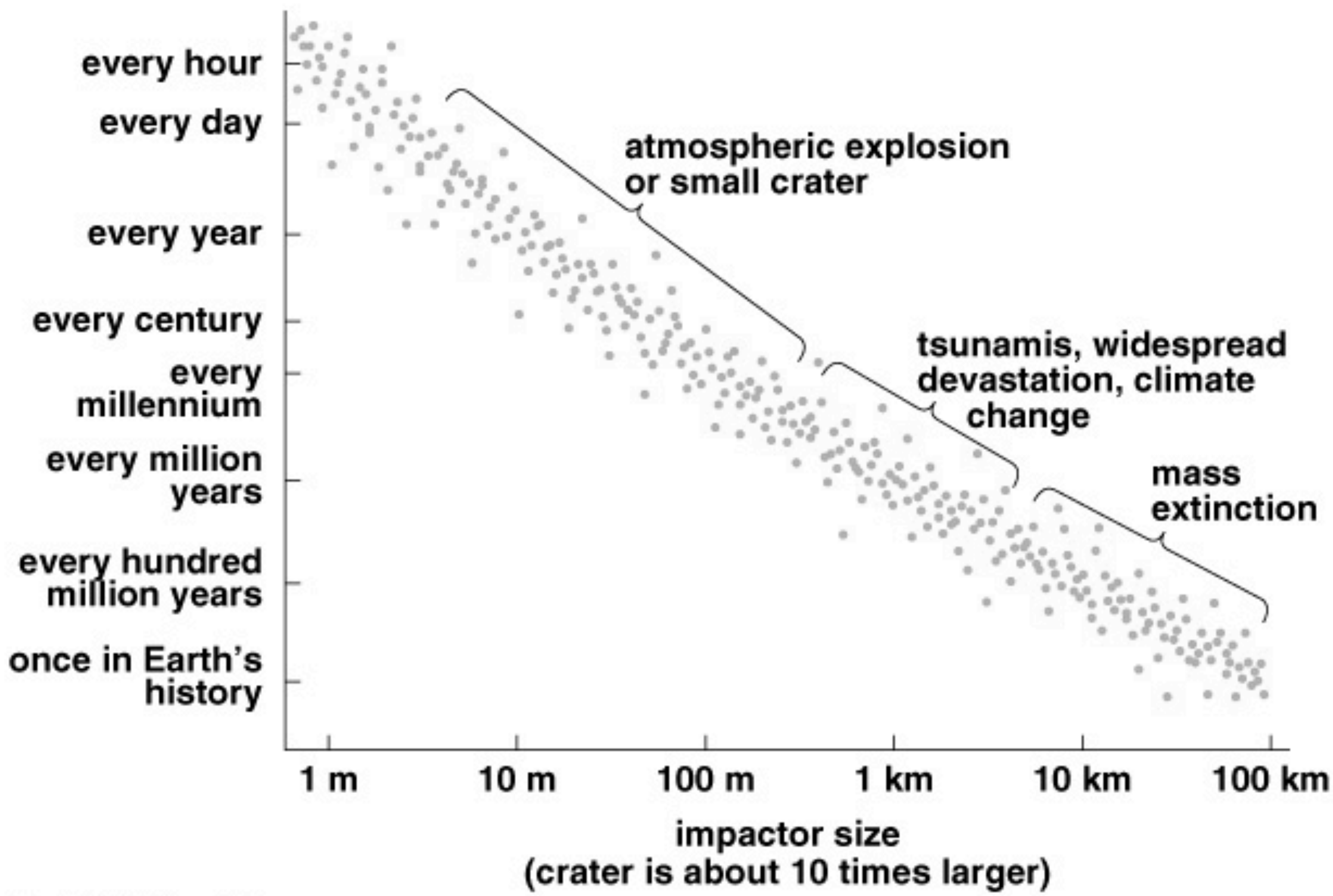


Drastic effects of impact on a terrestrial planet

- 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, lava from the interior may 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.**
- **New survey telescopes (LSST, PanSTARRS) will search more systematically.**

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.

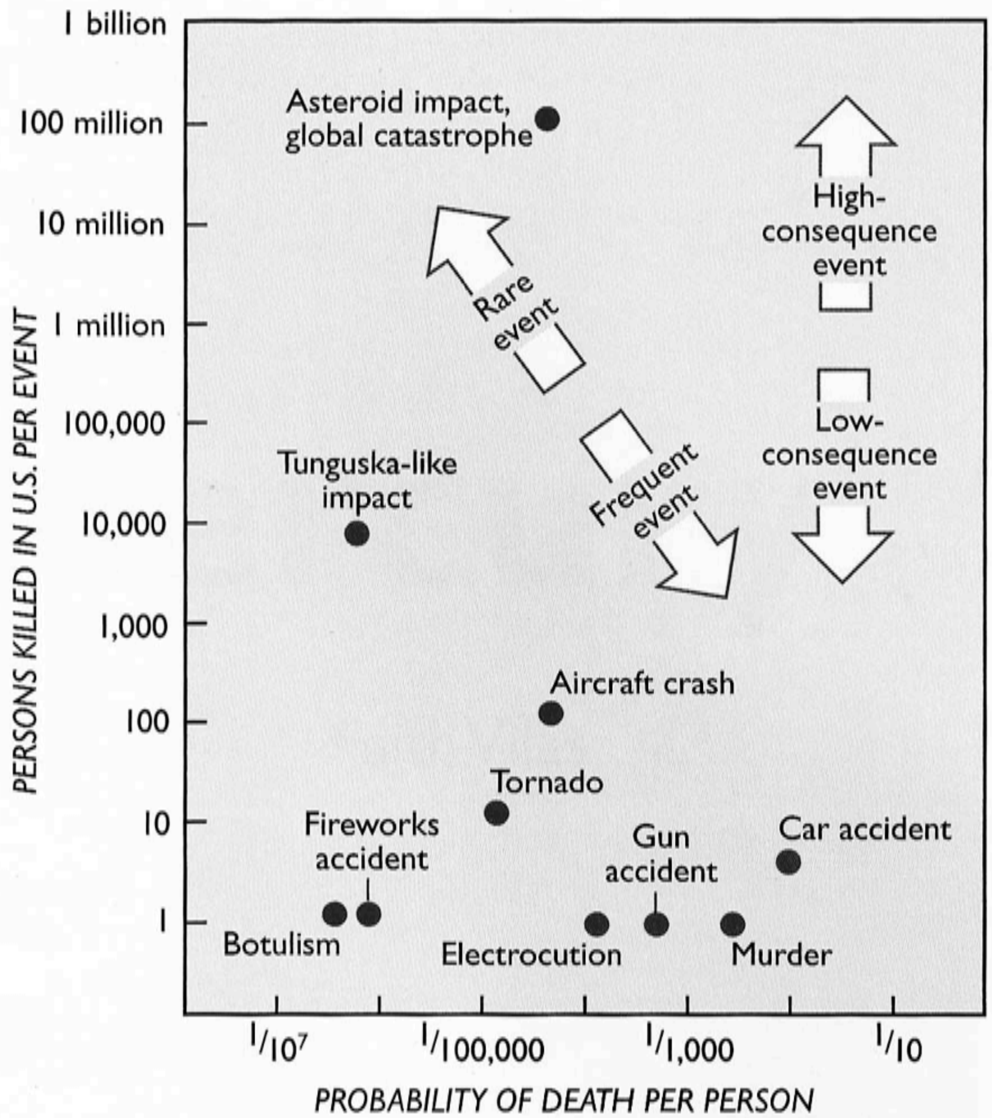


Figure 19. Averaged over a human lifetime, the chance of being killed by an asteroid or comet impact is about the same as dying in a plane crash. Impacts are much rarer than aircraft accidents, but orders of magnitude more persons would be killed if even a small asteroid stuck Earth.

- **Low probability of a rare but high-consequence event**
- **Difficult for policy-makers and public opinion to deal with**

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 event once every 100 million years**
- **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?"**