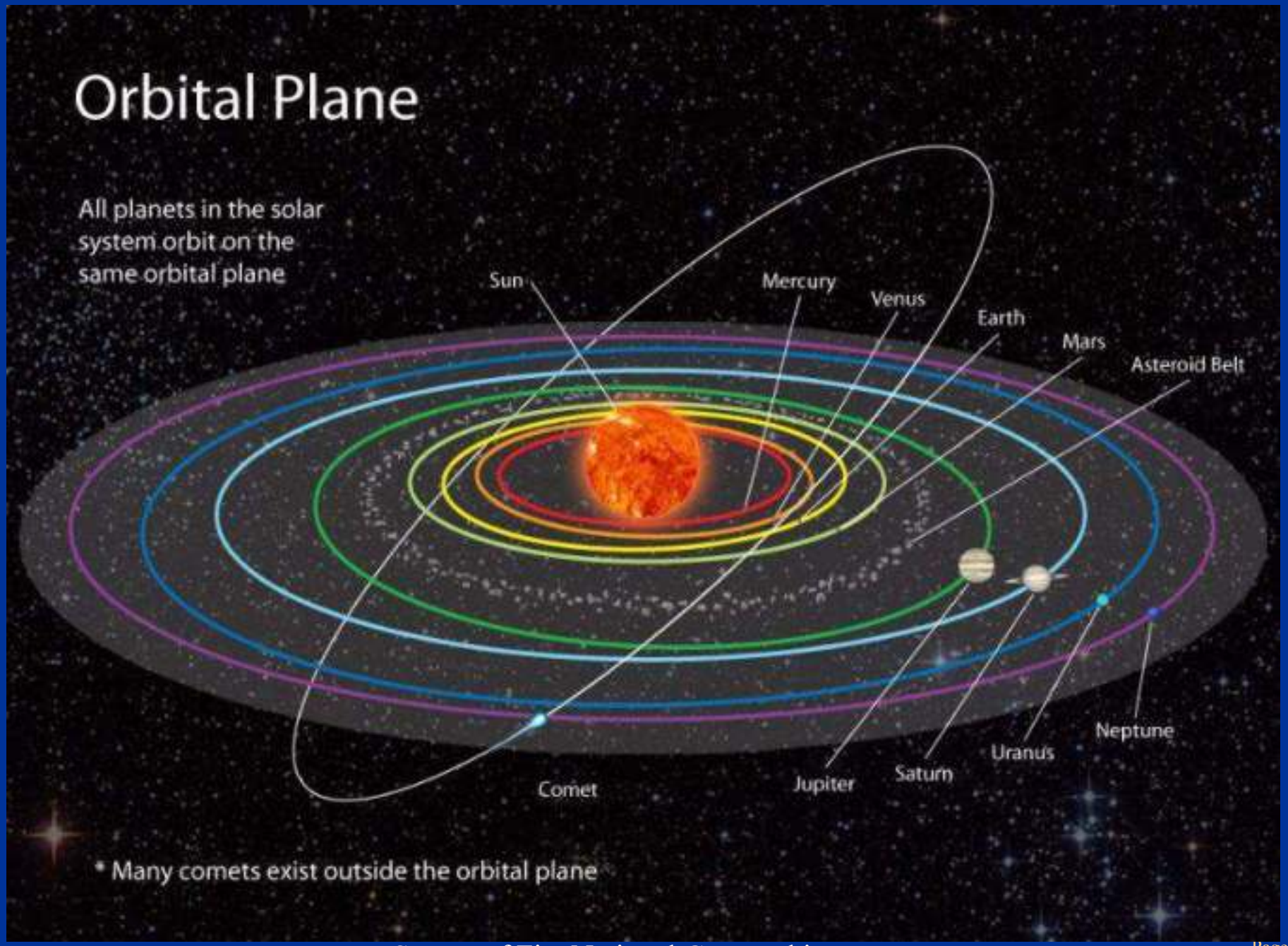
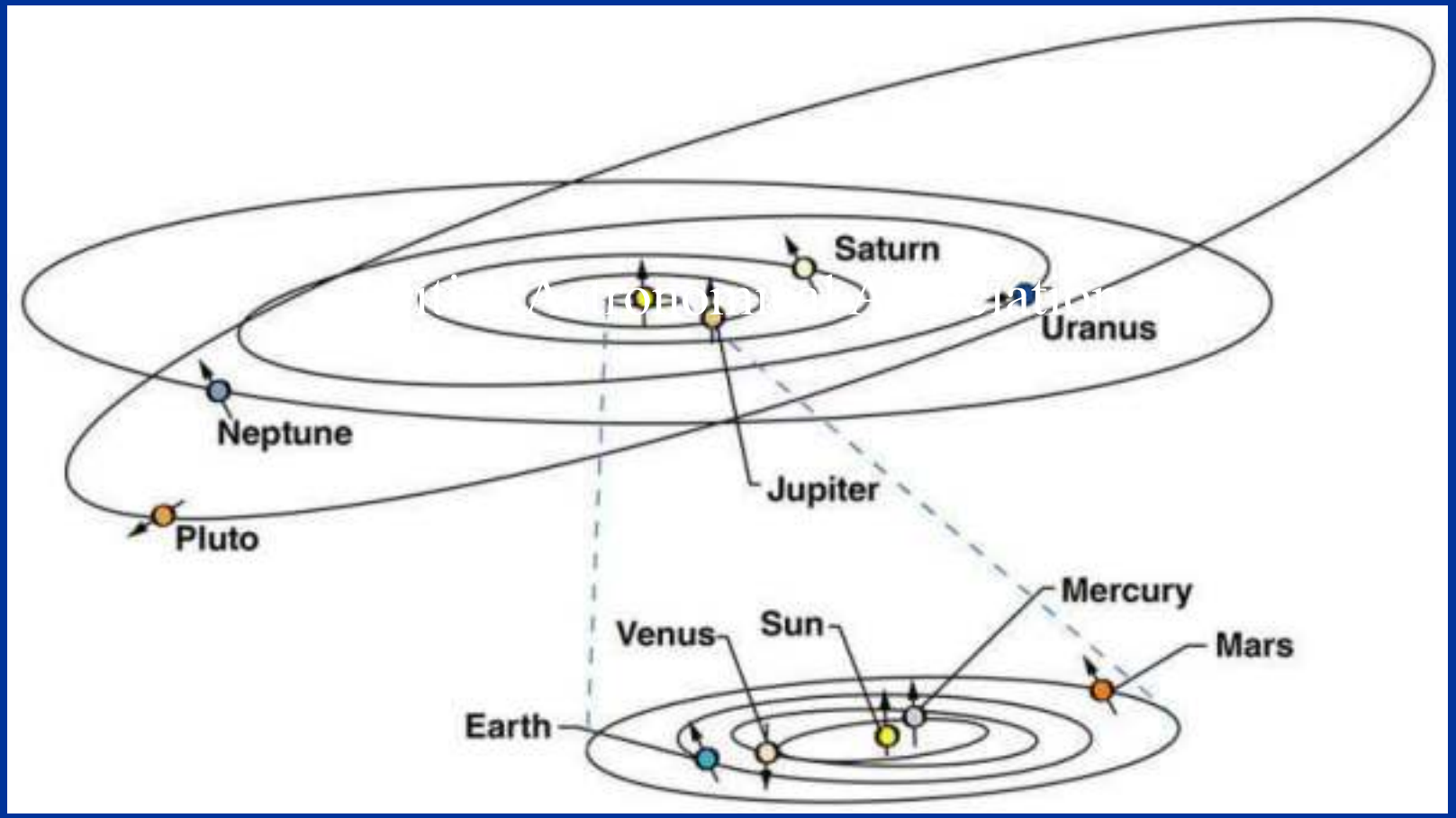
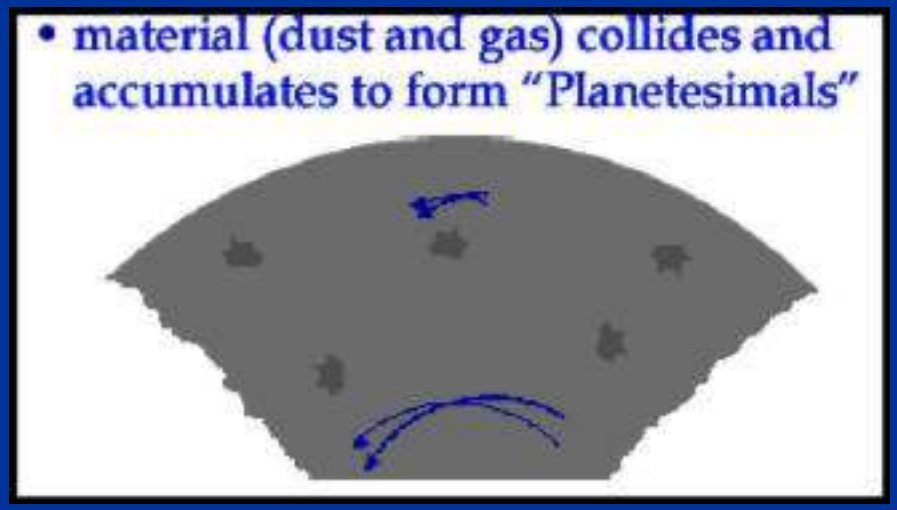


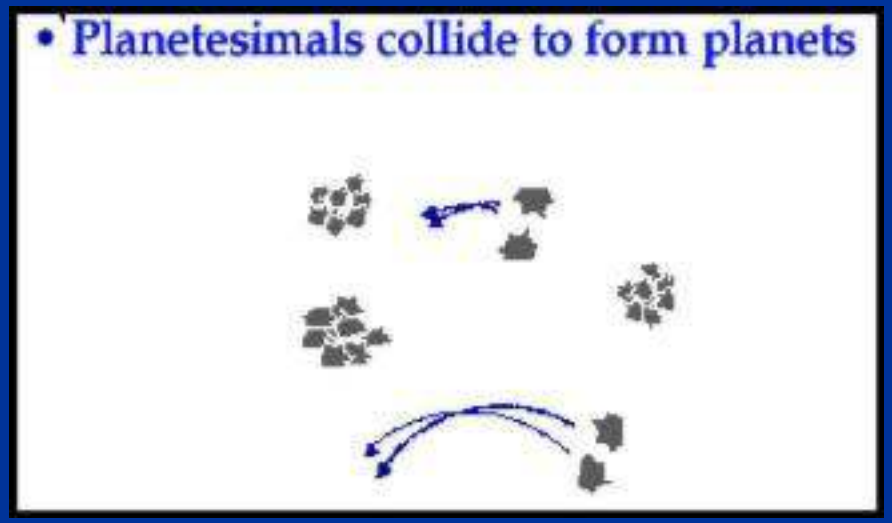
Source of Fig. National Geographic



Source of Fig. British Astronomical Association

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





- **https://www.slideserve.com/arthur-diaz/lecture-14-meteorites-and-cosmic-collisions**

Solar System Evolution: 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

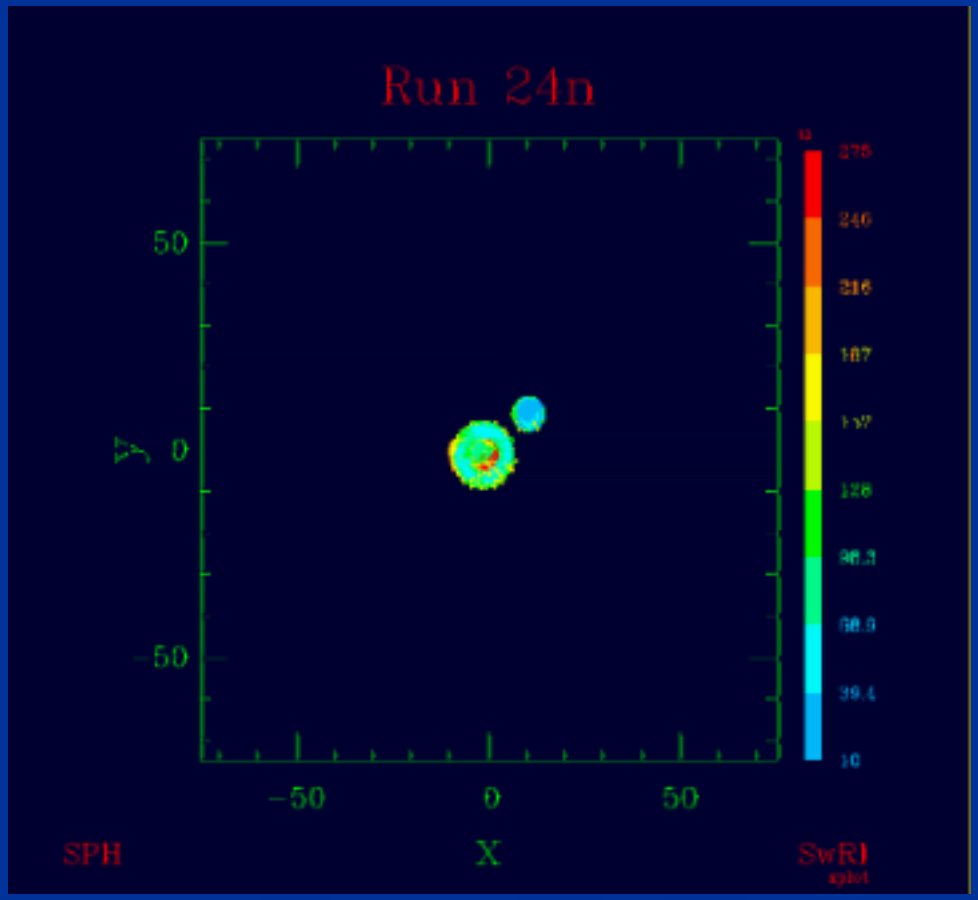
Role of cosmic collisions in evolution of Solar System

- 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?

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

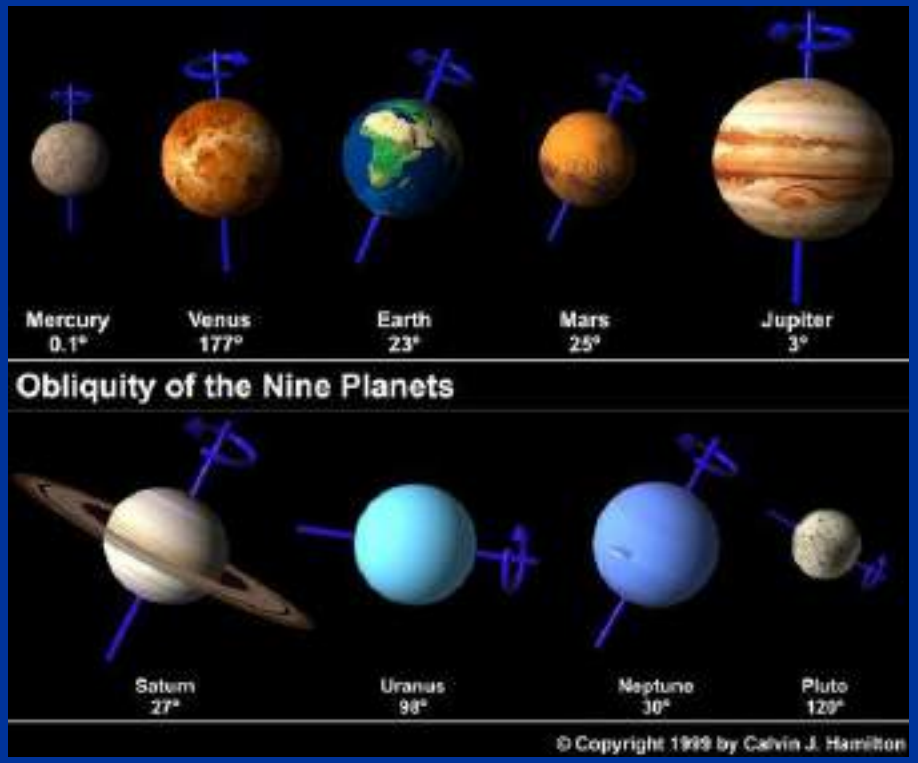
Formation of the Moon….



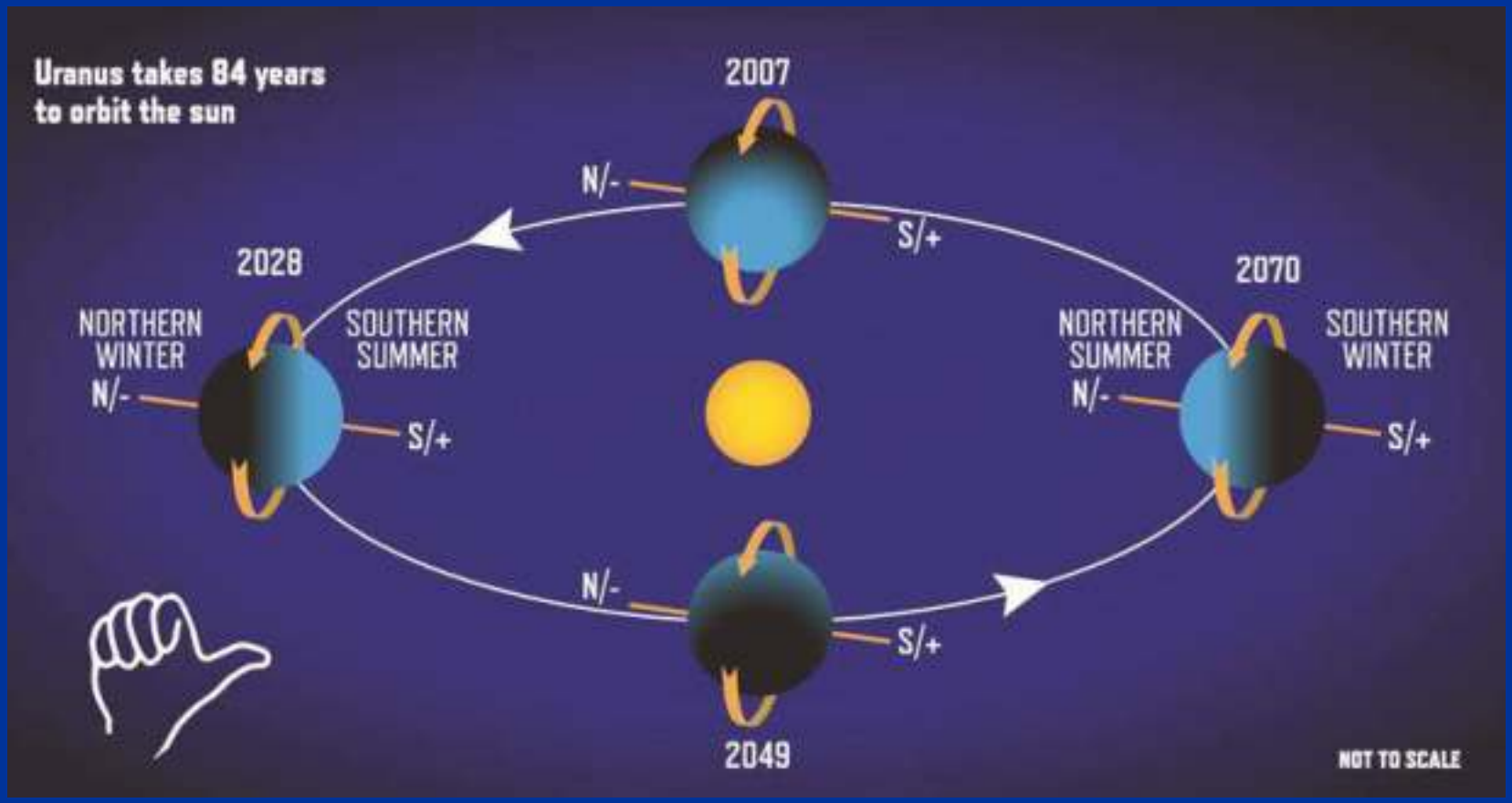
- Large planetesimal collides with Earth at glancing angle
- Removed material is from mantle of Earth

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**



Uranus' rotation axis lies in plane of its orbit



Source of fig. https://creation.com/planets-uranus-and-neptune

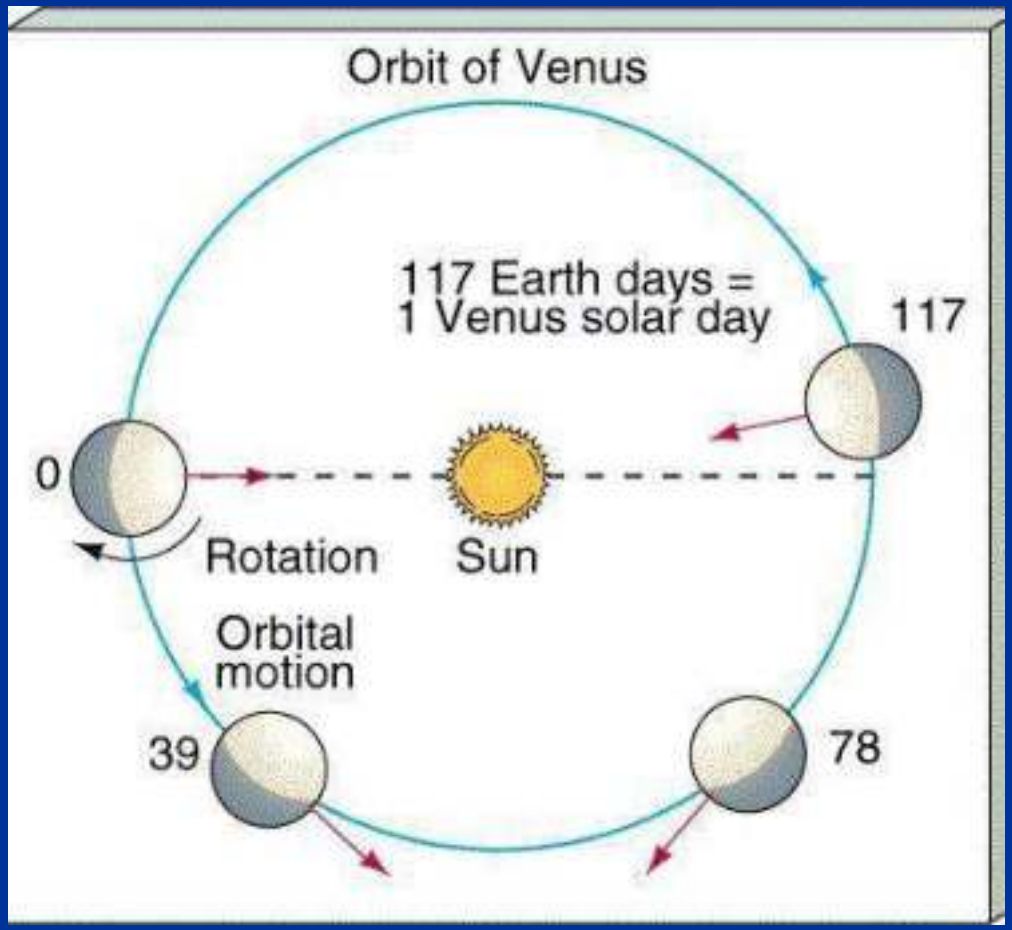
Collision with a massive body is best way to explain this

- **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**

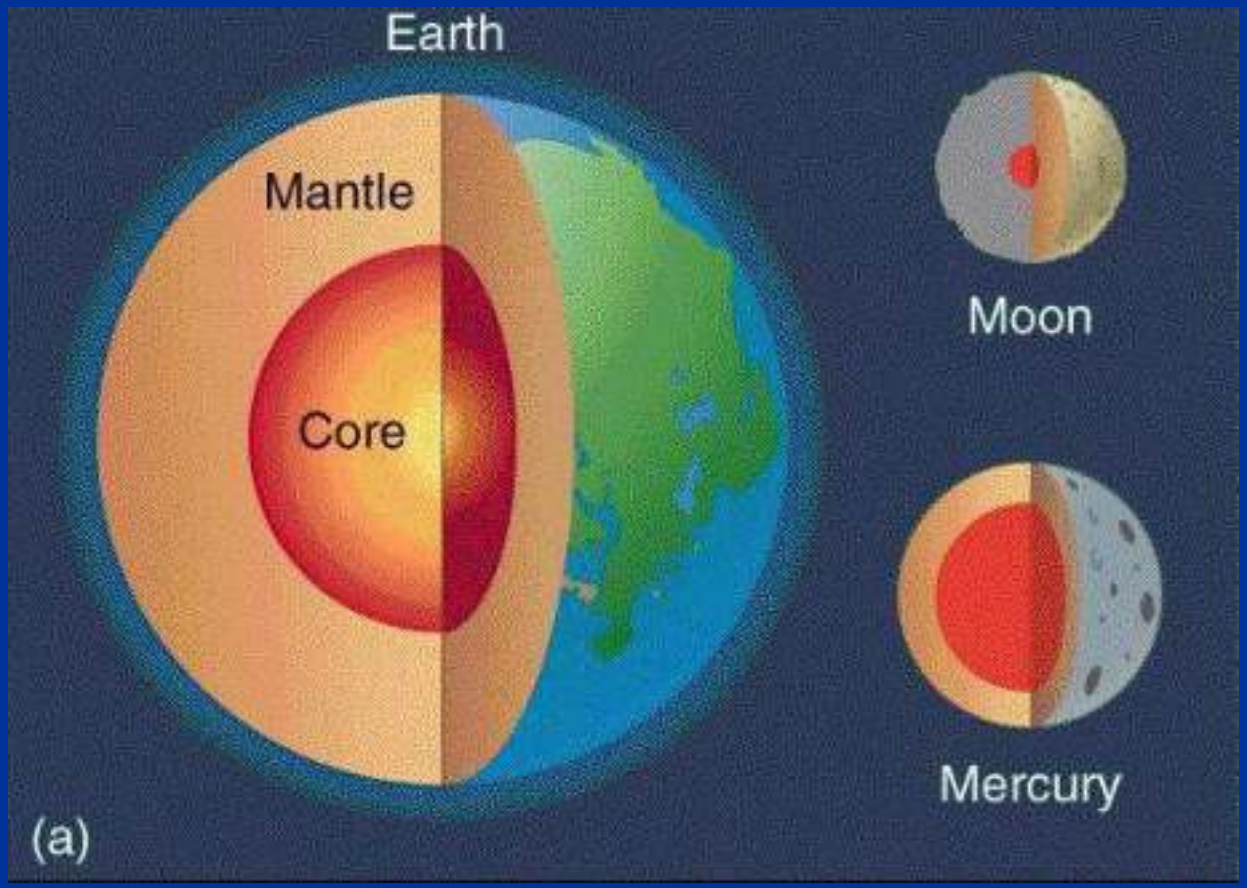
Venus rotates "backwards" compared with all other planets



- **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**



"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**

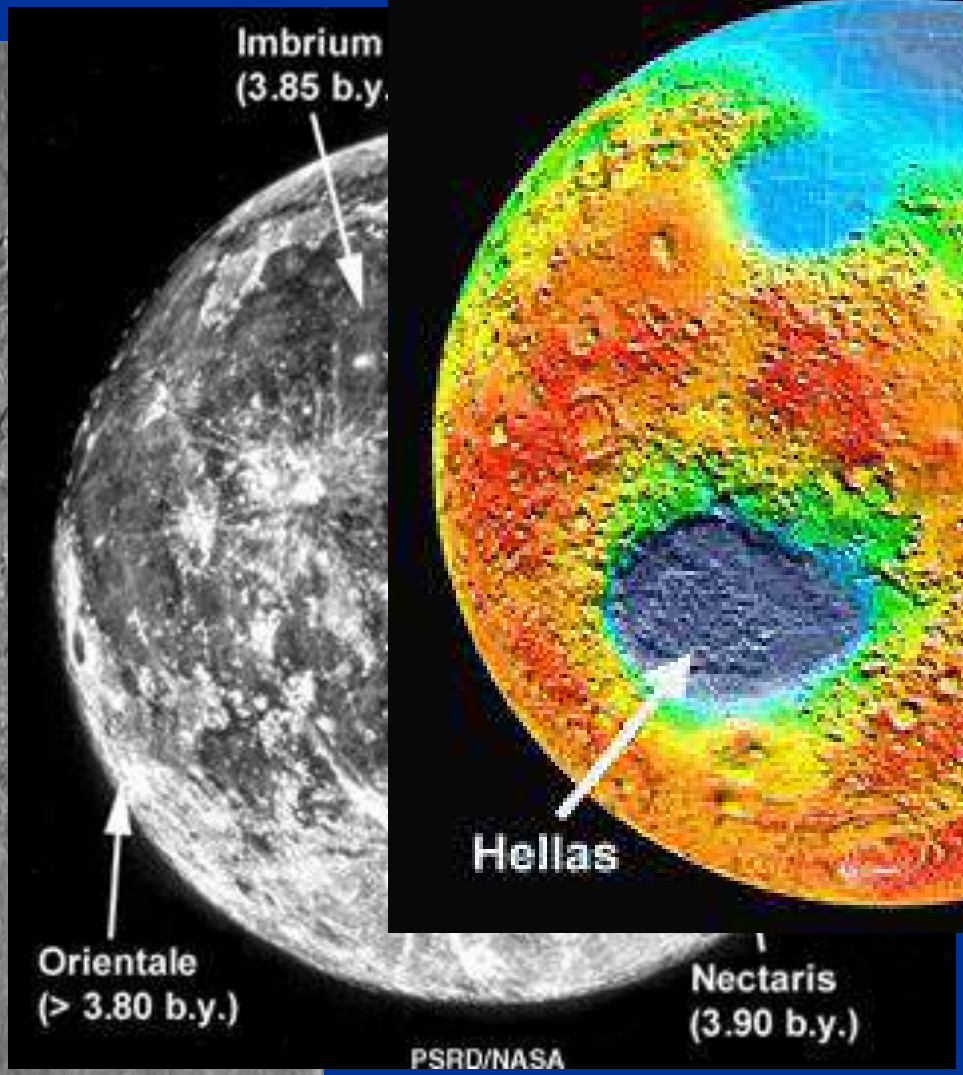
https://en.wikipedia.org/wiki/File:Lunar_cataclysm.jpg

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" ?

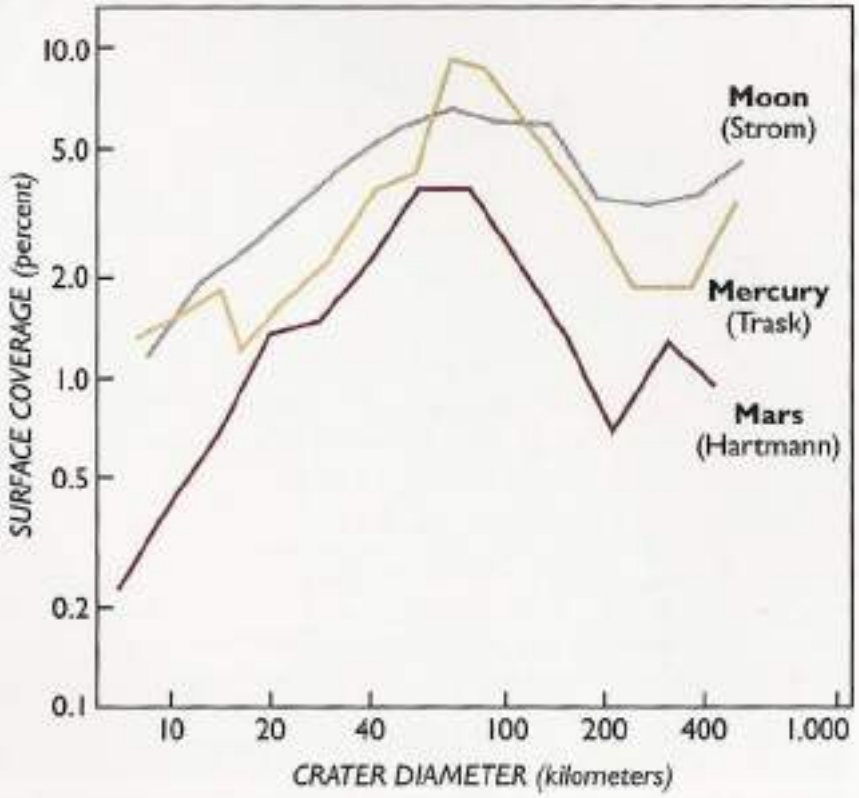


Figure 13. Crater size distributions on the highlands of the Moon, Mercury, and Mars (authors whose data have been used are named by each curve). The coverage on all three bodies peaks for craters with diameters of 40 to 100 km, and the distributions' similar shapes suggest that the same population of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

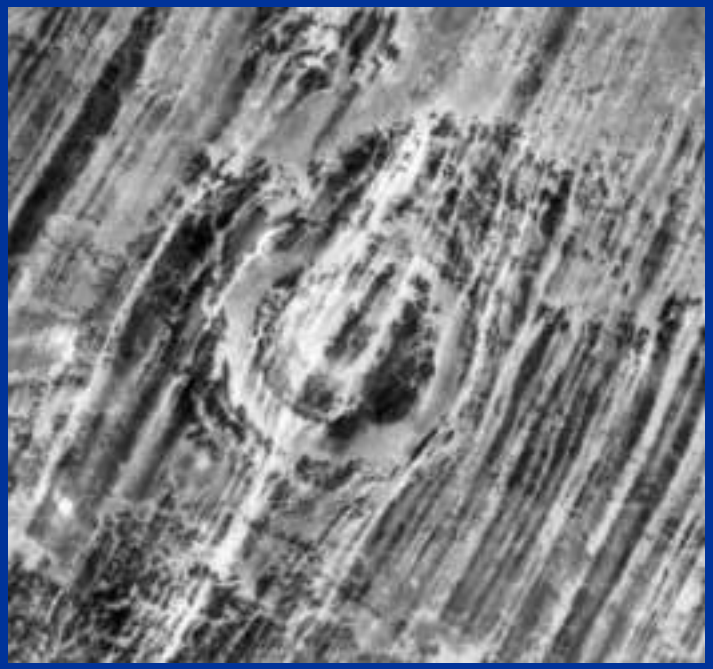
One theory: a real spike in impacts

- 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

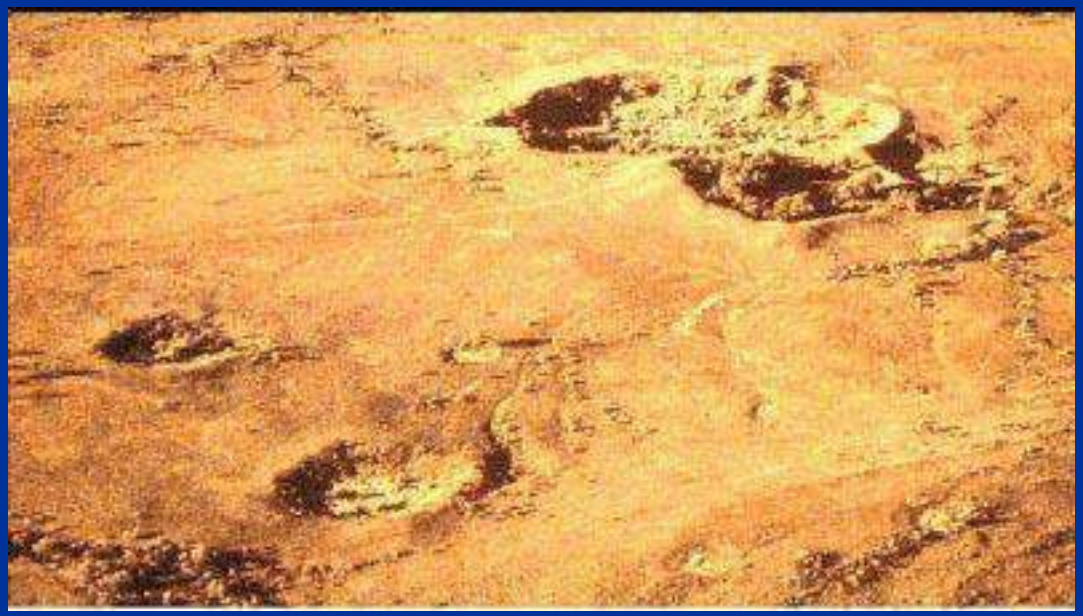
- But most craters got eroded away, subducted, or drowned
- A tour of craters on Earth:

Algeria



Chad (Africa) from airplane

Earth's craters



Clearwater, Canada

Henbury, Australia

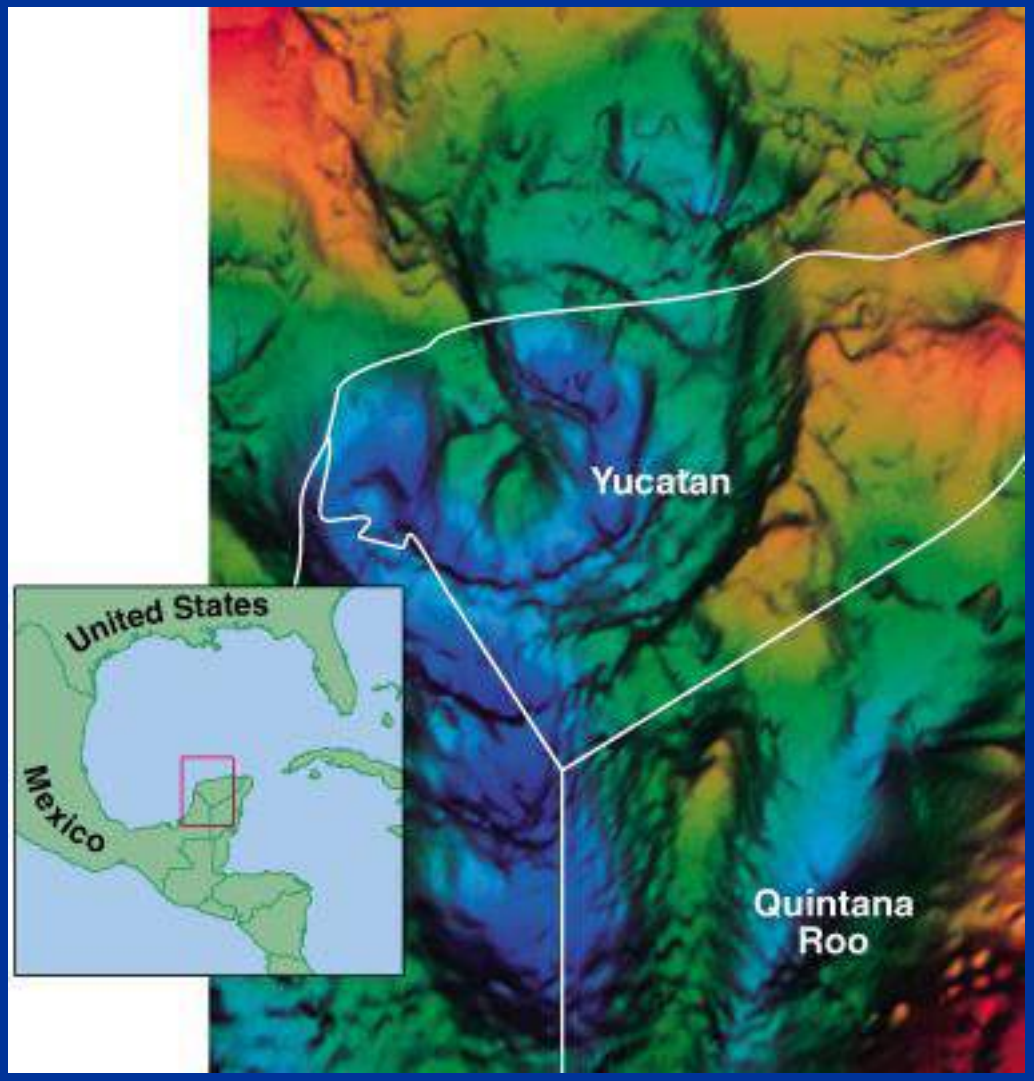
Earth's craters, continued

Tswaing, South Africa

New Quebec, Canada

Arizona's Meteor Crater, the most famous example

Giant impact 64 million years ago: dinosaur extinction



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

- Earth was bombarded by a devastating storm of meteoroids and asteroids four billion years ago has been found in Earth's oldest rocks
- Sedimentary rocks from Greenland and Canada – Archaean, the oldest on Earth - that date from the waning phases of the Late Heavy Bombardment
- chemical fingerprints of the meteorites left over from the Late Heavy Bombardment have been detected- 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 $\propto d^3$)

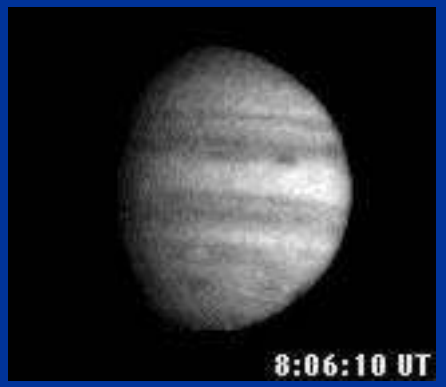
Credit: Bob O'Connell, U Virginia

Collision of Comet Shoemaker-Levy 9 with Jupiter, 1994

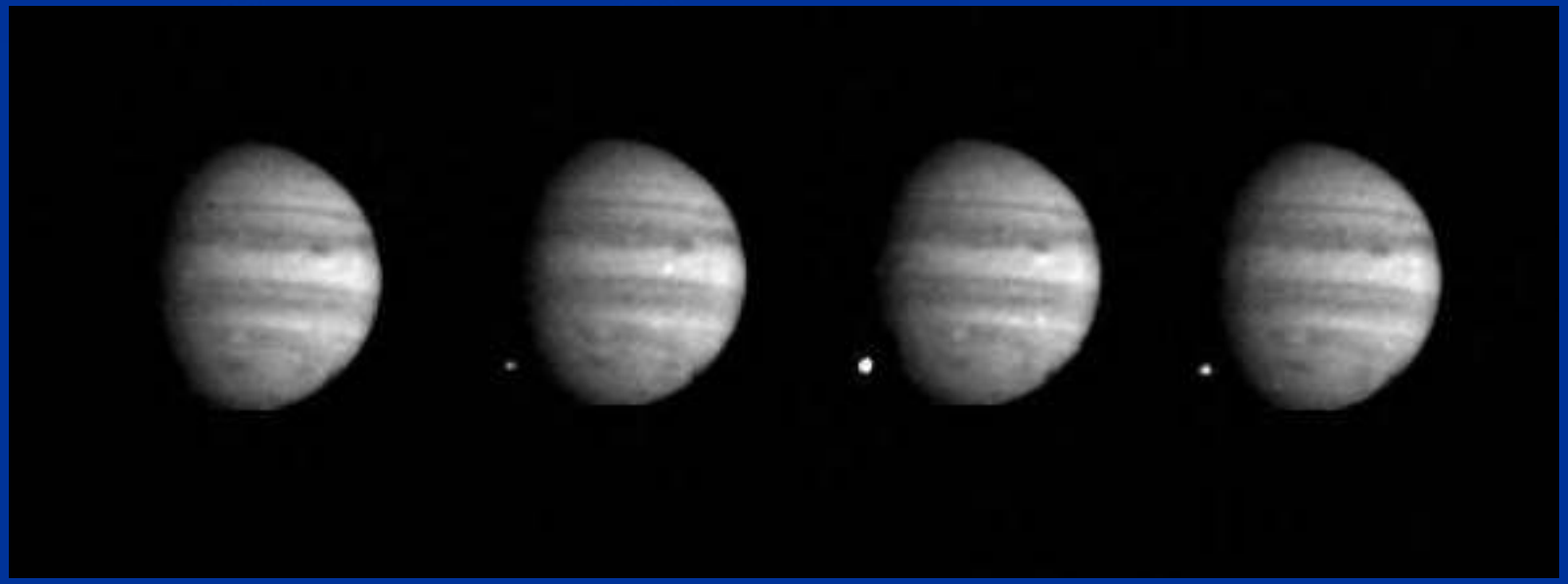
- **Comet discovered March 1993, after it was captured into orbit around Jupiter**
- **In 21 separate pieces! Broke up due to Jupiter's tidal forces**
- **All 21 fragments hit Jupiter in one week in July 1994**

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**



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**

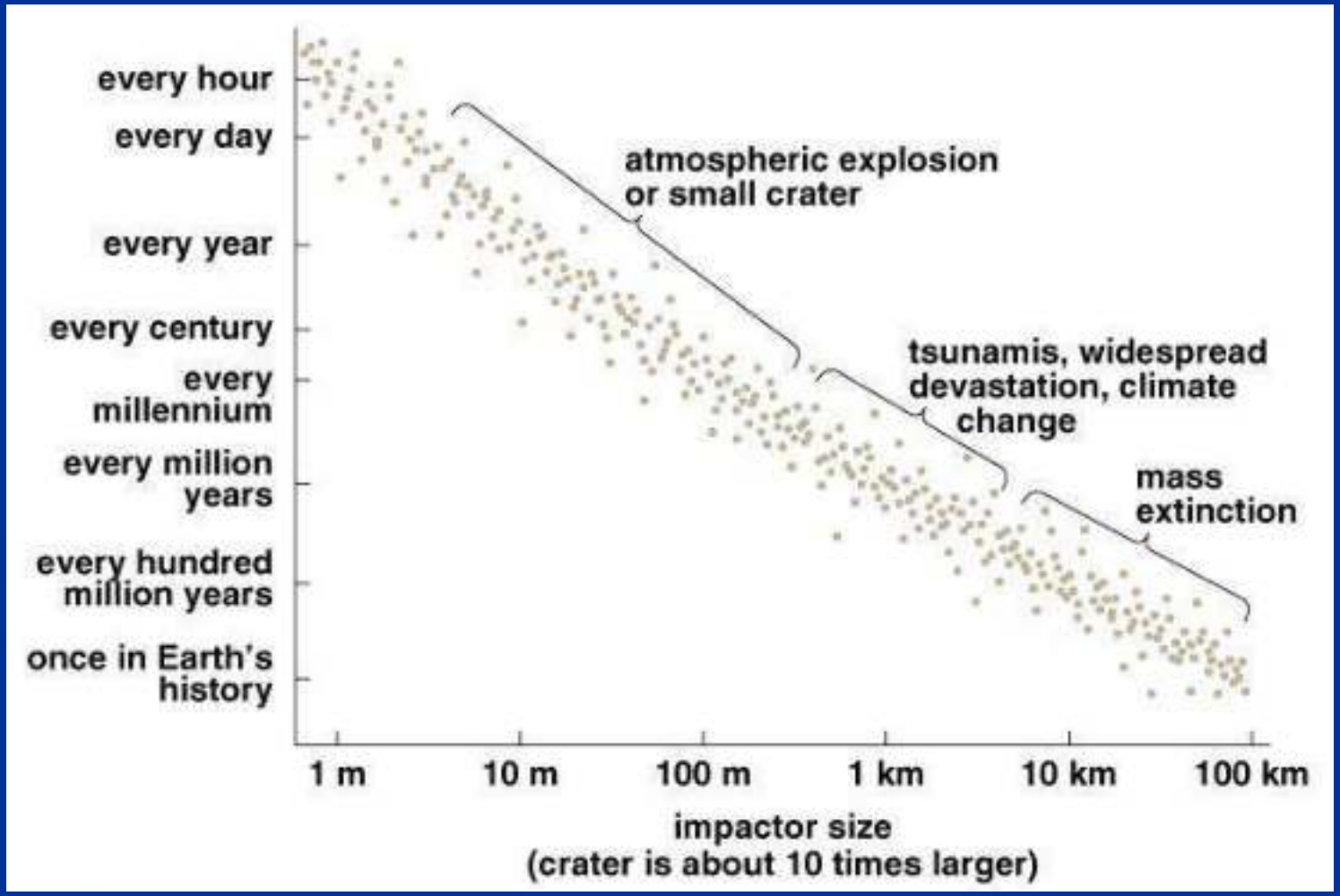
What if a Shoemaker-Levy 9 size comet were to hit the Earth?

Drastic effects of impact on a terrestrial planet

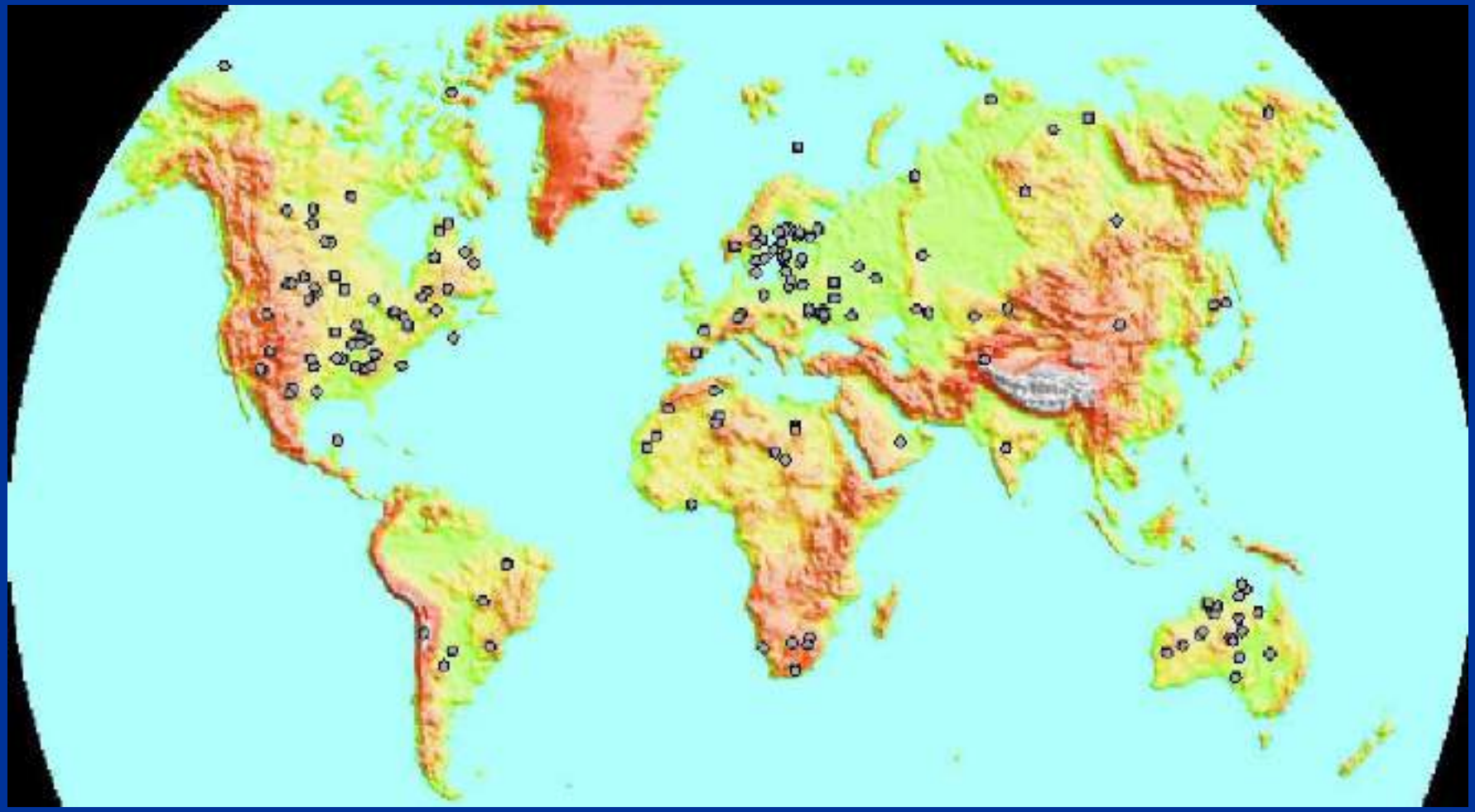
- At “ground zero” rock, water, biomass are vaporized or melted
- Deeper rock is shock recrystallized (ultra high pressures) and fractured
- Series of deep fractures form, lava from the interior may erupt
- Shockwaves obliterate life just outside of “ground zero”
- Earthquakes (and impact itself, if 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!)

- **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?"**

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.**

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.
	2	A somewhat close, but not unusual encounter. Collision is very unlikely.
Events Meriting Concern	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.
	5	A close encounter, with a significant threat of a collision capable of causing regional devastation.
Threatening Events	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.
	8	A collision capable of causing localized destruction. Such events occur somewhere on Earth between once per 50 years and once per 1000 years.
Certain Collisions	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.

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?**