Satellites and minor bodies of the inner Solar System

Planets and Astrobiology (2023)

G. Vladilo and S. Ivanovski

Satellites of rocky planets

- Mercury and Venus do not have satellites
- Mars has two satellites of very small size (~10 – 20 km)

- Only the Earth has a satellite with a relatively large size
  - this is a further specificity of Earth with respect to other rocky planets of the Solar System

    in addition to: hydrosphere, continuous tectonic activity, etc.

The Moon

- Moon's mass ~ 0.012 M_{Earth} and radius ~ 0.27 R_{Earth}
- Mean density: ρ_{Moon} = 3.341 g cm^{-3} < ρ_{Earth}=5.515 g cm^{-3}
- The size of the core is not known, but it is probably less than 4% in volume
- The Moon does not have a hydrosphere, nor a significant atmosphere
- Synchronous rotation (tidally locked to Earth)
- Very large surface temperature excursions

The Moon's surface

- The Moon's surface material provides an example of processes of alteration in absence of atmosphere and magnetic field:
  - Solar wind
  - Cosmic rays
  - Micrometeorites
- The result of this surface processing is a surface layer of thin, porous material, called regolith
  - The regolith layer has a thickness of a few meters above the solid rock
  - The term "regolith" comes from studies of terrestrial geology, meaning a layer of loose, heterogeneous superficial material covering solid rock

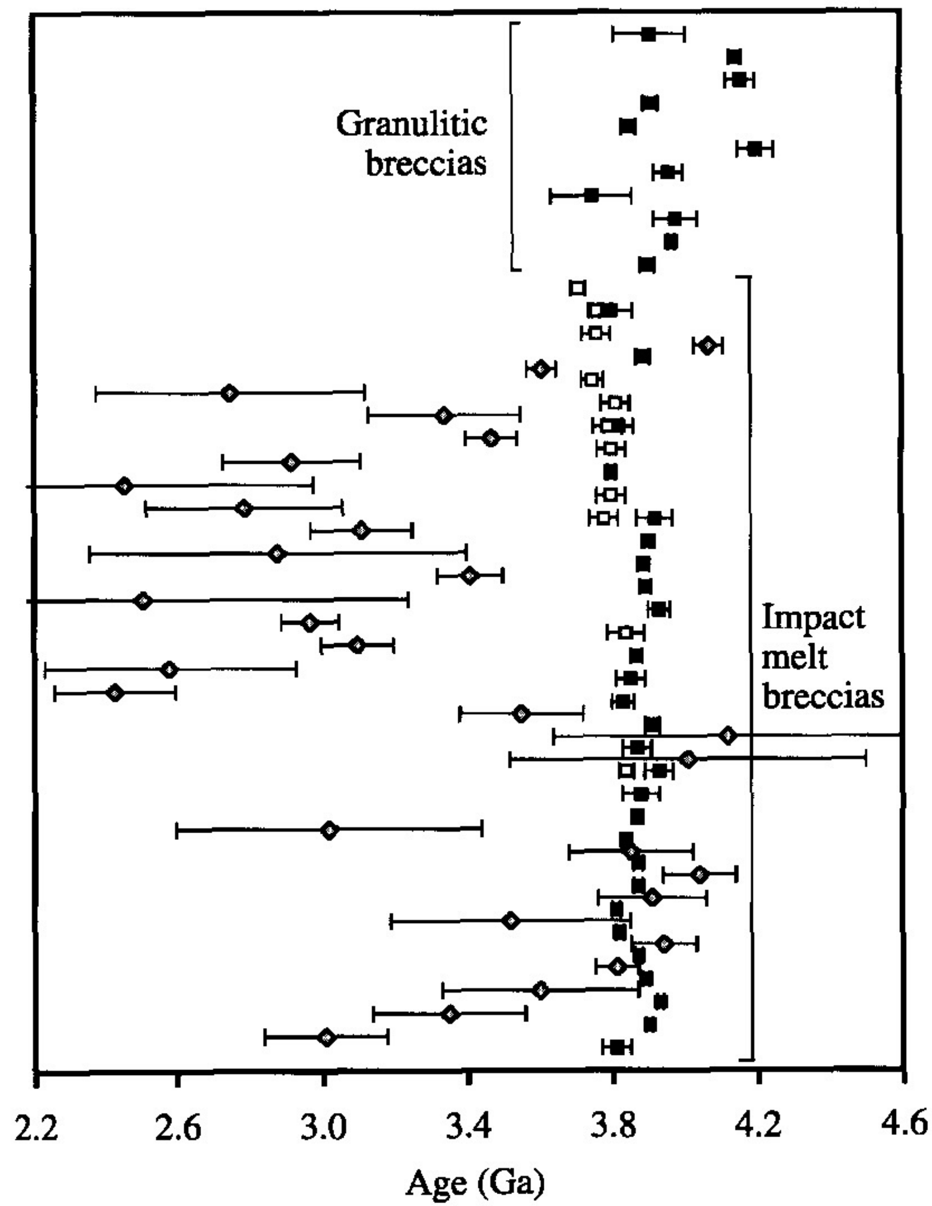
- As a result of its small size, the internal heat sources of the Moon, and the geological activity have decayed rapidly after its formation
- Due to the lack of an atmosphere and of geological activity, the Moon surface has preserved the characteristics acquired in the course of the history after its formation
  - The surface is very rich of impact craters
  - Moon's craters provide a record of the history of minor bodies collisions in the inner Solar System at the location of the Earth
  - Since Moon's craters can be dated accurately, we can reconstruct the history of impacts on Earth

Ages of Moon's impact craters

A peak in the frequency of impacts is found around 3.8 Ga

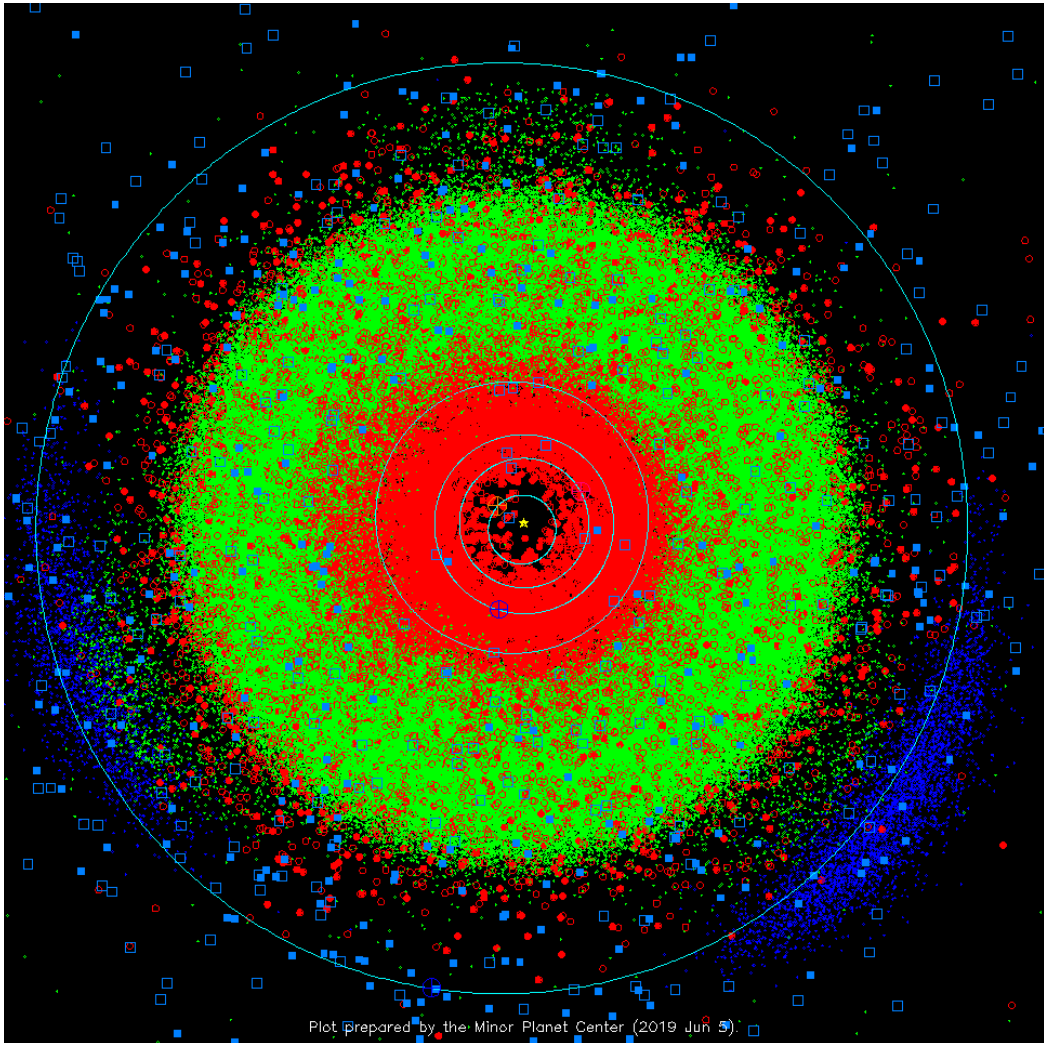
This peak indicates the existence of an episode of dynamical instability in the Solar System at that epoch

Since this episode takes place quite late with respect to the epoch of formation of the Solar System (4.5 Ga), this event of intense collisions is called the "Late Heavy Bombardment"



Minor bodies in the inner Solar System: the asteroid belt(also called Main Belt)

green: asteroid belt



Blue: Trojans in Jupiter's orbit

http://www.minorplanetcenter.net

Classification of asteroids

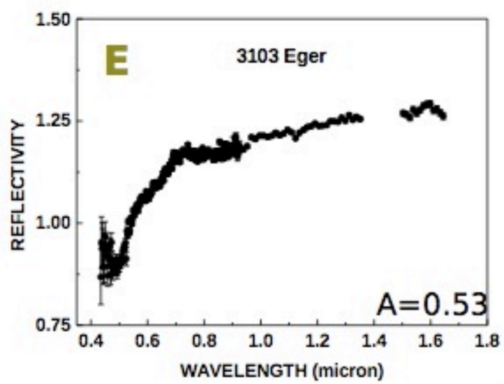
- Asteroids are classified according to spectroscopic and/or dynamical measurements

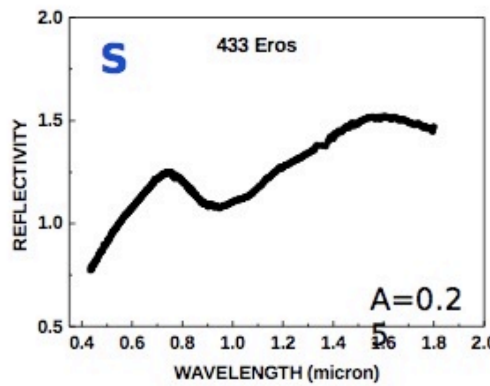
- Spectroscopic/reflectivity observations provide a taxonomical classification related to the physical/mineralogical properties of the surfaces
  - Accurate spectroscopic/reflectivity data are available only for a fraction of asteroids
- Dynamical measurements provide a classification in the space of orbital parameters
  - A large database is available for performing a classification of asteroid families

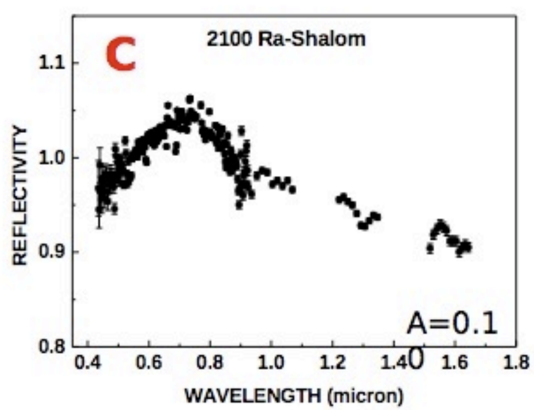
Taxonomical classification of asteroids

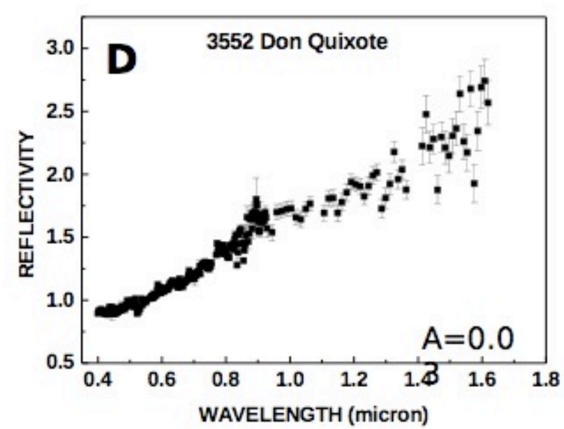
- Based on the study of their reflectivity in different spectral bands
  - The spectral response is indicative of the mineralogy

    Examples: type E: Enstatite, type S: Silicates, …







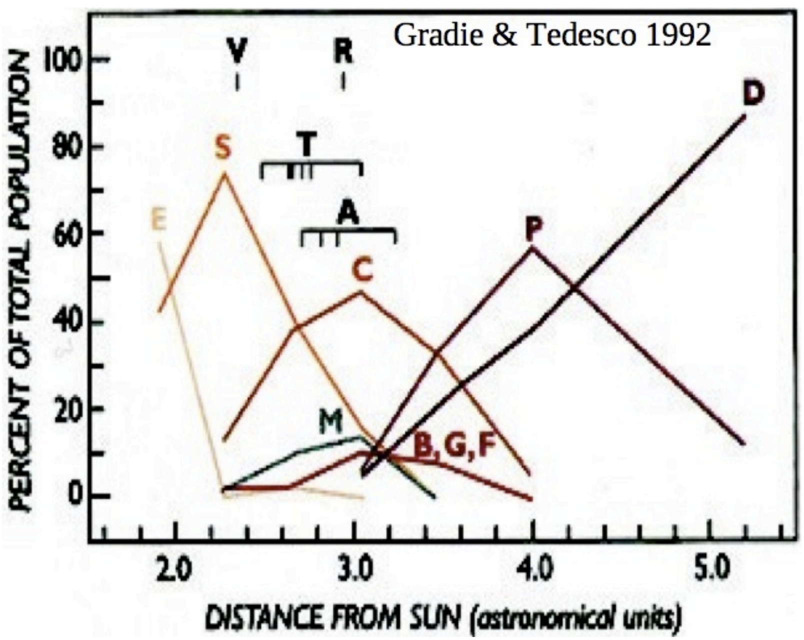


Taxonomical types and mineralogy of asteroids

Tax.Type	Minerals
A	Olivine ± FeNi metal
V	Pyroxene ± Feldspar
E	Enstatite Mg-rich pyroxenes
M	Metal ± Enstatite Hydrates Silicates + Organics?
S	Metal ± Olivine ± Pyroxene
O	Olivine+Pyroxene
Q	Olivine+Pyroxene (+metal)
R	Olivine+Orthoyroxene
C	Iron-bearing hydrated Silicates
P	Anhydrous silicates + organics
D	Organics+Anhydrous silicates

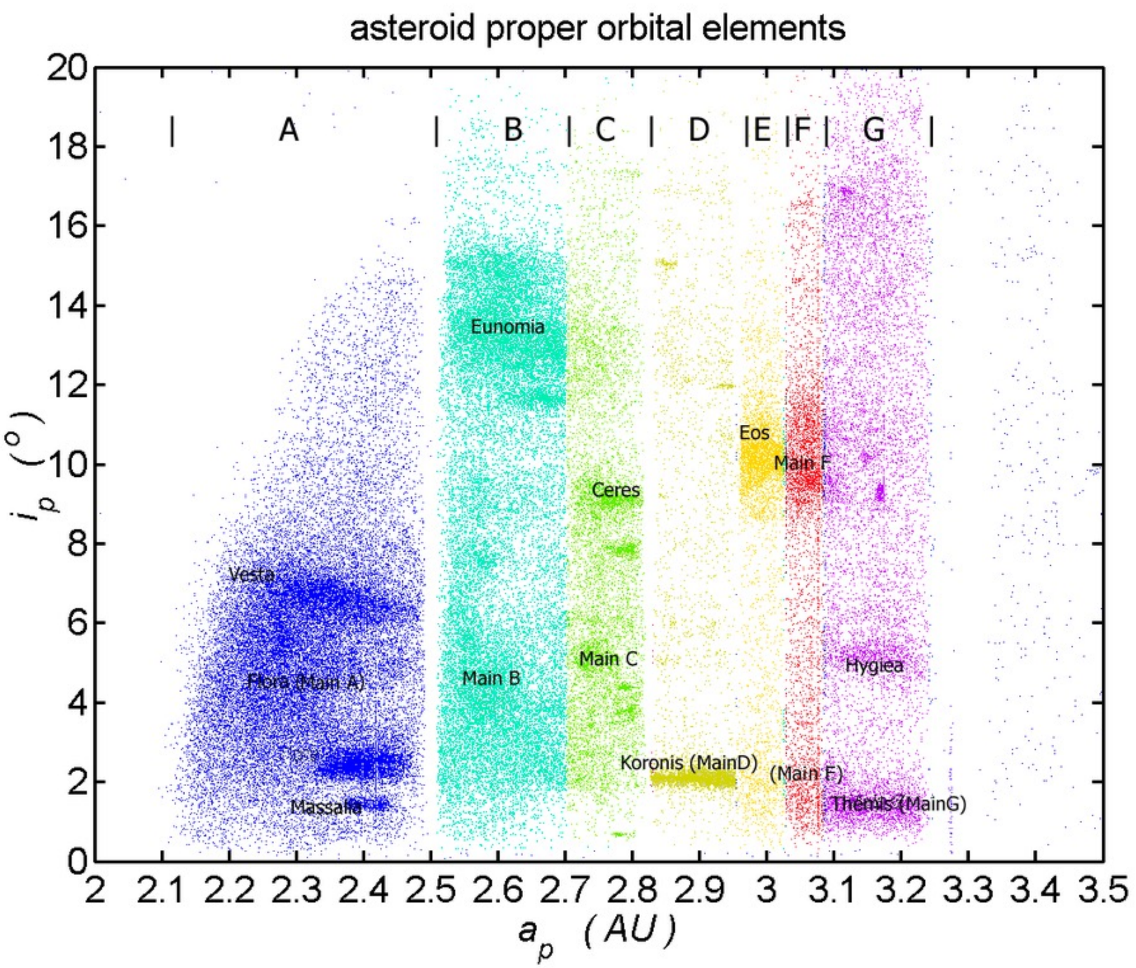
Radial distribution of asteroid types

- The radial distribution of the types varies with heliocentric distance
- The radial distribution probably reflects a temperature gradient in the Solar System
  - Bodies closest to the Sun are the most processed
  - The most distant bodies are believed to be more primitive

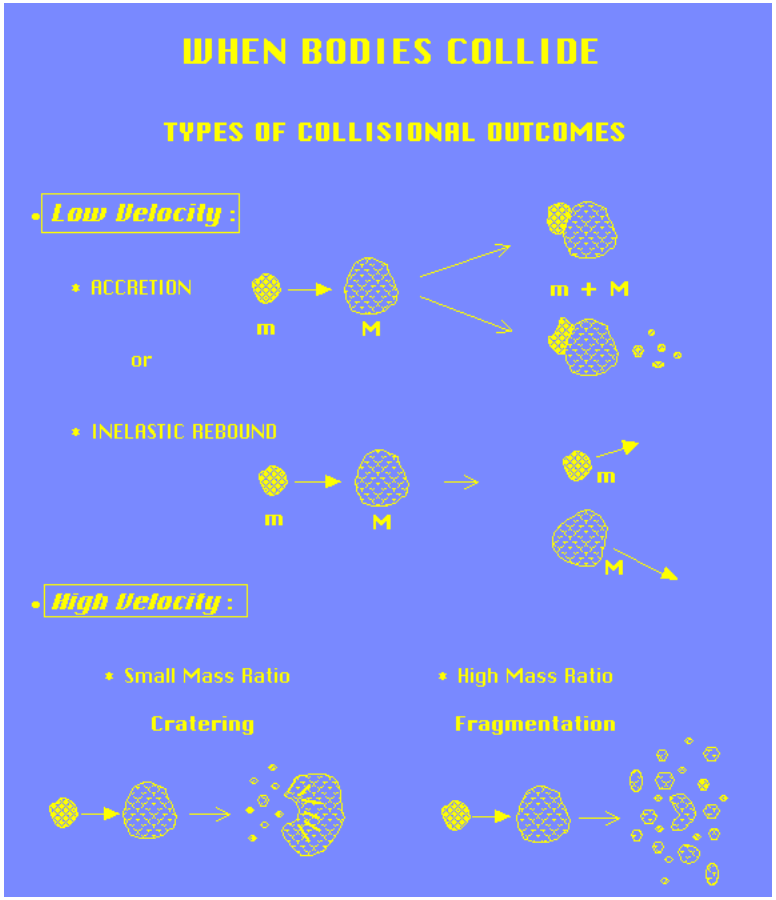


Dynamical classification: asteroid families

An asteroid family is a population of asteroids that share similar proper orbital elements, such as semimajor axis, eccentricity, and orbital inclination. The members of each family are thought to be fragments of one asteroid collision



Collisions: possible formation of satellites



From Galileo mission we discovered that (243) Ida (diameter of 52 km) has a small satellite (1.5 km), named Dactyl, orbiting at a distance of about 100 km.

Largest bodies in the asteroid belt

Name	R [km]	M [kg]	ρ [g/cm^3]	a [AU]	e	i [º]
Ceres	473	9.4×10^{20}	2.2	2.77	0.076	10.6
Vesta	262	2.6×10^{20}	3.5	2.36	0.099	6.4

Ceres is a dwarf planet, the only one in the asteroid belt

Vesta is the largest asteroid

Both have been recently observed with the *DAWN NASA* space mission

Ceres

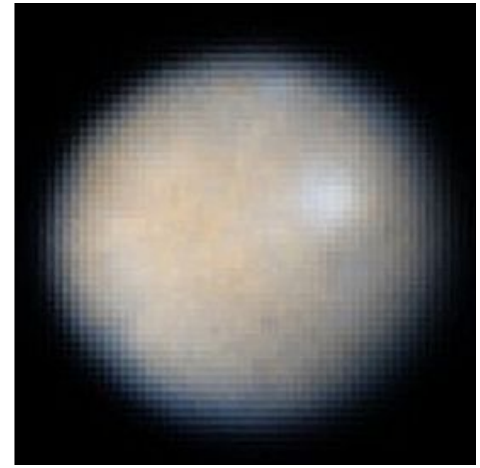
The dwarf planet in the asteroid belt

Ceres comprises 25 percent of the asteroid belt's total mass. Computer models show that nearly round objects such as Ceres have a differentiated interior. This sets Ceres apart from its asteroid neighbors, which are undifferentiated.

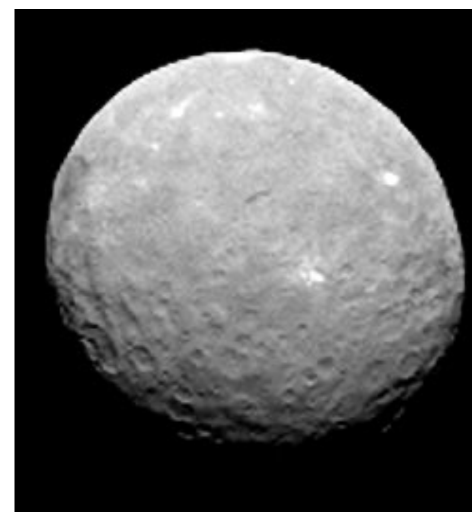
The Herschel Space Observatory found evidence for water vapor on Ceres. The vapor may be produced by *cryovolcanoes* or by ice sublimating near the surface. This suggests that Ceres contains *large amounts of water ice* beneath its surface.

Ceres' water would be in the form of ice and located in the mantle, which wraps around the dwarf planet's solid core.

Ceres from *HST*



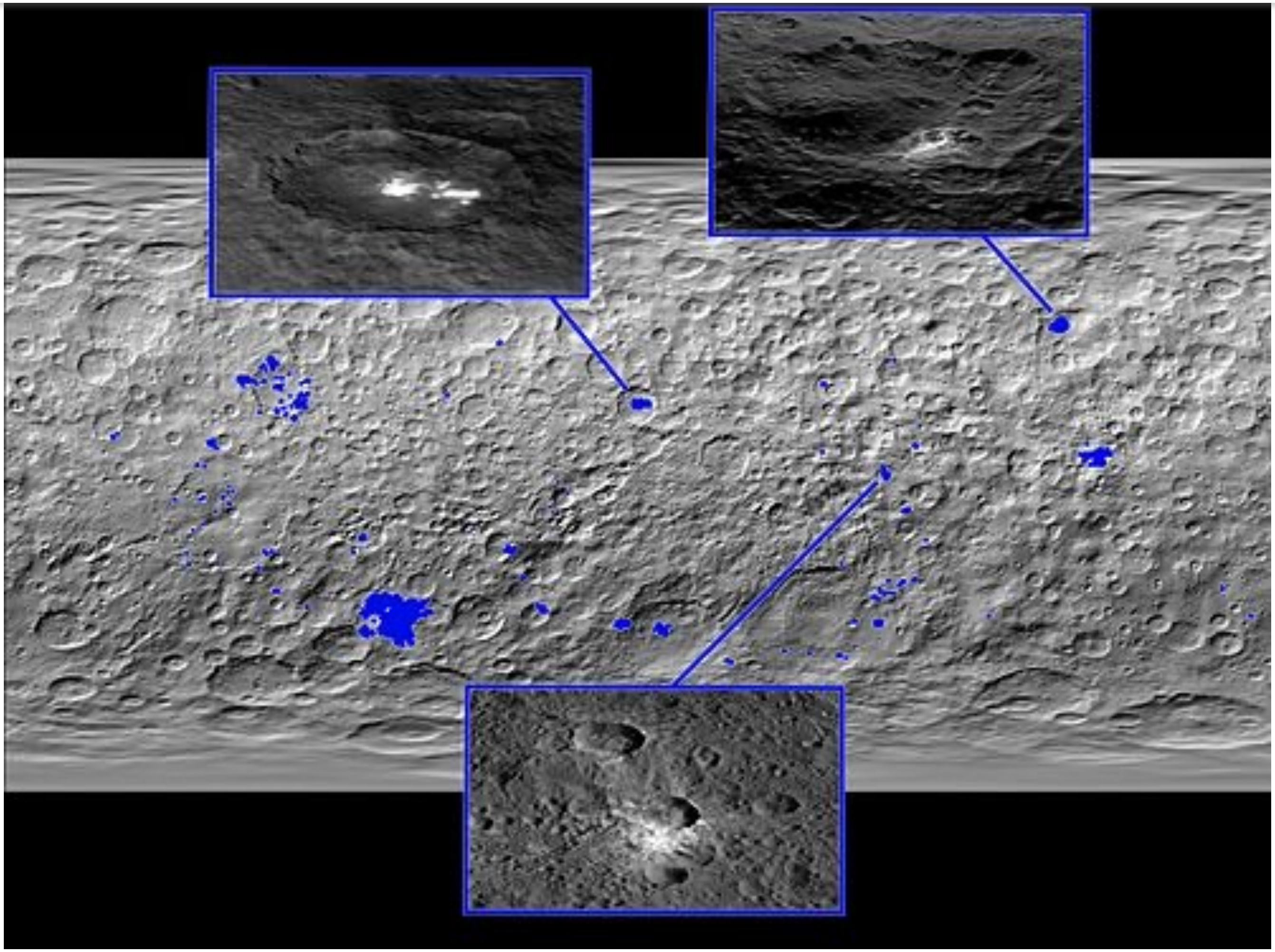
Ceres from *DAWN*



Bright spots on Ceres

The DAWN mission has revealed the presence of bright spots on Ceres' surface

The bright spots are best explained as resulting from briny water erupted from Ceres' interior that subsequently sublimated, leaving behind only the salt deposits

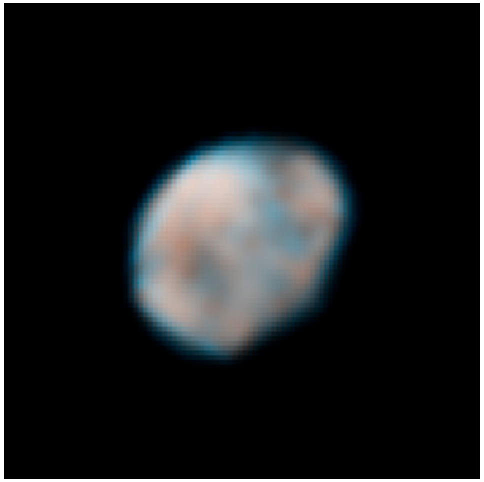


Vesta

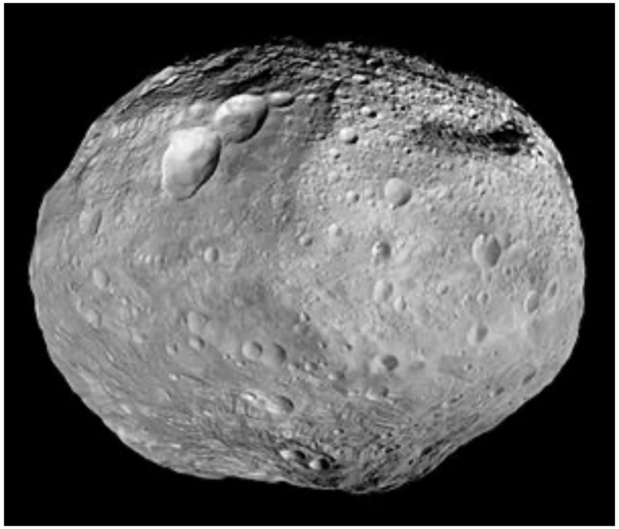
Vesta is the second-most-massive body in the asteroid belt, though only 28% as massive as Ceres. The density (3.46 g/cm^3) is higher than that of most asteroids. It has a differentiated interior.

Vesta's shape is close to a gravitationally relaxed oblate spheroid. Analysis of Vesta's shape and gravity field using data gathered by the Dawn spacecraft has shown that Vesta is currently not in hydrostatic equilibrium

Vesta from *HST*



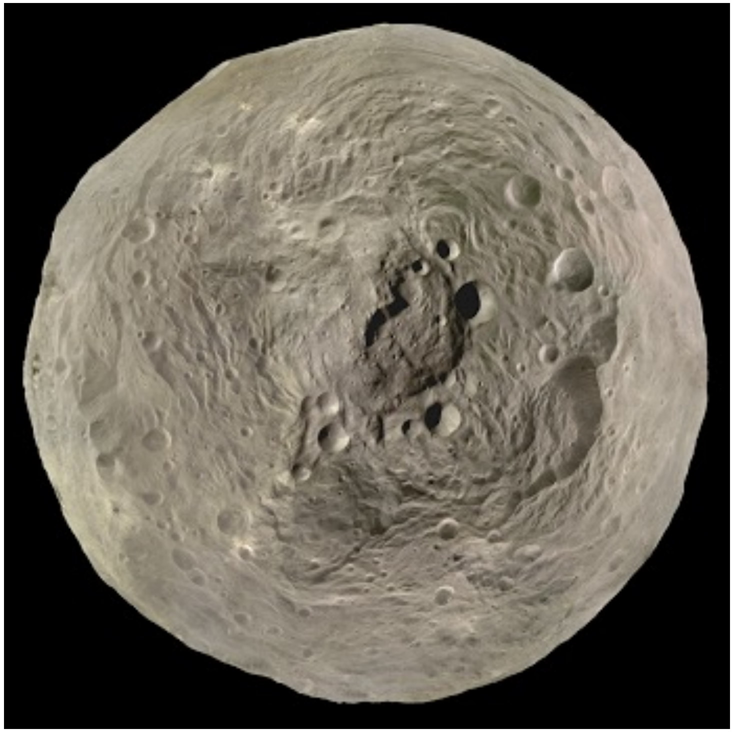
Vesta from *DAWN*



The DAWN mission has revealed the presence of huge craters in the south pole of Vesta

Vesta craters

The surface of Vesta displays many impact craters. The most prominent are the 500-km-wide Rheasilvia crater, centered near the south pole, and the 400 km-wide Veneneia crater.

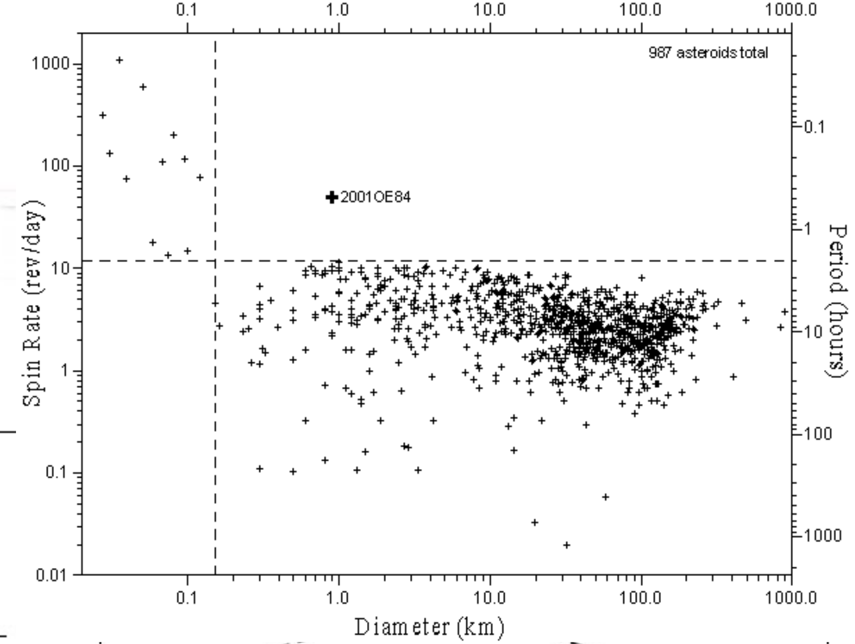


It is estimated that the impact responsible for such craters excavated about 1% of the volume of Vesta, and it is likely that *the Vesta family and V-type asteroids are the products of this collision*. It would also be the *site of origin of the HED meteorites*

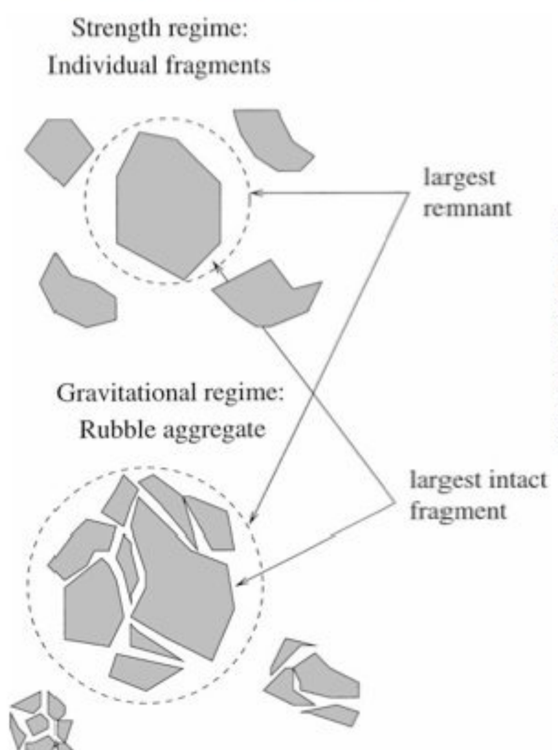
Asteroid structure

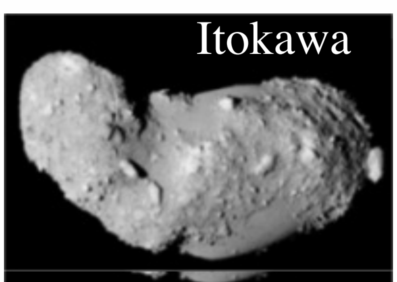
«Rubble piles»: most in the 200 m-10km range

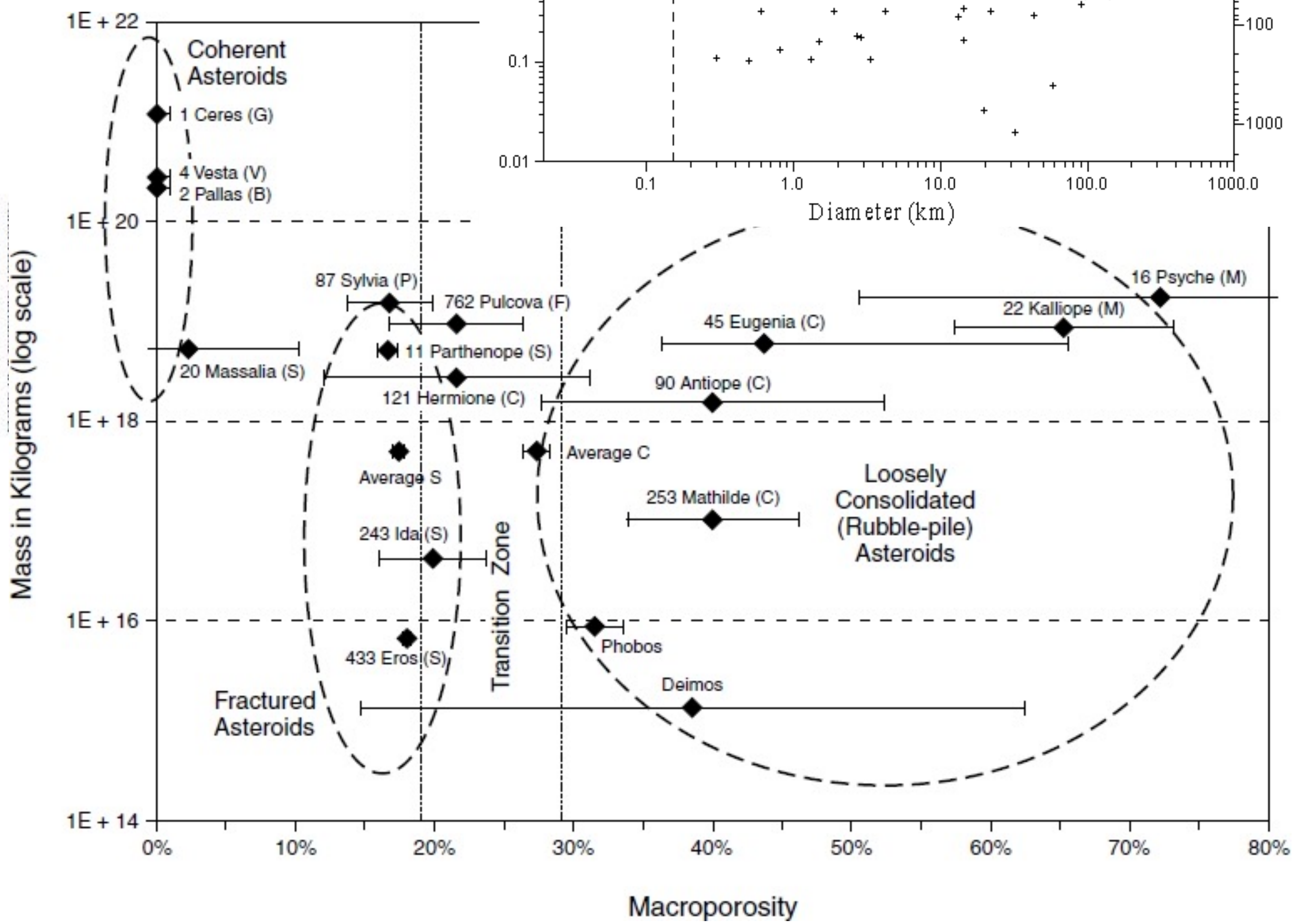
Spin barrier limit at 2.2h for D>200m



Benz &Asphaug 1999

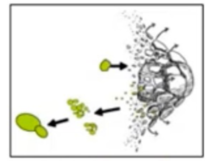






Asteroid characterization from sample return missions

Itokawa vs Ryugu : physical features

	(25143) Itokawa 1998 SF36	**(162173) Ryugu** 1999 JU3
shape	elongated   **Rubble pile**	spinning top  In the past, the rotation period was 3.5 h ? **Rubble pile**
rotation period	12.132 h	7.63262 h
pole direction [λ,β]	[128.5° , -89.66°]	[179.3° , -87.44°]
size	X=535 m, Y=294 m, Z=209 m (±1 m)	diameter: equ. 1000m pol. 876m (±4 m)
mass	$(3.510 \pm 0.105) \times 10^{10}$ kg	$(4.50 \pm 0.06) \times 10^{11}$ kg
volume	$(1.84 \pm 0.092) \times 10^{7}$ m^3	$(3.77 \pm 0.05) \times 10^{8}$ m^3
bulk density	1.90 ± 0.13 g/cm^3	1.19 ± 0.02 g/cm^3
macro-porosity	40%	more than 50%
geometric albedo	~30%	4.0±0.5% Tatsumi et al. (2020), A&Ap

(Image credit : JAXA)

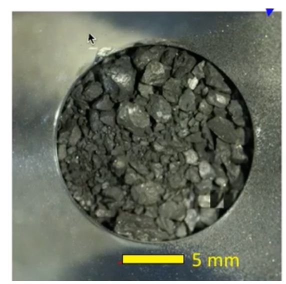
Fujiwara et al. (2006) Science 312

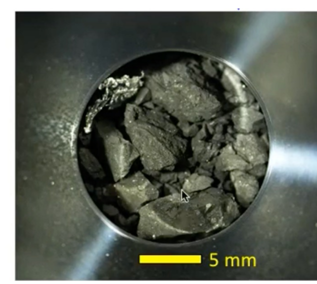
Watanabe et al. (2019) Science 364

Itokawa (S-type) vs Ryugu (C-type)

Surface: smooth and rough vs only rough

Craters: small, no distinct vs large





Ryugu boulders might be fluffy and surface material has an extremely low strength

Yarkovsky effect

The Yarkovsky effect is the weak non gravitational force felt by asteroids due to the emission of thermal photons.

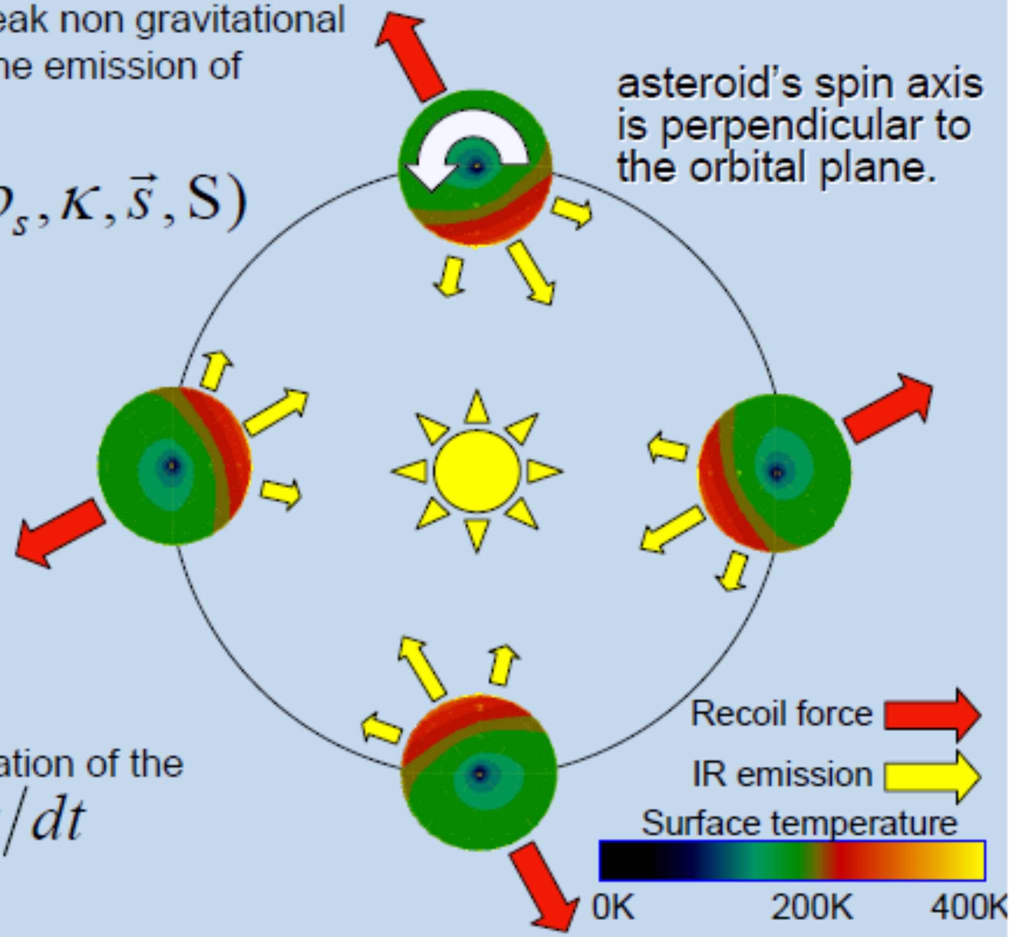
$$f \equiv f(D, A, \varepsilon, \rho_b, \rho_s, \kappa, \vec{s}, \mathrm{S})$$

f recoil force
D diameter
A *albedo*
ε emissivity
κ thermal conductivity
ρ_b bulk density
ρ_s surface density
$\vec{s}$ spin vector
S shape

Vokrouhlicky, 1998.

The recoil force f causes a variation of the semimajor axis of the orbit da/dt

Bottke et al., 2002, 2006



Near Earth Asteroids

Lifetimes of 10^6 - 10^7 years: most of them end in a Sun-grazing orbit or are ejected from the Solar System, while ~ 10 - 15 % of them collide with a terrestrial planet (Bottke et al. 2000).

Population replenished via orbital resonances.

A “seriousness scale”:

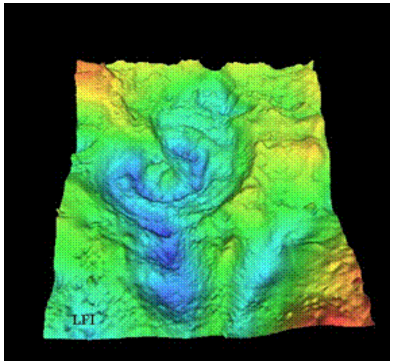
1. Complete disintegration in the upper atmosphere (most common case, no risk).

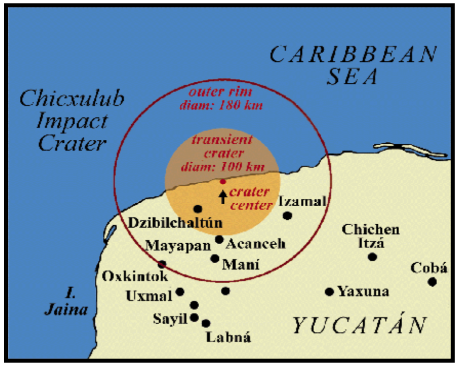
2. Disintegration in low atmosphere: local effects due to the explosion.

3. Global effects: degradation of the environment all over the planet.

4. Planetary catastrophe: strong climate change, mass extinctions.

K-T event, ~ 65 million years ago (10 km, 10^8 megaton)

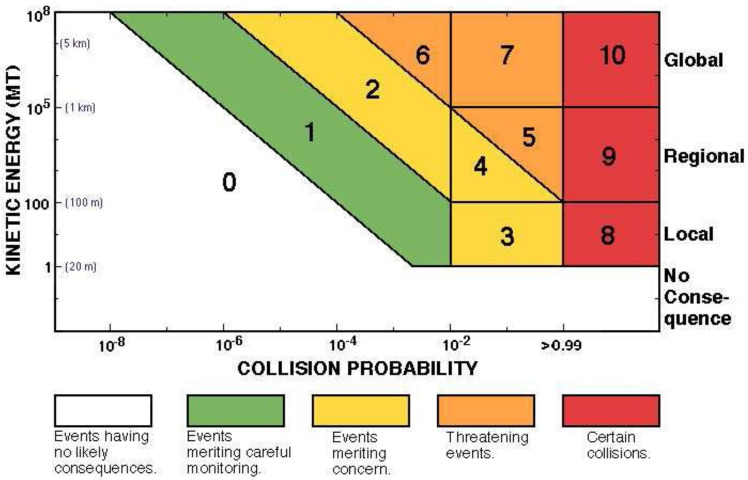




Impact energy measured in “megaton”, i.e. the amount of energy released in the detonation of one million tons. Hiroshima bomb releases 13 kiloton and modern nuclear weapons release tens of megaton

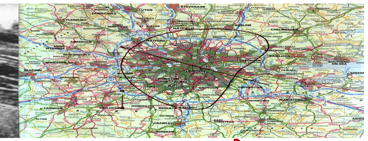
Near Earth Asteroids: risks

The Torino Scale



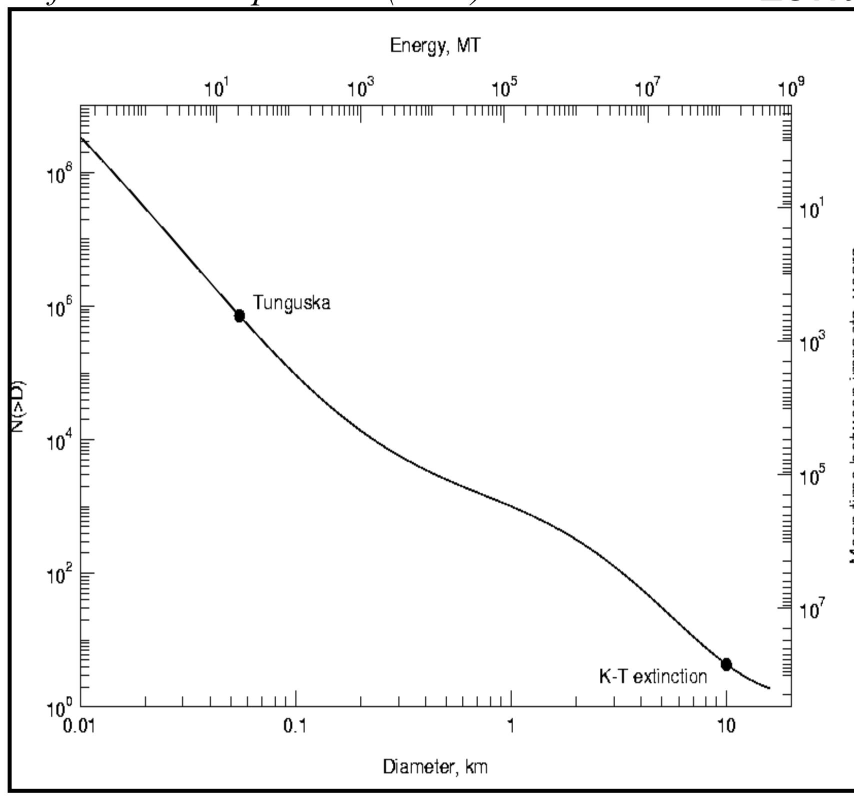
No Hazard	0	The likelihood of collision is zero, or is so low as to be effectively zero. Also applies to small objects such as meteors and bolides that burn up in the atmosphere as well as infrequent meteorite falls that rarely cause damage.
Normal	1	A routine discovery in which a pass near the Earth is predicted that poses no unusual level of danger. Current calculations show the chance of collision is extremely unlikely with no cause for public attention or public concern. New telescopic observations very likely will lead to re-assignment to Level 0.
Meriting Attention by Astronomers	2	A discovery, which may become routine with expanded searches, of an object making a somewhat close but not highly unusual pass near the Earth. While meriting attention by astronomers, there is no cause for public attention or public concern as an actual collision is very unlikely. New telescopic observations very likely will lead to re-assignment to Level 0.
	3	A close encounter, meriting attention by astronomers. Current calculations give a 1% or greater chance of collision capable of localized destruction. Most likely, new telescopic observations will lead to re-assignment to Level 0. Attention by the public and by public officials is merited if the encounter is less than a decade away.
	4	A close encounter, meriting attention by astronomers. Current calculations give a 1% or greater chance of collision capable of regional devastation. Most likely, new telescopic observations will lead to re-assignment to Level 0. Attention by the public and by public officials is merited if the encounter is less than a decade away.
Threatening	5	A close encounter posing a serious, but still uncertain threat of regional devastation. Critical attention by astronomers is needed to determine conclusively whether or not a collision will occur. If the encounter is less than a decade away, governmental contingency planning may be warranted.
	6	A close encounter by a large object posing a serious, but still uncertain threat of a global catastrophe. Critical attention by astronomers is needed to determine conclusively whether or not a collision will occur. If the encounter is less than three decades away, governmental contingency planning may be warranted.
	7	A very close encounter by a large object, which if occurring this century, poses an unprecedented but still uncertain threat of a global catastrophe. For such a threat in this century, international contingency planning is warranted, especially to determine urgently and conclusively whether or not a collision will occur.
Certain Collisions	8	A collision is certain, capable of causing localized destruction for an impact over land or possibly a tsunami if close offshore. Such events occur on average between once per 50 years and once per several 1000 years.
	9	A collision is certain, capable of causing unprecedented regional devastation for a land impact or the threat of a major tsunami for an ocean impact. Such events occur on average between once per 10,000 years and once per 100,000 years.
	10	A collision is certain, capable of causing a global climatic catastrophe that may threaten the future of civilization as we know it, whether impacting land or ocean. Such events occur on average once per 100,000 years, or less often.

Second level: Tunguska, 1908 (50 m, 12 megaton)



Photos from Kulik expedition (1927).

· **London**

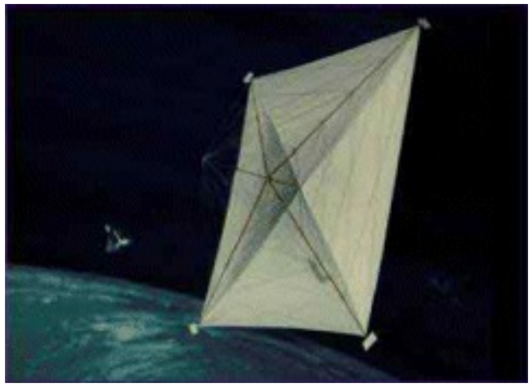


Event frequency:

- 20 kiloton (all released in the atmosphere): ~ 1 year
- 10 megaton: ~ 10^2 years
- 10^5-10^6 megaton: ~ 10^6 years

Near Earth Asteroids: mitigation strategies

Two approaches: *deflection* or *fragmentation*



http://spaceguard.rm.iasf.cnr.it/tumblingstone/issues/num9/dabramo.htm

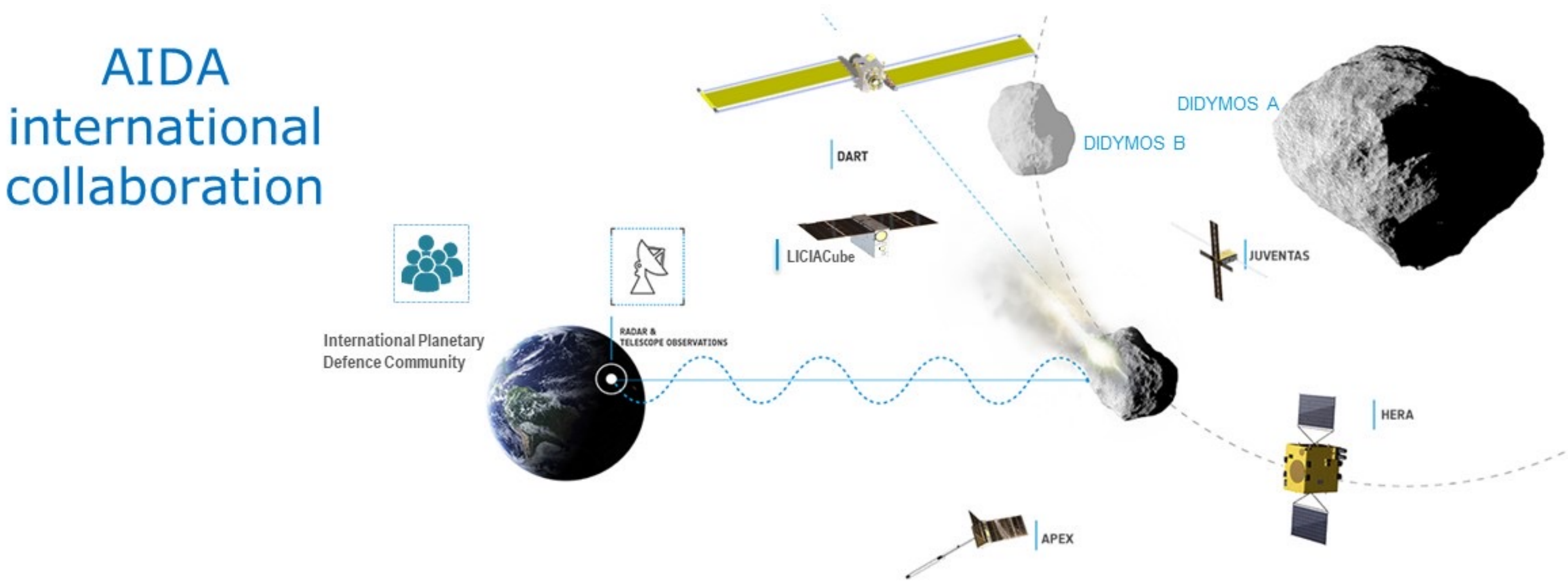
Warning: the fragmentation procedure appears to be risky and in some cases even impossible for at least two reasons:

- huge amounts of nuclear explosive have to be put in orbit

- it is very difficult to predict the right amount of energy required, we cannot exclude that the asteroid's fragments falls on the Earth anyway

Example: Asteroid Impact and Deflection Assessment

Contribution to AIDA initiative



AIDA

Synergy from

DART
First demonstration of asteroid deflection by kinetic impact on Didymos B, to change its orbit

with

LICIACube
First prompt imaging of the impacted surface, ejecta plume evolution and of the non-impacted hemisphere of Didymos B

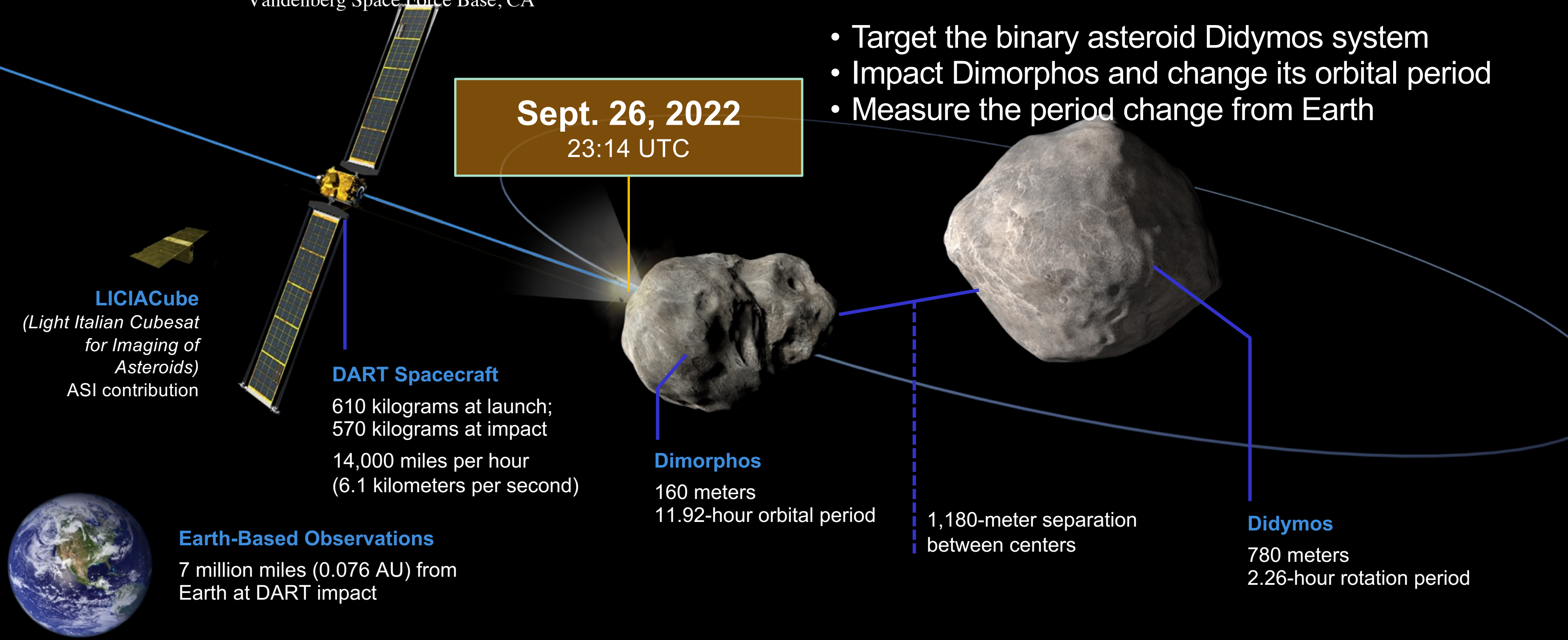
+

Hera
Mass of Didymos B
Detailed dynamical characterization, investigation of final crater, overall characterization of the asteroids

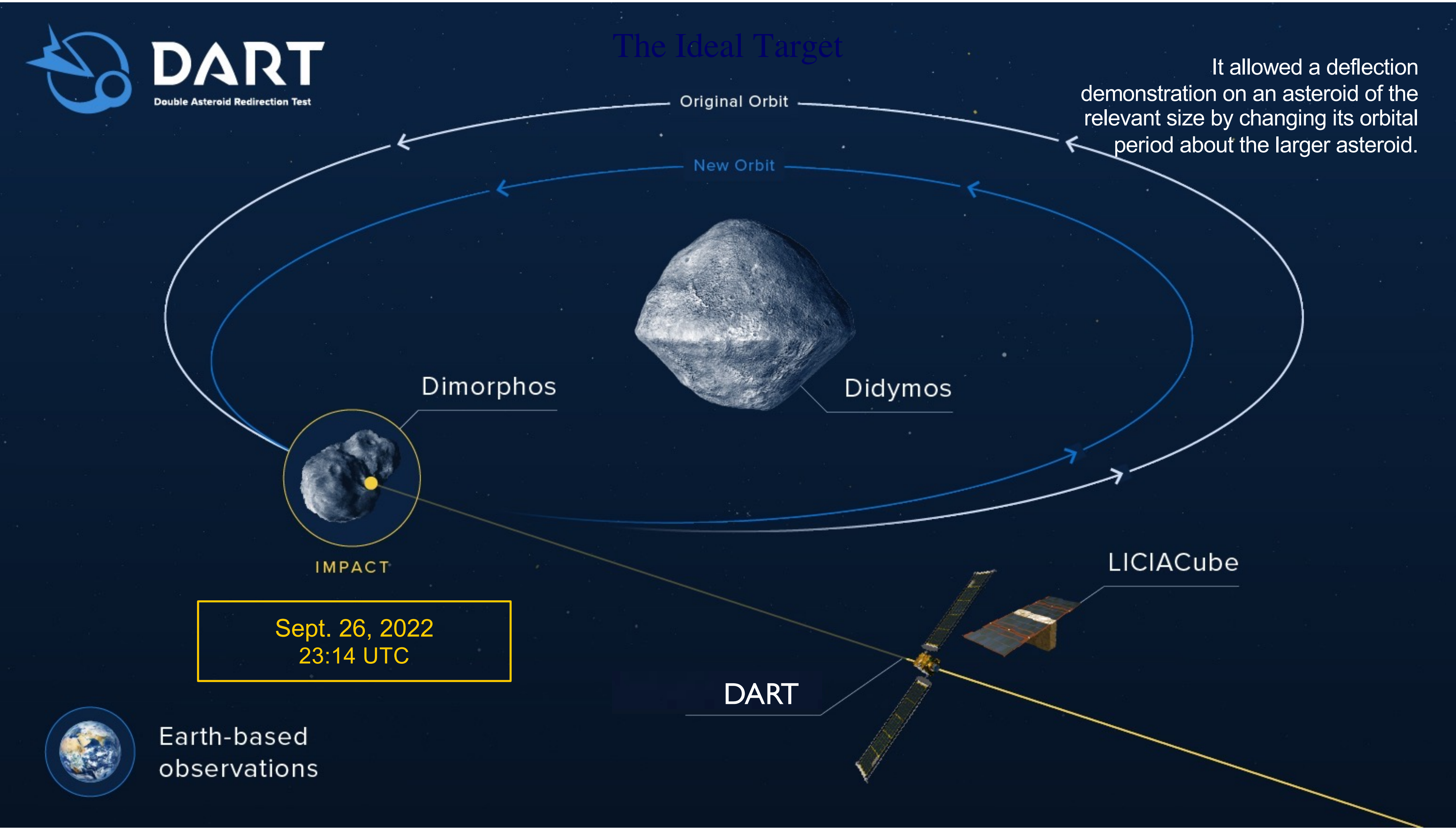
DART
Double Asteroid Redirection Test

NASA's first test mission for planetary defense

- Target the binary asteroid Didymos system
- Impact Dimorphos and change its orbital period
- Measure the period change from Earth

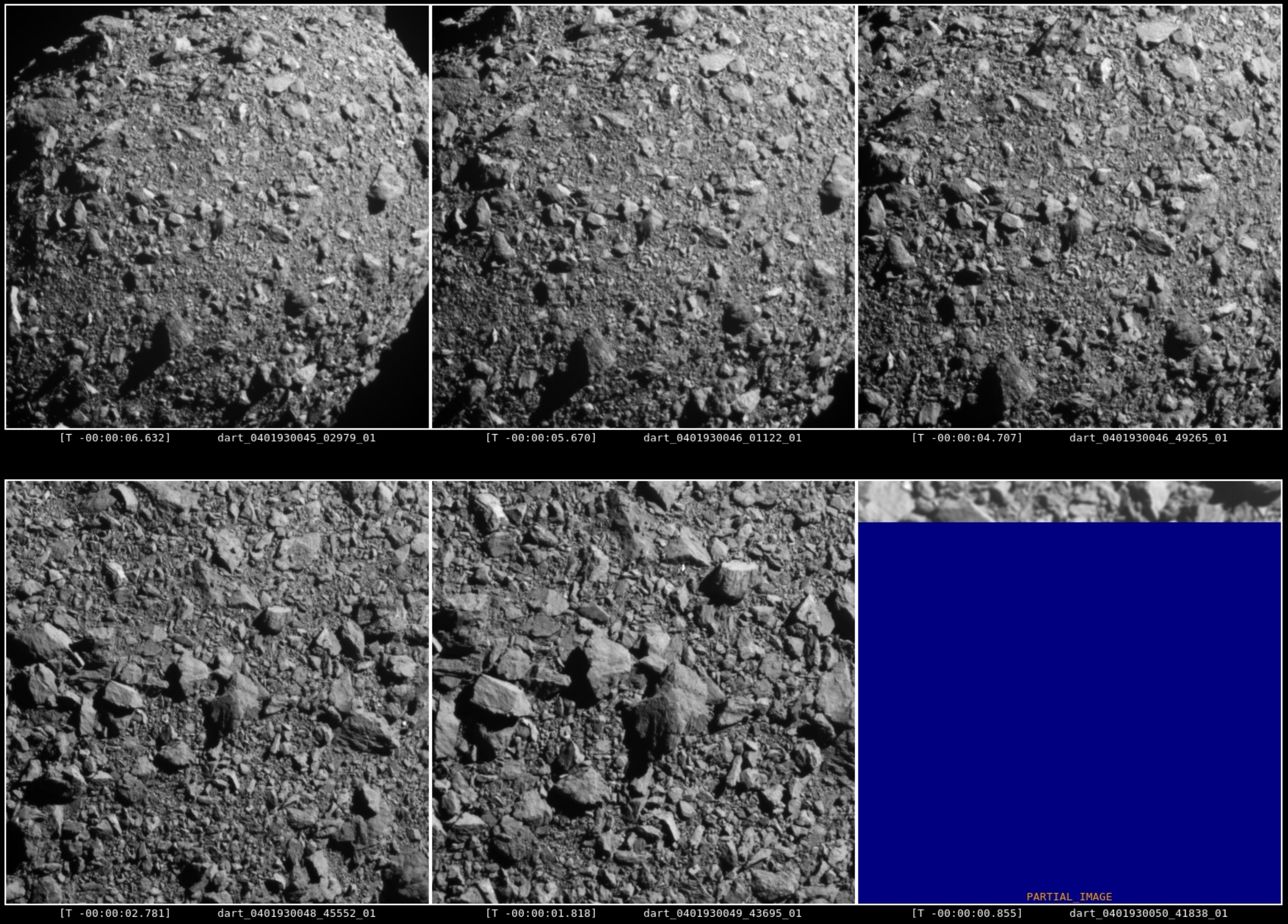


24 May 2023

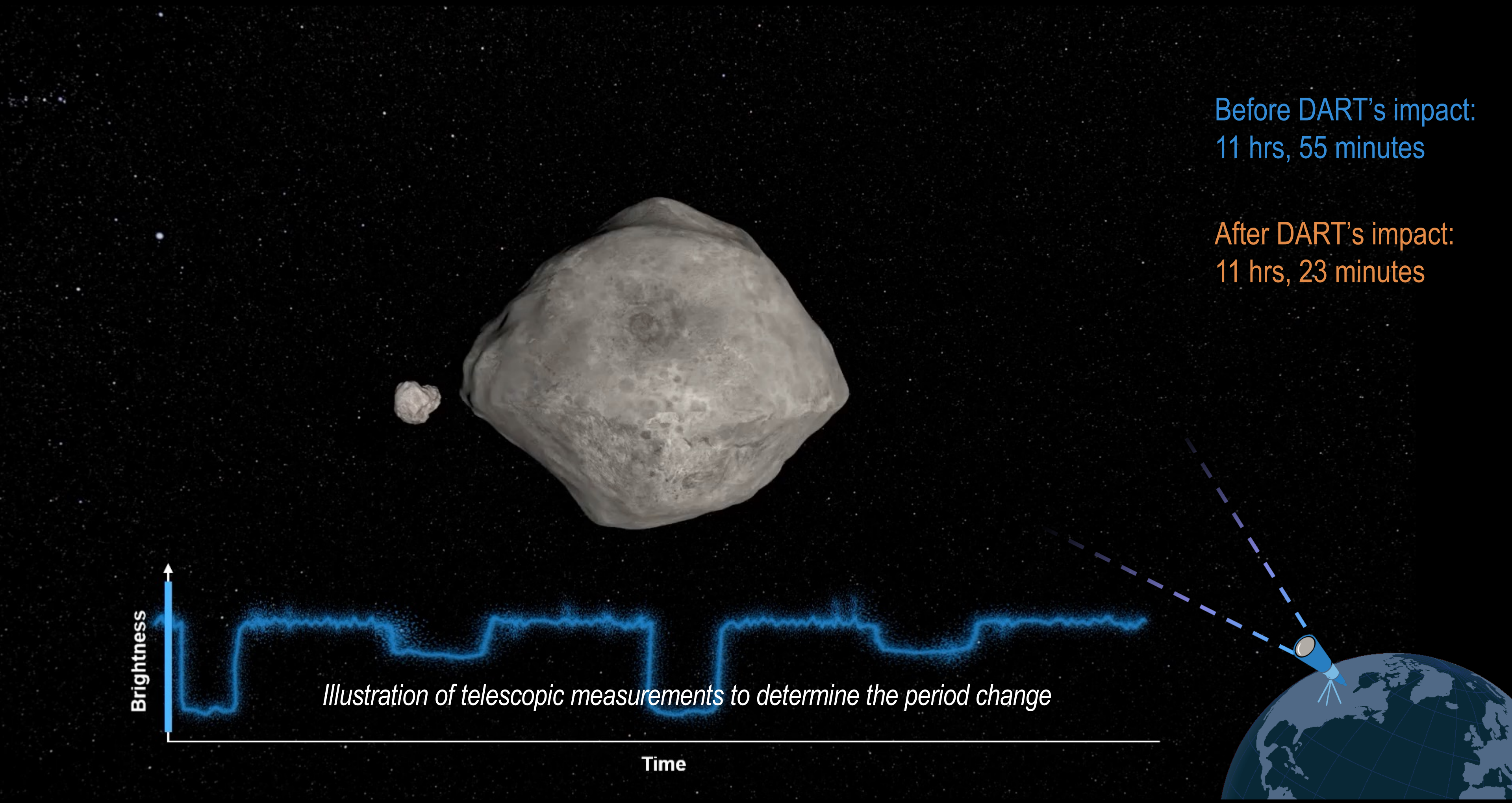


The Ideal Target
DART
Double Asteroid Redirection Test
It allowed a deflection demonstration on an asteroid of the relevant size by changing its orbital period about the larger asteroid.
Original Orbit
New Orbit
Dimorphos
Didymos
IMPACT
Sept. 26, 2022
23:14 UTC
LICIACube
DART
Earth-based observations

DART DRACO
Final images



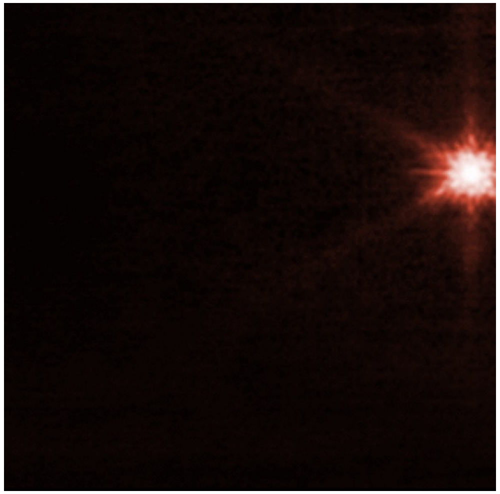
Credit: NASA/Johns Hopkins APL


Before DART's impact:
11 hrs, 55 minutes
After DART's impact:
11 hrs, 23 minutes
Brightness
Illustration of telescopic measurements to determine the period change
Time

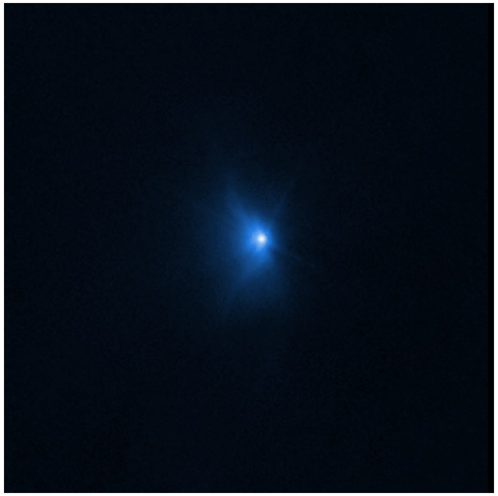
24 May 2023

LICIACube

Synergy with JWST and HST observations



Credits: James Web Space Telescope



Credits: Hubble Space Telescope

September 26, 2022

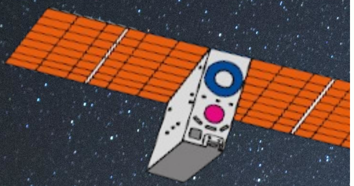
Las Cumbres Observatory 1 m telescope in South Africa

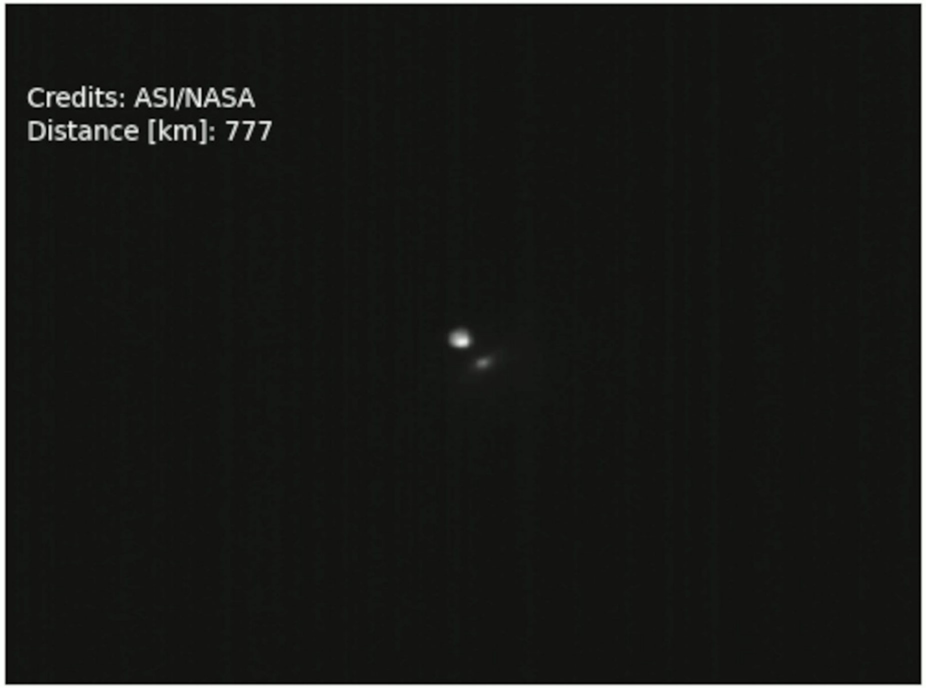
4 minutes pre-impact to 37 minutes post-impact

Credit: Tim Lister, Joseph Chatelain, Rachel Street, Edward Gomez, Joseph Farah / Las Cumbres Observatory.

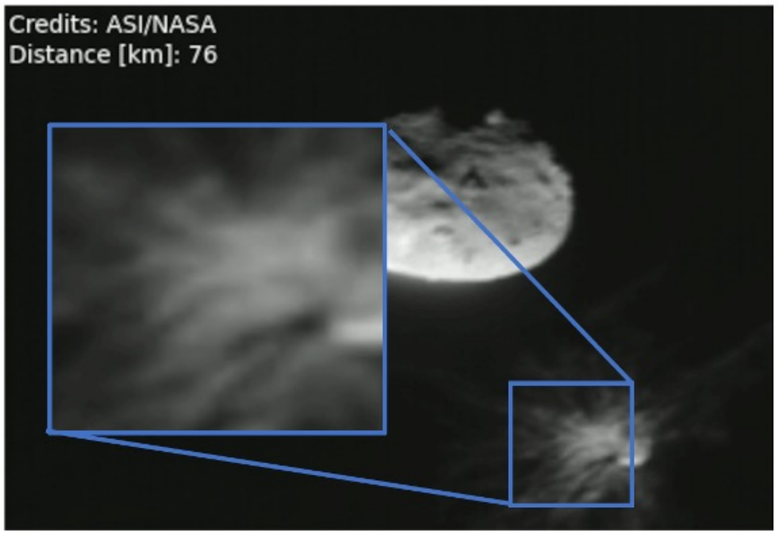
24 May 2023

Post-impact

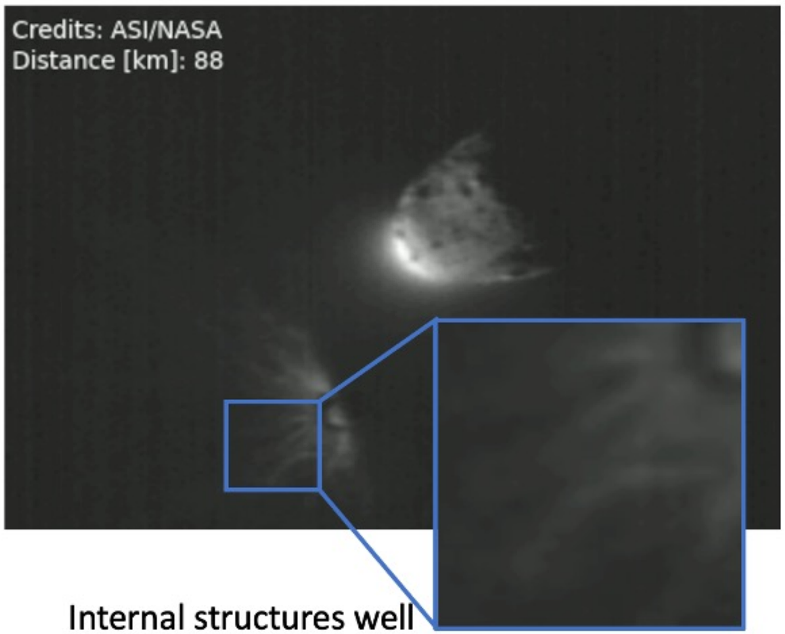




Post-impact



Non –homogenous dust distribution and local collimated structures



Internal structures well defined even in very close vicinity of Dimorphos

stavro.ivanovski@inaf.it

Meteorites

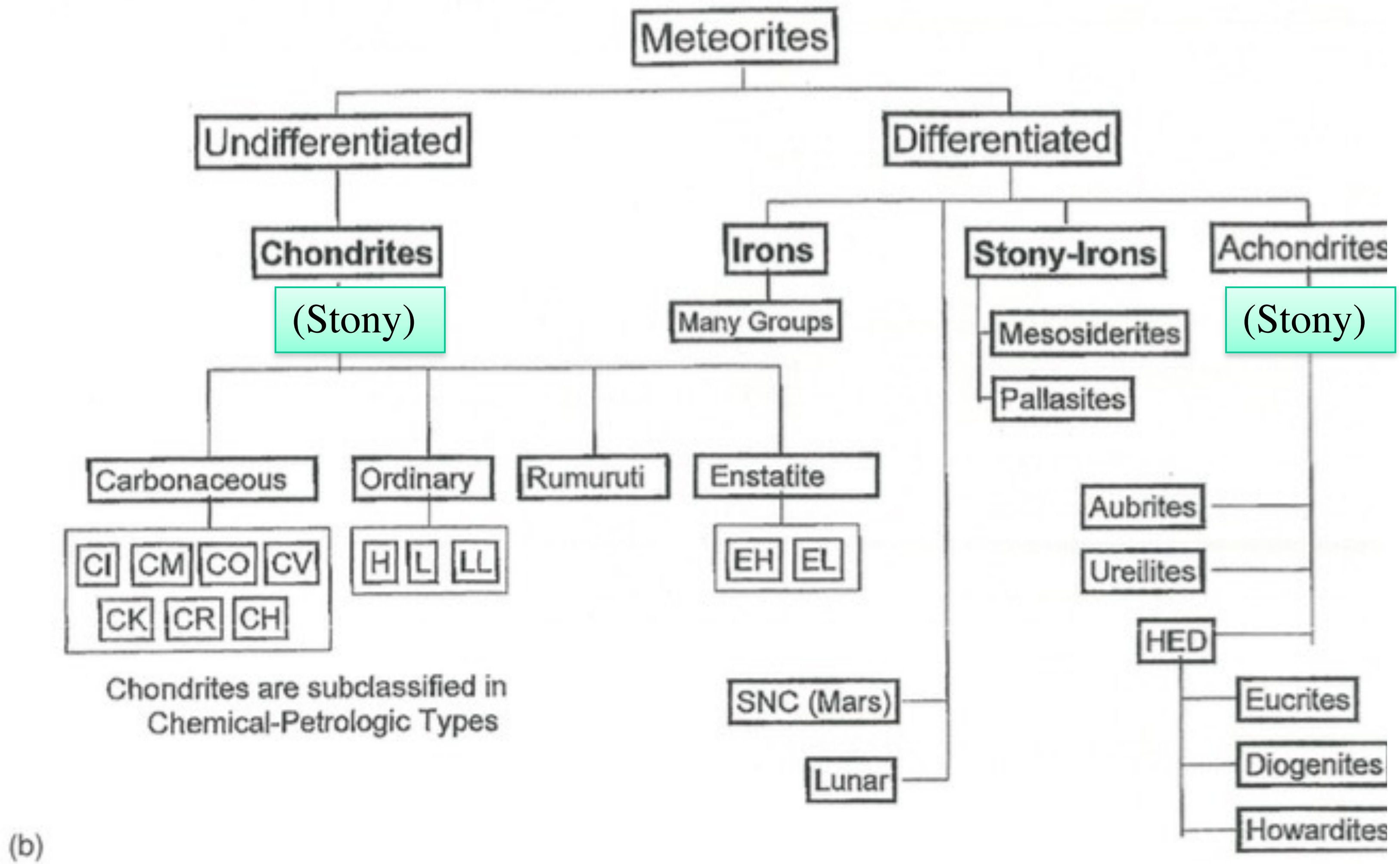
- Most meteorites are fragments of asteroids
  - A few are fragments of Mars or Moon's surface
- Meteorites provide a unique information on the first stages of the formation of the Solar System
  - Dating, primordial chemical composition, material from which planets accreted, planetary formation mechanisms and time scales, chemical differentiation processes, …
- Meteorites are classified according to their chemical composition and structure
  - Meteoritic classes are associated with asteroid types
  - The classification of meteorites is quite complex, featuring many subdivisions

Classification of meteorites

Different types of classification exist

One traditional subdivision is between condrites and non-condrites

Alternatively, between stony and "irons"



Chondrites

- Chondrites are believed to be the most pristine material of the Solar System, originated from undifferentiated bodies
- They are composed of a *matrix* that features a large number of *inclusions*
- The matrix consists of a fine-grained (micrometre-sized or smaller) dust
  - It is an optically opaque mixture of mineral grains
  - Represents the least processed material
- The main types of inclusions are:
  - Chondrules
    - Grain-shaped structures mostly composed of silicates
    - Believed to be produced in very short and intense heating episodes
  - CAI
    - Calcium-Aluminum inclusions, highly refractory, probably the oldest material found in the Solar System
    - Metal FeNi, troilite (FeS), olivine compounds

Examples of chondrites

- Ordinary chondrite
  - LL3

The matrix represents a small part of the structure of chondrites

The structure is dominated by the inclusions

- Carbonaceous chondrite with CAI
  - CV3

In carbonaceous chondrites the inclusions are less evident

Carbonaceous chondrites CI

- Very rare meteorites
- Important because very pristine and rich of organic material
- Of astrobiological interest

The Allende meteorite is an example of carbonaceous condrite

- They do not show inclusions
  - Inclusions are believed to have been deleted by aqueous alterations that took place in the asteroidal body
  - The lack of inclusions suggests that in the past, the parent asteroids must have experienced cometary-like activity

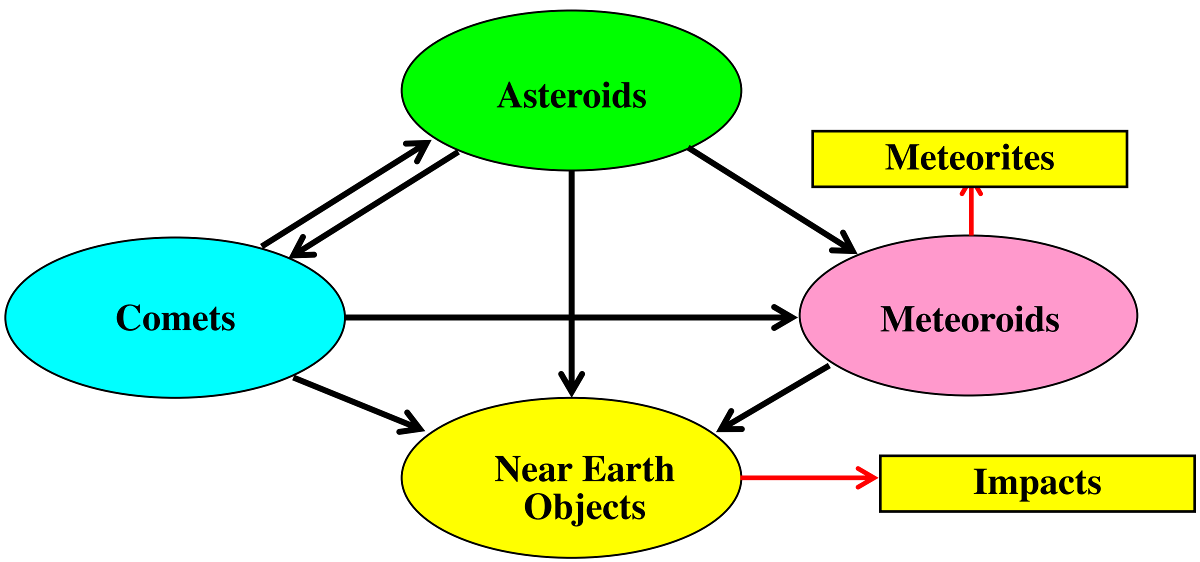
Chondritic meteorites are 4.56 x 10^9 years old

Carbonaceous chondrites as transporters of water

The discovery of Main Belt Comets demonstrate that ice exists and may be quite common in the Main Belt, and supports the theory that outer main belt could be a likely source of terrestrial water.

The source of the water on Earth can be traced through isotopes abundances: D/H ratio in the oceans (~ 156 ppm) is very close to the mean value of the D/H ratio of the water inclusions in carbonaceous chondrites (which are believed to come from the outer asteroid belt), and half that measured in comets (e.g., Morbidelli et al. 2000, M&PS 35,1309).

Hartogh et al. 2011, Nature 478, 218:"Ocean-like water in the Jupiter-family comet 103P/Hartley 2" D/H ~ 161 ppm



Minor bodies of the Solar System

Non chondritic meteorites

– Characterized by material that has been processed
– They show evidence of melting and/or differentiation of primitive material, suggesting an origin in differentiated bodies
– They do not show inclusions: the inclusions have been probably metamorphosized
– Probably fragments of asteroids in advanced of final stages of formation
– In a very few cases, fragments of Mars and the Moon

Lodranite

Non condritic, primitive

Eucrite

Non condritic, differentiated acondritic

Alteration and processing of meteorites

The different characteristics of meteorites (and asteroids) are believed to be due to the type of processing (alteration) experienced during the stages of formation or at later epochs

Two important types of alterations are aqueous and thermal processing

Such types of alterations cast light on the evolution of the meteorites and their parent bodies

Evolutionary history of meteorites