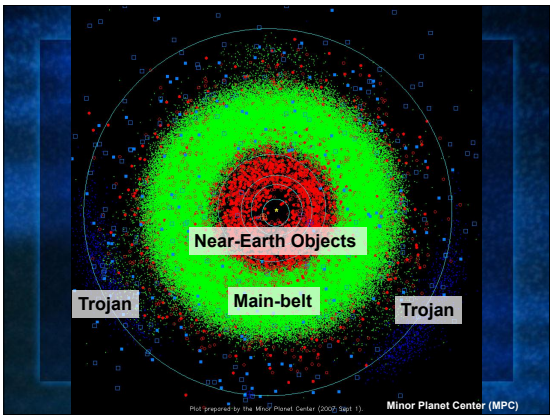
# Introduction to Asteroids

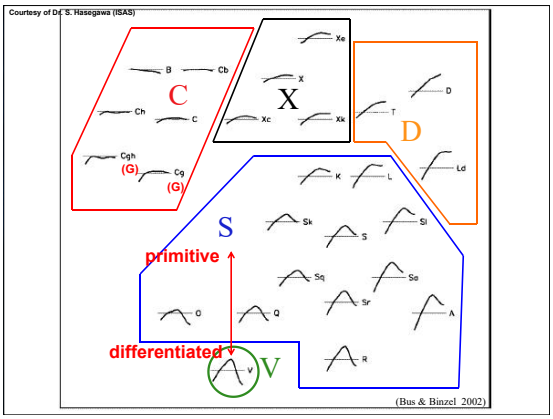
1. Classifications
2. History of Primordial Main-belt
3. Present State of Main-belt
4. Near-Earth Asteroids (NEOs)

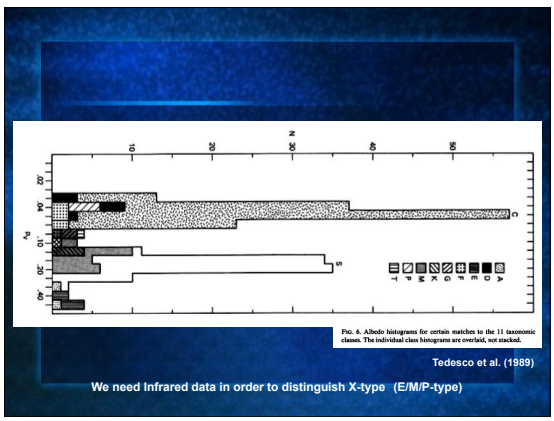
# 1. Classification




## Classification (I) Taxonomic Type

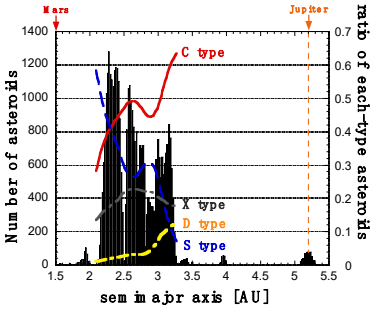
- Asteroids are categorized based on spectra (or color) and albedo, which may be related to the asteroid ' s surface composition.
- Originally, they classified only three type of asteroids:
  - C: Carbonaceous (~70% of known asteroids, extremely dark (albedo=0.03) )
  - S: Silicaceous (~20% of known asteroids, relatively bright (albedo=0.1-0.2))
  - M: Metallic (albedo=0.1-0.2)
- Nowadays, the following types are commonly used:
  - C-group (B, F, G, C-types) → Dark carbonaceous objects
  - S-type → Silicaceous (stony) objects
  - X-group (M, E, and P-types)→ M: Metallic, P: Dark objects
  - D-type → **Similar to comet nuclei**
  - Q-type → Ordinary-chondrite-like objects
  - V-type → (4) Vesta-like objects
  - A-type, T-type, R-type



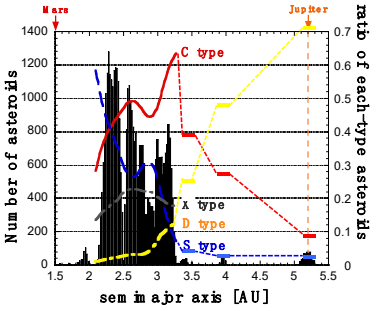




We need Infrared data in order to distinguish X-type (E/M/P-type)

Courtesy of Dr. S. Hasegawa (ISAS)

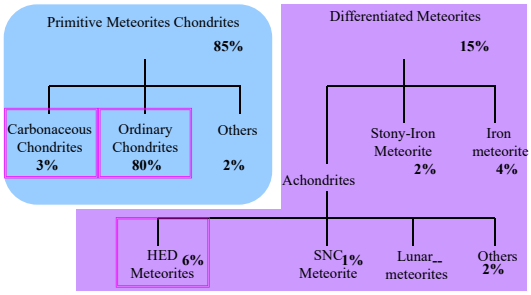



(Bus and Binzel 2002)




(Bus and Binzel 2002, Usui et al. 2011, Kasuga et al. in press)

## Meteorite Classification




Courtesy of S. Hasegawa (ISAS)


## 4 Vesta and HED meteorites

- The diameter of 4 Vesta is 530km, and the mass is ~9% of the total asteroids.
- HED meteorites consist of Diogenites, Eucrites and Howrdites, and these meteorites fall into the category of basalt ( 현무암), which is a kind of volcanic rock.
- Vesta is thought as the parent body of HED meteorites due to the similarity of the reflectance spectra.
- There are no chondrules in HED, which suggests that HEDs are the differentiated meteorites.
- Hubble Space Telescope image shows an impact crater near the south pole of Vesta. The diameter of this crater is 460km and the depth is 13km. The color measurements suggest the floor is olivine upper-mantle. About 1% of Vesta was excavated by the impact event, and the volume is sufficient to account for the Vesta family members. The authors argue that this crater is the site of origin for HED meteorites.

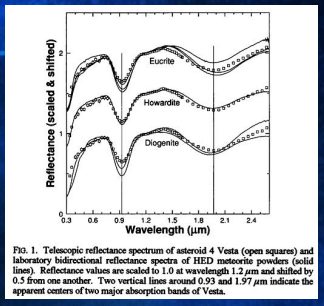
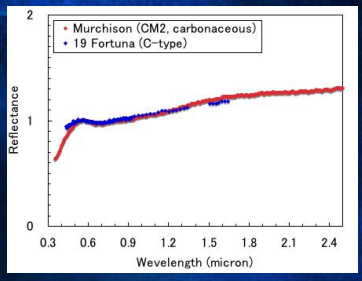



FIG. 1. Telescopic reflectance spectrum of asteroid 4 Vesta (open squares) and laboratory bidirectional reflectance spectra of HED meteorite powders (solid lines). Reflectance values are scaled to 1.0 at wavelength 1.2 $\mu$m and shifted by 0.5 from one another. Two vertical lines around 0.93 and 1.97 $\mu$m indicate the apparent centers of two major absorption bands of Vesta.

(Hiroi et al. 1994 )

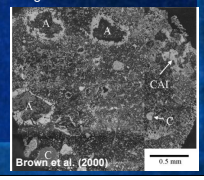
## C-type asteroid and carbonaceous chondrite



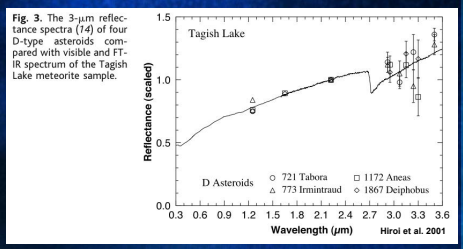

Original data from SMASS2 SMASSIR, Gaffy et al.

## D-type Asteroids and Tagish Lake Meteorite

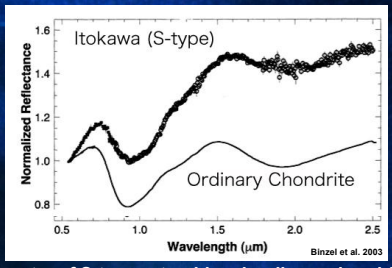
- D-type asteroids have a very low albedo and a featureless red spectrum. Both optical colors (spectra) and albedos of D-type asteroids are similar to those of the comet nuclei. Therefore, D-type asteroids are thought as the cometary nucleus.
- Tagish Lake meteorite landed on the lake's frozen surface. The trajectory was determined by the photographs of the fireball associated with the meteorite. It is found that the meteorite came from the outer region of the main-belt. Laboratory measurements show that it is a new type of primitive meteorite, even though it is similar to most primitive chondrites in some properties.
- The spectrum of the light reflected by the Tagish Lake sample was measured, and compared with those of telescopic spectrum of various asteroids, and found it shows good match with the D-type asteroids.




Brown et al. (2000)



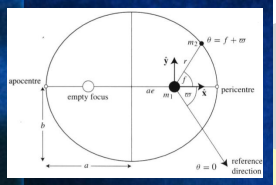

**Spectral similarity between Tagish Lake Meteorite and D-type Asteroids**

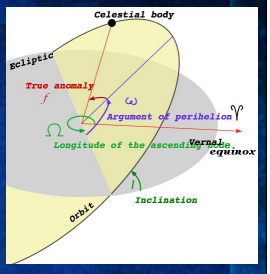



**Spectra of S-type asteroid and ordinary chondrite**

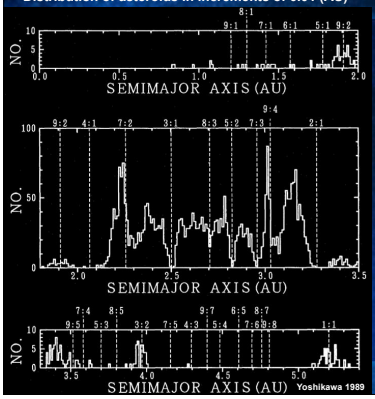
## Classification (II) Orbit groups

- Some asteroids have been placed into groups based on their orbital characteristics.
- An asteroid family is a group of minor planets that share similar semimajor axis, eccentricity and inclination. These groups are referred to as 'Family'. About 1/3-1/4 of asteroids in the main belt are members of family.
- The families are thought to form as a result of collisions between asteroids. Since the family members has the same origin, they have close taxonomic type unless the parent body was undifferentiated.
- Vesta family has variation in the taxonomic type because they were formed from a large differentiated bodies. The catastrophic collision, which generated the family, occurred >$10^7$ years ago.



**Distribution of asteroids in increments of 0.01 (AU)**

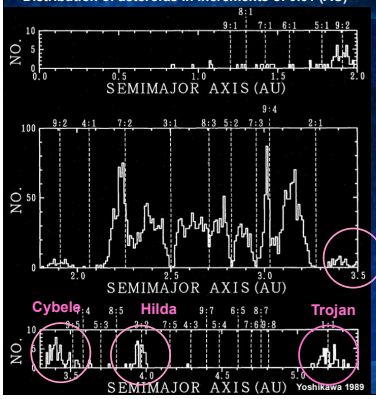



**Inner Main Belt**

This histogram clearly shows gaps (Kirkwood gaps) in the asteroid main-belt. These gaps (labeled "3:1", "5:2", "7:3") are caused by mean-motion resonances between an asteroid and Jupiter. For example, the 3:1 Kirkwood gap is located where the ratio of an asteroid's orbital period to that of Jupiter is 3:1, which means the asteroid completes 3 orbits for every 1 orbit of Jupiter.

From the dynamical studies, it is known that the effect of the resonances change the asteroid's orbital elements (inclination and eccentricity) significantly.

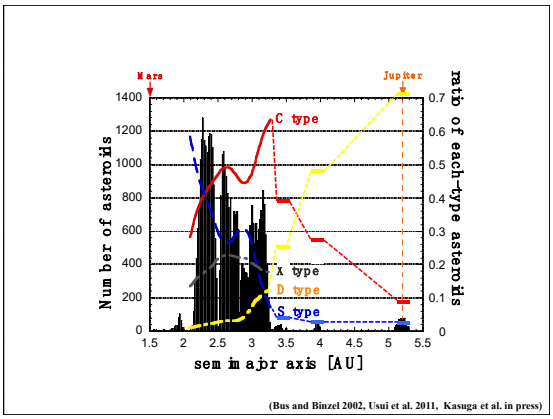
**Distribution of asteroids in increments of 0.01 (AU)**



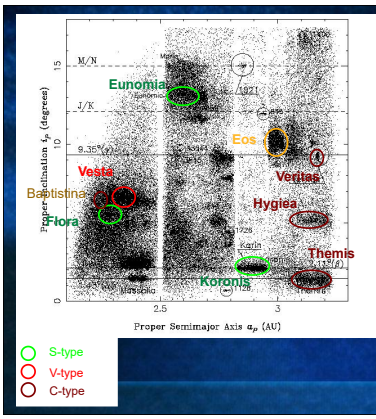

**Outer Main Belt**

Hilda asteroids have a mean orbital radius between 3.7 AU and 4.2 AU. The asteroids are in a 3:2 resonance with Jupiter. 34% are D-type, 28% P-type (Dahlgren et al. 1997).

Trojan asteroids have a mean orbital radius between 5.0 AU and 5.4 AU, and lie in elongated, curved regions around the two Lagrangian points 60° ahead and behind of Jupiter. Most of Trojan asteroids is D-type asteroids, and only a few belong to the P-type (chapter by Barucci et al.).




(Bus and Binzel 2002, Usui et al. 2011, Kasuga et al. in press)




| Family | Taxonomic type |
|---|---|
| Themis | C |
| Koronis | S |
| Eos | K |
| Flora | S |
| Vesta | V |
| Eunomia | S |
| Hygiea | C |
| Veritas | C (P, D) |

## 2. History of the Primordial Asteroid Belt

1. Formation of Main-Belt Asteroids
2. Dynamical Excitation of the Primordial Main Belt

## 2.1 Formation of Main-Belt Asteroids (1)

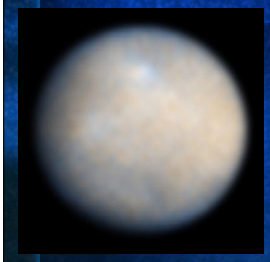
- The process by which the main belt took on its current attributes are believed to linked to planet formation.
- The sequence of planet formation in the inner solar system can be divided into four stages:

1. The accumulation of dust in the solar nebula into kilometer-sized planetesimals
2. Runaway growth of the largest planetesimals via gravitational accretion into numerous protoplanets isolated in their feeding zones
3. Oligarchic growth of protoplanets fed by planetesimals residing between their feeding zones
4. Mutual perturbations between Moon-to-Mars-sized planetary embryos and Jupiter, causing collisions, mergers, and the dynamical excitation of small-body population not yet accreted by the embryos.

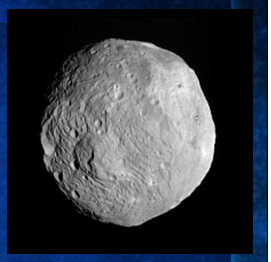
(Safronov, 1969; Weidenschilling, 2000)

## Formation of Main-belt

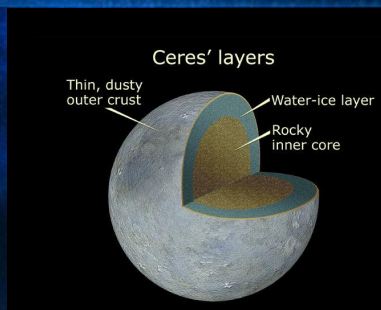
1. **Accumulation of dust particles into km-sized planetesimals: While short-lived isotopes were incorporated, asteroids grew up into planetesimals from inside to outside.**
2. **The theory is consistent with the fact that there are differentiated big asteroid at 2.4 AU (Vesta) while primitive asteroid at 2.8 AU (Ceres).**



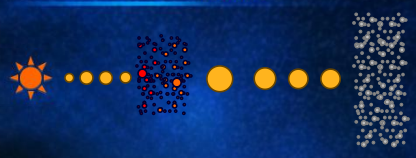
1 Ceres at 2.77 AU
(D~900 km)



4 Vesta at 2.36 AU
(D~530 km)



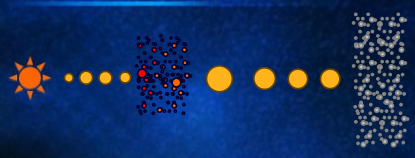

## Dynamical Excitation of Main-belt



1. Large mass depletion: Model results suggest the primordial main belt contained 2–10 $M_{\oplus}$ of material. The current main belt, however, is depleted of mass, such that it only contains $5 \times 10^{-4}$ $M_{\oplus}$ of material.

1. Strong dynamical excitation. Initially, the eccentricities and inclinations of asteroids within the primordial main belt were low enough that accretion could occur. The median $e$ and $i$ values of asteroids in the current main belt, however, are high enough that collisions produce fragmentation rather than accretion.

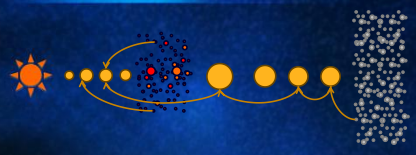
## Dynamical Excitation of Main-belt



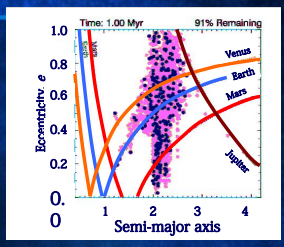
1. Radial mixing of asteroid types. Asteroid thermal models suggest that the outer main belt should contain more "primitive" objects than the more heated/processed inner belt. This trend is roughly reproduced in the current orbital distribution of the taxonomic classes, with S-type asteroids dominating the inner belt, C-type asteroids dominating the central belt, and D-/P-type asteroids dominating the outer main belt.

2. The boundaries between these main taxonomic types, however, are not sharp; some C and D asteroids can be found in the inner main belt, while some S-type asteroids can be found in the outer main belt.

## Current Main-belt



1. Migration into inner orbits :
2. From TNO to Centaur, Jupiter-family comets :




Large fraction of Near-Earth asteroids have been delivered through the dynamical interaction with gas giants (particularly Jupiter)

Courtesy of Bill Botkke

## Chronology

- Meteorites provide the clock for timing planetesimal formation.
- According to the high-resolution chronological studies by short-lived radio-nuclides (e.g., $^{26}$Al decaying to $^{26}$Mg) ,
  1. the calcium-aluminum-rich inclusions (CAIs), considered the first condensates of matter in the solar system, have an estimated formation age of ~4571 m.y.
  2. Some 2 m.y. after the formation of the CAIs, asteroids with diameters D > 10 km had formed in the asteroid belt.
- Objects that had accreted significant amounts of $^{26}$Al were heated as $^{26}$Al decayed into $^{26}$Mg.
- In some cases, the heat budget on these asteroids was high enough to produce aqueous alteration, or even differentiation.

## Chronology of the Universe

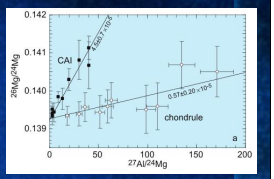
우주의 연표 (연대기)

| | |
|---|---|
| 13.7 Gyr | Big bang; formation of the elements H and He |
| 13.4 Gyr | First stars and galaxies; first supernova explosions produce the heavy elements (C,N,O,Si,Fe,…) |
| 12 Gyr | Formation of the milky way |
| 4.567 Gyr | Formation of the solar system; at this point in time the interstellar medium has been enriched with 1% heavy elements |
| 4.5 Gyr | Formation of the earth and the moon |
| 4.45 Gyr | Layer structure of the earth |
| 4.4 Gyr | Solid earth crust |
| 4.2 Gyr | Early ocean |
| 4 Gyr | Plate tectonics |
| >3.5 Gyr | Earth's magnetic field |
| >3.5 Gyr | Origin of life |
| 2.3 Gyr | Formation of oxygen-rich atmosphere; formation of ozone |
| 0 Gyr | Today |

## Short-lived isotope

$^{27}$Al (stable) — $^{24}$Mg (stable), $^{25}$Mg (stable)
$^{26}$Al (unstable) → $^{26}$Mg (stable)
$T_{1/2}$=0.72m.y.

$^{40}$Ca (stable) — $^{39}$K (stable)
$^{41}$Ca (unstable) → $^{41}$K (stable)
….
$T_{1/2}$=0.1m.y.

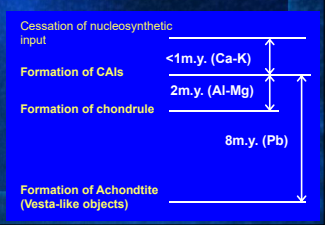



The evidence of $^{26}$Al is found in both CAIs and the chondrules as enhancements of $^{26}$Mg, we can deduce the time interval between the formations of CAIs and the chondrules.

On the other hands, $^{41}$Ca is found in CAIs but not in the chondrite. This constrains the time interval between the cessation of nucleosythetic input to the solar nebula and the formation of CAIs to <1m.y.

## 2.1 Formation of Main-Belt Asteroids (3)

- Assuming that Vesta is the ultimate source of the HED meteorites, a considerable amount of information can be inferred about Vesta ' s history. For example, it is considered that differentiation ended on Vesta by ~4565 m.y., 6~8 m.y. after the formation of the CAIs.



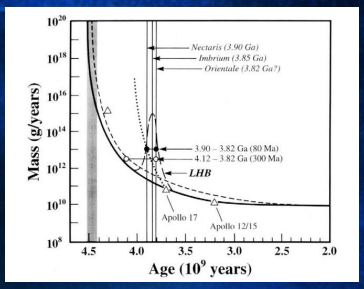
## 3. Present state of the main belt

- The evolution of the primordial main belt occurred over a relatively short time span (on the order of ~100 m. y. or less).
- Once this dramatic epoch ended, however, the evolution of the remaining population occurred more slowly.
- The Late Heavy Bombardment (LHB) refers to an events ~3.9G.y. ago where the inner solar system was ravaged by numerous impactors.


Lunar mare (달의 바다)

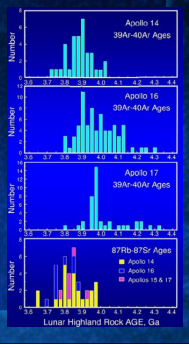
Lunar highland

## Evidence for LHB (1)




C. KOEBERL 2003

## Evidence for LHB (2)

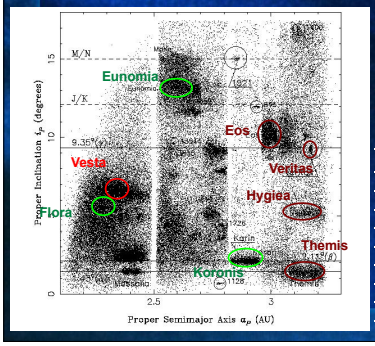



Kring (2005)

## 3-1. Asteroids: Impact collision

- After the dispersion of gas component, collisions are the principle geologic process occurring on asteroids today.
- Mutual collisions between asteroids have ground down earlier populations, processing their members into smaller and smaller fragments.
- The nature of the size distribution of the bombarding asteroid population is such that numbers increase strongly as size decreases.
- For this reason, asteroids are likely to experience numerous cratering events before eventually being disrupted by a more energetic impact.
- Existence of “asteroidal families” also suggest catastrophic collision occurred in the past.

## Asteroidal families




S-type
V-type
C-type

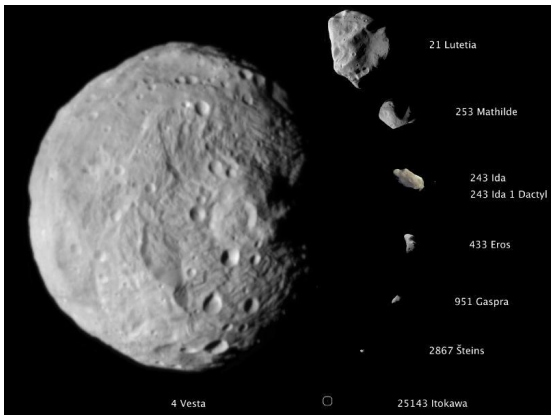
| Family | Taxonomic type |
|---|---|
| Themis | C |
| Koronis | S |
| Eos | K |
| Flora | S |
| Vesta | V |
| Eunomia | S |
| Hygiea | C |
| Veritas | C (P, D) |

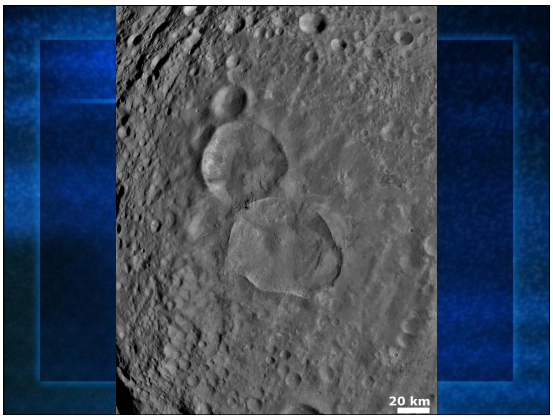
## Collisions among Asteroids (1)

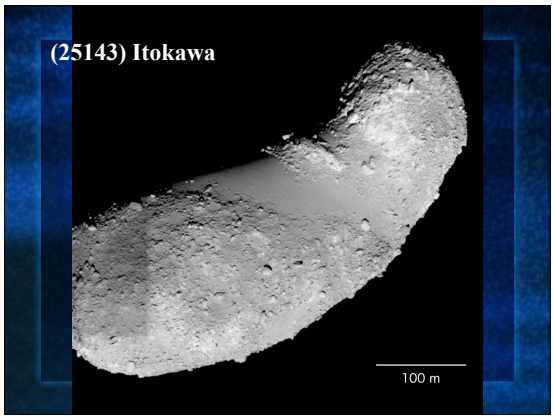
- Much of our knowledge about asteroidal impact was deduced from asteroidal families and laboratory impact experiments.
- We have made significant progress in the understanding of 'high-velocity impact' over the last decade. It is mainly obtained through the observations by spacecrafts.
- However, images of asteroid (e.g. Gaspra, Ida, Mathilde, Eros,…) were analyzed in the 1990's, and it became apparent that we were missing something important. For example, each of these bodies had sustained a collision energetic enough to produce a multi-kilometer crater (e.g. Mathilde). The only way to explain the existence of these large craters was that some unexplored aspects of impact physics were allowing these objects to escape catastrophic disruption.

## History of Asteroid Mission

| Name | Year | Spacecraft | Mission type | Taxonomy | Orbital group |
|---|---|---|---|---|---|
| **Gaspra** | 1991 | Galileo | Fly-by | S | Flora family |
| **Ida** | 1993 | Galileo | Fly-by | S | Koronis family |
| **Mathilde** | 1996 | NEAR-Shoemaker | Fly-by | C | Main-belt |
| (Braille) | 1999 | Deep Space 1 | Fly-by | Q | Mars-crossing |
| **Eros** | 2000 | NEAR-Shoemaker | Rendezvous +landing | S | Mars-crossing |
| (Annefrank) | 2002 | Stardust | Fly-by | S | Augusta family |
| **Itokawa** | 2005 | Hayabusa | Rendezvous +sampling | S | NEO |
| Lutetia | 2010 | Rosetta | Fly-by | M | |
| Vesta | 2011 | Dawn | Multi-rendezvous | V | Main-belt |



(951) Gaspra

©NASA

(243) Ida


Ida and its satellite Dactyl

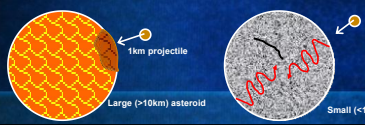
©NASA

(253) Mathilde

Enigma
1. Big craters
2. No ejecta bracket
3. Low density

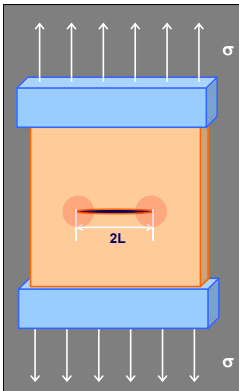
©NASA/JPL

- Impact processes vary according to the size and composition of asteroids.
- Imagine a body 10-km in diameter striking a rock-like ~1km-sized asteroid. Since weak material does not transport energy efficiently, much of the impact energy is deposited near the impact site . This behavior provides insight into why 10km-sized asteroids can have such enormous crater (Eros, Gaspra and Ida).
- A Collisions on monolithic asteroids produce compressive waves that easily reach the far side of the object. The reflected compressive wave turns into a tensile wave that can produce damage and spalls.




## Griffith Theory (supplement)

**Why do large cracks tend to propagate more easily than small ones?**




- Surface energy $U_s$:
The surface energy of the crack can be written in terms of $\gamma$. If the total crack length is $2L$, the surface energy for both sides of the crack is:

$$U_s = 4L\gamma$$

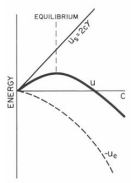
- Elastic strain energy $U_e$:
If the load is kept constant, the potential energy of the system is kept constant. Thus we need to consider changes in the stored elastic energy for the material energy term. From the solution by Inglis (1913), the mechanical energy can be represnted by:

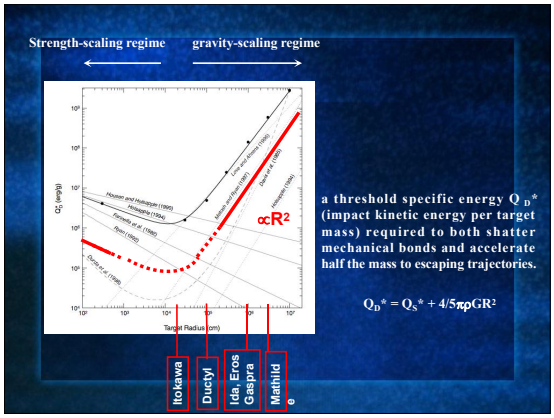
$$U_e = \frac{\pi L^2 \sigma^2}{E}$$

The total energy of the system is sum of the these energy terms, $U=-U_e+U_s$

$$\frac{dU}{dL} = \left( -\frac{\pi L^2 \sigma^2}{E} + 4L\gamma \right)' = 0$$

$$\sigma = \sqrt{\frac{2E\gamma}{\pi L}} \quad \propto L^{-\frac{1}{2}}$$




a threshold specific energy $Q_D^*$ (impact kinetic energy per target mass) required to both shatter mechanical bonds and accelerate half the mass to escaping trajectories.

$$Q_D^* = Q_S^* + 4/5\pi\rho GR^2$$

- Fractured or shattered asteroids (moderate RTS, low porosity) contain significant numbers of faults and joints that help to suppress the tensile wave, such that the object is more difficult to disrupt.

- Asteroids with rubble-pile structures or highly porous structures (low RTS, moderate to high porosity) absorb impact energy via compression, with little to no tensile wave developed in the structure. When impact energy is damped, craters may form by compaction.

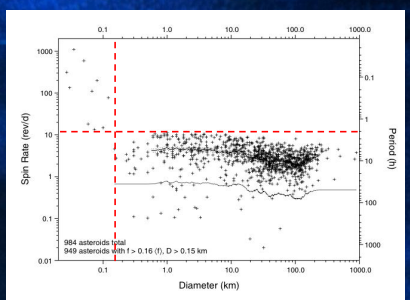
- Collisions on monolithic (high RTS, low porosity) produce compressive waves and tensile wave that can produce damage and spalls.

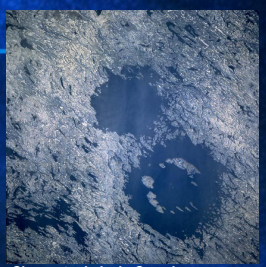

## Impact Strength

Davis et al. (1979) defined a threshold specific energy $Q_D^*$ (impact kinetic energy per target mass) required to both shatter mechanical bonds and accelerate half the mass to escaping trajectories . Davis et al. (1985) expressed impact strength:

$$Q_D^* = Q_S^* + 4/5\pi\rho GR^2$$

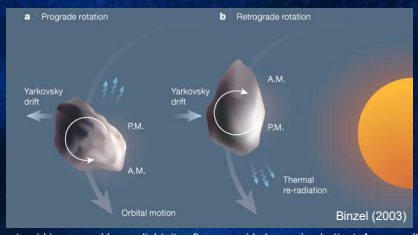
Shattering strength — Gravitational binding energy



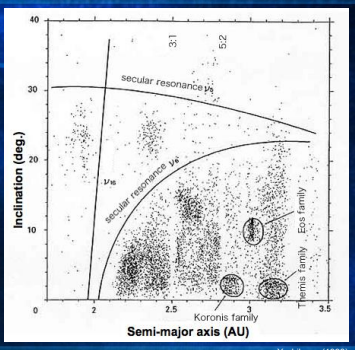
Clearwater Lake in Canada:
~15% of the largest craters on Earth are doublets (Bottke & Melosh 1996)

## Yarkovsky Effect




Binzel (2003)

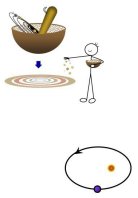
An asteroid is warmed by sunlight, its afternoon side becoming hottest. As a result, that face of the asteroid re-radiates most thermal radiation, creating a recoil force on the asteroid and causing it to drift a little. The direction of the radiation depends on whether the asteroid is rotating in a prograde (anticlockwise) manner (a) or in a retrograde (clockwise) manner (b).



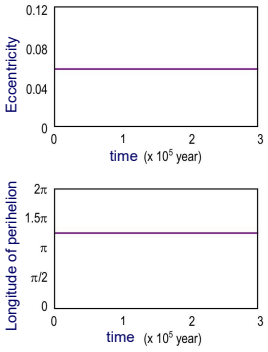

Yoshikawa (1998)

## Motion of Test Particle

Courtesy of M. Nagasawa

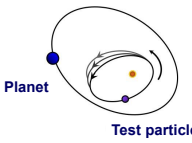


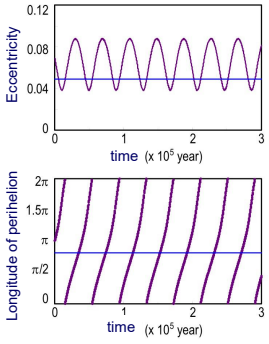
Orbit remains stationary




## Motion of Test Particle with a planet

Courtesy of M. Nagasawa

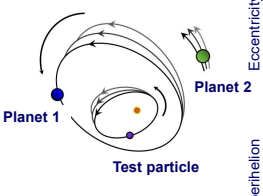


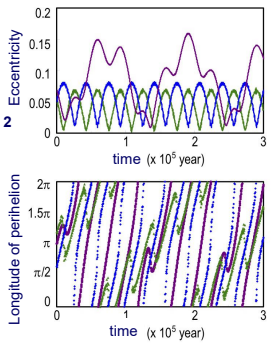

- ✓ Perihelion moves by planetary perturbation
- ✓ Period of '$e$' = Period of '$\omega$'

## Motion of Test Particle with two planets

Courtesy of M. Nagasawa



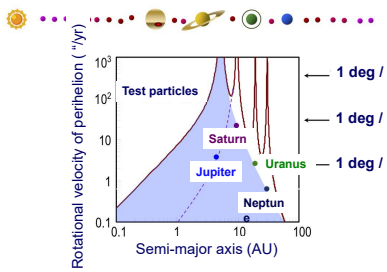

Perihelion of planet also moves




## Rotational velocity of perihelion

Courtesy of M. Nagasawa

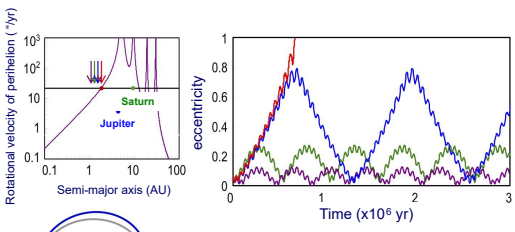
… depends on the mass and the distance of planets

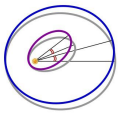



Rotates rapidly near planets. Largely influenced by Jupiter

Courtesy of M. Nagasawa

## What happens if the rotational velocity is equal to that of planet?



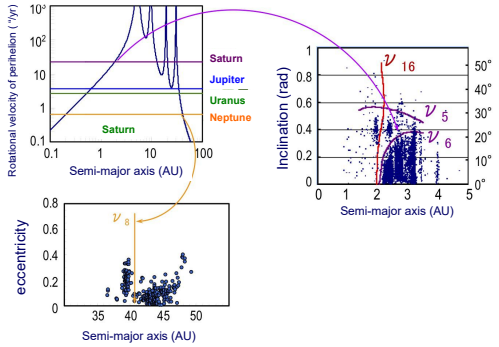



**Eccentricity keeps increasing over time**

**Secular resonance**

Courtesy of M. Nagasawa

## Secular resonance in the current solar system




## From Main-Belt to NEOs

- A scenario for how asteroids and meteoroids are delivered from their parent bodies in the main belt to the inner solar system is the following:

  (1) An asteroid undergoes a catastrophic disruption or cratering event and ejects numerous fragments; most are not directly injected into a resonance (because most ordinary chondrites have cosmic-ray-exposure ages between 10 m.y. and 100 m.y., which are longer than the average dynamical lifetime of NEOs).

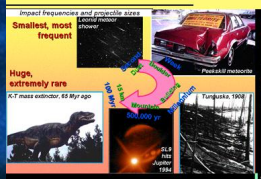
  (2) D < 20 km fragments start drifting in semimajor axis under the Yarkovsky effect.

  (3) These bodies jump over or become trapped in mean-motion and secular resonances that change their eccentricity and/or inclination.

  (4) These asteroids are pushed onto planet-crossing orbits. Finally, they become members of the Mars-crossing and/or NEO populations.

## Asteroid Impact Hazard

Southwest Research Institute




There is an enormous variety of projectiles from interplanetary space that impact the earth. Reading clockwise from the upper left, there are dust grains that create "shooting stars" all the time to the "dinosaur killers" that strike only about once every hundred million years.

| OBJECT DIAM. | IMPACT ENERGY | CHANCE PER 100 YR | CHARACTER OF DAMAGE |
|---|---|---|---|
| ~3 km | 1.5 mil. MT | 1 in 50,000 | Global climate disaster; most killed; civilization destroyed |
| ~1 km | 80,000 MT | 0.02% | Devastation of large region or an entire ocean rim |
| ~300 m | 2,000 MT | 0.2% | 5 km crater; huge tsunami or destruction of small nation |
| ~100 m | 80 MT | 1% | Exceeds greatest H bomb; 1 km crater; locally devastating |
| ~30 m | 2 MT | 40% | Stratospheric explosion; damage within tens of km |
| ~10 m | 100 kT | 6 per century | Broken windows, little serious damage on ground |
| ~3 m | 2 kT | 2 per year | Blinding flash, could be mistaken for atomic bomb |

The table shows the range of threatening impactors of practical concern, ranging from the "civilization destroyer" down to the "harmless" 2 kiloton atmospheric blast, which however could be mistaken for a nuclear attack in a place of international tension. SwRI researchers in Boulder are evaluating the impact hazard and what might be done about it.

www.boulder.swri.edu/~cchapman/ Chapman (2003)