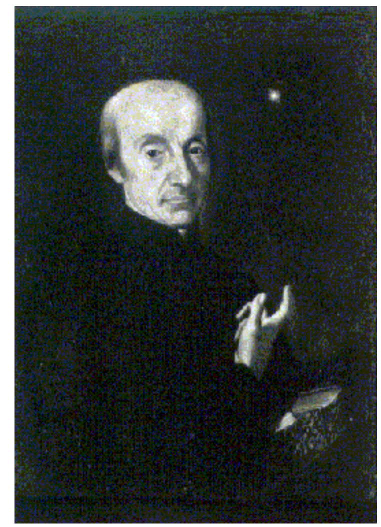
During the night of April 26, 1861, Giovanni Schiaparelli discovered a new asteroid, which was later named (69) Hesperia. This was his only one asteroid discovery.

A little story: the Titius-Bode "Law":

$$D_n = 0.4 + 0.3 \cdot 2^n \qquad n = -\infty, 0, 1, 2, 3, \ldots$$

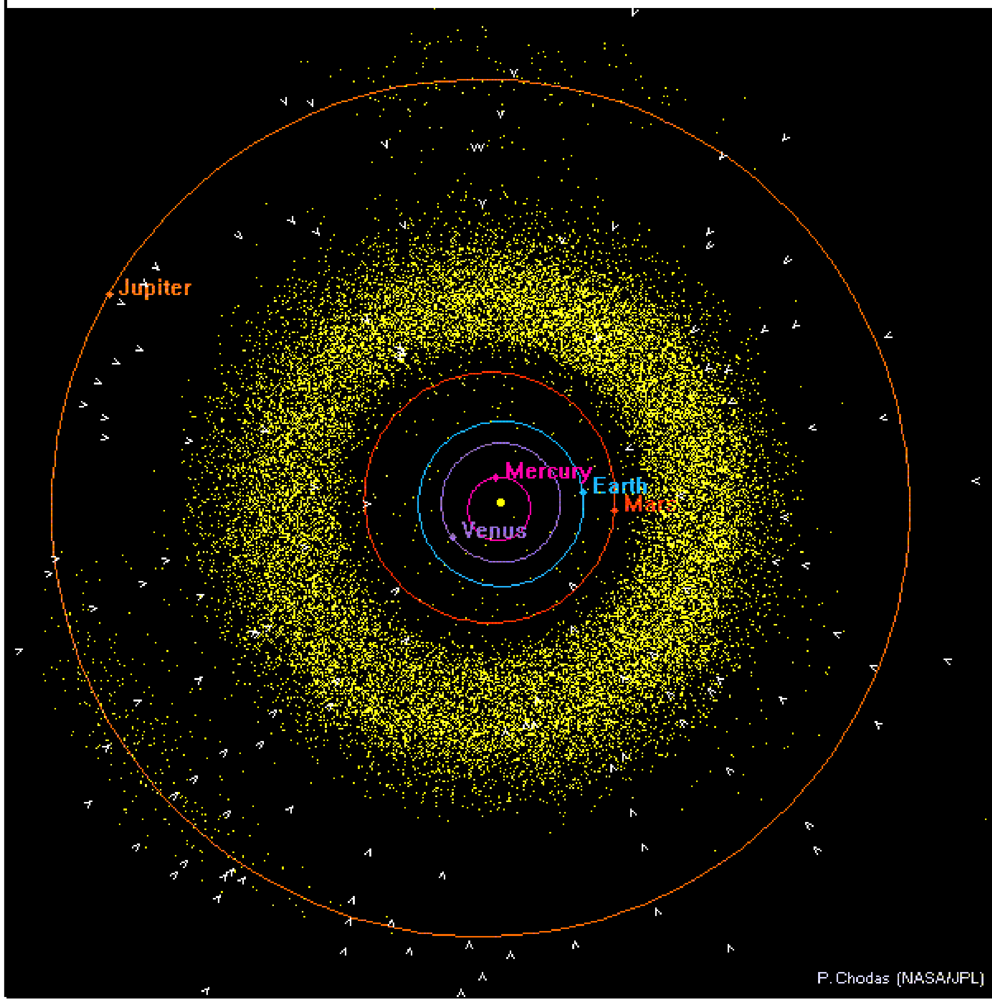
$D_{-\infty} = 0.4$	*a* (Mercury) = 0.39 AU
$D_0 = 0.7$	*a* (Venus) = 0.72 AU
$D_1 = 1.0$	*a* (Earth) = 1.00 AU
$D_2 = 1.6$	*a* (Mars) = 1.52 AU
$D_3 = 2.8$	*a* (??) = 2.8 AU
$D_4 = 5.2$	*a* (Jupiter)= 5.20 AU
$D_5 = 10.0$	*a* (Saturn)= 9.54 AU
$D_6 = 19.6$	*a* (Uranus)= 19.18 AU



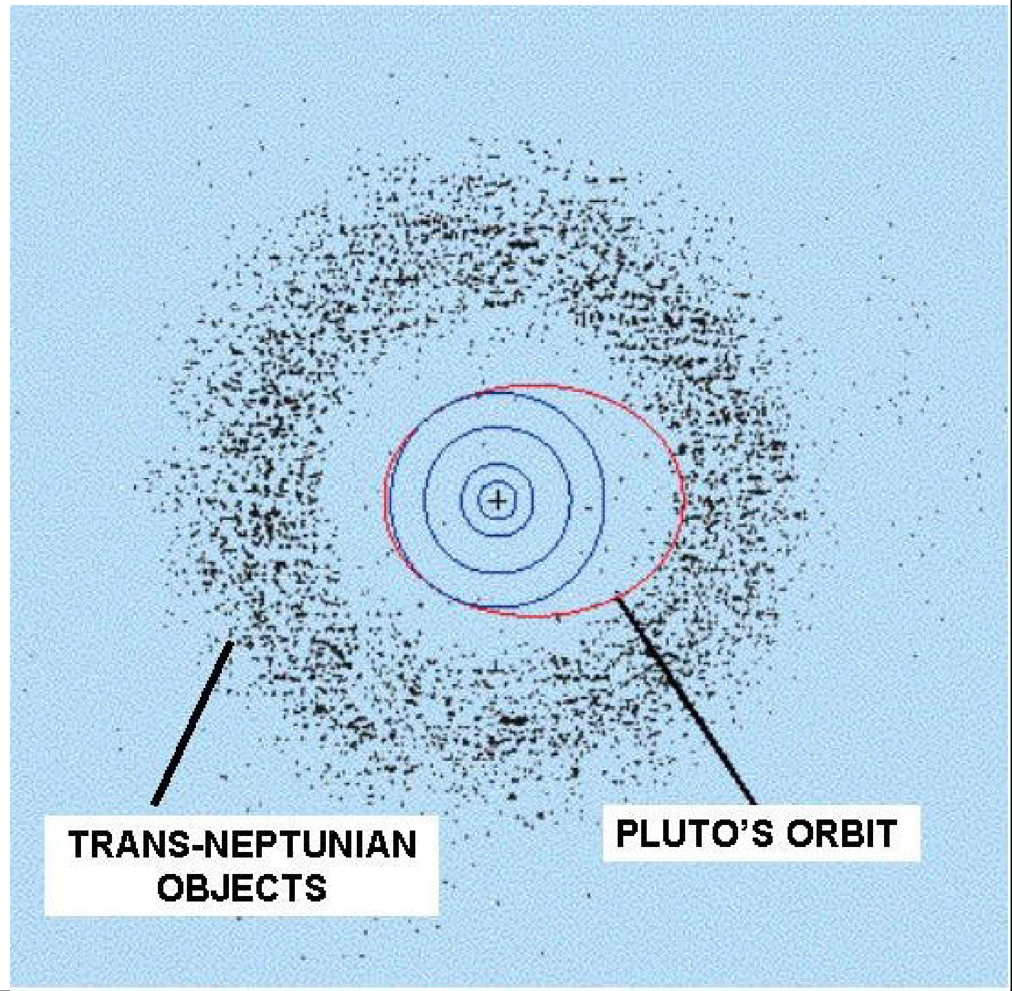
a(Ceres) ~ 2.8 AU

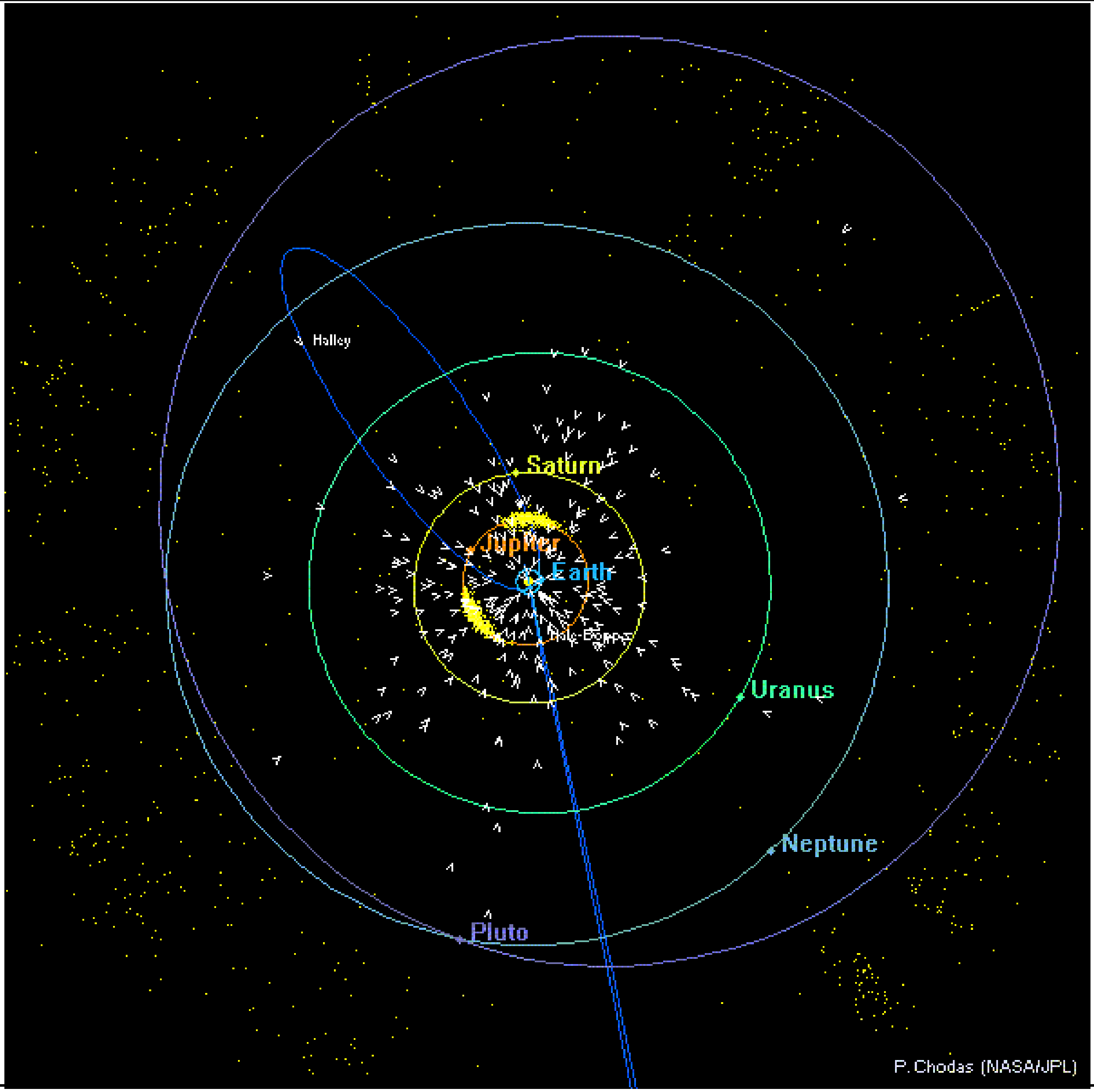
The asteroid main belt and the Kuiper belt

Asteroids



TNOs

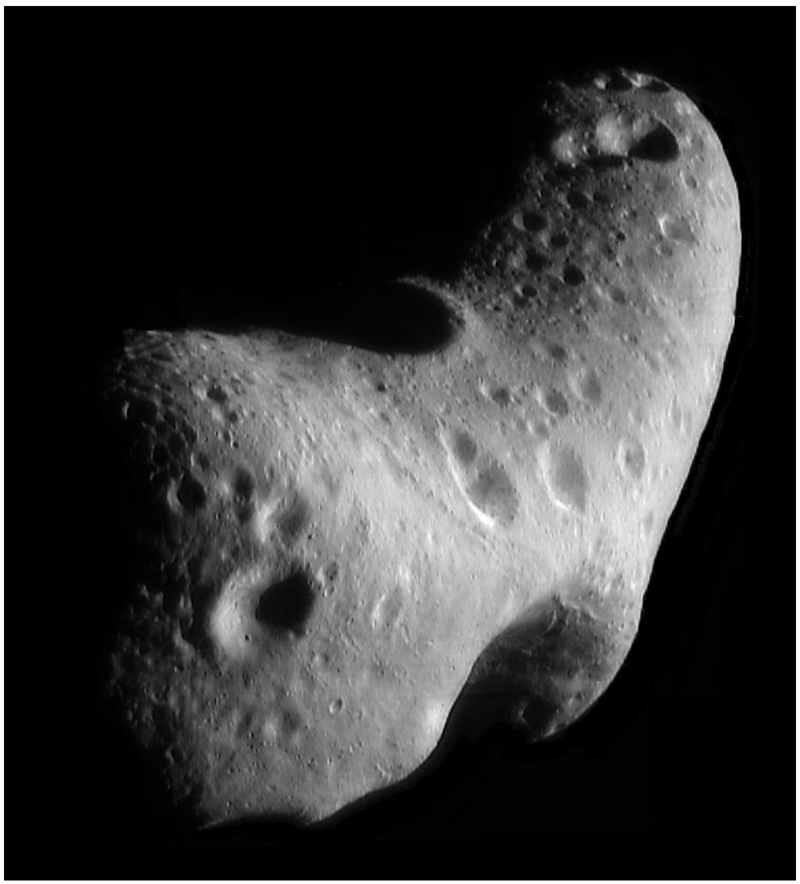




Comets and TNOs

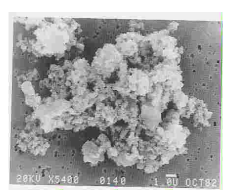
Minor bodies: small actors in Solar System's history

comets

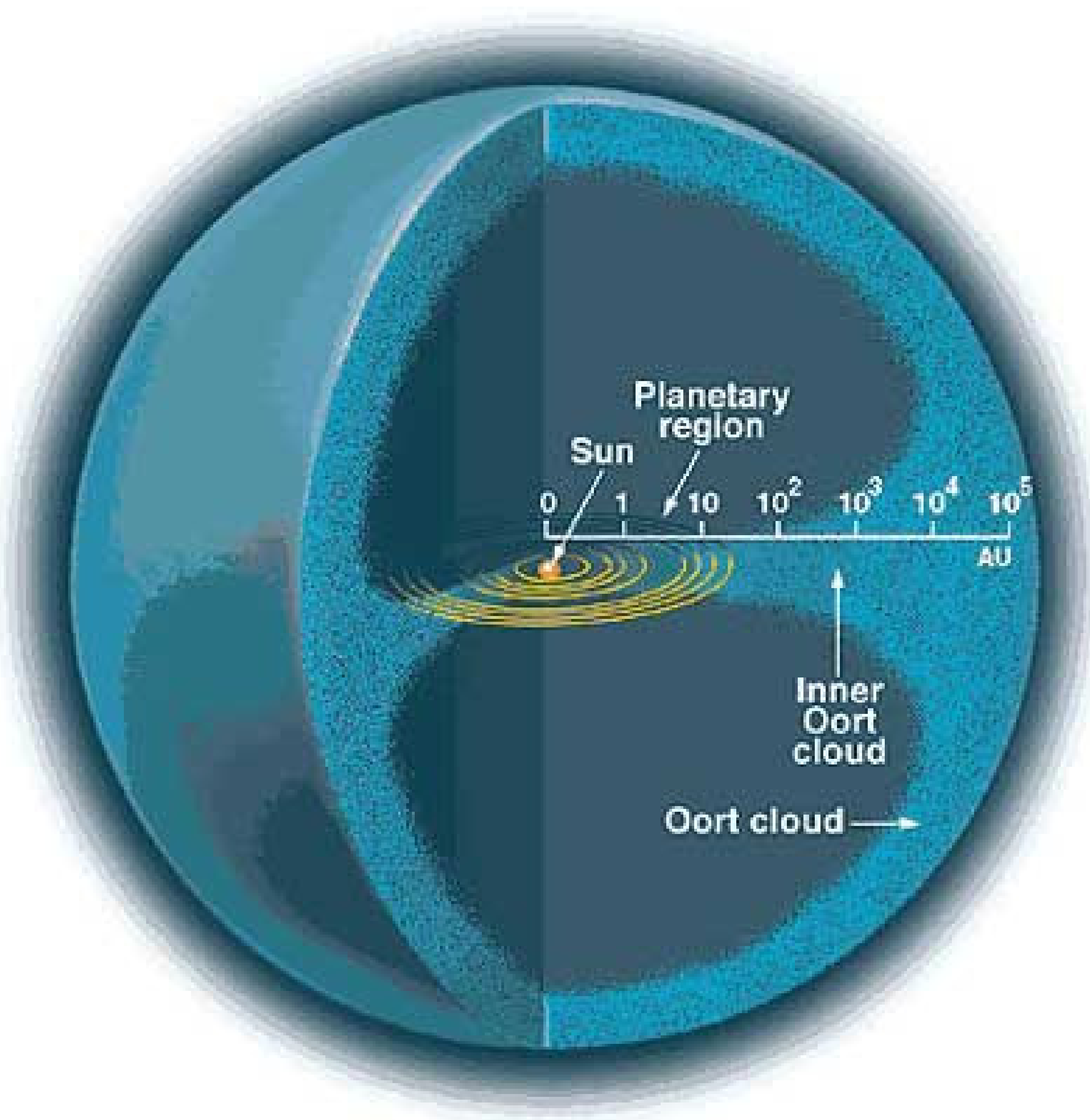


asteroids

dust



Meteoroids and meteorites



The most important differences between different classes of minor bodies are mainly related to **different heliocentric distances** and the corresponding differences in the **abundance of volatile elements (ices)** in their compositions.

Here, we focus on the asteroids, the small bodies orbiting mainly at heliocentric distances between Mars and Jupiter.

A few, fundamental considerations

Asteroids are rocky bodies

Asteroids are *not* stupid pebbles

Pebbles are pieces of rock and they are *not* stupid

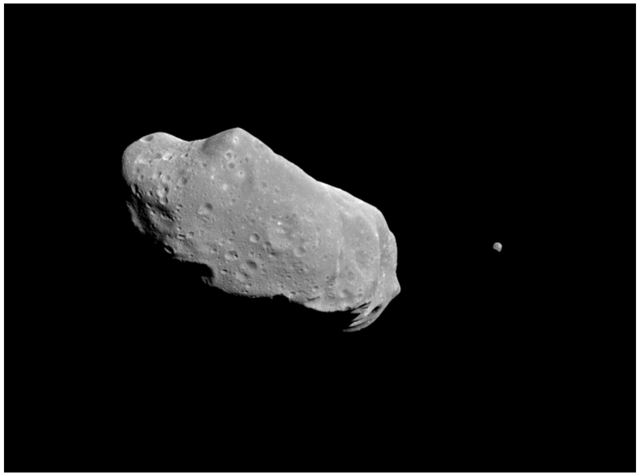
Rocks are aggregates of minerals

Minerals are solid-state chemical compounds

Rocks have long and very interesting histories, which date back to the epoch of formation of the Solar System

There are two main reasons to study asteroids

Purely scientific interest



Collision hazard

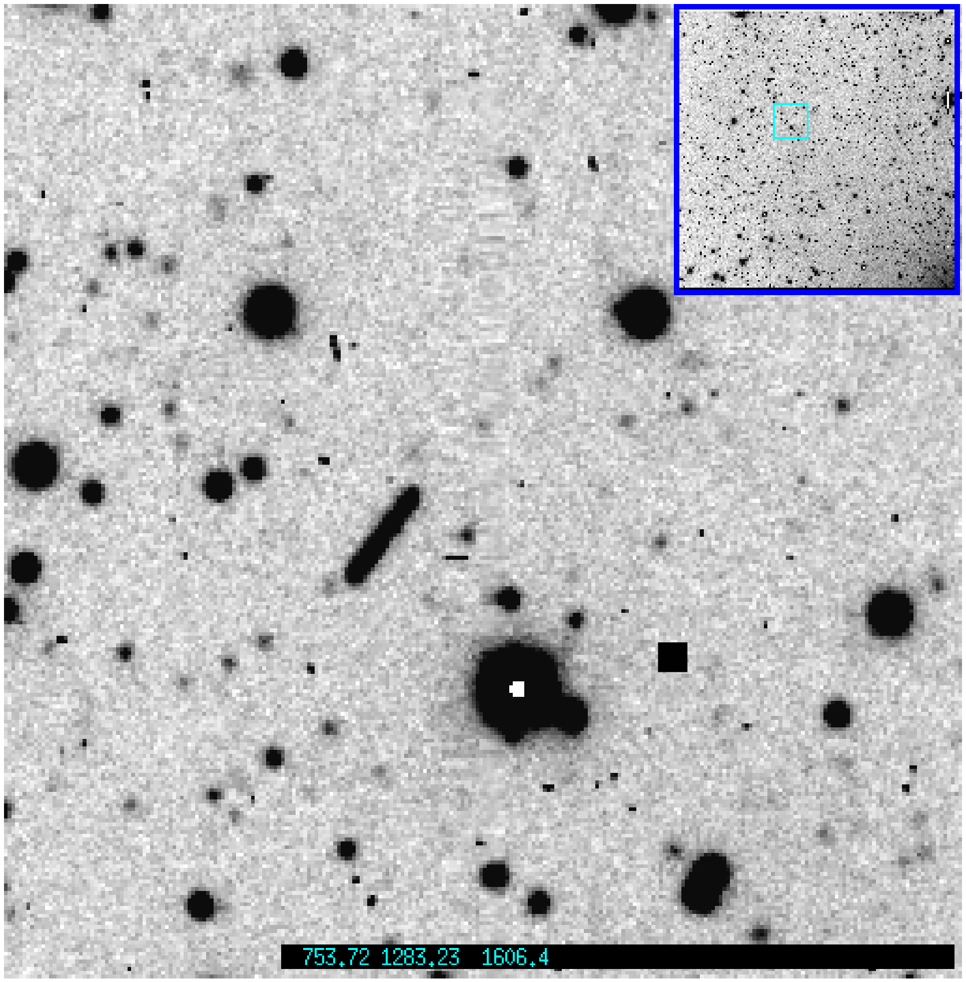
What we would like to understand:

- what they are made of
- their structures
- how old they are
- their histories
- their evolutionary processes
- how many they are, and their size distribution
- what they can tell us about Solar System’s history

Observing Techniques (Remote Observations)

- Astrometry
- UBVRI Photometry
- IR Photometry (Thermal Radiometry)
- Polarimetry
- Spettrophotometry and Spettroscopy
- Radar
- High-Res. Imaging
- Occultations

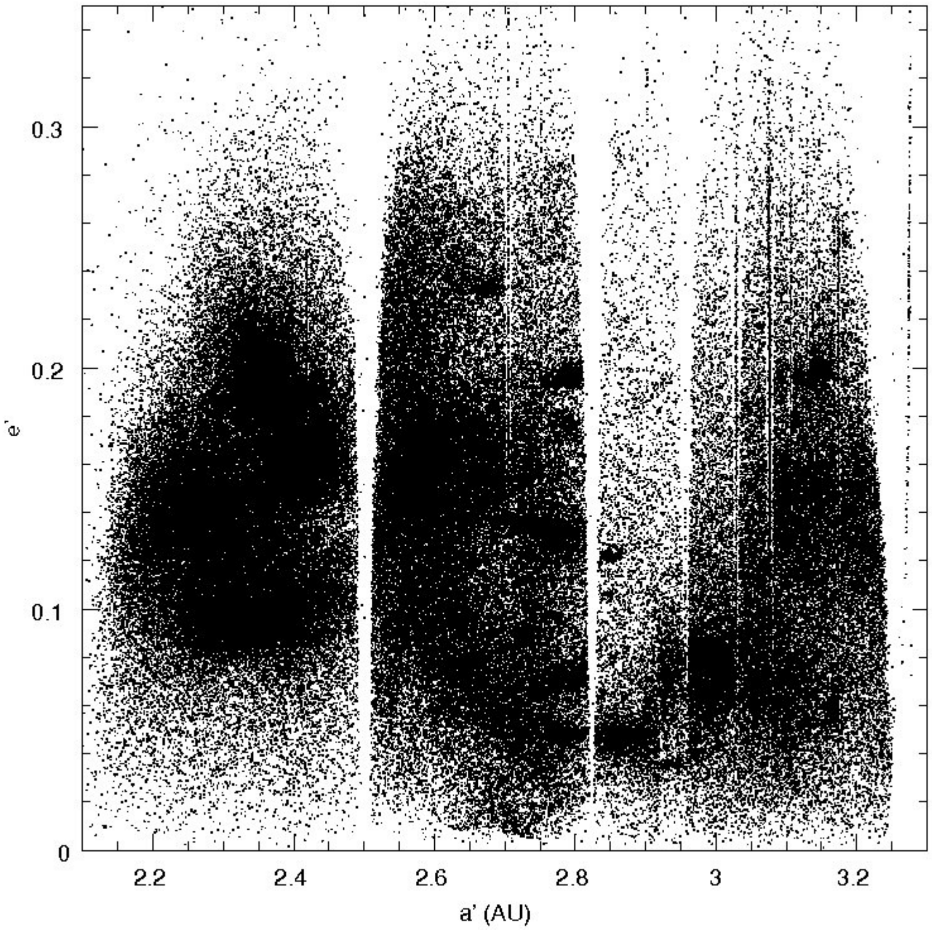
+ Space Missions (*in situ* exploration)

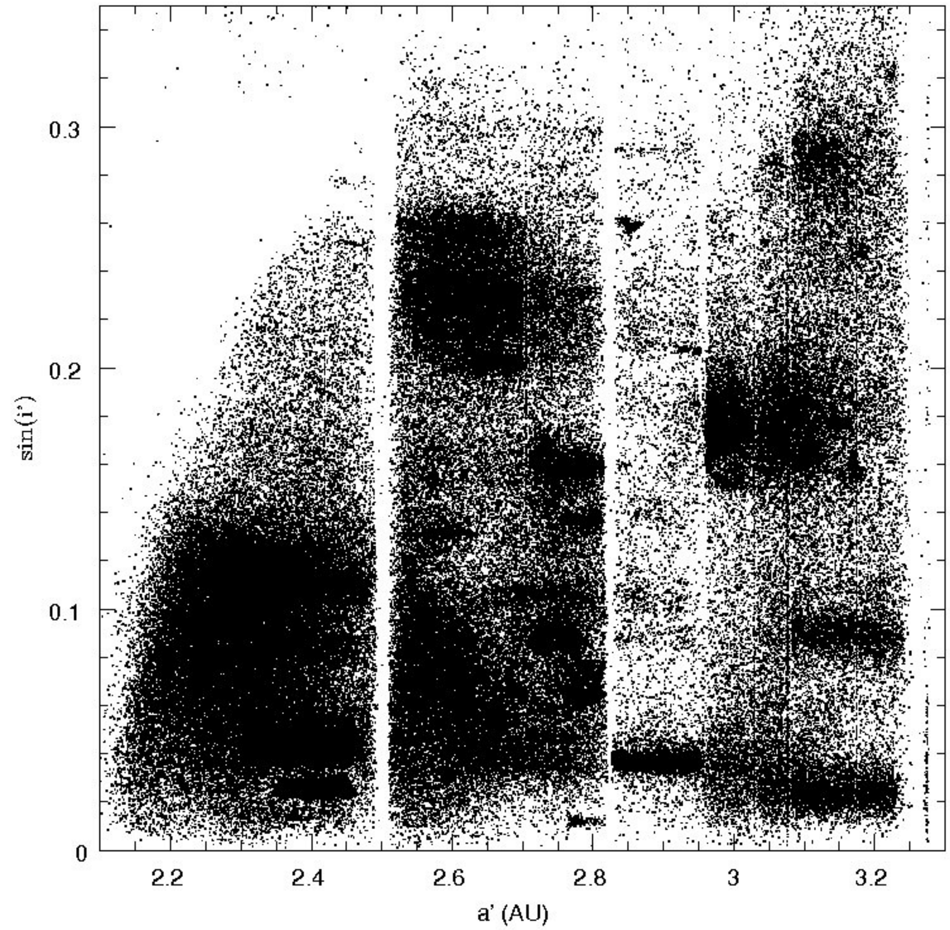


It took a long time to make a transition from this ...

... To this

Astrometry: the orbits

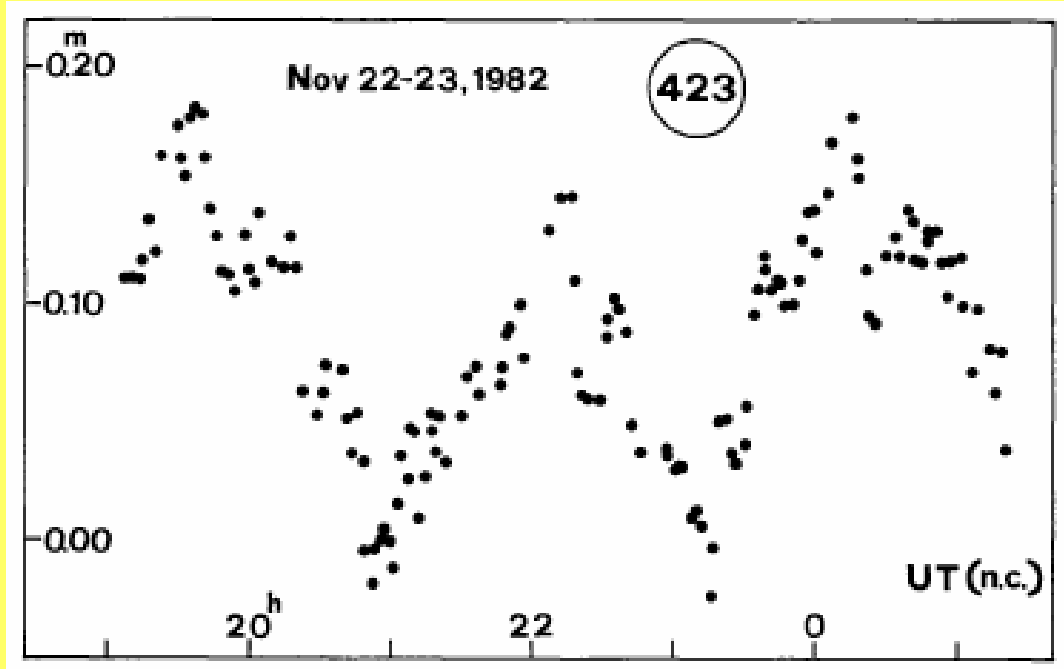




UBVRI Photometry:

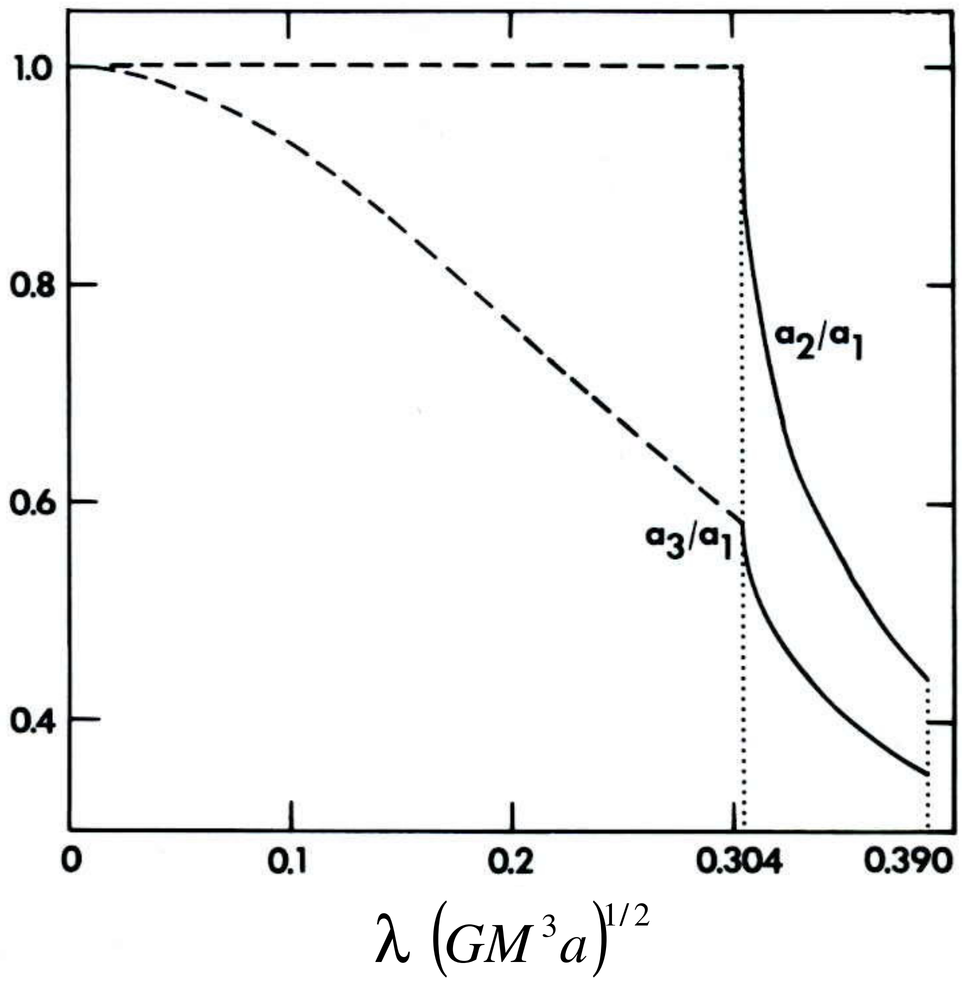
(423 Diotima, Di Martino and Cacciatori., 1984)

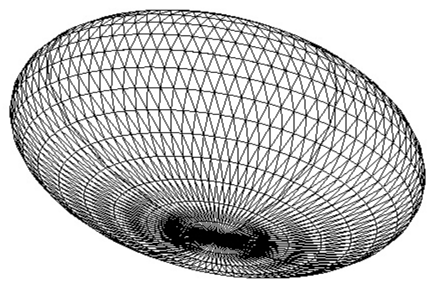
- spin periods
- spin axis orientation
- binarity
- overall shapes
- colours



Discovery of LASPAs: Large-Amplitude Short-Period Asteroids

Chandrasekhar's sequences of equilibrium shapes





a_2/a_1, a_3/a_1: axial ratios;

l: adimensional angular momentum

a: average radius

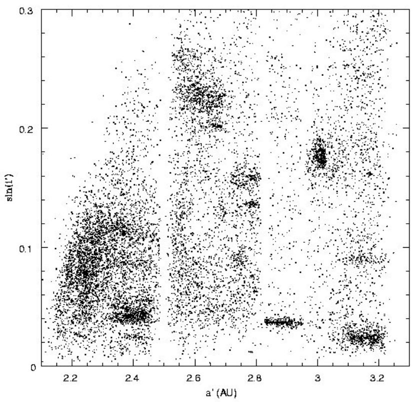
M: mass

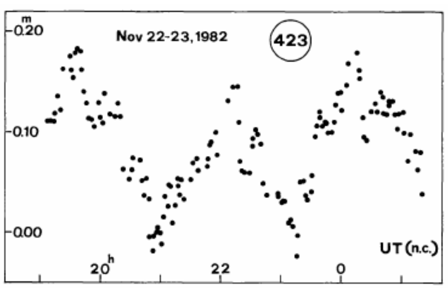
Triaxial Equilibrium Shapes among the Asteroids ?

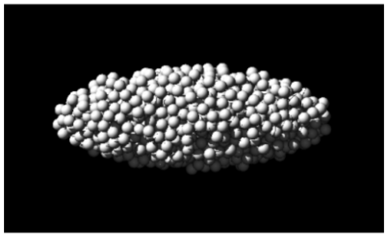
Farinella et al. (1981)

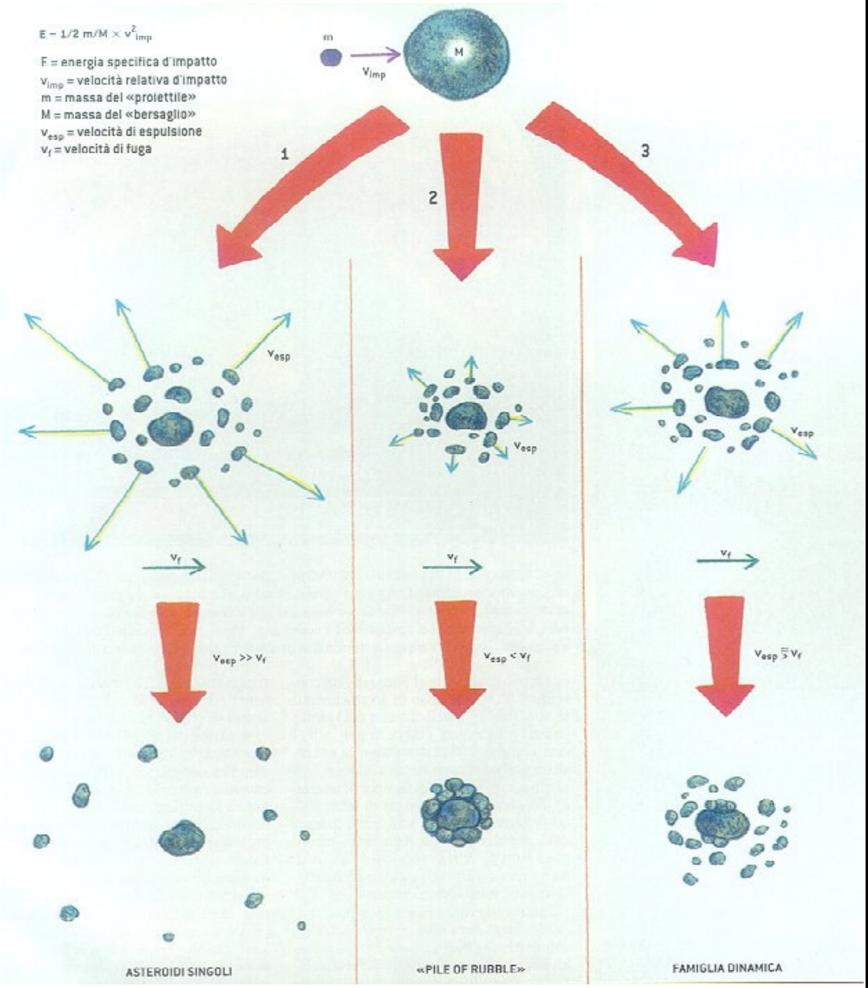
Families + LASPAs

Evidence of *collisional evolution* as a fundamental process for the asteroid population





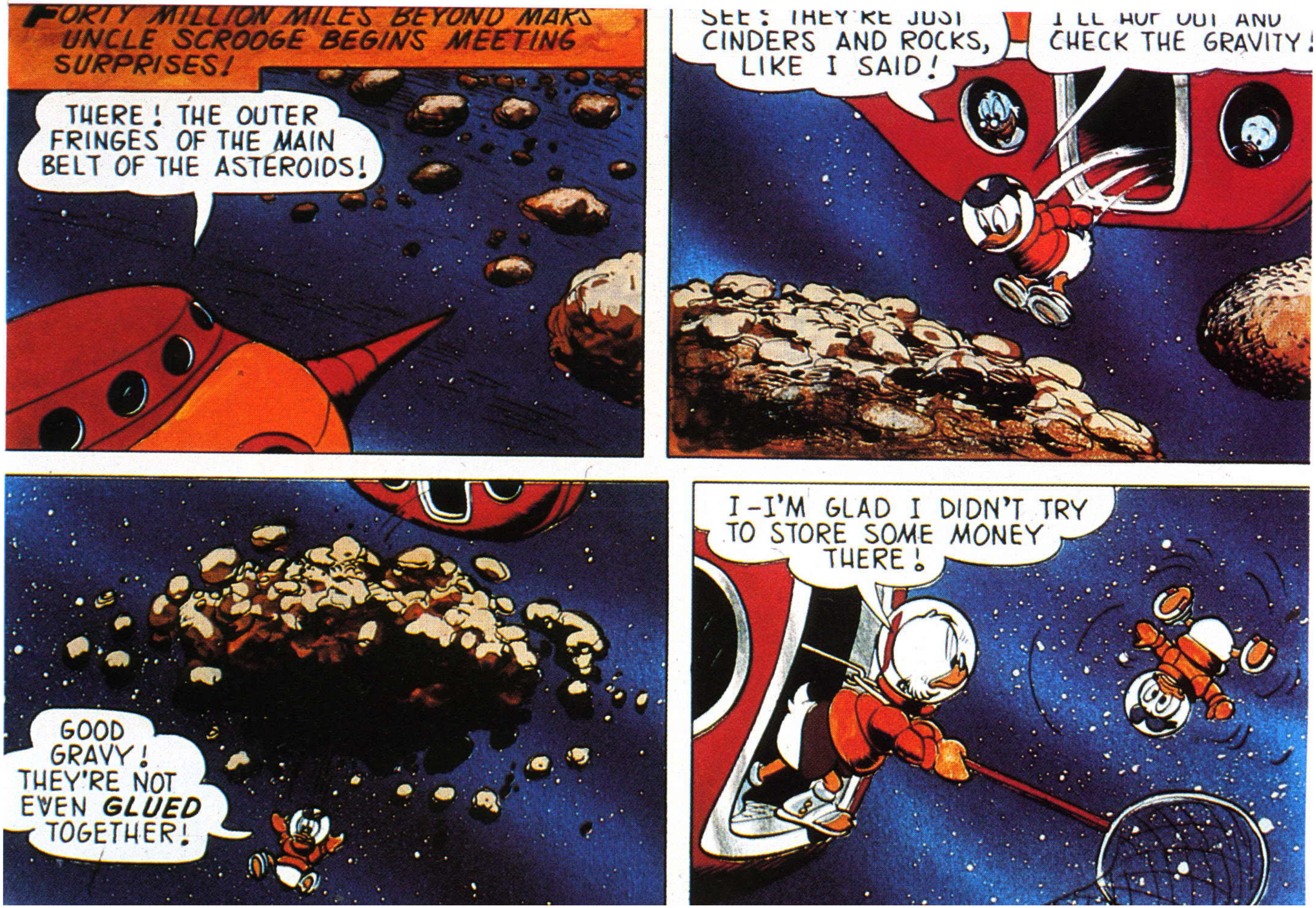


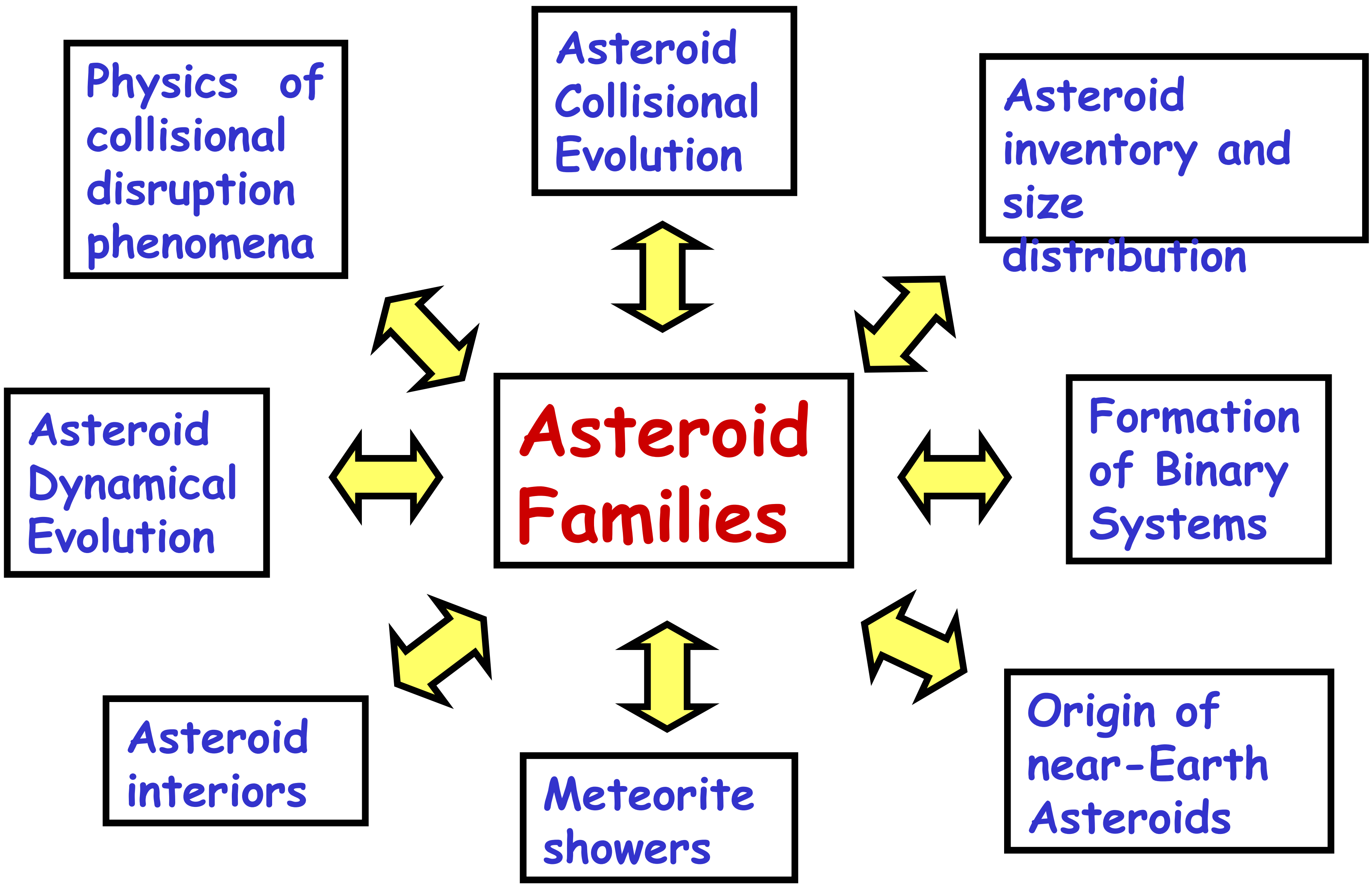


Asteroids as “rubble piles”

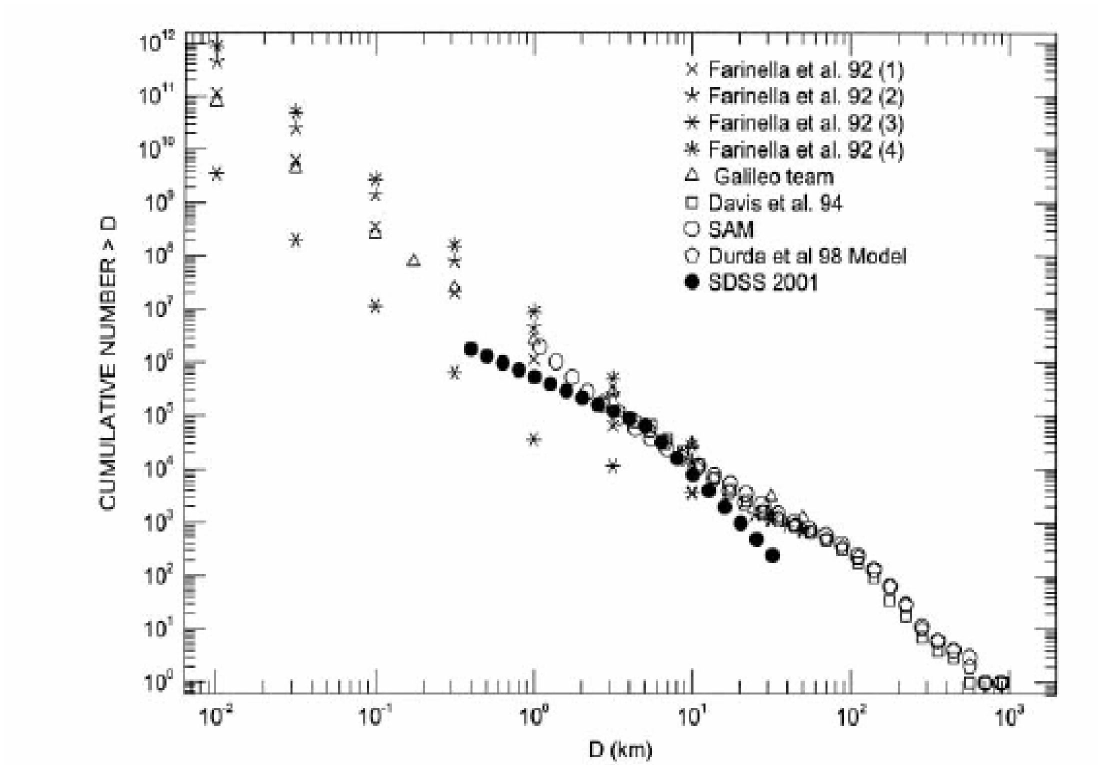
Schiaparelli and his legacy

Alberto Cellino – Milano, October 20, 2010



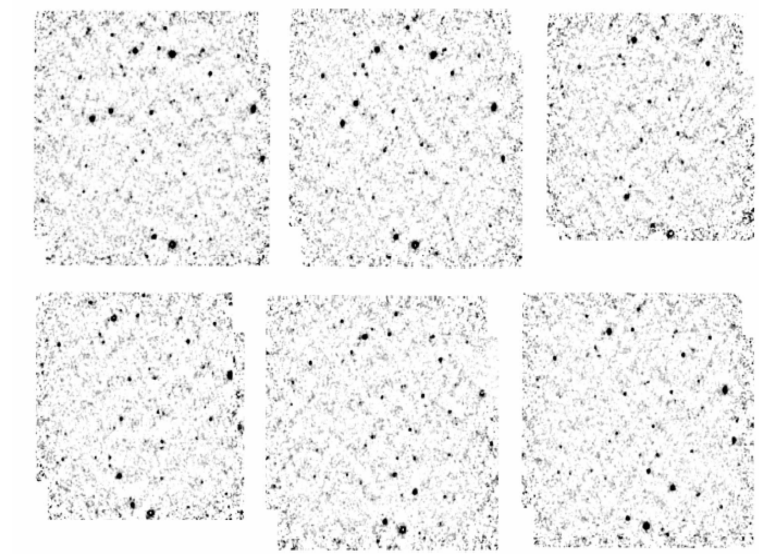

Physics of collisional disruption phenomena
Asteroid Collisional Evolution
Asteroid inventory and size distribution
Asteroid Dynamical Evolution
Asteroid Families
Formation of Binary Systems
Asteroid interiors
Meteorite showers
Origin of near-Earth Asteroids

Asteroid Inventory and Size Distribution



Different models of the cumulative asteroid size distribution. The debated role of families

ISO frames from Tedesco and Désert, 2002



Discrepancies between results of ground-based surveys at visible wavelengths (SDSS, Subaru) and thermal IR observations from space.

H	D	dN	Family dN
3.25	980.9	1.0	–
3.25	779.2	0.0	–
4.25	618.9	0.0	–
4.25	491.6	2.0	–
5.25	390.5	1.0	1.0
5.75	310.2	3.0	1.0
6.25	246.4	8.0	1.0
6.75	195.7	17.0	5.0
7.25	155.5	38.0	5.0
7.75	123.5	64.0	5.0
8.25	98.1	91.0	–
8.75	77.9	116.0	–
9.25	61.9	164.0	–
9.75	49.2	185.0	–
10.25	39.1	224.0	–
10.75	31.0	338.0	–
11.25	24.6	554.0	–
11.75	19.6	789.7	–
12.25	15.6	1548.0	–
12.75	12.4	2992.3	–
13.25	9.81	5671.8	–
13.75	7.79	10463.9	–
14.25	6.19	18630.7	–
14.75	4.92	31739.6	–
15.25	3.91	51398.5	–
15.75	3.10	78939.8	–
16.25	2.46	115400.3	–
16.75	1.96	162026.4	–
17.25	1.55	221080.1	–
17.75	1.23	296503.1	–
18.25	0.98	394278.9	–

The size distribution used by Bottke *et al.*, (2005).

N ≥ 1 km ~ $1.2 \cdot 10^6$

To be compared with SDSS estimate:

N ≥ 1 km ~ $7 \cdot 10^5$

(Ivezic et al., 2001, 2002)

and with SAM prediction:

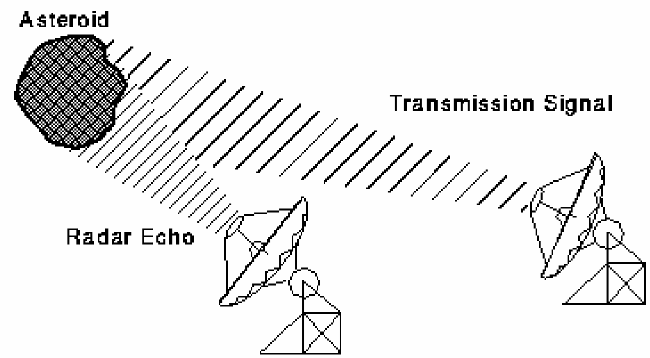
N ≥ 1 km ~ $1.7 \cdot 10^6$ (Tedesco et al., 2005)

The big problem is to convert H into D, having at disposal insufficient information on the albedo of the objects

Most asteroids are faint objects, and they are quite small: their apparent angular sizes are usually beyond the limits of high-resolution imaging from the ground.

How can we derive sizes and masses of objects which are so small by means of remote observations?

A powerful remote-sensing technique: RADAR



Limited applicability, due to the problem of r^{-4} dependence of the radar echo. Great for NEAs

Radar "image" of 4179 Toutatis

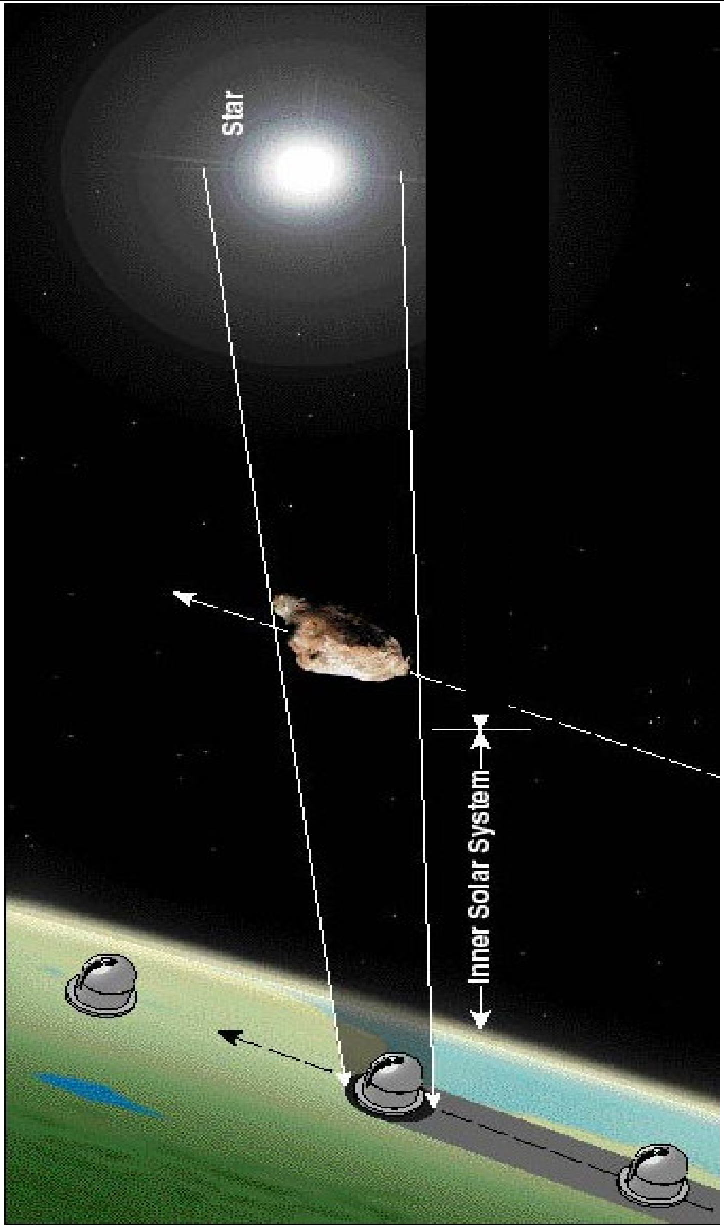
Occultation monitoring:

Excellent in principle, ***but very difficult in practice***.

Problems due to insufficient knowledge of asteroid orbits and star positions.

Very limited extent of visibility stripes (and wheather problems)

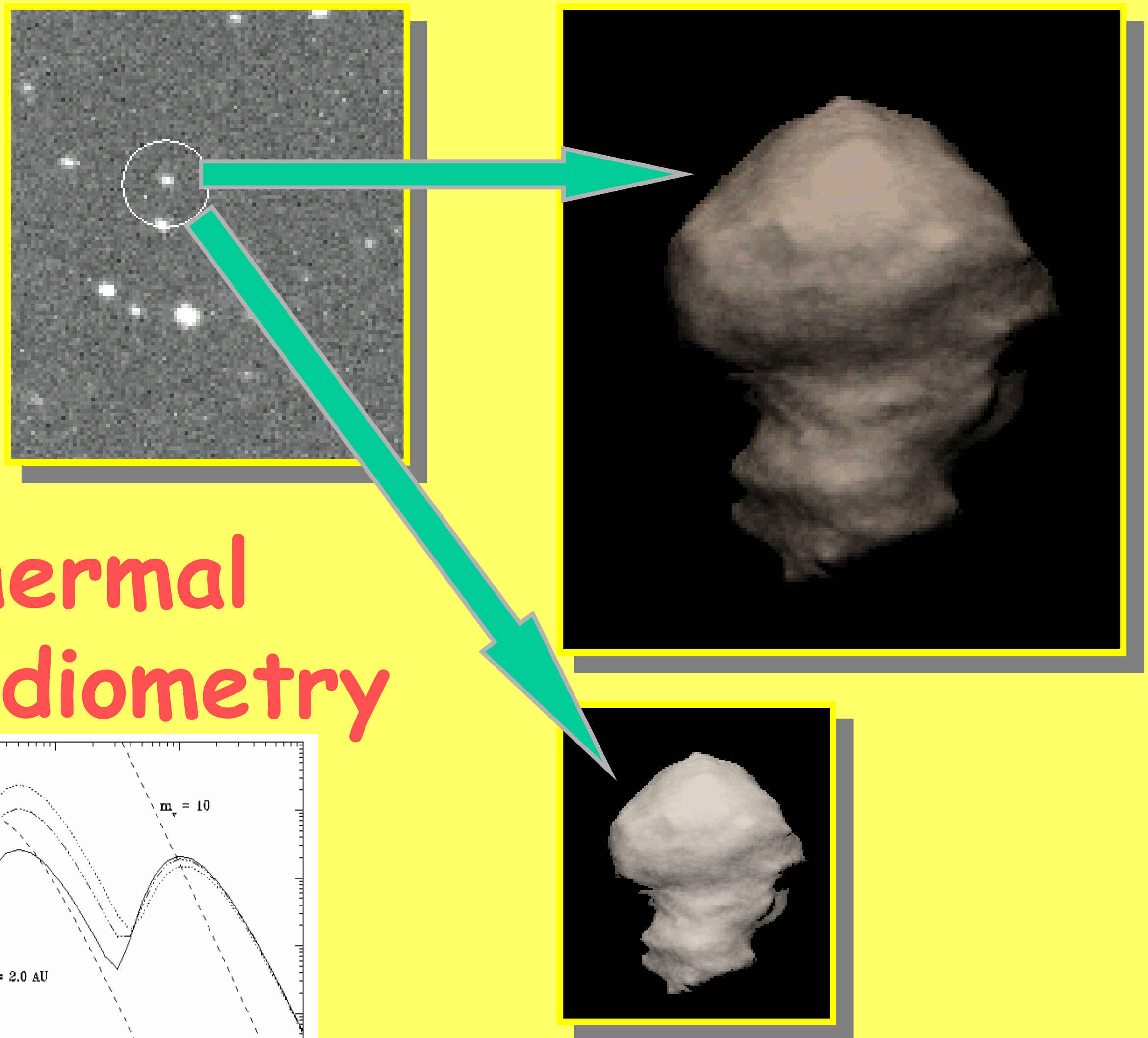
Waiting for GAIA !

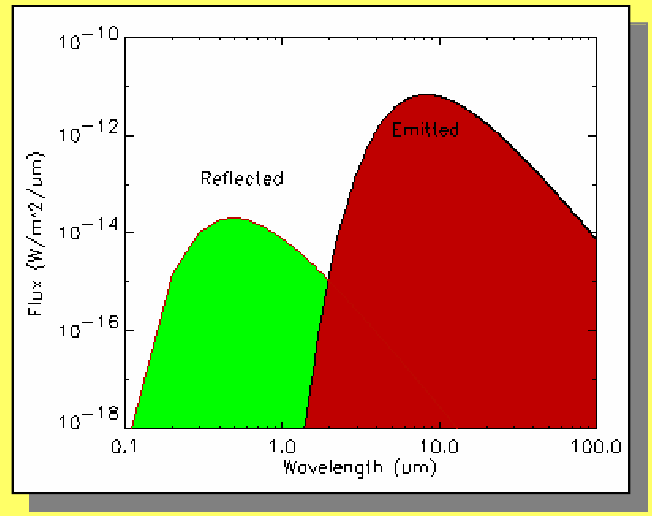


INAF --Osservatorio Astronomico di Torino

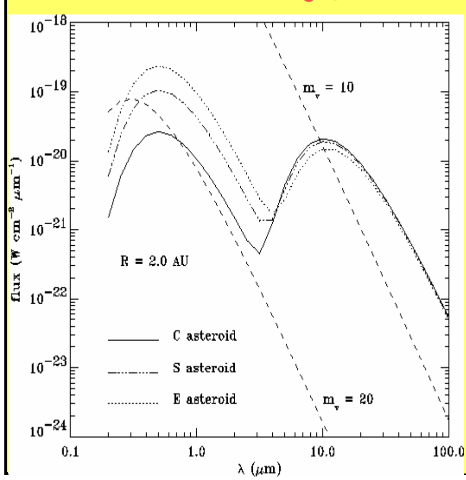
Schiaparelli and his legacy

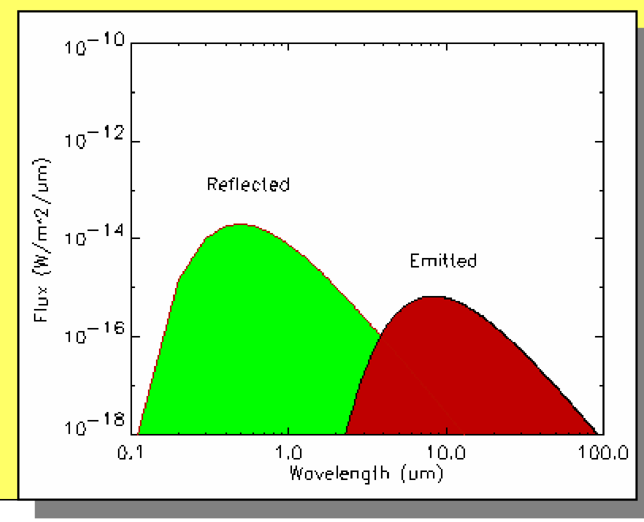
Alberto Cellino – Milano, October 20, 2010



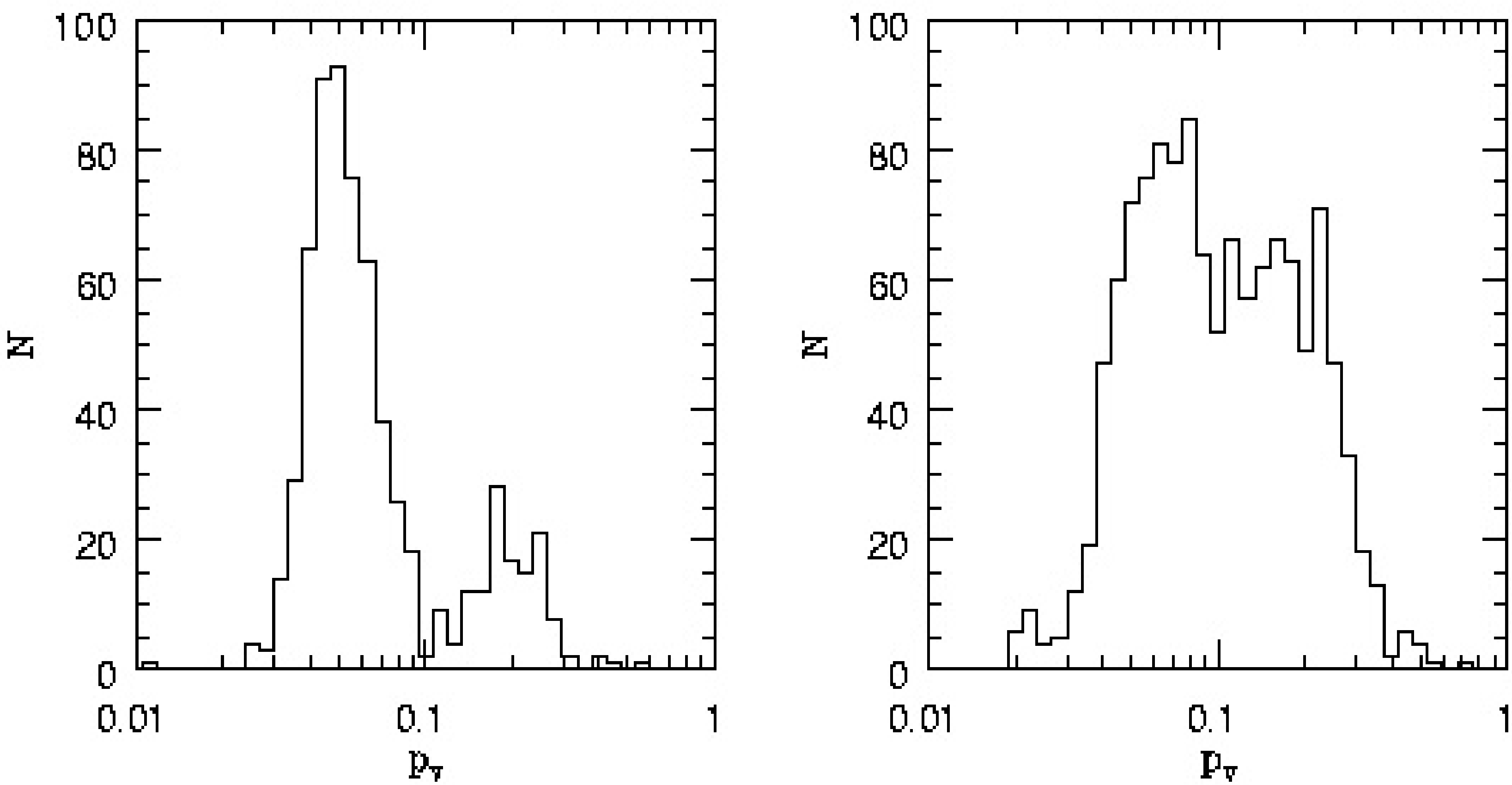


Thermal Radiometry





IRAS albedo distributions

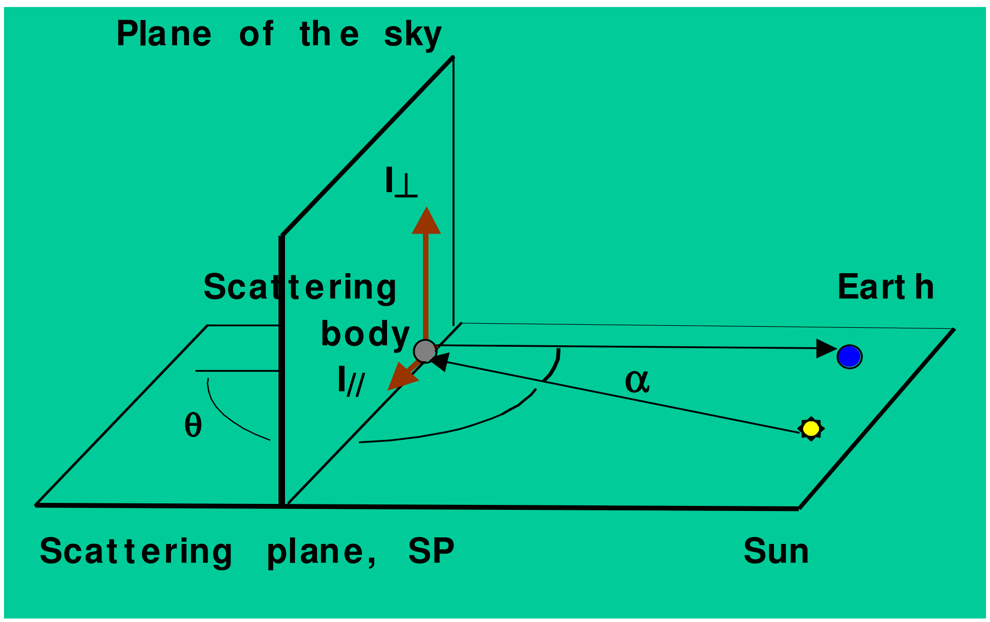


D > 50 km **D < 50 km**

Problem: Is this true?

Asteroid Polarimetry: What do we measure ?

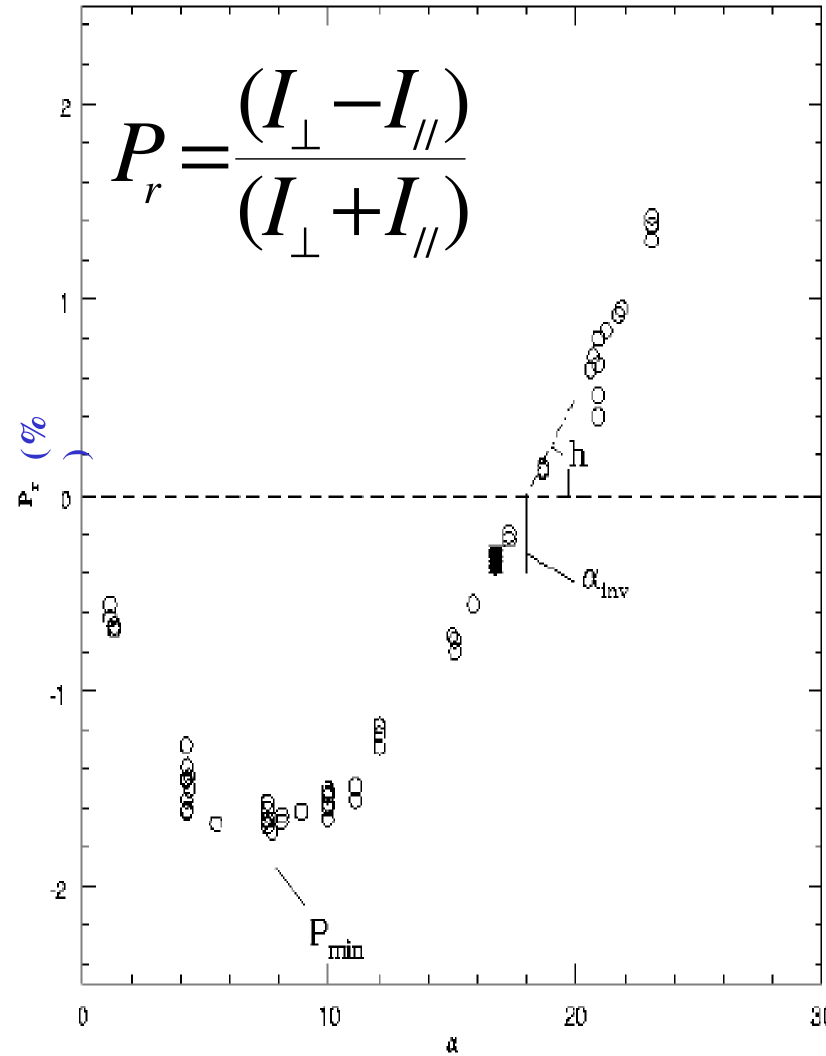
Partial linear polarization and polarization – phase curves.

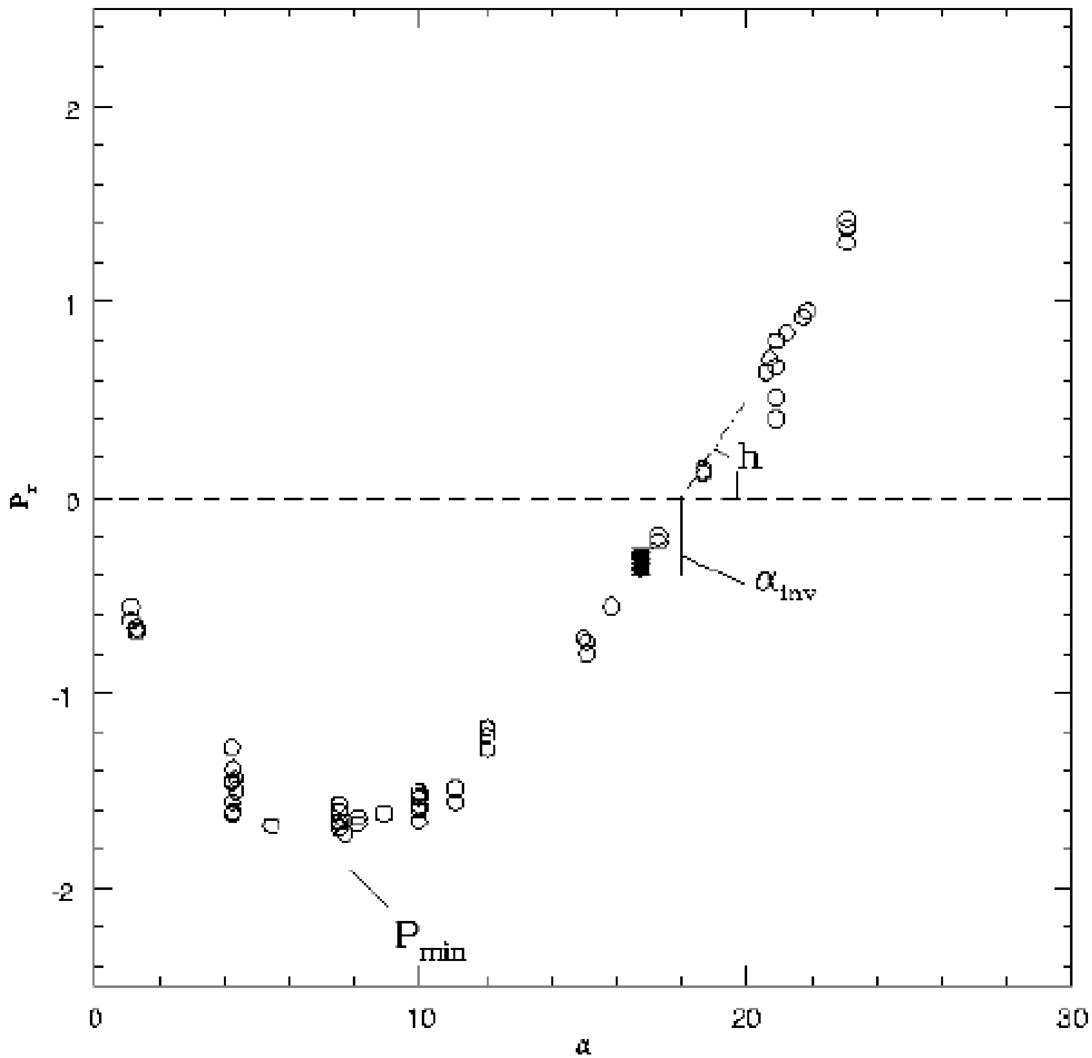


- Presence of a “Negative polarization branch”
- Curve described by a few parameters

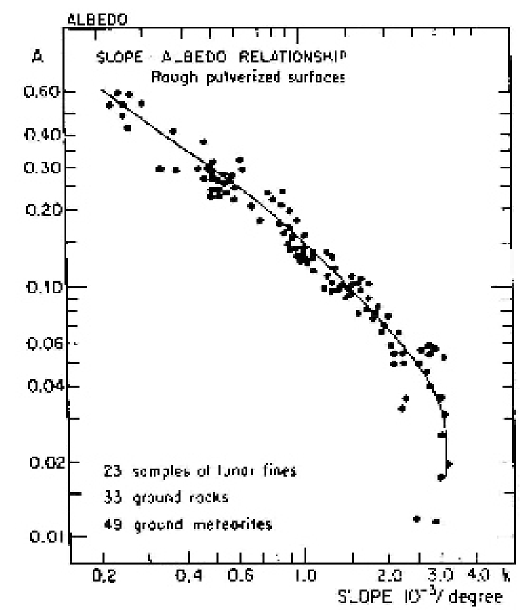
1 Ceres

$$P_r = \frac{(I_\perp - I_{//})}{(I_\perp + I_{//})}$$





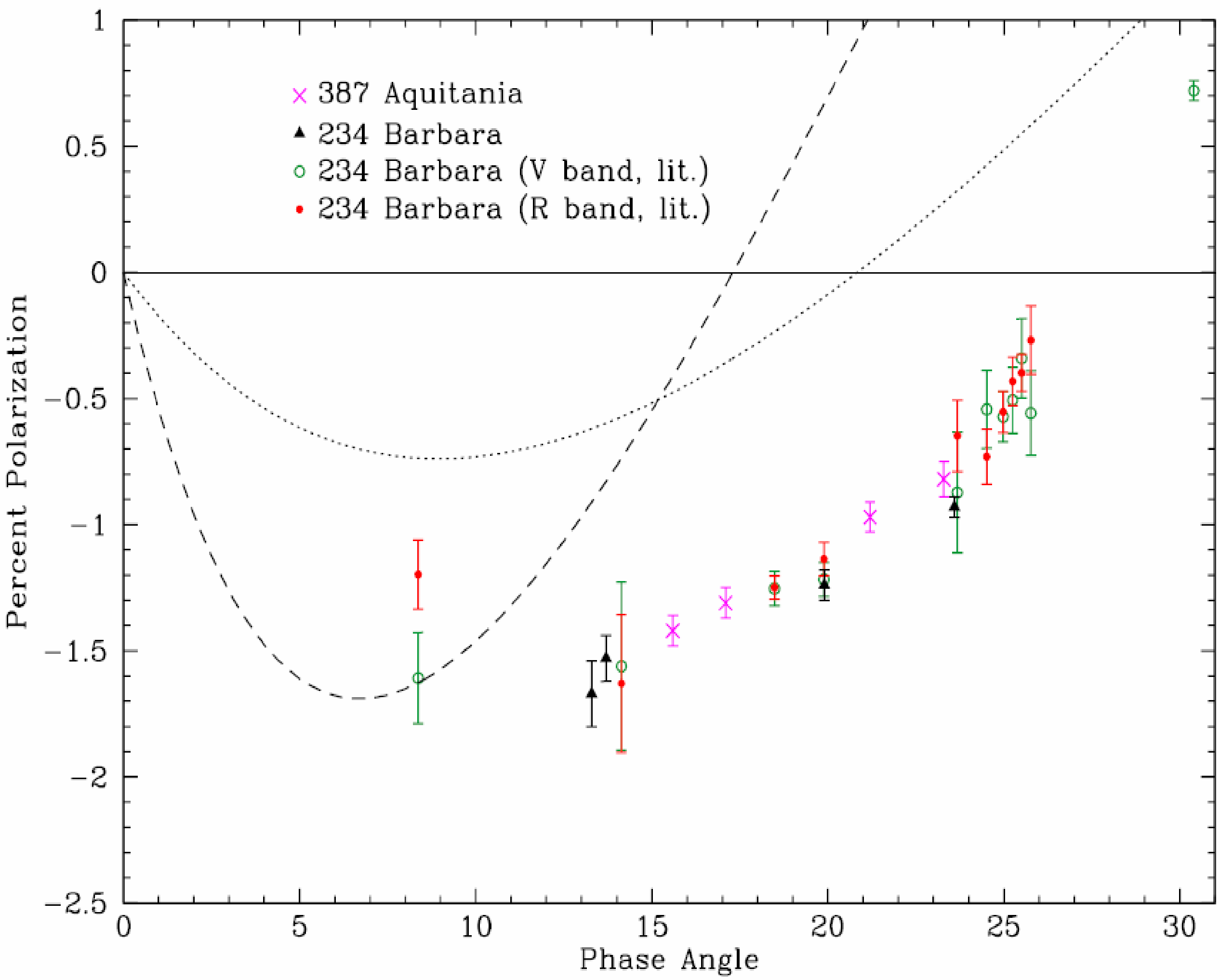
The derivation of the Albedo from polarimetric properties.



$$\log p_V = C_1 \log (h) + C_2$$

$$\log p_V = C_3 \log (P_{min}) + C_4$$

Recent developments: The discovery of the "Barbarians"



Known objects:

234 (Ld),

172, 236, 387, 980

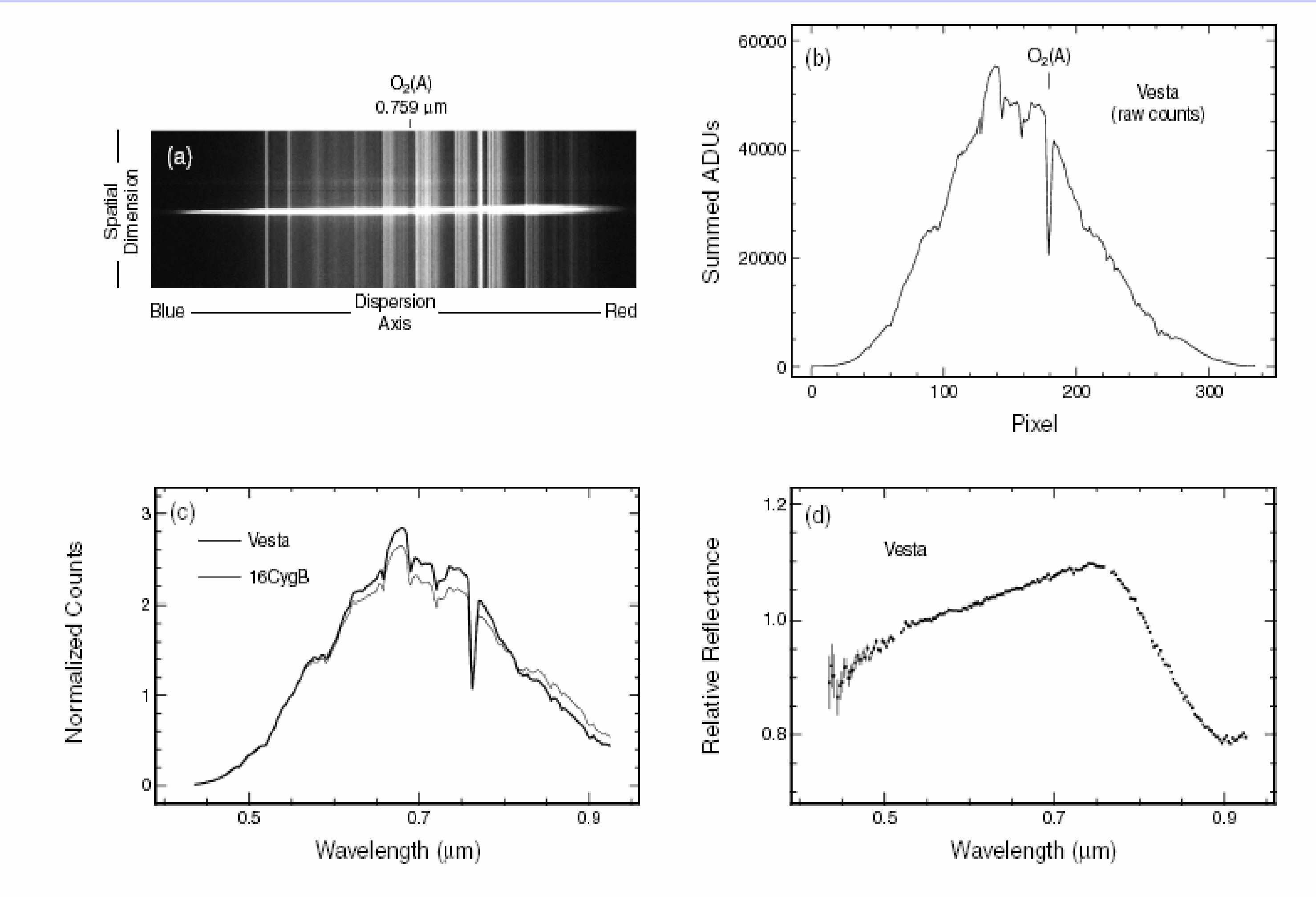
(L -types)

679 (K-type)

(dashed and dotted lines show, for a comparison, typical polarization-phase curves for B-type ((24) Themis) and L-type ((12) Victoria) asteroids, respectively)

Masiero and Cellino (2009)

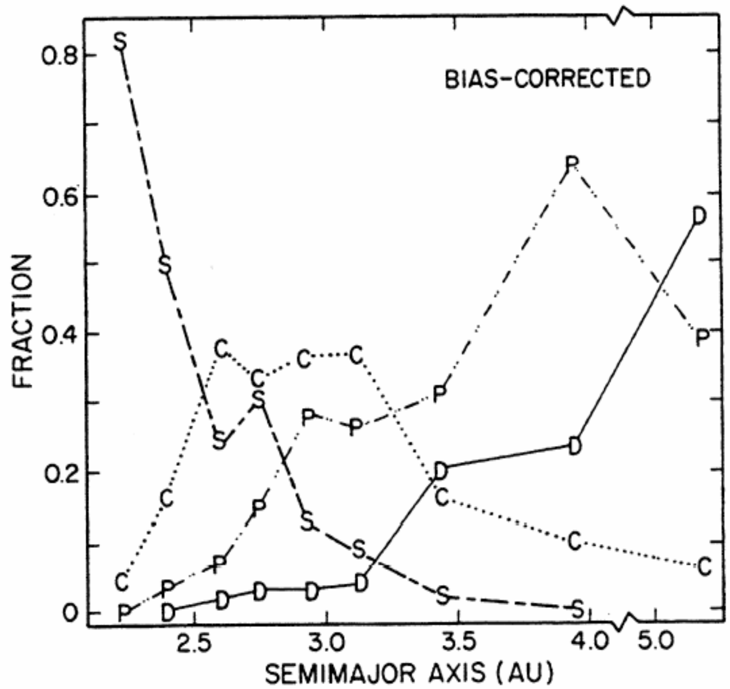
Spectroscopy and Spectrophotometry

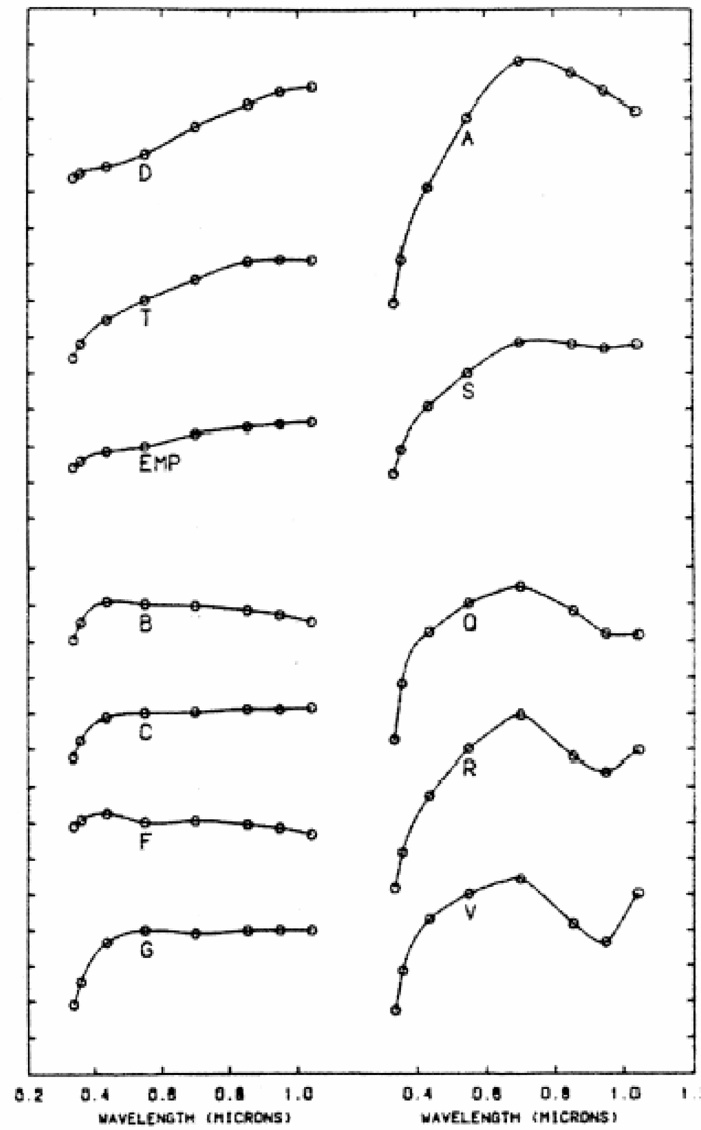


(From Bus *et al.*, 2002)

Asteroid taxonomy has been traditionally based on spectrophotometric properties, in the wavelength range covering UBVRI colors.

The distribution of different taxonomic classes as a function of heliocentric distance is related to the general composition gradient of our Solar System





The mineralogical interpretation of reflectance spectra

Asteroid taxonomic classes and their general interpretation.

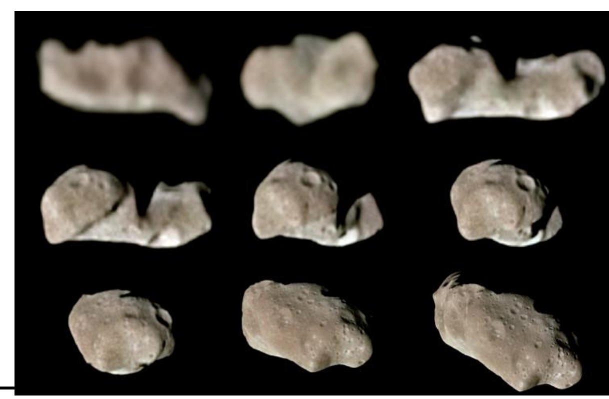
Type	Probable Surface Mineralogy	Albedo	Abundance	Bell's Superclass
A	Olivine or olivine-metal	High	Rare	Igneous
B, *F*, *G*	Hydrated silicates, carbon, organics	Low	Fairly rare	Metamorphic
C	"	Low	Common	Primitive
D, *P*	Carbon/organic-rich silicates	Very low	Common	Primitive
E	Enstatite, iron-free silicates	Very high	Rare	Igneous
M	Metal, metal + enstatite	Moderate	Moderately rare	Igneous
Q	Olivine + pyroxene + metal	Moderate	Rare	Primitive
R	Pyroxene + olivine	Moderate	Rare	Igneous
S	Metal, olivine, pyroxene	Moderate	Common	Igneous
T	Similar to *P* and *D* (?)	Moderate	Rare	Metamorphic
V	Pyroxene, feldspar	Moderate	Rare	Igneous

Interpretation of taxonomic classes in terms of comparison with meteorites (M -> Metal; C -> Carbonaceous,...)

Generally OK, BUT...

The problem of the origin of Ordinary Chondrites from S-class asteroids: spectral inconsistencies.

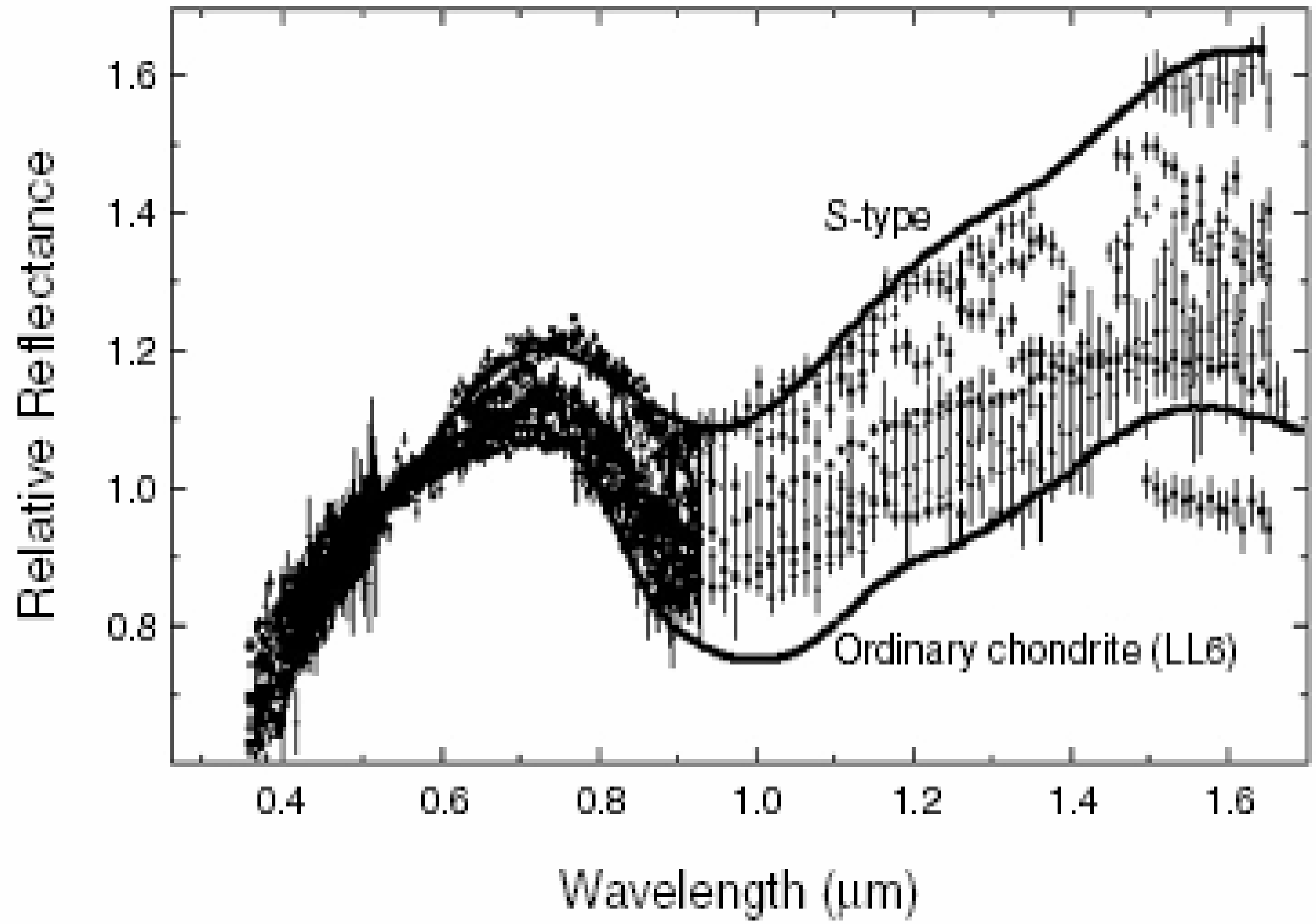
??



OC - like spectra among Near-Earth asteroids

S-class NEAs "fill the gap" between OC and main-belt S-class spectra.

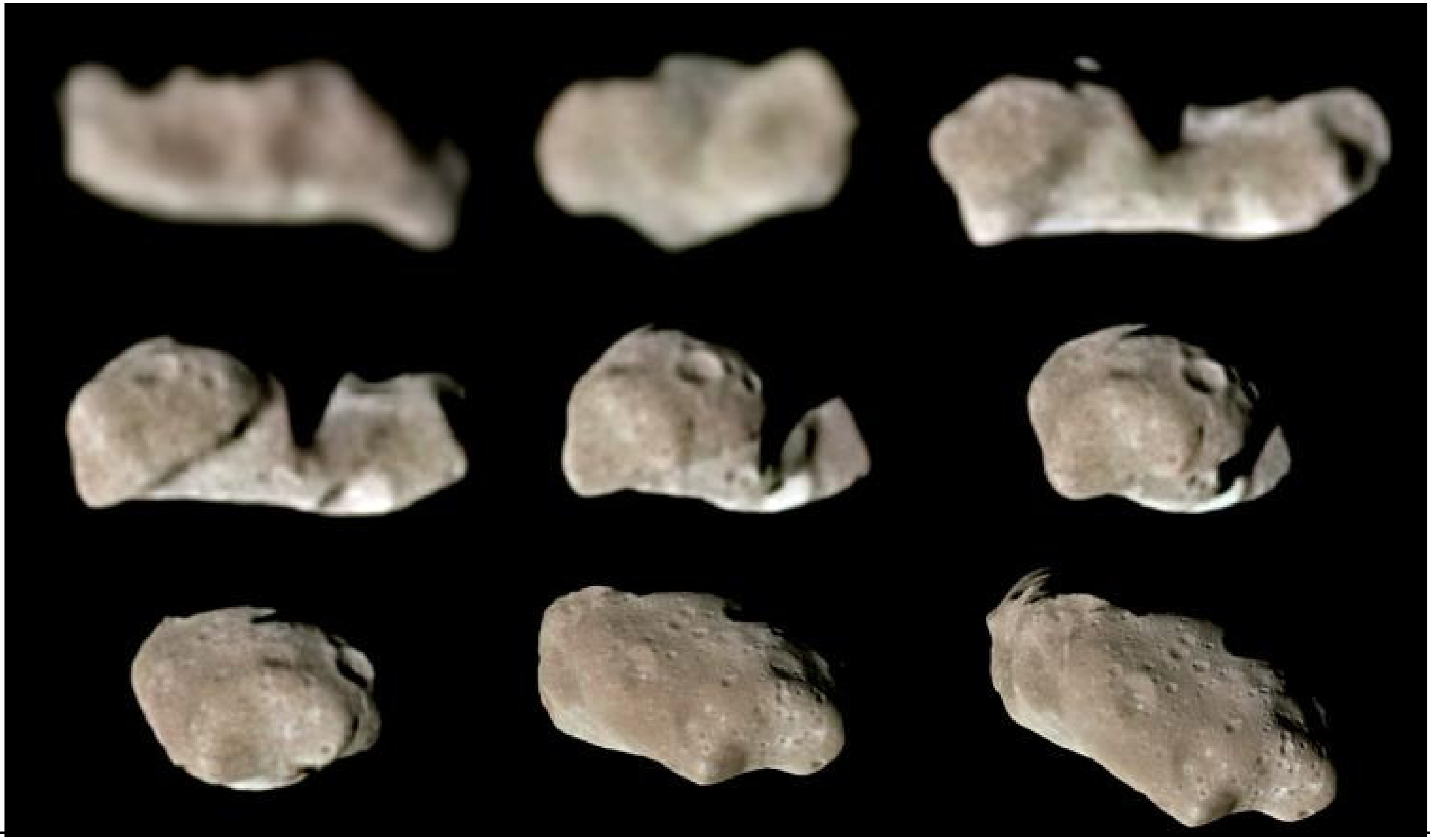
This is very important, because NEAs are young objects, since their orbits are not stable



(From Binzel *et al.*, 2001)

Spectroscopic results in agreement with in situ exploration of 243 Ida by the Galileo probe.

Space weathering at work.

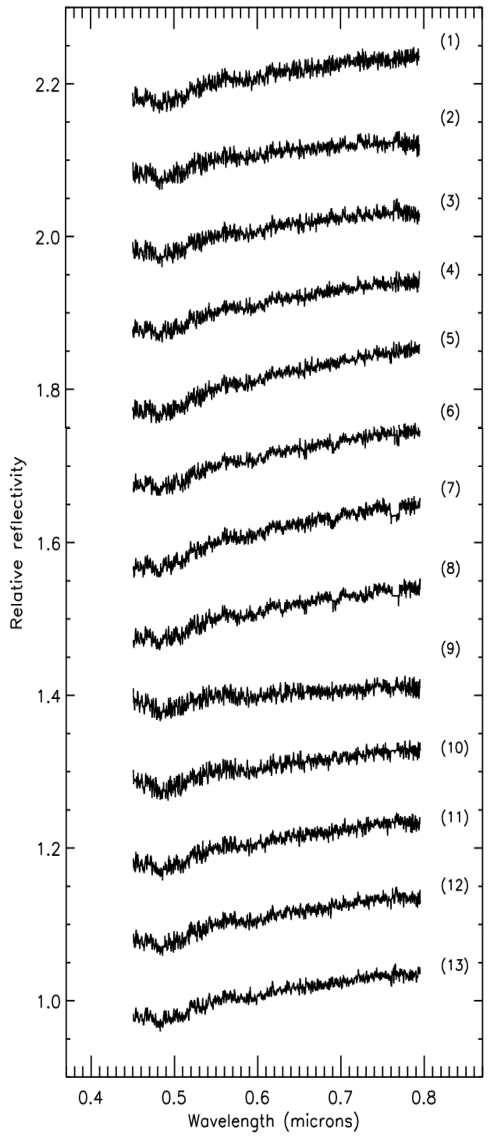


Another problem: 3-μm hydration features among M-class asteroids

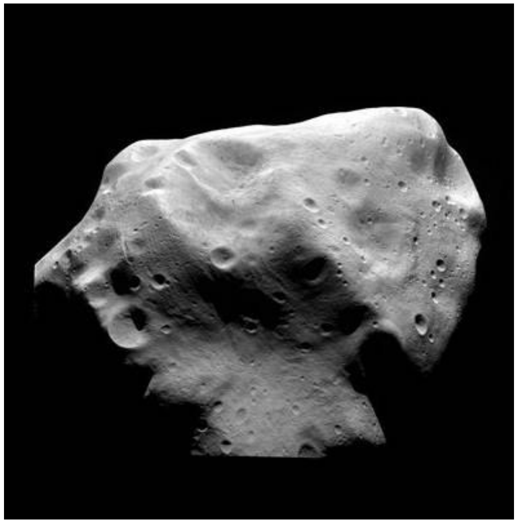
Tholen Class	3 μm Observed	3 μm With Band*	3 μm Percent	0.7 μm Observed	0.7 μm With Band	0.7 μm Percent
C	32	20	63	45	20	44
B	1	1	100	1	0	0
G	5	5	100	6	6	100
F	5	1	20	5	2	40
T	4	3	75	5	0	0
D/P	20	3	15	22	4	18
K/L	5	2	40	1	0	0
S	24	1	4	4	0	0
E	6	4	67	1	0	0
M/W	27	10	37	23	1	4

*Uncertainties vary, so the band depth limits are not uniform in these data.

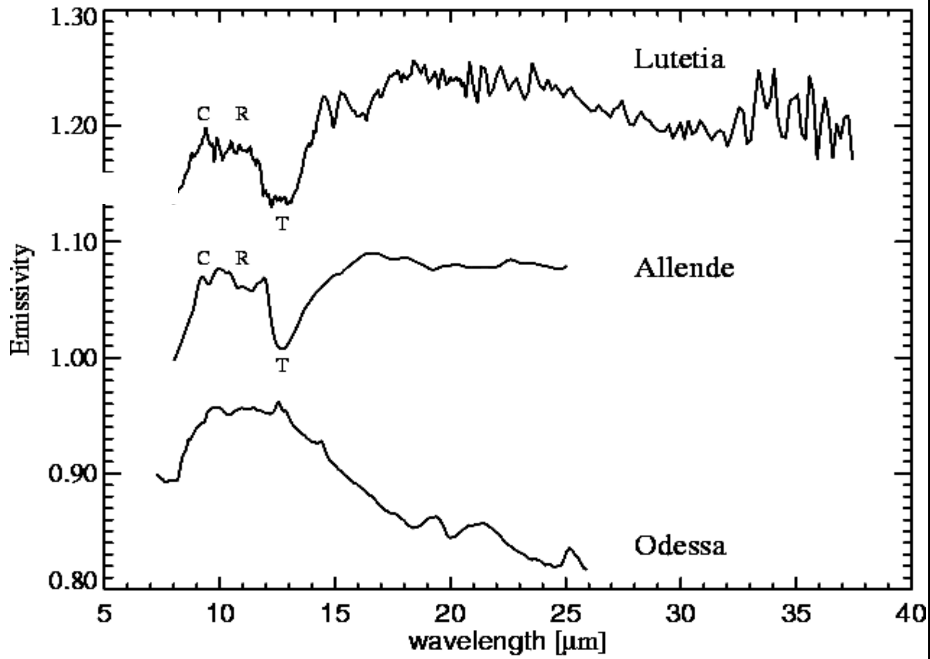
(From Rivkin *et al.*, 2002)



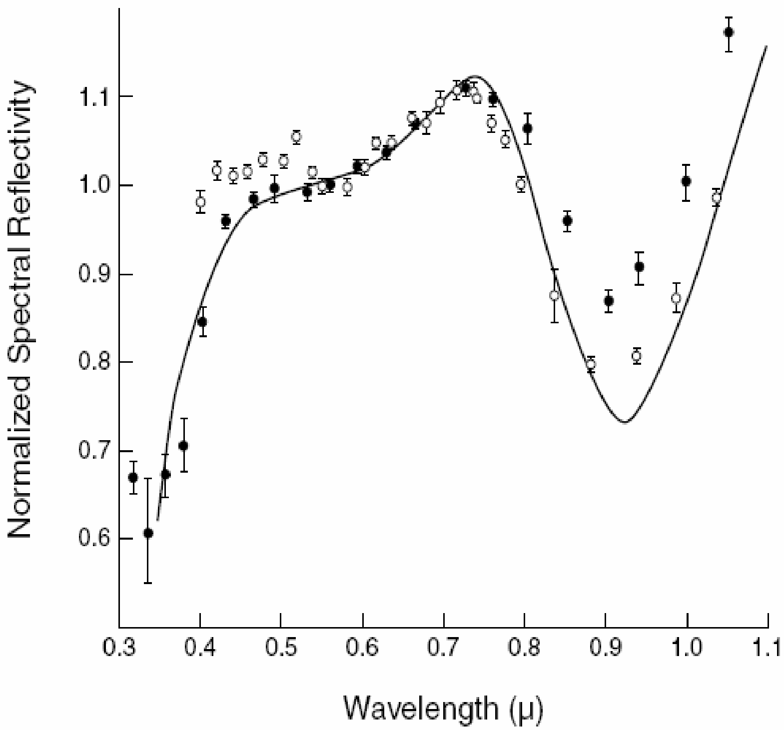
Example: (21) Lutetia, visited by Rosetta, is no longer classified as M-type, since the IR spectra contradict its old classification based on radiometric albedo.

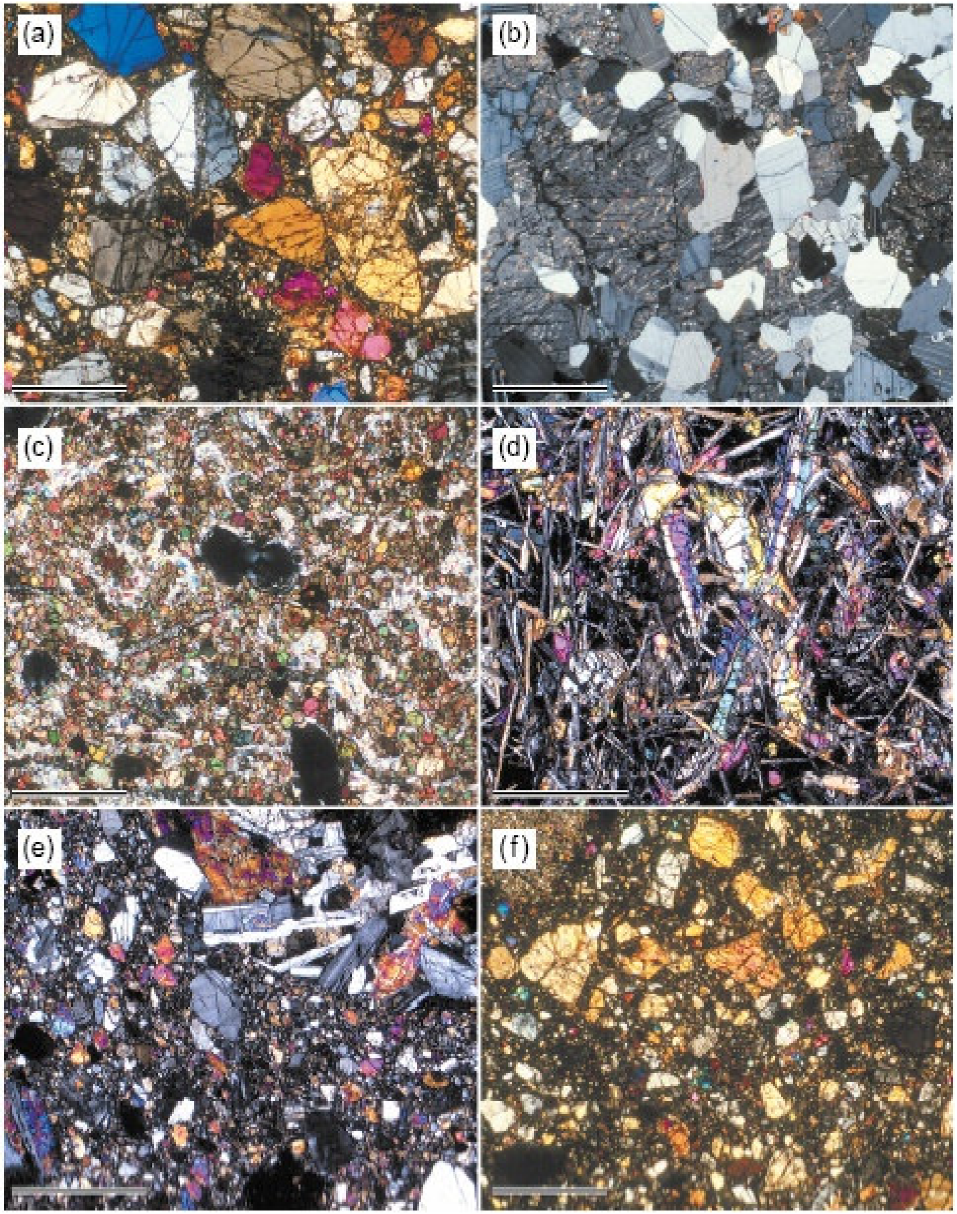


The IR spectrum of Lutetia has little to do with that of the metallic meteorite Odessa, whereas it is very similar to that of the carbonaceous chondrite Allende



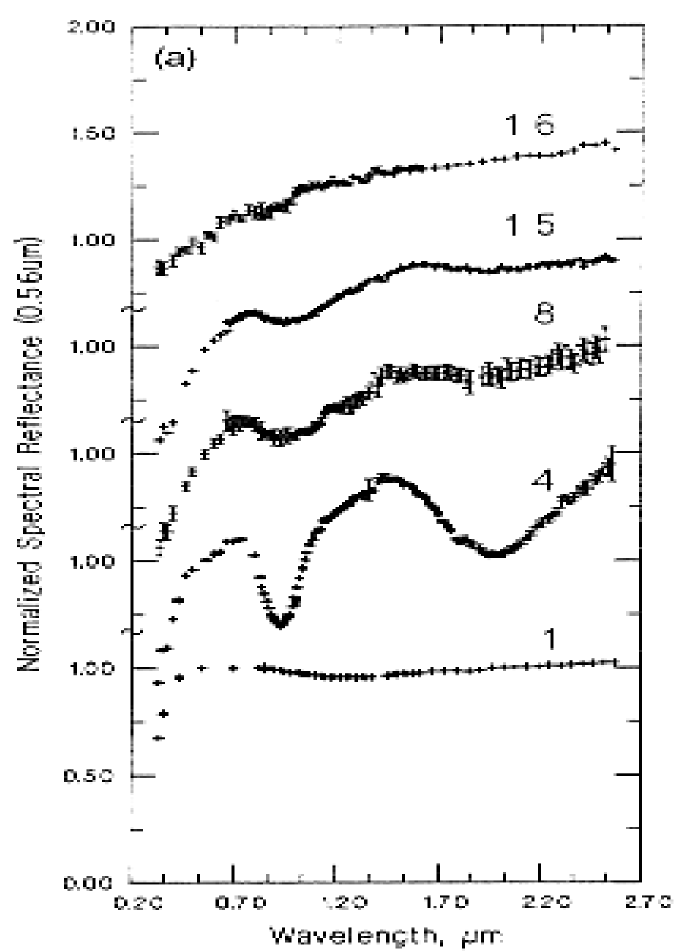
HED meteorites: basaltic composition. Likely pieces of Vesta in our labs.

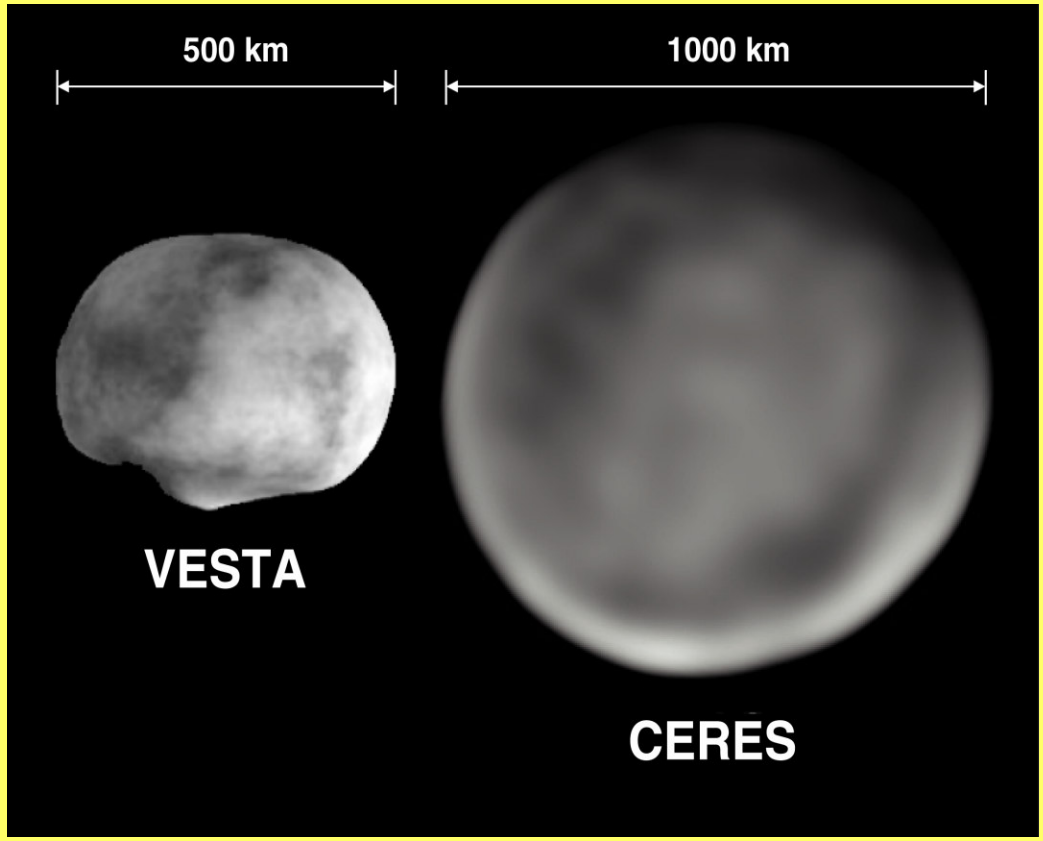




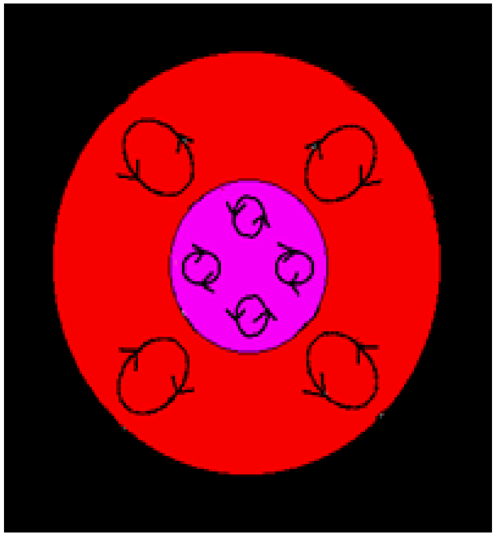
… now waiting for DAWN !

Ceres and Vesta: the big paradox

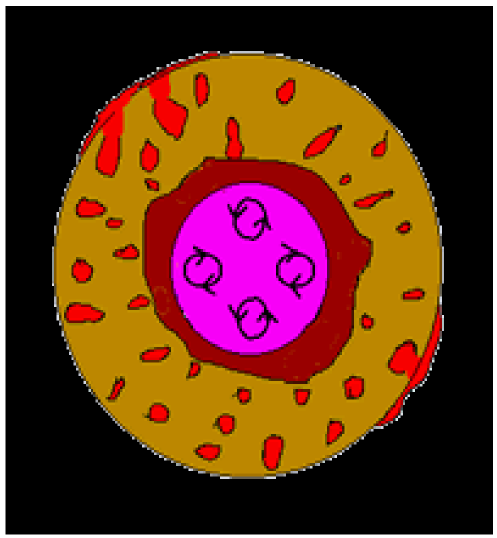




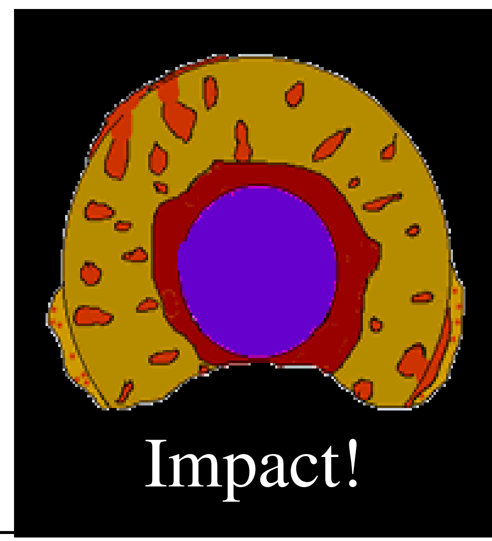
Big Problem: Why are they so different?



Shortly after it formed, Vesta almost completely melted and underwent differentiation. Likely heat source: radiogenic nuclides like Al^{26}



Volcanic eruptions covered Vesta's surface with lava, producing the present basaltic crust



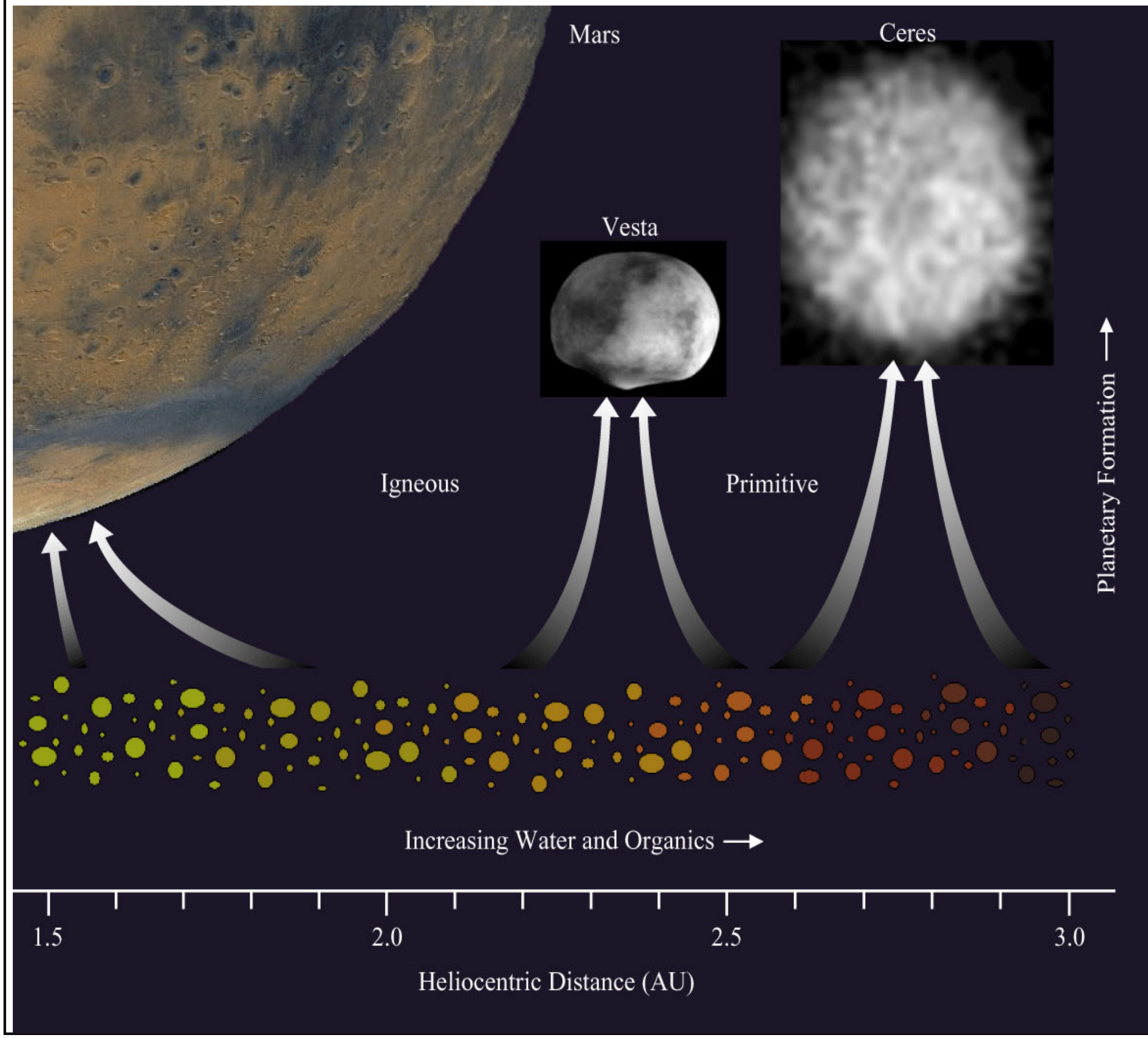
Formation of a big crater and the dynamical family of Vesta (V-type asteroids).

A quick story of Vesta

Properties of Ceres

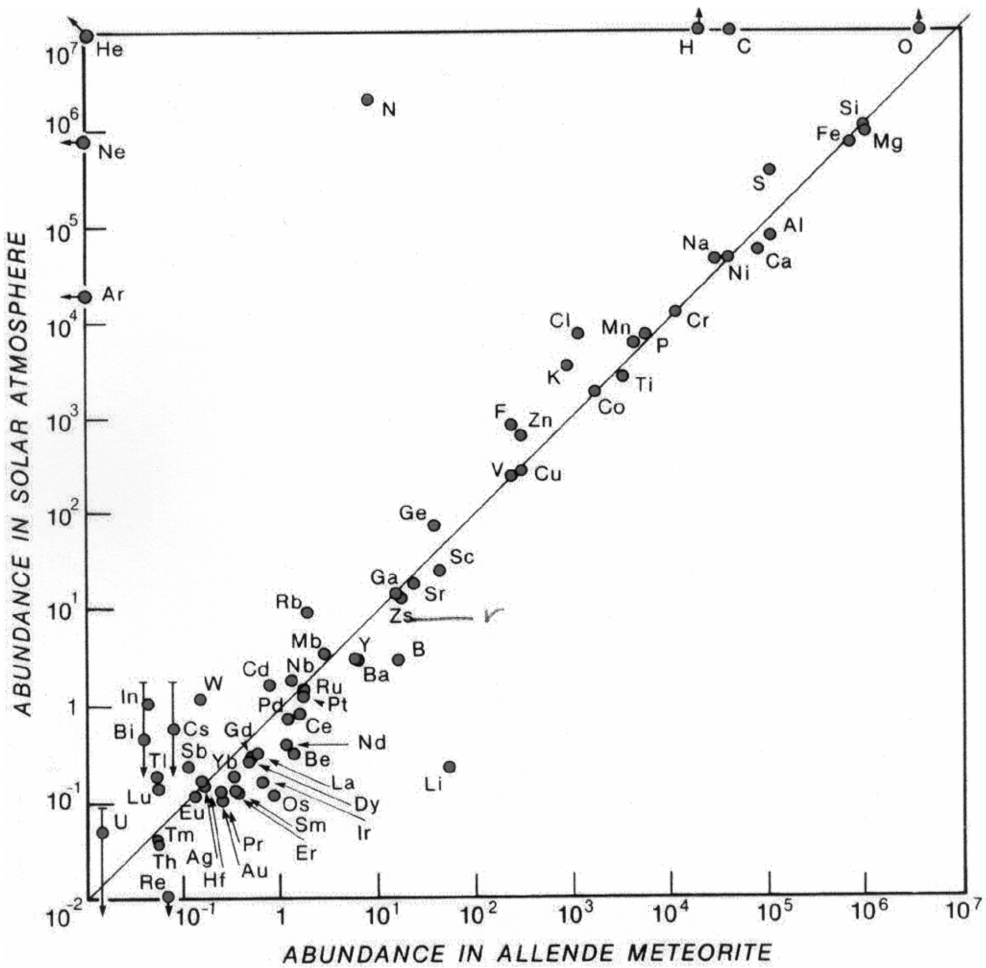
- Ceres is a dwarf planet
- It contains most of the mass between Mars and Jupiter
- It is spectrally similar to primitive Carbonaceous Chondrite Meteorites.
- Water ice and clay minerals have been tentatively detected on its surface
- Ceres might be a possible source of carbonaceous chondrite meteorites, namely the most primitive bodies of our Solar System

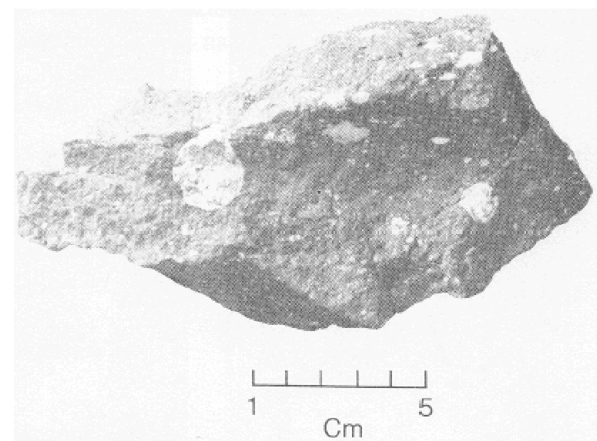
How this is possible ?



Being twice as larger than Vesta, Ceres should have grown even faster. If it was made of the same material of Vesta, it should have experienced full differentiation. Can a reasonable difference in bulk composition adequately explain this puzzle ?

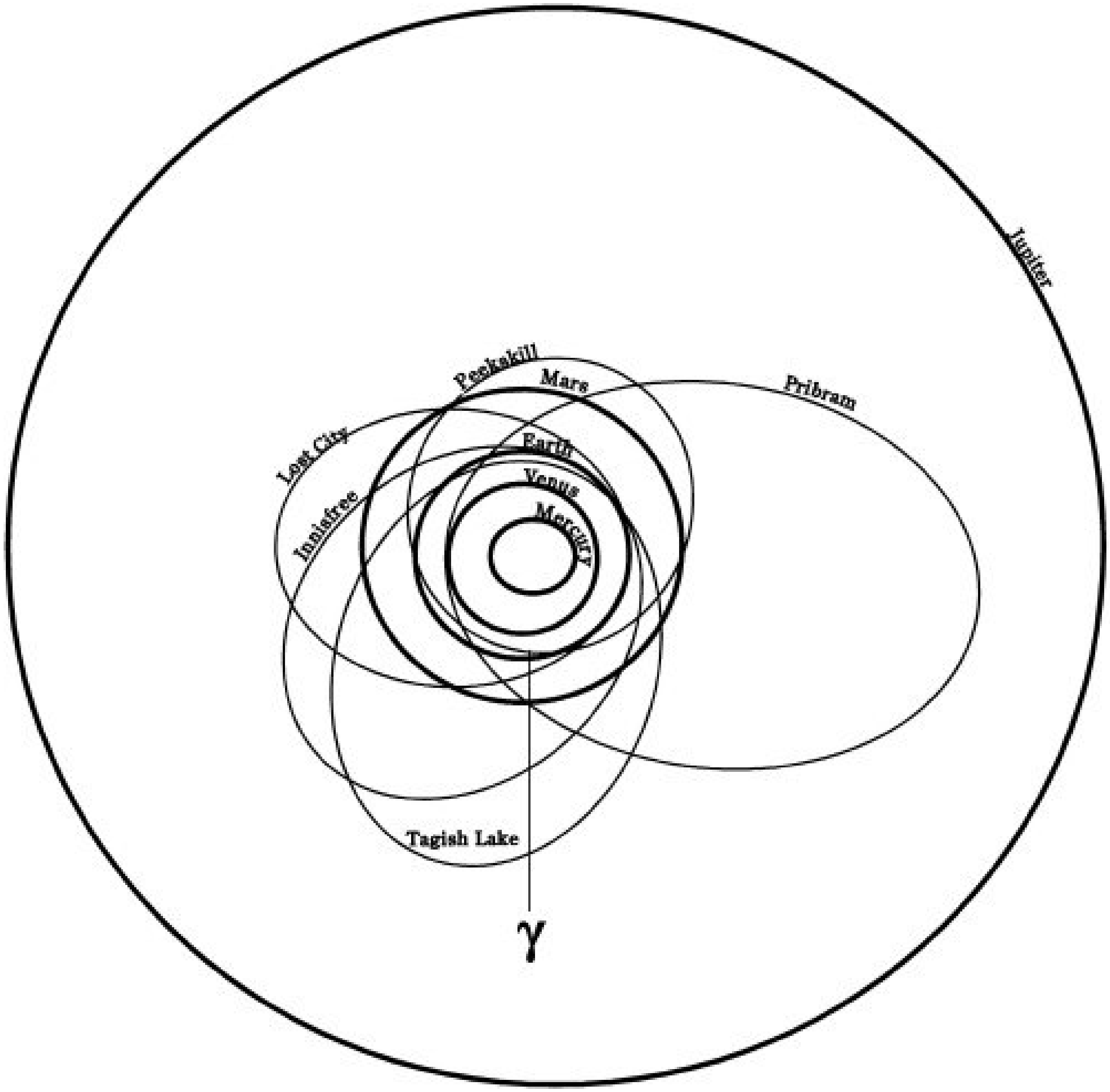
Asteroids belonging to the C taxonomic class bear strict similarities with the most primitive classes of meteorites, the Carbonaceous Chondrites.





Except for the most volatile elements (i.e., more volatile than nitrogen), CI Carbonaceous Chondrites are excellent models of bulk solar system composition.

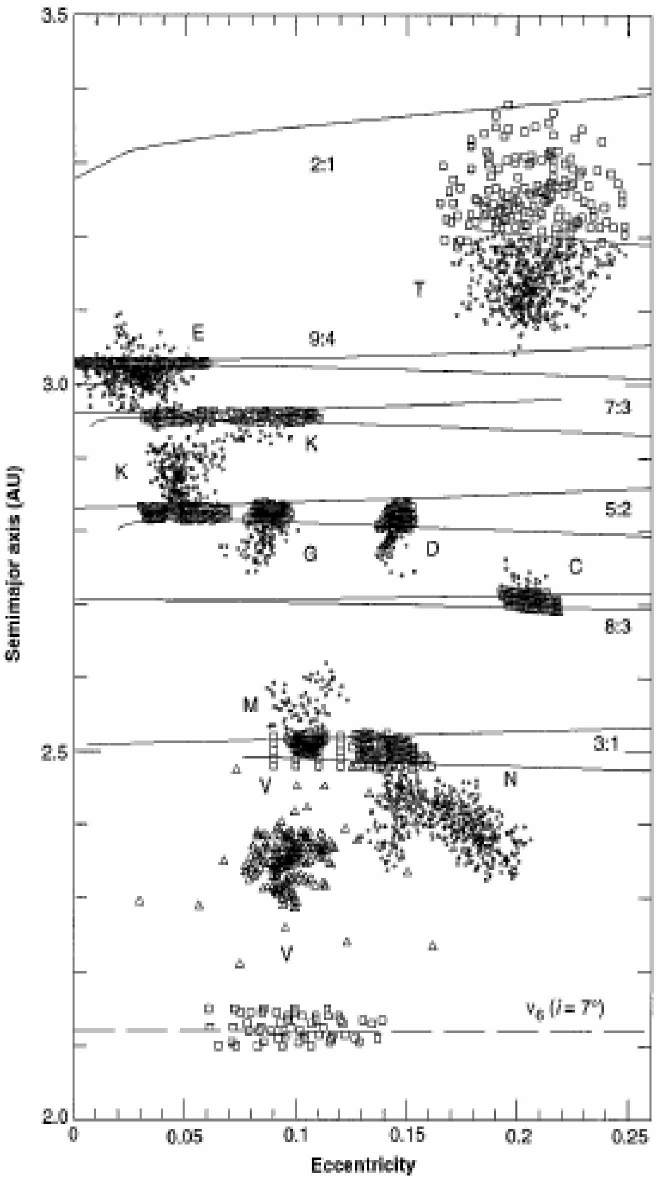
They are the oldest available samples of Solar System material



The orbits of 5 meteorite-producing fireballs. [Brown et al., 2000]

In all known cases, the aphelion of the orbit of the impactor was in the asteroid main belt.

If meteorites come from the asteroid belt, some of the most primitive samples of Solar System material that we have in our labs are asteroid pieces.

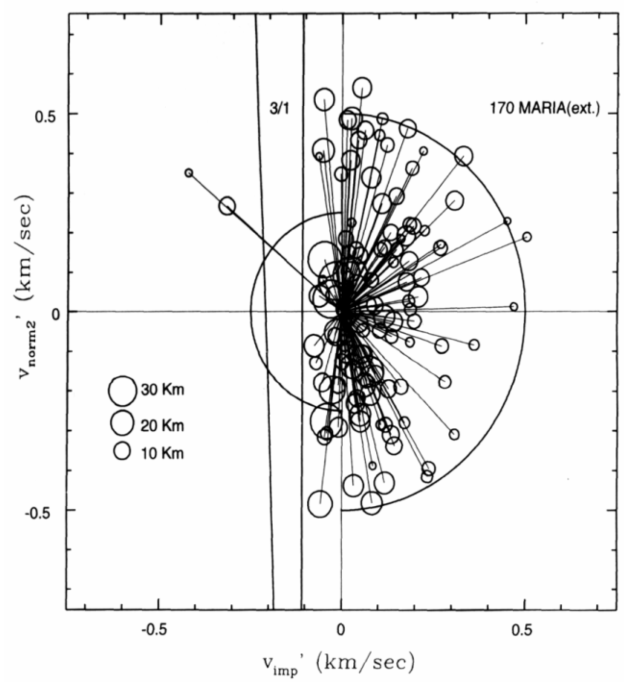


Families as possible sources of near-Earth objects and meteorite showers.

Resonances are dynamical paths from the asteroid main belt to the inner regions

Sooner (immediate injection into resonance) **or later** (Yarkovsky) **they go!**

(From Gladman *et al.*, 1997)



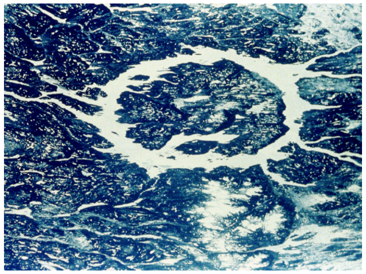
IMPACT FREQUENCIES ON THE EARTH

TUNGUSKA-like (15 MT): 1 every < 1000 years

Tunguska event: June 30, 1908. Devastated area = 2000 km^2

REGIONAL CATASTROPHES (10,000 MT): 1 every 100,000 years

Wolf Creek Crater, Western Australia. Age = 300,000 years, Diameter = 850 m



GLOBAL CATASTROPHES (>1,000,000 MT): 1 every 1-10 million years

Manicouagan Crater, Quebec, Canada, Diameter = 100 km

Schiaparelli and his legacy

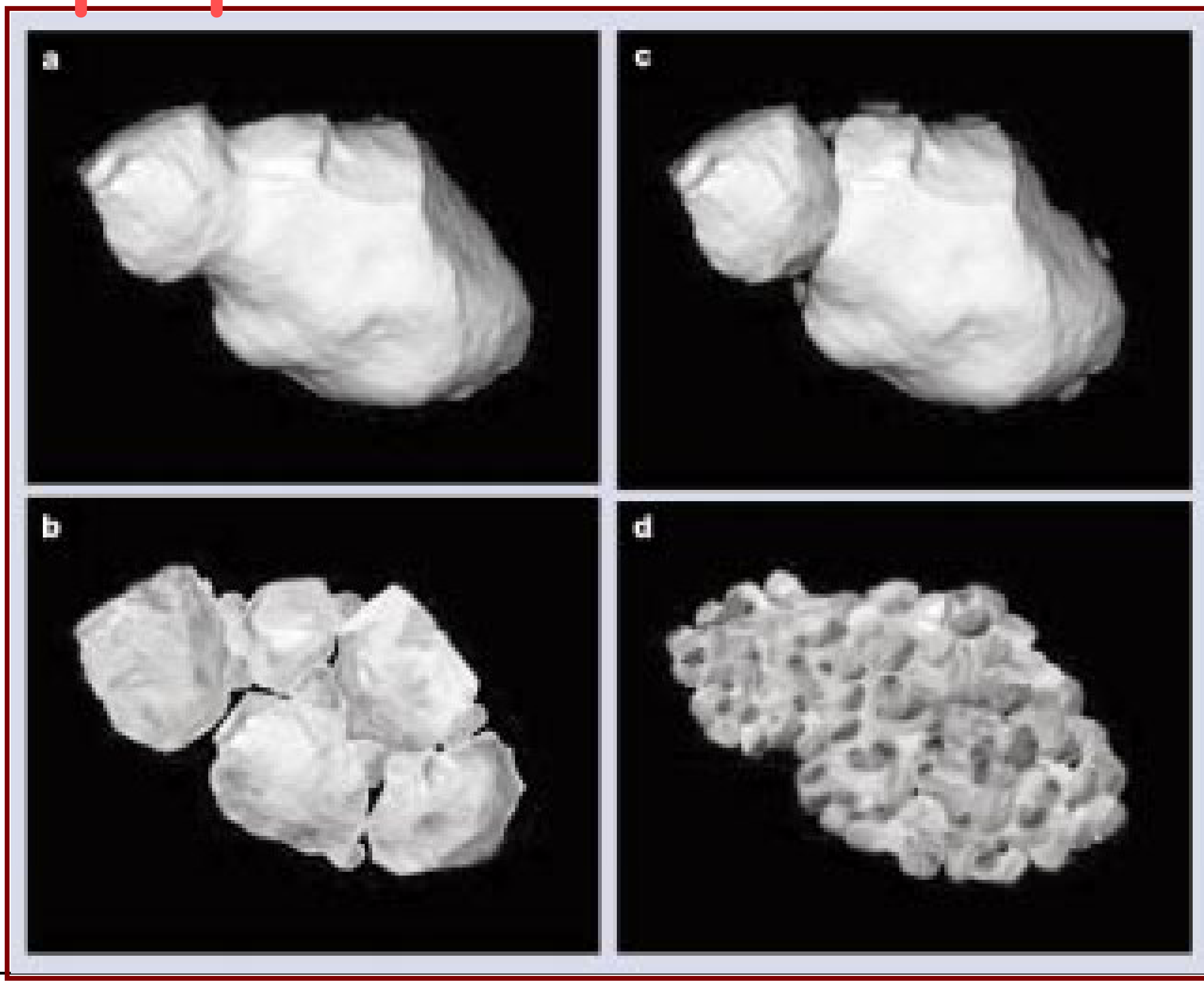
Alberto Cellino – Milano, October 20, 2010

THE TORINO SCALE

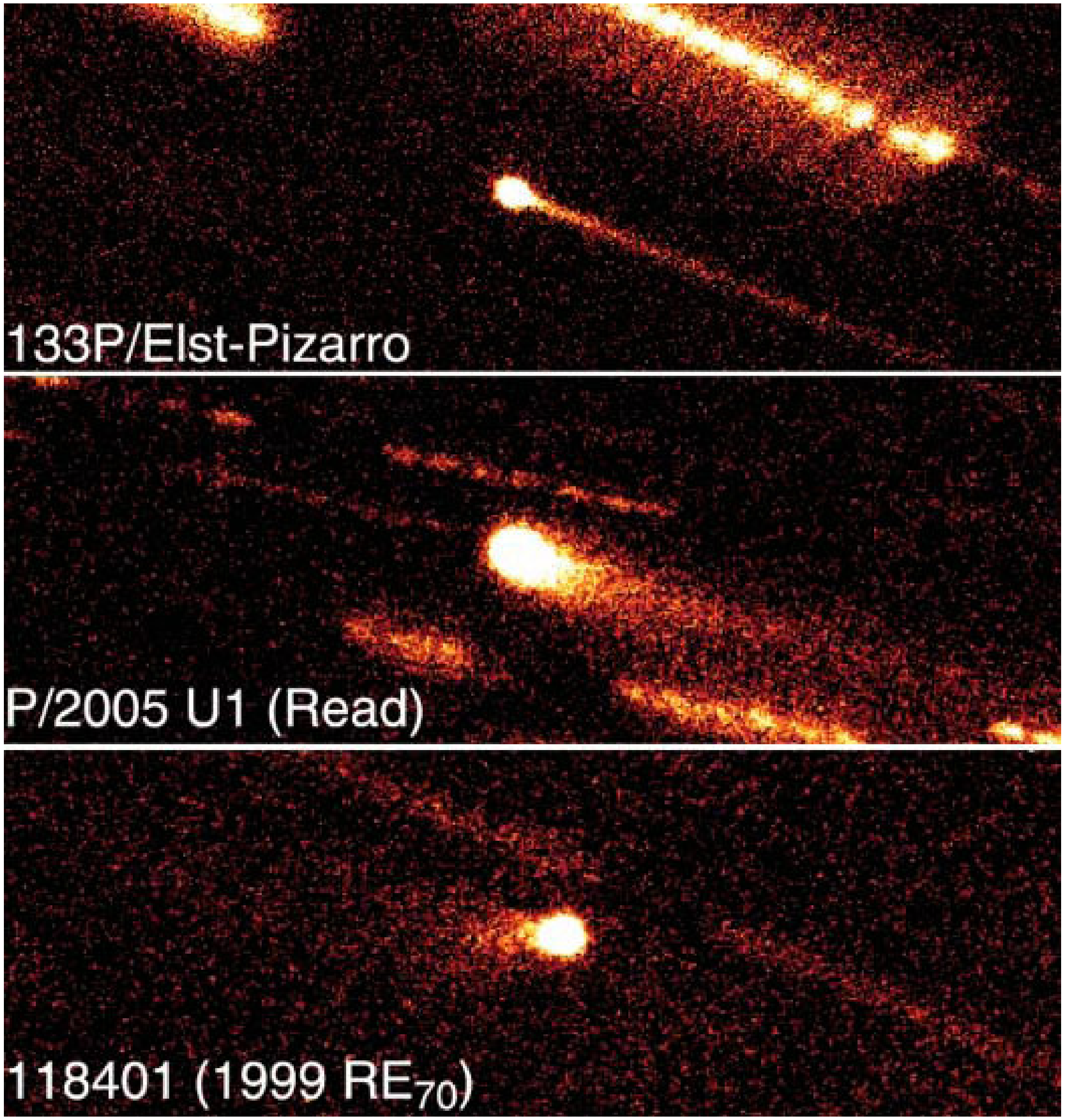
Assessing Asteroid and Comet Impact Hazard Predictions in the 21st Century

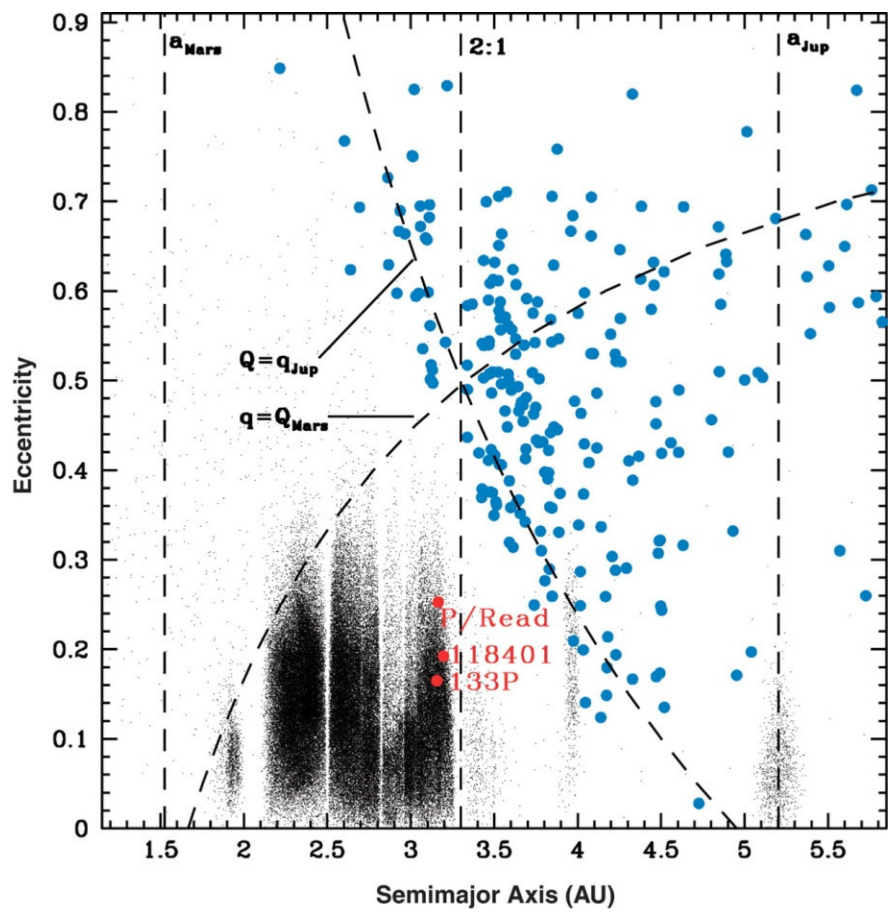
Events Having No Likely Consequences	0	The likelihood of a collision is zero, or well below the chance that a random object of the same size will strike the Earth within the next few decades. This designation also applies to any small object that, in the event of a collision, is unlikely to reach the 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.

The big question for mitigation purposes: What's Inside?



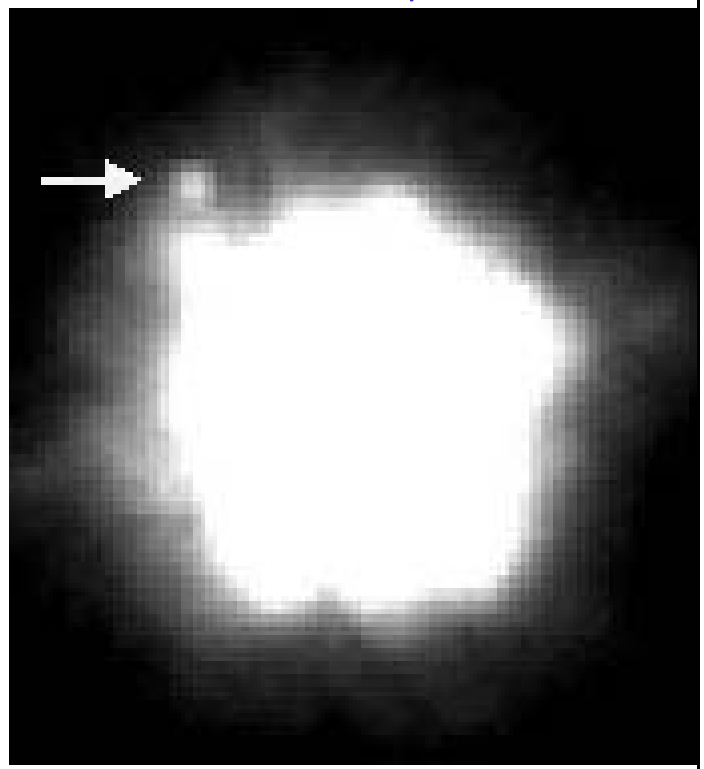
The discovery of main-belt comets



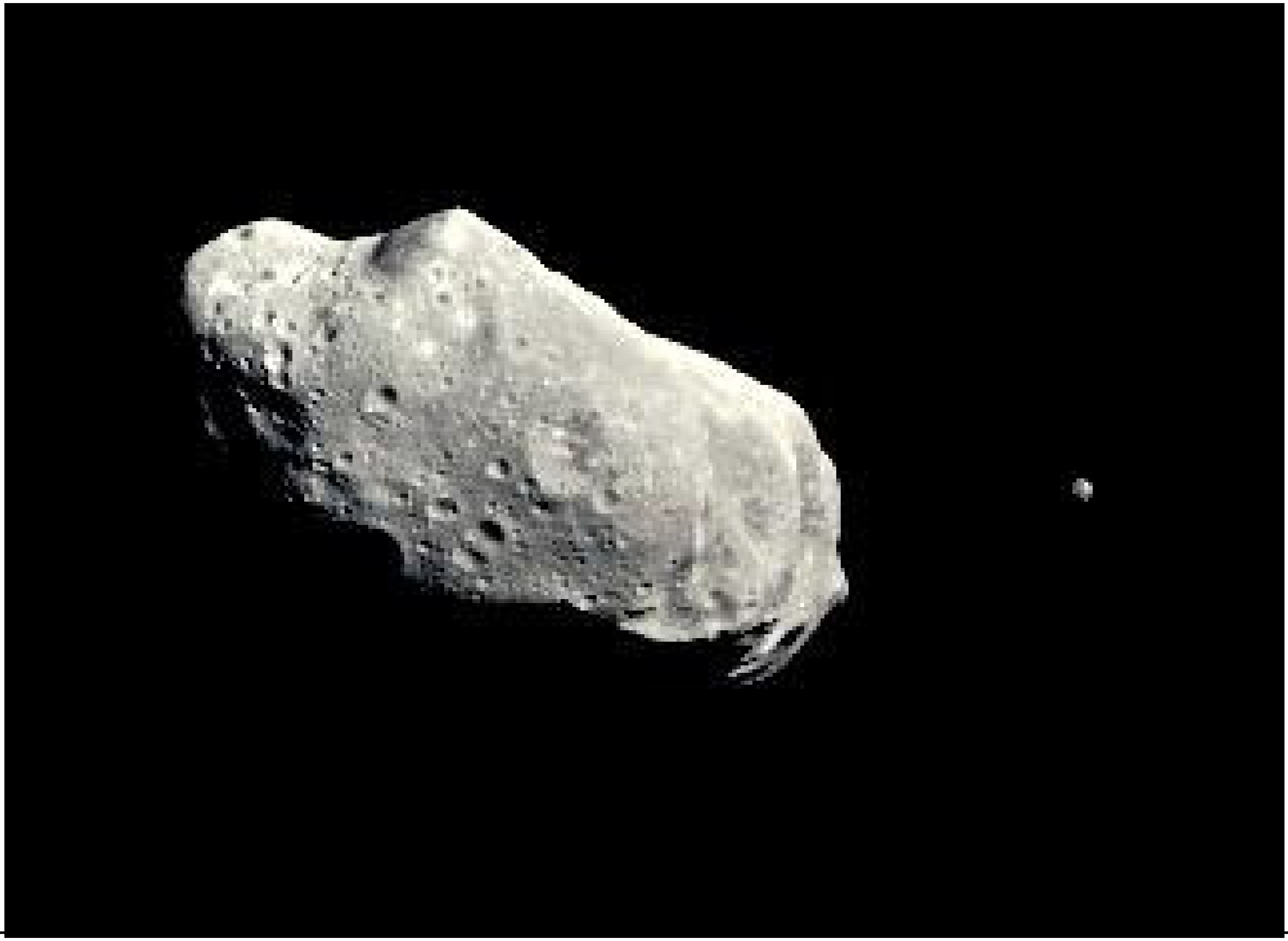


High-Resolution Imaging: The discovery of Binary Systems

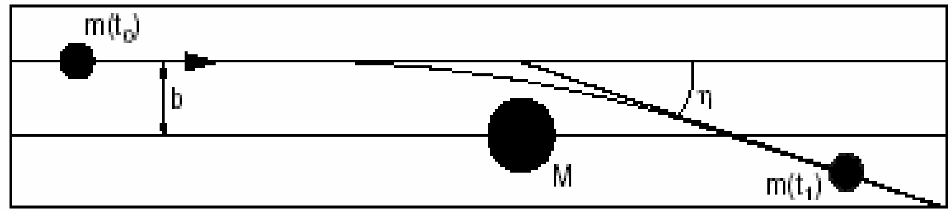
⇐ 90 Antiope, 45 Eugenia ⇓



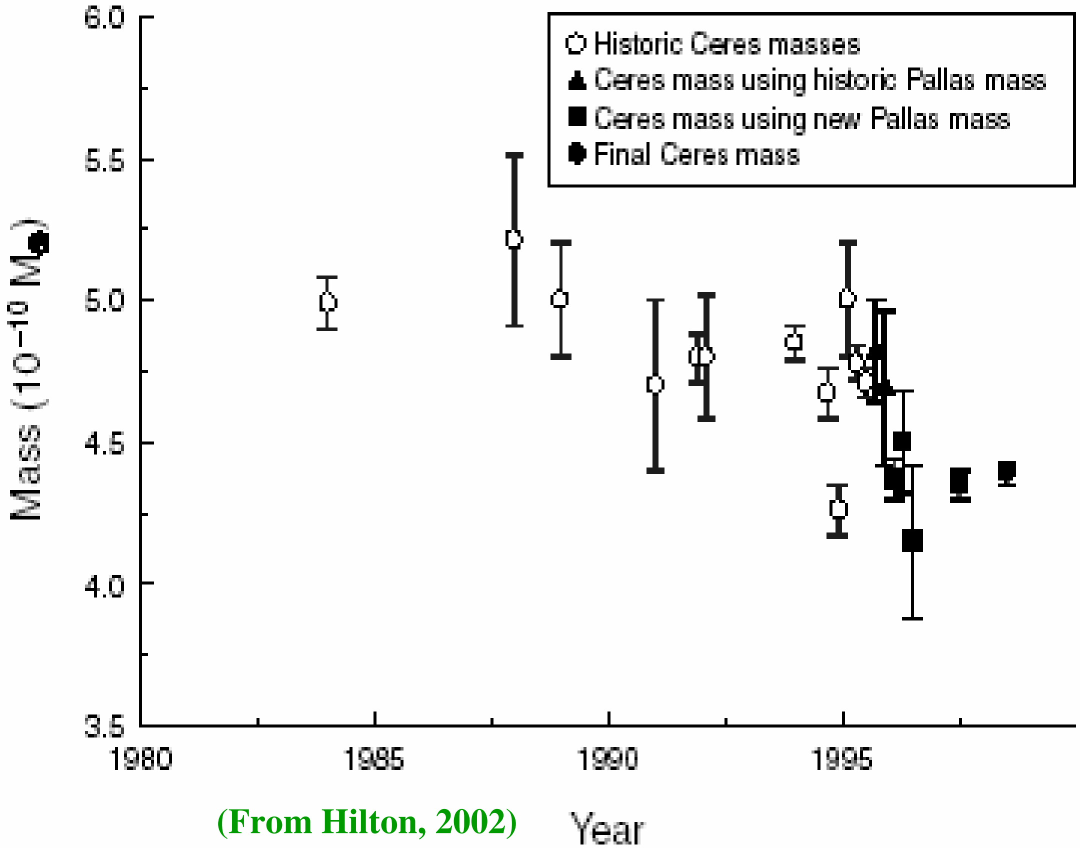
The *in situ* discovery of the first Binary asteroid: Ida



Determination of asteroid Masses: the Classical Technique



Mutual close encounters between asteroids

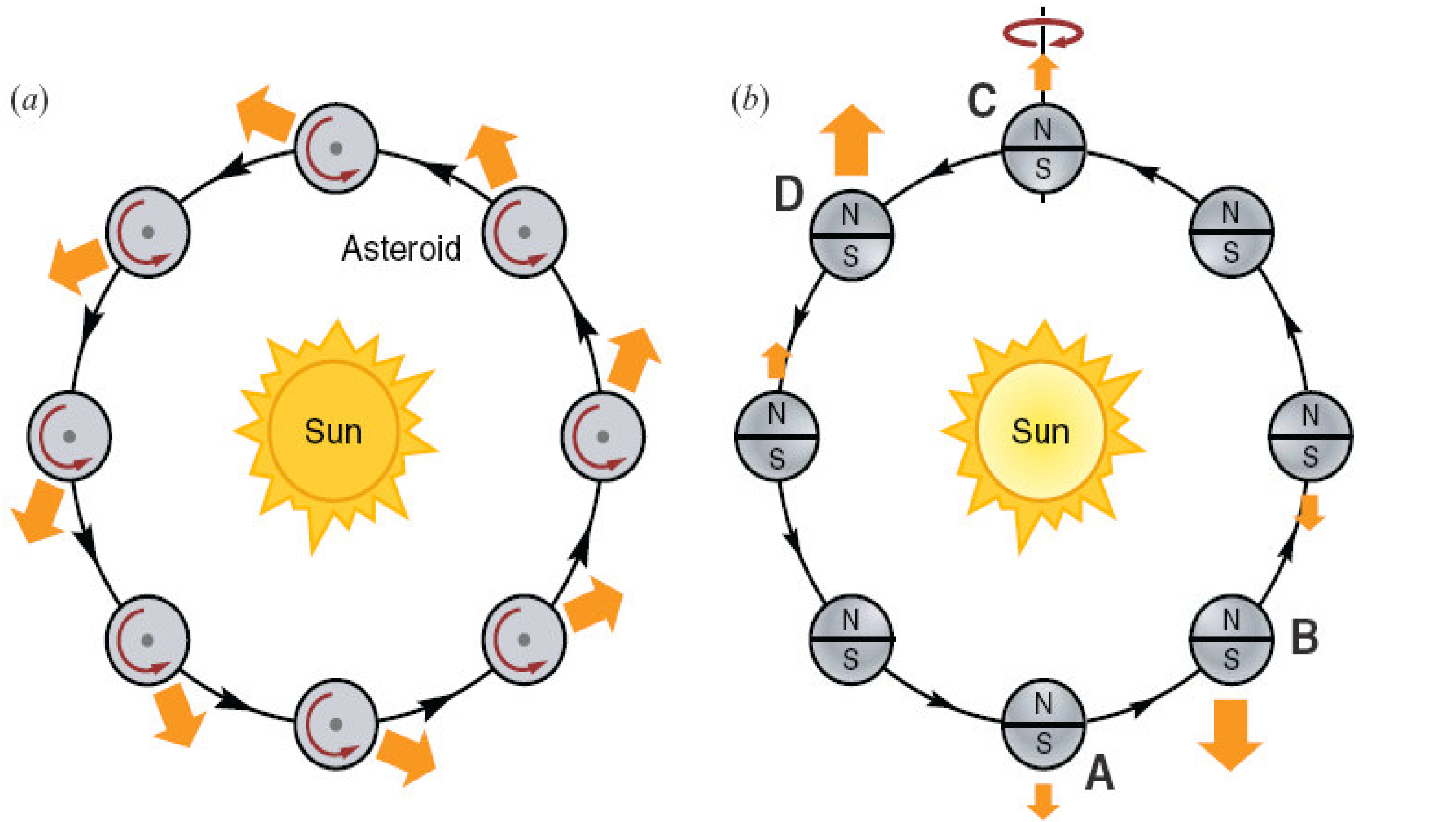


(From Hilton, 2002)

Very big uncertainties !

Waiting for Gaia !!

Recent discoveries: The link between physical and dynamical properties: Diurnal (a) and seasonal (b) Yarkovsky effect



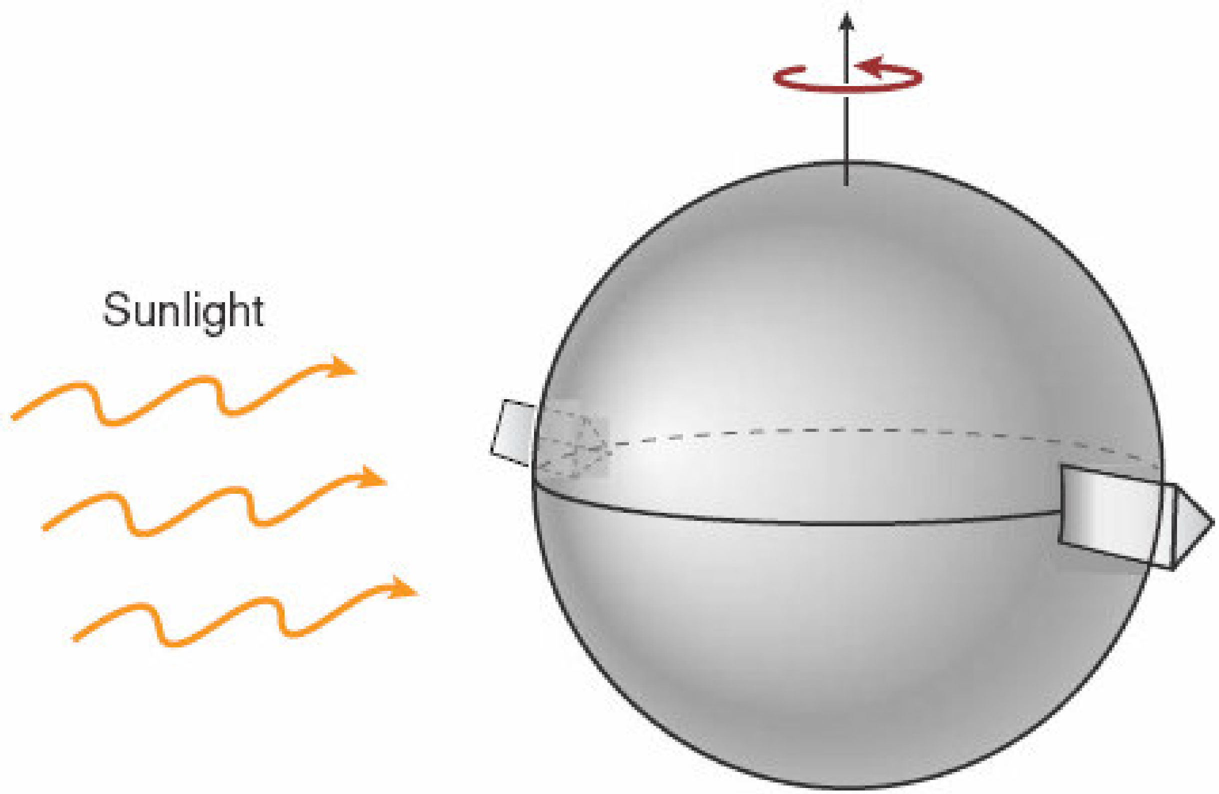
The value of the Yarkovsky acceleration depends on many physical parameters:

- Obliquity angle
- Spin rate
- Object size (it vanishes for both large and very small sizes)
- Surface conductivity (thermal inertia)
- Heliocentric distance: $(da/dt) \approx a^{-2}$

Very nice example of a link between physical and dynamical properties. The problem is that the effect is intrinsically quite complicated.

The YORP effect

(Yarkovsky-O'Keefe-Radzievskii-Paddack)



Spin up of an asymmetrical asteroid. The asteroid is modeled as a sphere with two wedges attached to its equator. The asteroid is considered a blackbody, so it absorbs all sunlight falling on it and then reemits the energy in the infrared as thermal radiation. Because the kicks produced by photons leaving the wedges are in different directions, a net torque is produced that causes the asteroid to spin up.

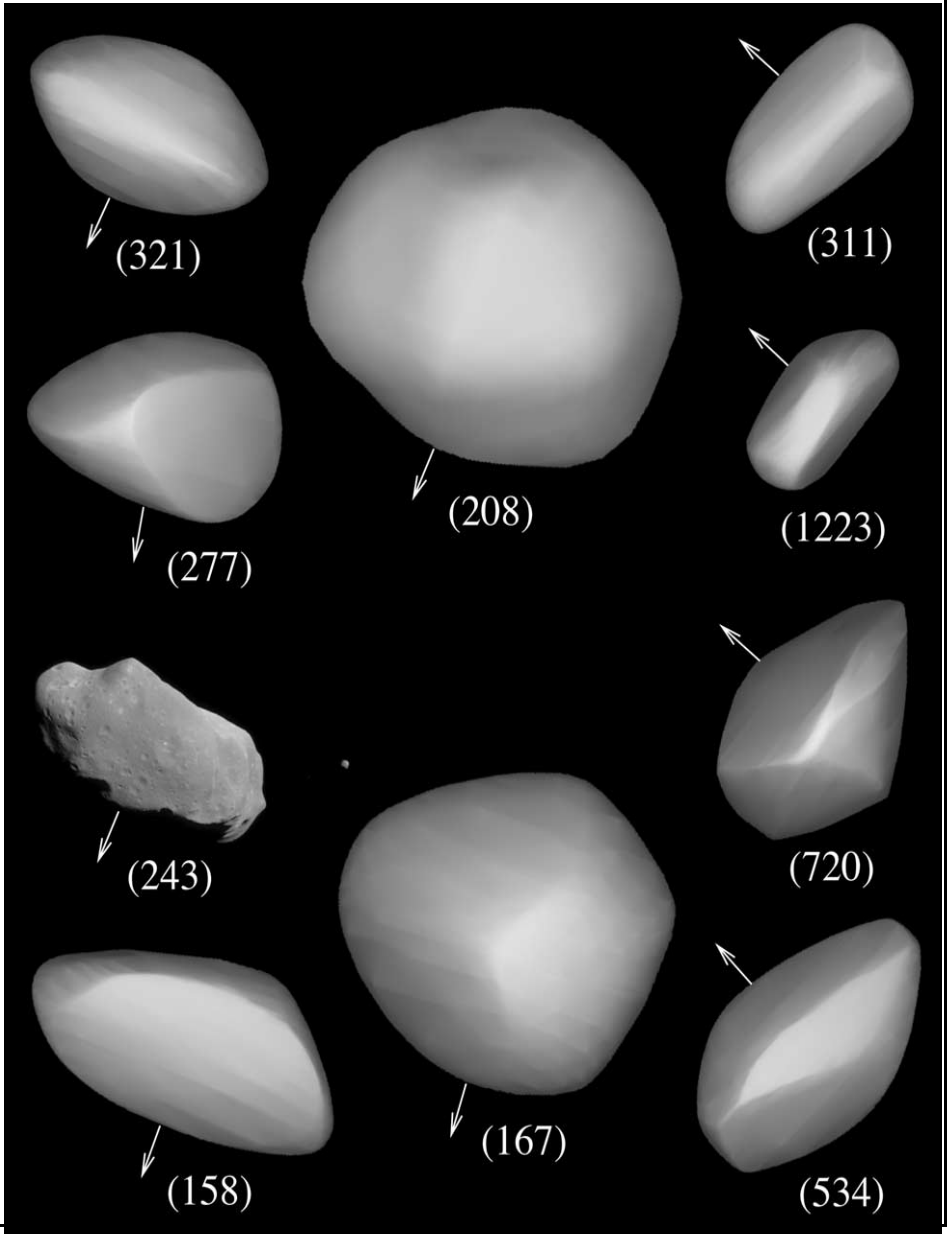
Expected evolution of spin period and obliquity angle

Koronis Family

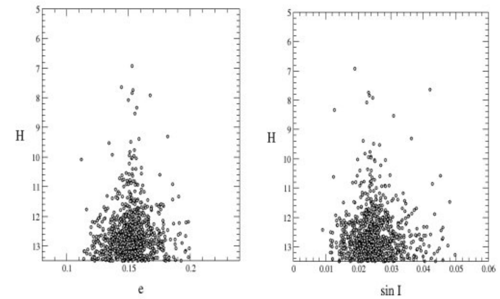
Distribution of spin axis directions from extensive photometric observations

Bimodality produced by the original collision, or by YORP evolution ?

Waiting for Gaia photometric data inversion



Problems



- Up to which size Yarkovsky is really effective?
- Does YORP strengthen or weaken Yarkovsky?
- Explanations of D *vs*. Proper elements relations
- Need of putting together the effects of events having different, and size-dependent time scales (resonance crossing, resonance-driven dynamical evolution, spin axis collisional realignment).
- Real families have *e* and *i* distributions which look often more dispersed than Yarkovsky-based simulations.
- Initial family structures not known *a priori*. Can they be estimated from the distributions of the largest members?

Summarizing:

Minor bodies are interesting and show a great diversity.

They include objects with different histories, which experienced different thermal evolutions.

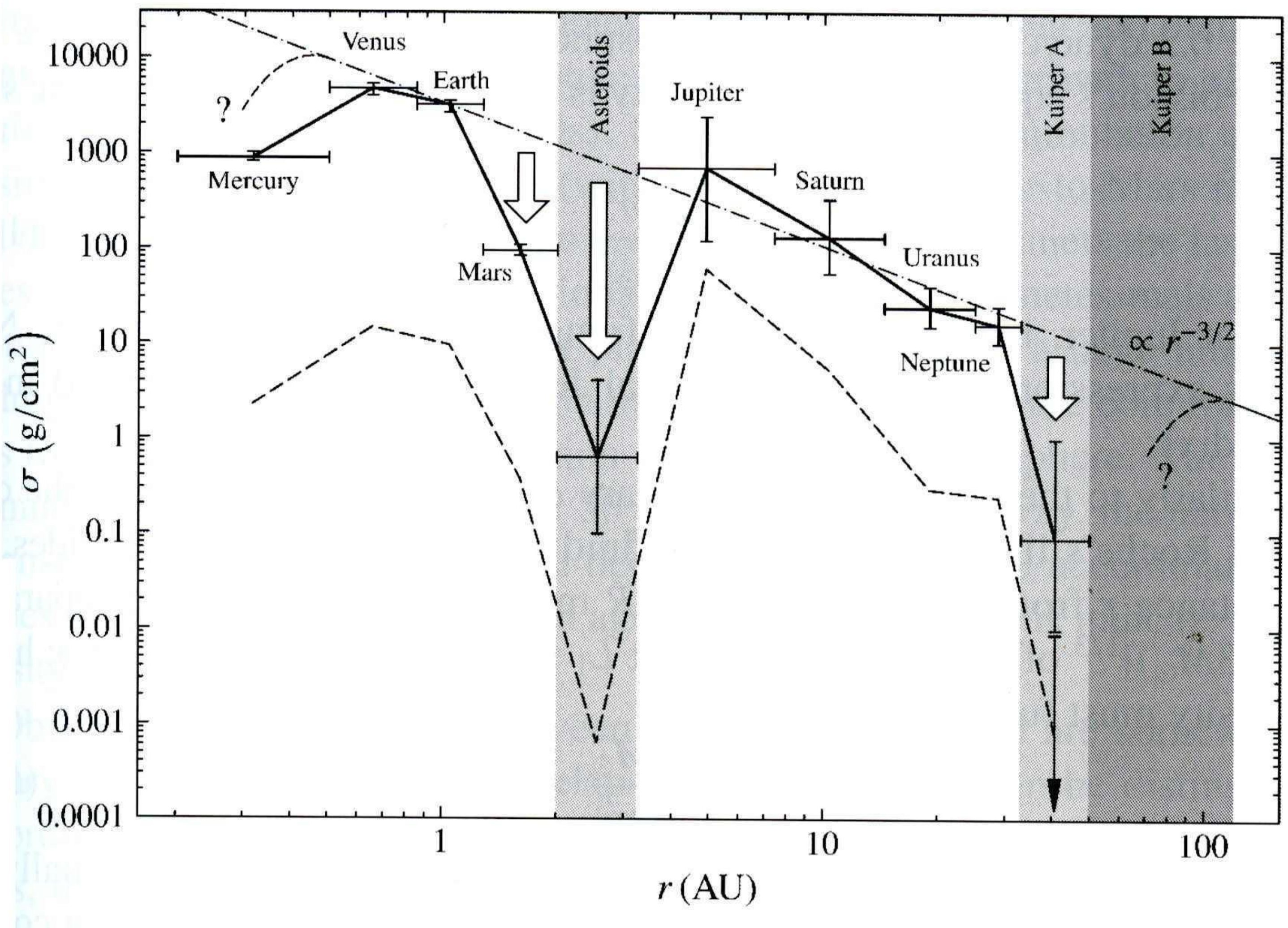
Samples of the most primitive material in the Sol.System.

Role of collisions and non-gravitational effects.

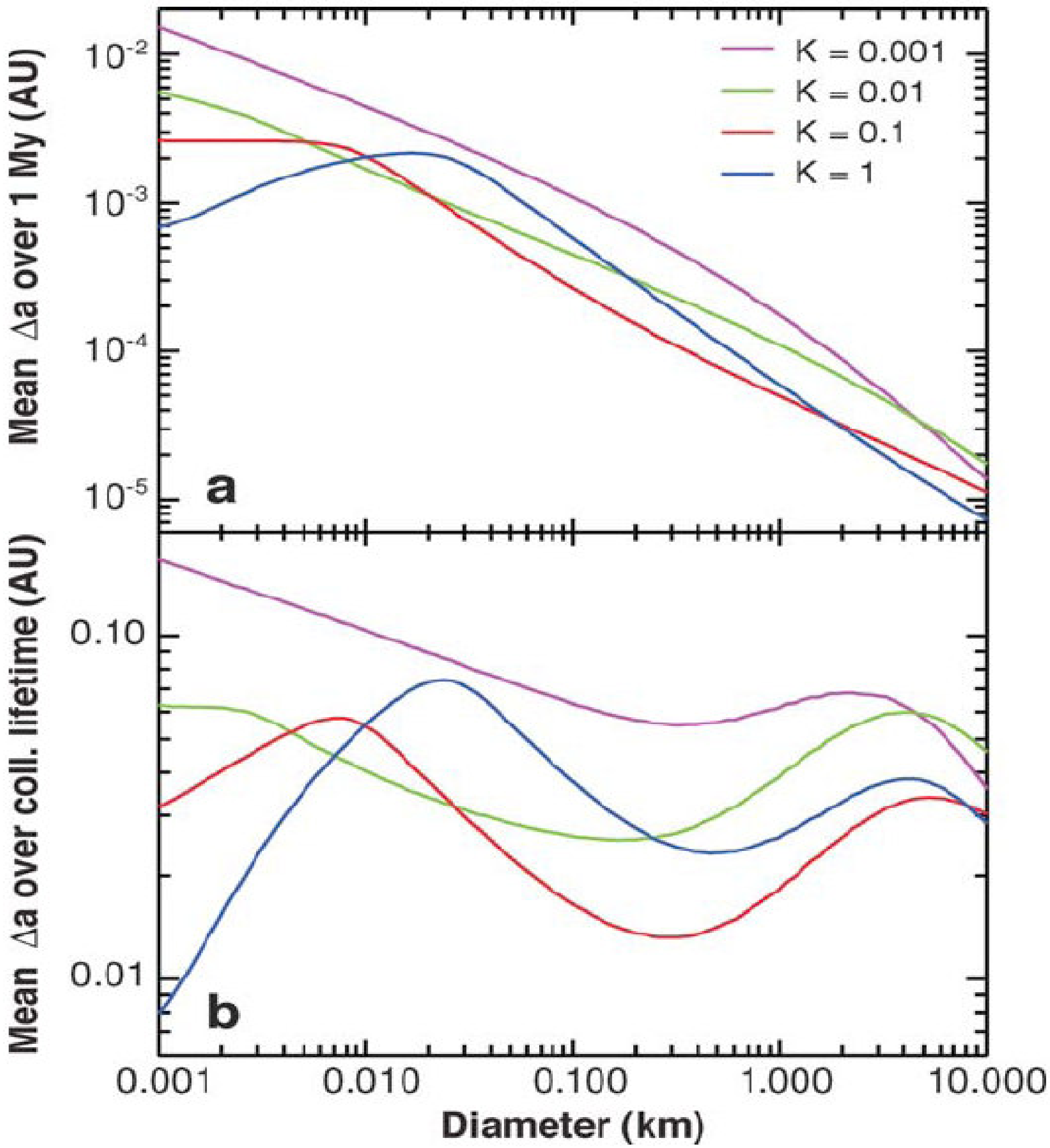
Binary systems are frequent.

Open problems: Inventory and size distribution; Ceres-Vesta paradox; internal structures; Yarkovsky effect; masses and densities; Main-Belt Comets; Barbarians; impact risk , etc., *only to mention asteroids*.

Thank you



The region occupied by the asteroid belt is severely depleted in mass.

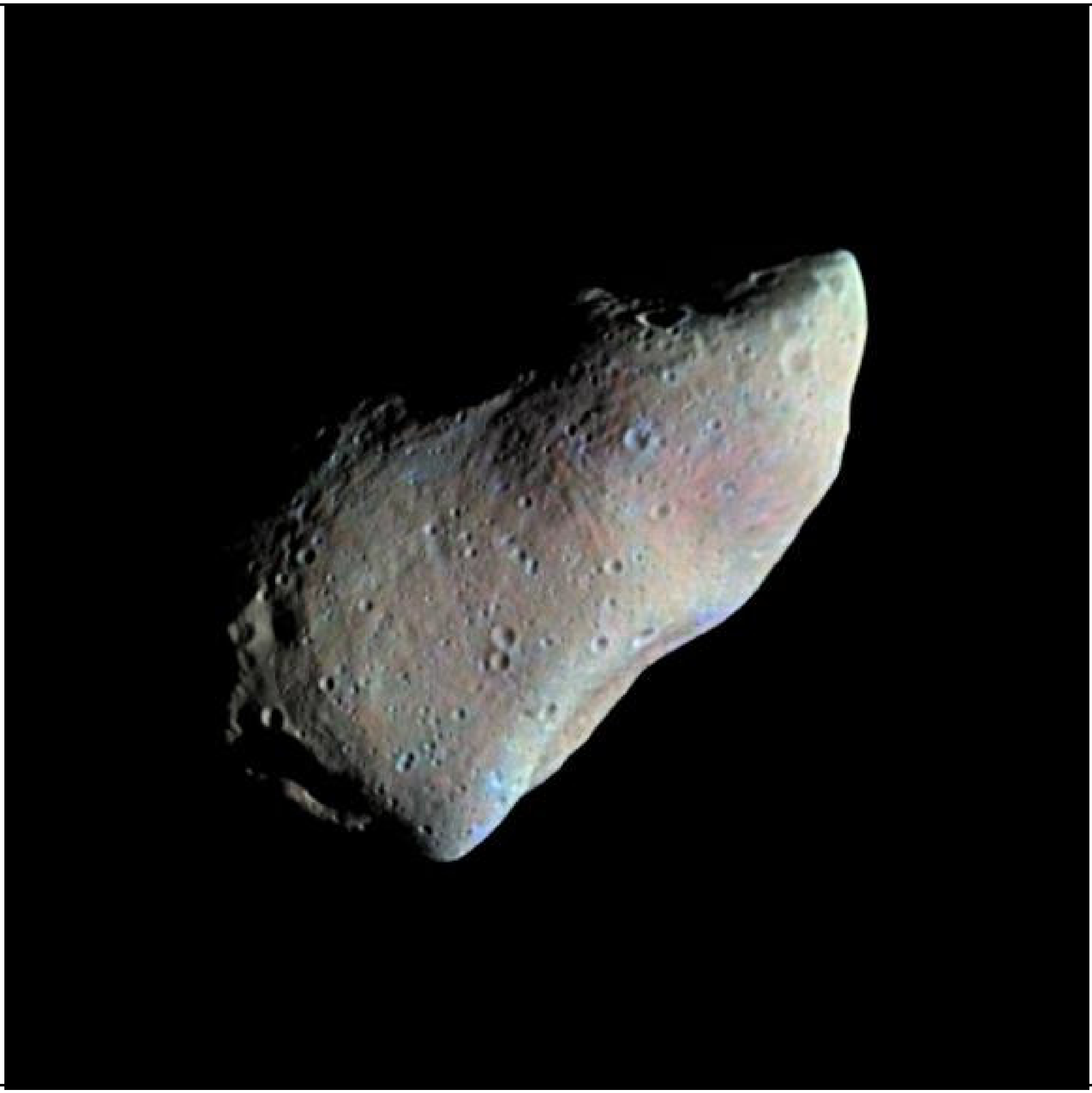


Computed mean drift rates in semi-major axis produced by the diurnal Yarkovsky effect in the inner belt for different possible values of thermal surface conductivity K (W/m^2)

(a): 1 My

(b): collisional lifetime

(Bottke *et al.*, 2006)

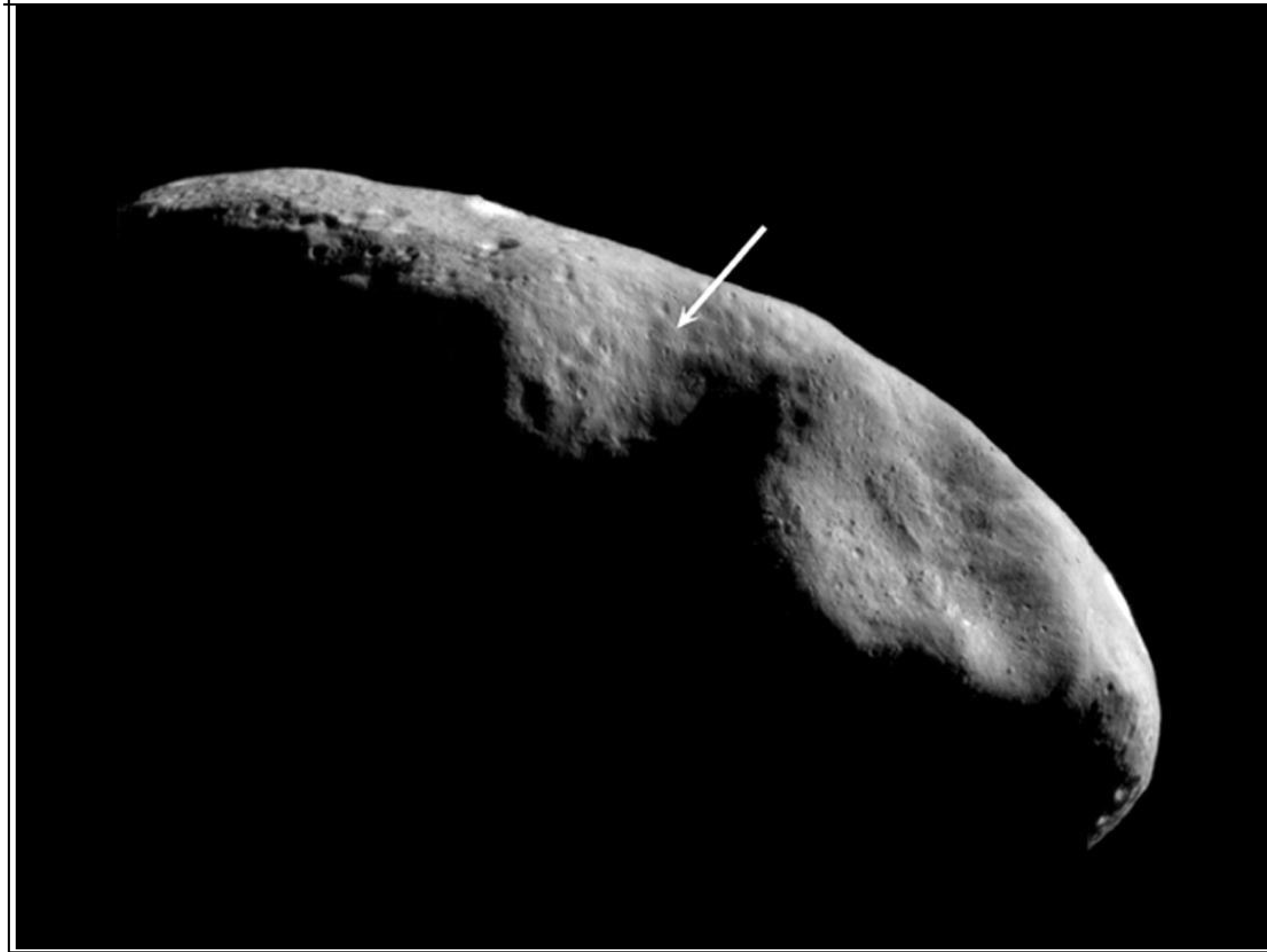


Gaspra

19 X 12 X 11 Km

GALILEO

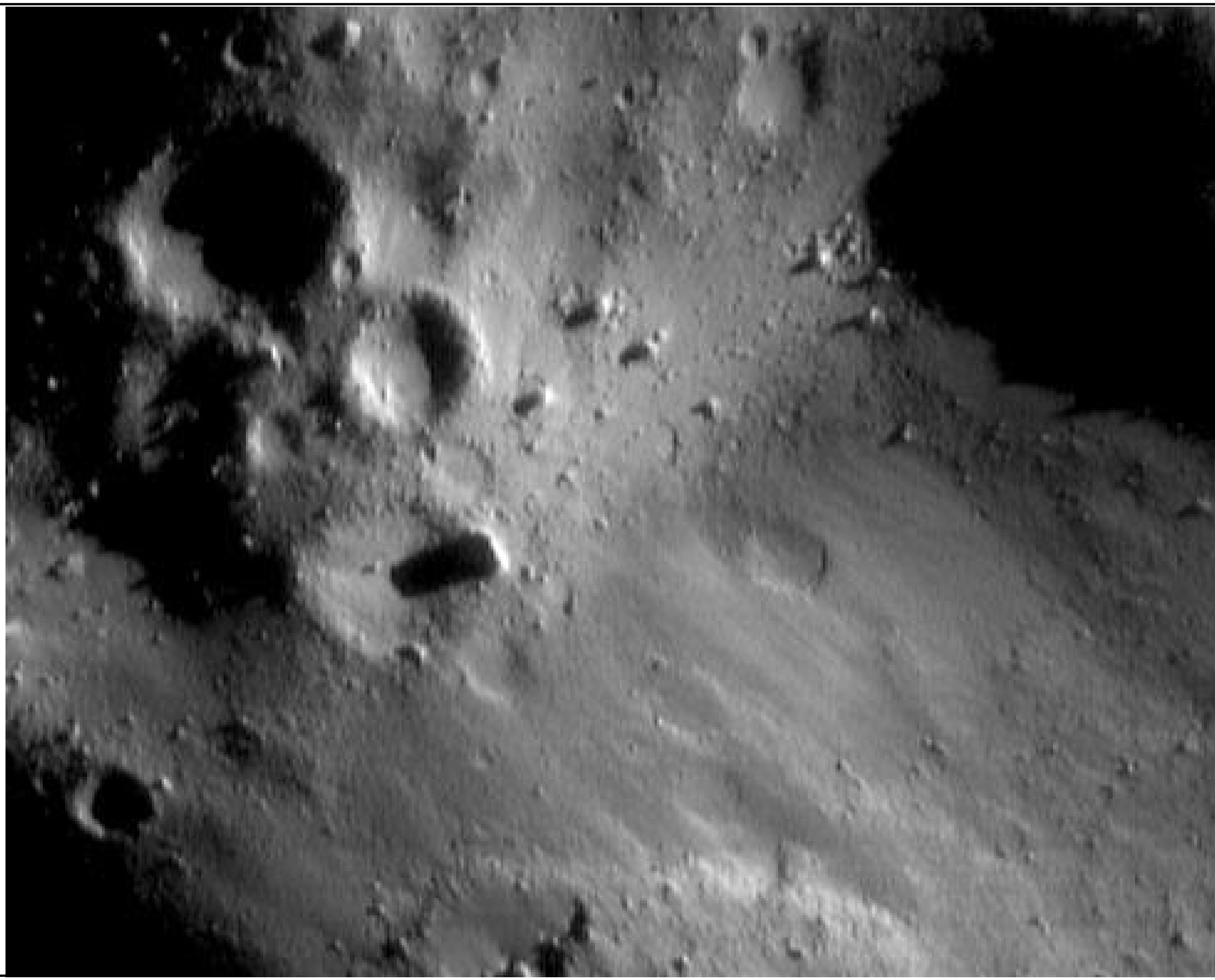
Mathilde 66 X 48 X 46 Km NEAR

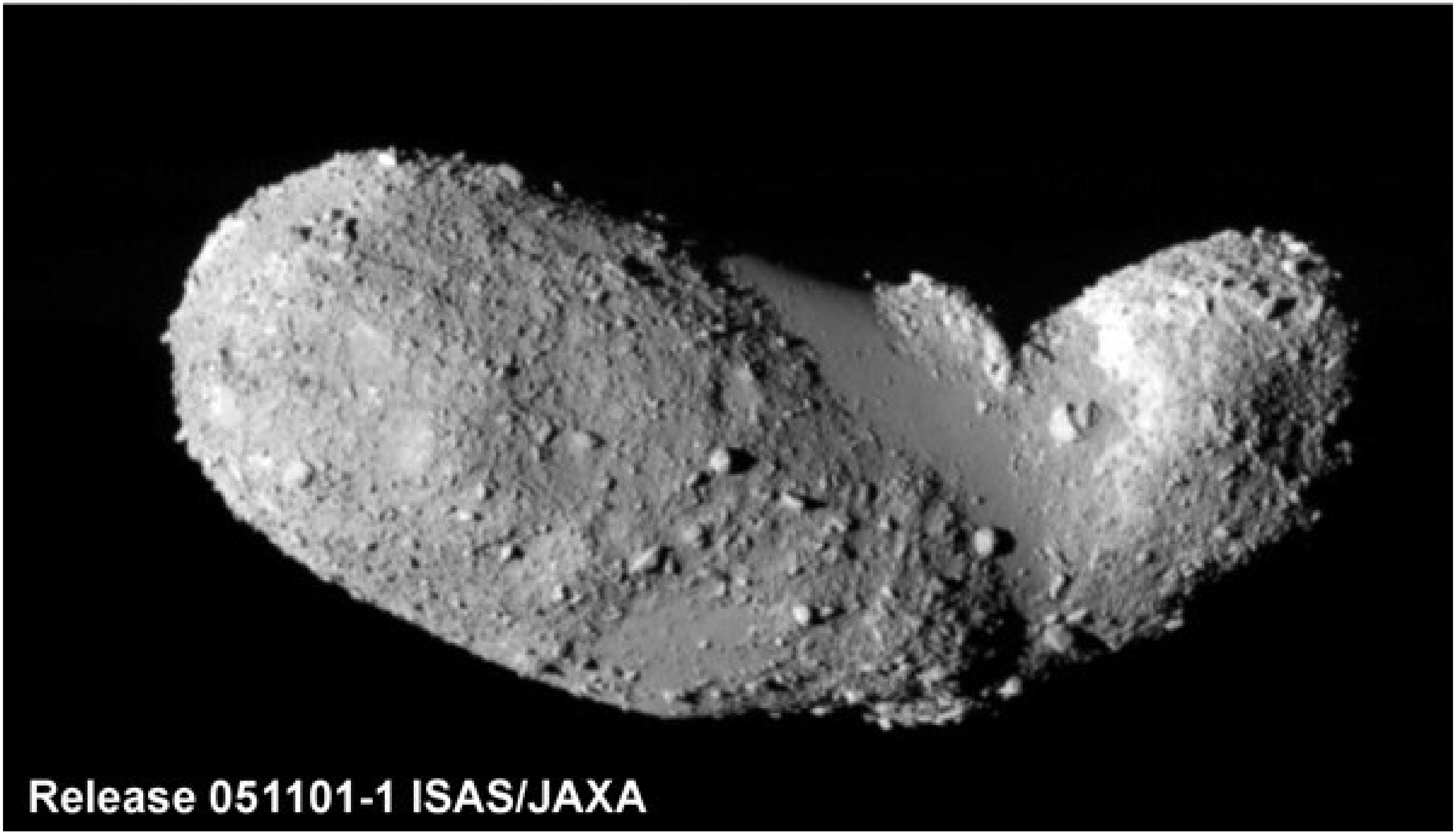


Eros

31 X 13 X 13 Km

NEAR





(25143) Itokawa

535 X 294 X 209 meters