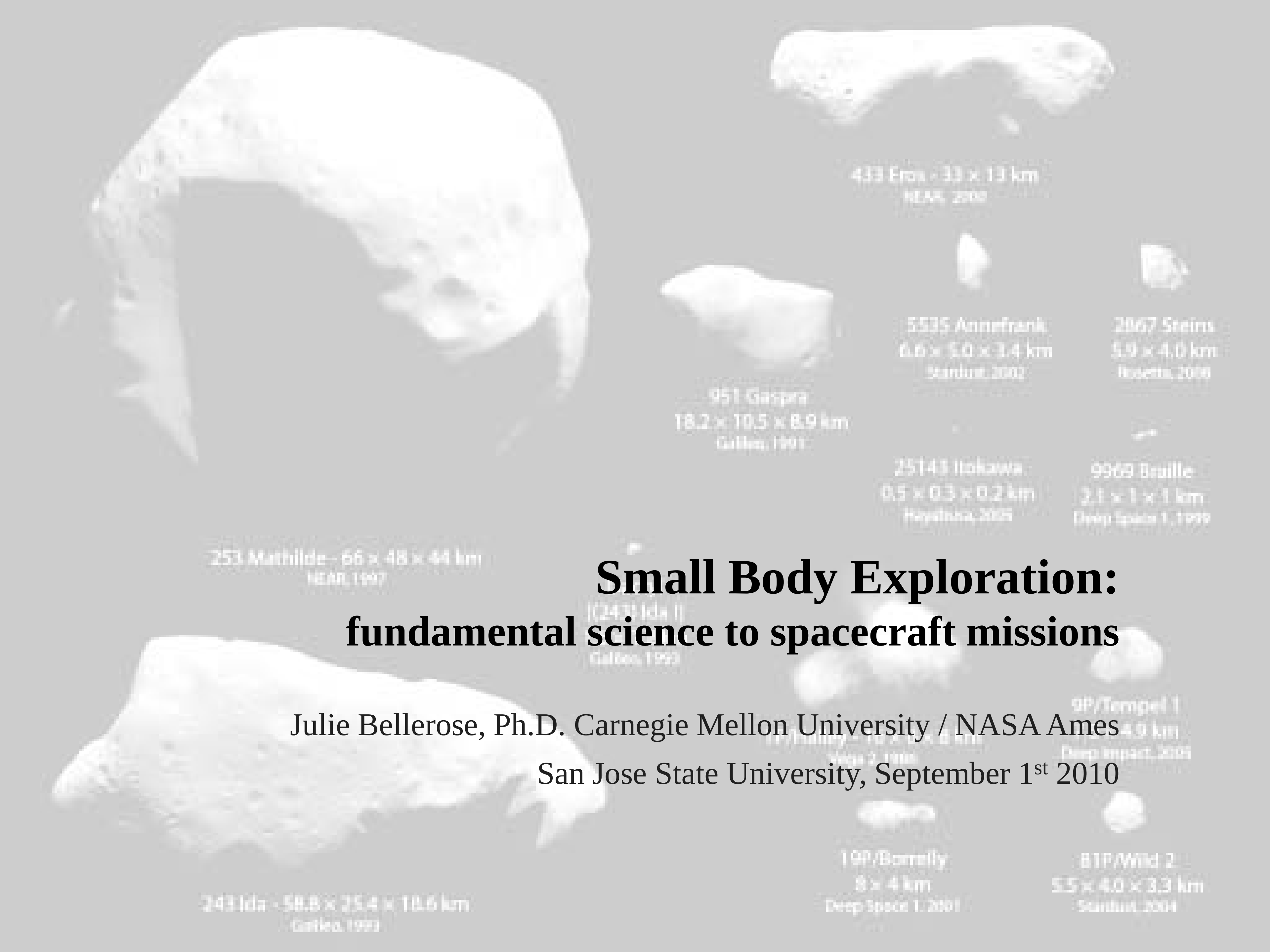
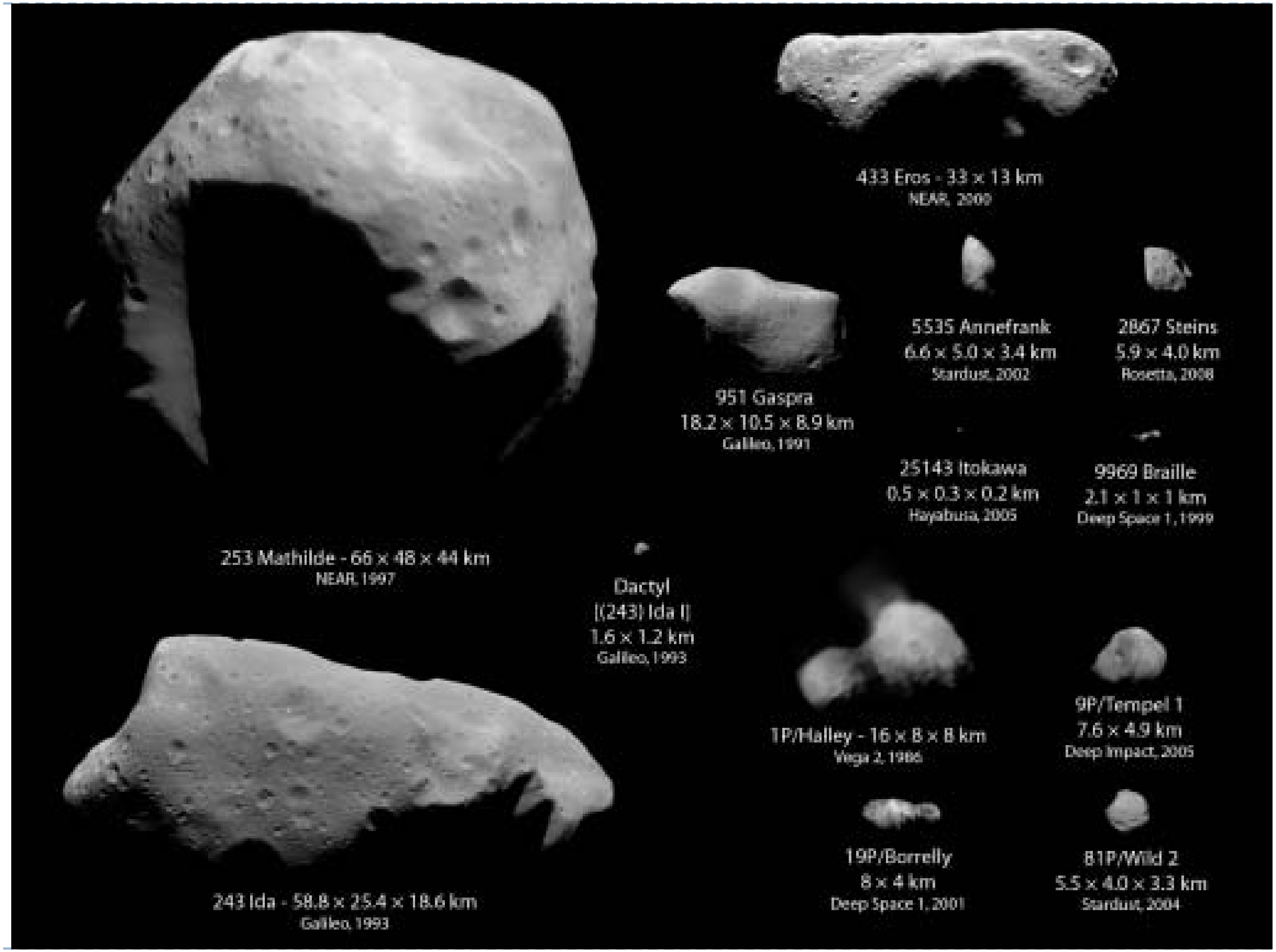


Small Body Exploration:
fundamental science to spacecraft missions

Julie Bellerose, Ph.D. Carnegie Mellon University / NASA Ames

San Jose State University, September 1st 2010

Asteroids and Comets visited to date – more to come!

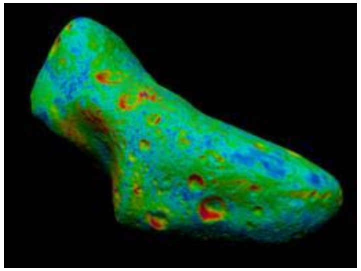


Some of the most Famous Asteroid Missions

NEAR landed on Eros as an end of mission option, obtaining valuable science especially from Gamma-ray spectroscopy.

Science outcome:

- First small body high resolution map.
- Established links between ordinary chondrites and S-type.
- Regolith was found to be meters deep.
- Performed C-type asteroid flyby, Mathilde



Courtesy: NASA

Hayabusa touched down twice on Itokawa, for a total of 30 min, for the only purpose of returning samples to Earth.

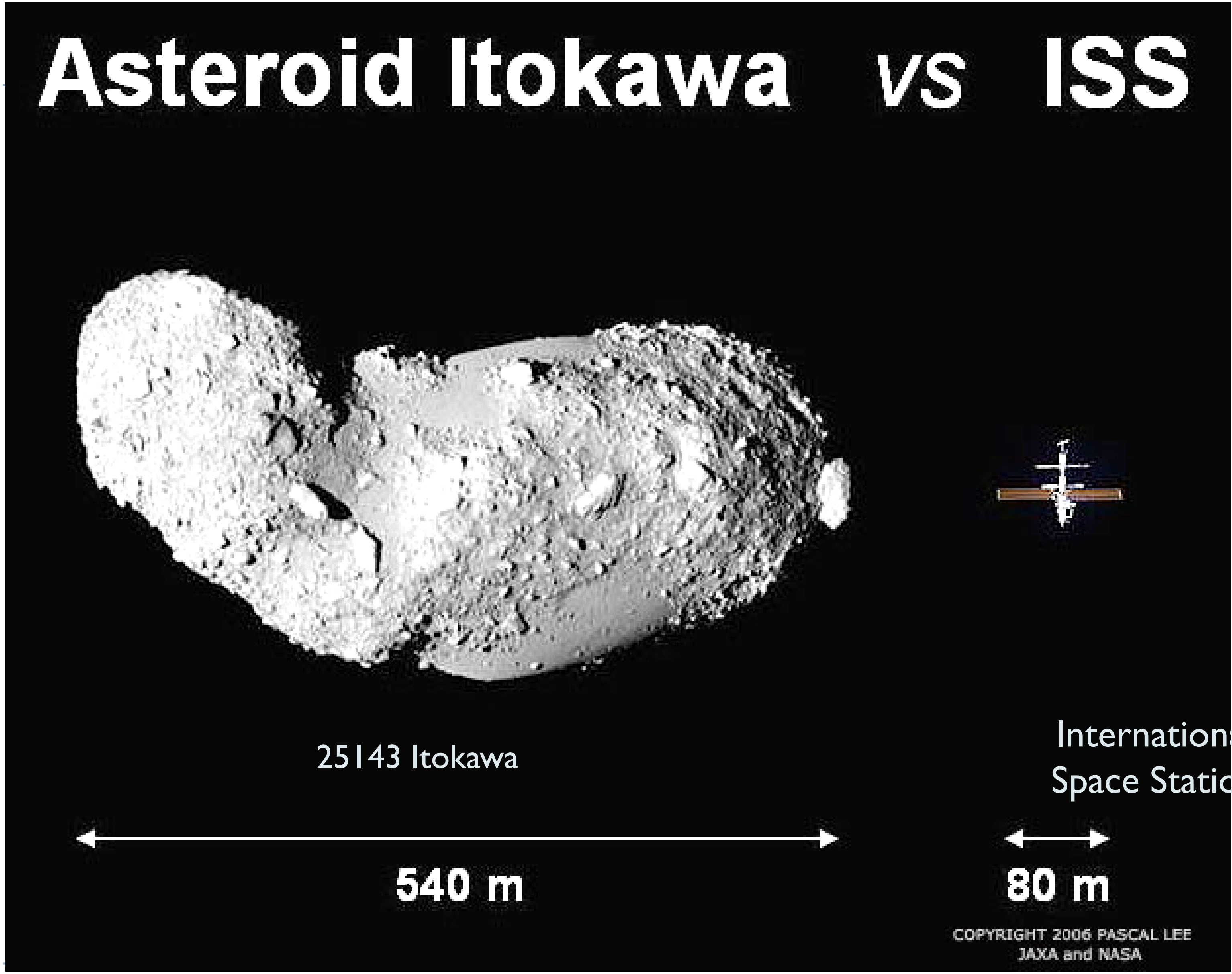
Science outcome:

- Highest resolution of asteroid surface to date
- Showed evidence of gravel migration.
- Returning samples (June 14th 2010)

Courtesy: JAXA

Hayabusa mission (2003-2010)

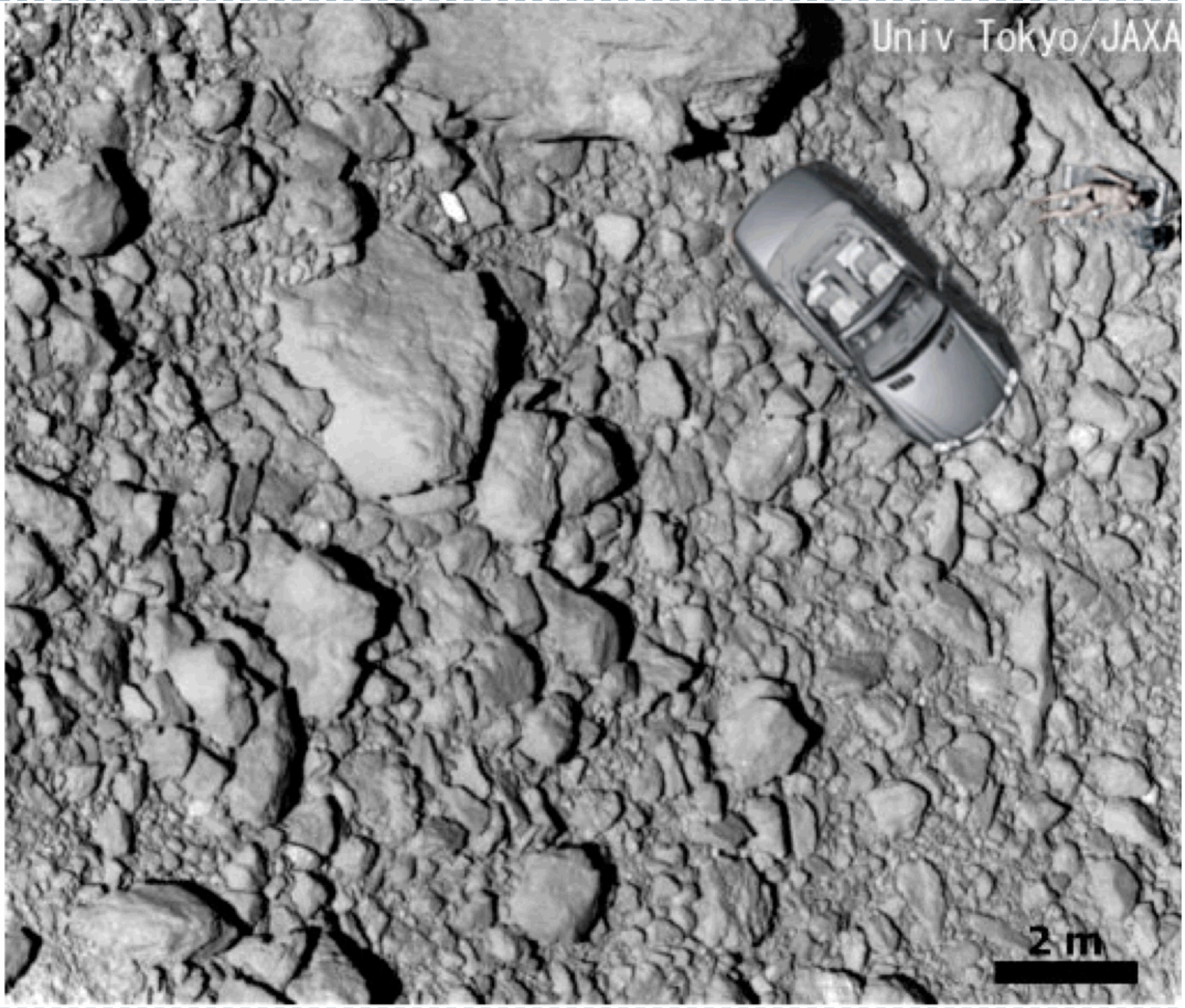
Courtesy: JAXA/ISAS



25143 Itokawa

International Space Station

25143 Itokawa



Hayabusa re-entry

Re-entry June 13th 2010, Australia

Grain size samples
Out-gassing unexplained

Motivation for Asteroid Missions

- Sending spacecraft to small bodies can provide answers and information to questions about the evolution and formation of our solar system.

- Specific scientific interest:
  - Formation and evolution of asteroids.
  - Fission processes through flybys or spin up.
  - External and internal composition.

- Missions to asteroids to date:
  - NEAR – to asteroid Eros, touch down in 2001 (NASA).
  - Hayabusa – to asteroid Itokawa, sample return for 2009 (JAXA).
  - Rosetta – to Comet Gerasimenko, flew by Stein and Lutetia(ESA)
  - Dawn – on its way to Ceres and Vesta (NASA).

- In progress…
  - Hayabusa-2 (Japan), OSIRIS-Rex (USA)… to be determined.

and many proposals…

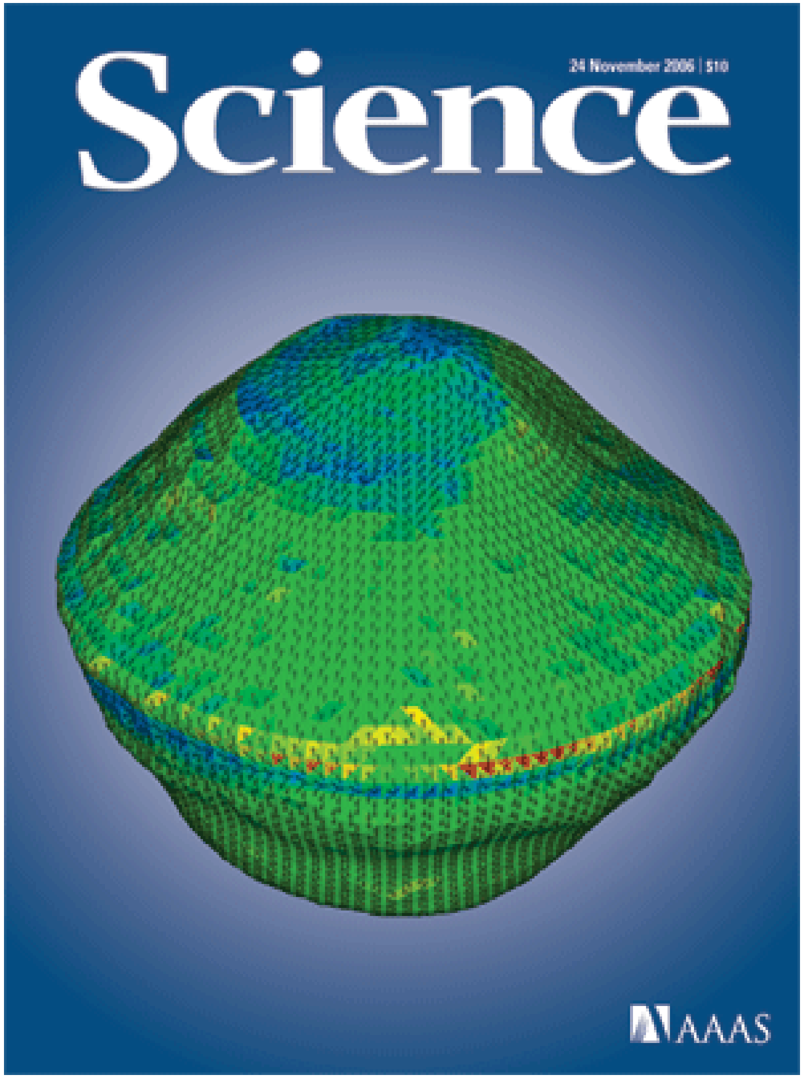
Interest in Binary Asteroids

- Of the small body population (asteroids and comets), we count 5000 Near-Earth Objects.

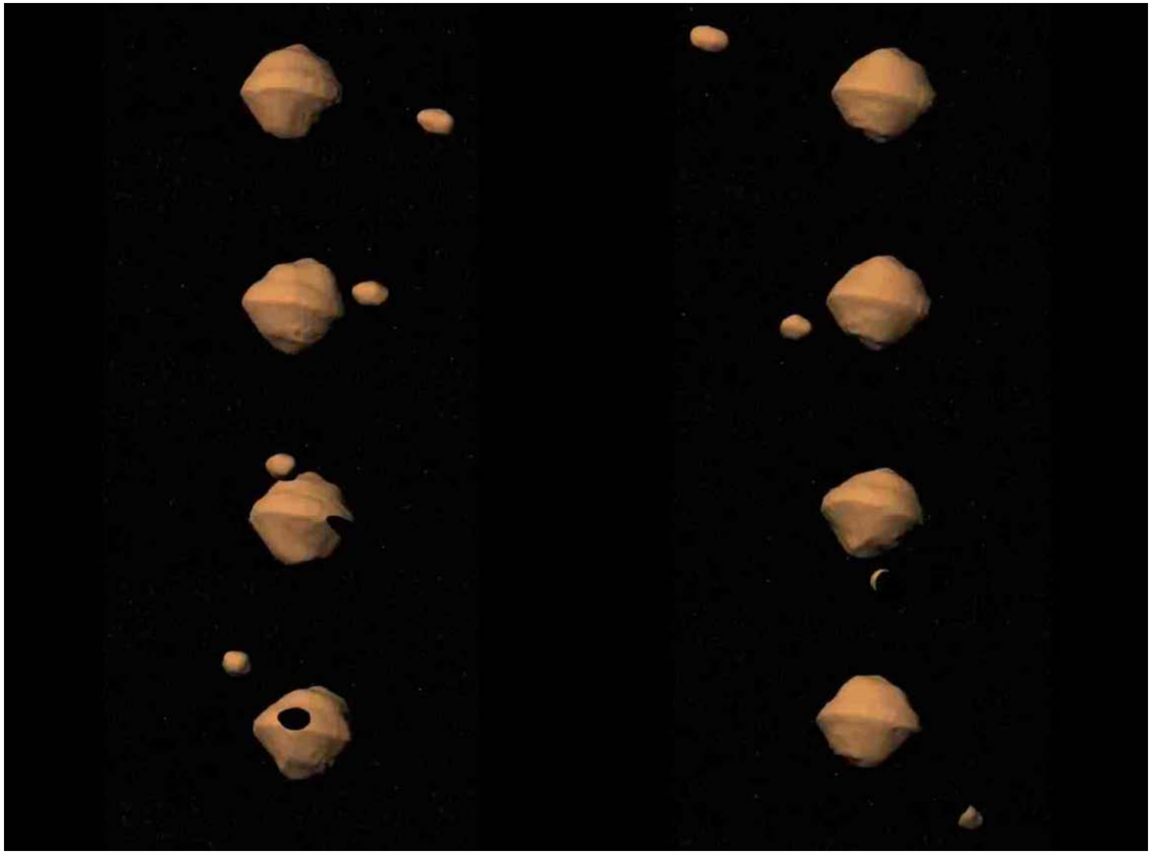
Hermes
Earth flyby
1937

- From current estimates: 15% of Near-Earth Asteroids are thought to be binaries.
  - If formed through fission, a binary may directly show its internal structure.
  - The binary system dynamics' may tell more about its formation and evolution.
- A binary asteroid system is most likely to be target of a NEO mission.
- Challenges in having vehicles in orbit about a binary system
  - Motion resembles a "mini" 3 body problem
  - The time scale of motion around these systems are on the order of 10's of hours
  - The motion is strongly perturbed by the system itself, close approaches to other bodies and solar effects.
  - Must account for non-spherical asteroid shapes
  - Need to design for low gravity environment.
  - Must understand binary evolution

From close approach observation of 1999 KW4



1999 KW4 System



1999 KW4

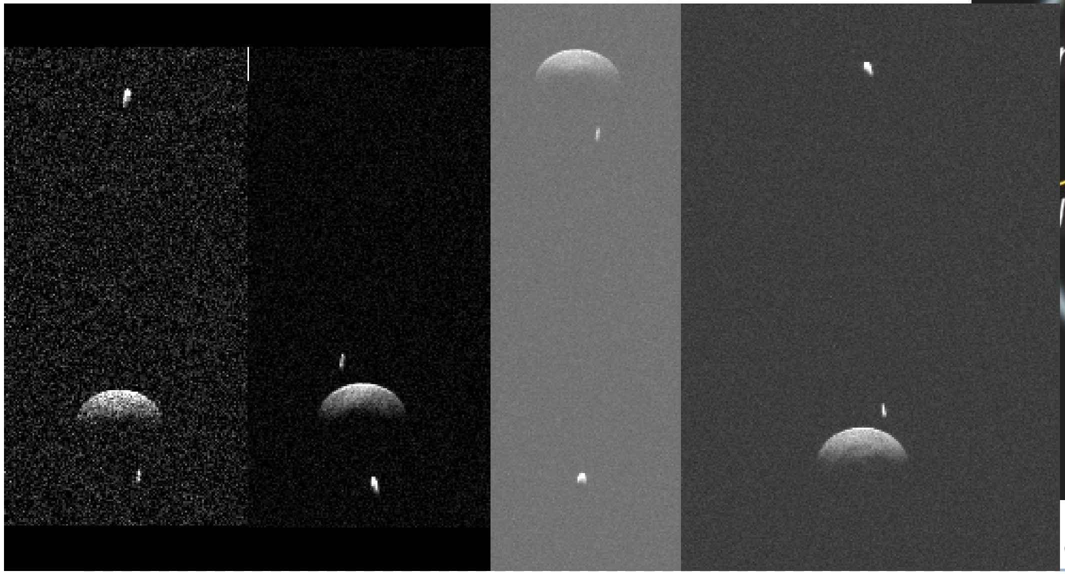
Approximated as an
ellipsoid-sphere system
- Primary: Alpha
- Secondary: Beta

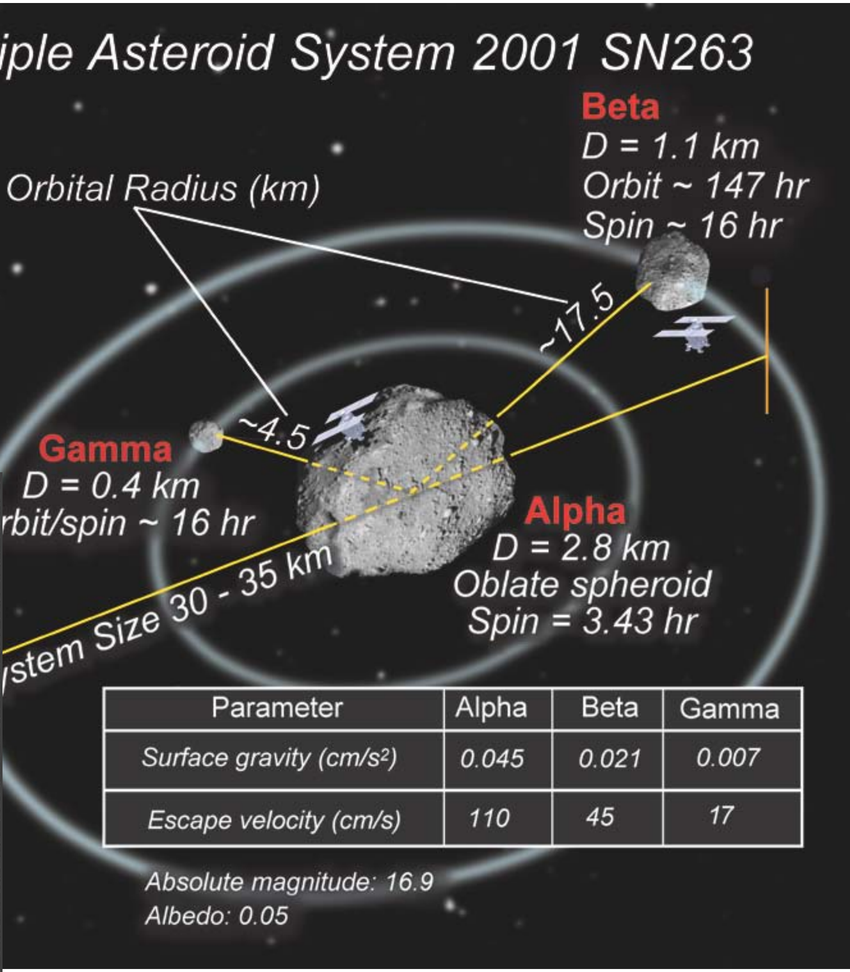
System parameters:
r = 2.54 km
- Total mass: 2.472E^{12} kg
- Mass fraction: 0.9457
- Ellipsoid: [1:0.8:0.6]
- Alpha spin rate: 2.8 hrs

w, orbit rate: 17.458 hrs

Triple Asteroid System 2001 SN263

- How do multiple asteroid systems form?
- How are they influenced by the Sun?
- How is the composition linked to our solar system?
- What does it tell us about our solar system formation and evolution?



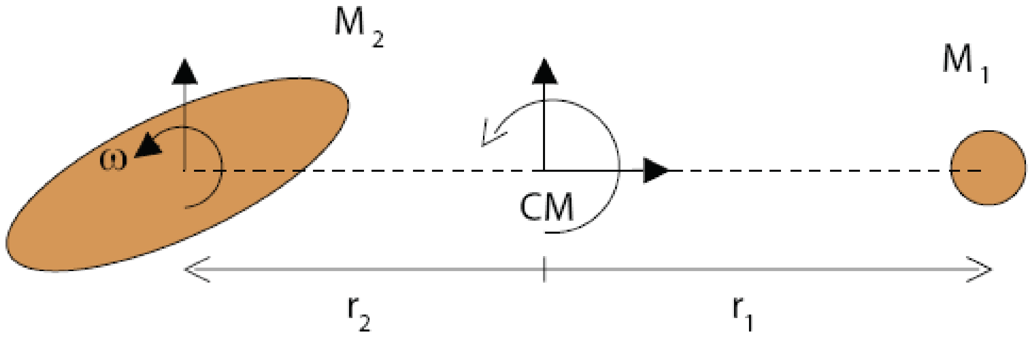


Parameter	Alpha	Beta	Gamma
Surface gravity (cm/s²)	*0.045*	*0.021*	*0.007*
Escape velocity (cm/s)	*110*	*45*	*17*

Absolute magnitude: 16.9
Albedo: 0.05

Courtesy: Nolan et al.,2008, NAIC & Cornell University, & NASA

A Simplified Approach of The Full Two-Body Problem



$$\nu = \frac{M_1}{M_1+M_2}$$

Ellipsoid parameters:

$$0 \le \gamma \le \beta \le \alpha$$

$$\boldsymbol{r_1} = (1-\nu)\boldsymbol{r_b}$$

$$\boldsymbol{r_2} = -\nu\boldsymbol{r_b}$$

- General expression for the mutual potential when the distributed body is modeled as an ellipsoid with constant density:

$$U_e = \frac{3}{4}\int_\lambda^\infty \phi(\boldsymbol{r}, v)\frac{dv}{\triangle(v)}$$

where $\phi(\boldsymbol{r}, v) = 1 - \frac{(x+\nu)^2}{1+v} - \frac{y^2}{\beta^2+v} - \frac{z^2}{\gamma^2+v}$

$$\triangle(v) = \sqrt{(1+v)(\beta^2+v)(\gamma^2+v)}$$

λ satisfies $\phi(\boldsymbol{r}, \lambda) = 0$ $\qquad 0 \le \gamma \le \beta \le \alpha = 1$

Equations of Motion: Hamiltonian form

- Energy and Angular momentum:

$$E = \tfrac{1}{2}\boldsymbol{p}\cdot\boldsymbol{p} + \tfrac{1}{2\nu}I_{zz}\omega^2 - U(\boldsymbol{q})$$

$$K = \tfrac{1}{\nu}I_{zz}\omega + \hat{\boldsymbol{z}}\cdot(\boldsymbol{q}\times\boldsymbol{p})$$

- A planar system can be reduced to a 2 DOF Hamiltonian system by elimination of angular momentum.

Let $\boldsymbol{q} = \boldsymbol{r}$ and $\boldsymbol{p} = \dot{\boldsymbol{r}} + \omega \times \boldsymbol{r}$

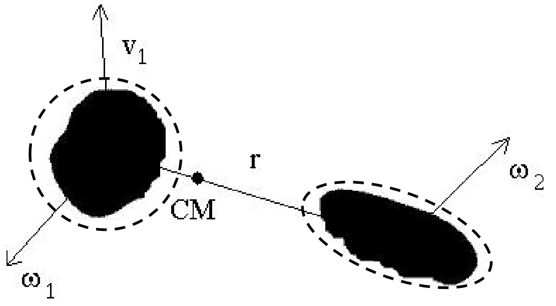
$$H(\boldsymbol{q},\boldsymbol{p}) = \tfrac{1}{2}\boldsymbol{p}\cdot\boldsymbol{p} + \tfrac{\nu}{2I_{zz}}\left[K - \hat{\boldsymbol{z}}\cdot(\boldsymbol{q}\times\boldsymbol{p})\right]^2 - U(\boldsymbol{q})$$

- The equations of motion are:

$$\dot{\boldsymbol{q}} = H_p \qquad \dot{\boldsymbol{p}} = -H_q$$

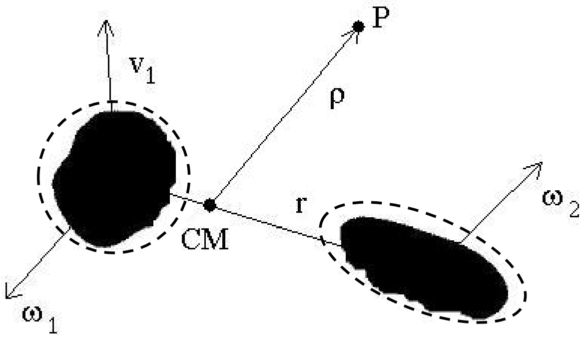
Dynamics of Particles/Spacecraft in the vicinity of a Binary System

- Binary system modeling
  - Danby and Maciejewski each investigated formulations for the mutual potential, method of reduction and established conditions for equilibrium configurations.
  - Simplified Full Two-Body Problem introduced by Scheeres.
  - Relative equilibria assumed for the current study.

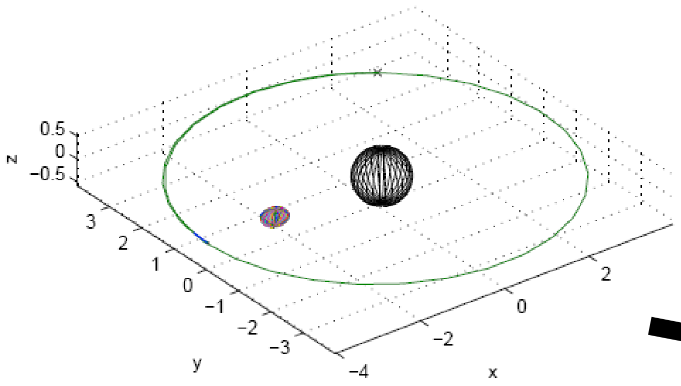


- Particles dynamics
  - Restricted Full Three-Body Problem

$$\ddot{\boldsymbol{\rho}} + 2\boldsymbol{\omega} \times \dot{\boldsymbol{\rho}} + \dot{\boldsymbol{\omega}} \times \boldsymbol{\rho} + \boldsymbol{\omega} \times (\boldsymbol{\omega} \times \boldsymbol{\rho}) = \frac{\partial U_e}{\partial \boldsymbol{\rho}} + \frac{\partial U_s}{\partial \boldsymbol{\rho}} + \mathrm{g}\hat{\boldsymbol{d}}_{\boldsymbol{BF}}$$

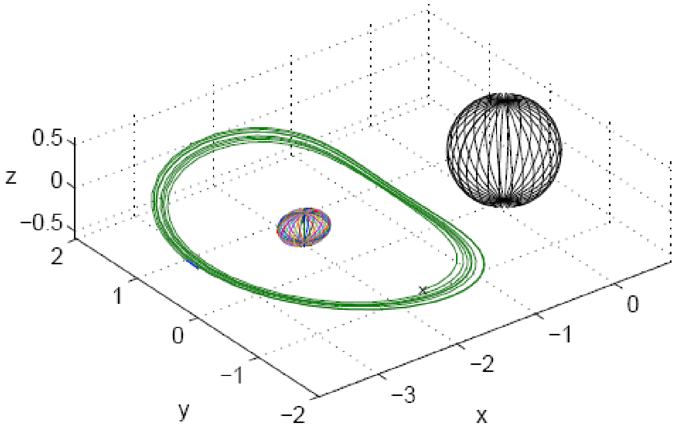


Insertion Reconnaissance Orbits



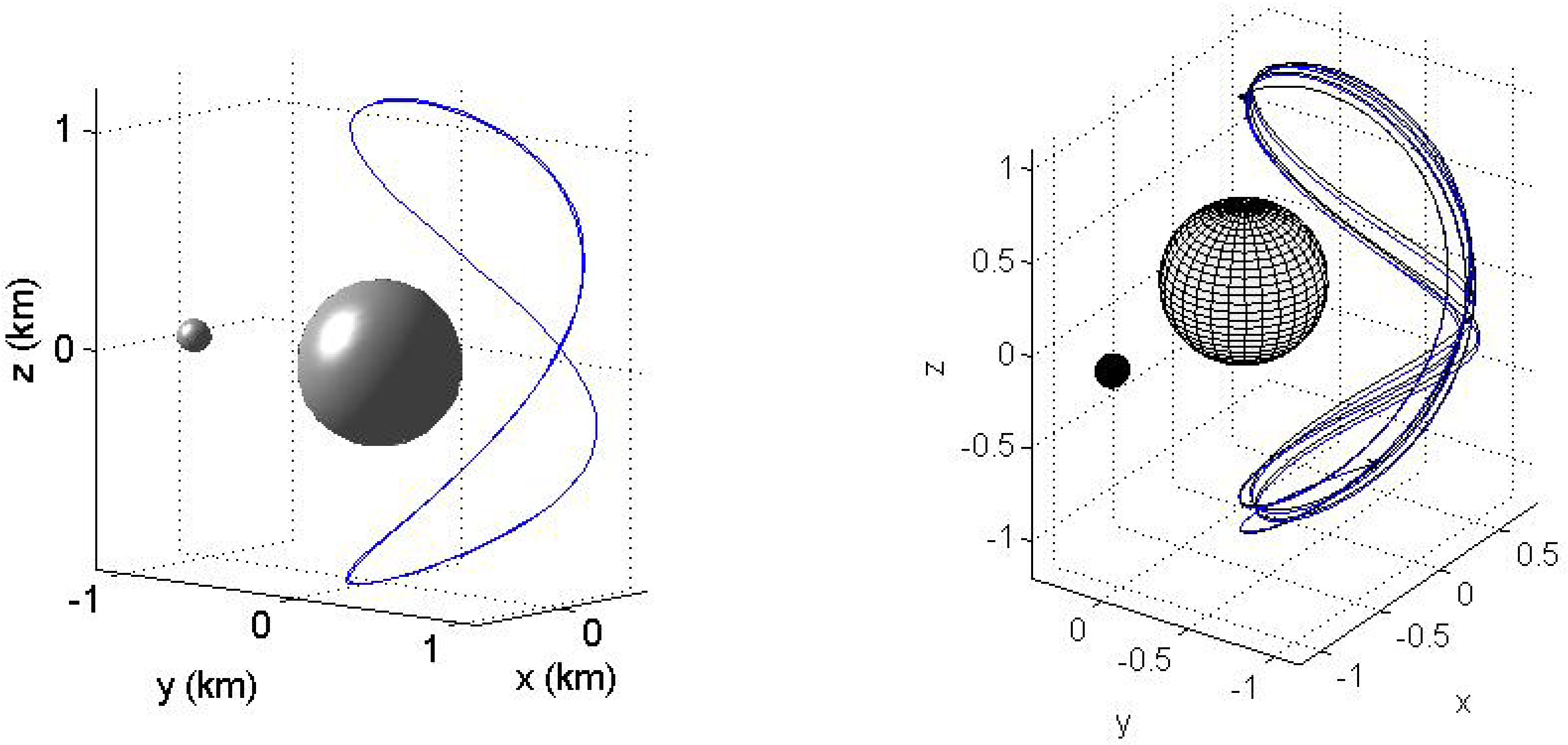
A Poincaré map is used to compute retrograde periodic orbits.

Reconnaissance orbit:
- Retrograde orbit design
- Semi-major axis: 4 km
- Inertial period: 38 hrs
- Binary-fixed period: 7 hrs



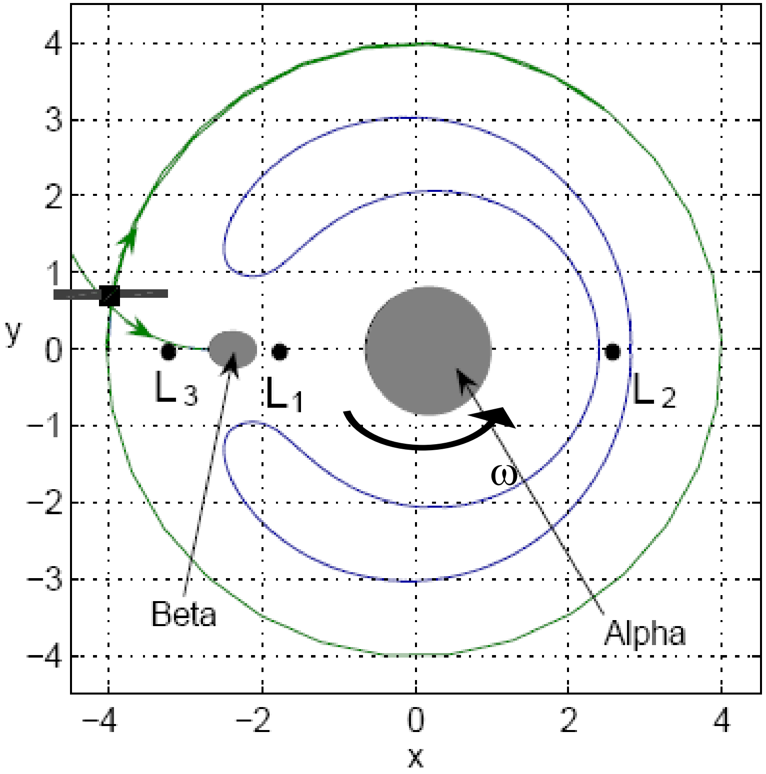
Unstable periodic orbits around Beta, with a semi-major axis of 3.5 km from Beta’s center of mass.

Case Study
NEA Binary System (65803) Didymos



Out of plane orbit for Didymos, as seen from the secondary rotating frame.

Approach the Binary by L_3 to Beta



- L_3 is the only entrance/exit region.
- Surface packages are ejected from the back of the spacecraft.
- The spacecraft stays on its retrograde orbit for communication.

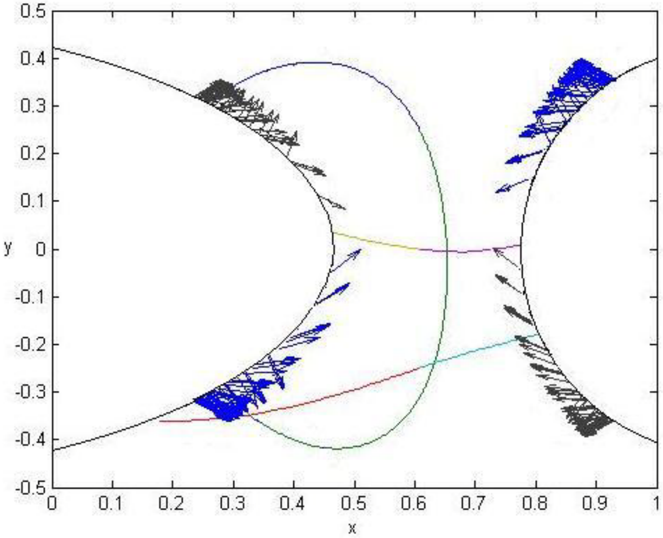
- The relative speed between the spacecraft and Beta is 0.87 m/s.

- The ejection speed is 1.06 m/s at 85^o from the binary *x* axis.

- The landing speed on Beta: 0.18 m/s.

Transition between the Binary Components

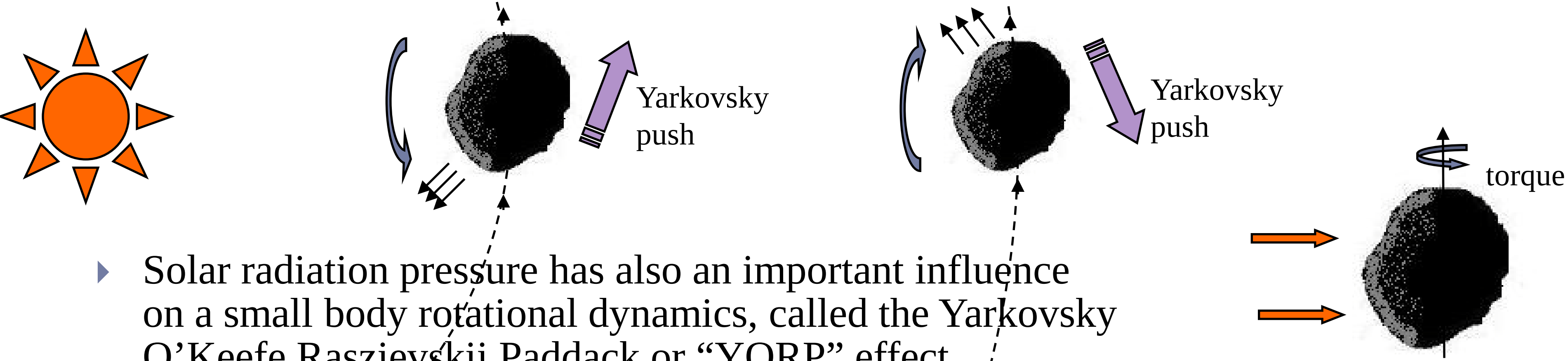
- Having surface constraints, conditions exist that allow transit or not, from one body to the other, using linearization about L1.



Transit and non-transit trajectories for a binary system with r = 1.8, n = 0.3 and ellipsoid parameters b = g = 0.5. The arrows are initial and final conditions on the surface of the bodies leading to non-transit trajectories.

Solar Radiation as a Small Body Evolution Mechanism

- Solar radiation pressure has been shown to be an important component in the evolution of small Near Earth Asteroids (NEA).
- The Yarkosky effect is a phenomenon related to the thermal emission of small bodies that induces perturbations to a small body orbit.



- Solar radiation pressure has also an important influence on a small body rotational dynamics, called the Yarkovsky O’Keefe Raszievskii Paddack or “YORP” effect.
  - The effects of YORP on the rotational dynamics of small bodies and their subsequent evolution under such force have been characterized (Scheeres, 2007).
  - Long-term simulations of secondary body formation due to angular acceleration from YORP have been shown (Holsapple and Michel, 2008).
  - Other recent studies have also included YORP as a mechanism leading to the formation of binary systems (Harries, 2008; Cuk, 2005-07)

Sun Interactions at the Surface of Small Bodies

- First evidence of dust levitation and possible electrostatic charge on the Moon…
  - Surveyor and the Apollo missions have recorded dust grains suspended above the lunar surface.
  - Experiments and modeling have started since the 60s, with continued refined work. (Singer and Walker, 1962; Criswell et al., 1974-8; Zook and McCoy, 1991).

From other small bodies…

- Lee made a first model estimate of electrostatic processes on asteroids in the Main Belt (1996).
- On the asteroid Eros, as observed by the NEAR mission, dust craters, or ponds, are believed to have formed from dust transport (Veverka et al., 2001; Robinson et al., 2001-03; Colwell et al., 2005-07).
- Observations from the Japanese spacecraft Hayabusa validate predictions on particles size observed due to interaction with solar effects (Science 2006, Scheeres et al. 2006). Spacecraft may also have detected dust cloud during approach.

Particular environment on NEAs:

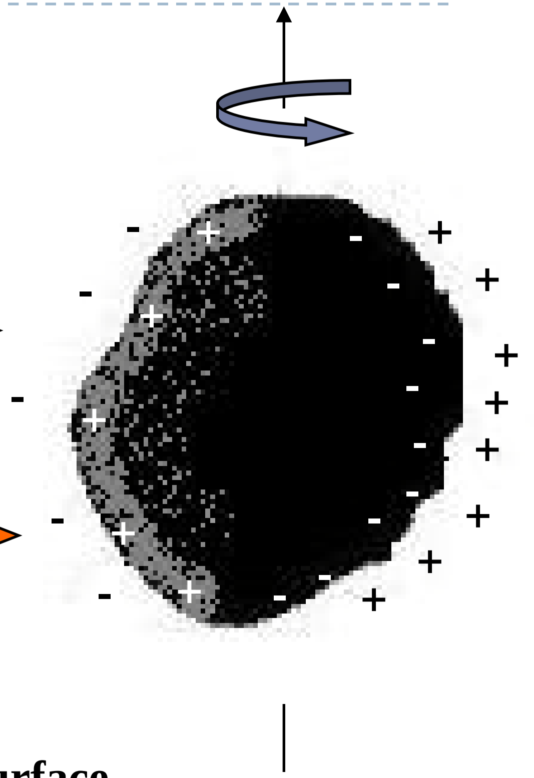
- Fast cycle/time scale for dust transport (spin period ~5 to 30 hrs)

→ **In small, low g asteroid environment, a larger amount of dust levitated and transported, and on larger height scale (100s m).**

→ **Such small bodies may in fact be under a possibly rapid resurfacing process.**

Charging Cycles on Small Bodies

- These dust clouds and ponds are thought to be related to electrostatic effects and transport from the space environment.
  - Charging currents on the surface are photoemission of electrons and collection of solar wind electrons/ions.
  - Net result is a positive surface charge on the dayside where photoemission dominates and a negative surface charge on the nightside where collection of solar wind electrons dominates.
  - As an asteroid rotates, it induces charging cycles, going from positive to strongly negative potential.



- **Dust charging:**

$$\frac{dQ_d}{dt} = I_{pe} - I_e - I_{sw}$$

Photoelectrons emitted by the grains

Photoelectrons to particles

Collection of solar wind electrons

- **The electric field strength is function of the height above the surface,**

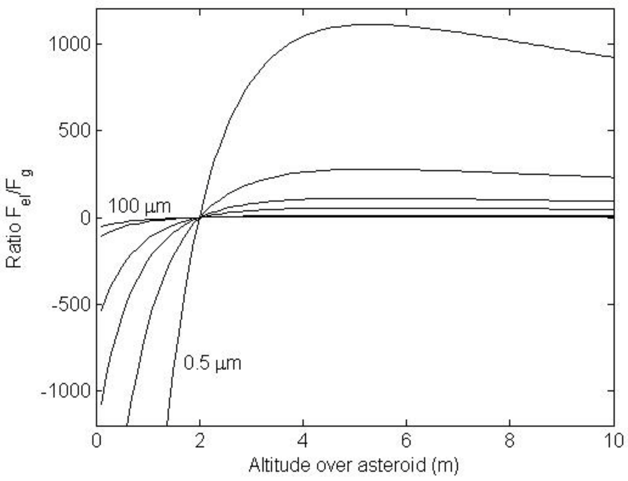
$$E(z) = 2\sqrt{(2)}\phi_s\lambda_D\left(1 + \frac{z}{\sqrt{(2)}\lambda_D}\right)^{-1}$$

λ_D is the Debye length at the surface,
ϕ_S is the surface potential,
Z is the height above the surface.

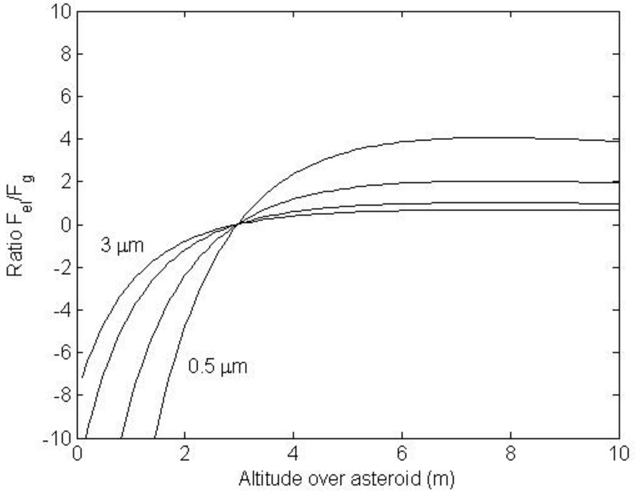
Surface potential from ~ 5 V during the day to ~ – 10s kV at night

Electrostatic versus Gravitational Fields

- Electric force compared to gravitational force for Itokawa and Eros, and for an Eros-like asteroid at Jovian Trojan distances.



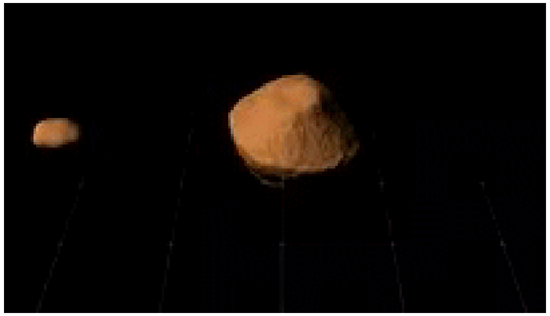
Itokawa
~ 100 μm particle size at least
can be stably levitated



Eros
~ 1 – 2 μm can be
stably levitated
(Colwell, 2005)

Conclusions and Future Work

- Robotic missions to small bodies become more and more numerous, including missions to binary asteroid systems
- Analytical models can give insights on binary system evolution, while numerical models provide improved accuracy.
- Solar influence is important in a binary asteroid system, especially for spacecraft applications and dust hazard mitigation.
  - The surface electrostatic charge can easily overcome the very low gravity.
  - Near field and surface dynamics are easily perturbed.
  - How much does this contribute to the system evolution?



What is coming up?…

- Current mission design include binary systems
- Refinement of formation and evolution modeling , dynamical analysis, mission applications and operations.

- Human missions to asteroids?...