Celestial and Spaceflight Mechanics Laboratory

Exploration of Small Bodies: Asteroids and Comets

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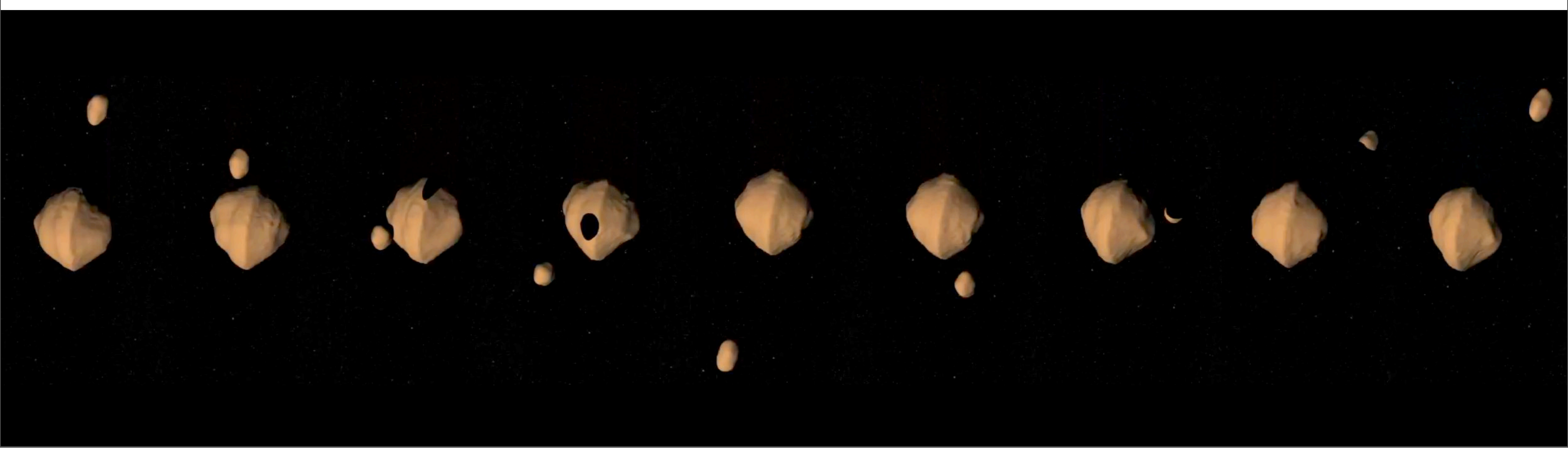
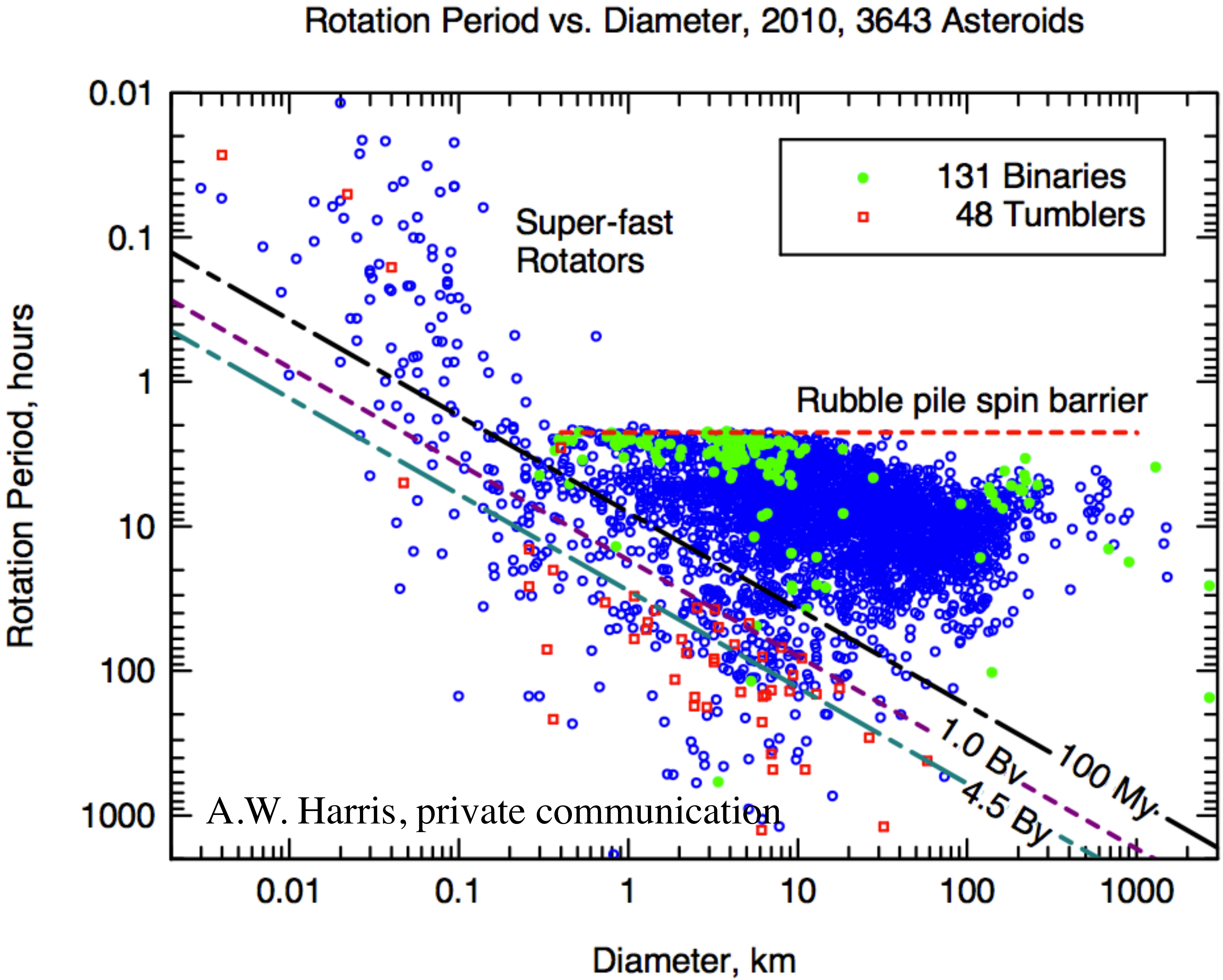
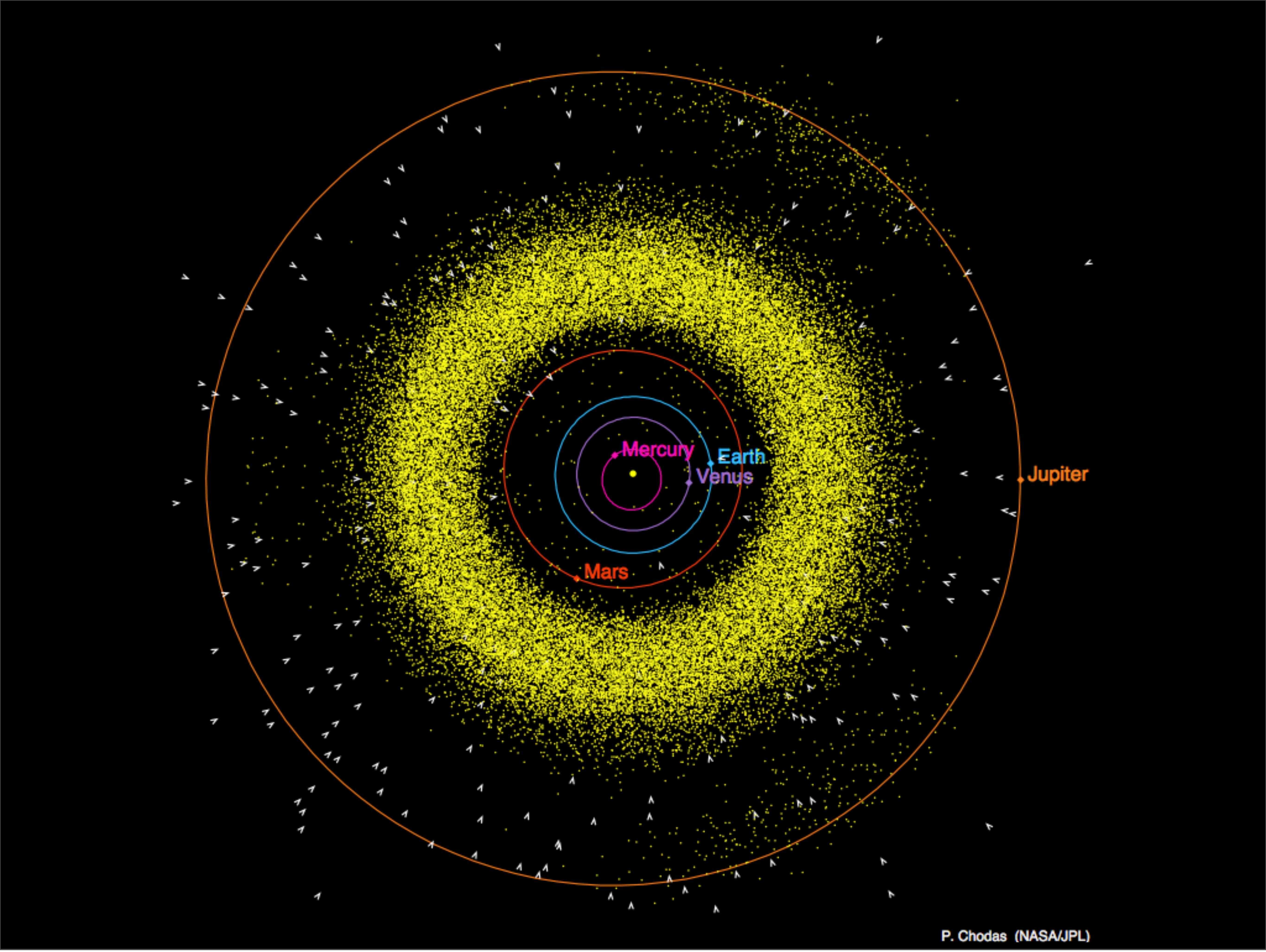


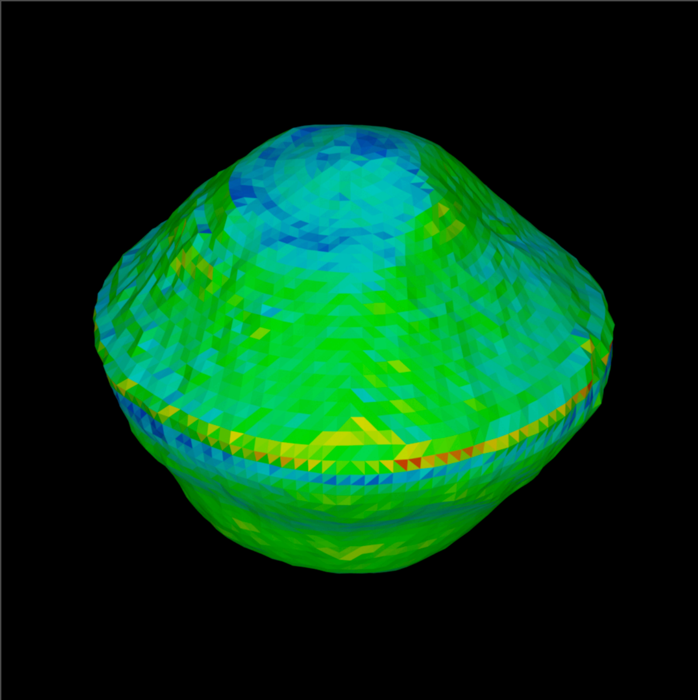
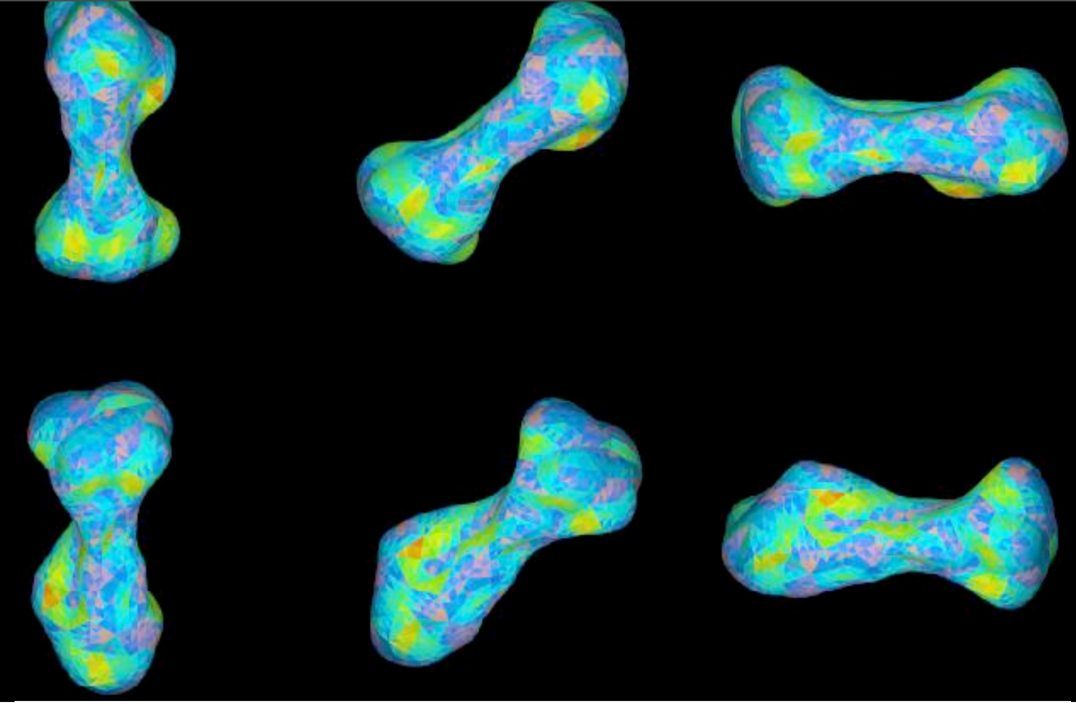
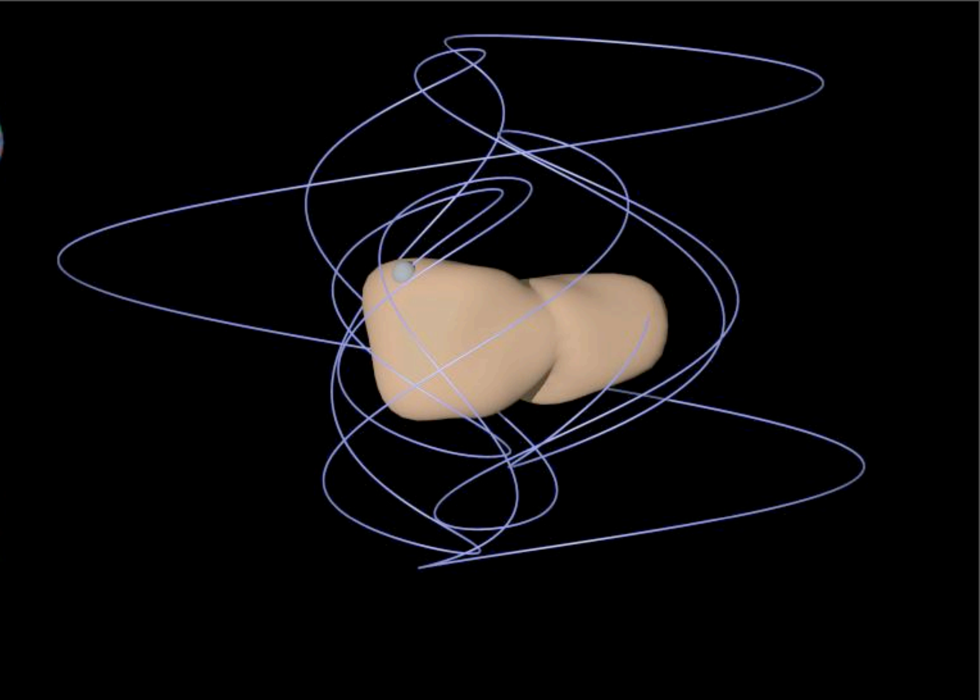
Near Earth Asteroids (NEA)

- What are NEA?
  - Asteroids that have migrated from the Main Belt into the inner solar system
  - Source of meteors and meteorites
  - Most are relatively small (< few km in size)
- How long do they survive?
  - Orbits evolve rapidly/chaotically due to planetary flybys
  - Have a relatively short life-time (half-life of ~15 Myrs)
    - Some removed by impacts with planets
    - Most removed by impact with the sun
- How are they different from Main-Belt NEA?
  - Recently discovered YORP effect dominates their life
  - At least 15% are binary or ternary systems
  - Are not fundamentally different from small asteroids in the Main Belt

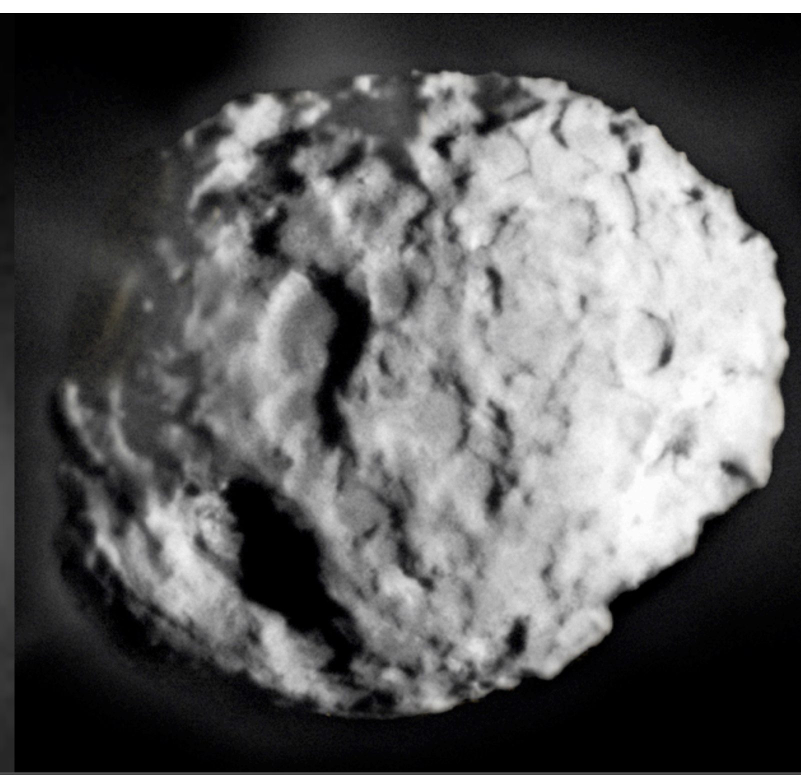


Rotation Period vs. Diameter, 2010, 3643 Asteroids
131 Binaries
48 Tumblers
Super-fast Rotators
Rubble pile spin barrier
1.0 By
100 My
4.5 By
A.W. Harris, private communication
Rotation Period, hours
0.01
0.1
1
10
100
1000
Diameter, km
0.01
0.1
1
10
100
1000


Mercury
Earth
Venus
Mars
Jupiter
P. Chodas (NASA/JPL)

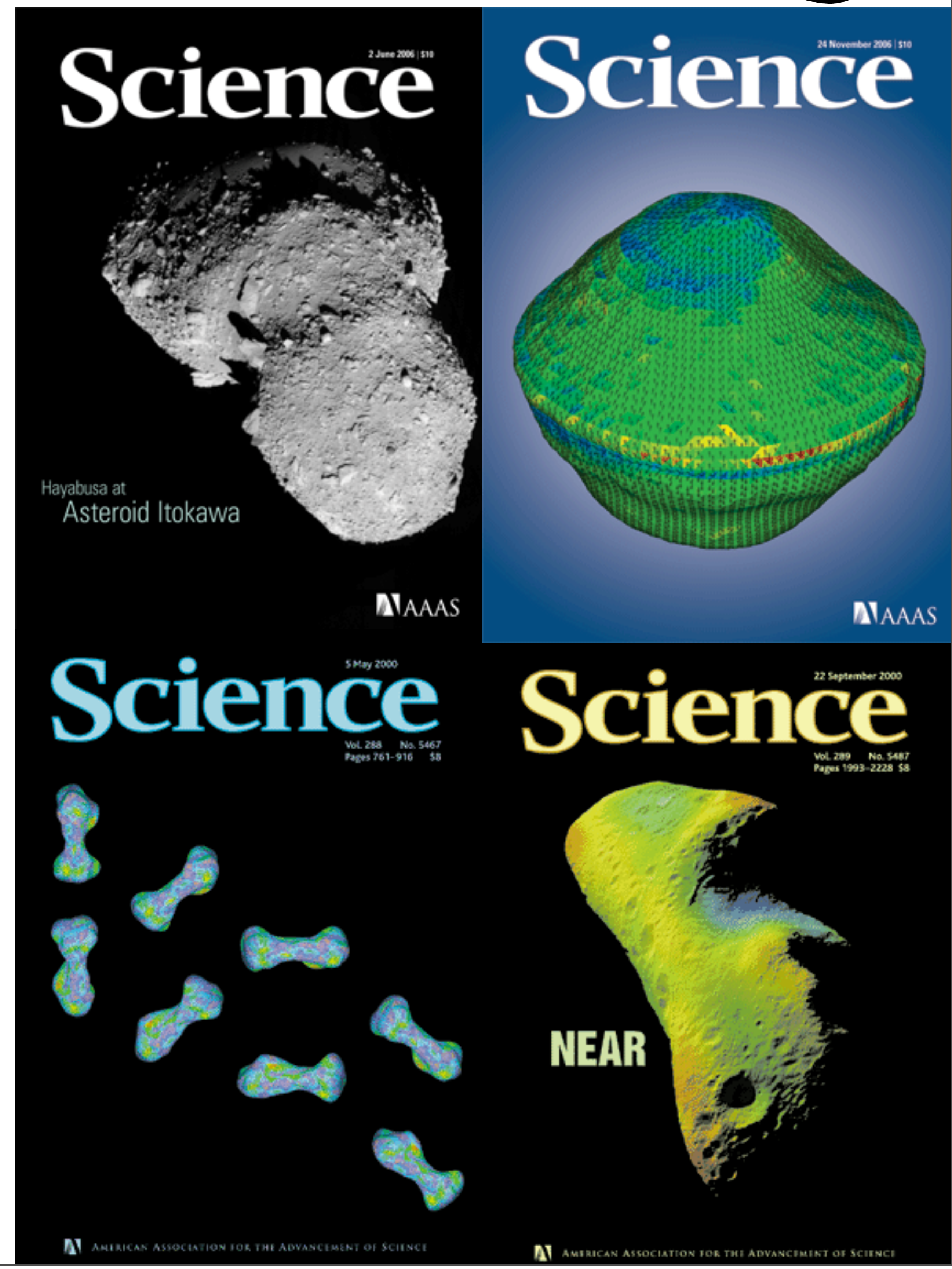
Why are we interested in Small Bodies?


Why are we interested? *Science*

- Small bodies are "remnants" of the early solar system.
  - Their retain material that dates back to the solar system's formation.
  - They act as the "tracer particles" that have recorded what all the major planets have done over time.

- They have shaped life on Earth.
  - By delivering water and minerals in the early history of the Earth.
  - By causing occasional wide-spread extinctions due to their impact.



Why are we interested?
Human Exploration

- Near Earth Asteroids are a natural destination for future human exploration missions.
- A human mission to an asteroid can be a “test run” for a Mars mission.
- Are currently being seriously considered by NASA for human exploration.

Why are we interested? *Society*

– Small bodies continually impact the Earth (e.g., shooting starts)
– Have caused large-scale extinctions in the past (e.g., the dinosaurs)
– If one were detected on a collision course, could we stop it?

RELAX. WE'RE TOO BIG TO FAIL.
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Gravity Tug Spacecraft Concept: Scientific American

What asteroids have we visited?

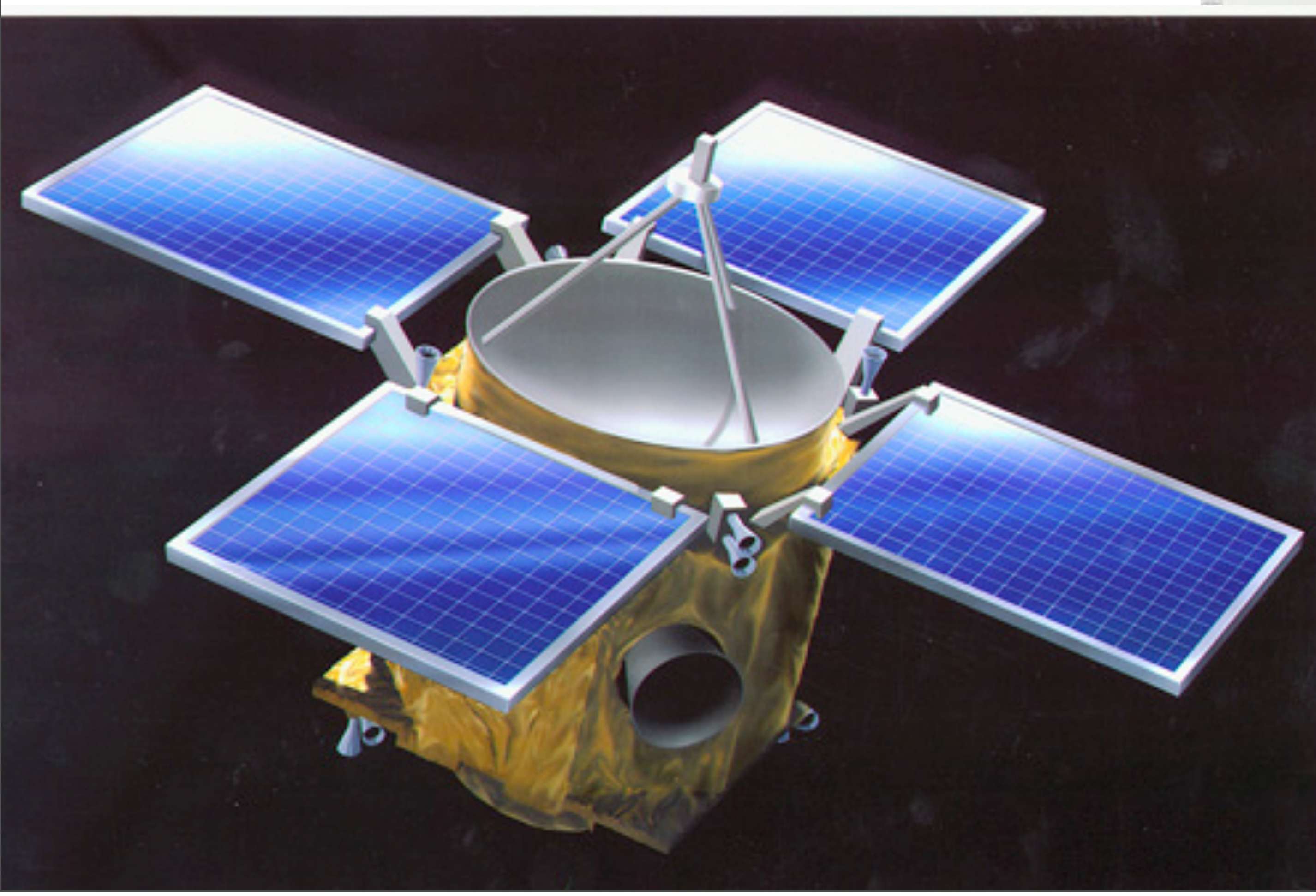
- Gaspra (Galileo S/C)
- Ida+Dactyl System (Galileo S/C)
- Mathilde (NEAR S/C)
- Eros (NEAR S/C)
- Itokawa (Hayabusa S/C)
- Steins (Rosetta S/C)

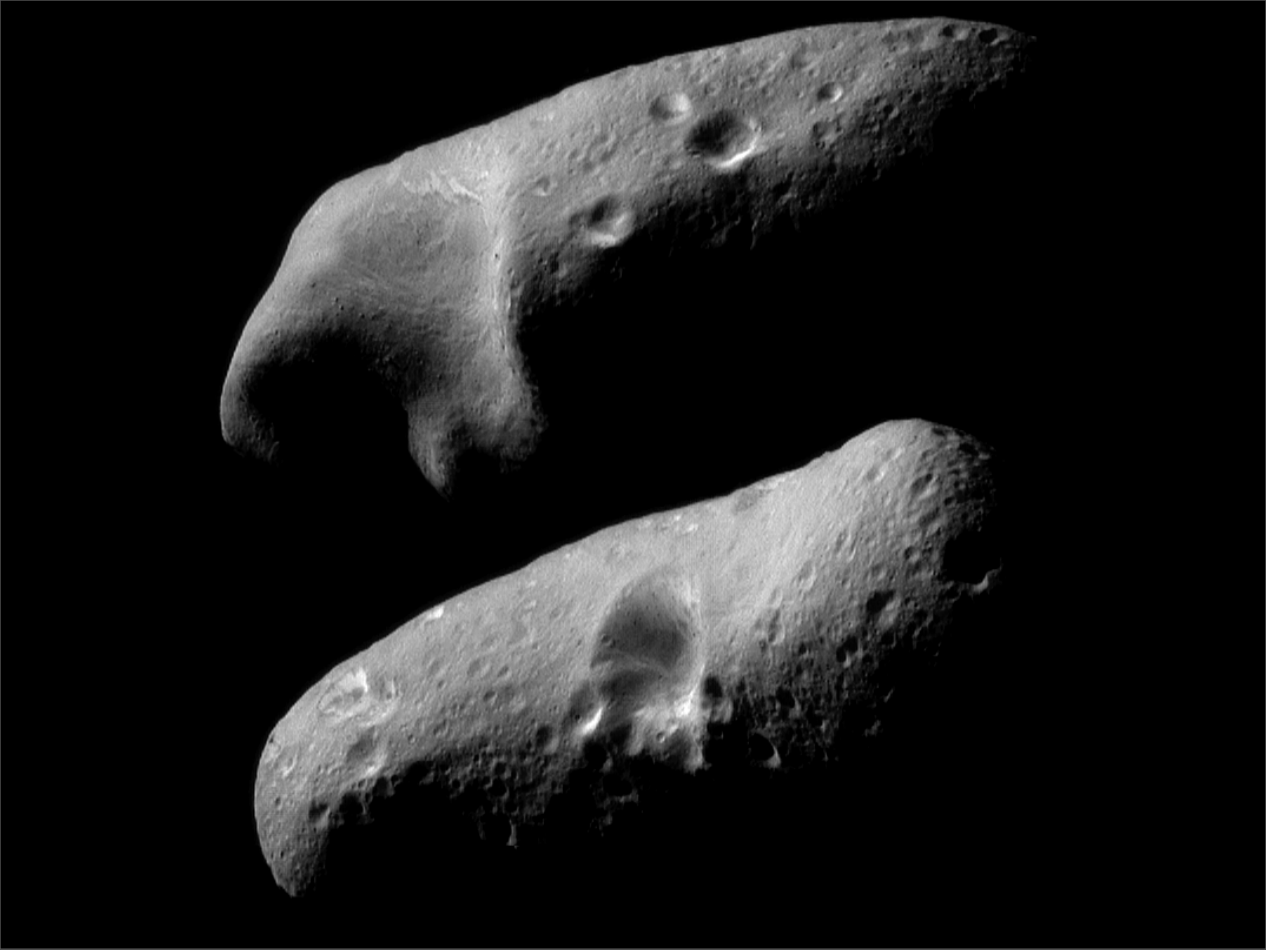
How do we observe them?

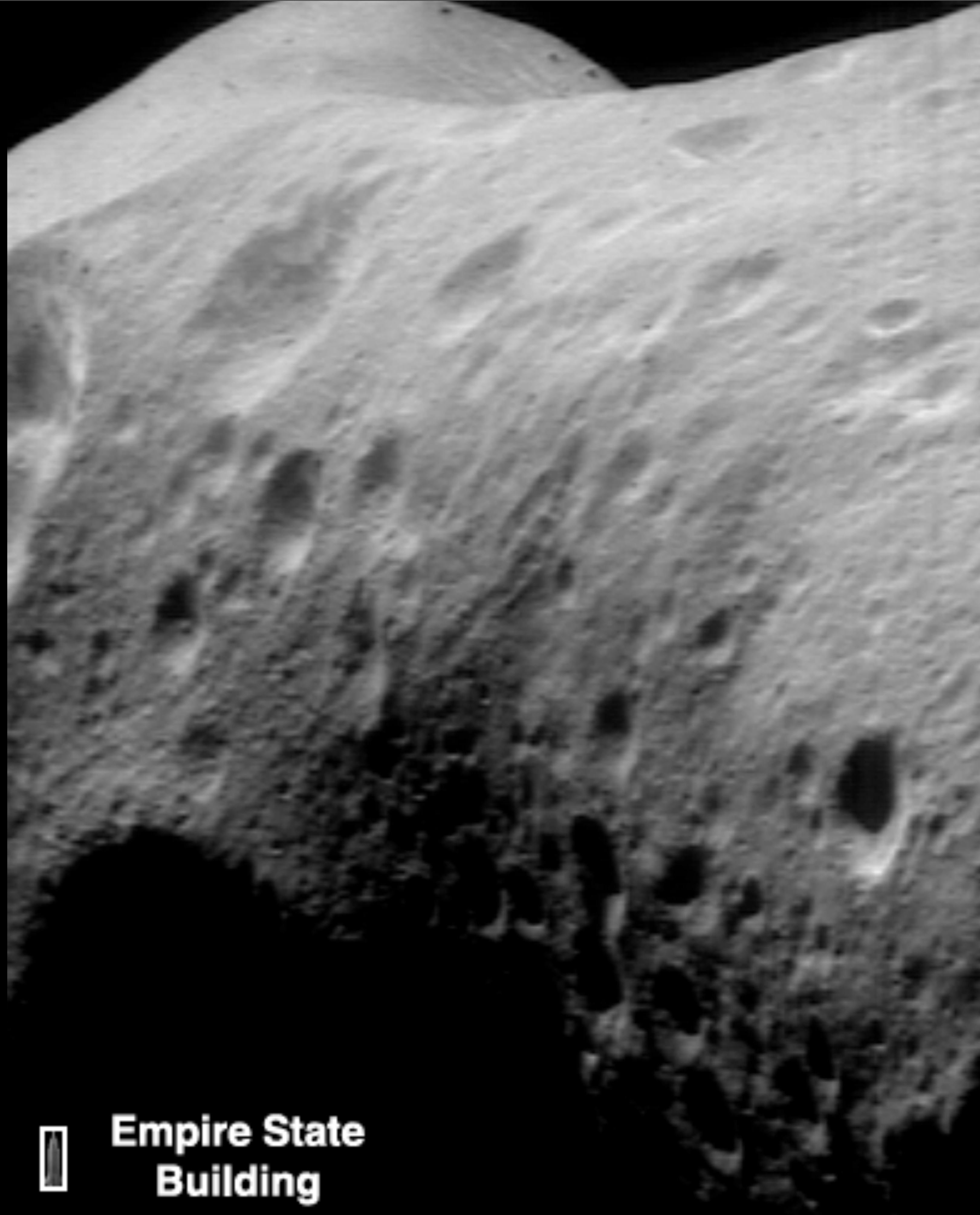
- Spacecraft flybys
- Spacecraft rendezvous
- Radar observations

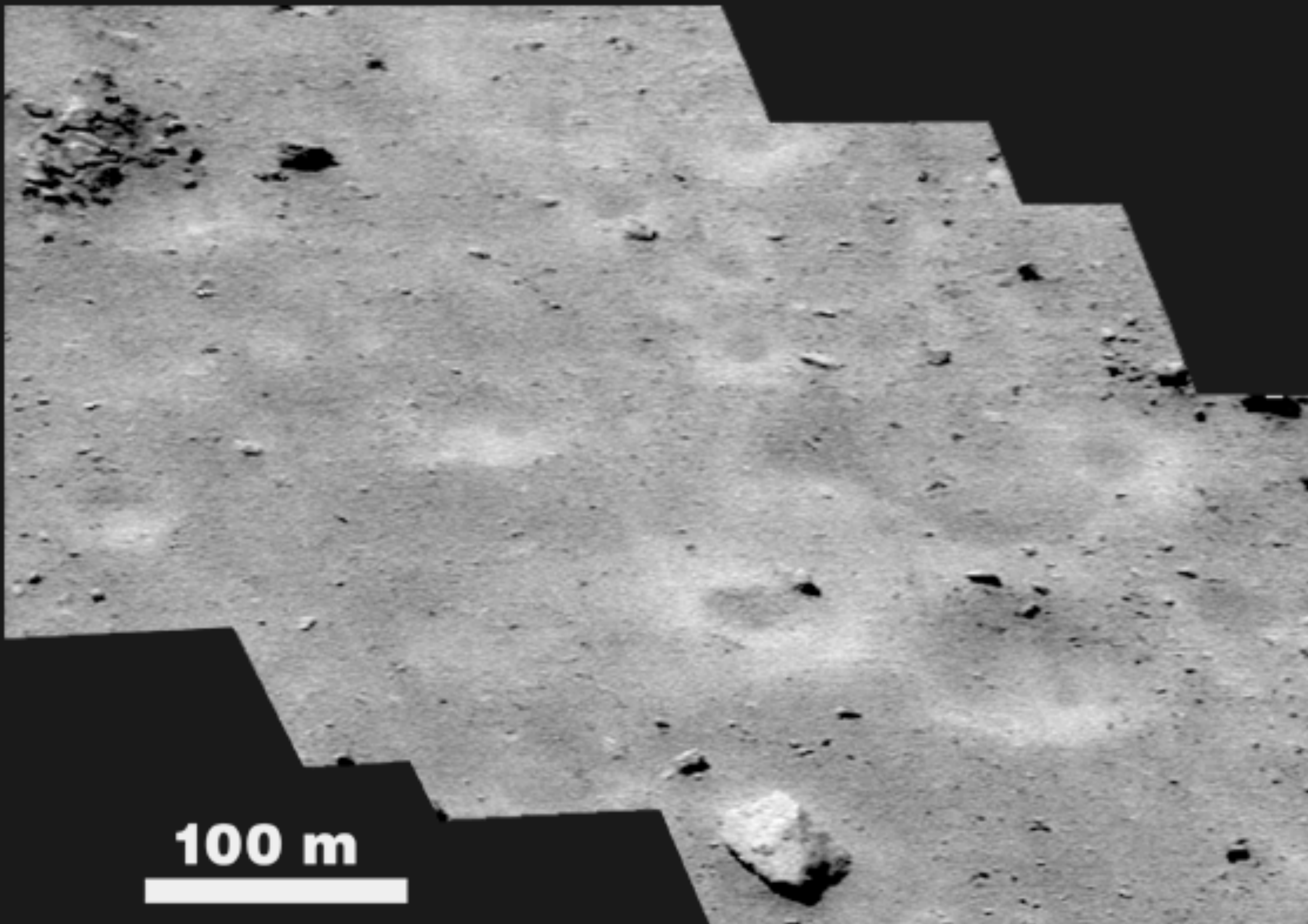
Near Earth Asteroid Rendezvous

- NASA space science mission
- Visited the asteroid Eros
- Launched 1996
- Arrived at asteroid 2001
- Landed on asteroid 2002

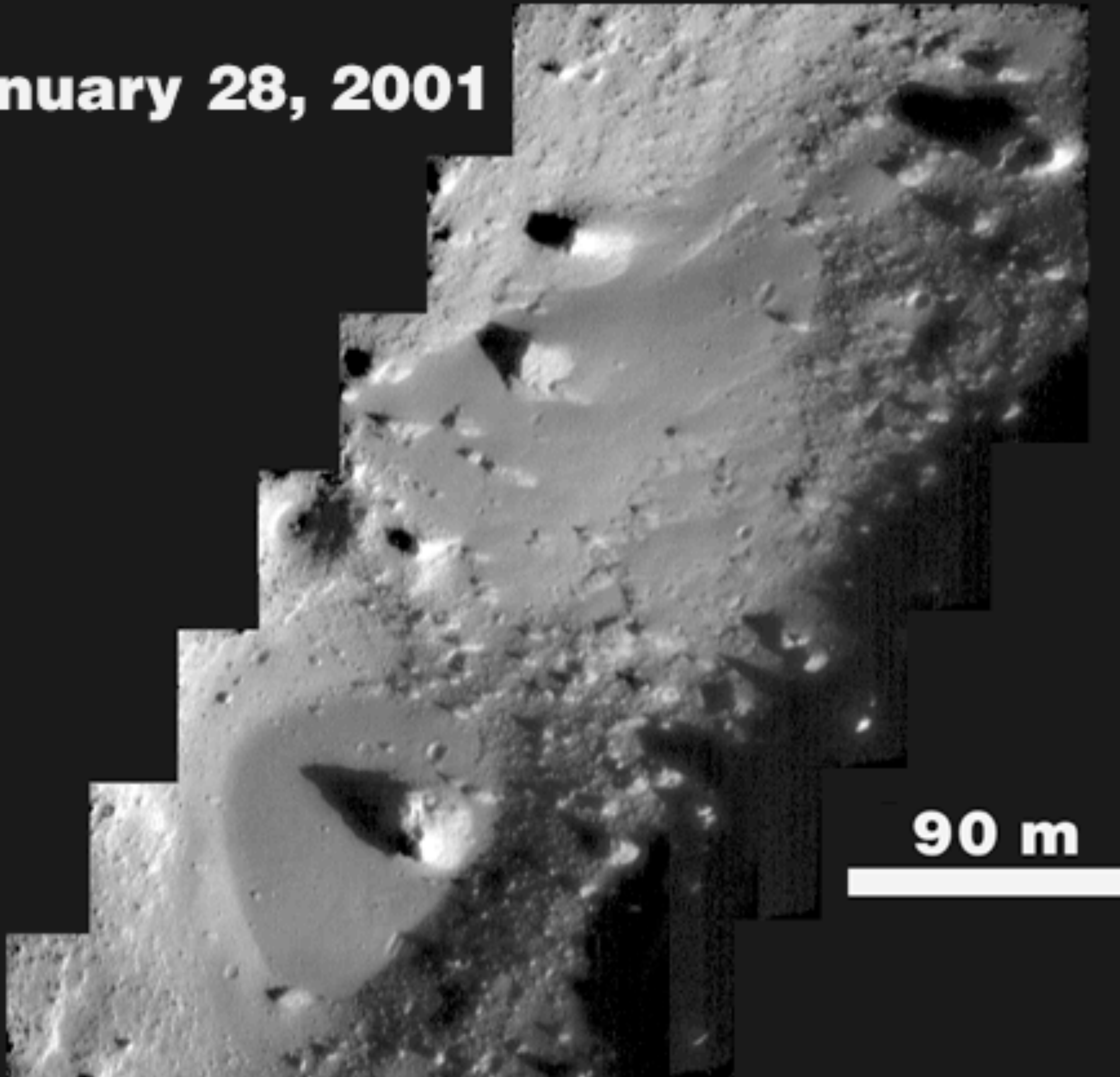


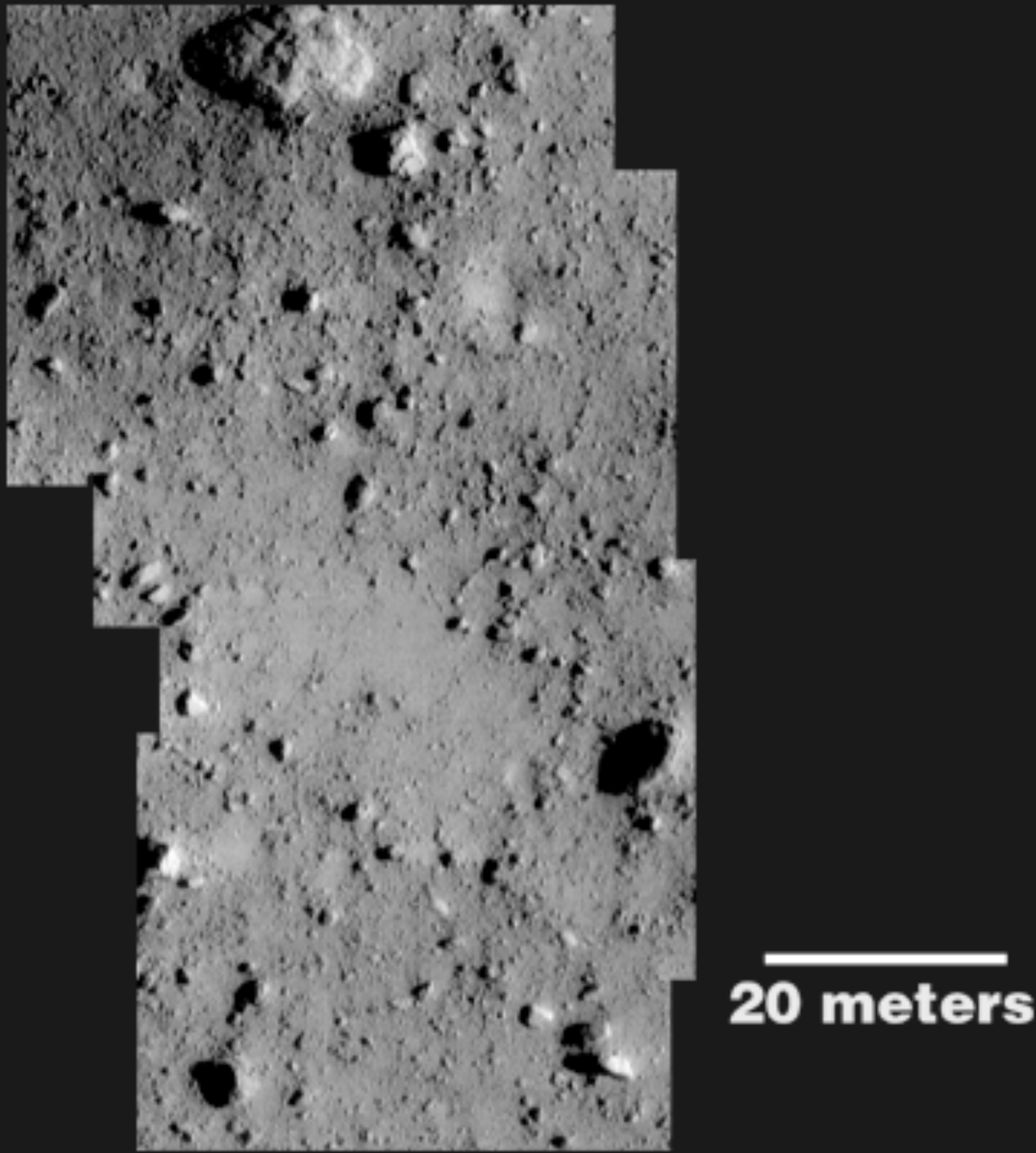


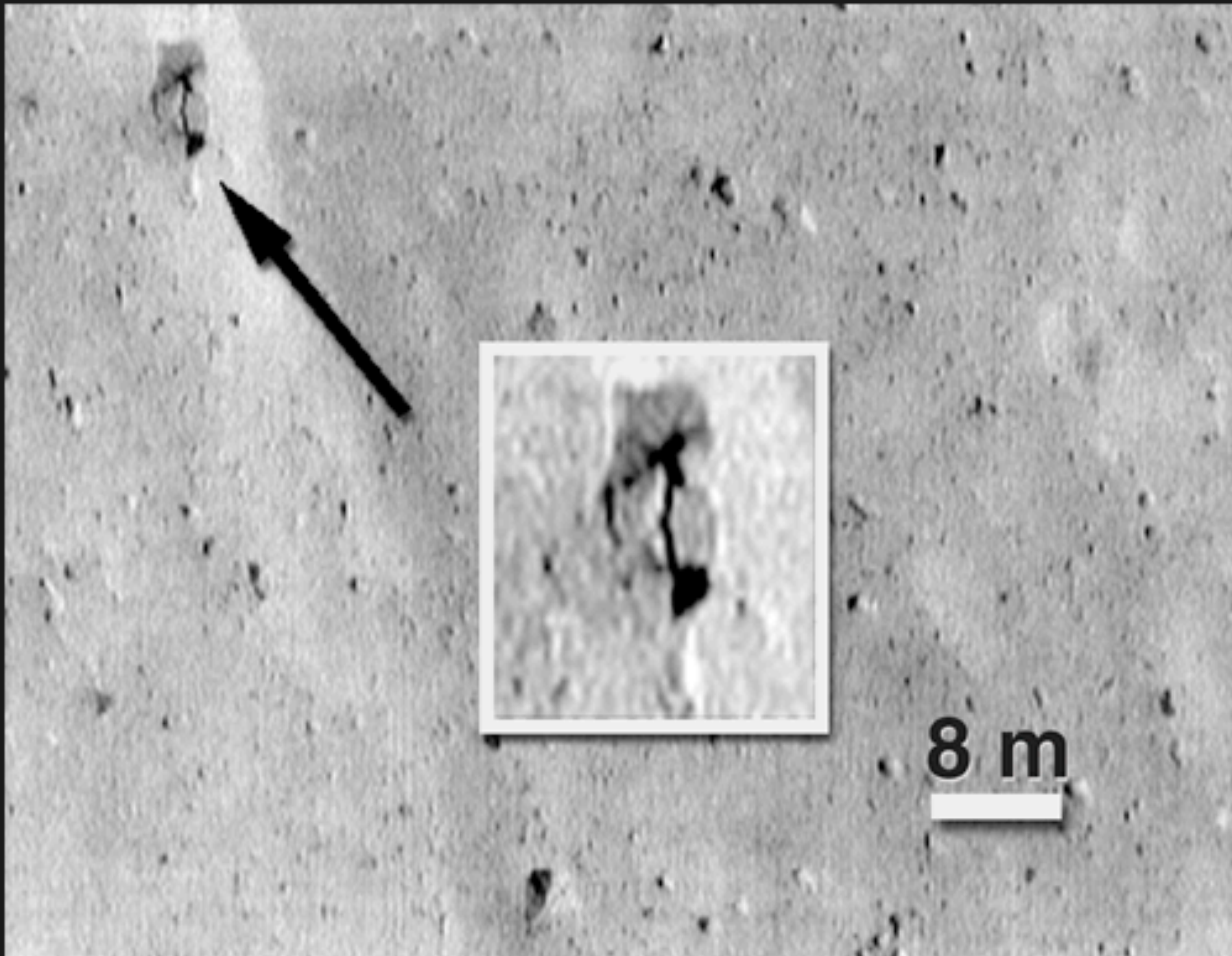

Empire State
Building

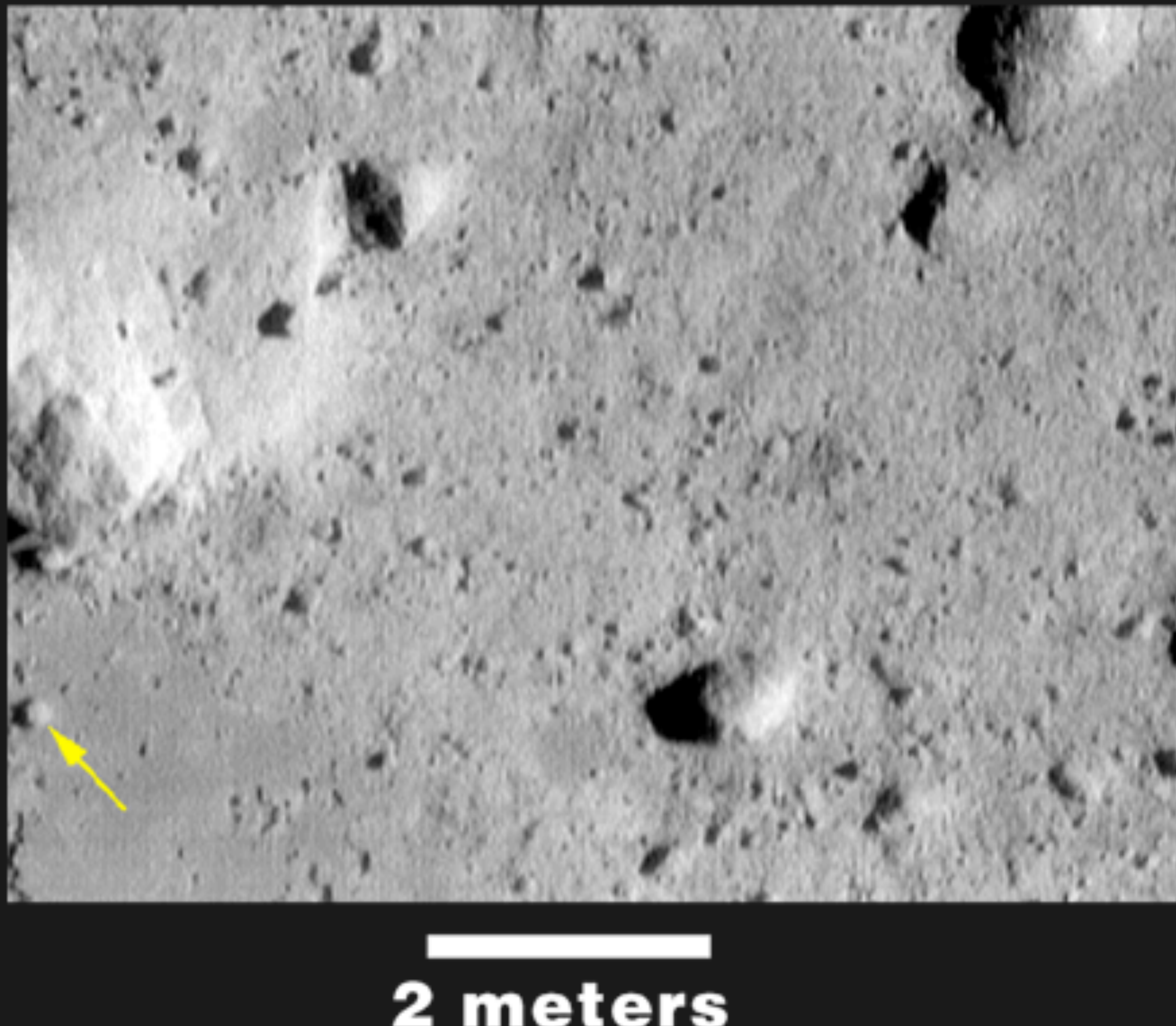

100 m

January 28, 2001



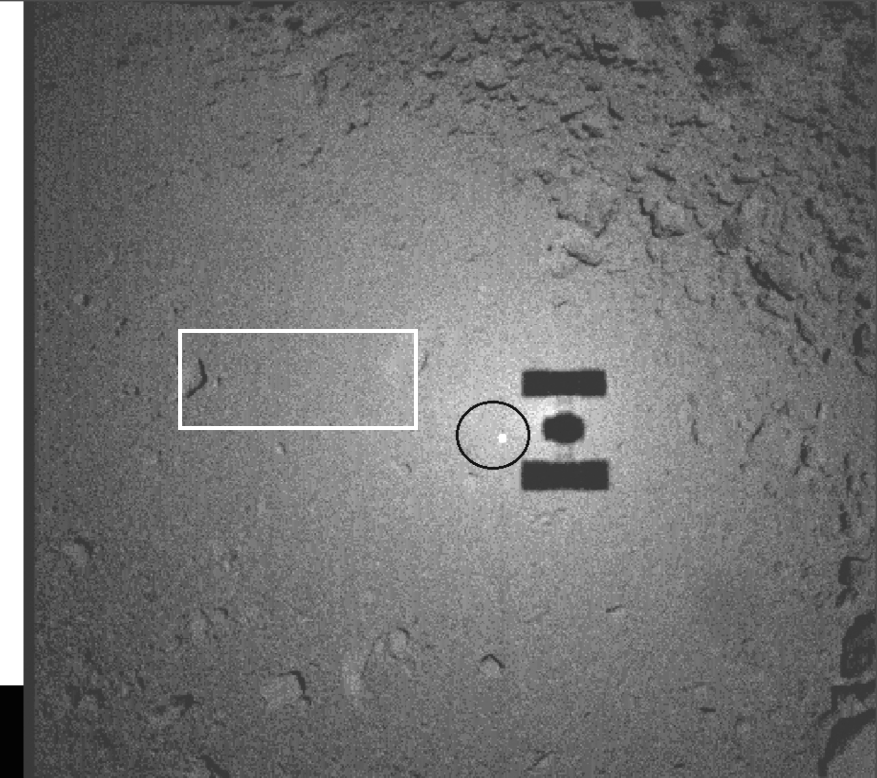

20 meters


8 m

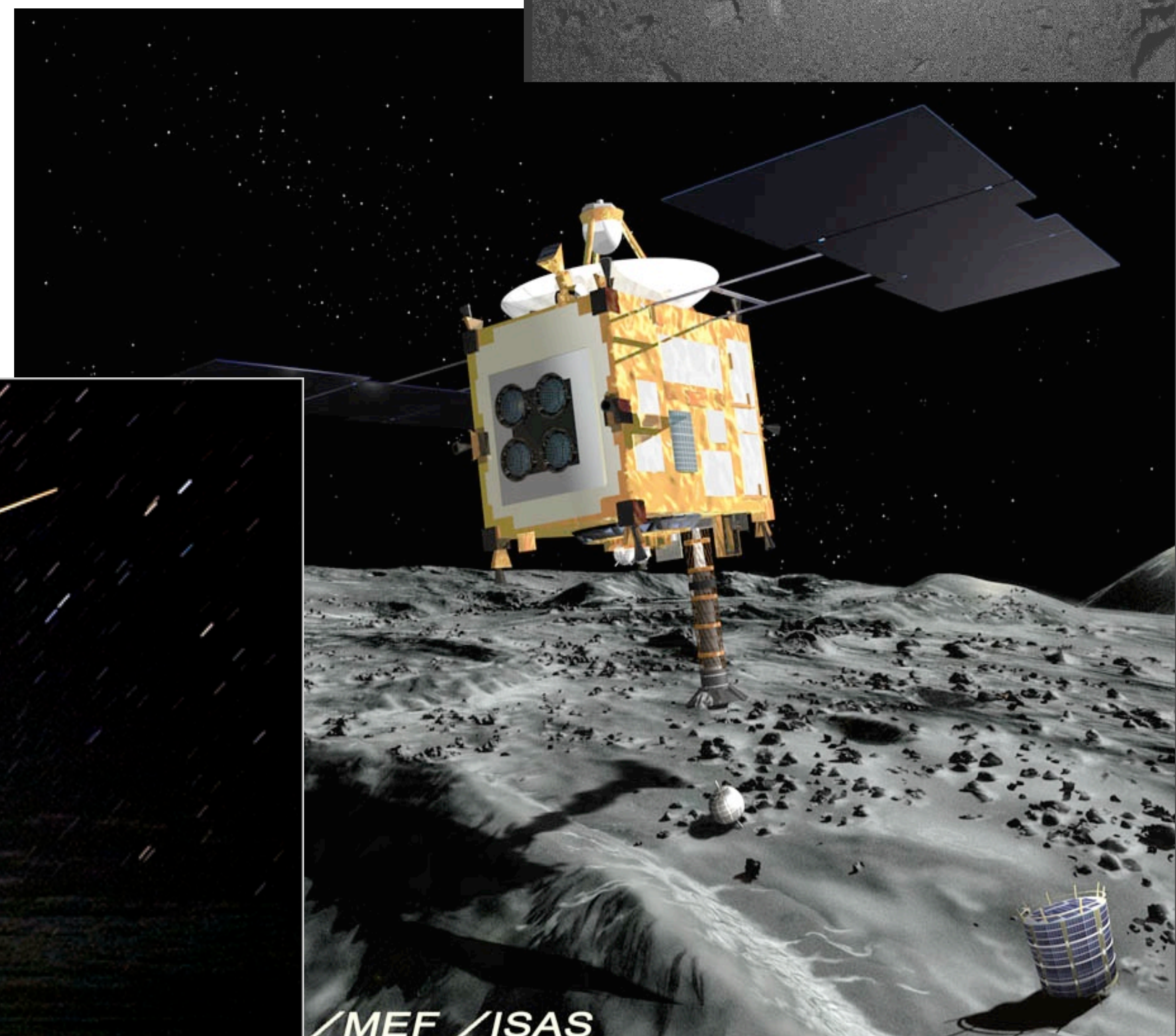


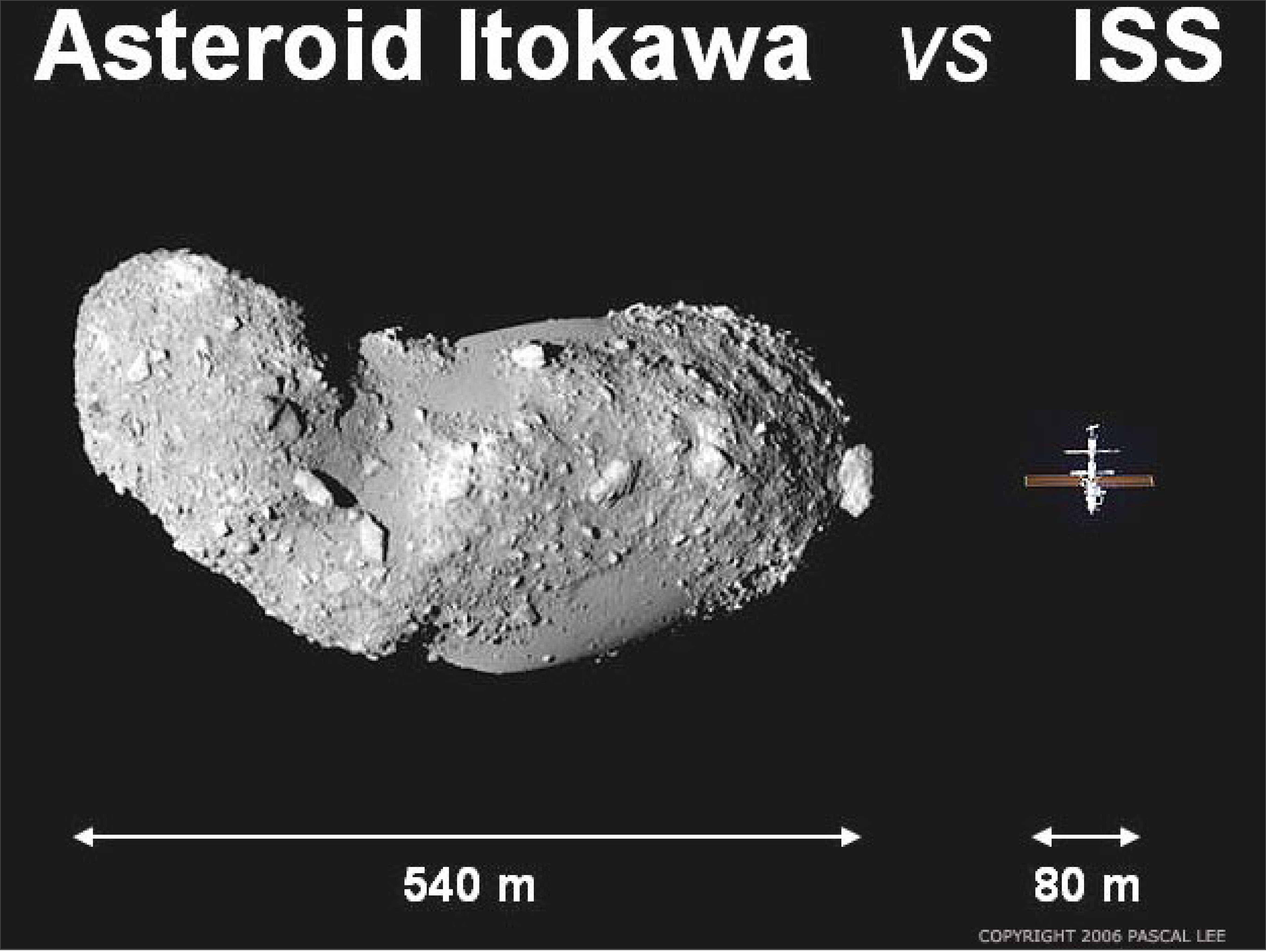
2 meters

Hayabusa Mission

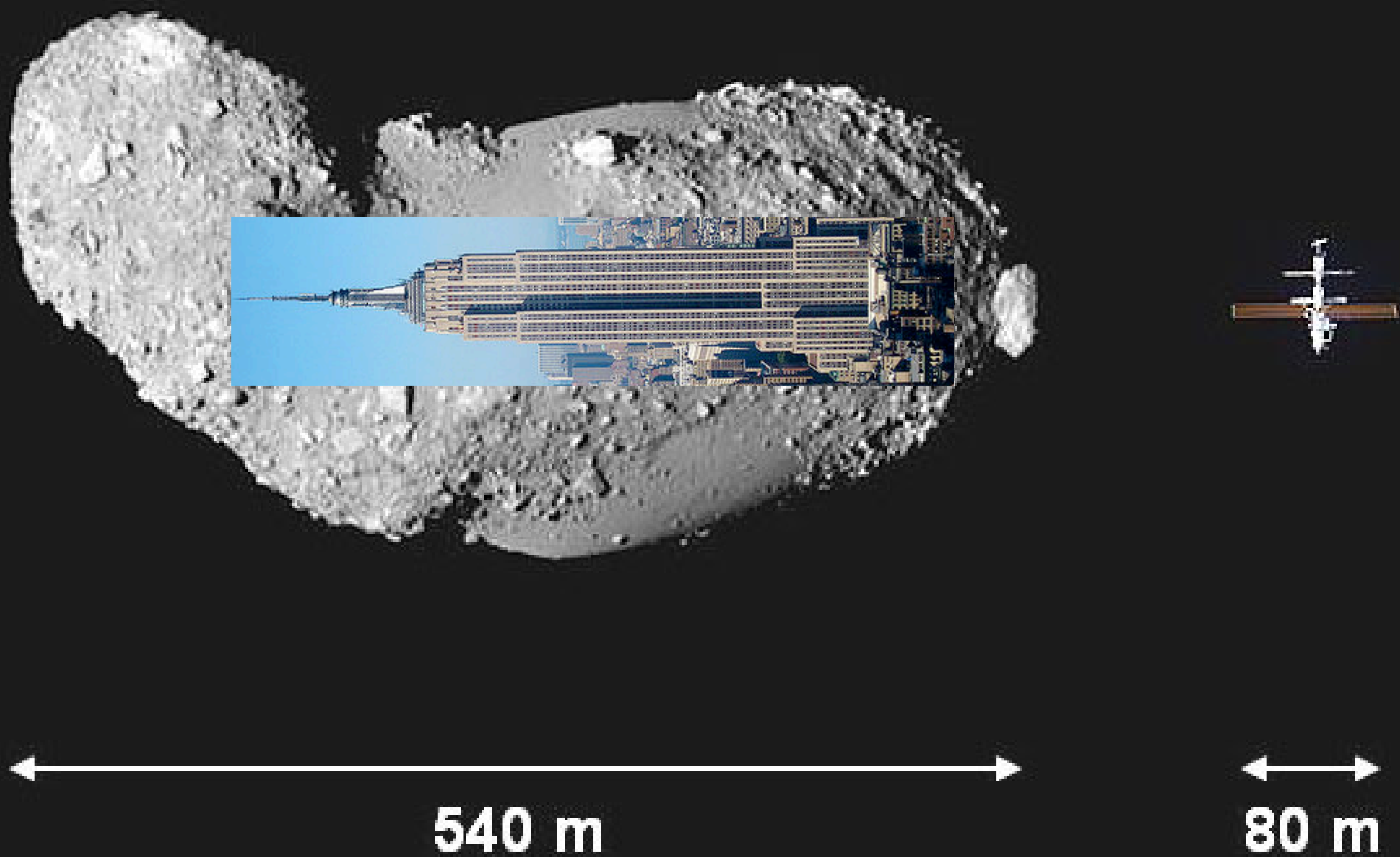


- Japanese sample return mission to asteroid Itokawa
- Launched 2003, arrived at asteroid in 2005, returned to Earth in 2010 after a long, tortuous odyssey.

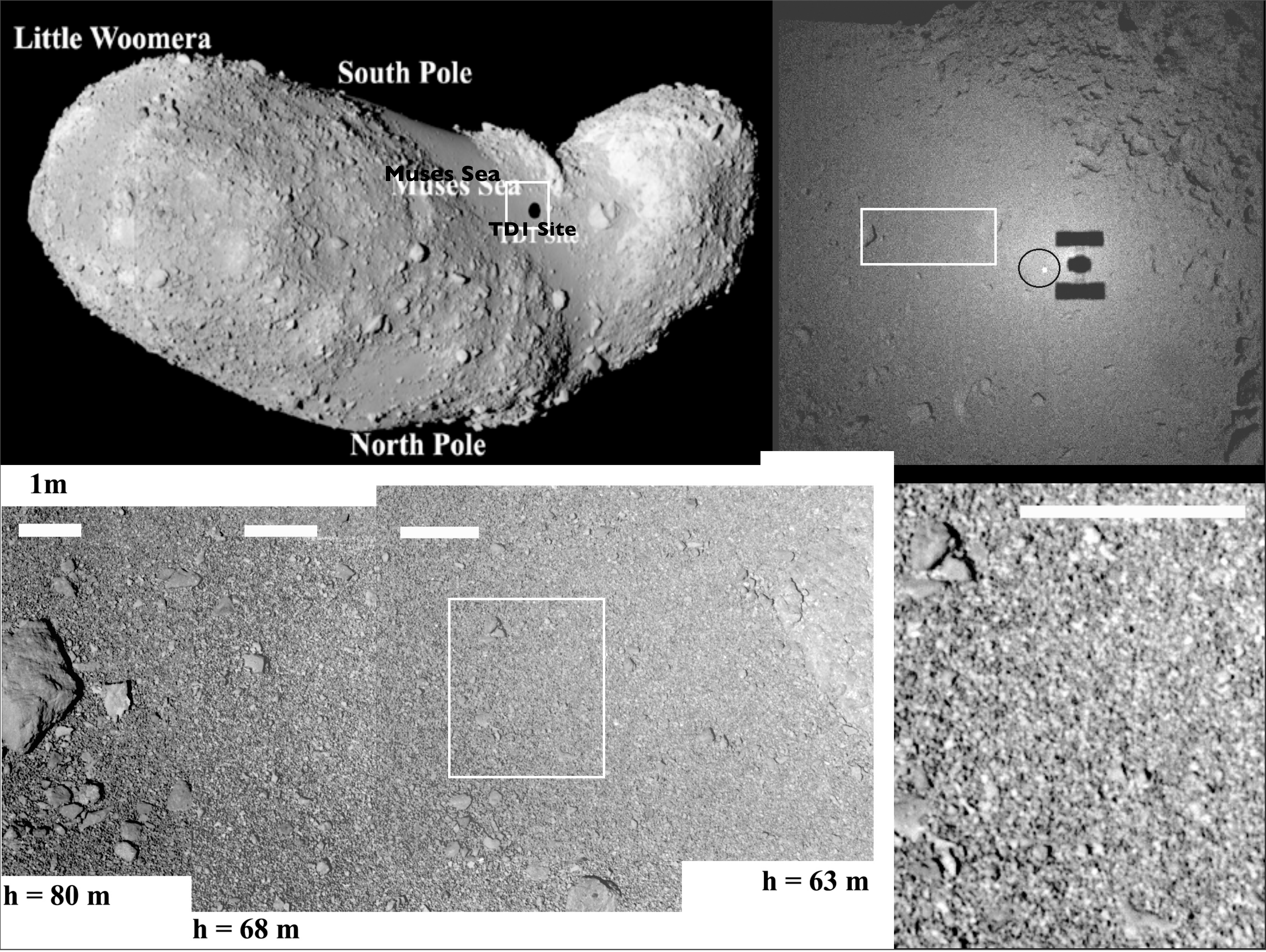


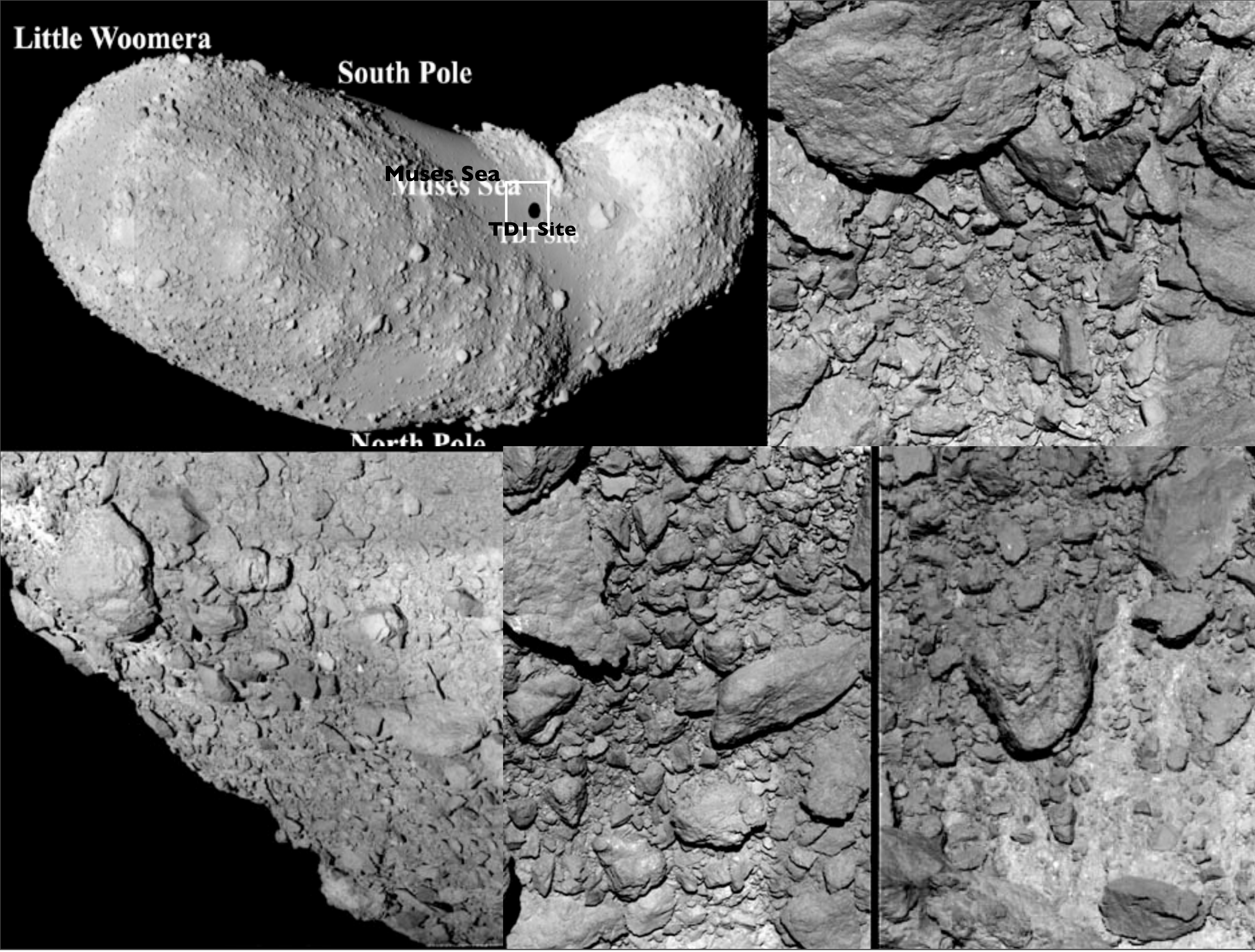

Asteroid Itokawa vs ISS
540 m
80 m
COPYRIGHT 2006 PASCAL LEE

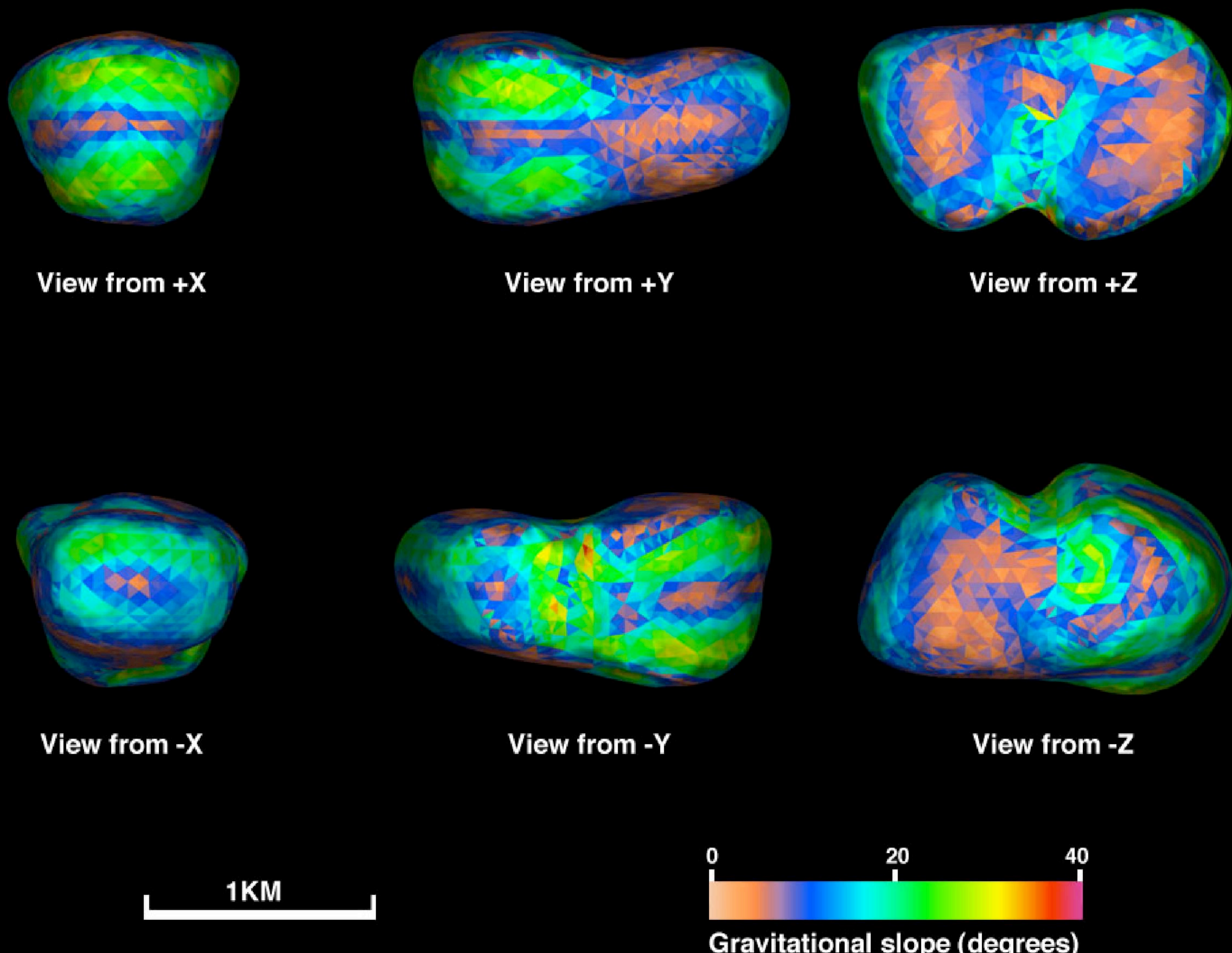
Asteroid Itokawa *vs* ISS

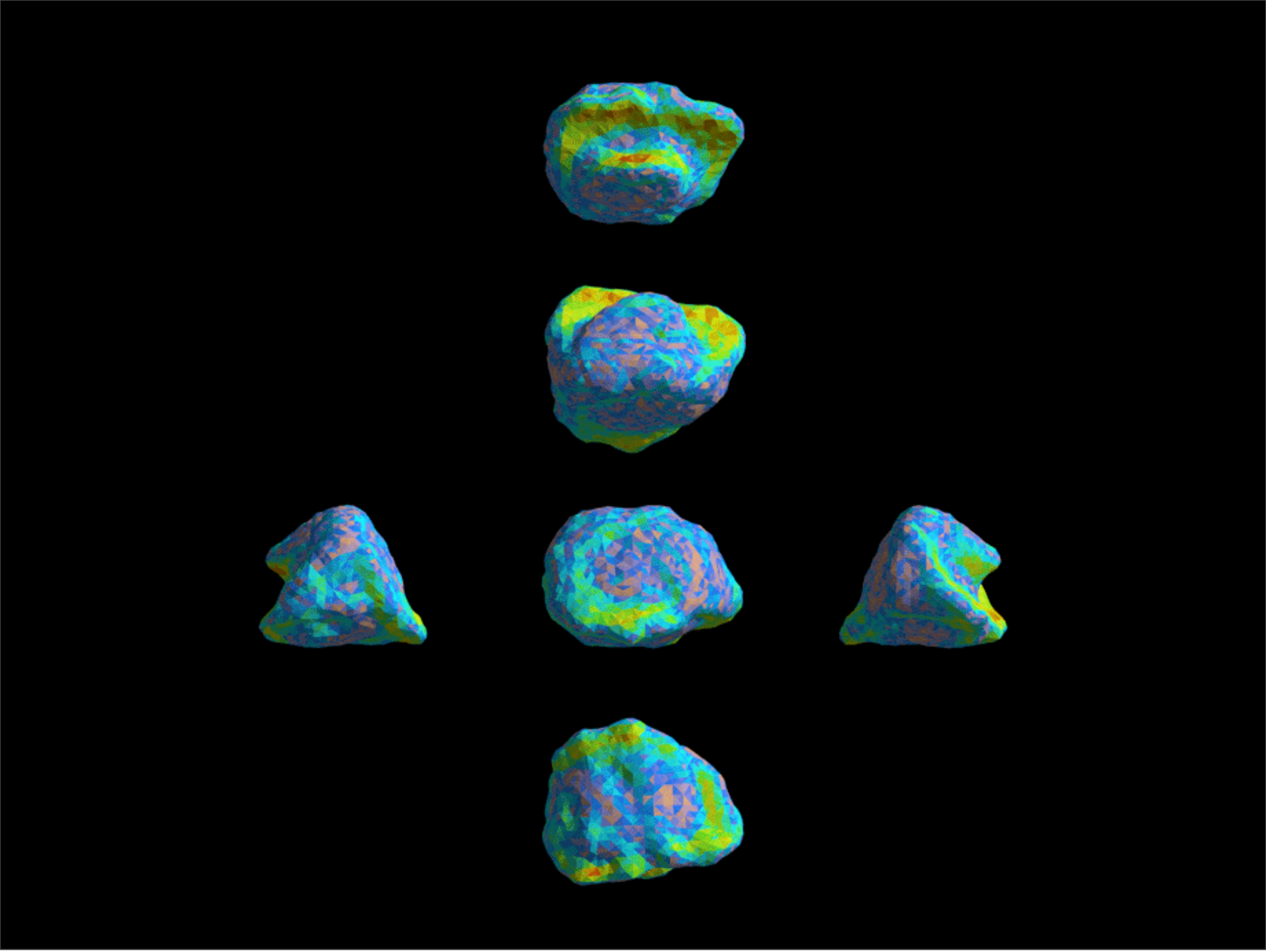


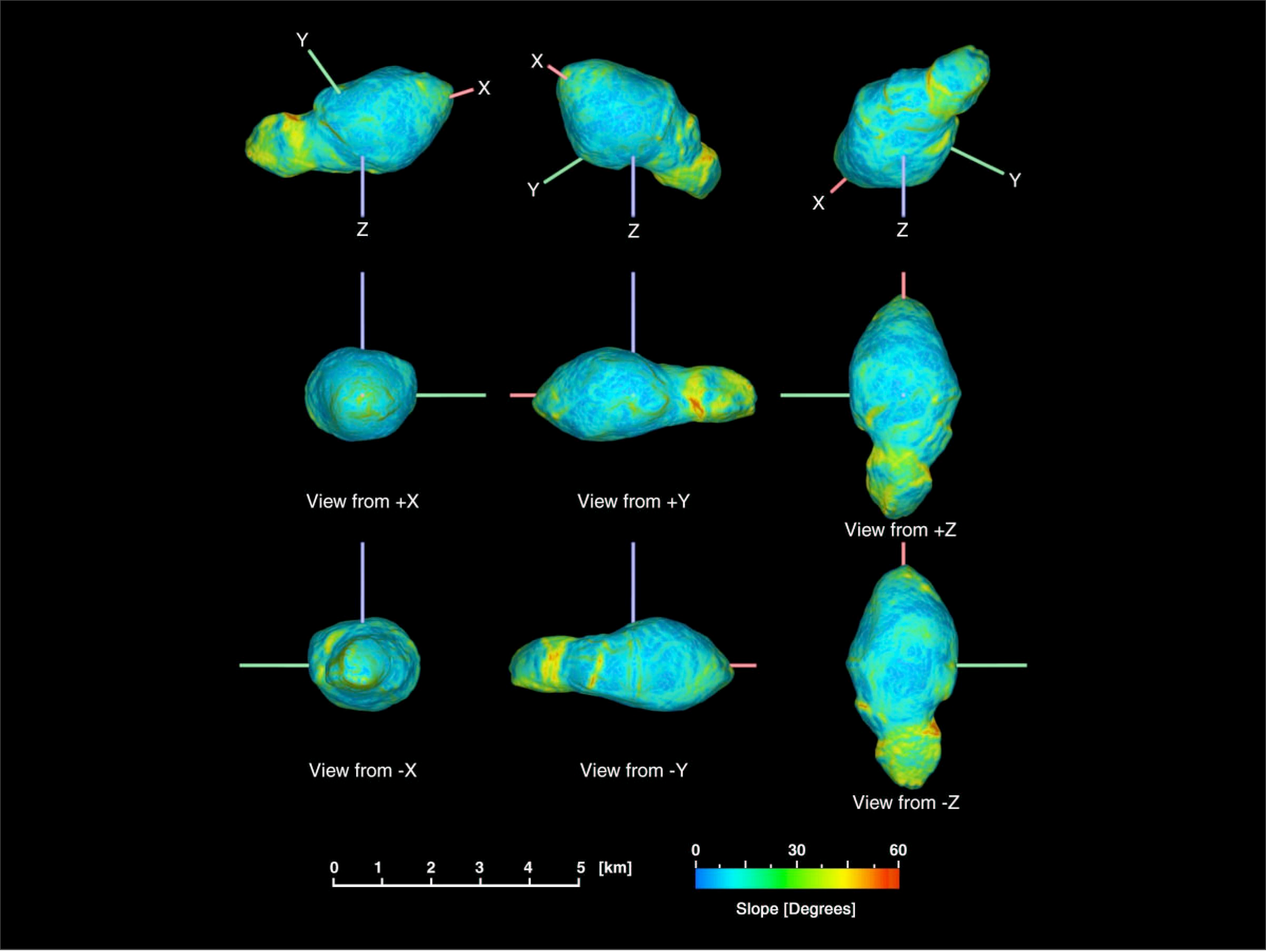

Science
HAYABUSA
Dust from Itokawa
AAAS



Little Woomera
South Pole
Muses Sea
TDI Site
North Pole
1m
h = 80 m
h = 68 m
h = 63 m

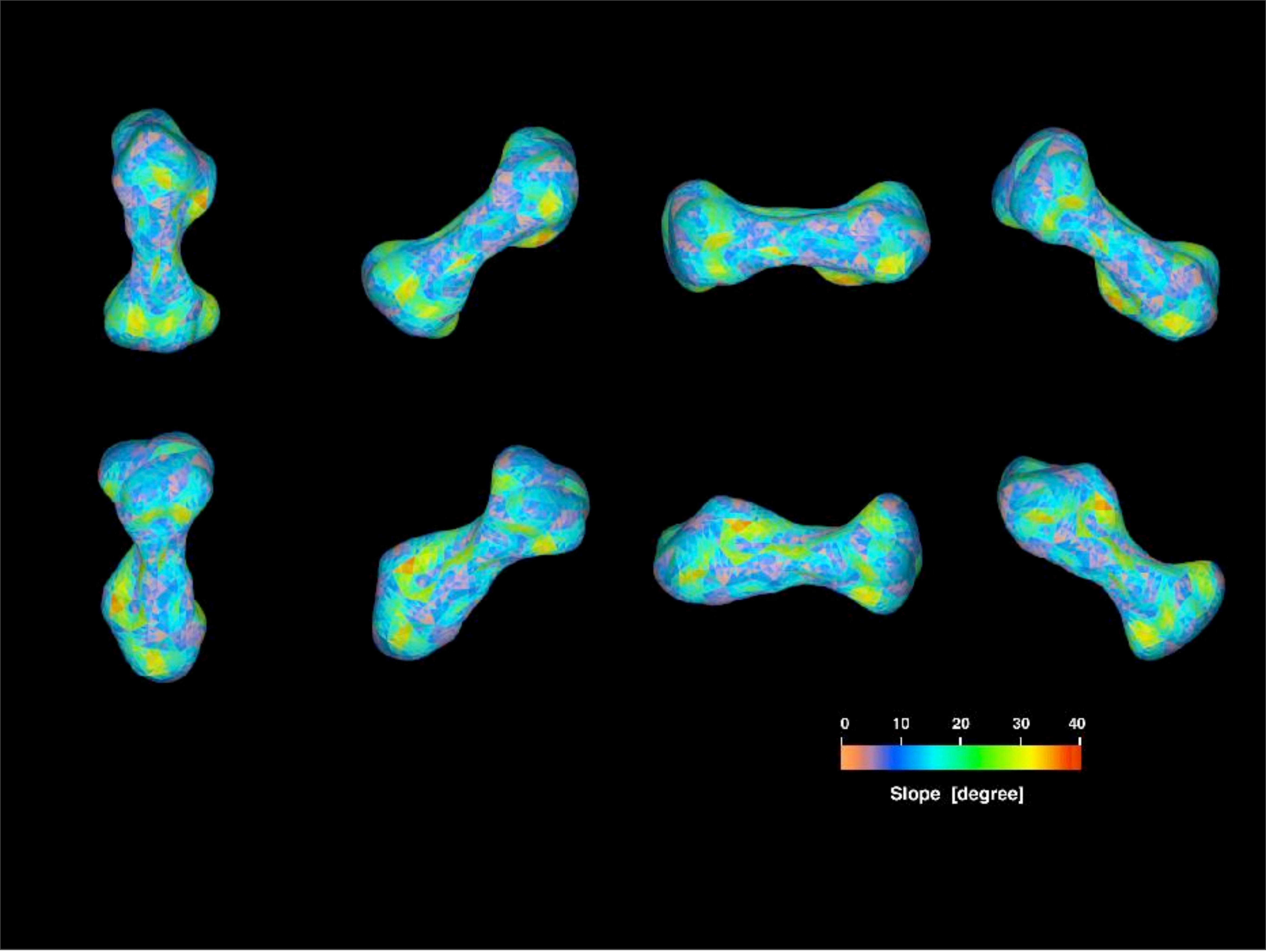

Little Woomera
South Pole
Muses Sea
TD1 Site
North Pole


View from +X
View from +Y
View from +Z
View from -X
View from -Y
View from -Z
1KM
0
20
40
Gravitational slope (degrees)




Y
X
Z
X
Y
Z
Y
X
Z
View from +X
View from +Y
View from +Z
View from -X
View from -Y
View from -Z
0
1
2
3
4
5
[km]
0
30
60
Slope [Degrees]


Toutatis
小行星间隔成像照片
CE-2卫星拍摄
北京时间
2012年12月13日16点30分09秒~24秒
成像距离 93km~240km
■最高分辨率 10m ■相对速度 10.73km/s ■交会距离 3.2km ■相距地球7,000,000km
@新华视点
weibo.com/xinhuashidian


0
10
20
30
40
Slope [degree]

Exploration of a Binary Asteroid...

from Earth

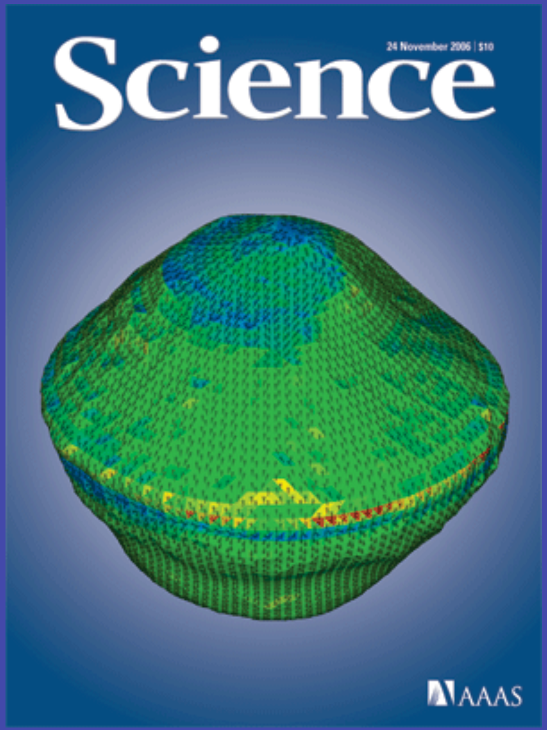
Radar Investigation of Asteroid (66391) 1999 KW4

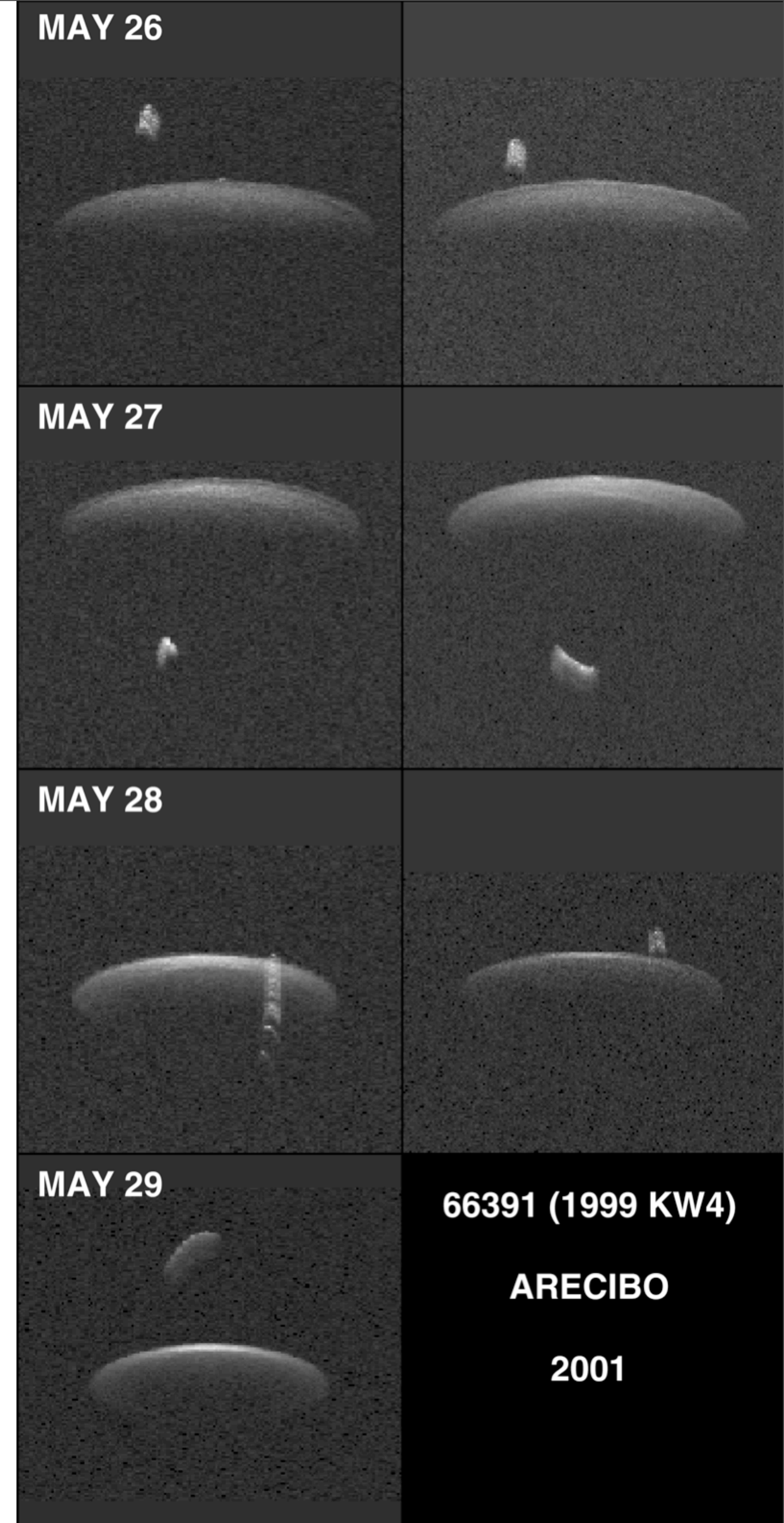
S.J. Ostro, J.-L. Margot, L. A. M. Benner, J. D. Giorgini, D. J. Scheeres, E. G. Fahnestock, S. B. Broschart, J. Bellerose, M. C. Nolan, C. Magri, P. Pravec, P. Scheirich, R. Rose, R. F. Jurgens, S. Suzuki, E. M. DeJong

Dynamical Investigation of Asteroid (66391) 1999 KW4

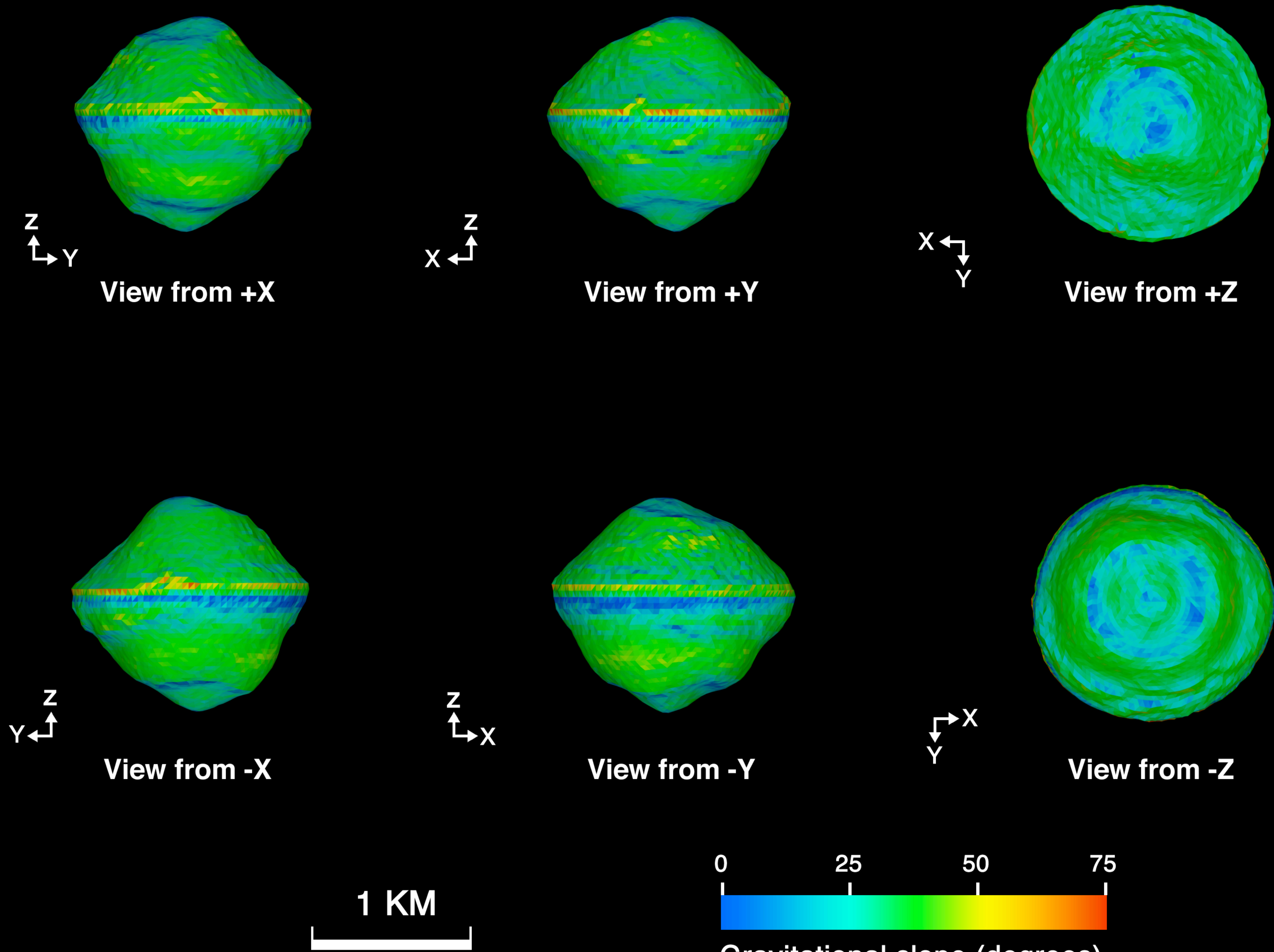
D.J. Scheeres, E. G. Fahnestock, S. J. Ostro, J.-L. Margot, L. A. M. Benner, S. B. Broschart, J. Bellerose, J. D. Giorgini, M. C. Nolan, C. Magri, P. Pravec, P. Scheirich, R. Rose, R. F. Jurgens, S. Suzuki, E. M. DeJong

November 24, 2006 Issue

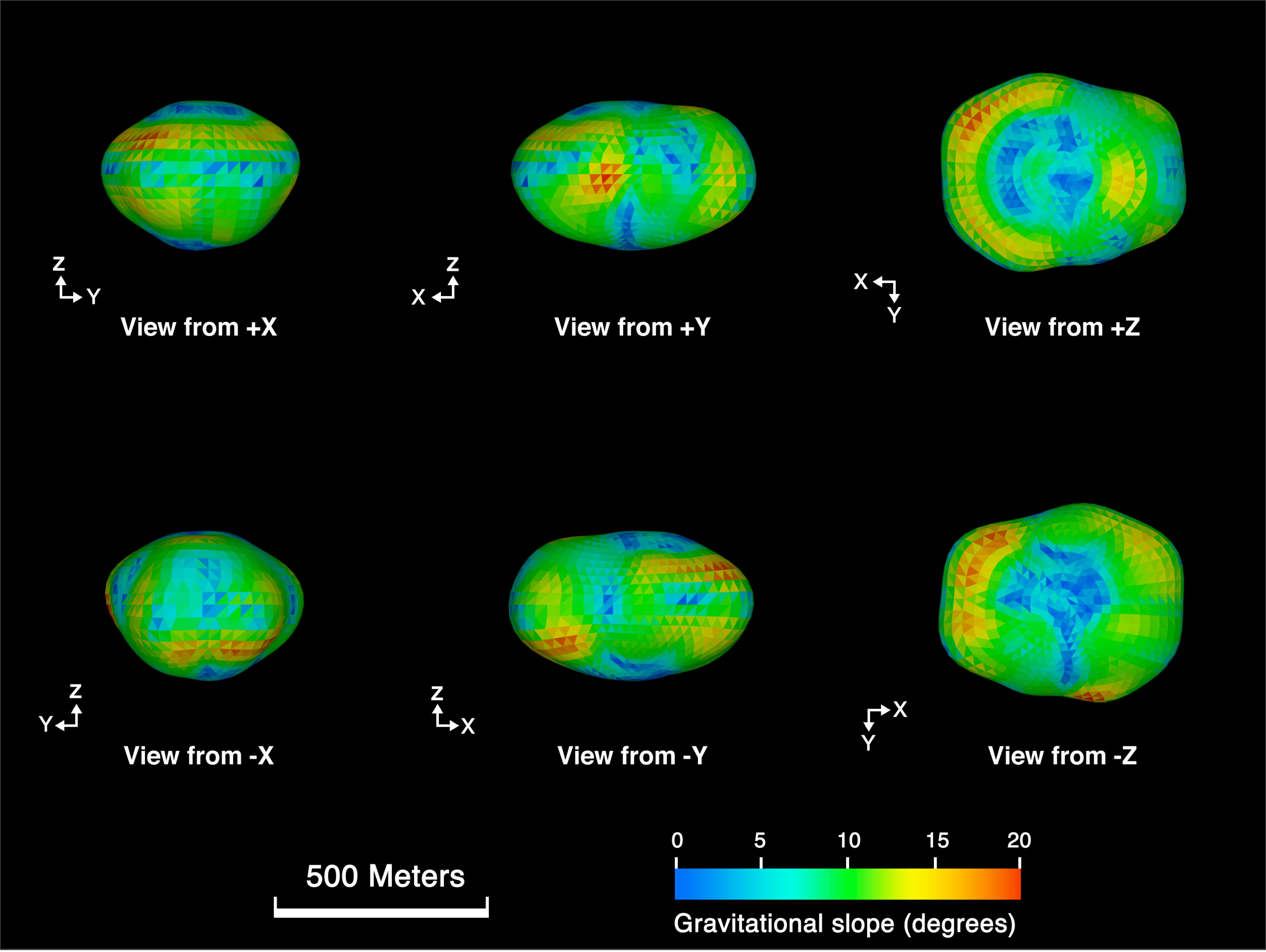




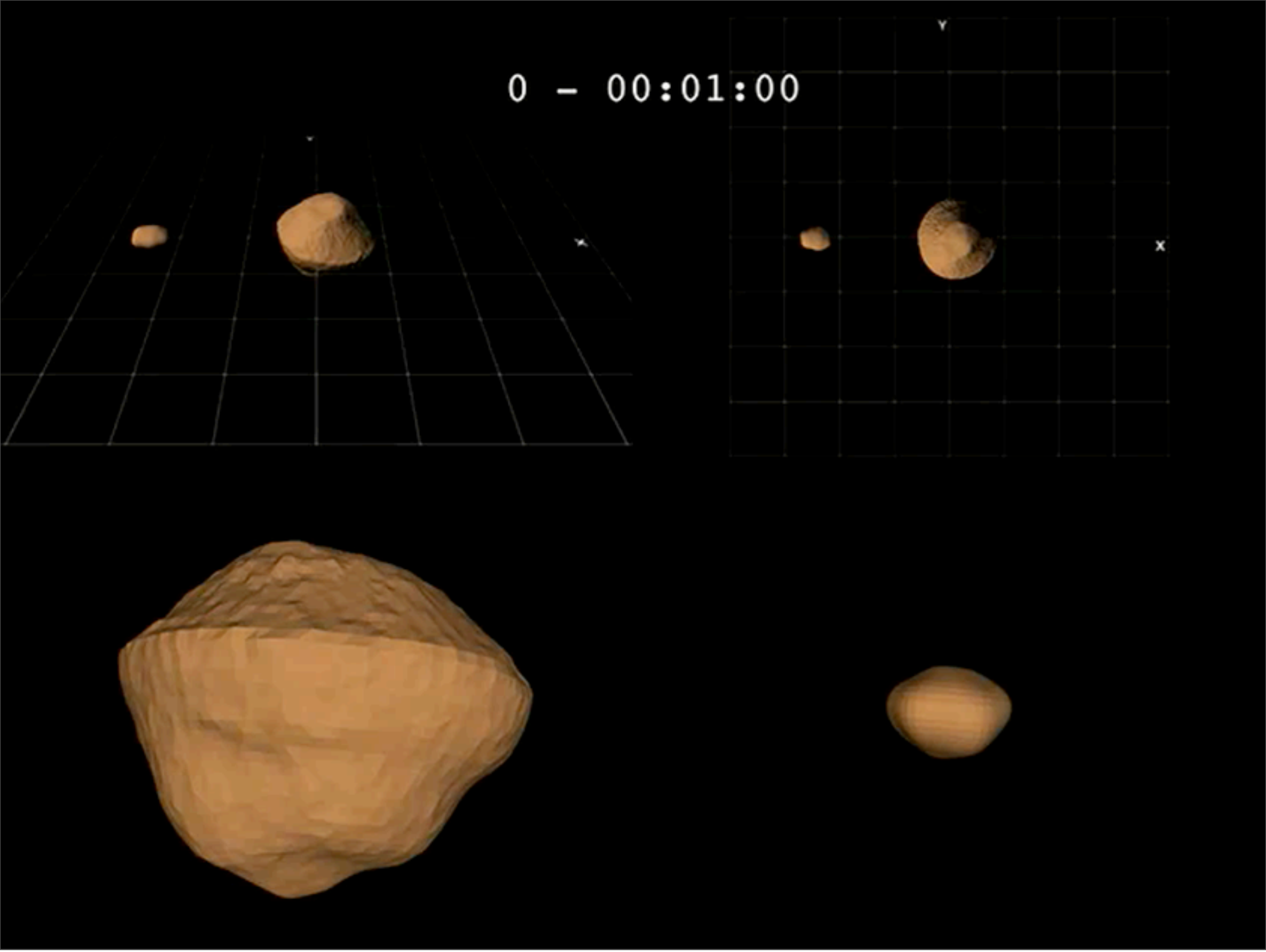
Raw range-Doppler radar data



Z
Y
View from +X
Z
X
View from +Y
X
Y
View from +Z
Z
Y
View from -X
Z
X
View from -Y
X
Y
View from -Z
1 KM
0
25
50
75
Gravitational slope (degrees)

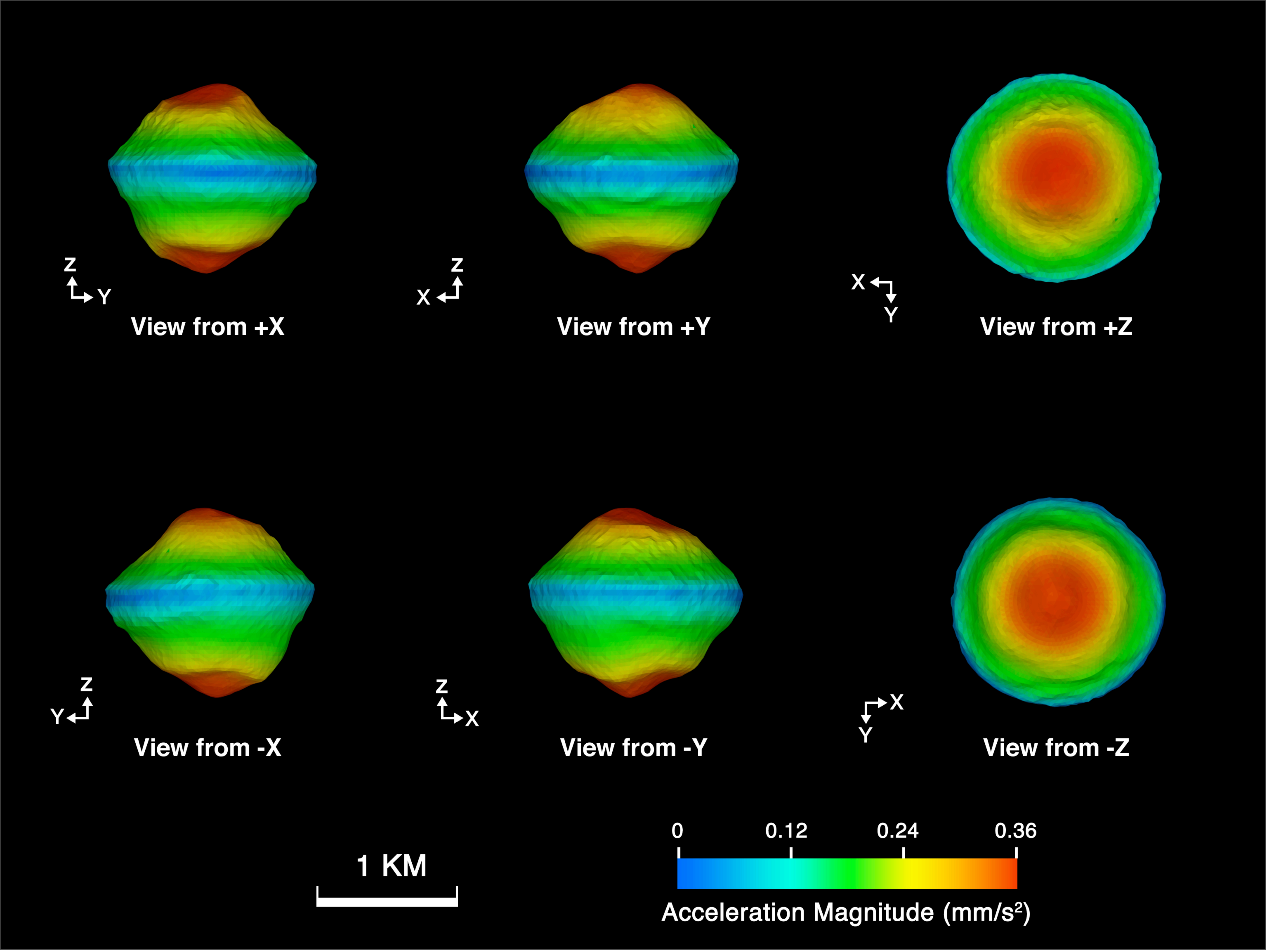


Z
Y
View from +X
Z
X
View from +Y
X
Y
View from +Z
Z
Y
View from -X
Z
X
View from -Y
X
Y
View from -Z
500 Meters
0
5
10
15
20
Gravitational slope (degrees)


0 - 00:01:00
Y
X

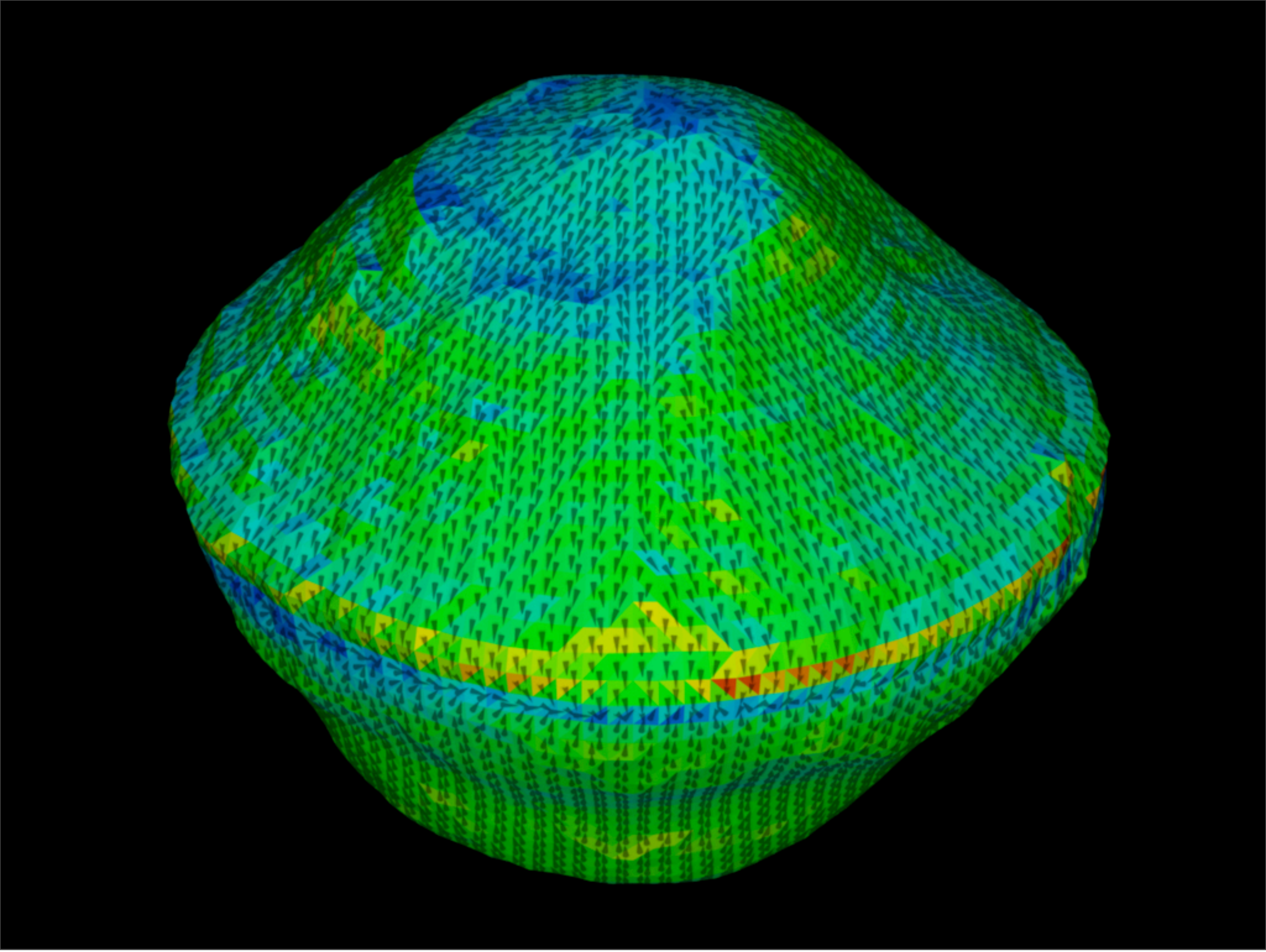
Extreme Environment on Alpha

- Alpha spins just shy of/at its disruption rate:


Z
Y
View from +X
Z
X
View from +Y
X
Y
View from +Z
Z
Y
View from -X
Z
X
View from -Y
X
Y
View from -Z
1 KM
0
0.12
0.24
0.36
Acceleration Magnitude (mm/s²)

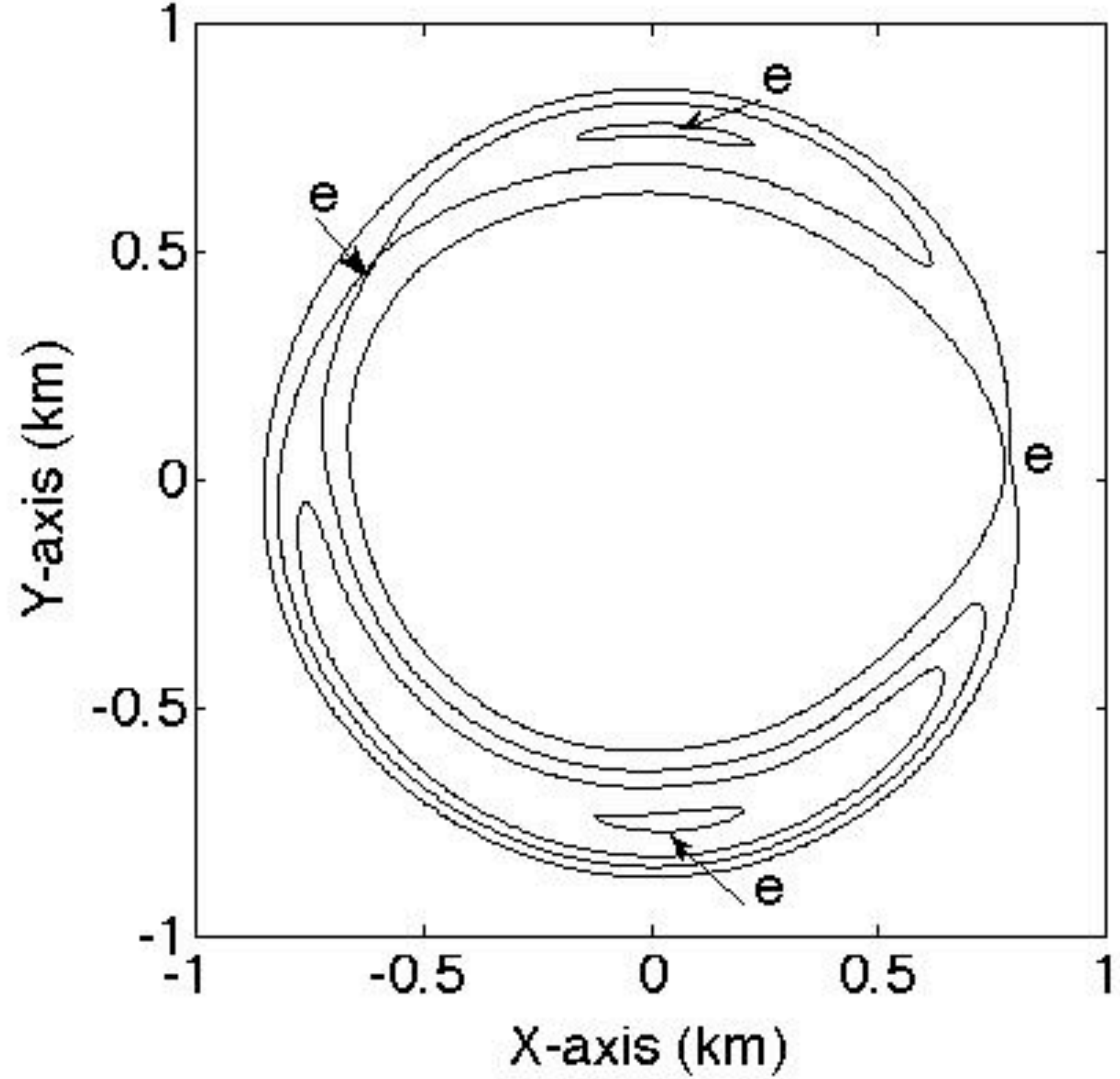
Extreme Environment on Alpha

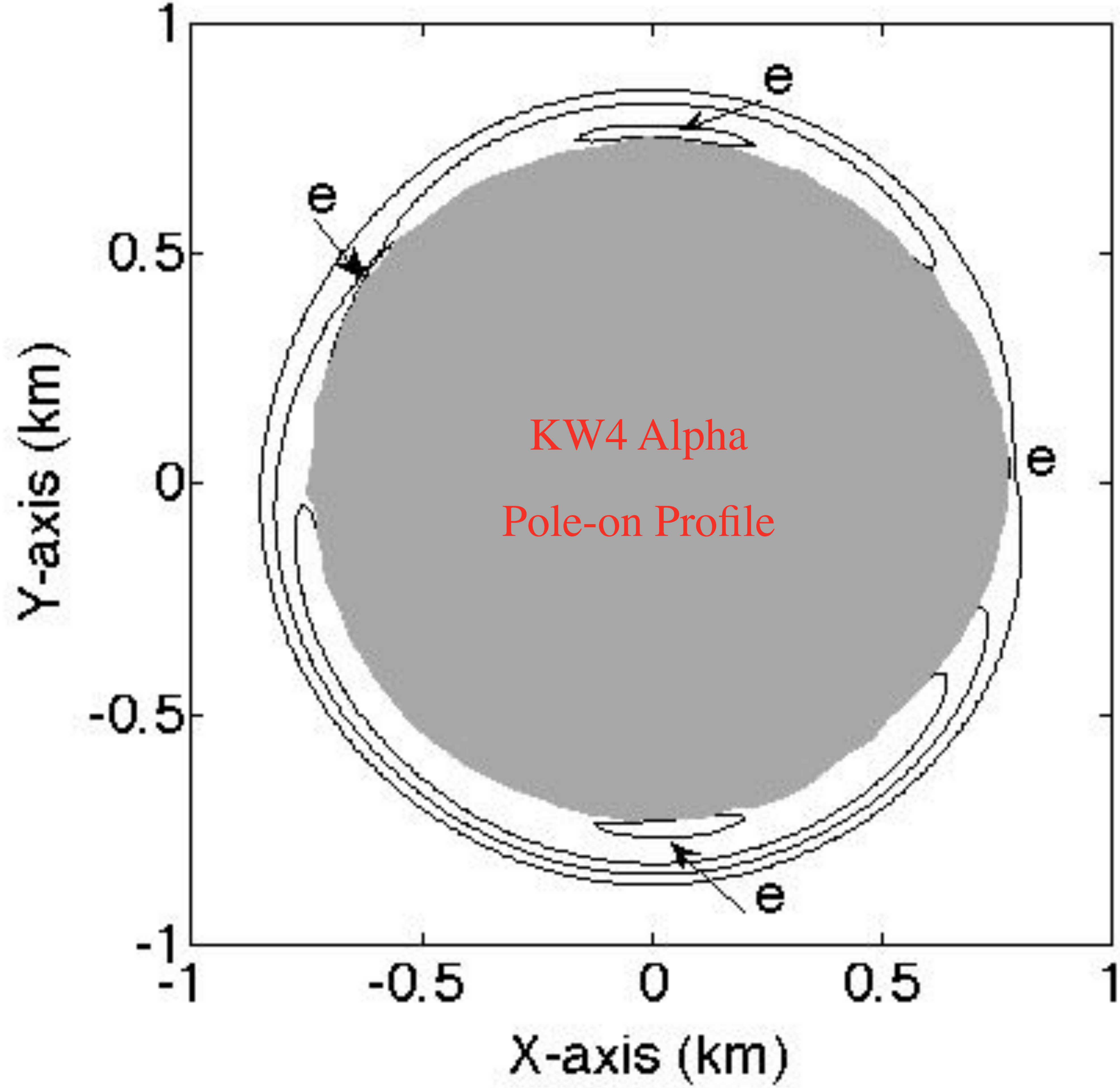
- Alpha spins just shy of/at its disruption rate
- The “lowest” point on Alpha is at its equator, the furthest point from its center.



Extreme Environment on Alpha

- Alpha spins just shy of/at its disruption rate
- The “lowest” point on Alpha is at its equator, the furthest point from its center.
- Particles on its surface are just meters or less from being in orbit

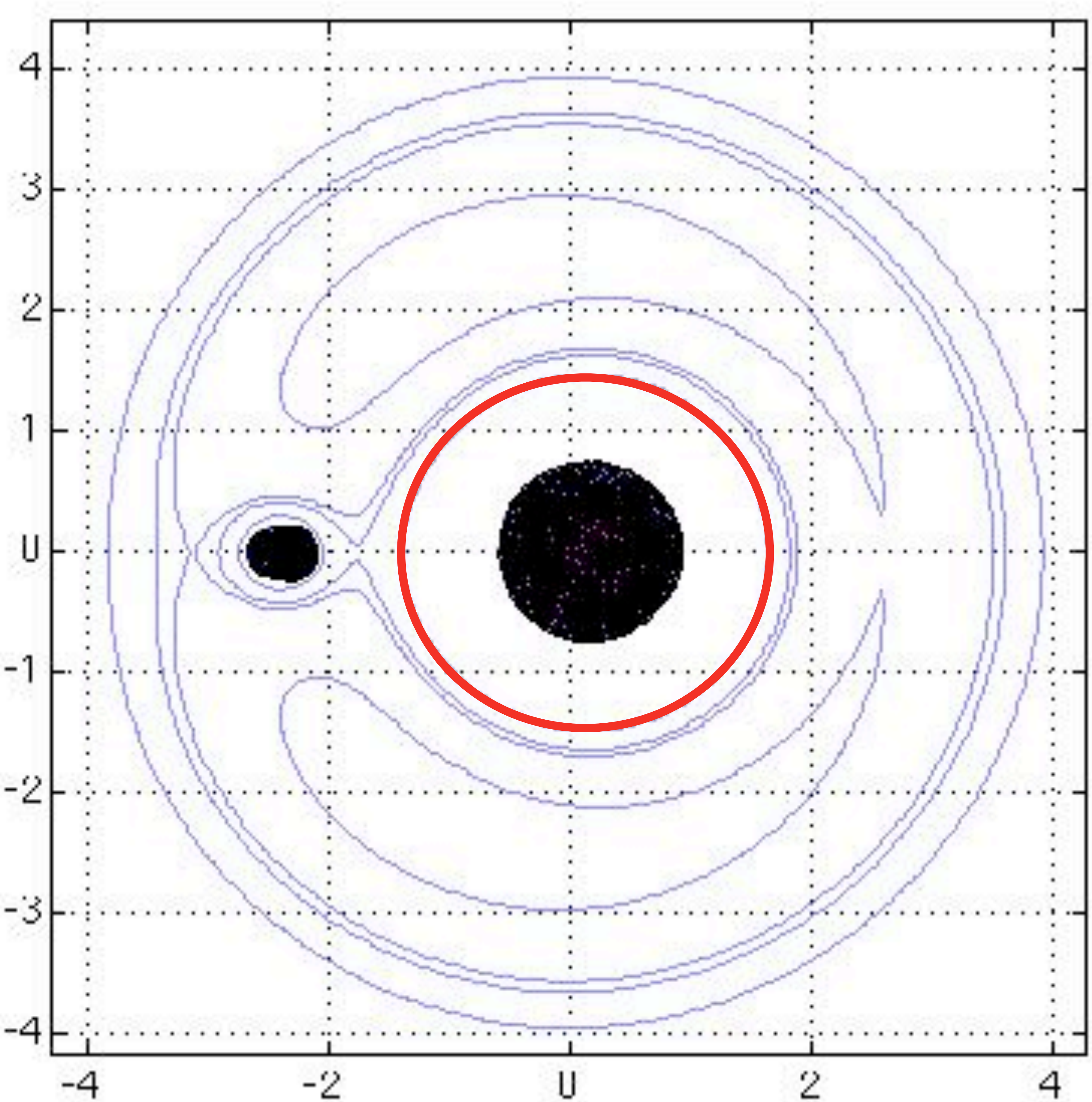

e
e
e
e
0.5
0
-0.5
-1
-1
-0.5
0
0.5
1
Y-axis (km)
X-axis (km)



KW4 Alpha
Pole-on Profile
e
e
e
e
Y-axis (km)
X-axis (km)
1
0.5
0
-0.5
-1
-1
-0.5
0
0.5
1

Extreme Environment on Alpha

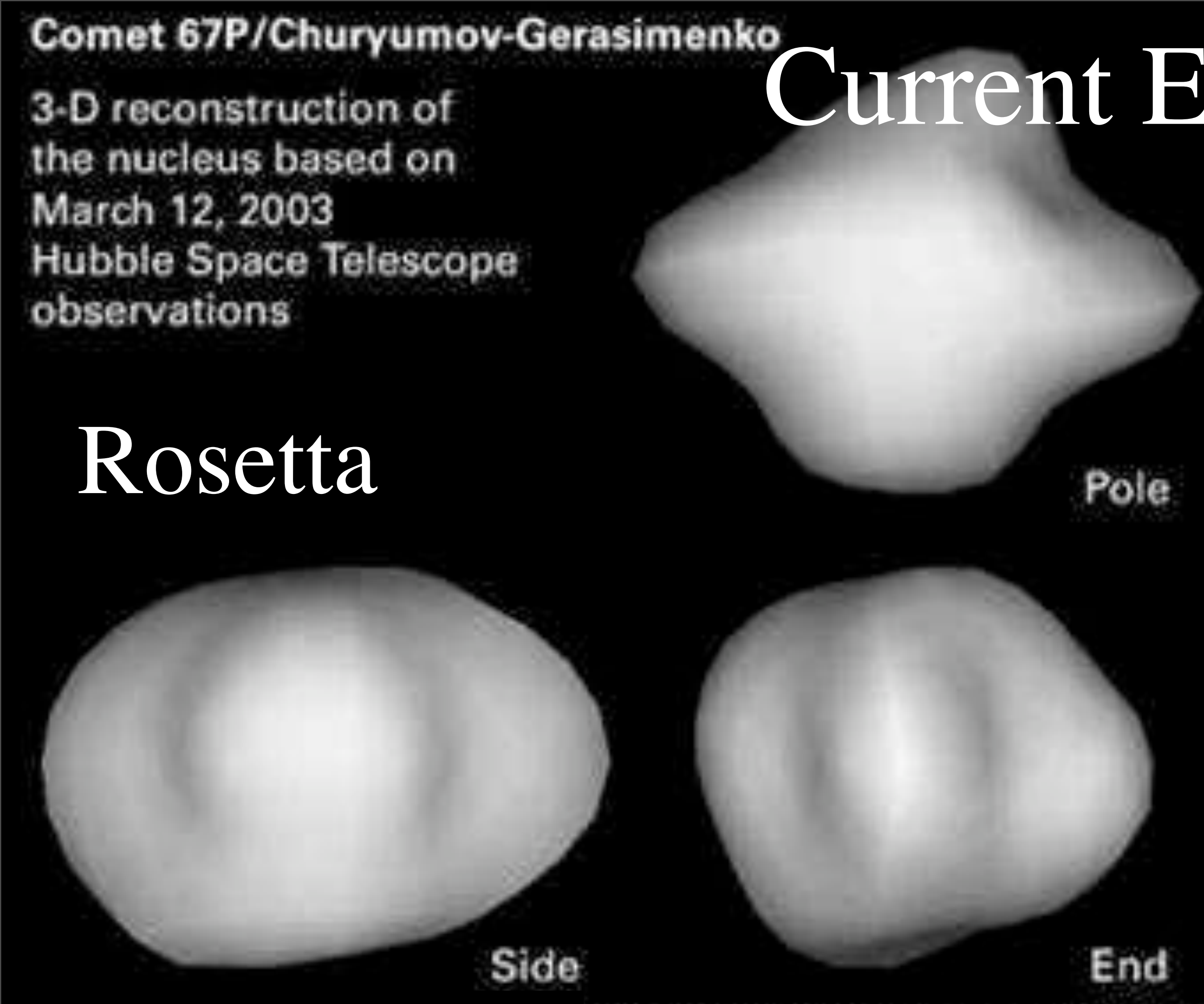
- Alpha spins just shy of/at its disruption rate
- The "lowest" point on Alpha is at its equator, the furthest point from its center.
- Particles on its surface are just meters or less from being in orbit
- Any loose material spun off of Alpha will be trapped by Beta
  - Will eventually fall back on Alpha
  - Will transfer angular momentum to the orbit
  - Will regulate Alpha's spin at its maximum rate

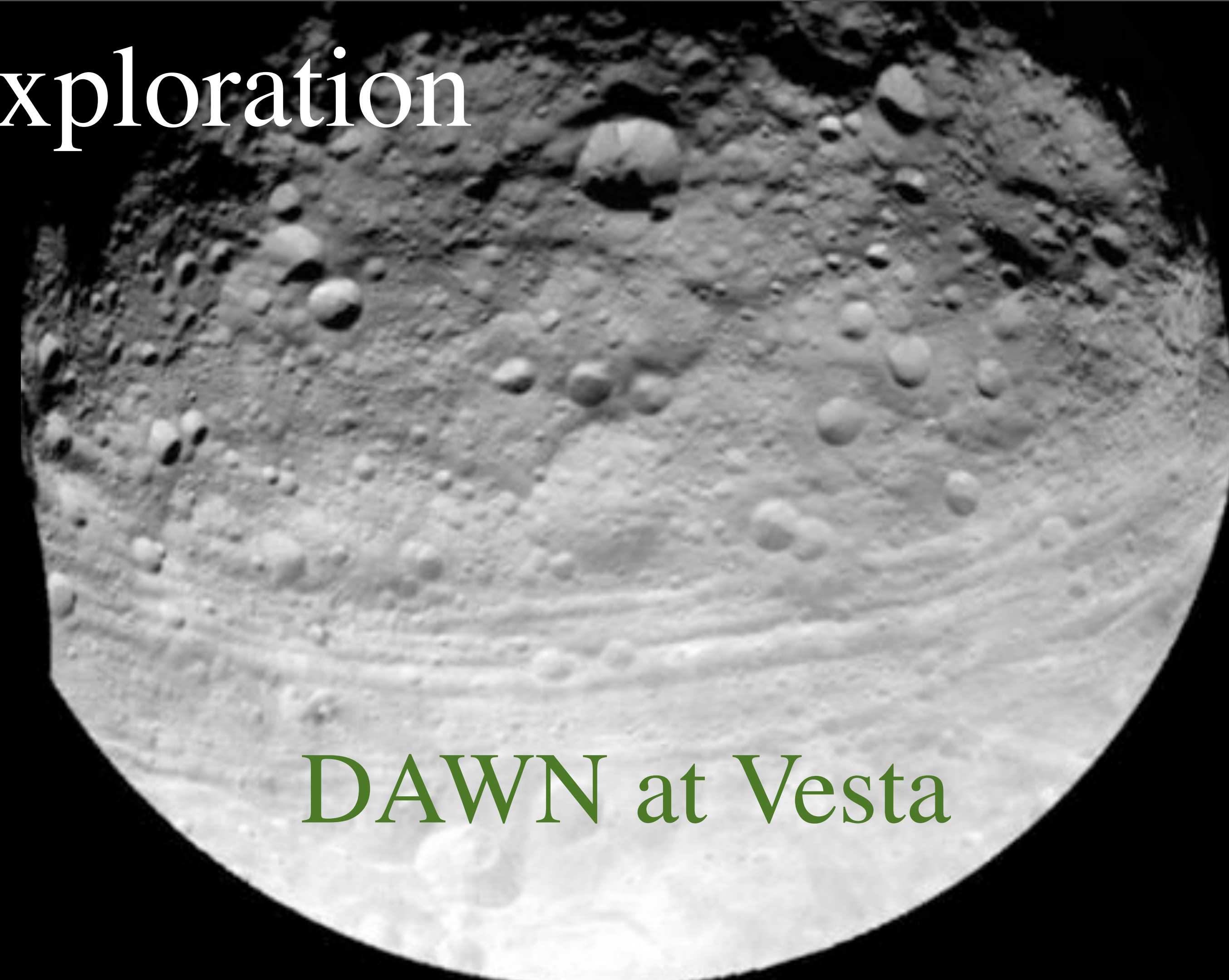


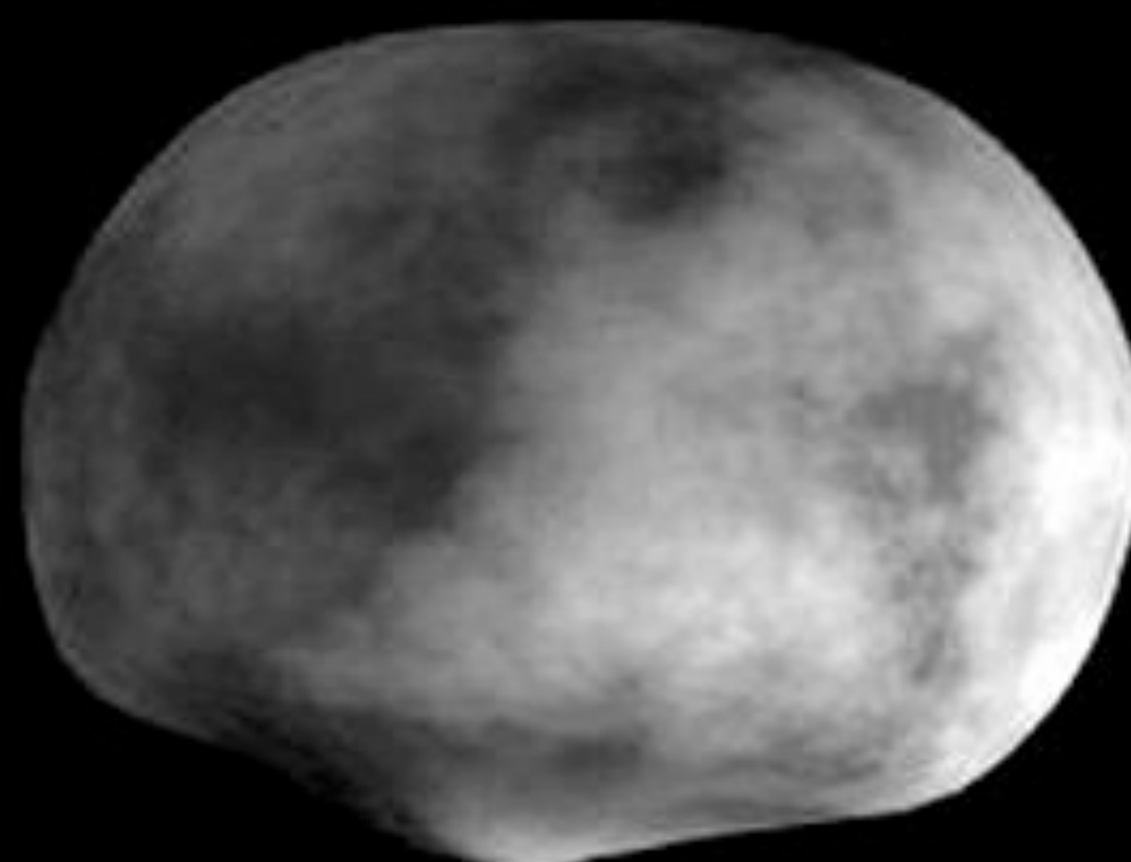
4
3
2
1
0
-1
-2
-3
-4
-4
-2
0
2
4


2001 May 21 - 00:00:00

Current Exploration

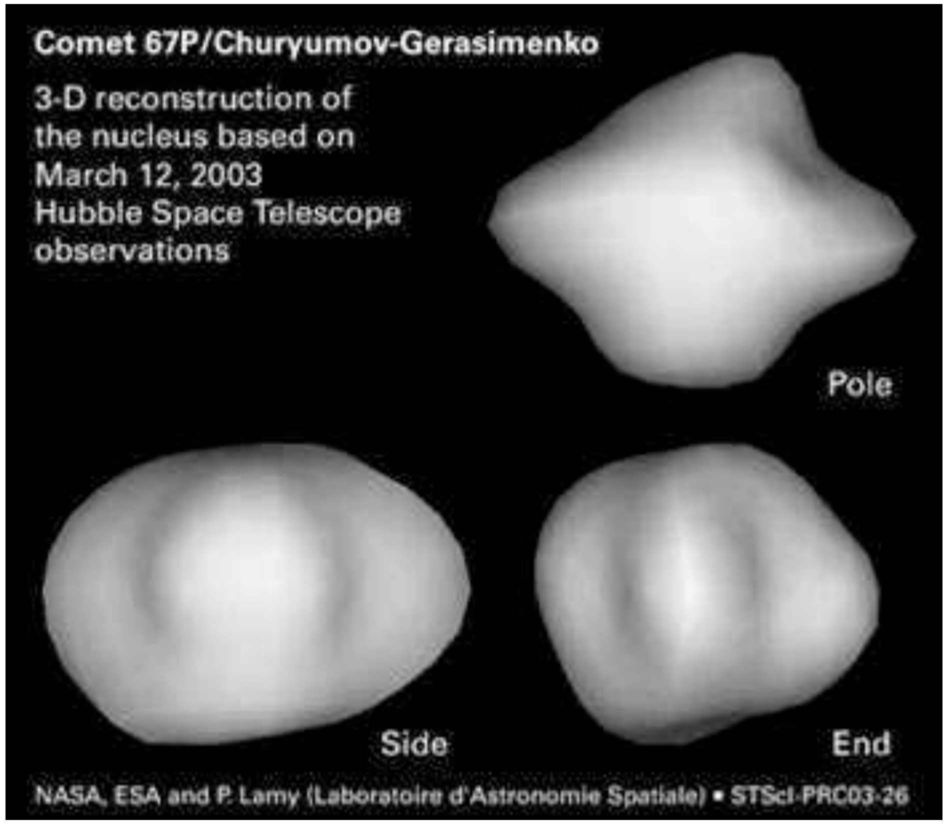






Case Study: Rosetta at 67P/CG

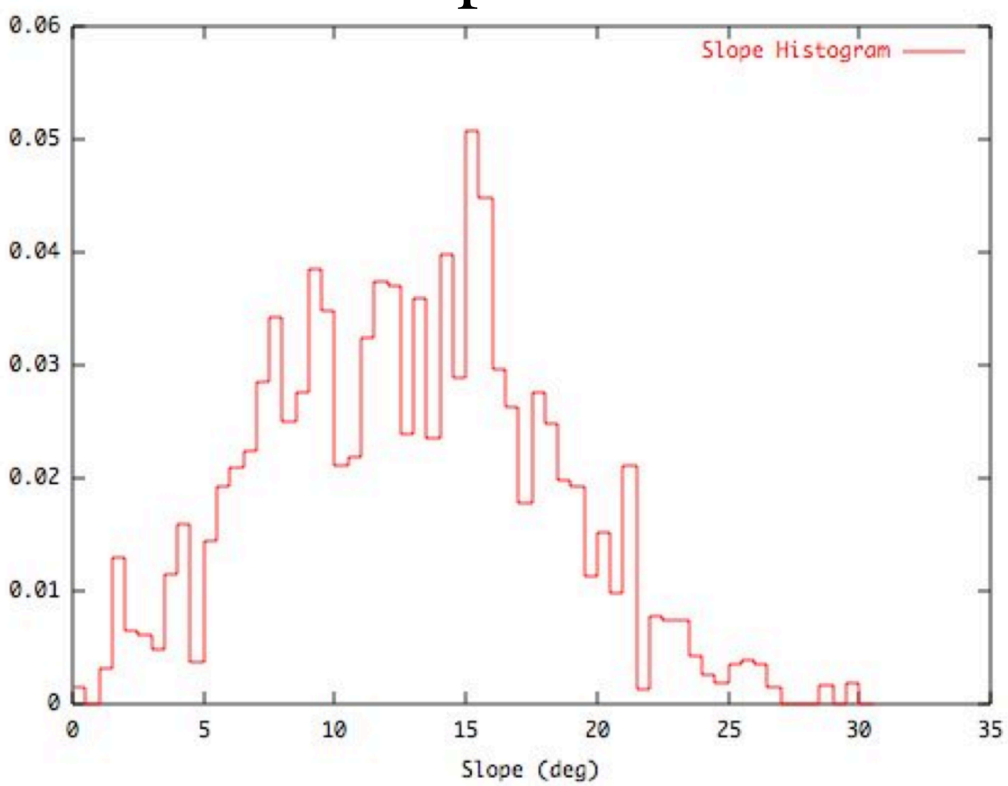
- Outgassing – a possibly dominant perturbation – is not discussed.
- Rosetta Spacecraft:
  - Mass ~ 2300 -> 1700 kg
  - Area ~ 77 m^2
  - B = Mass / Area ~ 30 -> 22 kg/m^2, we use 26 kg/m^2
- Comet 67P/C-G:
  - Mean radius ~ 1.9 km
  - Bulk density ~ 0.37 g/cm^3
  - Spin period ~ 12.55 h
  - Obliquity ~ 138°
  - Orbit:
    - d = 1.25 -> 5.69 AU
    - a = 3.468 AU, e = 0.64
  - Shape: From P. Lamy, et al.



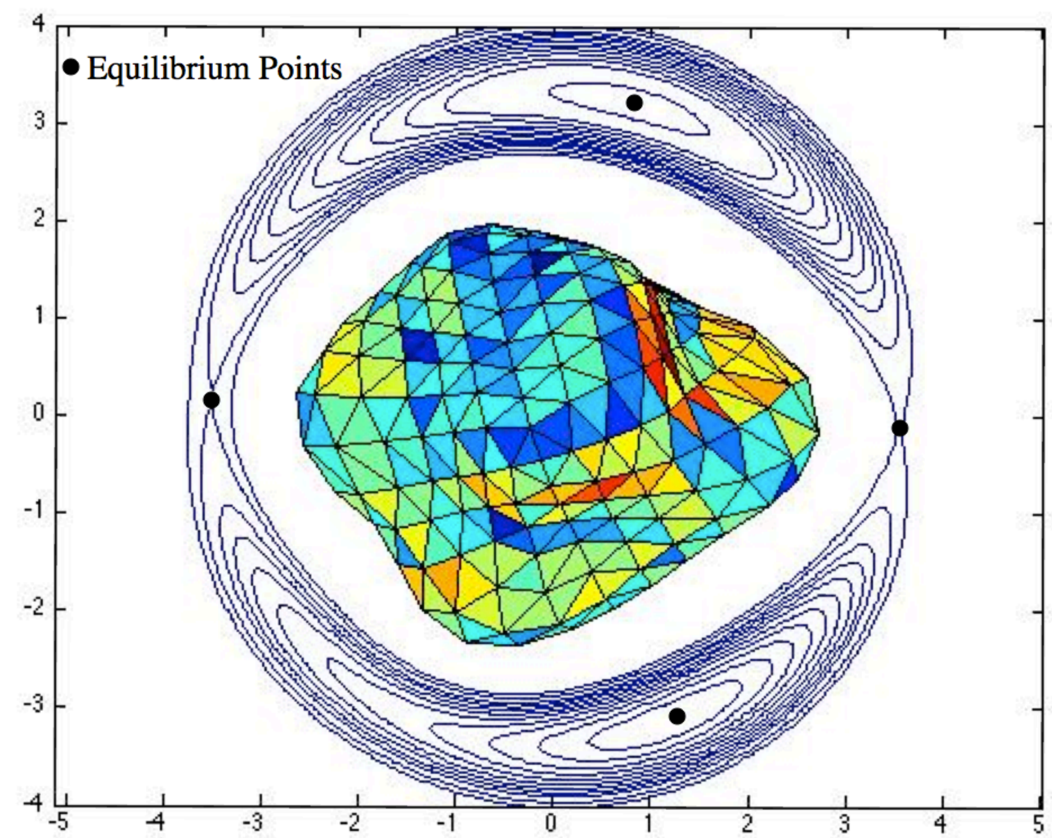
Near-Surface Environment

- Comet 67P/CG has 4 relative equilibria (synchronous 1:1 orbits) due to gravitation and rotation alone
  - All are unstable and do not have direct application
  - Can be used to characterize impact limits

Surface Slope Distribution

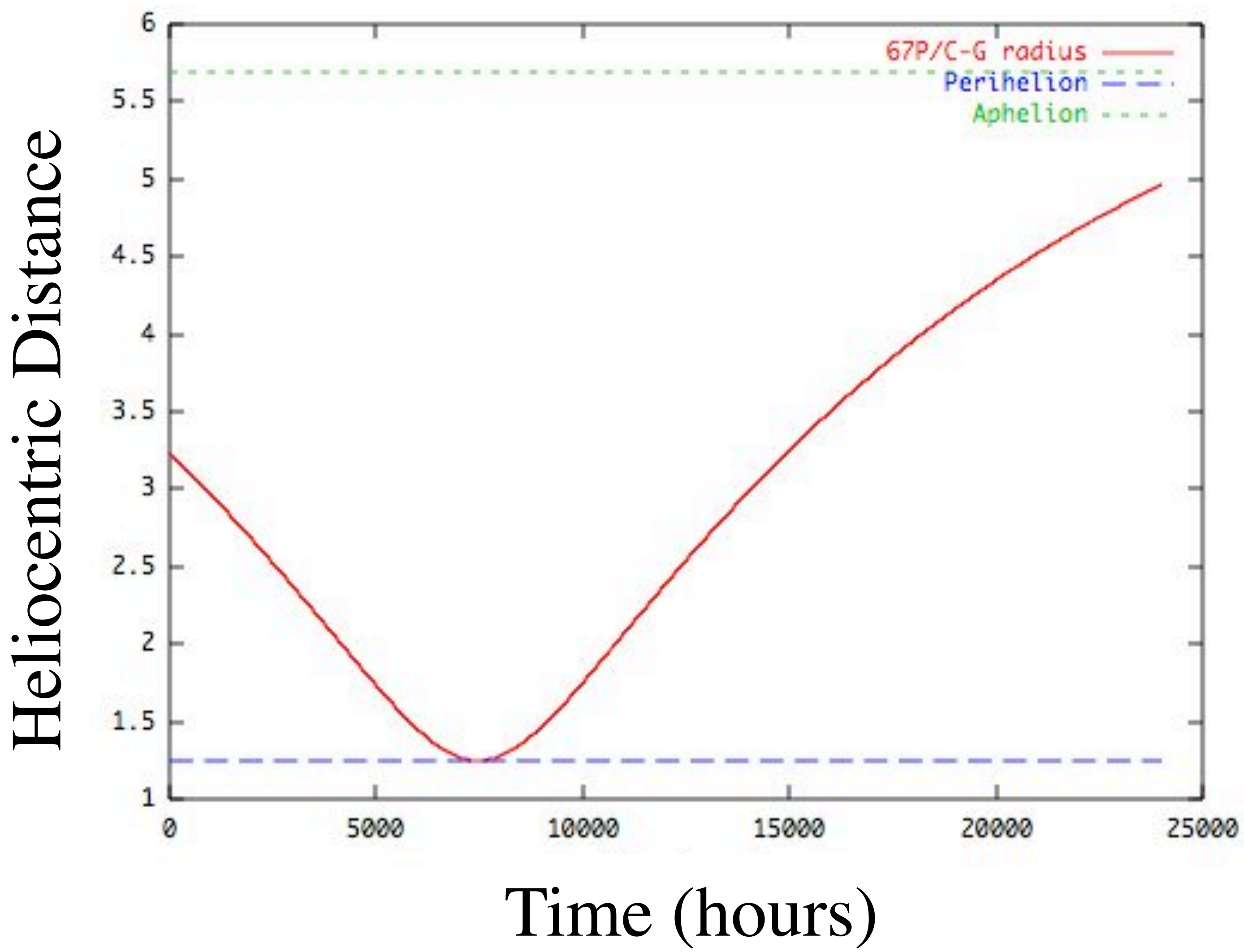


Blue = 0°
Red = 30°



Orbital Results for 67P/C-G

- Ran a series of orbits to test predictions of the theory
  - Full detailed gravity field, rotation state, heliocentric orbit
  - Consistent initial comet true-anomaly of -125°
  - Runs propagated for 1000 days (unless impact occurs)

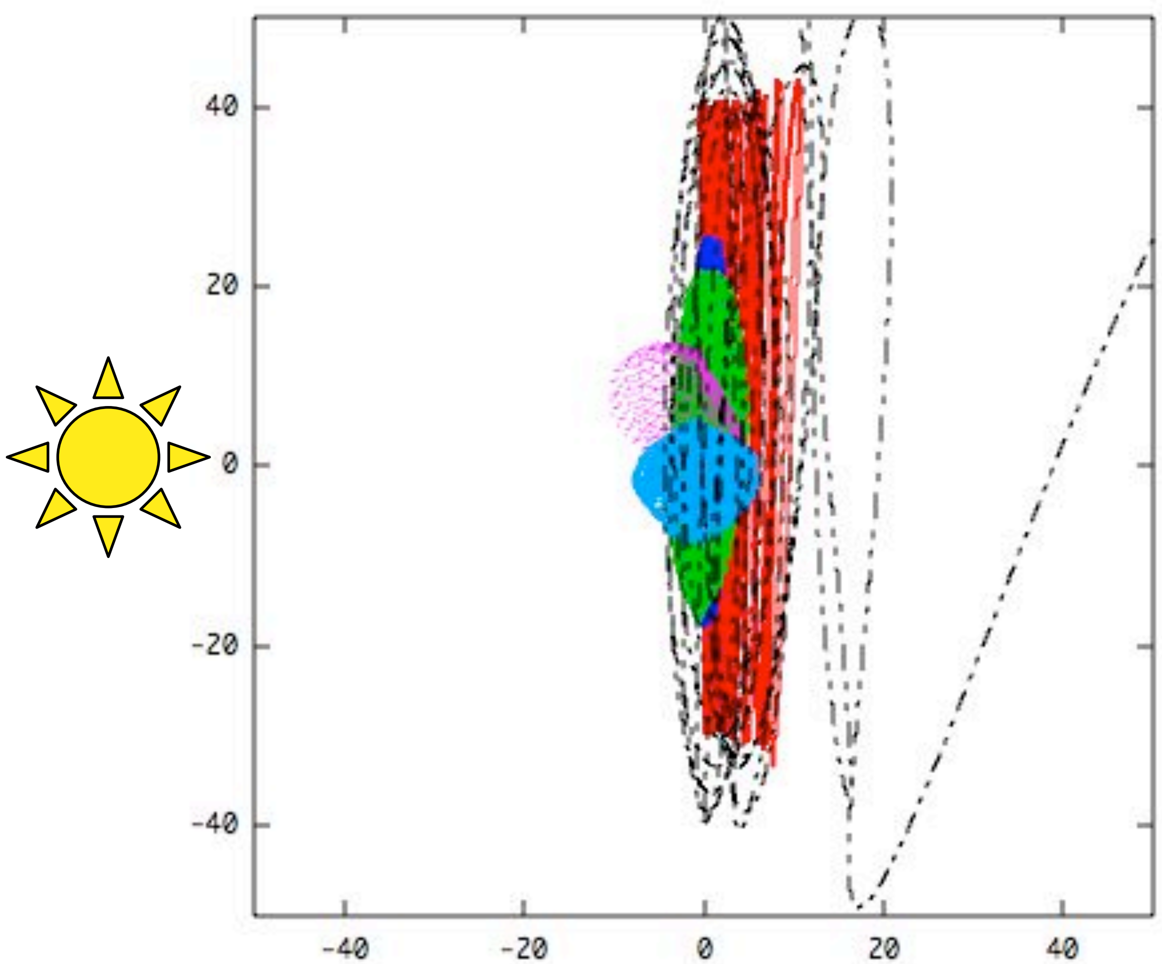


Terminator Orbits

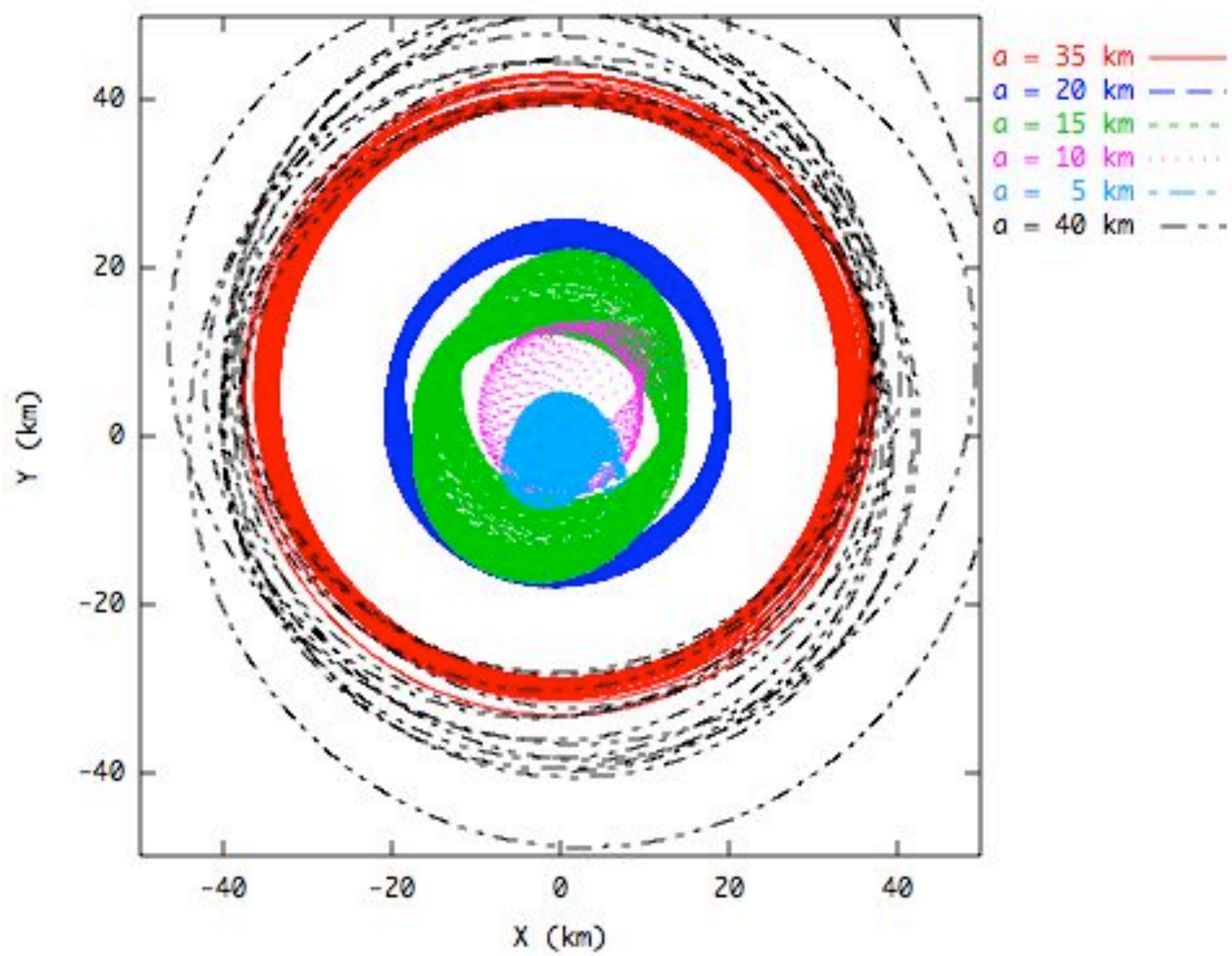
Outer and Inner orbits are unstable

Outer orbits are stripped by SRP force when comet comes close to perihelion

Inner orbits are destabilized by interactions with the nucleus gravity field



Side-on View

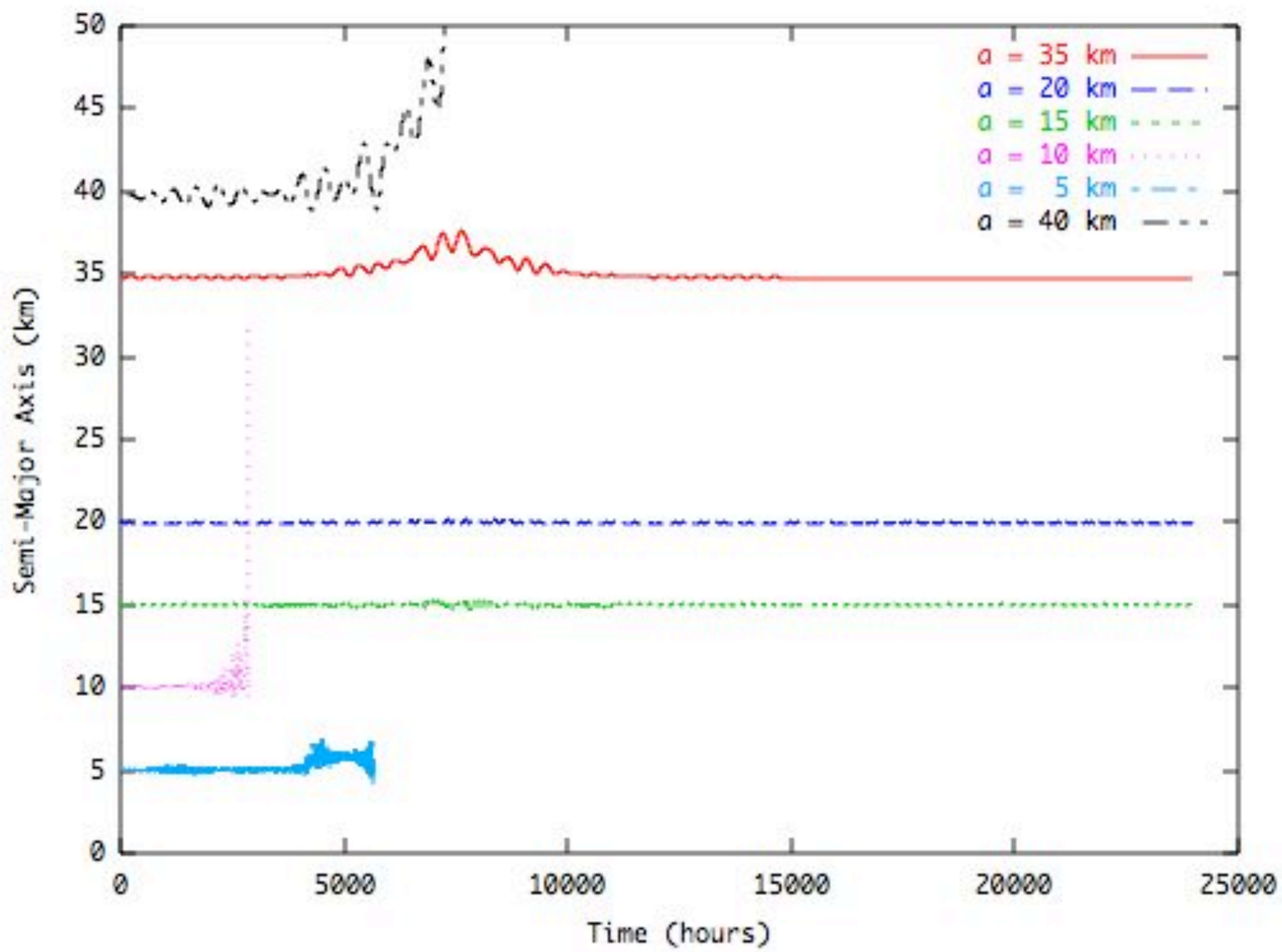


View from the Sun

D.J. Scheeres, A. Richard Seebass Chair, University of Colorado at Boulder

Terminator Orbits

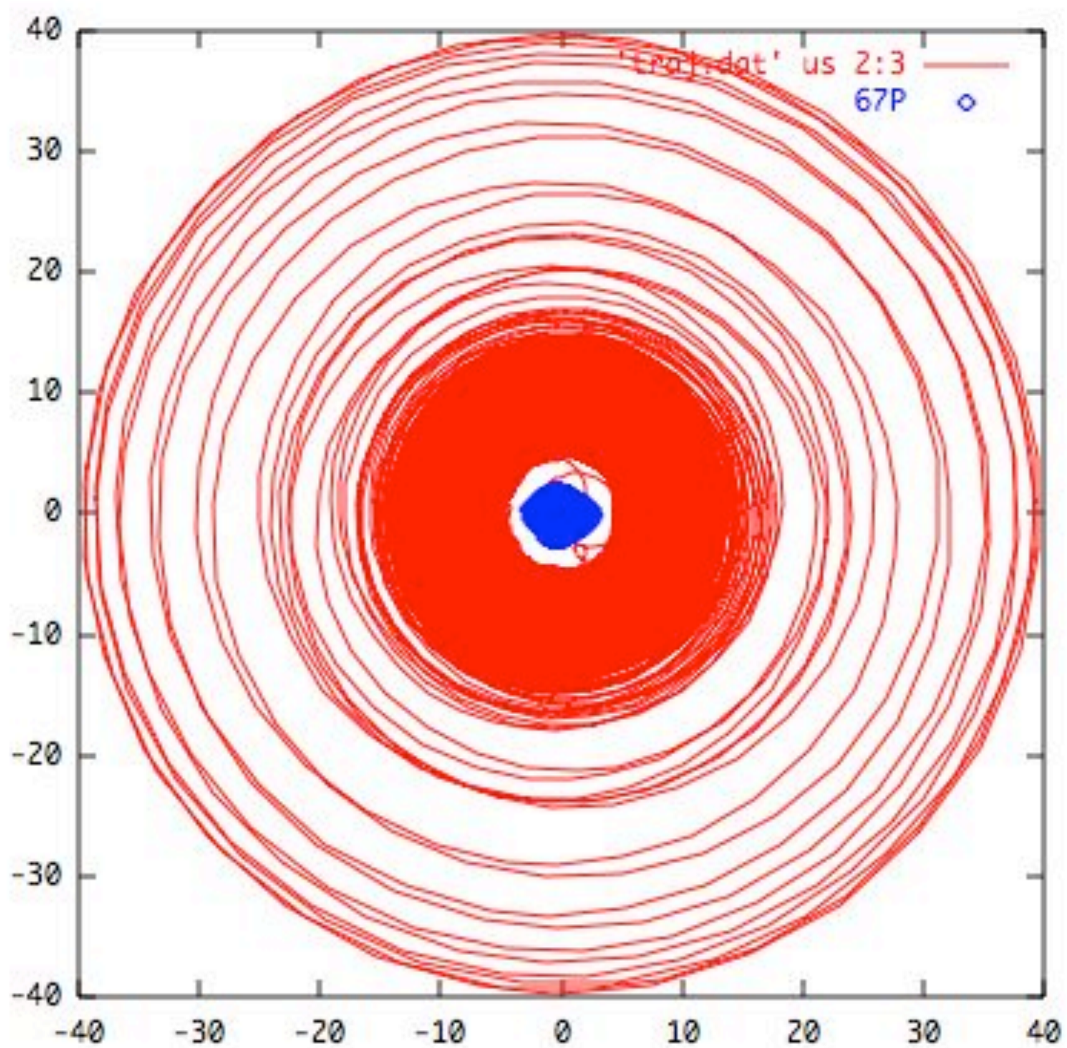
- Semi-Major axis evolution through perihelion:

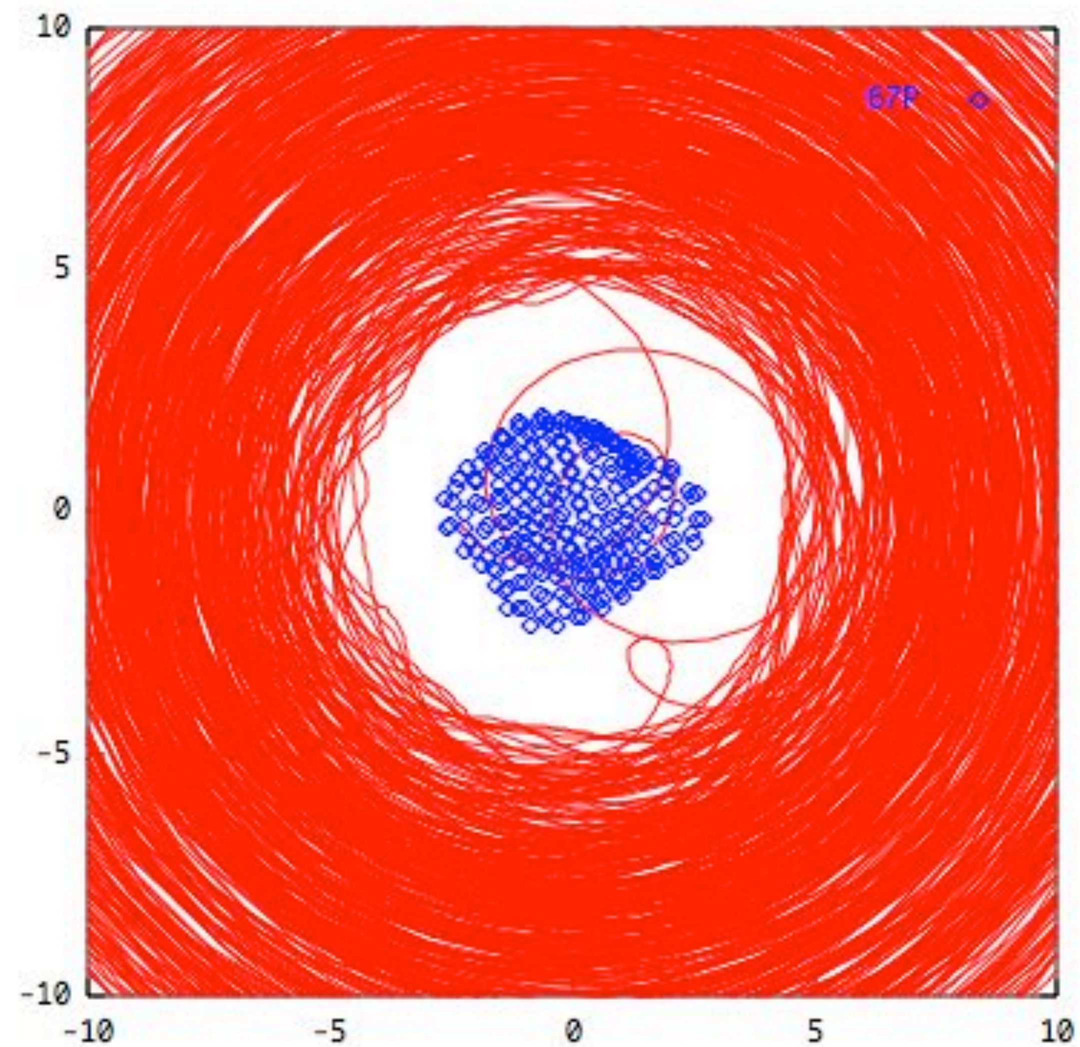


Orbital Stability Limits:
~15-35 km semi-major axis
Will change with density

Close Orbit Stability

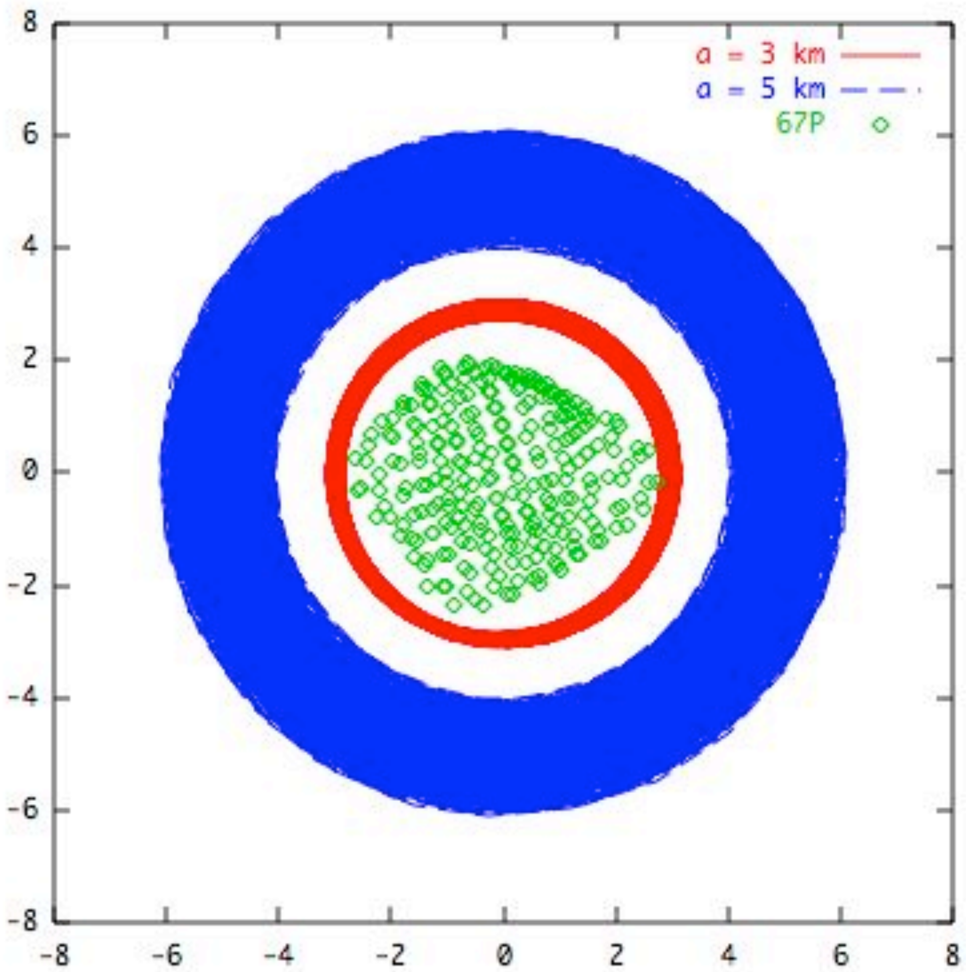
- Due to the instability of the equilibrium points close to the body and due to SRP far from the body, all direct orbits are highly unstable
- At best can be controlled over short time spans.





Close Orbit Stability

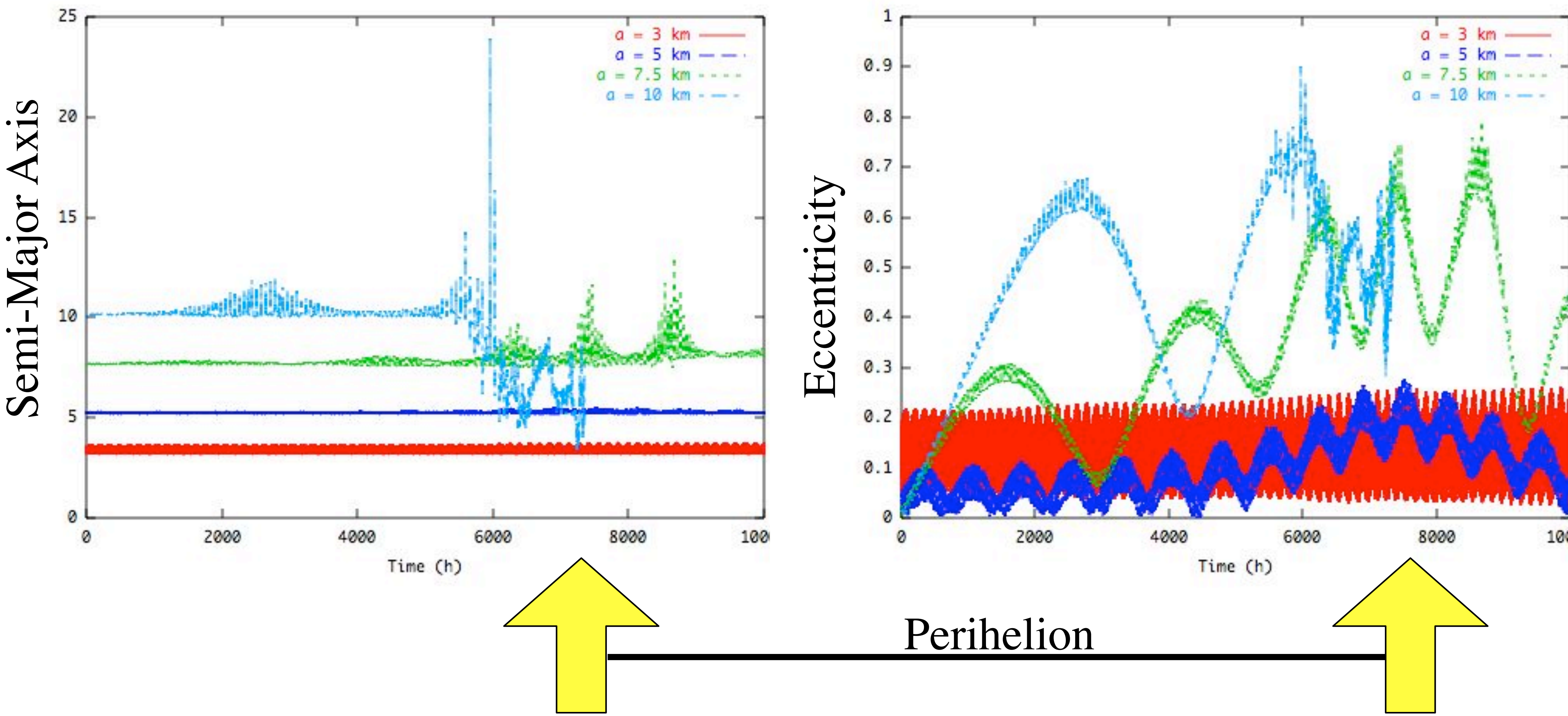
- Only retrograde orbits "close" to the nucleus are stable:
  - Orbits of radius 5 km and less are strongly stable, but will be very susceptible to outgassing jets



- Retrograde Orbits about the nucleus.
- Inner orbit is stable, corresponds with the limiting member of a stable periodic orbit family (neglecting SRP).
- Larger orbit is stable, but is strongly perturbed by SRP forces (due to larger semi-major axis).
- Increase in orbit size will lead to instability.

Close Orbit Stability

- Orbits of size 7.5 km and larger are destabilized by SRP



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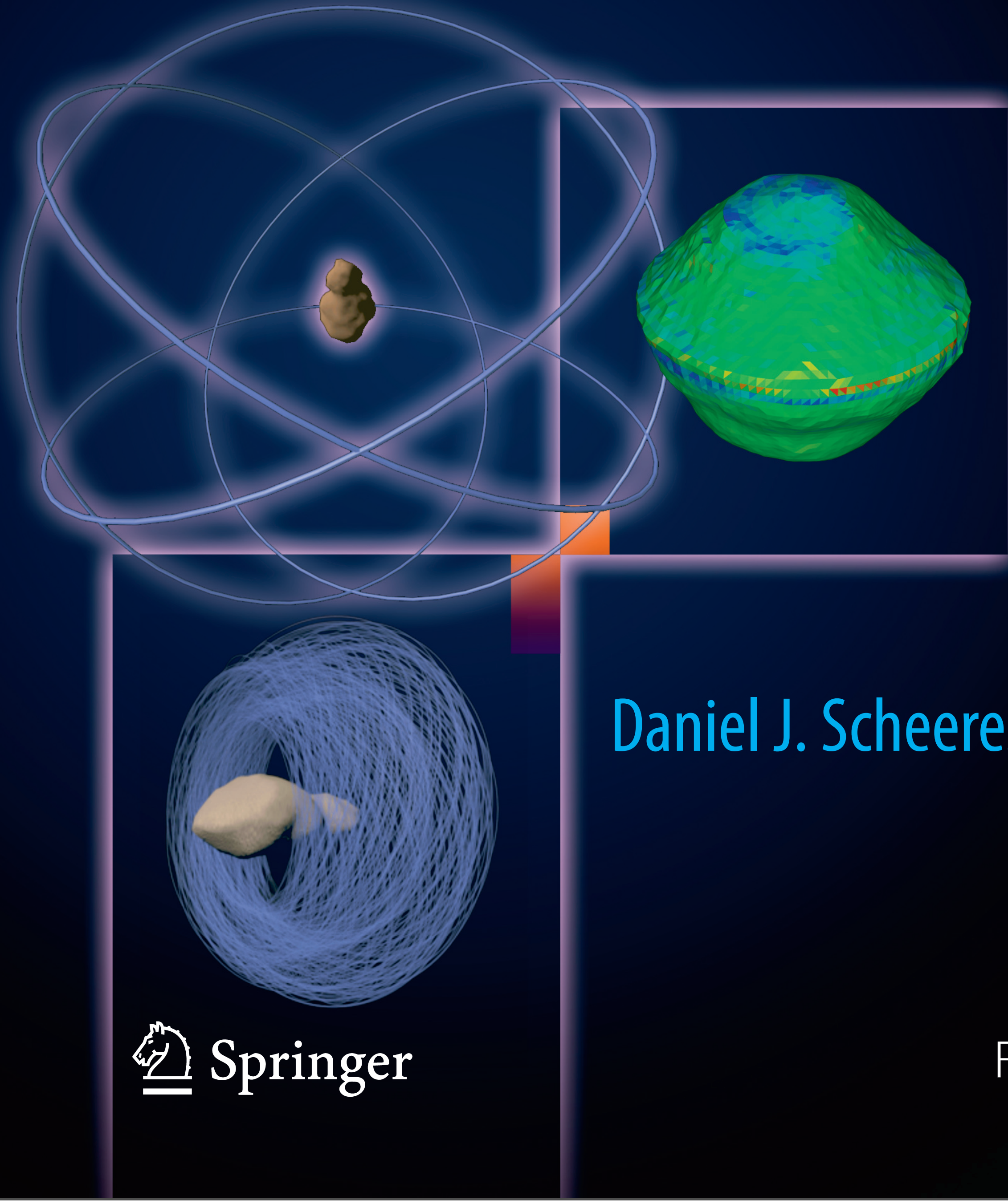
PRAXIS

Scheeres

ORBITAL MOTION IN STRONGLY PERTURBED ENVIRONMENTS

ORBITAL MOTION IN STRONGLY PERTURBED ENVIRONMENTS

Applications to Asteroid, Comet and Planetary Satellite Orbiters



Daniel J. Scheeres

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PRAXIS

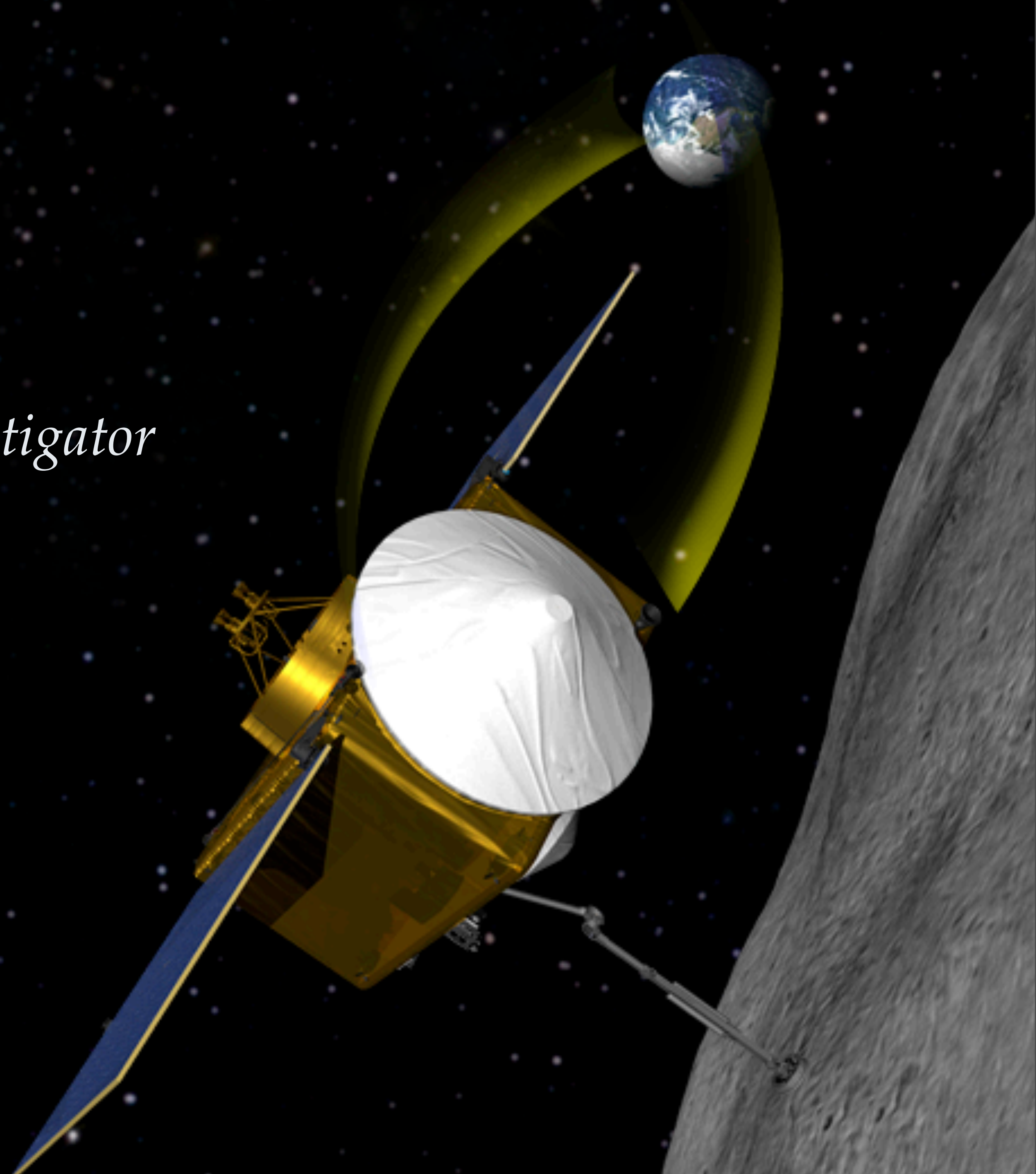
Future Exploration

OSIRIS-REx

Asteroid Sample Return Mission

OSIRIS-REx
Asteroid Sample Return Mission

Dante S. Lauretta – Principal Investigator



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What is OSIRIS REx?

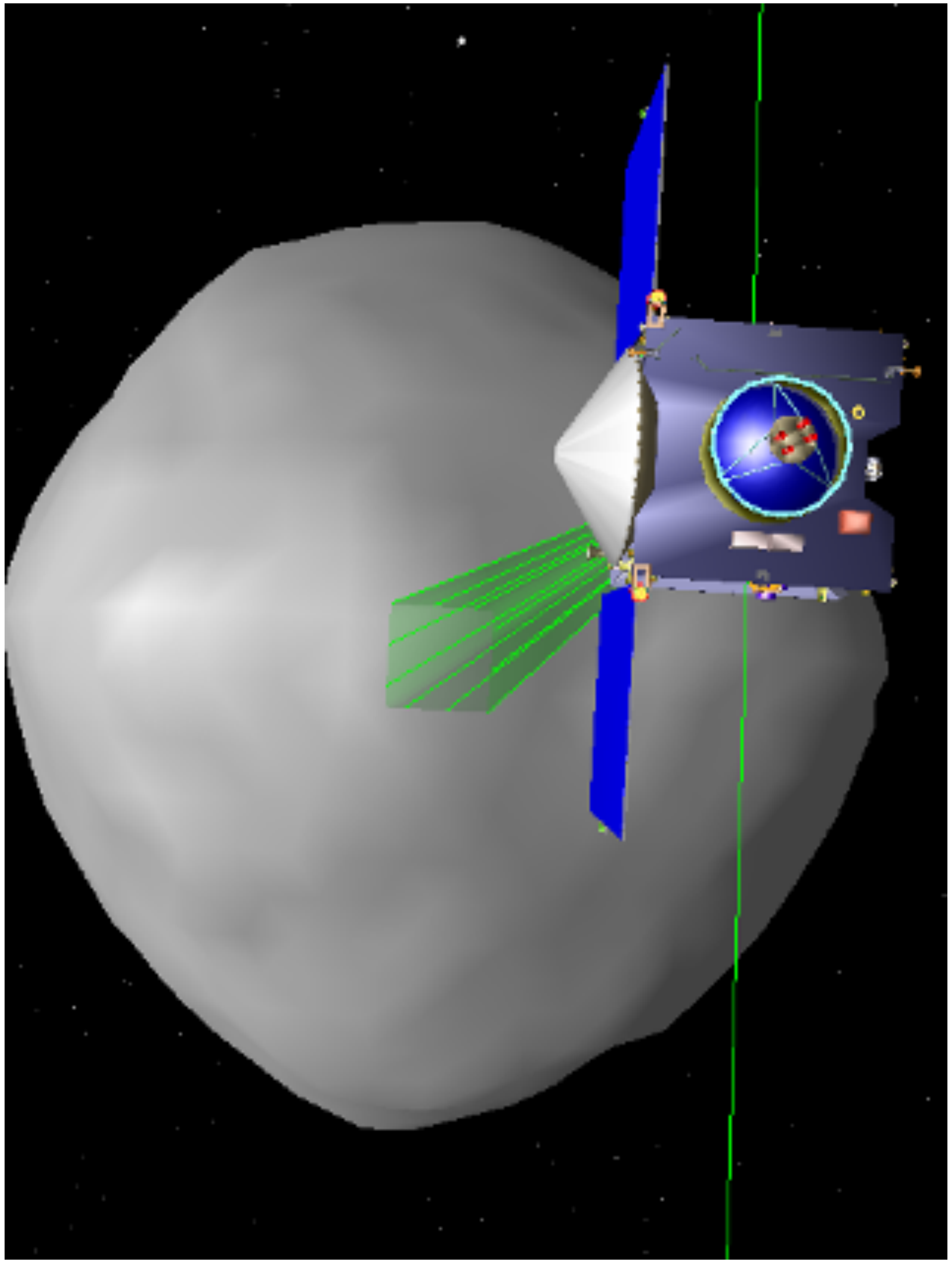
- **OSIRIS REx is a sample return mission** that returns at least 60 g (and as much as 2 kg) of **pristine carbonaceous regolith** from asteroid 1999 RQ36
- Currently in Phase B:
  - Launch in 2016
  - Rendezvous with 1999 RQ36 in 2020
  - Return to Earth in 2023
- **OSIRIS REx is an acronym**
  - **Origins**
    - provide pristine sample to reveal the origin of volatiles and organics that led to life on Earth
  - **Spectral Interpretation**
    - provide ground truth for ground-based and space based spectral observations of B-type carbonaceous asteroids
  - **Resource Identification**
    - identify carbonaceous asteroid resources that we might use in human exploration
  - **Security**
    - quantify the Yarkovsky Effect on a potentially hazardous asteroid, thus providing a tool to aid in securing the Earth from future asteroid impacts
  - **Regolith Explorer**
    - Explore the regolith at the sampling site *in situ* at scales down to sub-millimeter

OSIRIS-REx Provides Exceptional Science Return

- For the **first time in space-exploration history**, a mission will return a large, pristine sample of a carbonaceous asteroid, a unique time capsule from the birth of our Solar System.
- Samples of 1999 RQ36 are critical to understand **the initial stages of planet formation and the origin of life**.
- The geological context is critical to linking the chemical and physical nature of the sample to the bulk properties of 1999 RQ36 and the **broader asteroid population**.

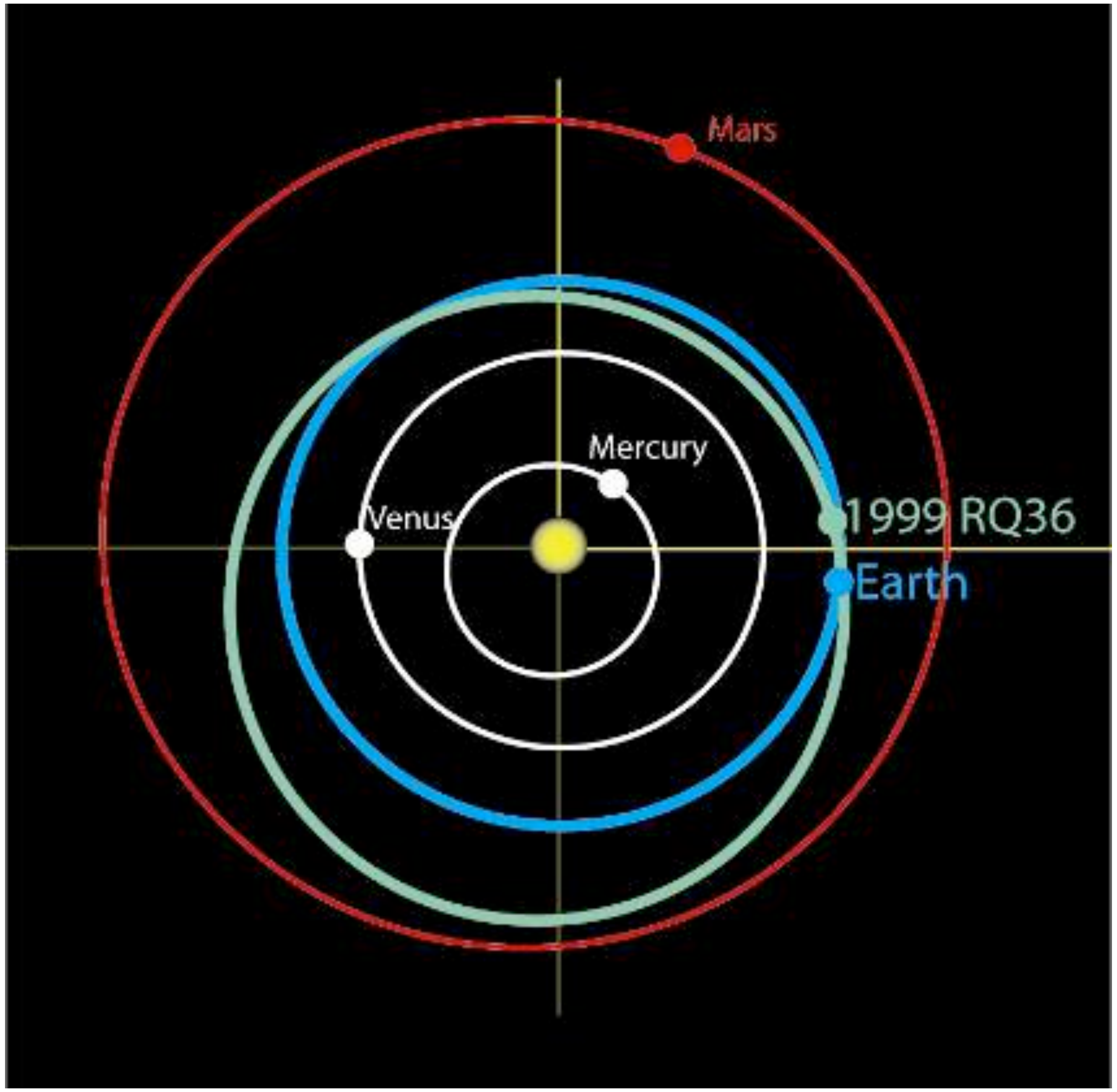
OSIRIS-REx ushers in a New Era of Planetary Exploration

- The team will apply **key flight experience** from NEAR & Hayabusa navigation to perfect **essential operational capabilities** in small-body proximity operations.
- OSIRIS-REx **executes precise S/C navigation** to acquire samples of 1999 RQ36 with no time critical events.
- These operational capabilities are **essential as humanity explores near-Earth space** to increase our understanding of Solar System bodies and develop *in situ* resource utilization processes.



OSIRIS-REX ADDRESSES THE IMPACT HAZARD

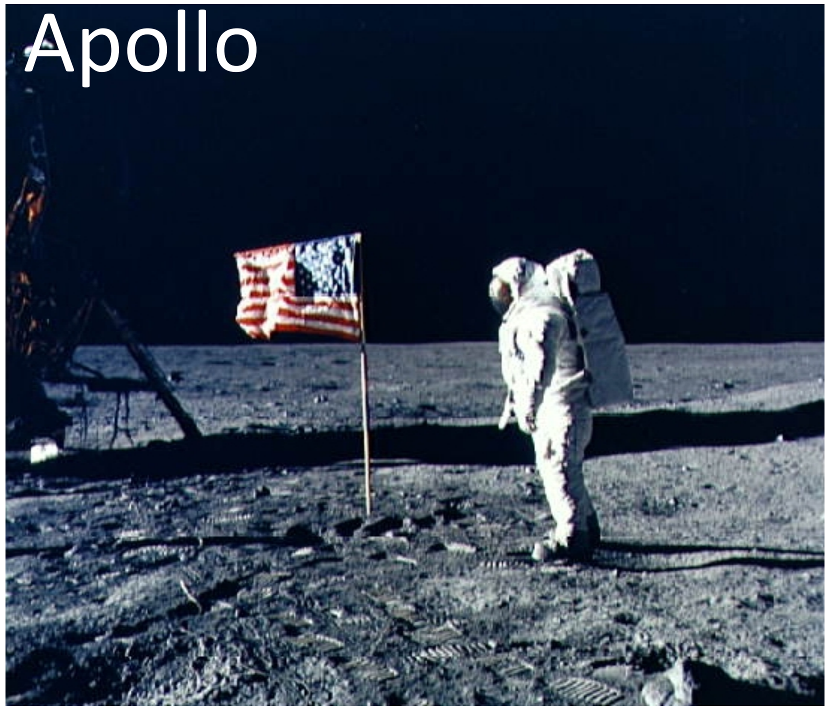
- 1999 RQ36 is the ***most* Potentially Hazardous Asteroid known**.
- It is not particularly hazardous now, but…
  - Its orbit evolves to intersect Earth ~150 years from now
  - **Impact odds are 1 in 1800** in 2182
- OSIRIS-REx serves as a "**transponder mission**."
- It has the dual objectives of refining the orbit to ascertain whether an impact is impending and characterizing the object to facilitate a possible deflection mission.

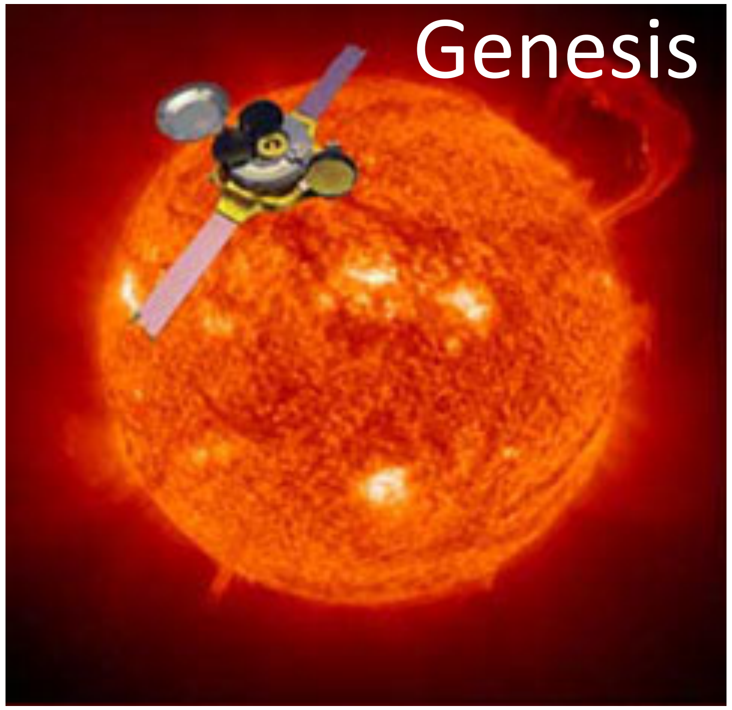


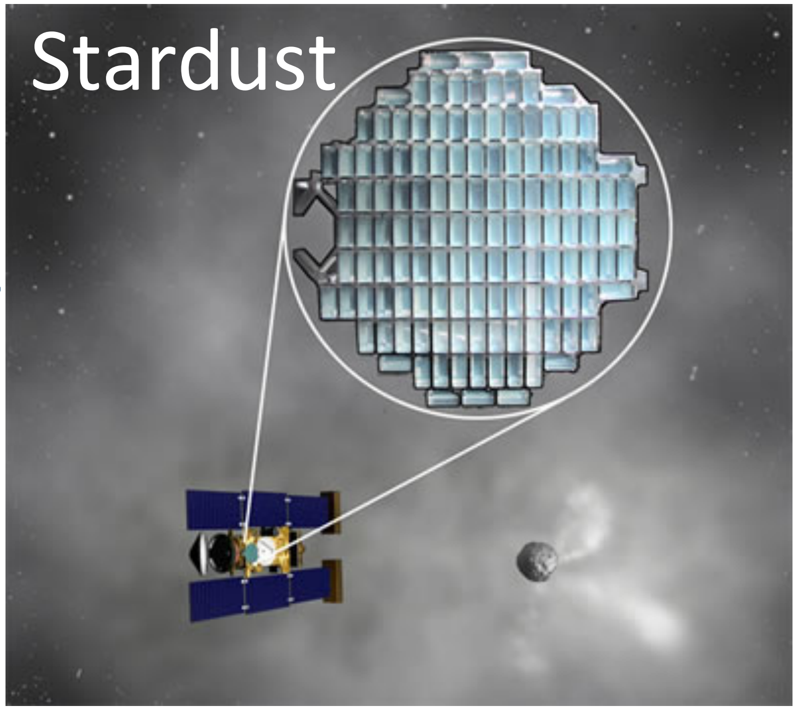
OSIRIS-REX CONTINUES NASA EXPLORATION OF THE SOLAR SYSTEM THROUGH SAMPLE RETURN

- **Apollo**
  - Revealed the magma-ocean stage of lunar history
  - Developed the Giant-Impact Hypothesis for the origin of the Earth and Moon
- **Genesis**
  - Revealed the chemical & isotopic composition of the Sun
- **Stardust**
  - Provided convincing evidence for aqueous activity on comets
- **OSIRIS-REx**
  - Delivers samples of the early Solar System never before analyzed in laboratories on Earth…

NASA's Sample Return Legacy







Goals of the Lectures

- Introduction to the modeling and mechanics at asteroids
  - Focus on mechanics and dynamics
  - Tools and concepts to work with data
- Mechanics of asteroids
  - Celestial Mechanics of rubble pile asteroids
  - Formation and evolution of asteroid systems
- Motion about and on small bodies
  - Space missions to small bodies
  - Environment on the surfaces of small bodies
  - Binary asteroid dynamics and evolution