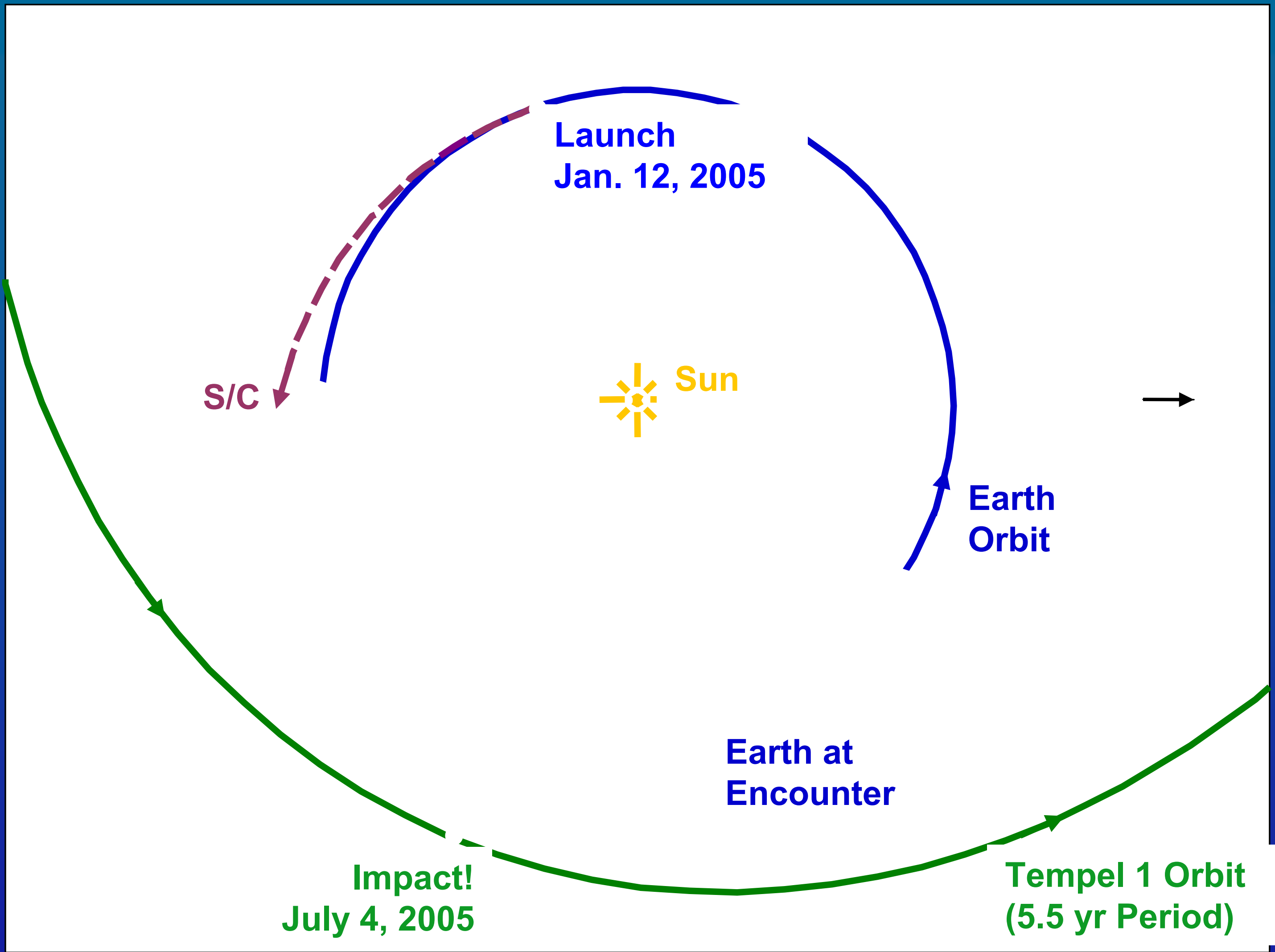
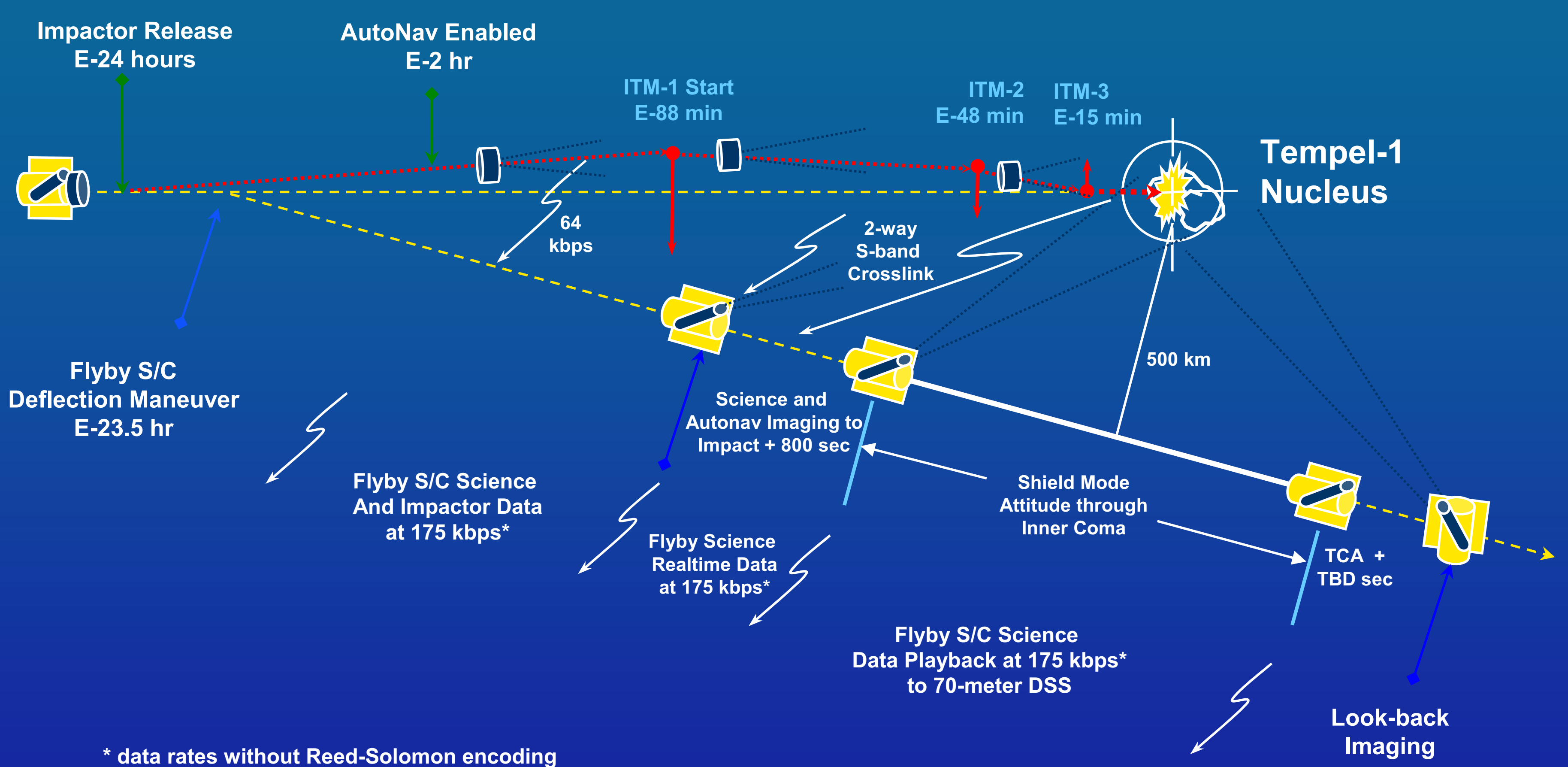
Deep Impact

- **Mating of flyby with impactor, April 2004**
  - **Last step prior to system environmental testing**
- **Impactor**
  - **1/3 ton**
  - **50% copper**
  - **Impactor Camera**
    - **10 μrad/pixel**
    - **White light**
- **Flyby**
  - **2/3 ton**
  - **Medium Res camera**
    - **10 μrad/pixel**
    - **8 filters**
  - **High Res Camera**
    - **2 μrad/pixel**
    - **8 filters**
  - **Near-IR Spectrometer**
    - **10 μrad/pixels & slit**
    - **1.05 < λ < 4.8 μm**
    - **230 < λ/δλ < 700**

Interplanetary Trajectory



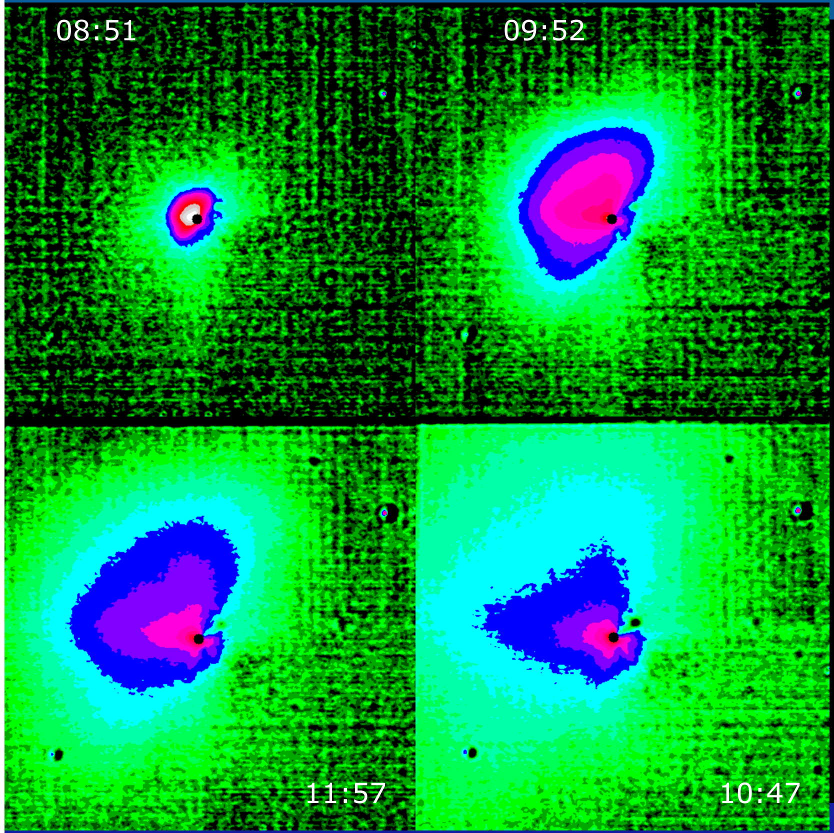
Encounter Schematic



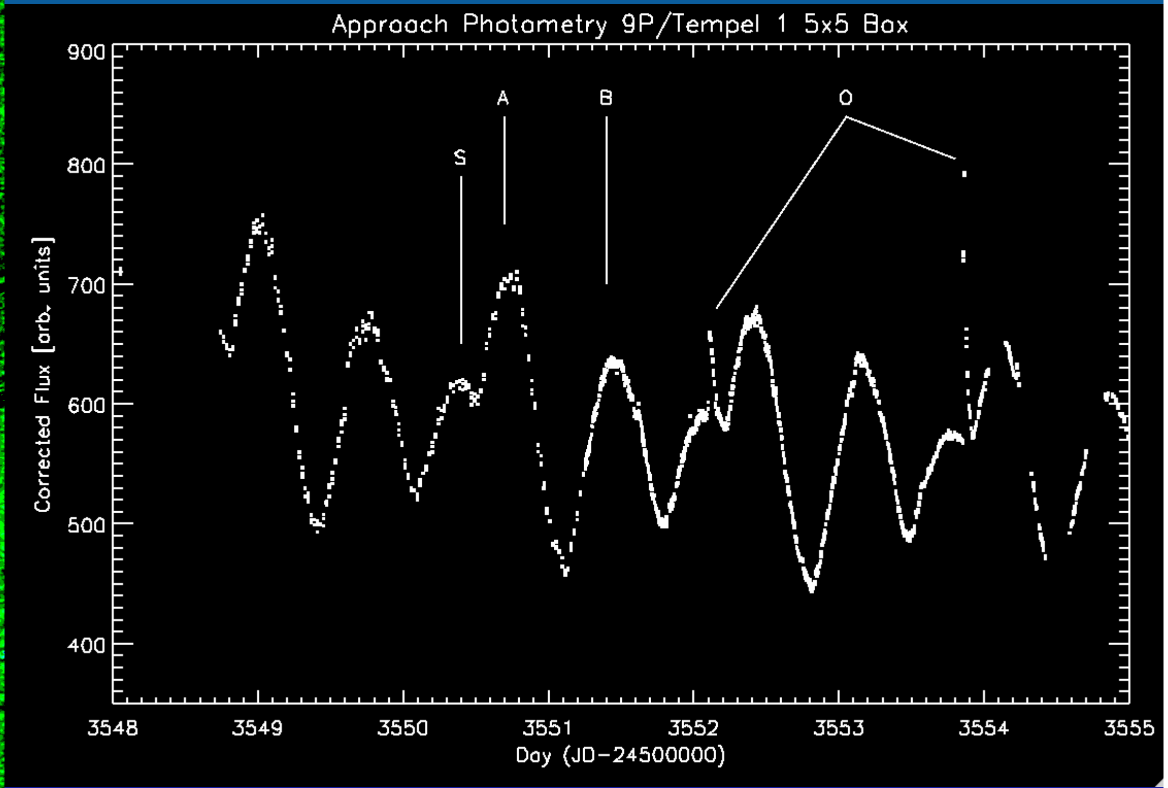
* data rates without Reed-Solomon encoding

Approach Photometry

~~Outbursts common - typically 2 per week~~
Outbursts correlated with rotational phase (2 phases with at least 3 outbursts each)
Thus, outbursts are endogenic and related to surface insolation
Probably super-volatiles close below surface but stochastic nature of outbursts not understood

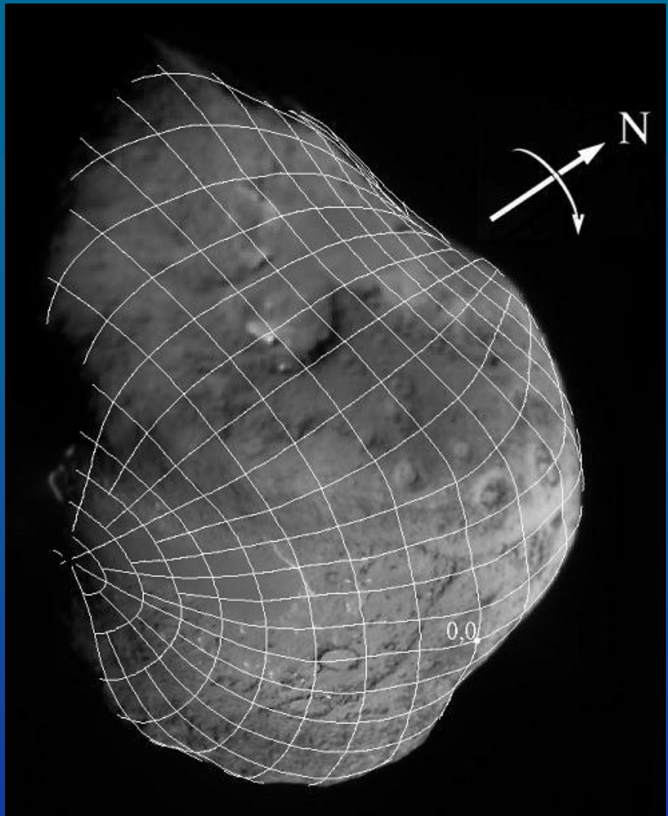


2 July Outburst by *D. Lindler*



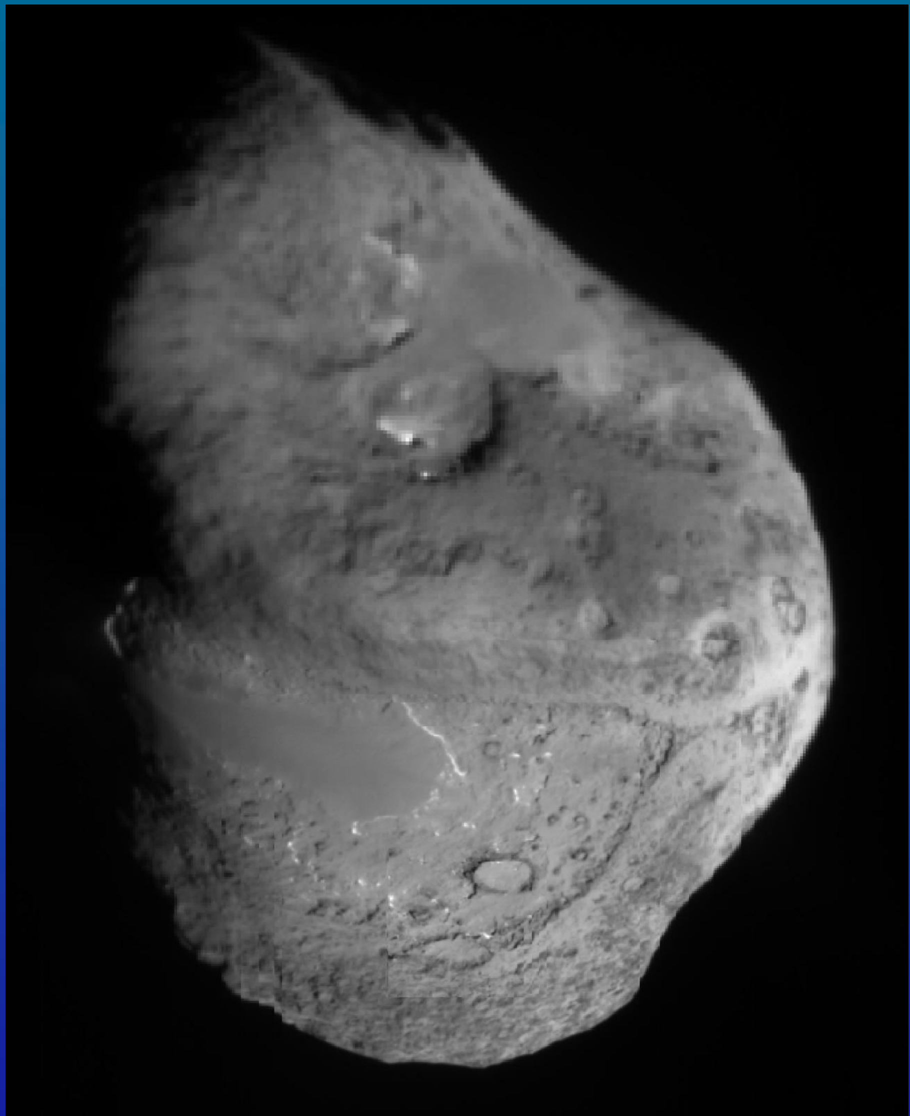
A'Hearn *et al.* 2005 *Science* **310**, 258

ITS Sequence

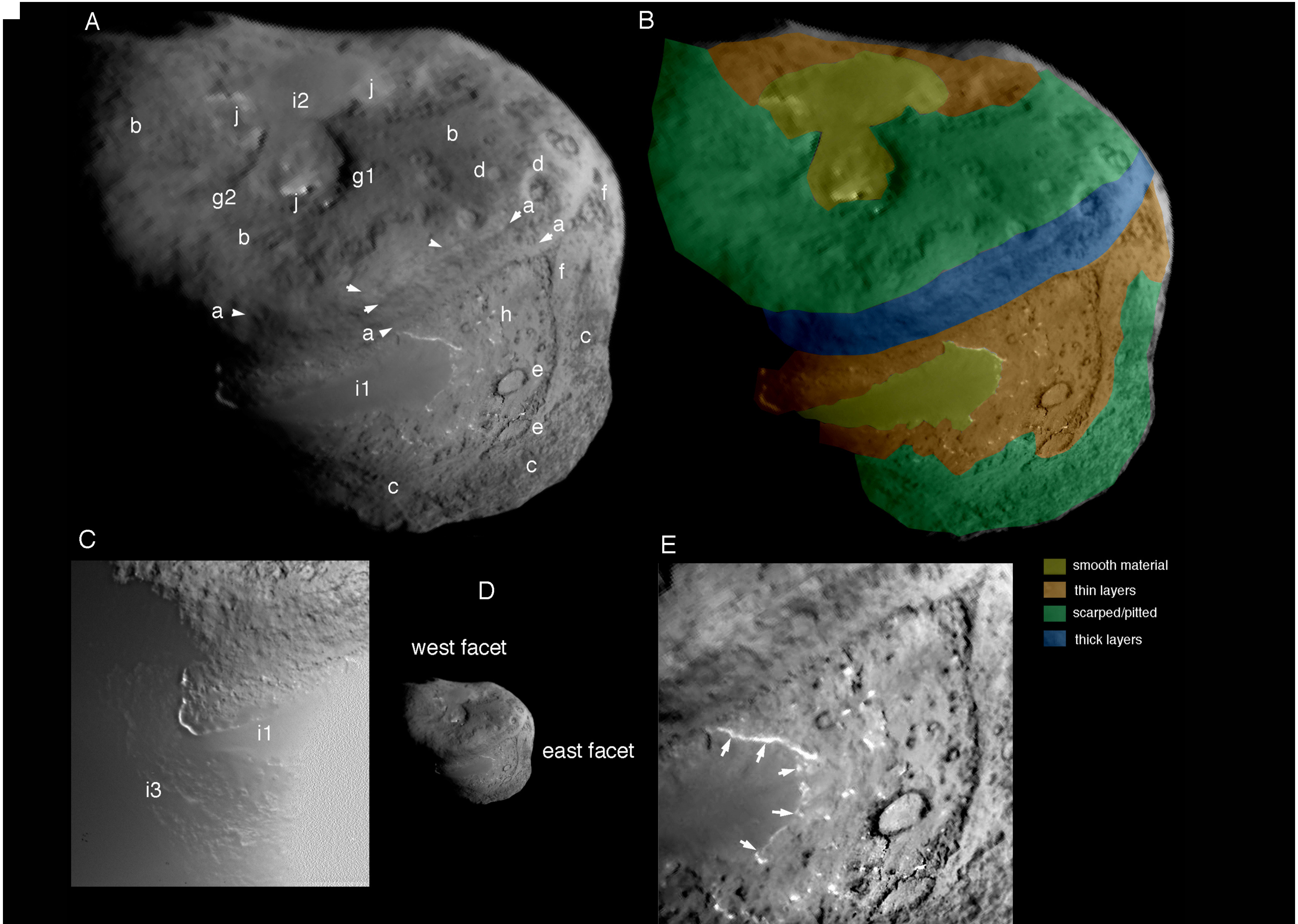


- ITS images - impact site indicated by arrows (now right side up - ecliptic north in upper right quadrant, sun to right)
- Sense of rotation - top is approaching
- Oblique impact - 36° from horizontal by shape model but 20 to 35° from assuming circular craters

ITS Composite Image



- Note geological features
  - Large, smooth surfaces
  - Round features = craters? (size-freq plot consistent)
  - Stripped terrain (old)
  - Scarps
  - Evidence of layers
- Overall Shape
  - Effective radius 3.0±0.1 km
  - Max-min diameters 7.6 and 4.9 km but still uncertain
  - Well-mapped surface is mostly in 3 large, more-or-less planar areas, i.e. the shape is as close to pyramidal as to ellipsoidal
- Impact site is between two craters near bottom of image.

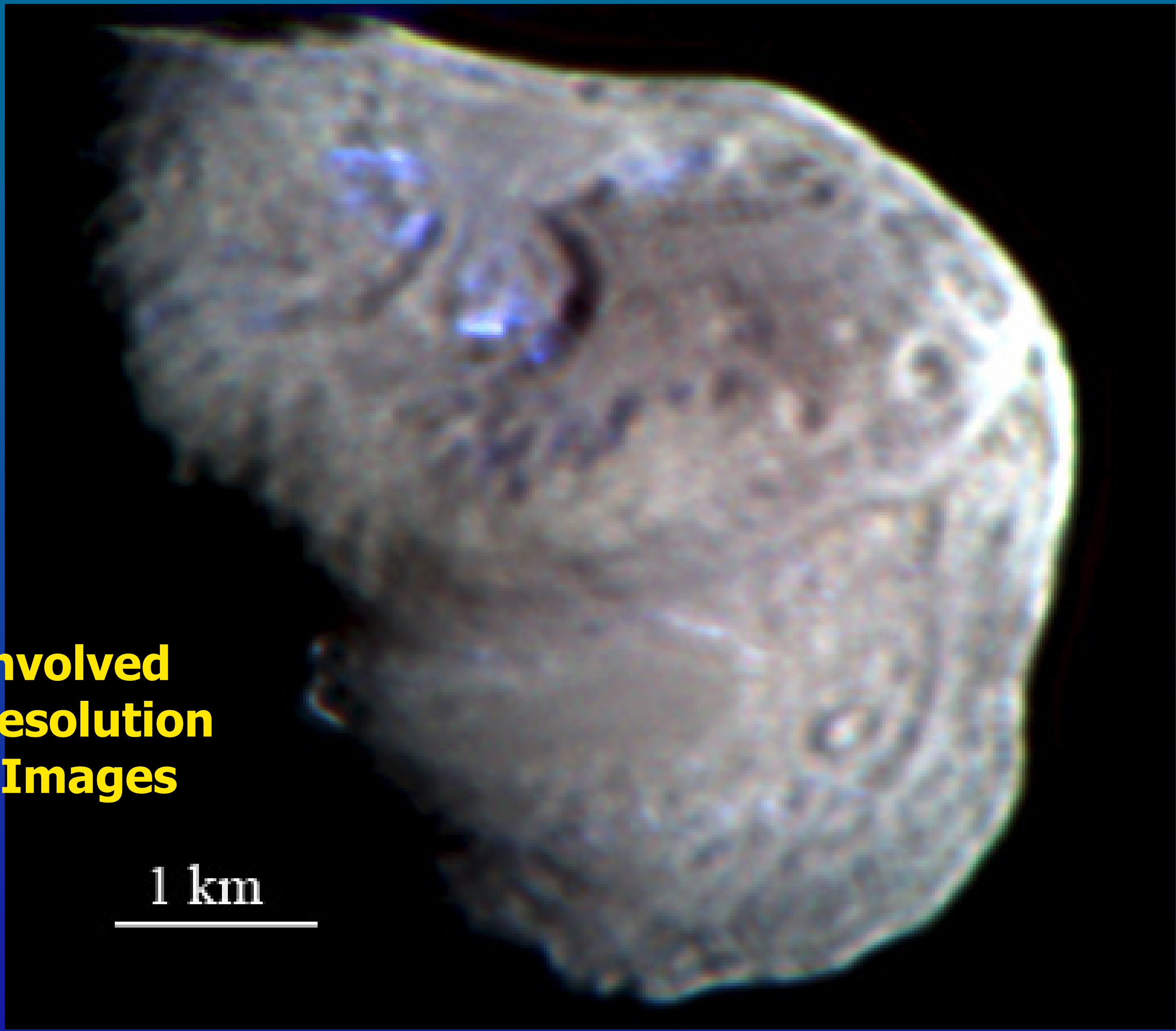


Thomas et al. (2006)

Tempel 1 Parameters

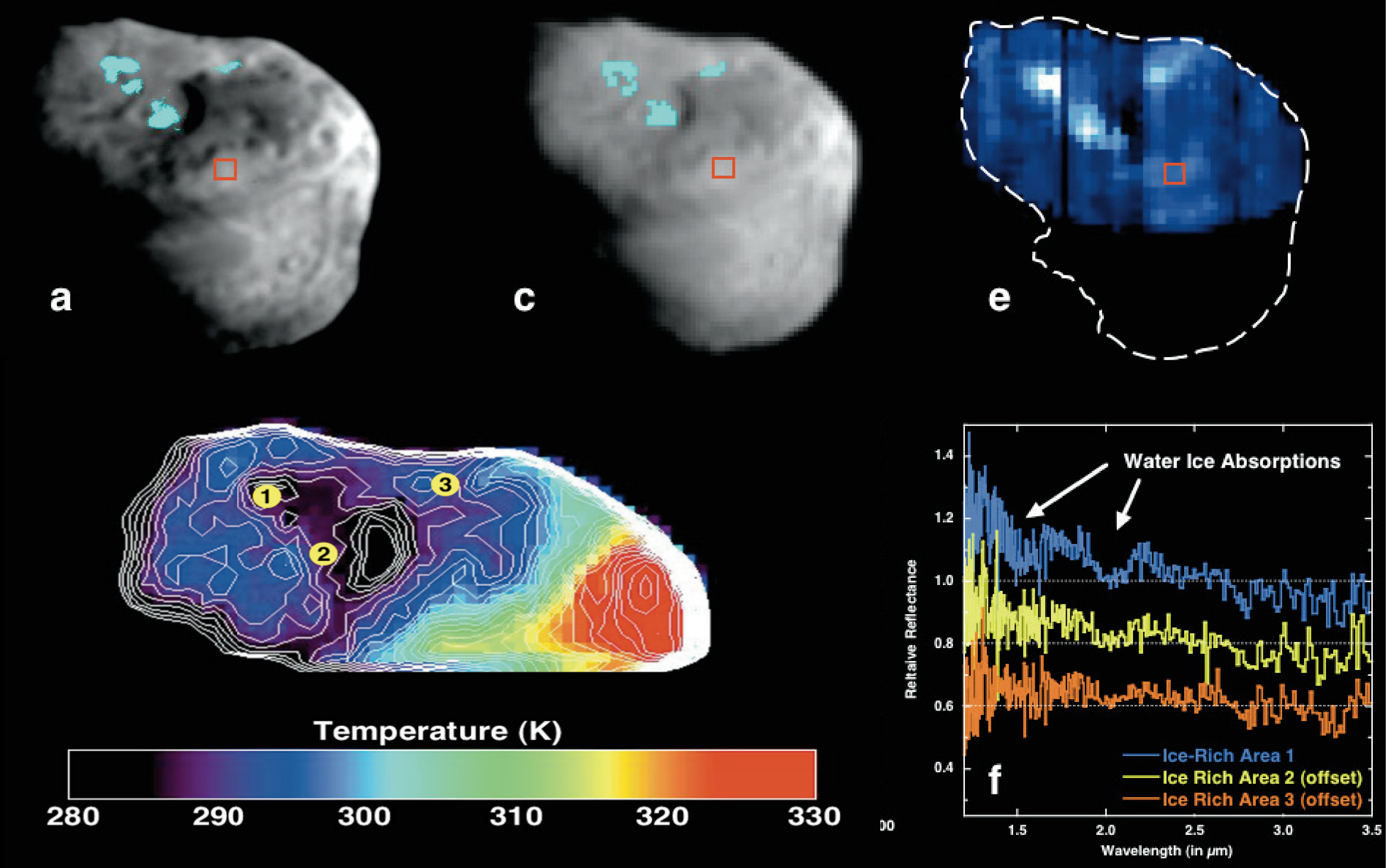
Mean radius: 3.0 ± 0.1 km
Diameter range: 5.0 - 7.5 km
Gravity: 0.024 - 0.030 cm $/s^2$
Area: 119 km^2
Range of gravitational heights: 0.73 km
Mean Density: 0.3 ± 0 .2 gm $/cm^3$

Anomalously Colored Regions



Deconvolved High Resolution Color Images

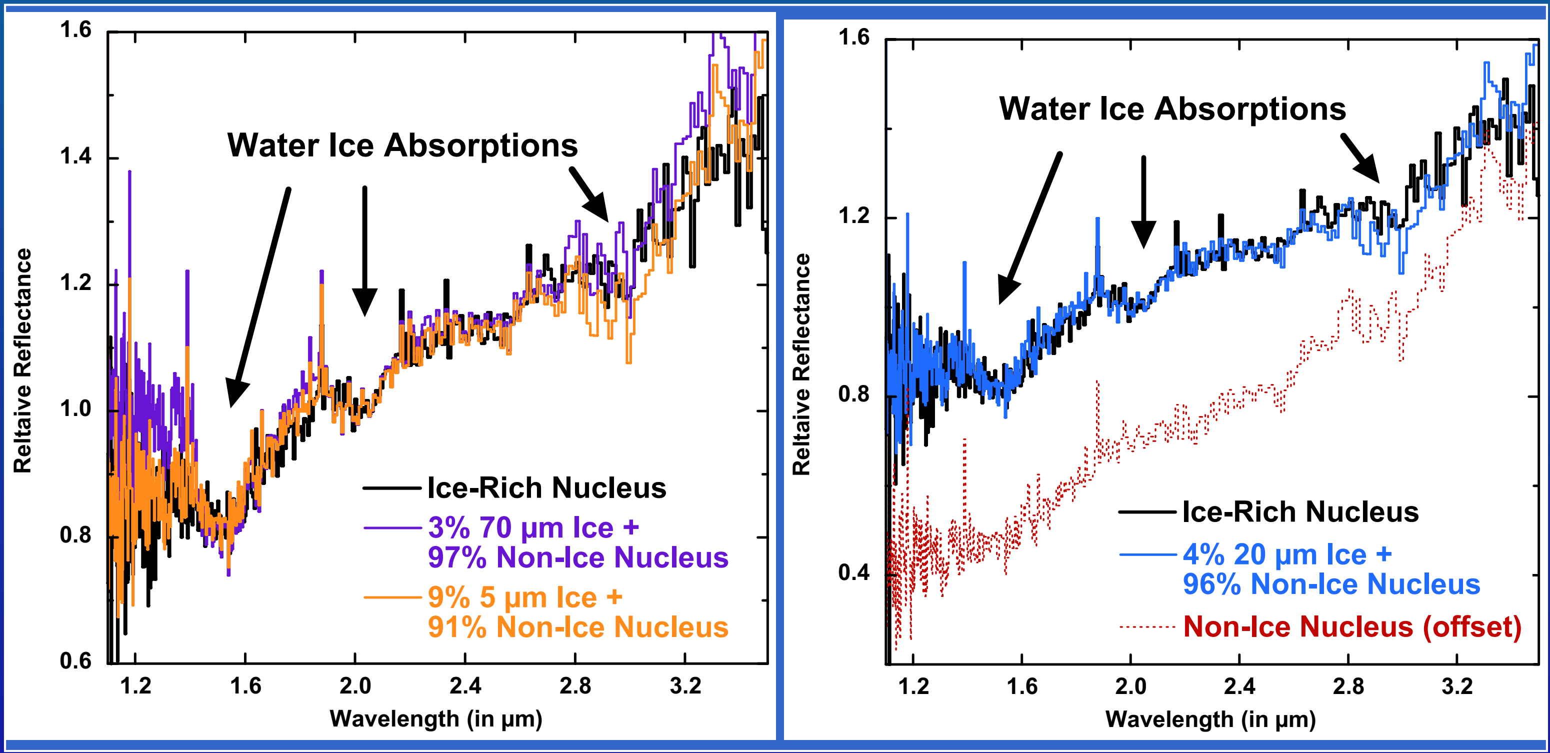
Sunshine et al. 2006, Science ***311****, 1453*



Sunshine et al. (2006)

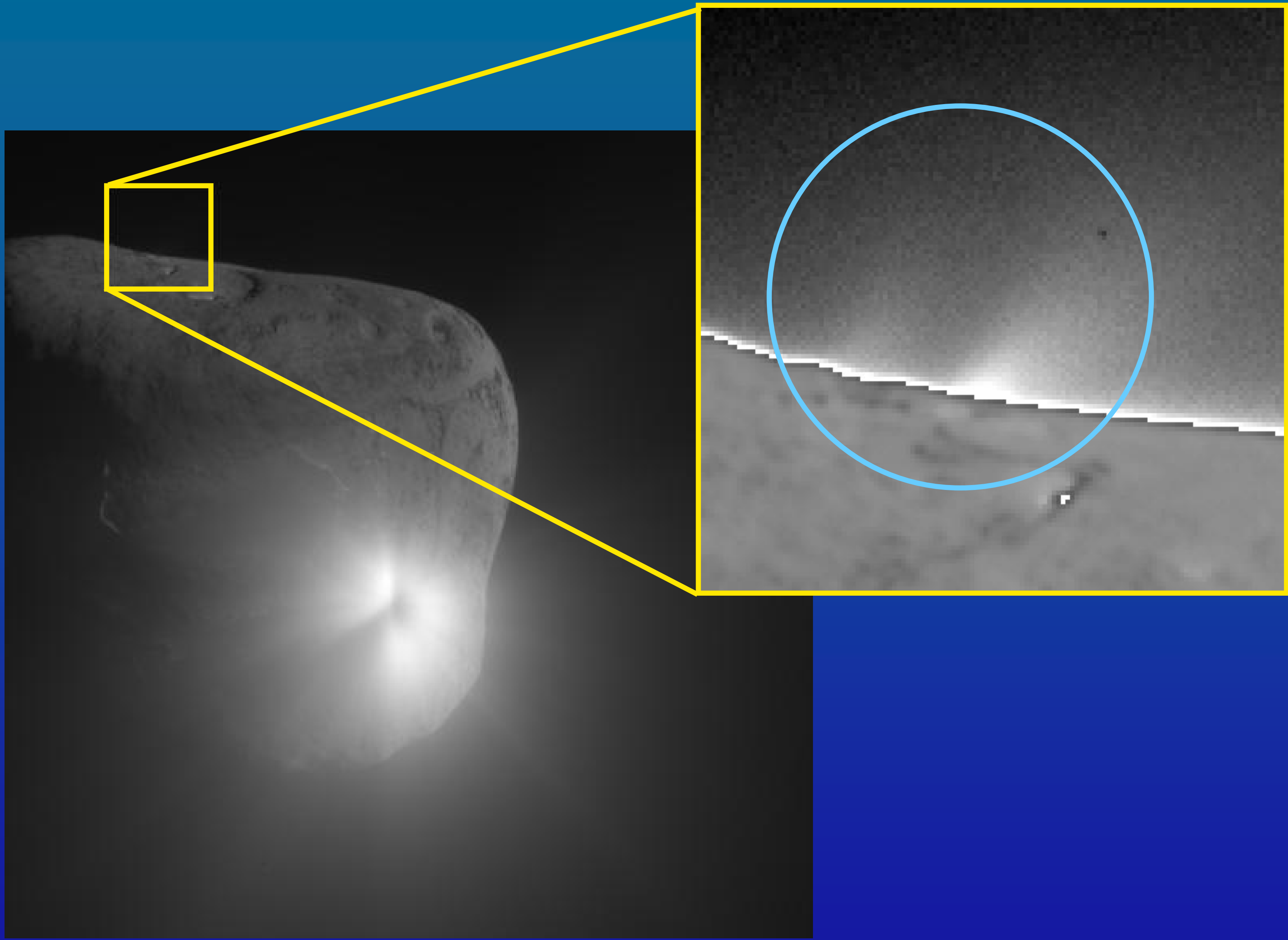
Modeling Surface Water Ice

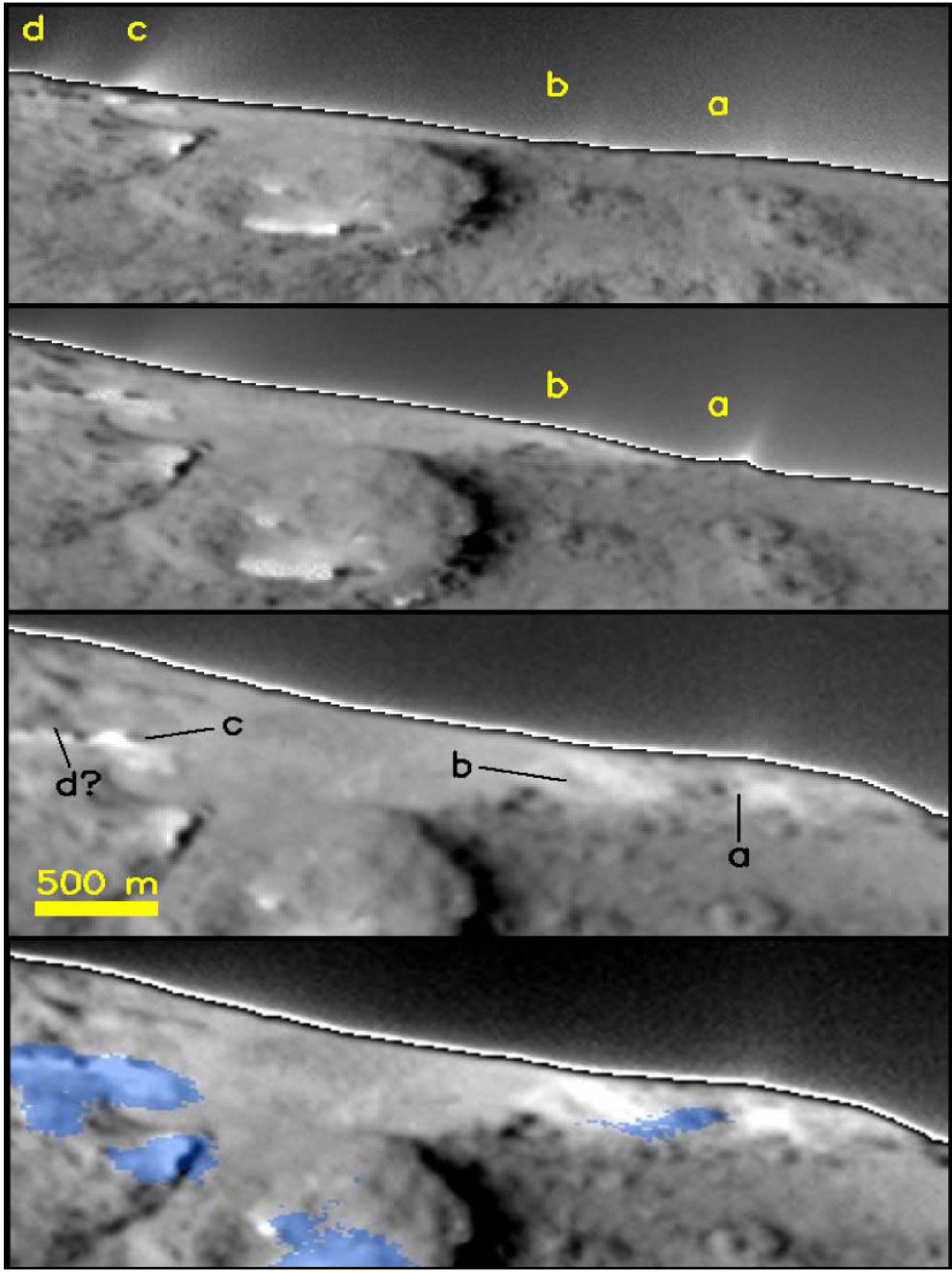
- Nominal (non-ice) nucleus + laboratory water ice
  - 3-6% water ice
  - 30 ± 10 µm size particles
- Not enough surface to be significant in overall outgassing
- Frost from source of outbursts on shoulder?



*Sunshine et al. 2006 Science **311**, 1453*

Activity off Limb

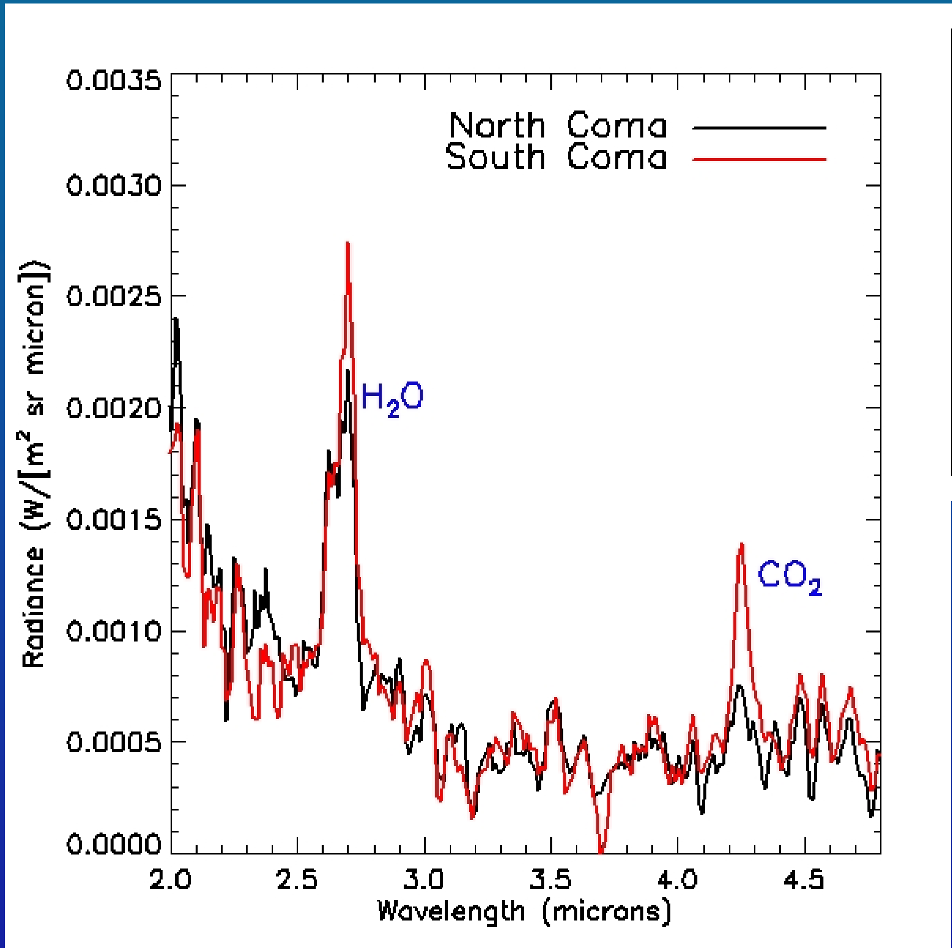


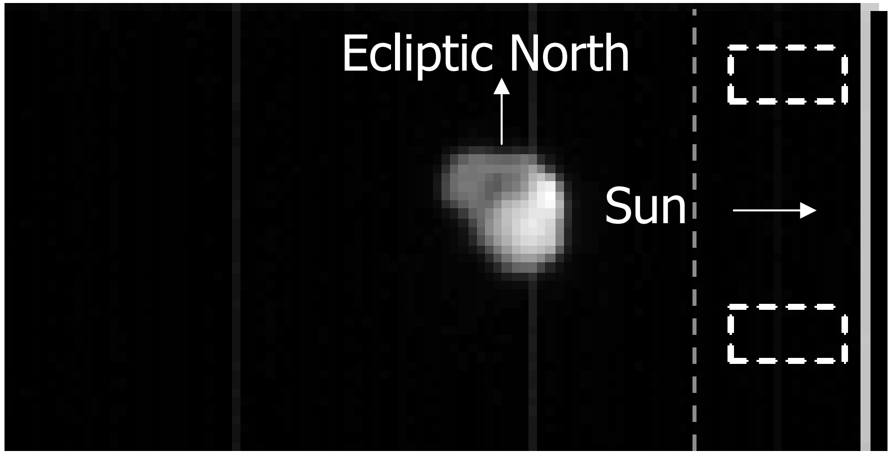


Sequence of Deep Impact images of the limb of the nucleus of comet Tempel 1, showing at least four small jets coming from the surface (“a”-“d”). As the horizon shifts with time (3 top panels), the jets pass through the plane of the sky where they are highlighted and can be traced back to their source region on the surface. Each of the jets appears to emanate from a dark possibly less active spot (letters a-d in the third panel) surrounded by brighter material. In the fourth panel, regions where water ice was detected are overlaid in blue.

Farnham et al. 2006

Detection of Asymmetric Inner Coma



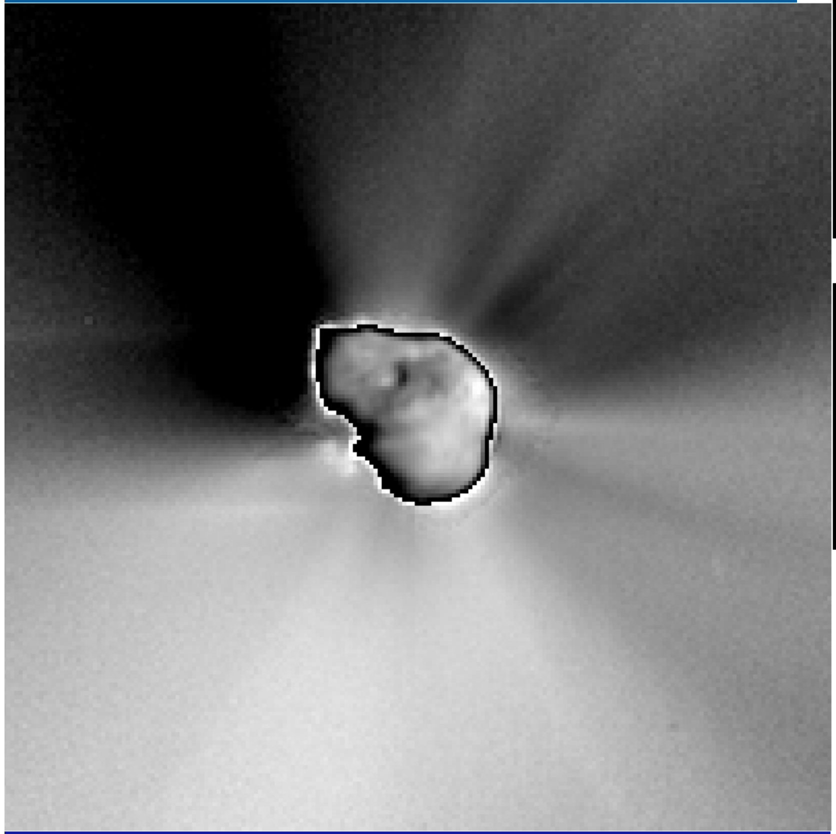


- 1 hour before impact
- ~440 m/pixel resolution
- Northern and southern regions examined
- **Spectra show comparable H_2O but factor of 2 increase in CO_2 relative to H_2O in the south**

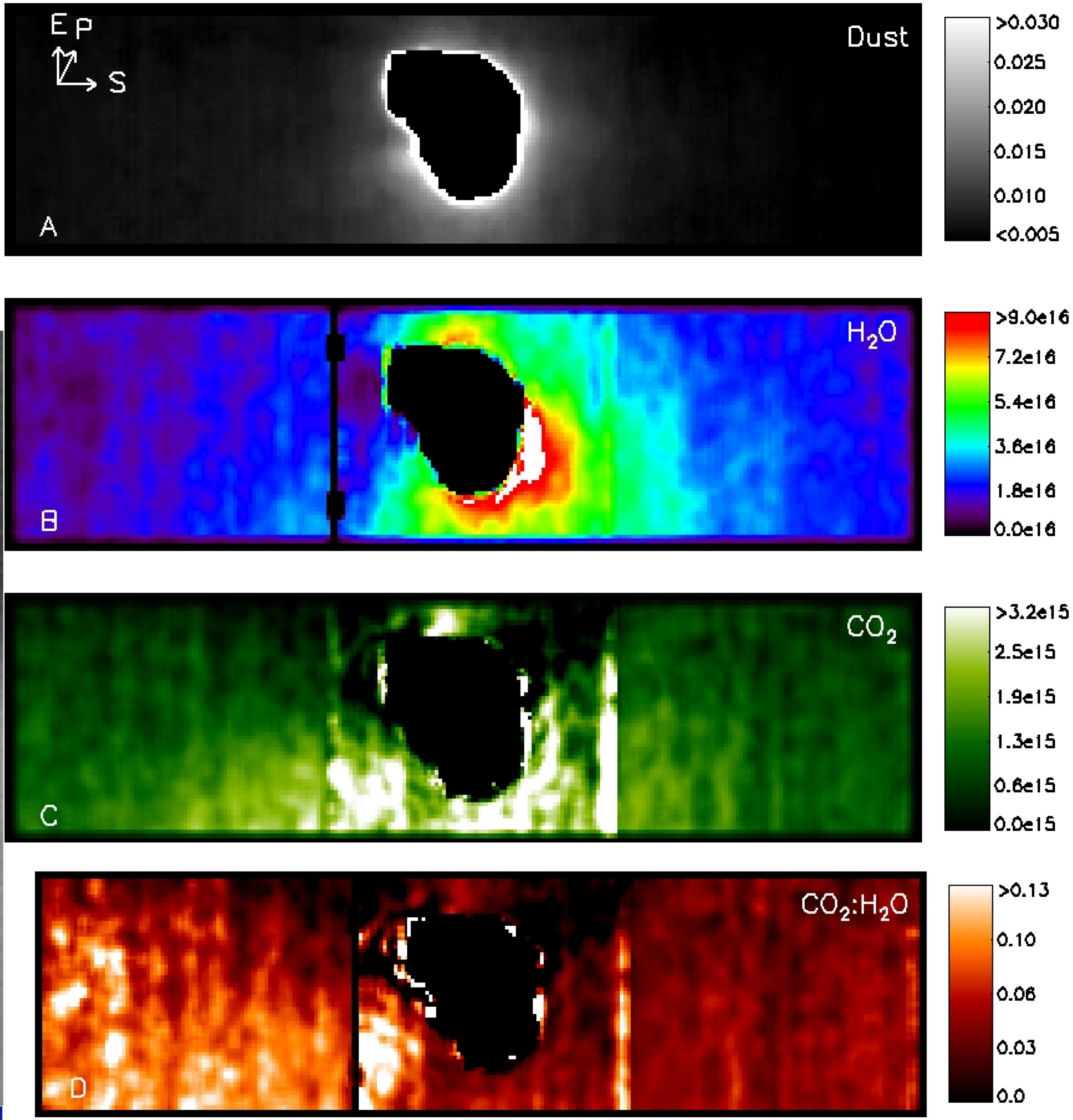
Spatial Distributions Vary by Species

P = positive rotational pole
E = Ecliptic north
S = Sunward

Dust is better correlated with CO_2 than with H_2O, but not perfectly with either

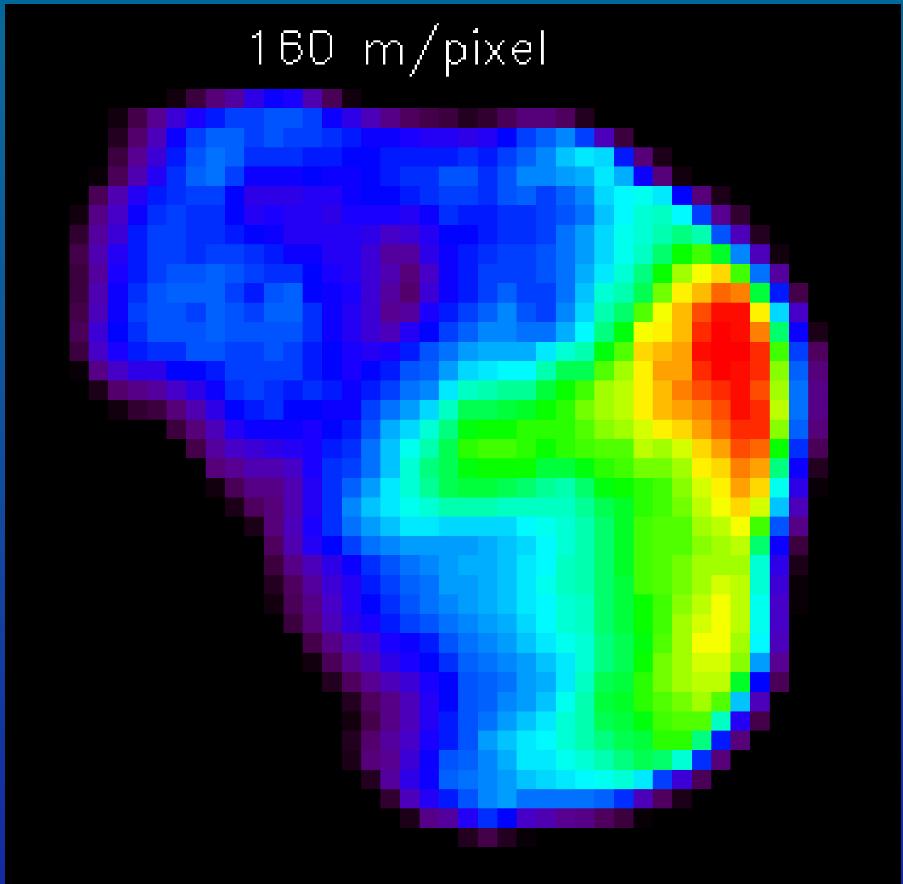


Farnham et al. 2006. Icarus, submitted



Feaga et al. 2006. Icarus, submitted

Thermal Map of Nucleus

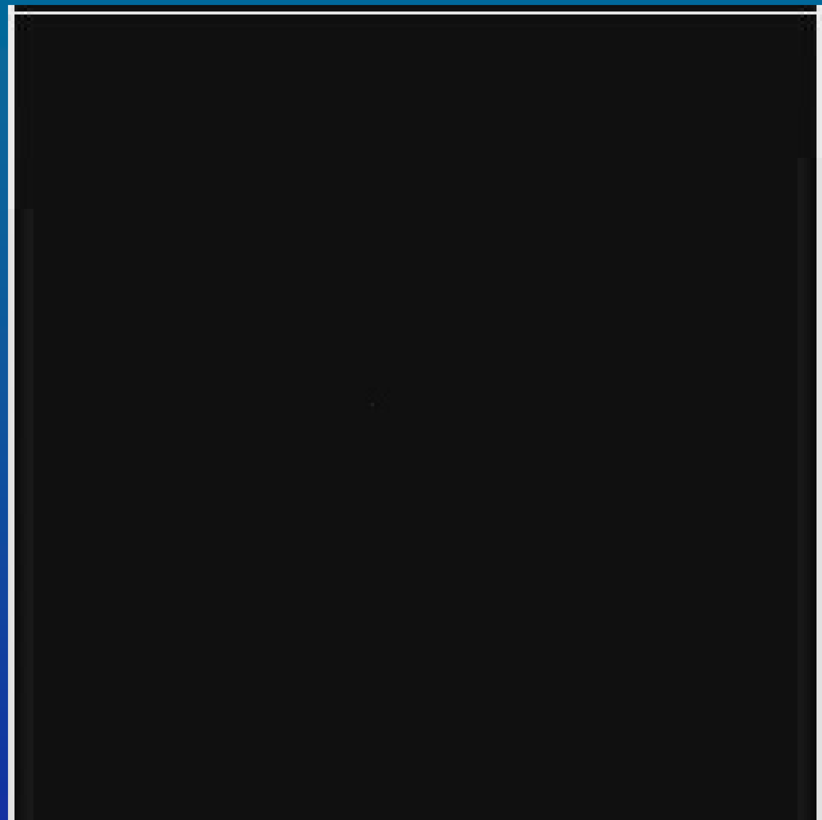


Groussin *et al.* 2006 *Icarus*, submitted

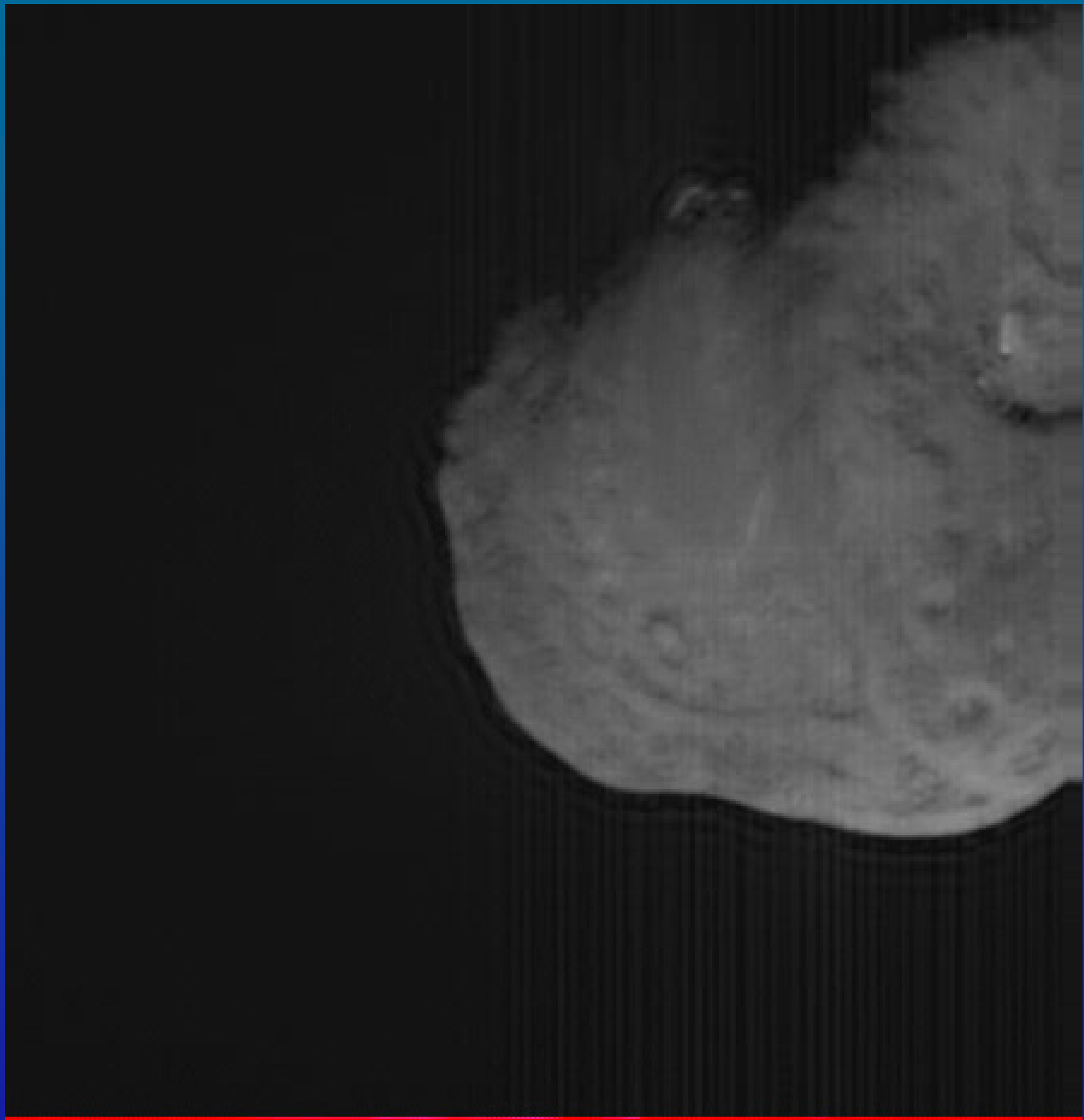
- First real thermal map of a nucleus
- Consistent with STM plus roughness to warm areas near terminator; I~<20 W K^{-1} m^2 $s^{0.5}$
- No locations as cold as sublimation temperature of H_2O ice
- Therefore ice must be below the surface but "not far" below
- Diurnal skin depth 3 cm, annual skin depth 0.9m for plausible separation of components of I

Impactor Approach

- Original movie (not registered) to show pointing jitter
- Note one big jitter early due to ITCM. Note big jitters in last 30 seconds due presumably to dust hits
- Orientation is “upside down” mirror image of “sky” to visualize landing on oblique surface (~35° from horizontal). Ecliptic north is roughly near the bottom



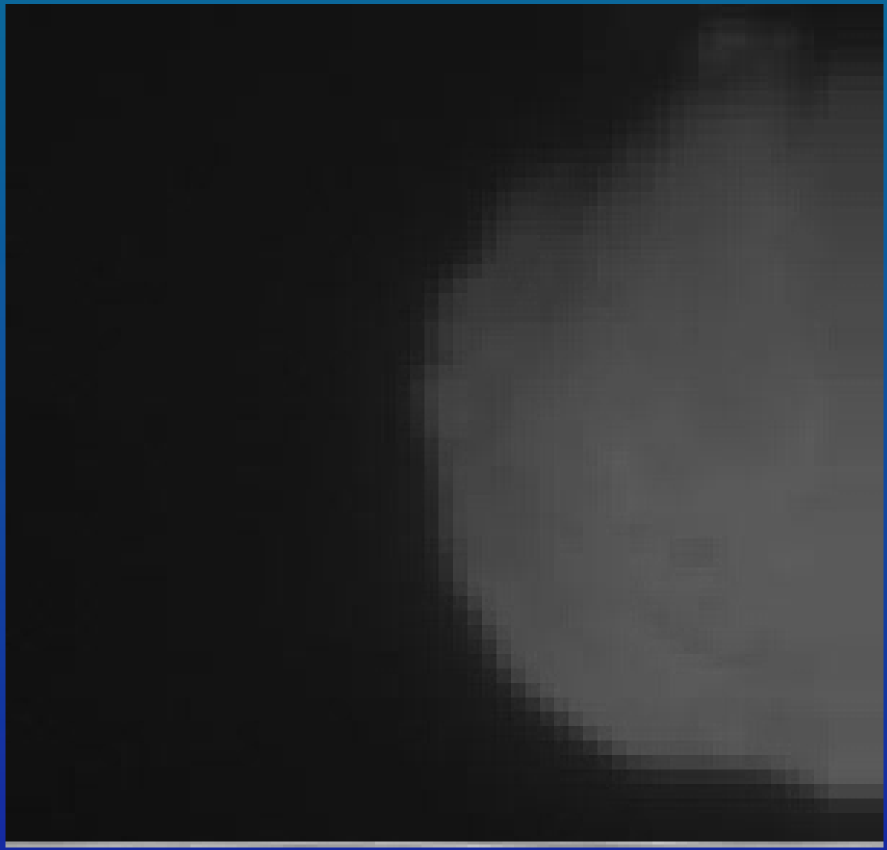
HRI Movie



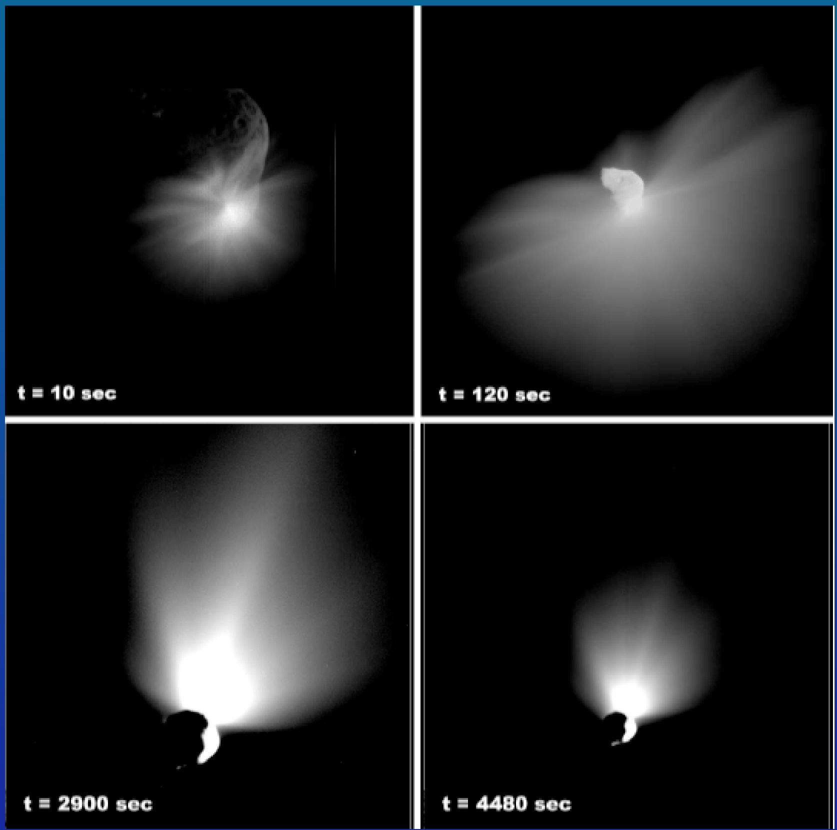
- Much slower frame speed than with MRI
- Longer period included in movie
- “Vertical bar” immediately after impact is bleeding of the saturated CCD, not real ejecta
- Note shadow cast by optically thick ejecta

MRI Movie

- Frames every 62 msec
- Initial stages of excavation only
- Small “poof” that goes rapidly to left at onset is hot, self-luminous plume of vapor + liquid or solid particles
- Later ejecta are cold
  - Water ice survives the ejection
  - Speeds start at few x 100 m/s and drop to below escape velocity as excavation continues



Simulating Impact

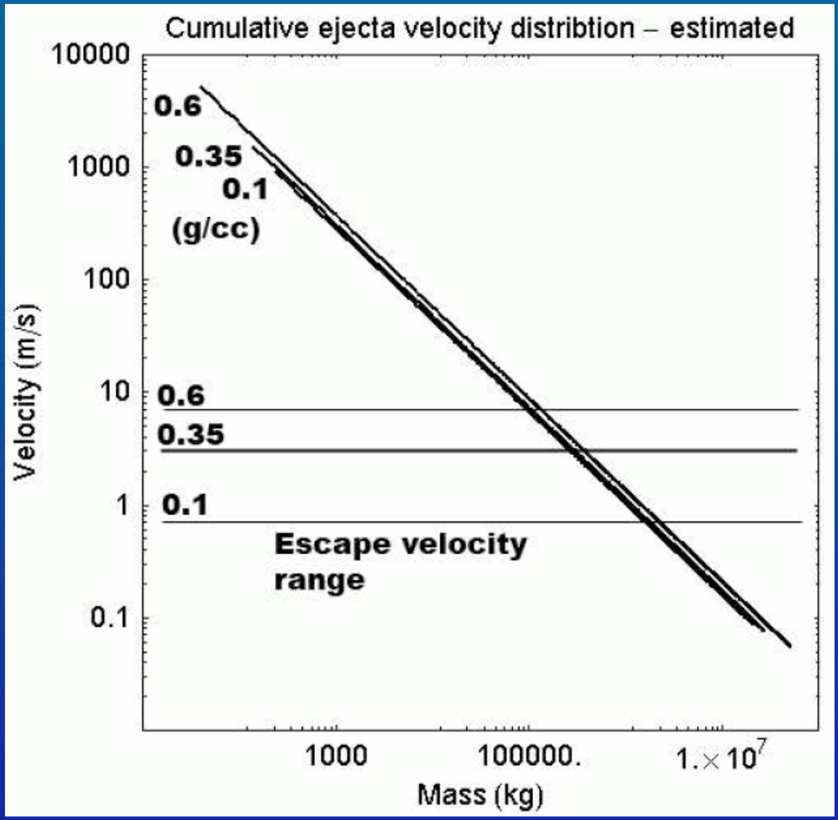


Richardson & Melosh 2007, *Icarus*, submitted

- Simulate ALL images with basic physics
- Ejecta curtain never seen to separate from surface/limb
  - Upper limit to strength 200 ± 100 Pa
- Fallback on ballistic trajectories is occurring
  - Gravity 30 ± 20 mgal
  - Mass 4×10^{16} g
  - Bulk density 0.35 ± 0.25 g/cc
  - Very high porosity!
  - Errors ± 2-σ
- Displacement of late ejecta anti-sunward fit by radiation pressure
  - Particle size few μm
  - Hold that thought!

Simulation Results

- Simulation estimates total mass ejected, momentum transferred, etc.
- Characteristics similar to what was described by Benz
- Solution probably not unique



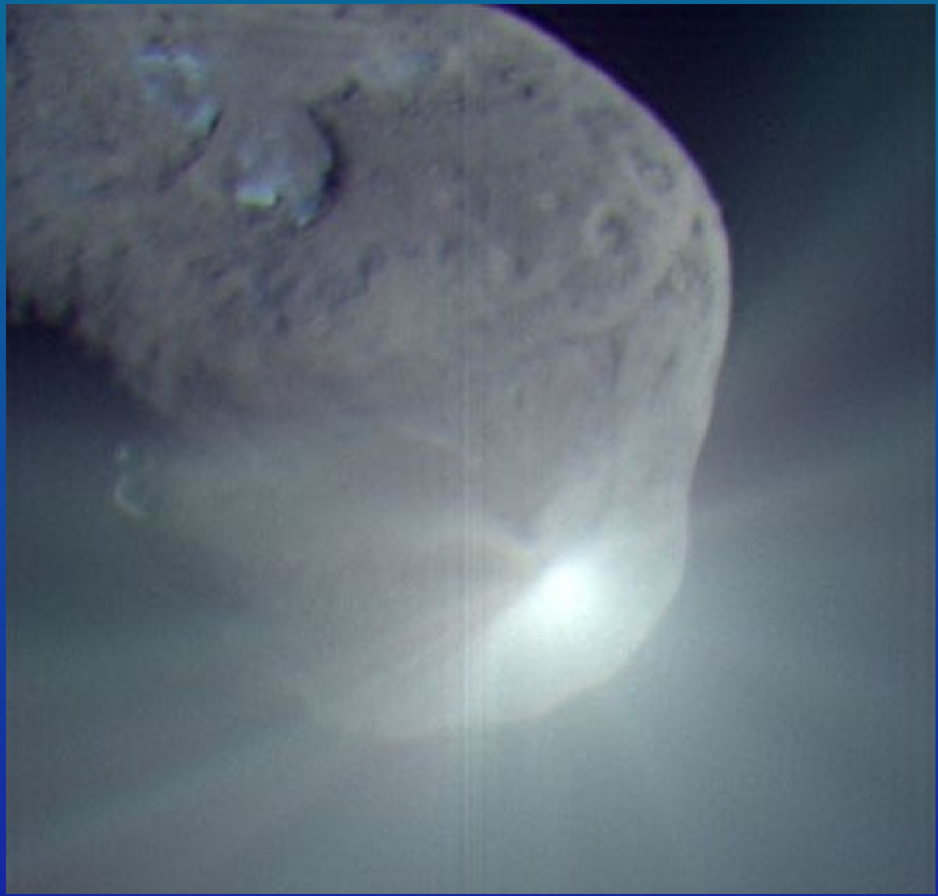
Richardson & Melosh 2007, *Icarus*, submitted

Energy & Momentum

- Kinetic energy (K.E.) of impactor: 19 GJ
- Orbital Change
  - < 1 GJ from change in orbital energy
  - Momentum transfer efficiency perhaps 2x-3x (model dependent)
  - Depends on obliquity of impact (ejecta momentum not anti-parallel to impactor momentum)
- Hot Plume ($\sim 10^0$ ton)
  - K.E. of plume has most of the impact energy
  - Sublimation and melting has 10% or less of impact energy
- Excavated material ($\sim 10^4$ ton)
  - K.E. << 1% of impact energy, but momentum exceeds input momentum
  - Sublimation of water MUST be due to sunlight evaporating excavated ice; total energy of sublimation >> impact energy

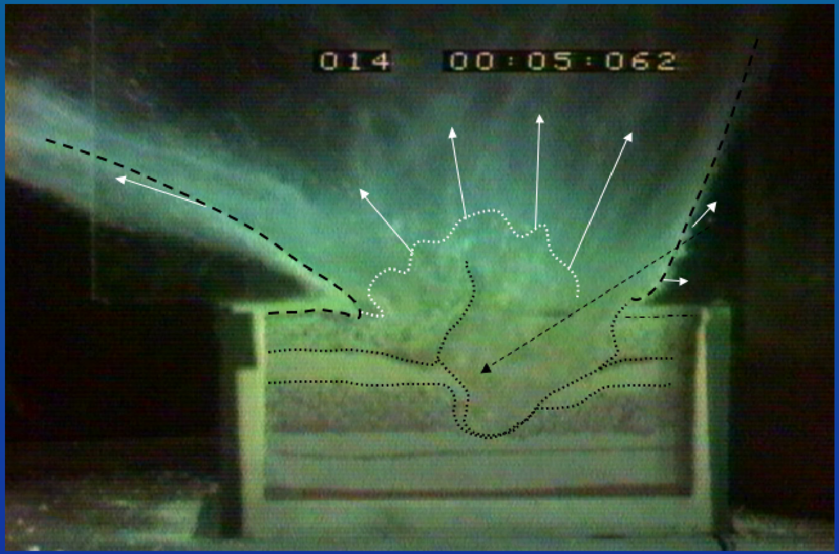
Deconvolved HRI Image

- IR + green + violet
- Forced to average gray
- Note very localized “bluish” areas
- Note curvature of ejecta in up-range direction
  - Consistent with lab experiments
  - Later (I+195s) detachment of these rays from crater suggests layering
  - Layering also suggested by hot plume in previous movie
  - Schultz *et al.,* in prep.
- Note smoothness of ejecta in radial direction
  - Primarily small particles
  - Rays from initial conditions



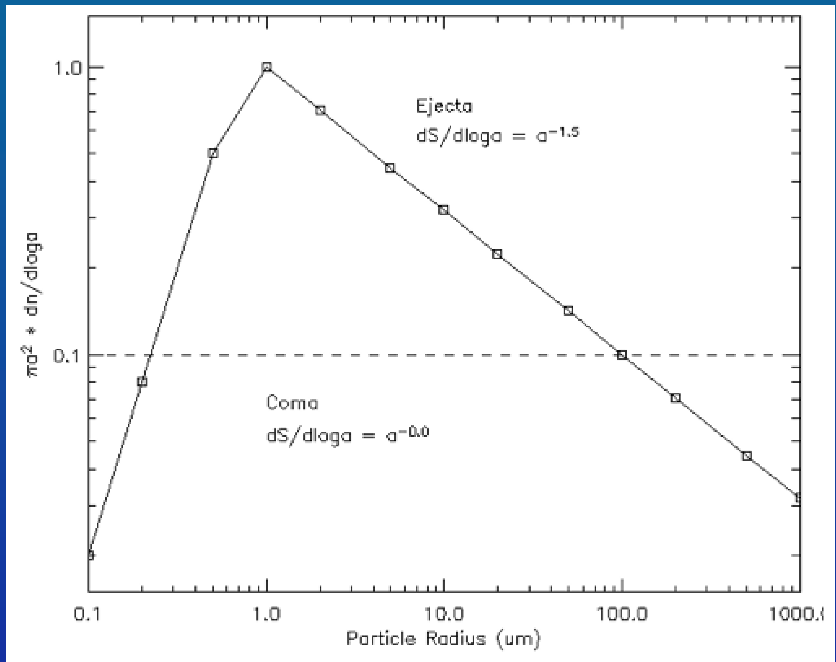
Structure Summary

- **Fine-grained material**
  - **No boulders**
  - **No hard crust**
- **Grains are fragile aggregates**
  - **fragment during excavation**
  - **Fragements ~1-3 μm**
- **Layers within 1 impactor diameter of surface at impact site**
  - **Topmost layer (few cm?) devoid of ice**
- **Layers are ubiquitous**
  - **Varying thickness**
  - **Some may be primordial**
  - **Smooth layers not yet explained**



Schultz *et al* 2007, *Icarus*, submitted

Size Distribution at E+45m



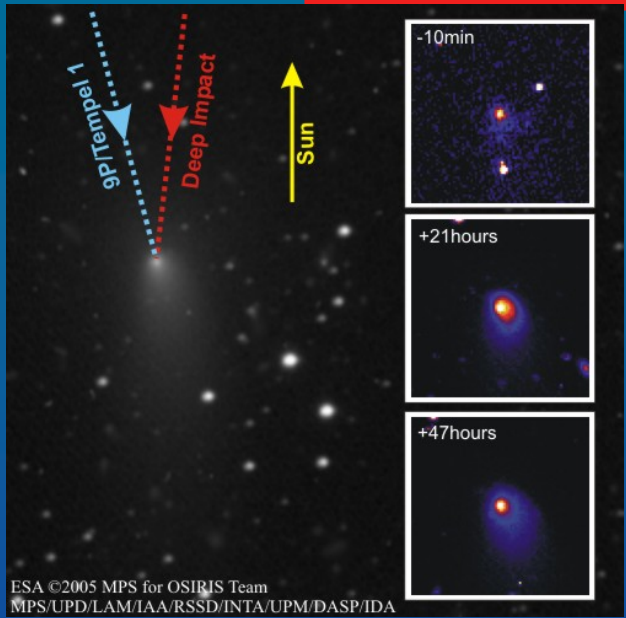
Lisse et al. 2006. Science, on-line

- Size distribution needed to successfully model SST spectra
- Distribution of surface area per unit mass - before (ambient release) and after (mechanically excavated grains) impact
- While largest particles still dominate total mass, they no longer dominate total cross-section
- Interpretation is that surface materials are all weak, large aggregates of smaller pieces with typical size of a few μm

Structure

- Pre-impact: normal dust release (approx. power law with mass dominated by largest particle)
- Post-impact: dominated by small (few μm) particles
  - No discrete clumps in ejecta (> few m)
  - Schleicher *et al.* 2006 - radiation pressure over a week consistent with small particles
  - Richardson & Melosh 2007 - radiation pressure on ejecta curtain consistent with small particles
  - Spitzer observations require peak size ~1 μm
  - Much of ejecta was ice in small (~2 μm) grains
- Layering (strength variation) within 1 impactor diameter of surface

Monitoring OH

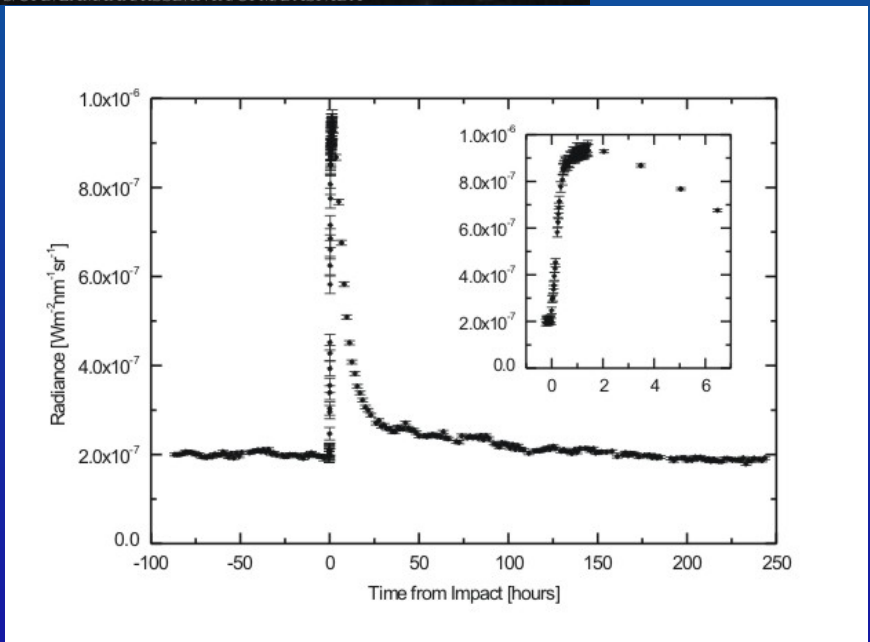


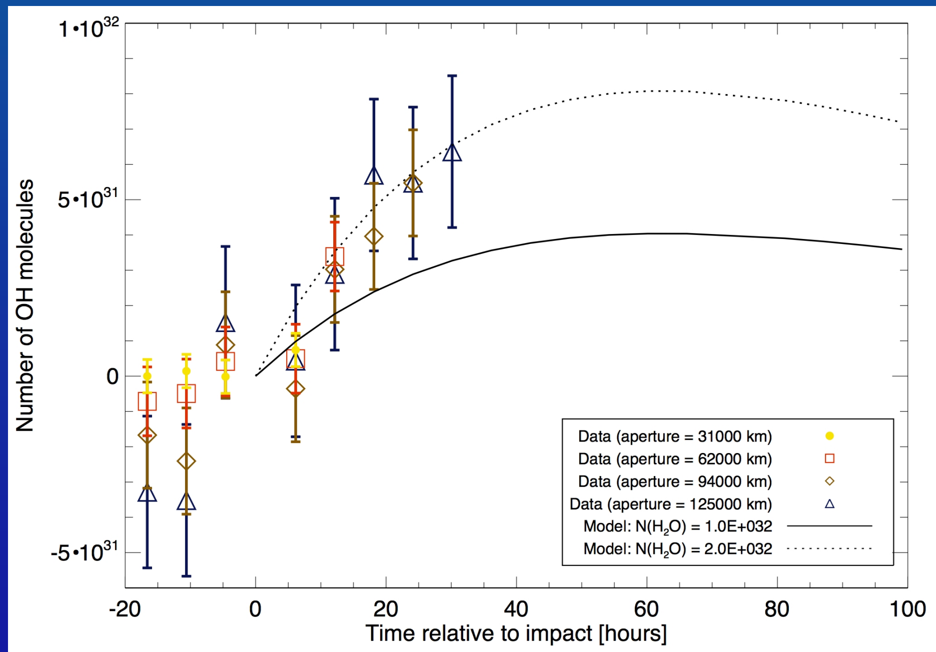
Küppers et al., 2005 Nature **437**, 987
Observations with OSIRIS on Rosetta

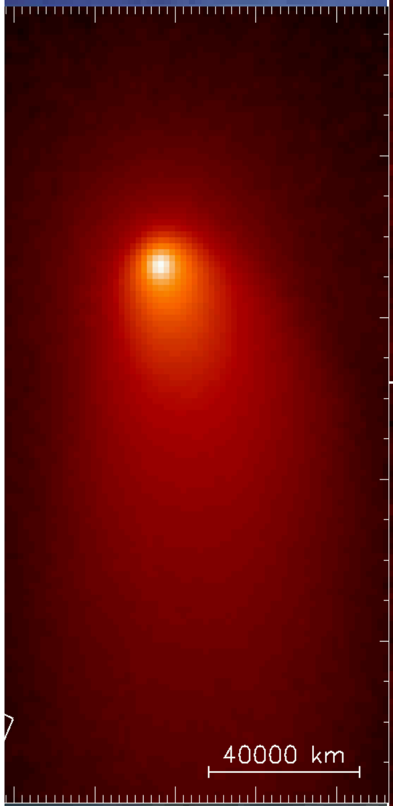
Enables determination of total water released in impact ~ 4000 tons original estimate, revised upward (4500 - 9000 tons) with better calibration

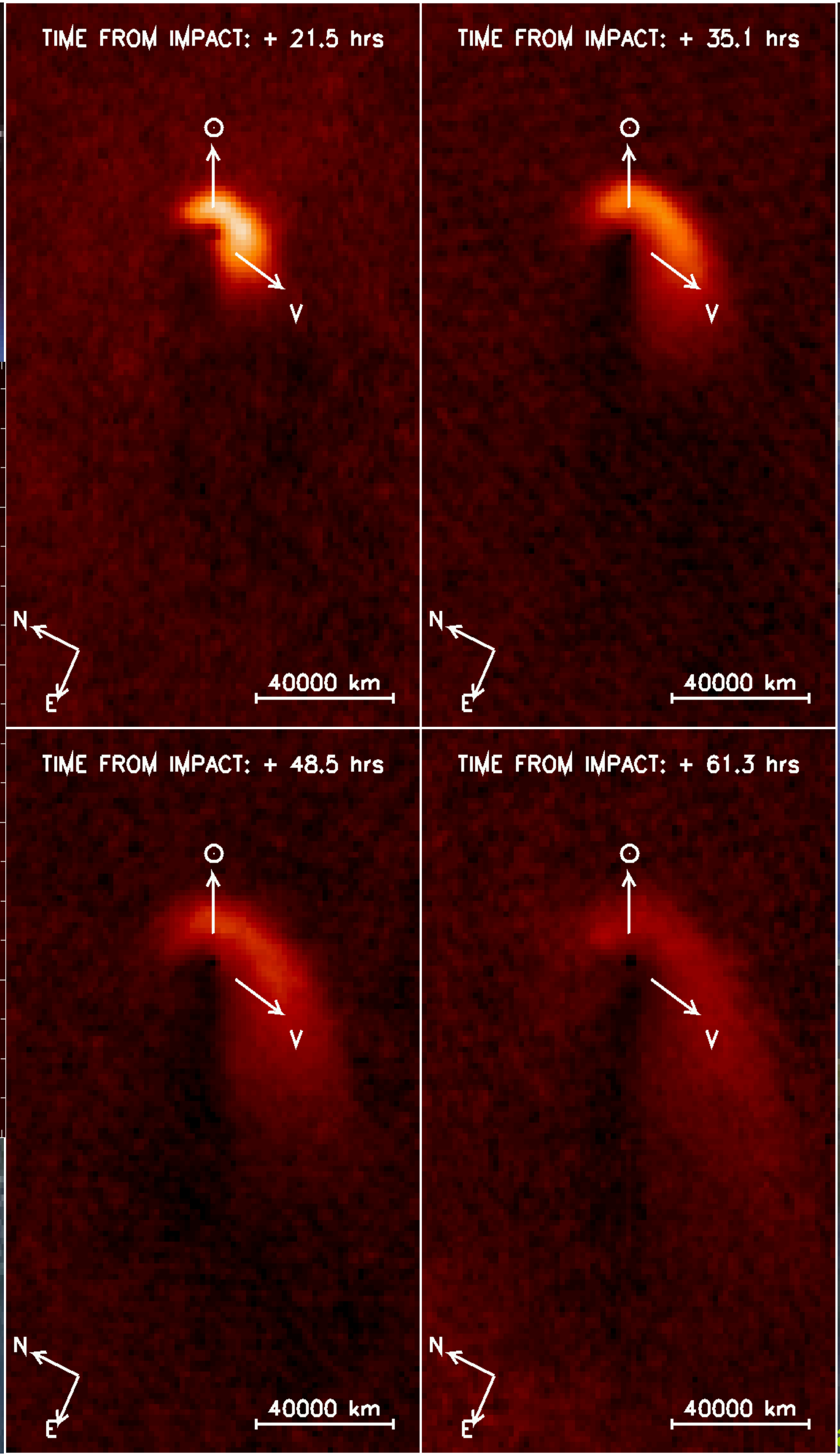
Many observers (incl. ODIN, ground-based OH) find 4 to 10x10^3 tons of water

Other species (CO best determined) of order 5-10% of water









Dust from impact

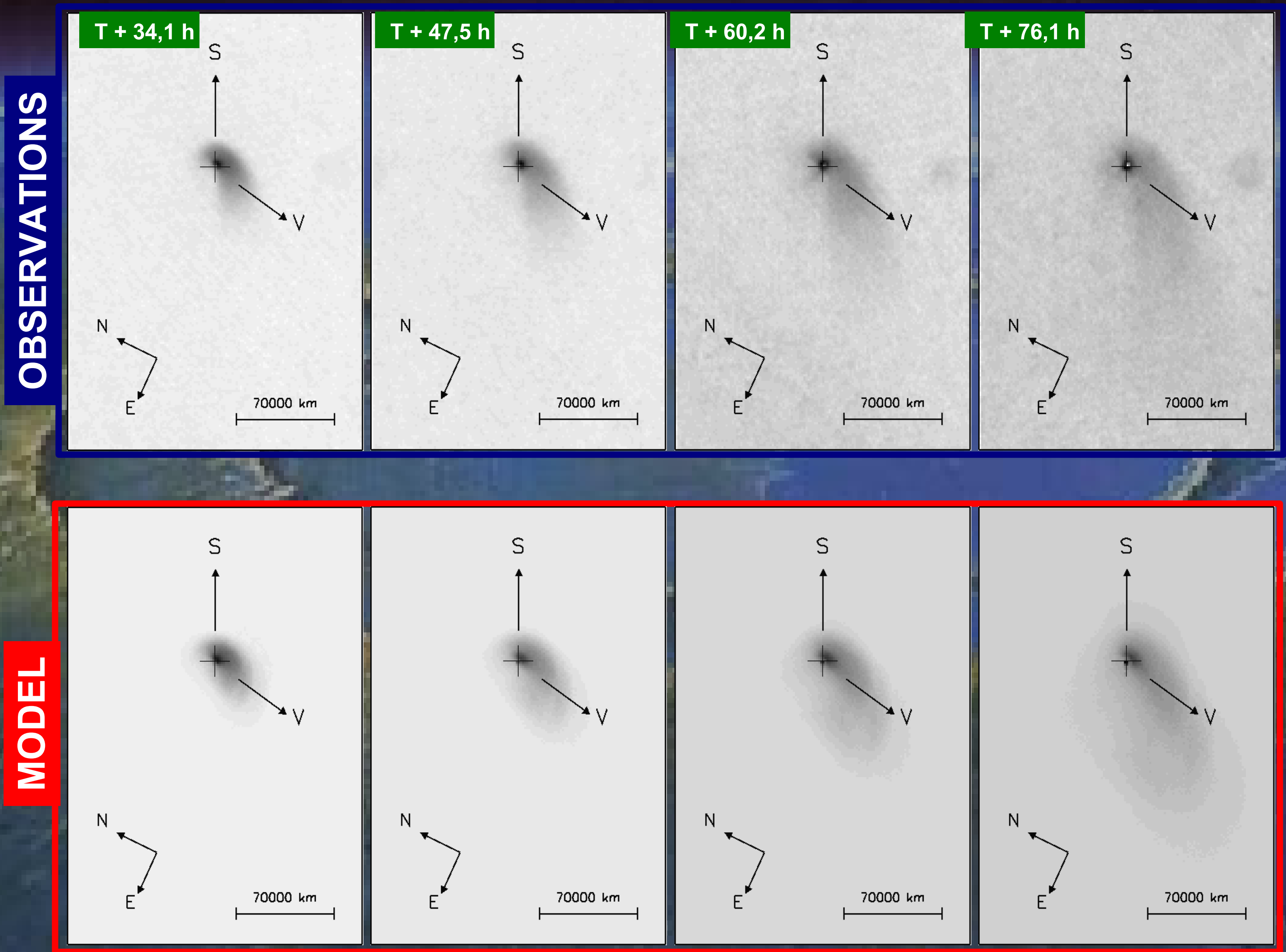
Post impact images minus pre impact image

OSIRIS images contain information about particle velocity and size distribution

L. Jorda et al.

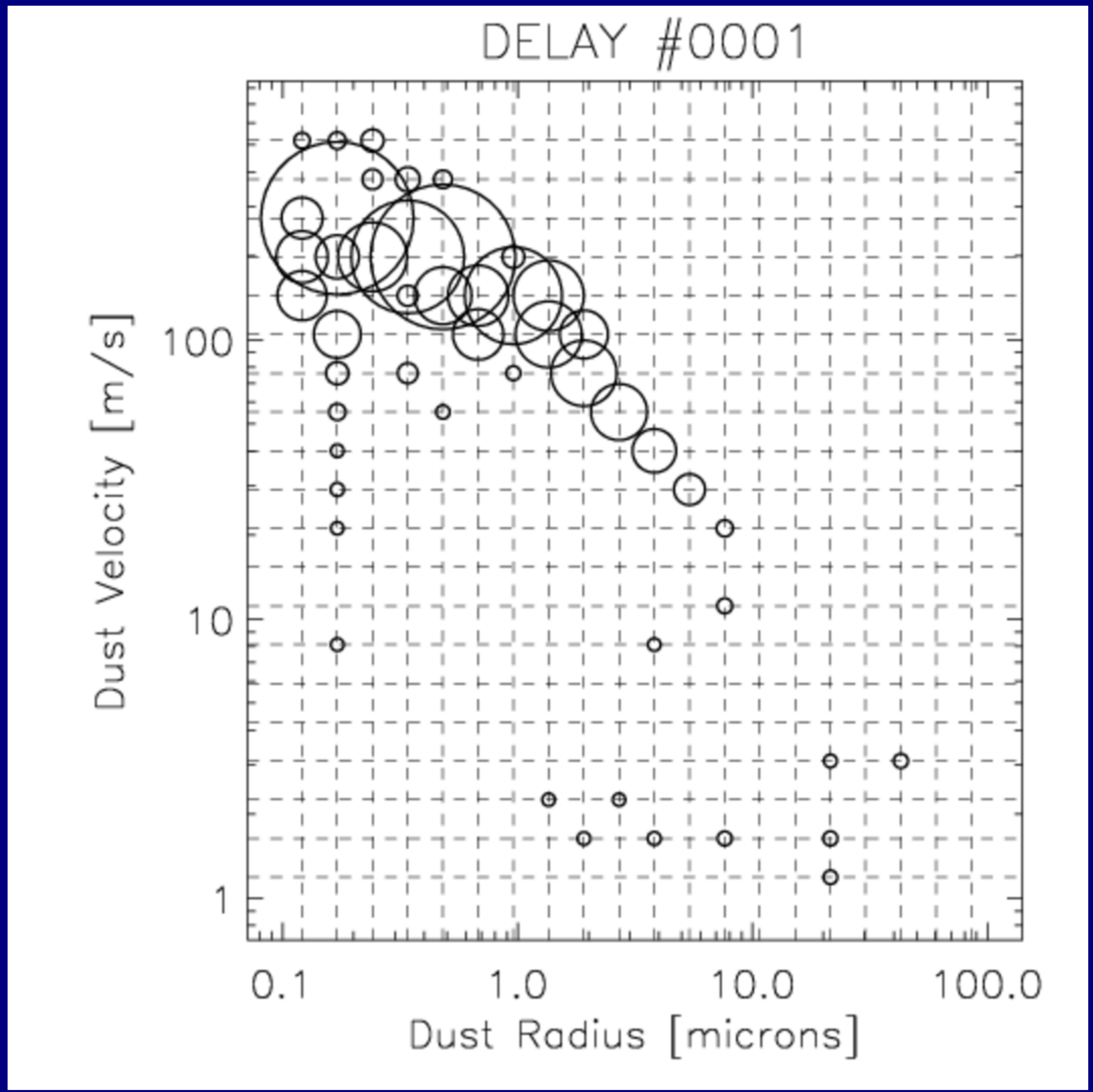
DUST MODELING

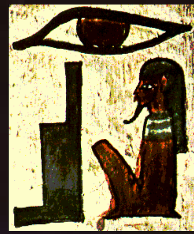
COMPARISON MODEL – OBSERVATIONS



DUST MODELING

DUST CROSS SECTION





RESULTS:

- 90 % of cross section for
  grains < 10 µm radius
- 80 % of cross section for
  grains < 1.4 µm radius

➔ cross section dominated
by *sub-micron grains*

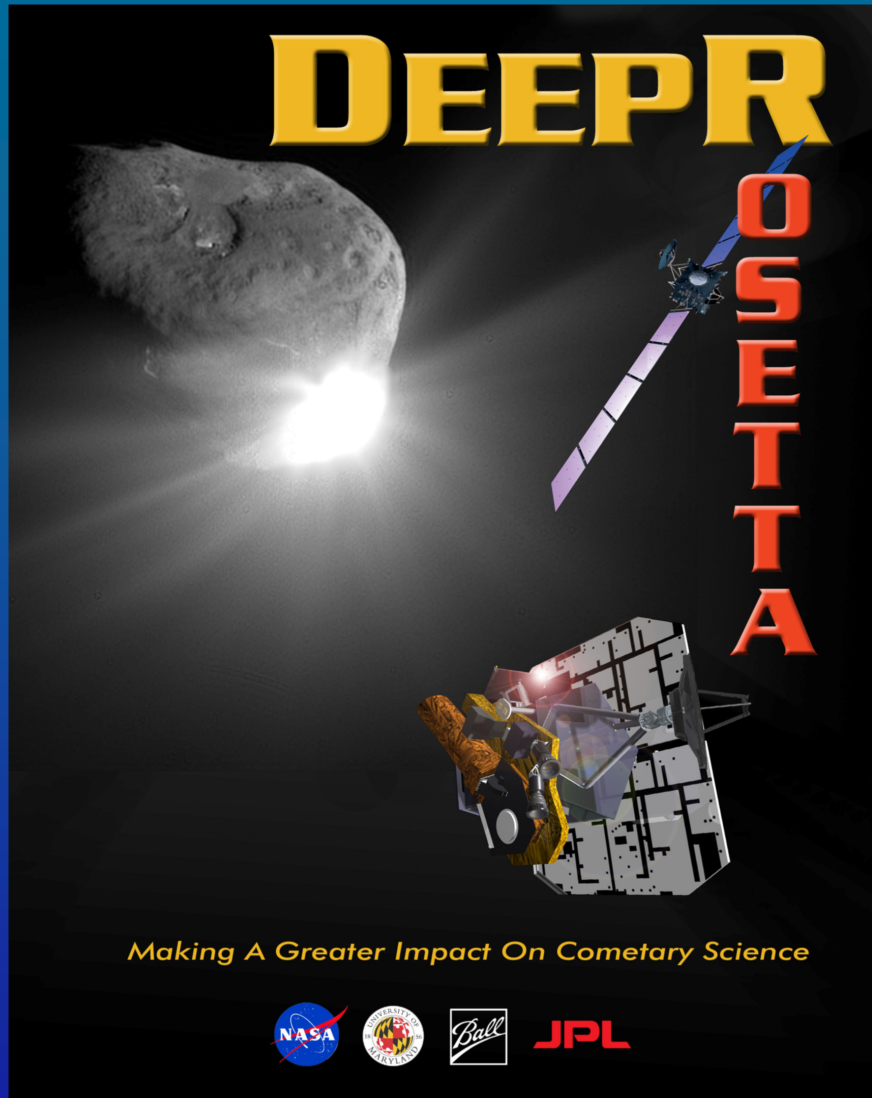
Deep Impact

- Crater formation in gravitational regime => tensile strength of cometary nucleus small
- Most dust in small particles
- Volatile components observed similar to other comets => not more volatiles than from surface
- Dust to gas (ice) ratio > 1

Tempel 1 Conclusions

- Second “cratered” nucleus
  - Nature of craters?
    - 2 distinct populations
- Layers – primordial
  - Different from previous comets?
- Smooth and hammocky terrains
  - Smooth: avalanche-like, activity, formed recently
  - Erosion rates of terrains have varied, slope retreats
- Spots of activity with water ice near surface
- Very low thermal inertia => thin porous dust cover
- Localized and focused activity (jets) but no corresponding landforms identified

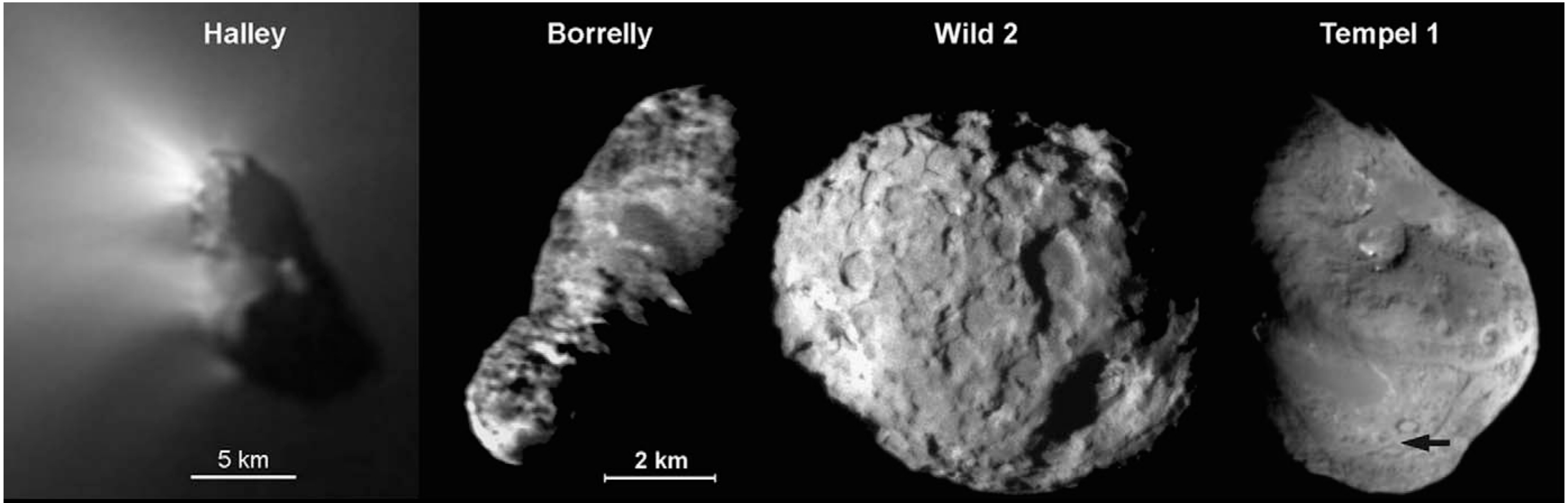
Deep
Impact
eXtended
Investigation of Comets
Michael F. A'Hearn
Principal Investigator
Extending the Renaissance in
our understanding of comets
March 30, 2006
JPL



DEEPR
OSETTA
Making A Greater Impact On Cometary Science
NASA
Ball
JPL

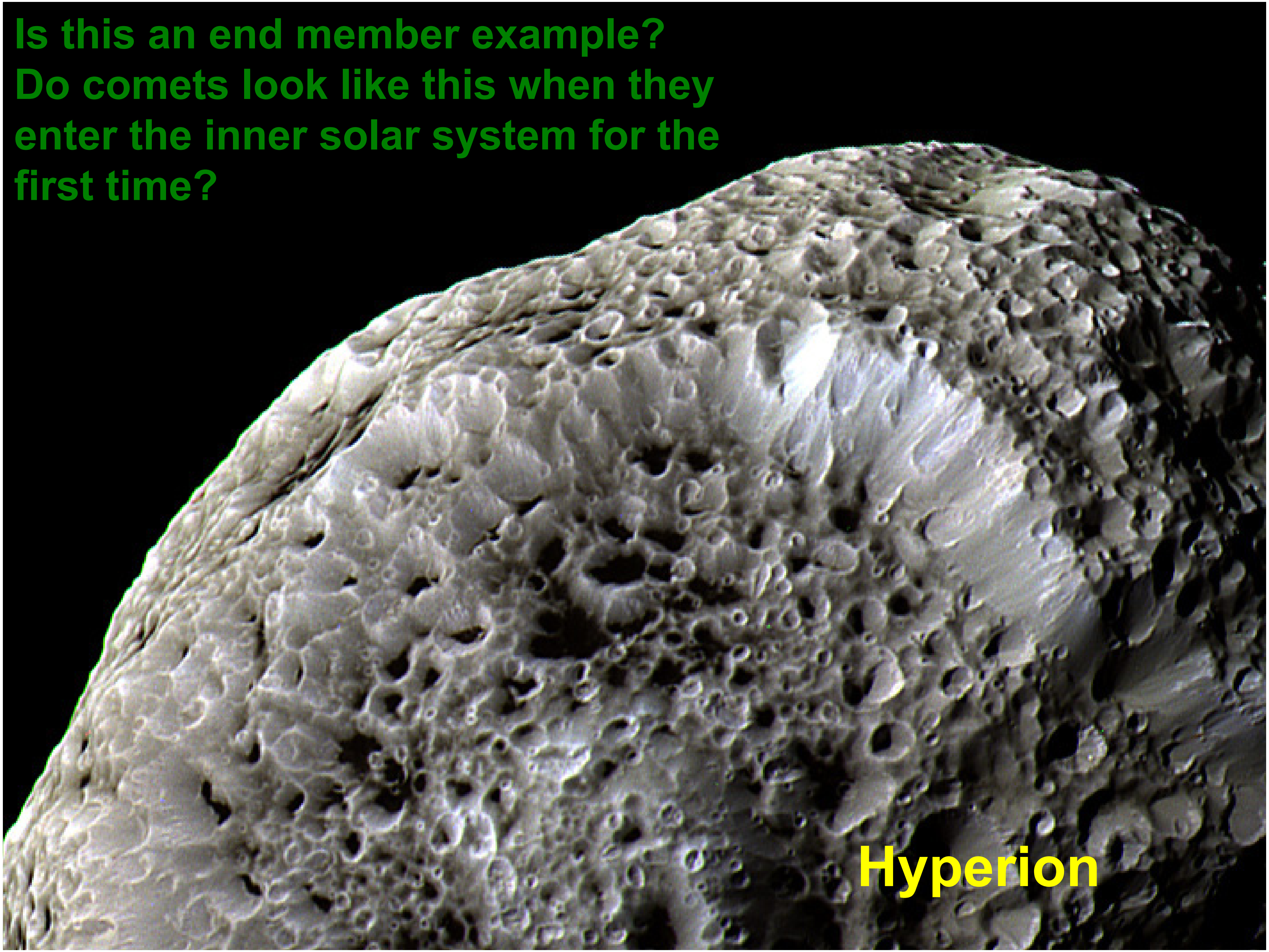
Comets - Asteroids

- **The irregular shape and size of the nuclei are similar to what can be found for asteroids**
- **Transition: asteroidal comets (MBC) – cometary asteroids (extinct comets)**
- **However, impact craters?**
- **Surface features on cometary nuclei are driven by activity resulting in possibly complex features**
- **For JF comets sublimation driven erosion is fast, even by terrestrial standards (several meters per orbit)**
- **Mass loss and decay are dominated by shedding of substantial pieces and by splitting**
- **Comet Halley: more mass in meteoroides than in its present day nucleus**
- **Consequently, imaging an evolved nucleus provides a look into its ‘interior’ structure**



Halley	Borrelly	Wild 2	Tempel 1
Very active Oort cloud comet, but activity still localized Very ablated, most of the nucleus mass in meteor stream Accentuated topography Depressions, range of hills, high outcrop	Evolved (ablated) JF comet No craters anymore visible Localized activity Smooth and mottled terrains, mesas Long ridges, large terrain unities	Strongly cratered surface (saturated) Young JF comet From early history Craters eroded Material lost in the order of 100 m Suggests only short time of sublimation activity	Eroded surface but craters (still?) visible Indication of thick layers Smooth (avalanche) layers Low thermal inertia Active spots covered only by thin dust layer
Most evolved	**Strongly evolved**	**Least evolved**	**Evolved**
Large scale landforms not in agreement with rubble pile assumption			

Is this an end member example?
Do comets look like this when they enter the inner solar system for the first time?



Summary

- The physical process of activity is one of the key questions of cometary physics
- Flybys have little contributed to answers

However:

- Flybys have changed the paradigm from the “icy conglomerate” (ice dominated) nucleus to a widely inactive highly porous body whose physical strength is controlled by dust (refractory material)

ROSETTA

67P/Churyumov-Gerasimenko

Orbit of 67P/Churyumov-Gerasimenko

Perihelion	r_h [UA]	Δ [UA]	m_1	Elong	Perigee	r_h [UA]	Δ [UA]	m_1	Elong
08-12-1582	**1.713**								
28-04-1721	**1.832**								
05-10-1855	**2.802**								
20-03-1956	**2.739**	**3.033**		**63°**					
24-02-1963	**1.265**	**1.650**		**51°**					
11-09-1969	**1.285**	**1.390**	**12.5**	**63°**	25-01-1970	**2.000**	**1.155**	**13**	**139°**
07-04-1976	**1.298**	**2.132**	*13.5*	**25°**	27-08-1975	**2.640**	**1.730**	**16**	**148°**
12-11-1982	**1.306**	**0.405**	**10.0**	**135°**	27-11-1982	**1.318**	**0.391**	**9.5**	**142°**
18-06-1989	**1.299**	**2.260**	*13.5*	**14°**	26-02-1990	**2.835**	**1.934**	**17**	**152°**
17-01-1996	**1.300**	**1.085**	**11.0**	**78°**	07-10-1995	**1.748**	**0.904**	**13.0**	**131°**
18-08-2002	**1.292**	**1.739**	**12.8**	**47°**	08-02-2003	**2.270**	**1.399**	**14.5**	**145°**
01-03-2009	**1.246**	**1.685**	***12.5***	**47°**	07-09-2008	**2.270**	**1.394**	***16***	**142°**
13-08-2015	**1.243**	**1.771**	***12.6***	**43°**	14-02-2016	**2.360**	**1.485**	***15***	**145°**
02-11-2021	**1.211**	**0.421**	***9.5***	**111°**	12-11-2021	**1.217**	**0.418**	***9***	**113°**

67P/Churyumov-Gerasimenko: Nucleus:

Dimensions: 4.8x3.6 km

Surface active ~5%

Rotation period = 12.3h

Orbital period 6.6 years

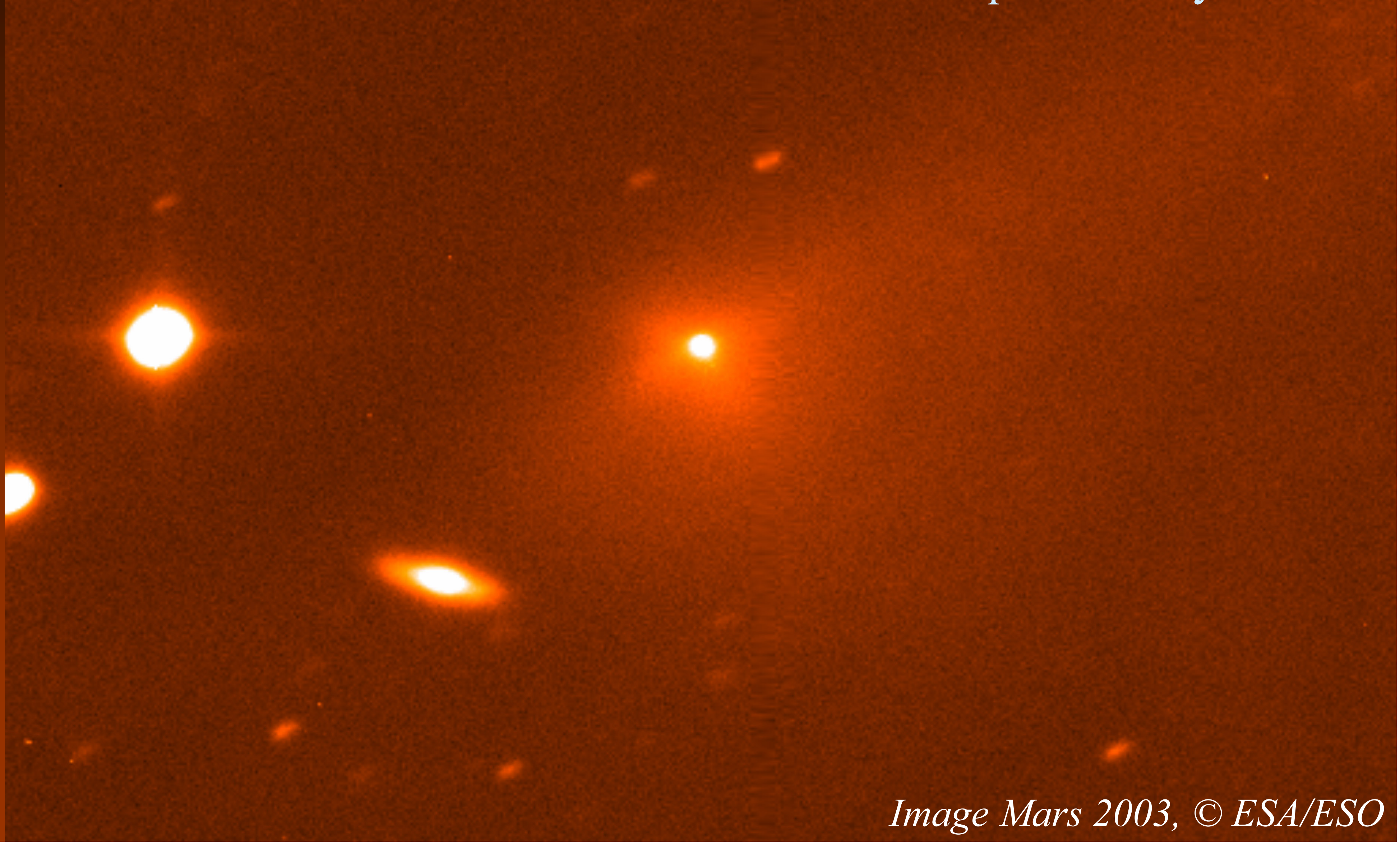


Image Mars 2003, © ESA/ESO

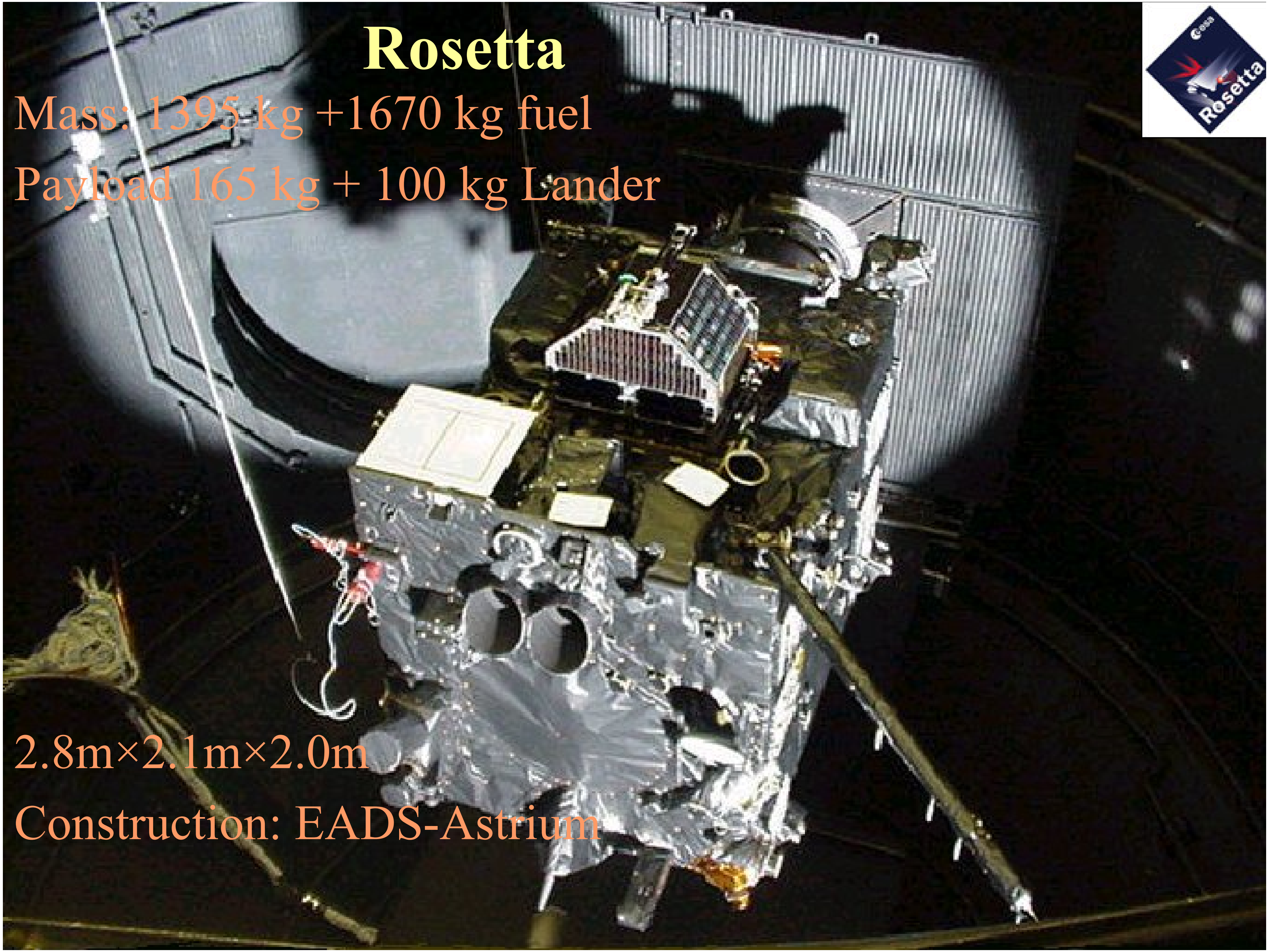
Rosetta

Mass: 1395 kg +1670 kg fuel

Payload 165 kg + 100 kg Lander

2.8m×2.1m×2.0m

Construction: EADS-Astrium



Remote sensing instruments

ALICE: Ultraviolet Spectrometer (70 nm – 205 nm) *PI: A. Stern (USA)*

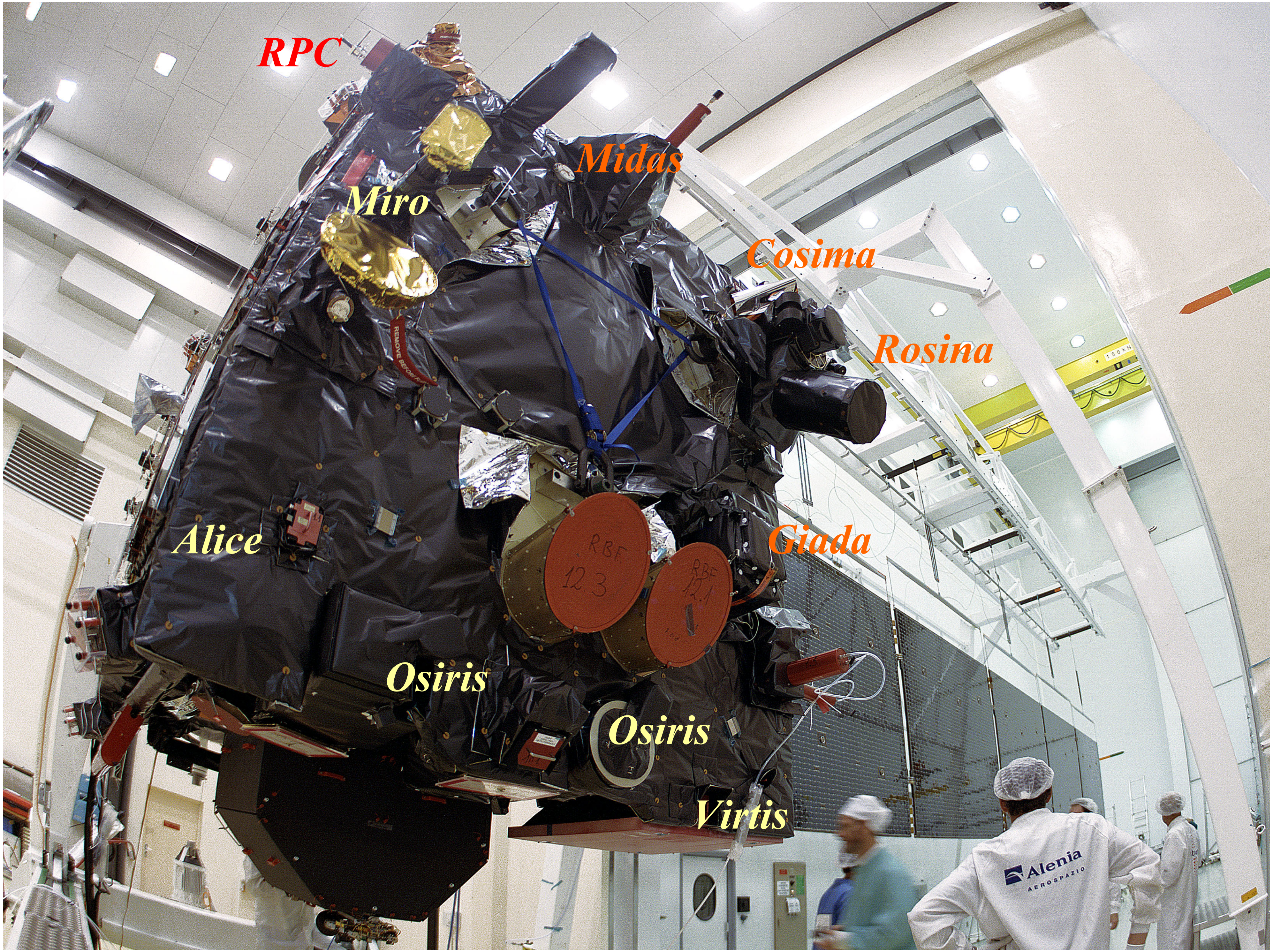
OSIRIS: Camera Visible (CCD 2k×2k 14bit 250 – 1000 nm):
Large FOV: WAC 140mm:12°
Narrow FOV: NAC 700mm: 2.4° *PI: H.U Keller (Germany)*

VIRTIS: Visible – Infrared spectrometers (0.25 – 5 mm)
Virtis-H spectrometer $\lambda/\Delta\lambda=1300$,
Virtis-M: spectro-imager 3.6°/ $\lambda/\Delta\lambda=200$ *PI: A.Coradini (Italy)*

MIRO: Microwave spectrometer (1.3 mm et 0.5 mm) *PI: S.Gulkis (USA)*

Indirect measurements:

RSI: Radio science *PI: M. Pätzold (Allemagne)*


RPC
Midas
Miro
Cosima
Rosina
Alice
Giada
Osiris
Osiris
Virtis
RBF 12.3
Alenia
AEROSPAZIO

Instruments to measure the nucleus environment

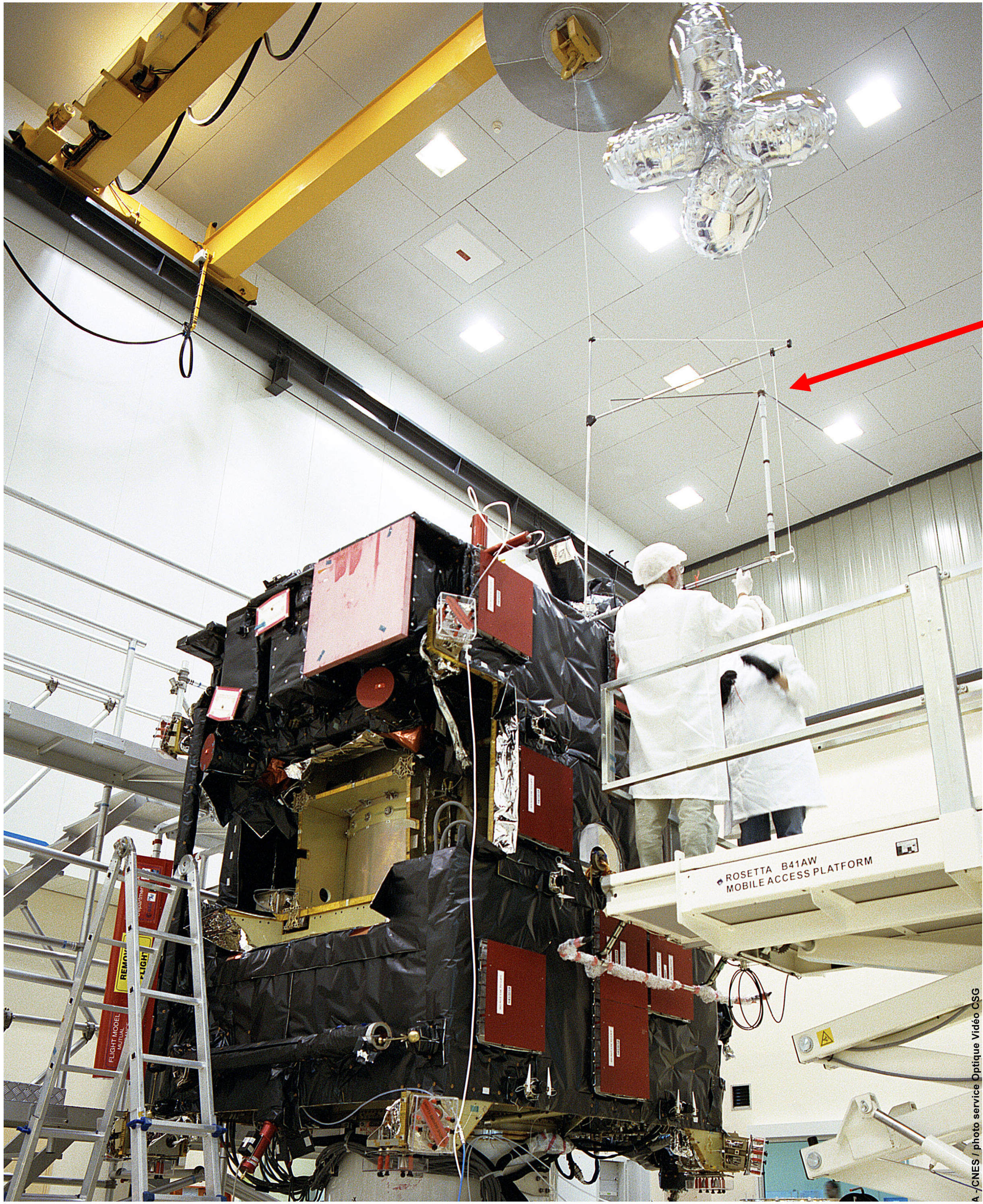
COSIMA: Dust mass spectrometer. *PI: J. Kissel (Germany)*

MIDAS: Dust microscopic analyser. *PI: W. Riedler (Austria)*

GIADA: Dust mass analyser: numbers, mass, speed, direction. *PI:L.Colangeli (Italy)*

ROSINA: Gas mass spectrometer (12 - 200 amu). *PI: H. Balsiger (Swiss)*

RPC: Plasma and magnetic field analyser (consortium)
PI: A.Eriksson (Sweden), J.Burch (USA), K.H. Glassmeier (Germany), R.Lundin (Sweden), J.G. Trotignon (France)



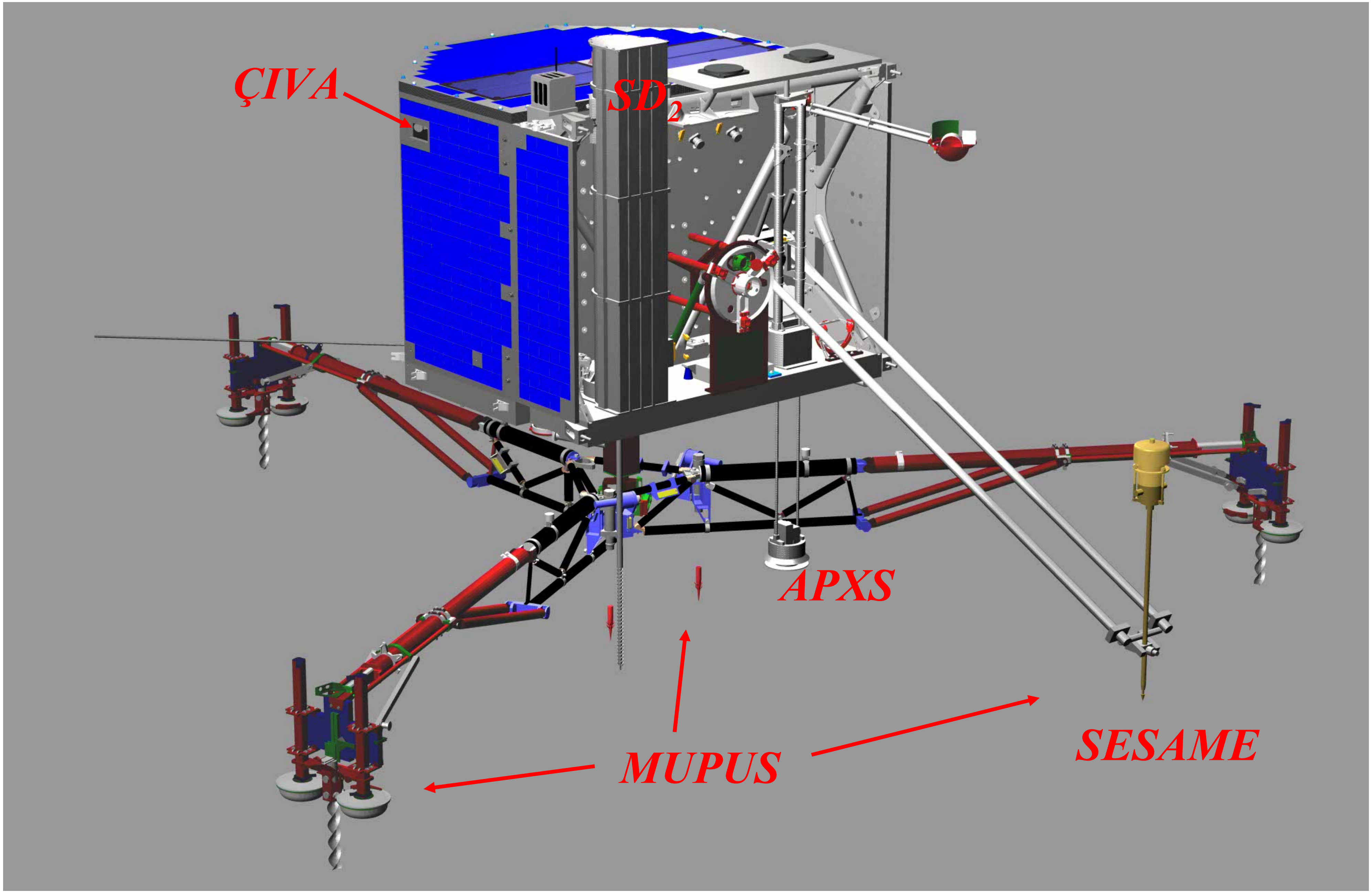
CONSERT

Antenna deployment test at ESTEC

Experiment combining antennas on the orbiter and lander to measure the nucleus interior by radio sounding at 90 MHz

PI:W.Kofman (France)

The Lander of Rosetta: Philae



Lander Philae : expériences

APXS: Alpha-proton-Xray spectrometer *PI: R. Riedler (Germany)*

COSAC: Gas analyser: elemental and molecular composition
PI: H. Rosenbauer (Germany)

MODULUS: gas analyser (isotopic composition) *PI: I. Wright (GB)*

SD2: Drill (down to 20cm) and sampling *PI: A.Ercoli Finzi(Italy)*

CIVA/ROLIS: 6 micro panoramic cameras 70° + microscope (res. 7µm) and a high resolution stereo camera.
PI: J.-P. Bibring (France), S. Mottola (Germany)

SESAME: 3 instruments to measure the properties of the nucleus surface: electric and acoustic sounding
PI: D. Möhlmann (Gemany) H. Laasko (Finland), I. Apathy (Hungary)

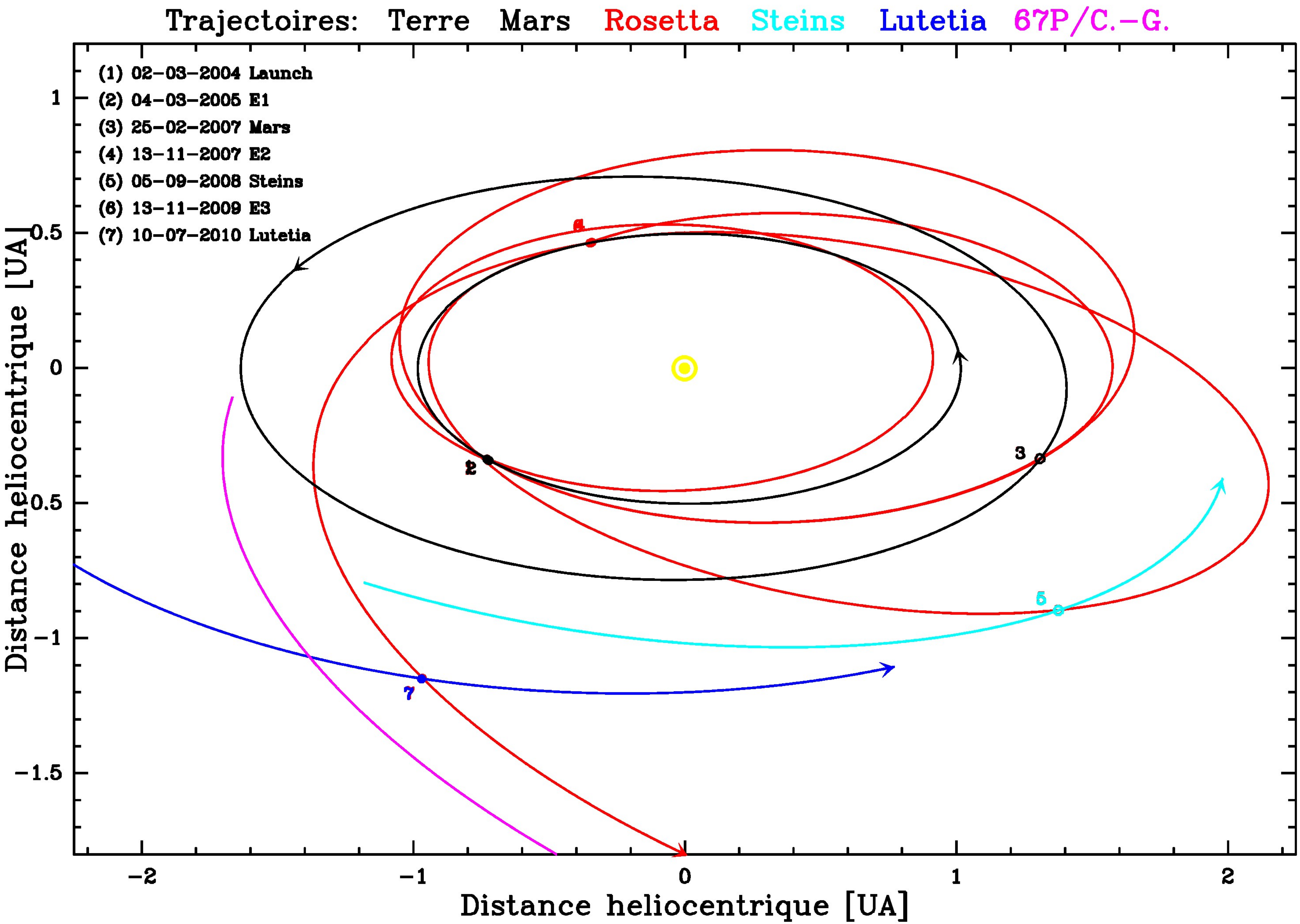
MUPUS: Mesuring the mechanical and thermal properties of the nucleus (part of the anchoring system) *PI: T. Spohn (Germany)*

ROMAP: Magnetometer and plasma measurements (interaction with the solar wind) *PI:U. Auster (Germany), I. Apathy (Hungary)*

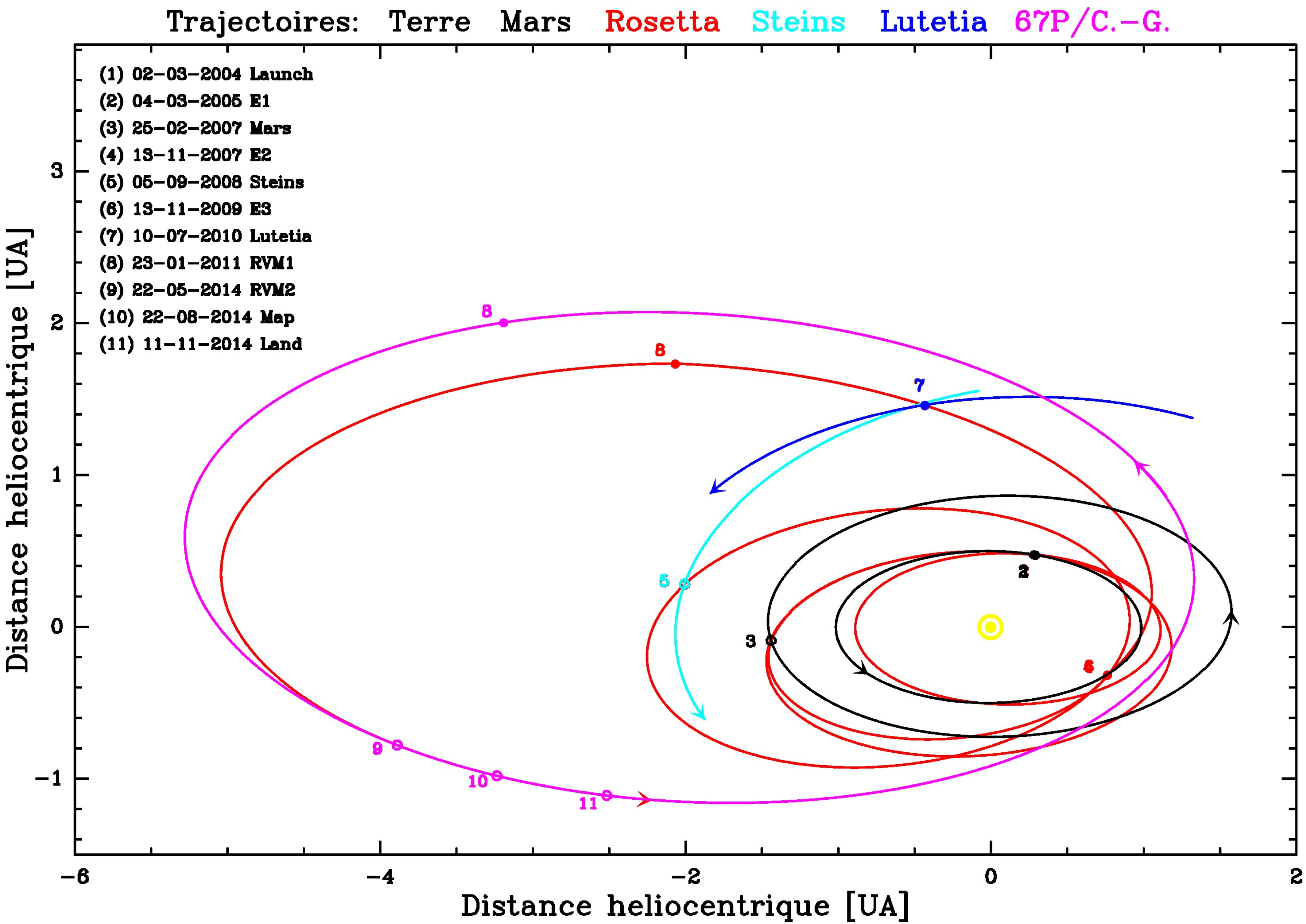
PHILAE

mounted on

ROSETTA



Trajectoires: Terre Mars Rosetta Steins Lutetia 67P/C.-G.
(1) 02-03-2004 Launch
(2) 04-03-2005 E1
(3) 25-02-2007 Mars
(4) 13-11-2007 E2
(5) 05-09-2008 Steins
(6) 13-11-2009 E3
(7) 10-07-2010 Lutetia
Distance heliocentrique [UA]
Distance heliocentrique [UA]



Trajectoires: Terre Mars Rosetta Steins Lutetia 67P/C.-G.
(1) 02-03-2004 Launch
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(4) 13-11-2007 E2
(5) 05-09-2008 Steins
(6) 13-11-2009 E3
(7) 10-07-2010 Lutetia
(8) 23-01-2011 RVM1
(9) 22-05-2014 RVM2
(10) 22-08-2014 Map
(11) 11-11-2014 Land
Distance heliocentrique [UA]
Distance heliocentrique [UA]

Mission to 67P/Churyumov-Gerasimenko

	Date	Distance	Speed ∞	Correction
Launch	**02 Mar.2004**	**0 km**	**3.543 km/s**	
Manœuvre	**11+16 Mai 2004**	**Δ=0.2 UA**		**Δv=153+5m/s**
Earth flyby	**04 Mar.2005**	**1954 km**	**3.9 km/s**	
Manœuvre	**29 Sep. 2006**	**r_h=1.0 UA**		**Δv= 81m/s**
Mars flyby	**25 Fév. 2007**	**200 km**	**8.88 km/s**	
Earth flyby	**13 Nov.2007**	**1400 km**	**9.3 km/s**	
(2867) Steins	**05 Sep. 2008**	**1700 km**	**9 km/s**	
Earth flyby	**13 Nov.2009**	**2300 km**	**9.3 km/s**	
(21) Lutetia	**10 Juil. 2010**	**3000 km**	**15.1 km/s**	
Manœuvre	**23 Jan. 2011**	**r_h=4.1 UA**		**Δv=740m/s**
Manœuvre/RDV	**22 Mai 2014**	**r_h=4.1 UA**	**0.65 km/s**	**Δv=648m/s**
Mapping phase	**22 Aout 2014**	r_h=3.5 UA		
Philae release	**10 Nov. 2014**	r_h=3.0 UA		

Portrait of Rosetta on 18 May 2004

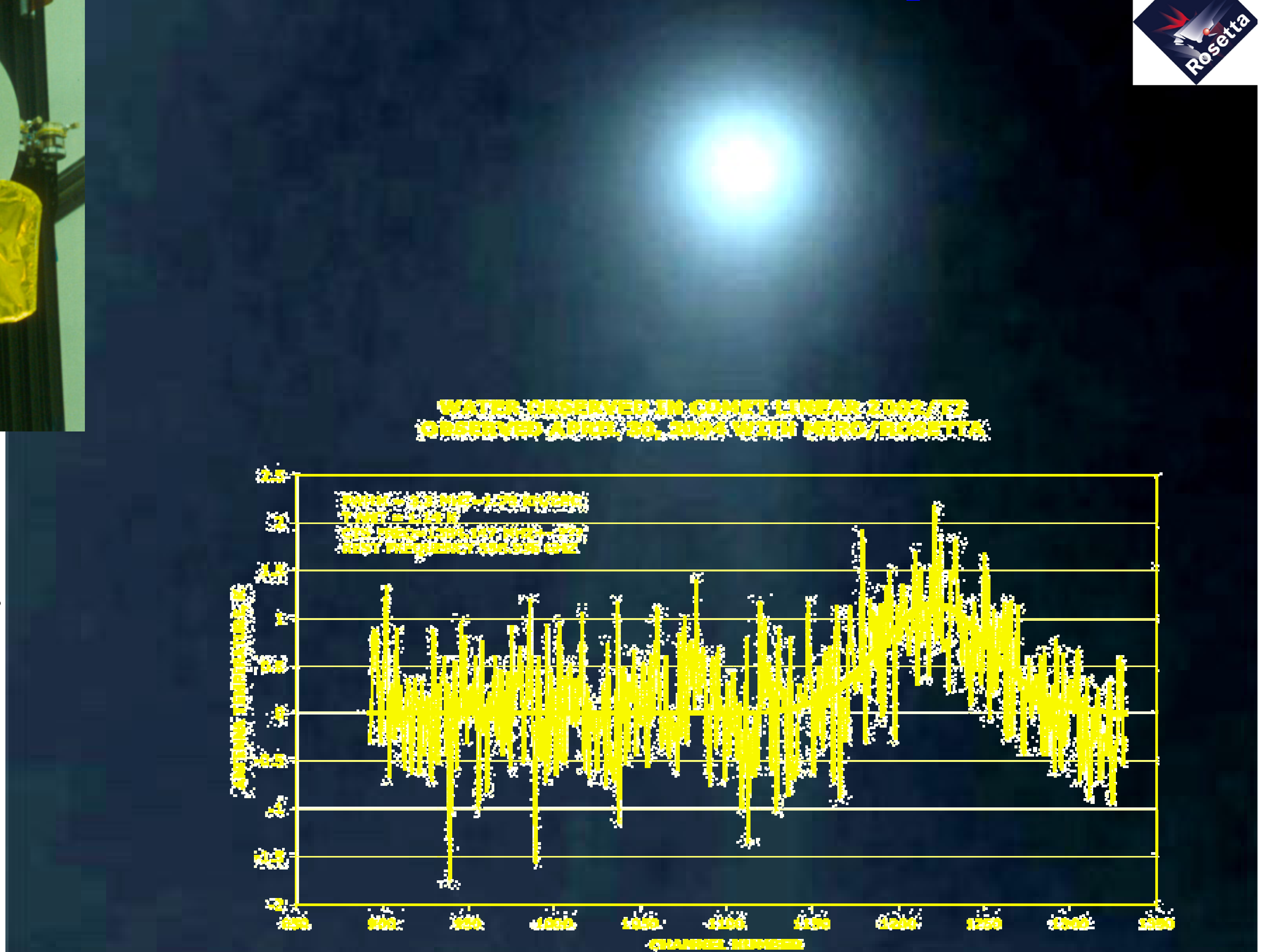
Images (enhanced) taken by the panoramic lander cameras

Images by CIVA-P of the solar pannelsof Rosetta

First comet observations by Rosetta

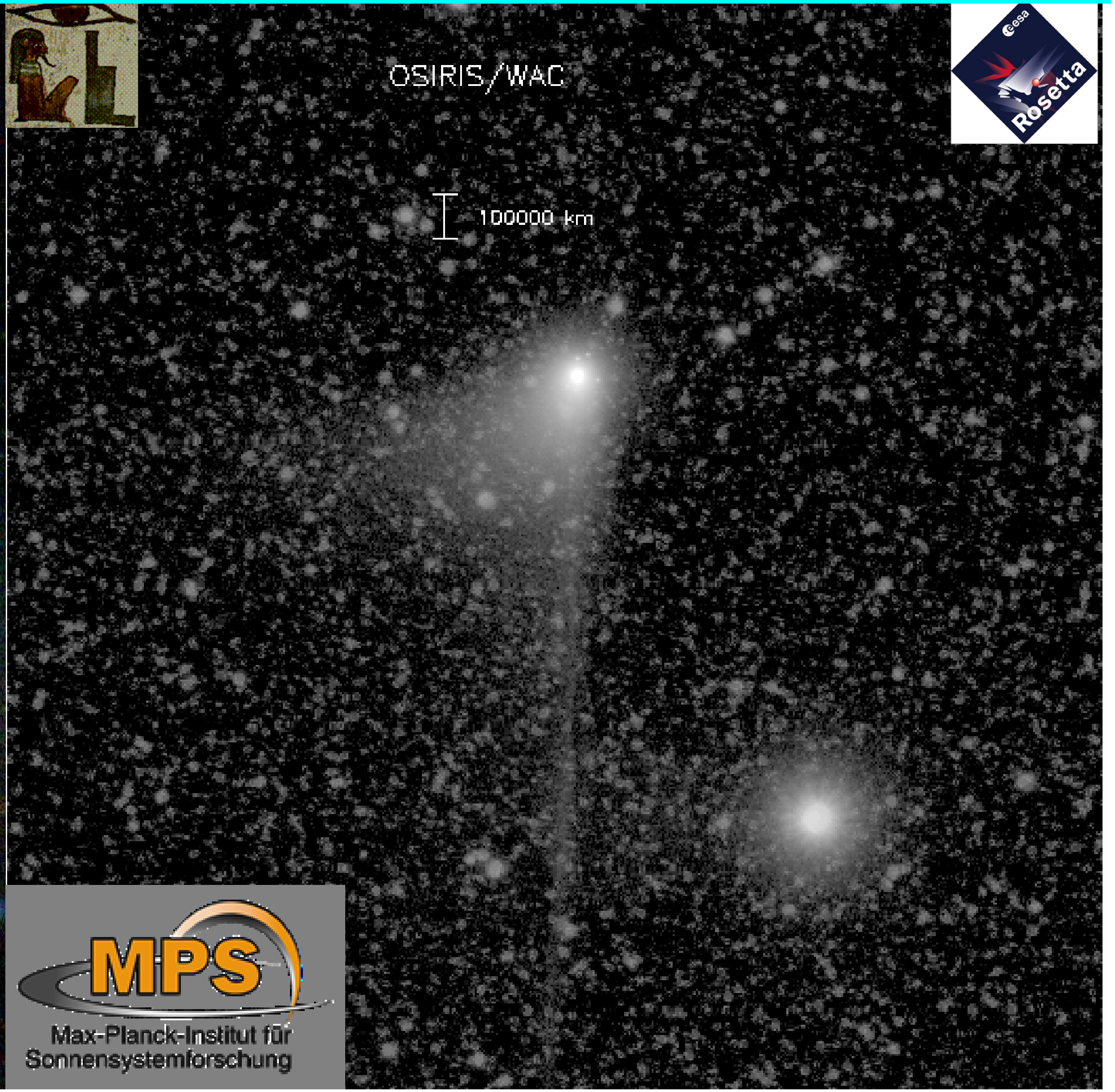
C/2002 T7 (LINEAR) on 30 April 2004

MIRO:* *Radiotelescope of 30cm:* *Mesurement of water production *(at 557GHz) (+CO, methanol, ammoniac)*

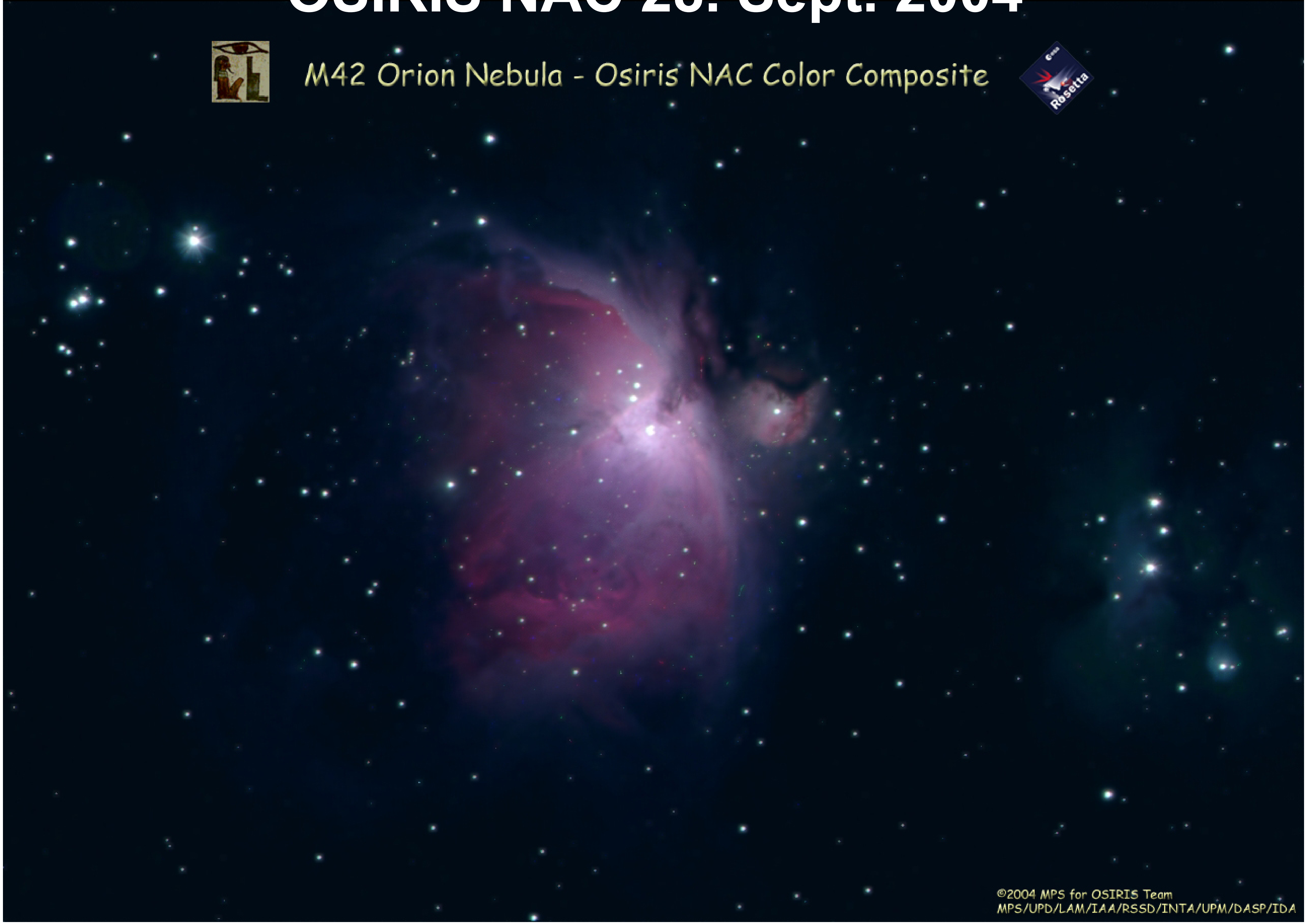


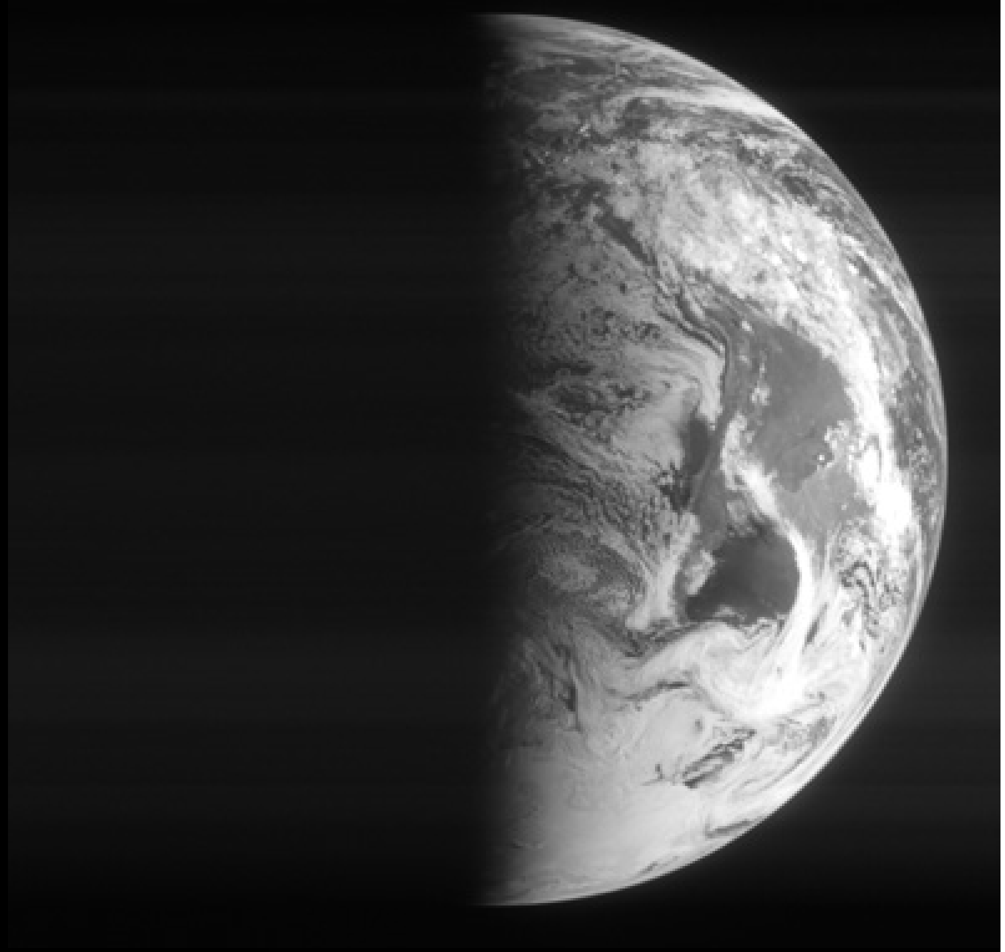
C/2002 T7: MIRO © JPL/NASA/ESA - OSIRIS © ESA/MPG/Keller

Images of comet C/2004 Q2 (Machholz) taken on 20 January 2005 by OSIRIS/Rosetta



OSIRIS NAC 28. Sept. 2004

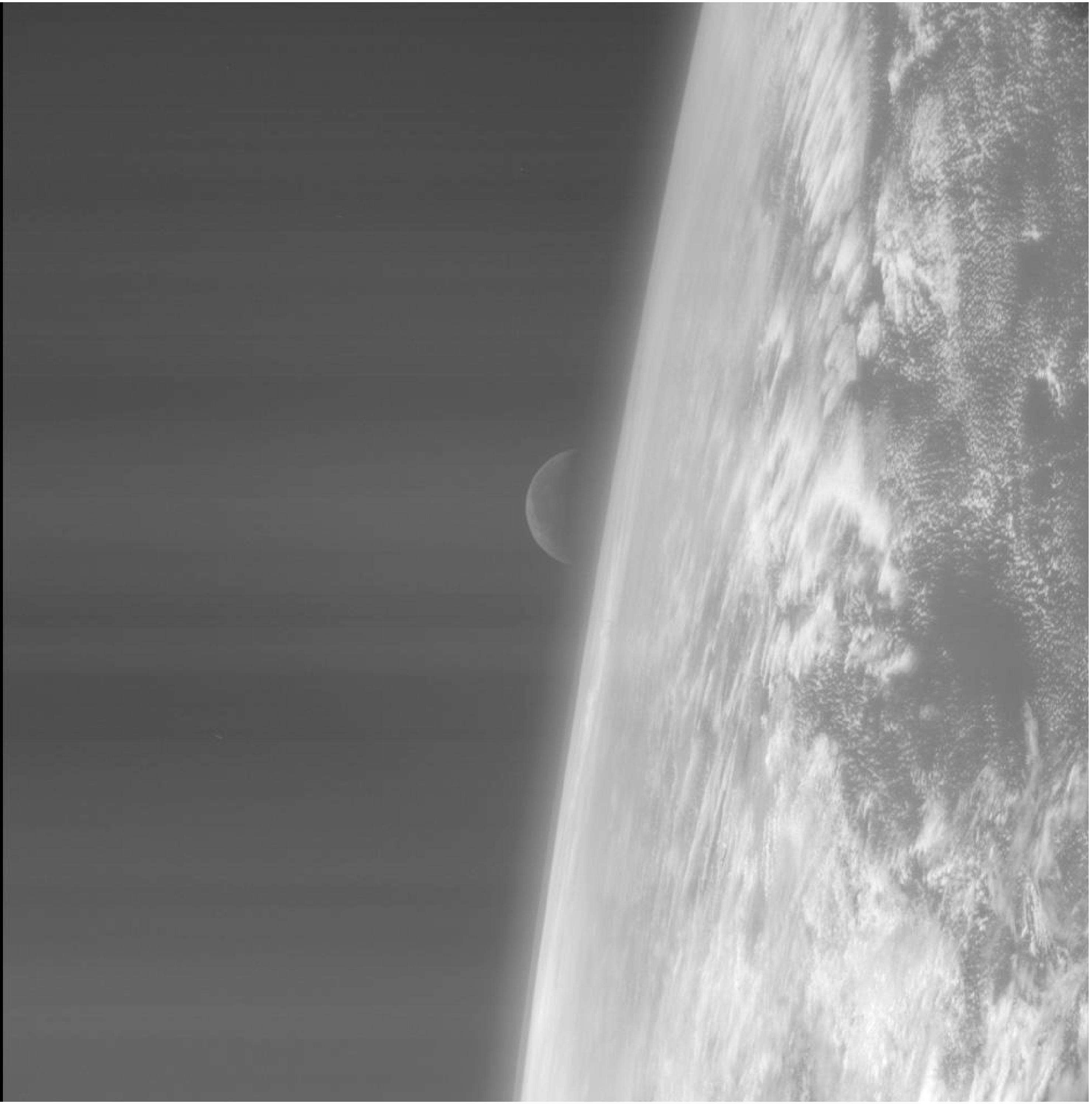


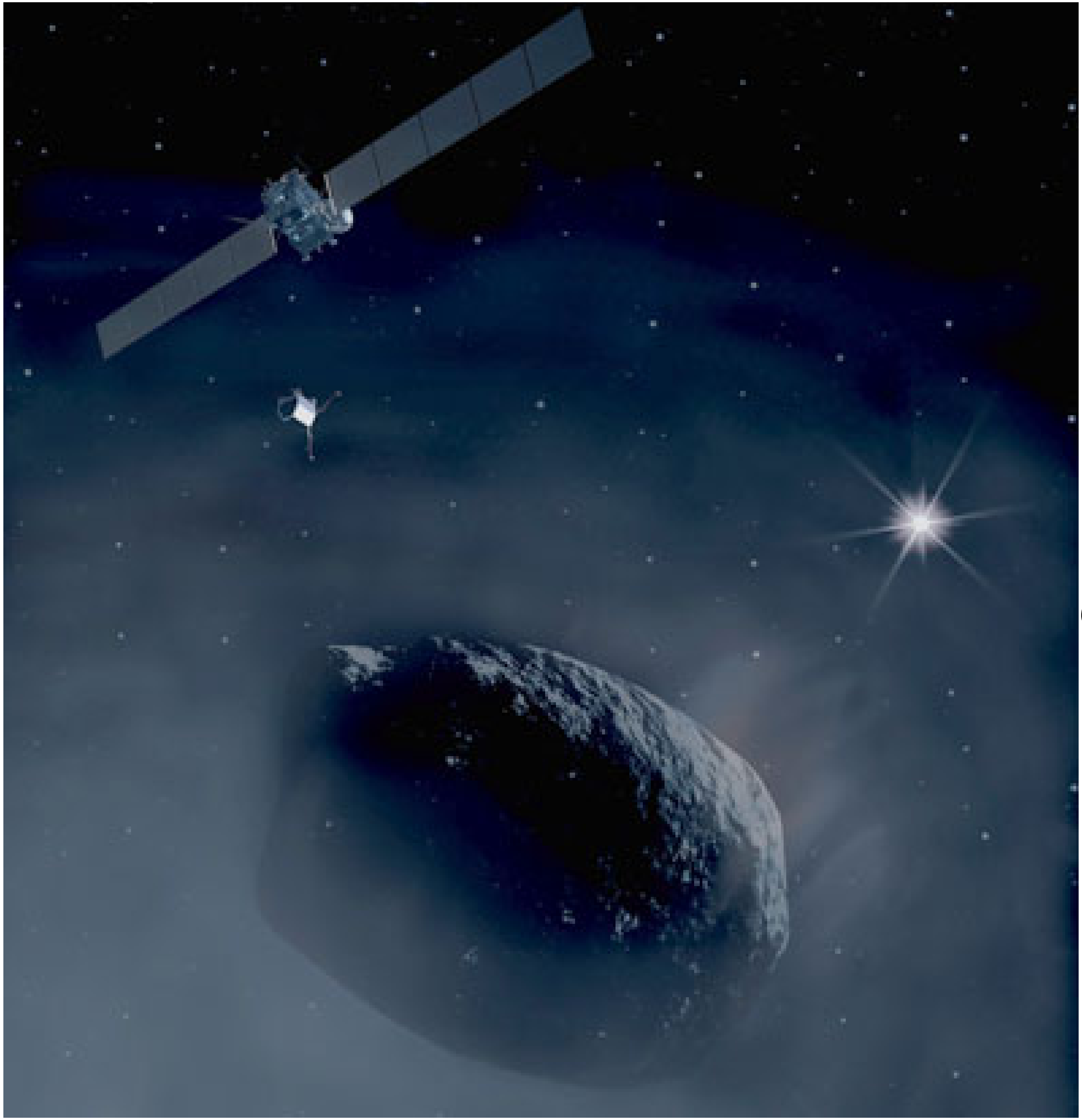


Images taken by the navigation cameras on 4 March 2005:
Moon (at 428061 km), before the flyby of Earth on 4 March at 15h10 ***Earth just after flyby on 5 March***

Flyby of the Earth by Rosetta on 4 March 2005 at 22h09:

Image taken by the navigation camera 3 min. before closest approach: the moon rises above the limb of earth





In November 2014:

Philae lands on the nucleus

67P/Churyumov-Gerasimenko

End of mission: August 2015 (at perihelion)

END