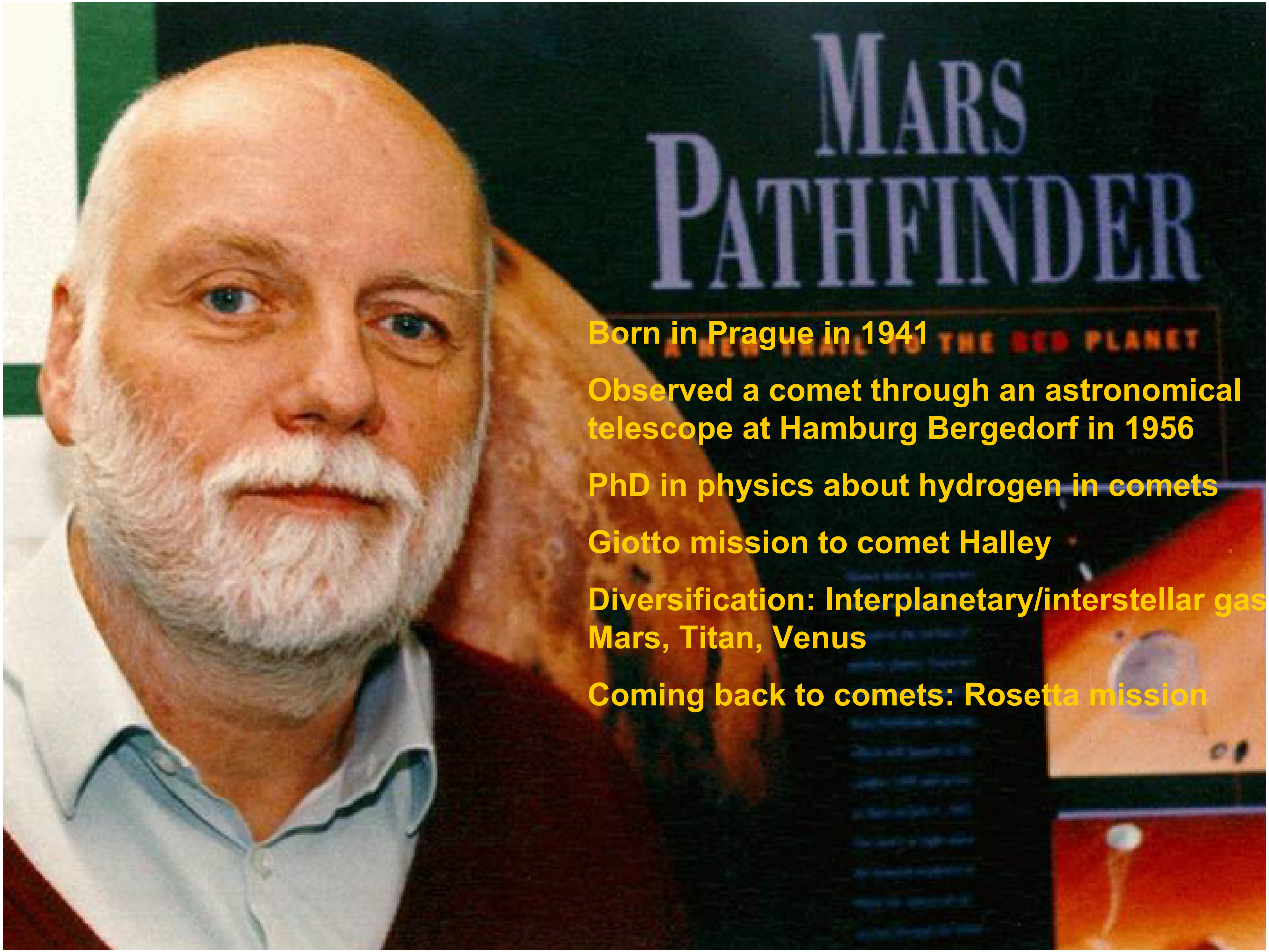
Nature and Physics of Cometary Nuclei

H. Uwe Keller

Max-Planck-Institut für Sonnensystemforschung



- Born in Prague in 1941
- Observed a comet through an astronomical telescope at Hamburg Bergedorf in 1956
- PhD in physics about hydrogen in comets
- Giotto mission to comet Halley
- Diversification: Interplanetary/interstellar gas Mars, Titan, Venus
- Coming back to comets: Rosetta mission

Overview

Comets – a short introduction

Historical look back

Sublimation, gas, and dust production

The comet Halley encounter(s)

Giotto mission as example

Consolidation of the nucleus model

a new paradigm

Statistics of nucleus sizes and albedos

Formation of nuclei

Structure – low density, porous, and low cohesiveness

Activity

Layers

Amorphous ice (?)

Temperature distribution

Overview continued

Thermal skin depth

Gas pressure, mantles, crusts

More space missions – comet Borrelly, Wild 2, and Tempel 1

Comet Borelly similar to comet Halley

The rough comet Wild 2 – craters and more craters

Interplanetary dust particles (IDP) bulding structures of nuclei (?)

Deep Impact – hitting comet Tempel 1

New results from the flyby

Results from the impact

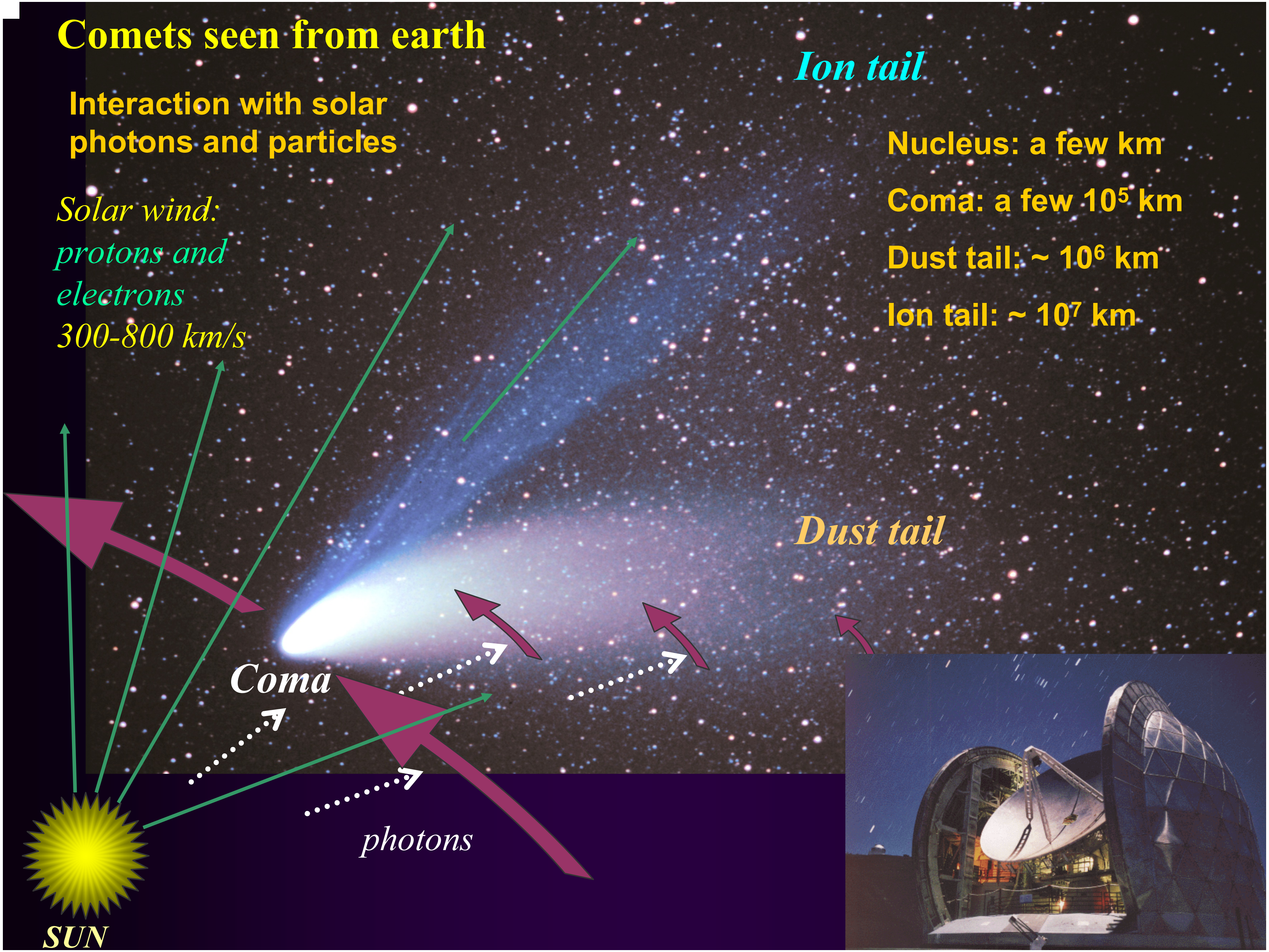
Rosetta OSIRIS observations of DI and results

Areas of activity revealed for the first time

Evolutional sequence of nuclei?

The future: Rosetta and its capabilities when it will meet comet C-G

With slides adapted from M. A'Hearn, N. Biver, D. Brownlee, W. Huebner, R. Speith, N. Thomas


Comets seen from earth
Interaction with solar photons and particles
Solar wind:
protons and electrons
300-800 km/s
Ion tail
Nucleus: a few km
Coma: a few 10⁵ km
Dust tail: ~ 10⁶ km
Ion tail: ~ 10⁷ km
Dust tail
Coma
photons
SUN

Comets

- The appearance near the sun (coma, dust and plasma tails) is grandious but the proper comet is its nucleus
  – Composed from material of the early solar system, mainly silicate dust, organic material, and water ice (refractories and volatiles)
  – Study of coma and dust to infer information about the nucleus properties and composition
  – Only recently cometary nuclei can be studied directly (with space missions)

Meteors and Comets

Leonid shower early 19^{th} century

Giovanni Schiaparelli connected meteor showers with comets

Perseids with comet Swift Tuttle in 1862

As a consequence comets were thought to be clumps of dust (sand bank model)

Whipple (1950/51) postulated a solid nucleus: conglomerate icy nucleus

based on presence of non-gravitational forces changing the orbital period by rocket effect of subliming gas

Supported by large production rates of water (UV obs. of H) and dust

Nucleus detected 1986 (comet Halley)

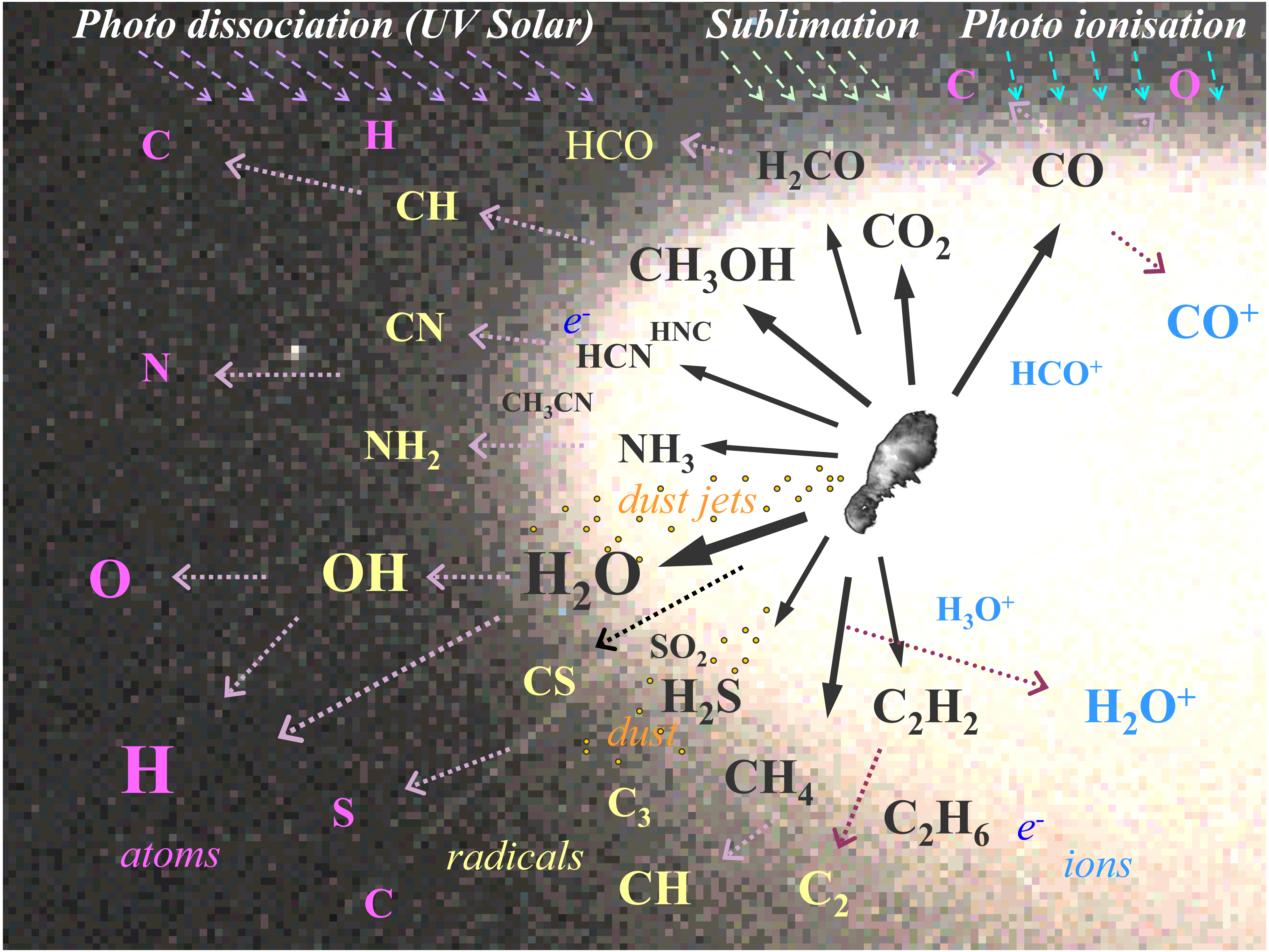
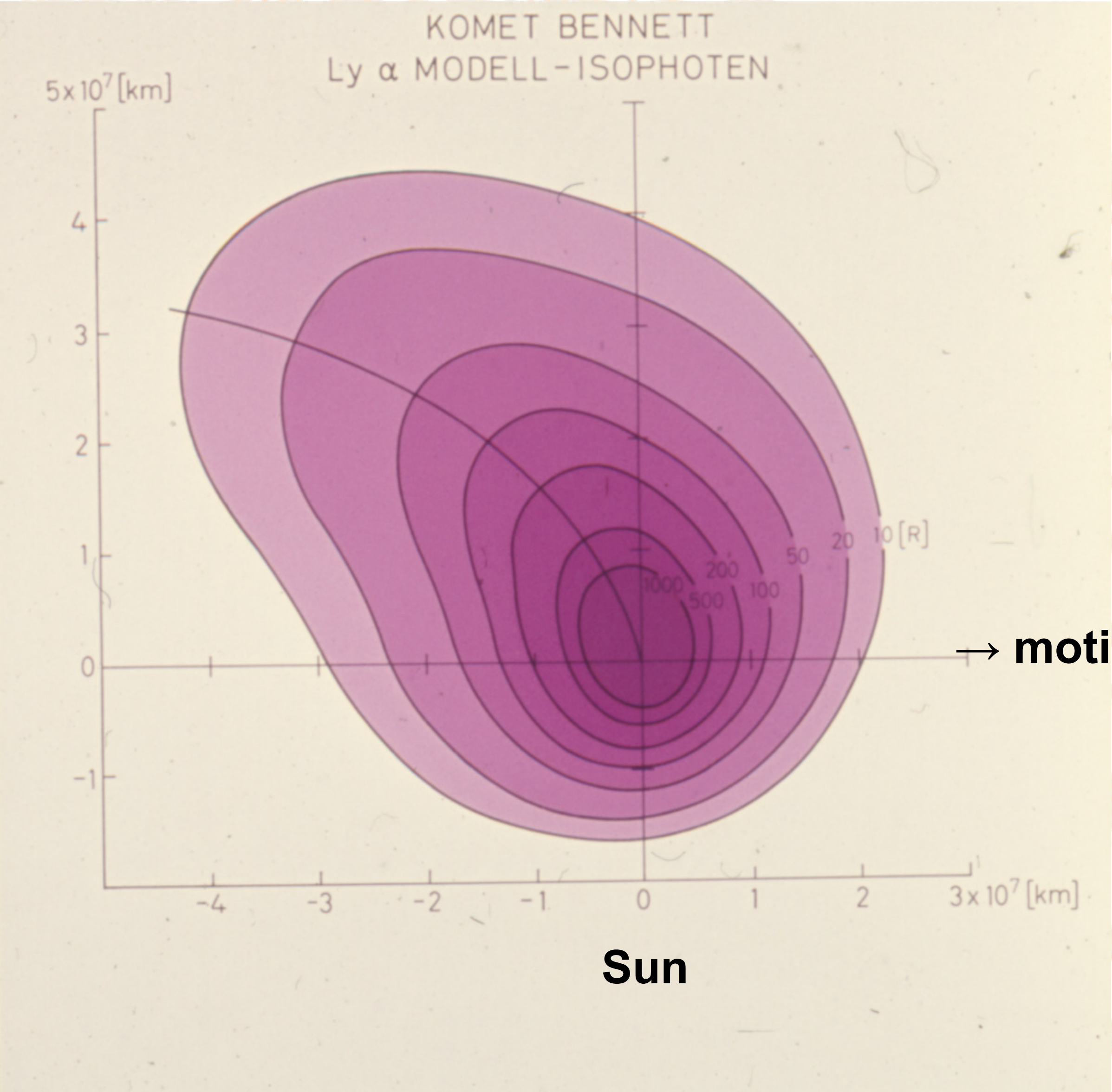


Photo dissociation (UV Solar)
Sublimation
Photo ionisation
C
H
HCO
H_2CO
CO
C
O
CH
CO_2
CH_3OH
CO+
CN
e^-
HNC
HCN
N
HCO+
CH_3CN
NH_2
NH_3
dust jets
O
OH
H_2O
H_3O^+
SO_2
CS
H_2S
C_2H_2
H_2O^+
H
dust
CH_4
S
C_3
C_2H_6
e^-
atoms
radicals
ions
C
CH
C_2

Ly α Isophotes - Model



→ motion

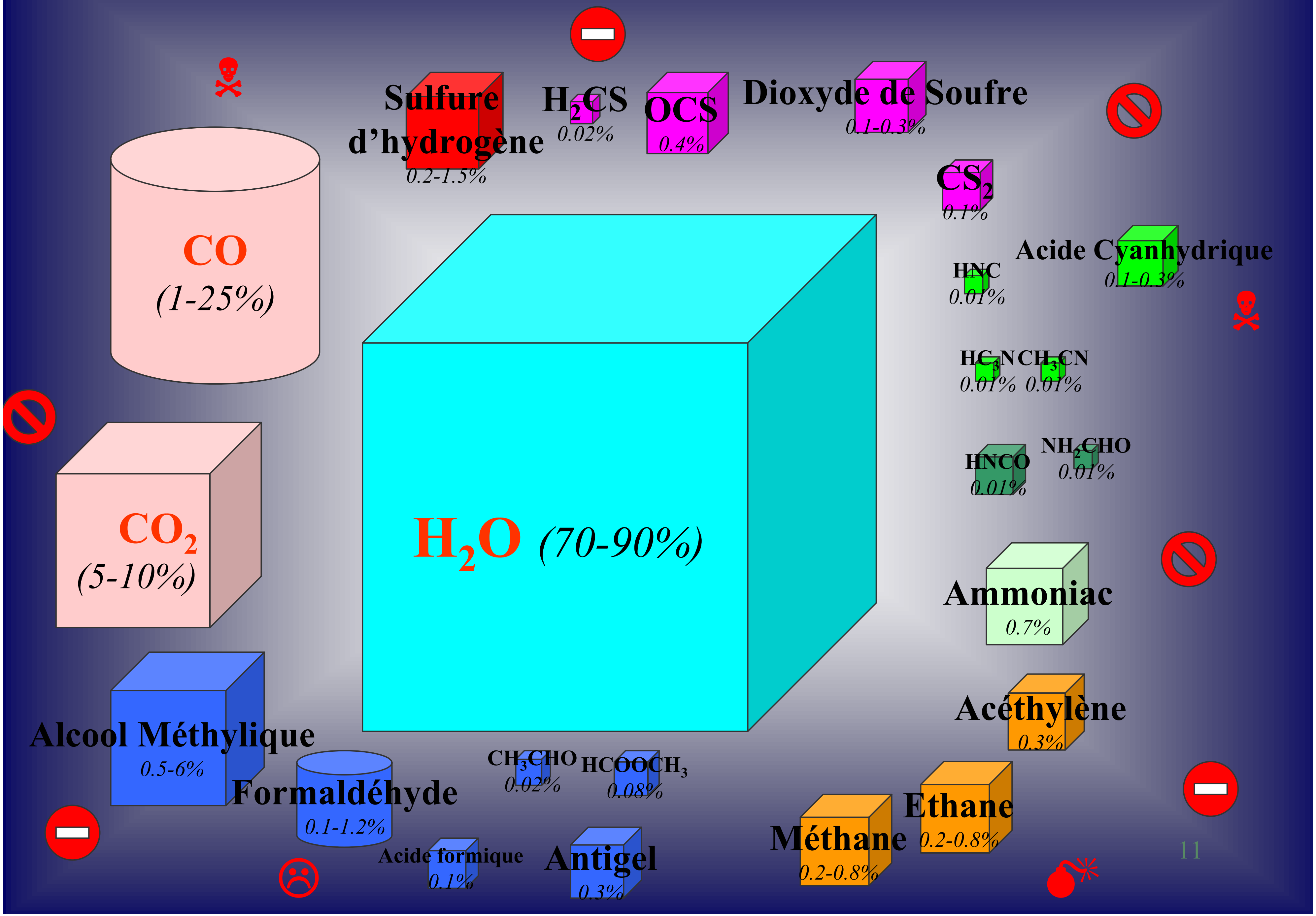
Sun

Hydrogen Coma of Comet Bennett

Hydrogen Coma

- Hydrogen atoms are created by dissociation of water molecules and subsequently of OH
- Excess energy provides large velocities between 8 and 20 km s^{-1}
- Very extended 10^7 km, to be observed in UV via Lyman alpha line, the resonance line of H at 121,6 nm
- The first strong evidence that water is the dominant volatile of the nucleus
- OH difficult to observe from ground (atmospheric absorption)

Molecules identified in the gas comae of comets



Sublimation Equilibrium

$$F_o(1 - A_0)\, r^{-2} \cos\theta = \sigma\, \varepsilon\, T^4 + Z(T)\, L(T)$$

$$Z = p\,(2\,\pi\, m\, k\, T)^{-1/2}$$

F_o = solar flux at 1 AU

A_0 = visible albedo of nucleus

ε = emissivity ~$(1 - A_{IR})$

σ = Stephan's law constant

k = Boltzmann's constant

L = latent heat of sublimation

Z = production rate of gas by sublimation of its ice

p = vapour pressure of subliming ice

Gas Production Rate Variations

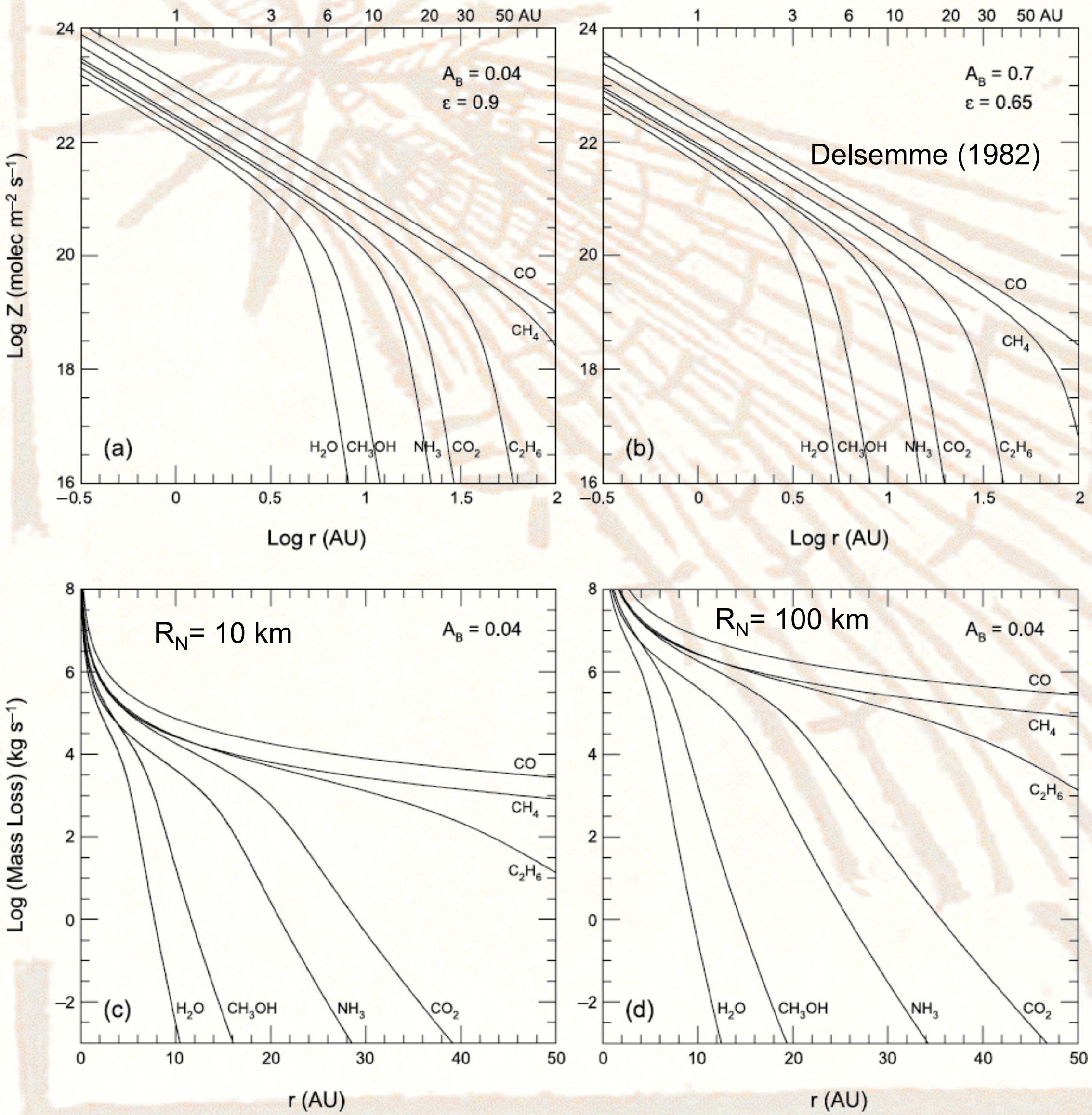
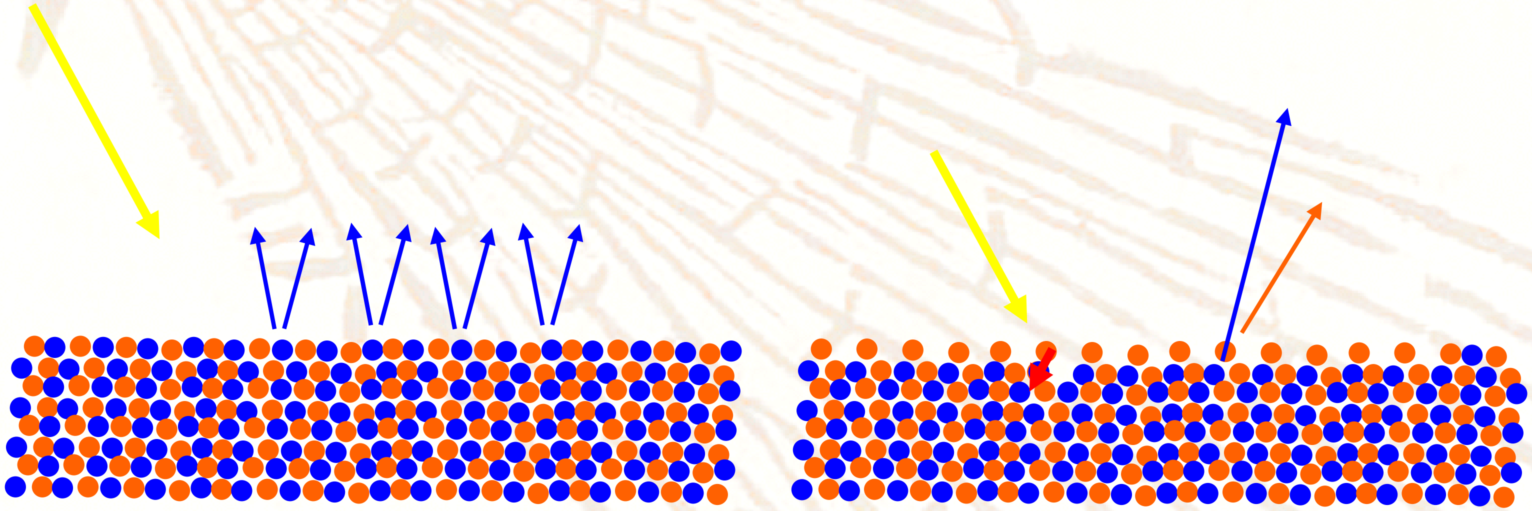


TABLE 1. Temperature regimes for onset of comet activity.

T (K)	Process	r (AU)
5	H_2 sublimation	>3000
22	N_2 sublimation	160
25	CO sublimation	120
31	CH_4 sublimation	80
35–80	Ice I_ah anneals	60–10
38–68	I_ah converts to I_al	55–15
44	C_2H_6 sublimation	40
57	C_2H_2, H_2S sublimation	24
64	H_2CO sublimation	20
78	NH_3 sublimation	14
80	CO_2 sublimation, I_al anneals	13
91	CH_3CN sublimation	9
95	HCN sublimation	8
99	CH_3OH sublimation	8
70–120	Ice I_al anneals	18–
90–160	Ice I_al → I_c phase change	11–
160	Ice I_c → I_h phase change	
180	Ice I_h sublimation	

Meech and Svoren (2004)

Lift-Off



Particle Lift Off

$$m_g \frac{d^2r}{dt^2} = -\frac{GMm_g}{r^2} + F_{drag}$$

$$N(r) = \frac{Q}{4\pi R_N^2 v_{th}} \left[\frac{R_N}{r}\right]^2$$

$$a_{crit} = \frac{9\mu m_H Q v_{th}}{64\pi^2 \rho_g \rho_N R_N^3 G}$$

μ is atomic weight of gas (H_2O)

Decimeter sized particles at high activity < 1 AU

Optically significant grains (0.01 to 1 μm) can be lifted off by

H_2O at r_h > 5 AU

CO_2 at r_h > 16 AU

Early Days

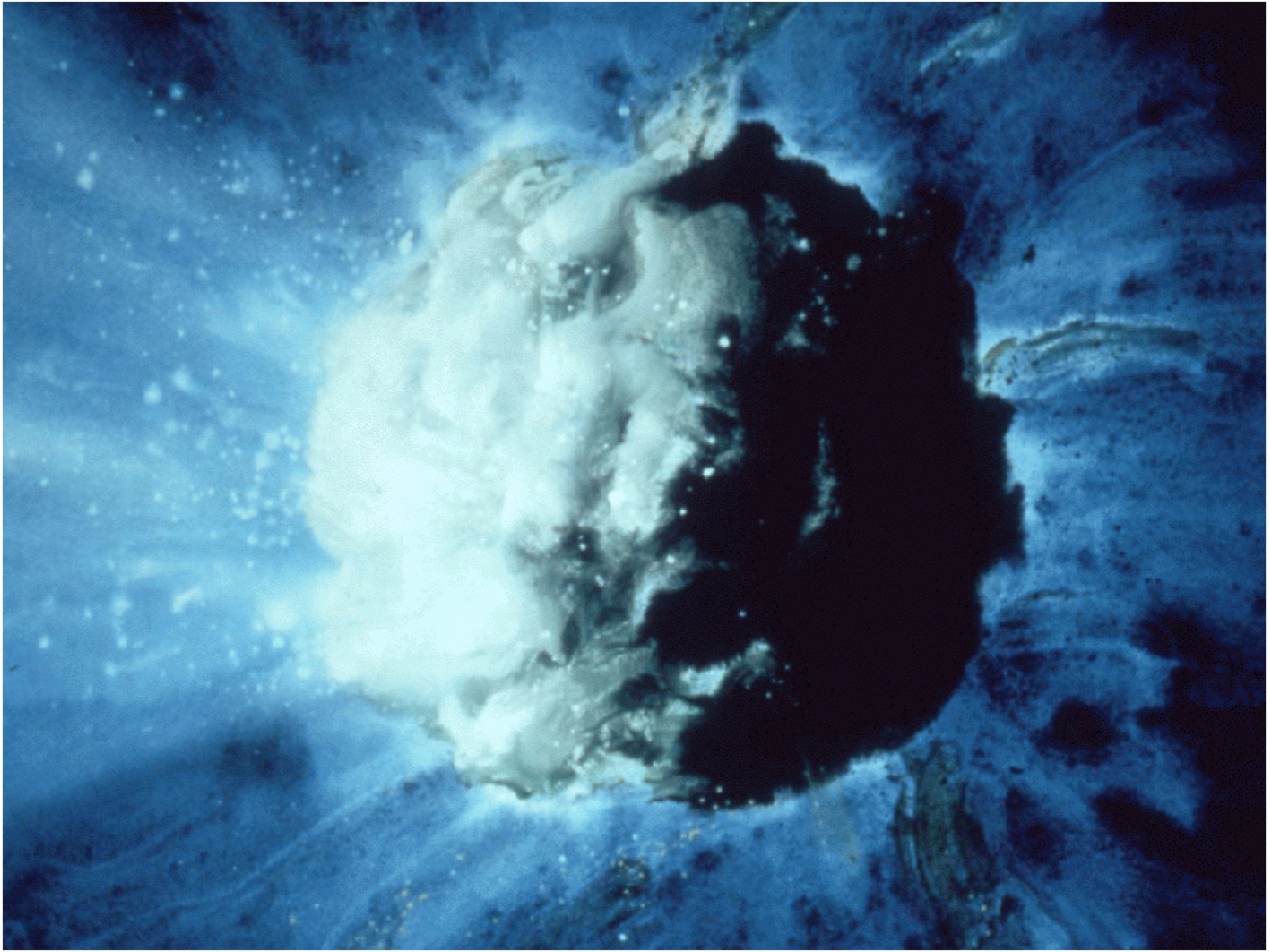
Brightness observations at large heliocentric distances (Roemer)
=> 0.5 km < R_N < 10 km (B α AR_N^2)
Orbit determination – non-gravitational forces (Whipple)
Determination of gas production rates (UV) => Halley type object:
R_N > 3 km
Determination of dust production rates and structures (Finson and Probstein, Sekanina) => dust to gas ratio, isotropic dust production
The combination of brightness obs. and water (hydrogen) production rates led to erroneous results of albedos > 0.6 (Delsemme and Rud)
Spectral photometry at large heliocentric distances (Cruikshank and co-workers)
=> dark and large
Radar observations => cloud of large boulders
Observations that do not resolve the nucleus cannot separate the size of the nucleus from its scattering properties
Second observational method is required to separate A from R:

- **Production rate of gas.**
- **Infrared observations to determine the size.**

Albedo and Nuclear Radius for Two Comets

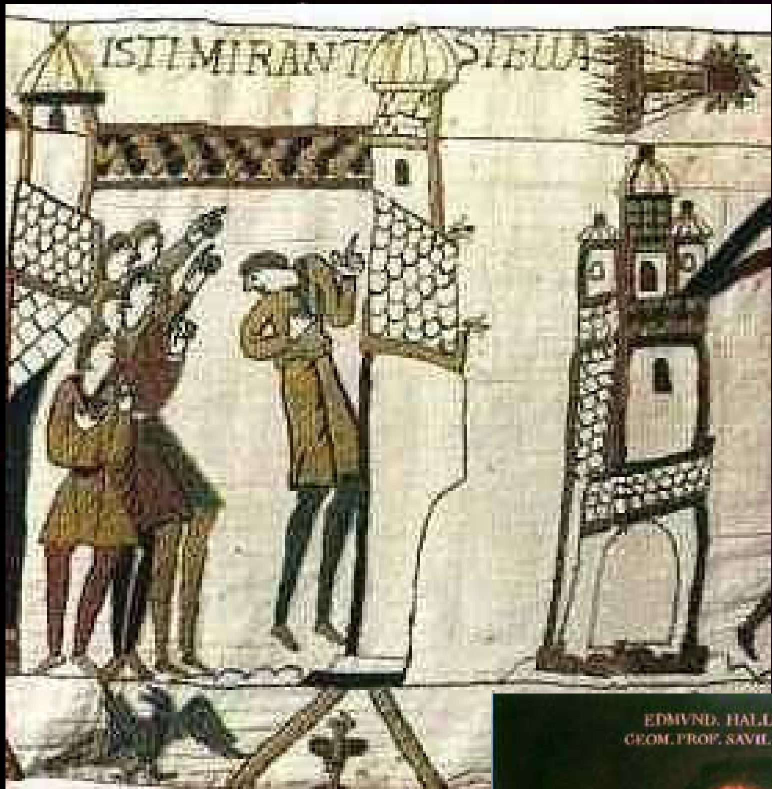
Comet	Bond Albedo *A*	Nuclear Radius *R*
Tago Sato Kosaka	0.63 ± 0.13	2.20 ± 0.27 km
Bennett	0.66 ± 0.13	3.76 ±0.46 km

Delsemme and Rudd (1973)



Halley's Comet,

First observed in China 240 BC

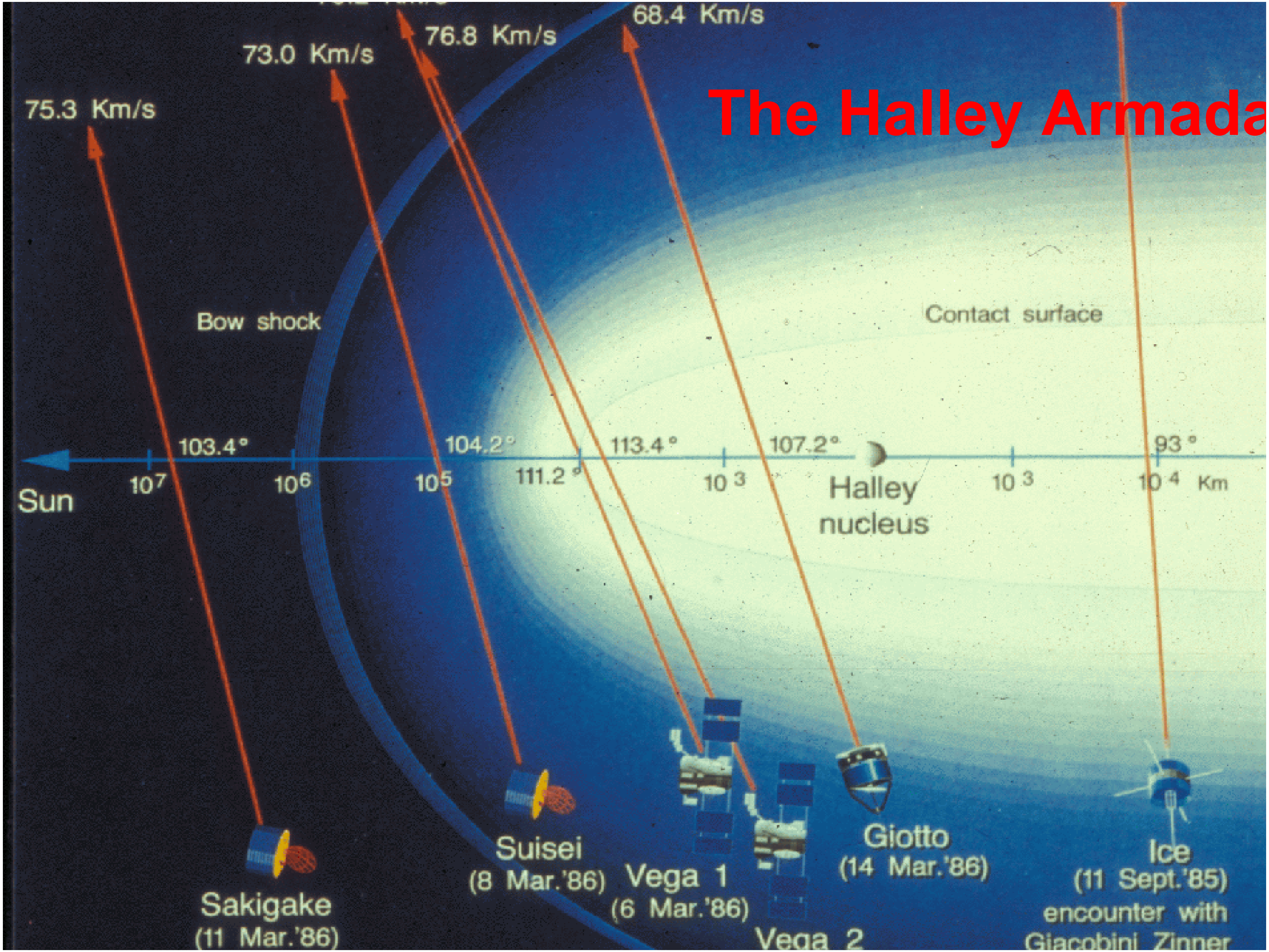


1066 Bayeux Tapestry

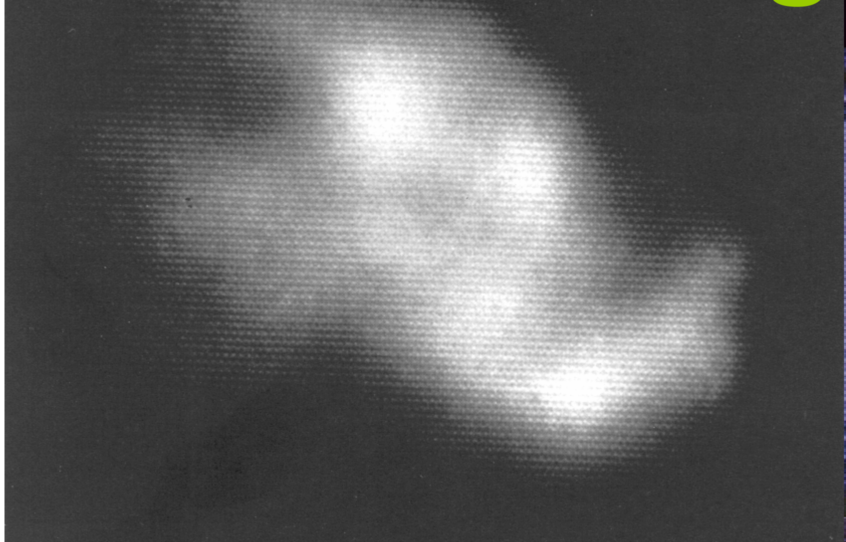
1305, Giotto di Bondone

1705, Edmond Halley

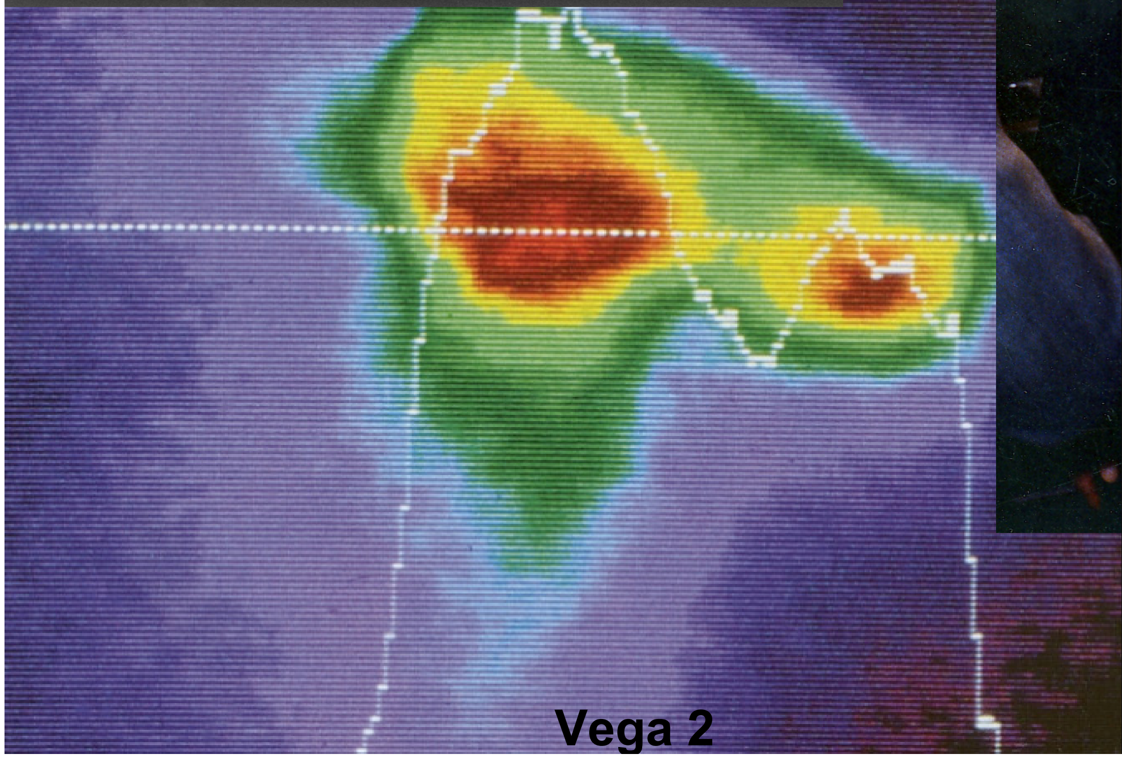
The Halley Armada



The Vega Encounters



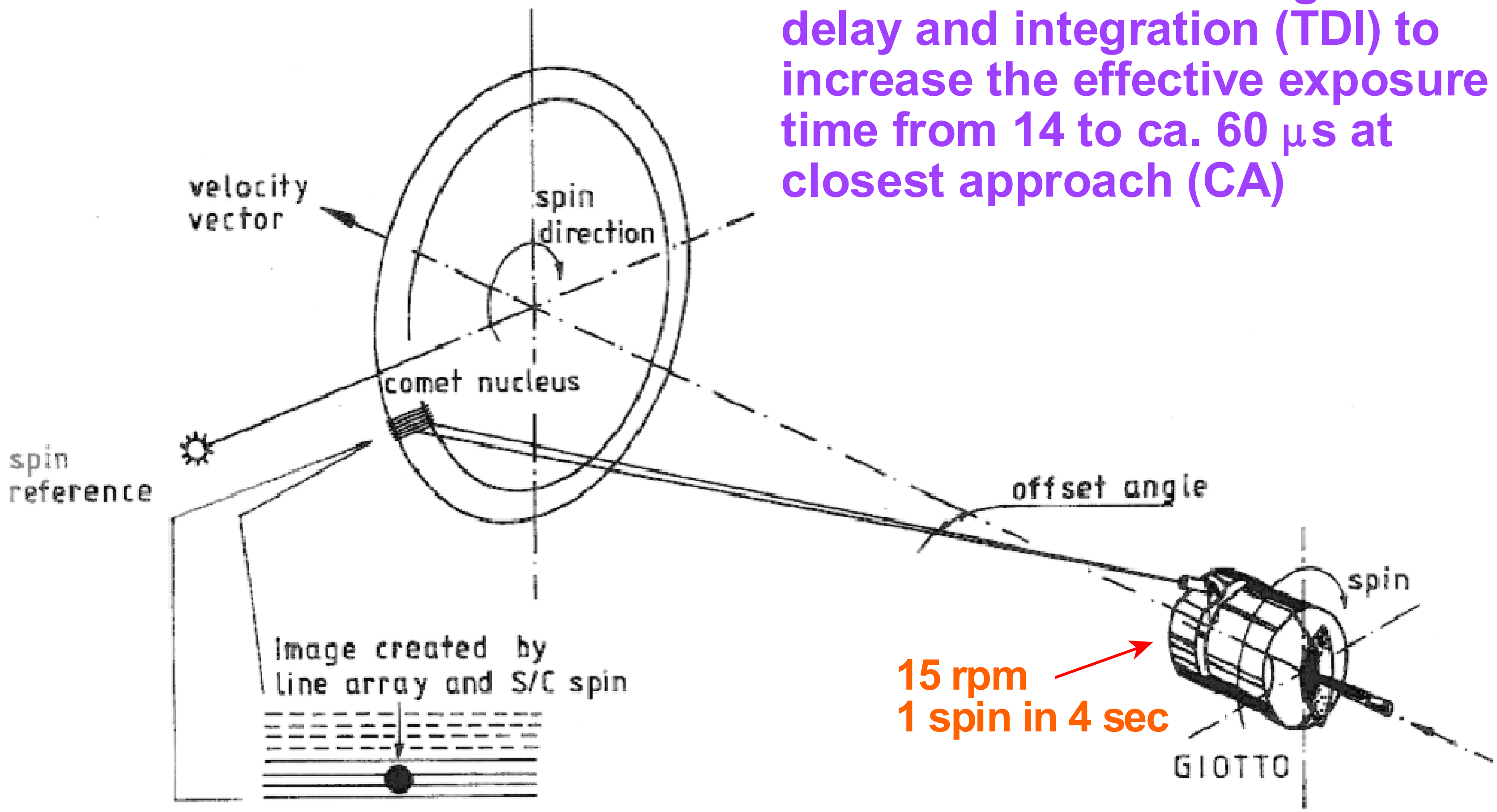
Vega 1



Vega 2

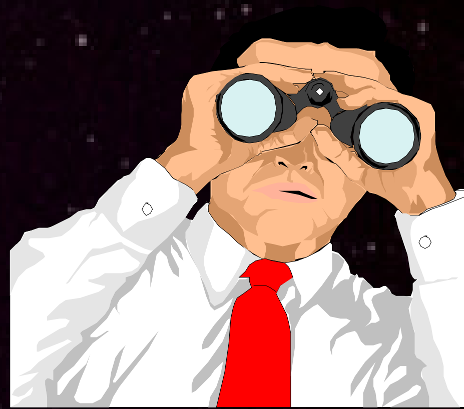
Vega 2

Line scan camera using time delay and integration (TDI) to increase the effective exposure time from 14 to ca. 60 μs at closest approach (CA)

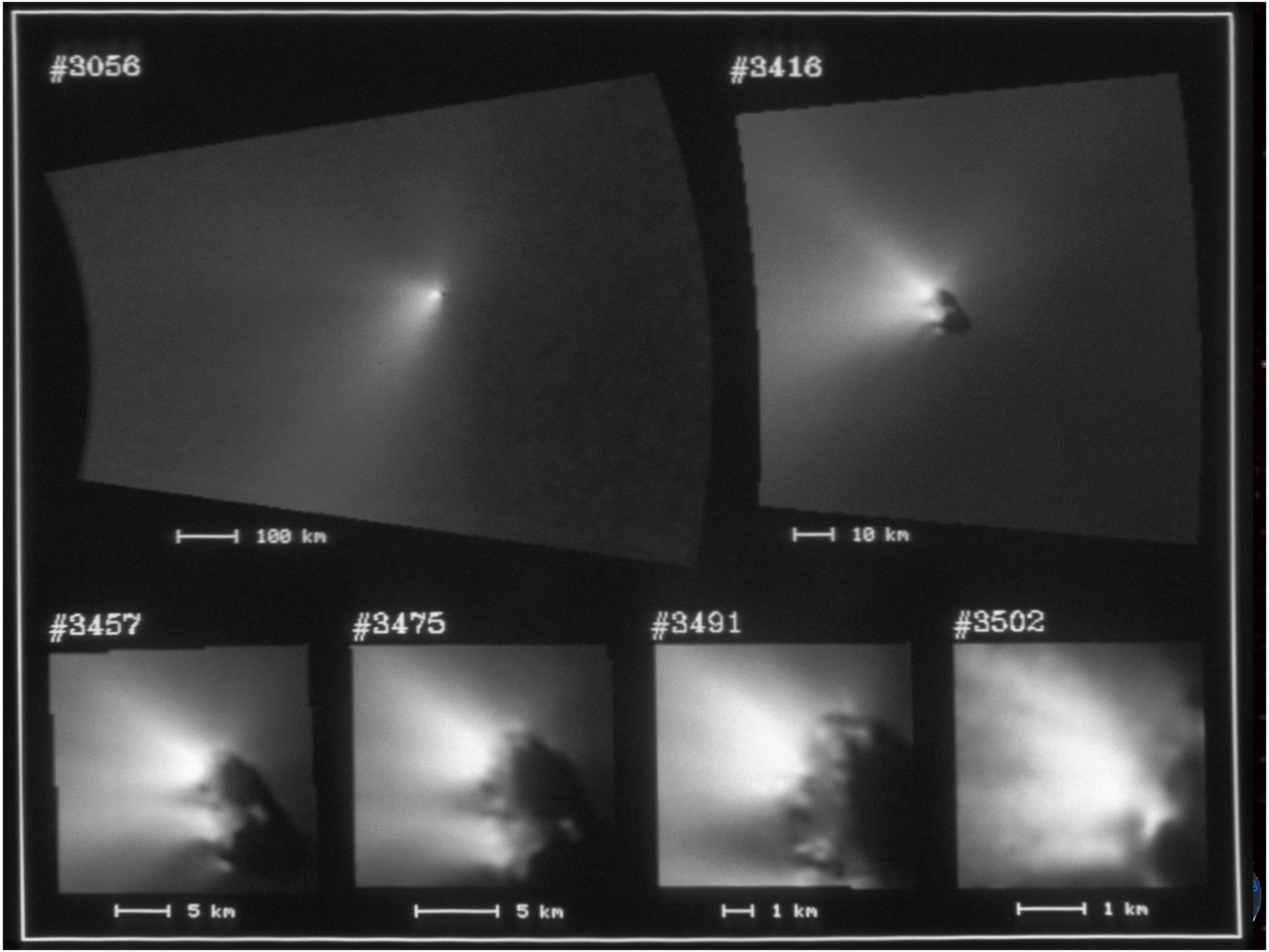


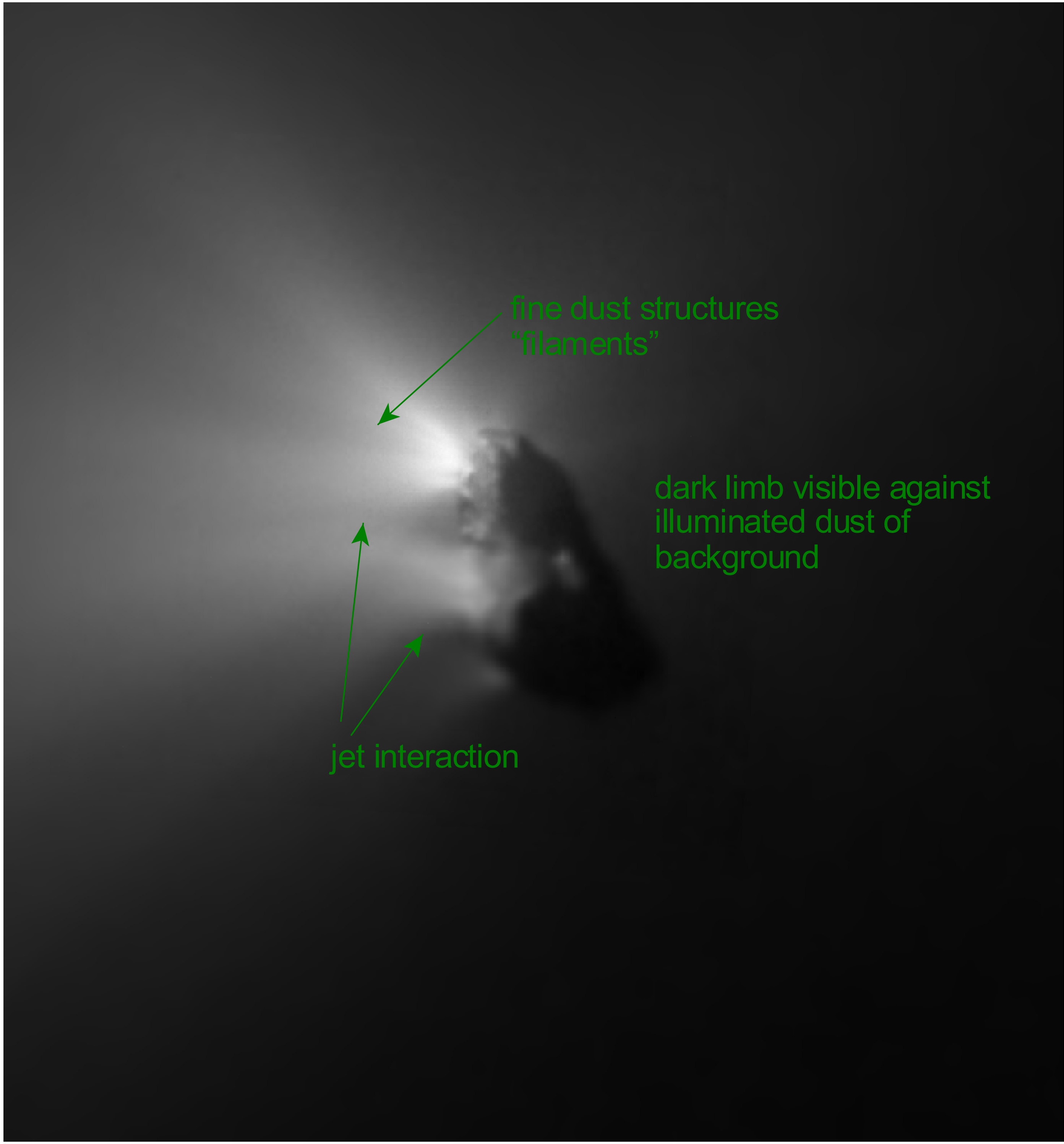
HMC Capabilities

Sit on a merry-go-round, look through binoculars with a field of view as small as the moon and try to observe a star on every rotation!



Taking an image of comet Halley's nucleus with HMC is like taking a portrait (75 x 75 m^2) of the pilot of a Concorde passing by in 400 m distance with twice the speed of sound (2200 km h^{-1})!


#3056
100 km
#3416
10 km
#3457
5 km
#3475
5 km
#3491
1 km
#3502
1 km

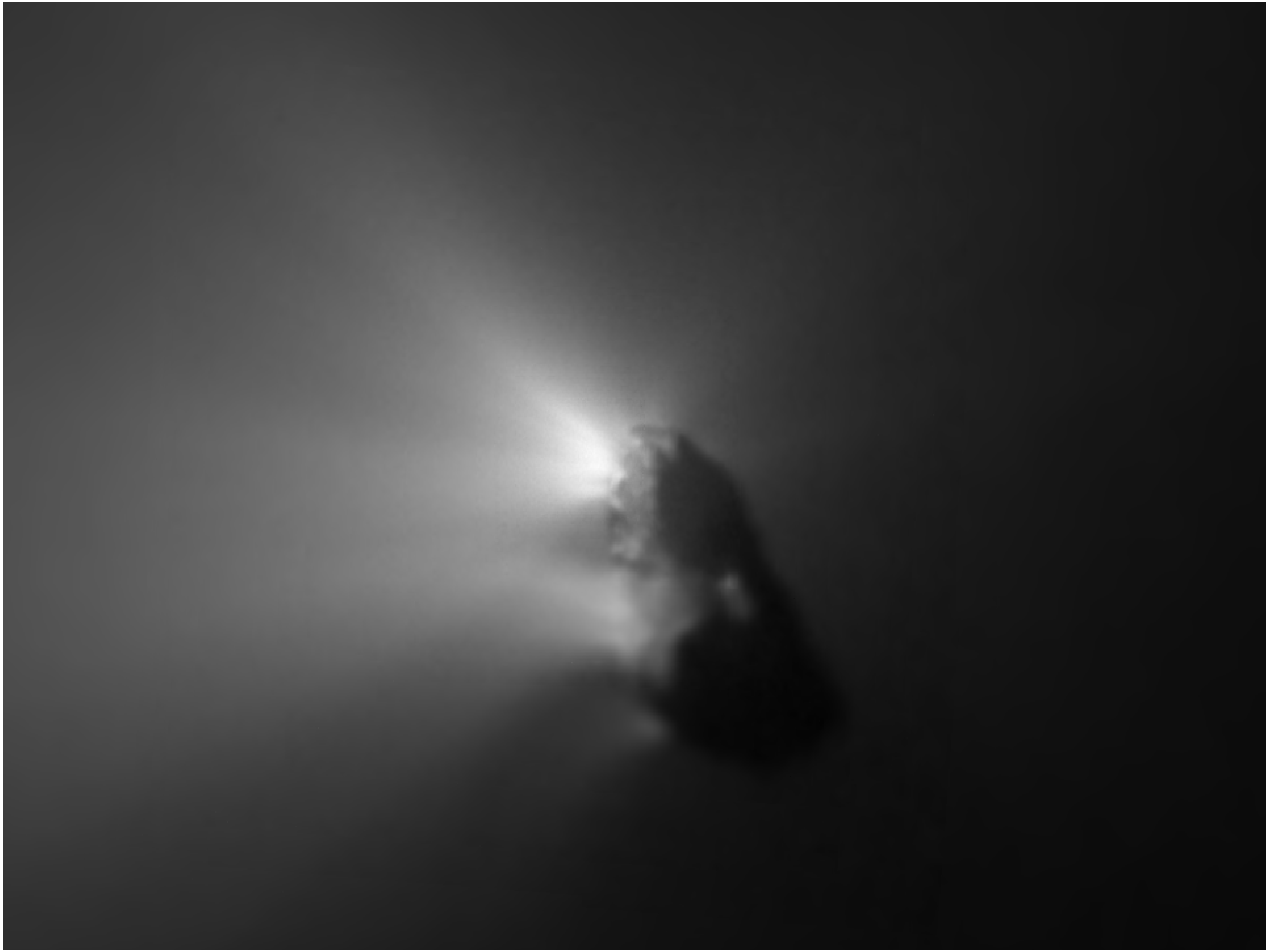


Composite image of comet Halley

68 images are combined

Scale changes from 500 to 49 m px^{-1}

Slight change of phase angle (< 13° for the last few images)

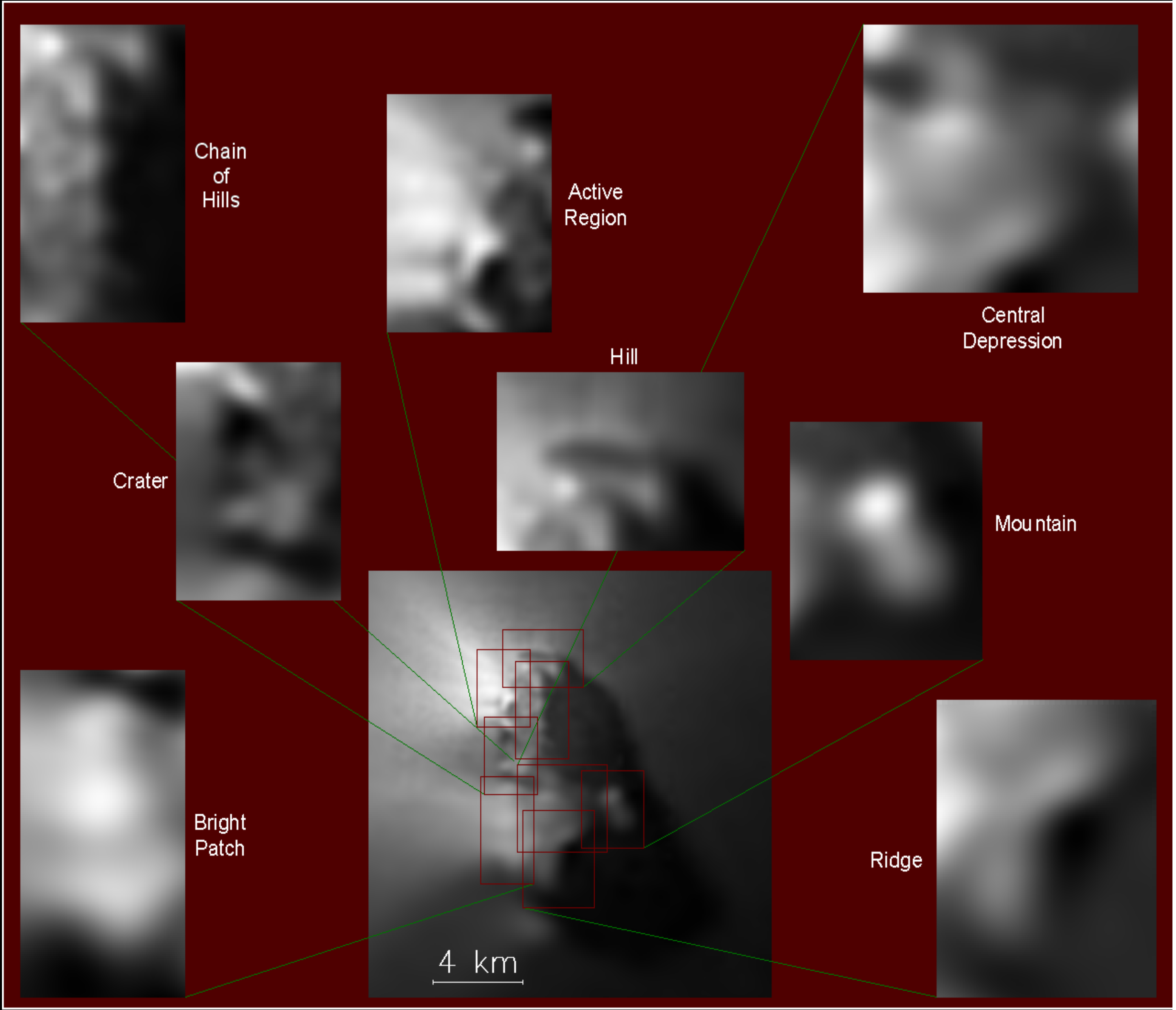


Comet Halley

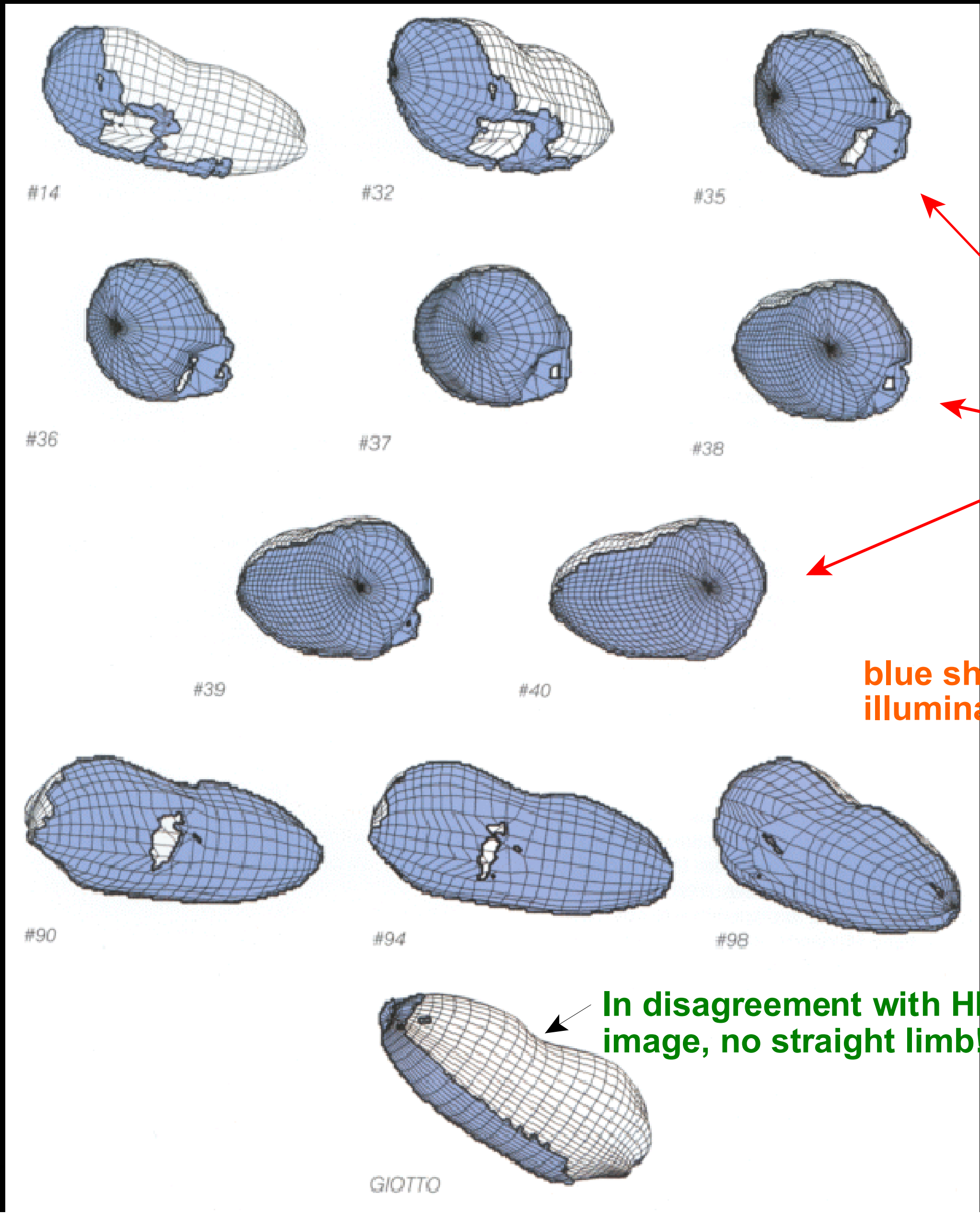
Elongated
15.3 x 7.2 x 7.2 km^3
Very dark albedo
No impact craters
Activity limited

Surface morphology: (limited information)
- smooth terrains
- hilly areas
- bright areas
- large outcroppings

Topographic roughness: 0.5 to 1 km



Nucleus Shape 3 D



Reconstruction of the shape of the nucleus of comet Halley
(from Szegö et al. 1995)

Size 15.3 x 7.2 x 7.2 ± 0.5 km

VEGA 1

blue shading indicates illuminated area

VEGA 2

In disagreement with HMC image, no straight limb!

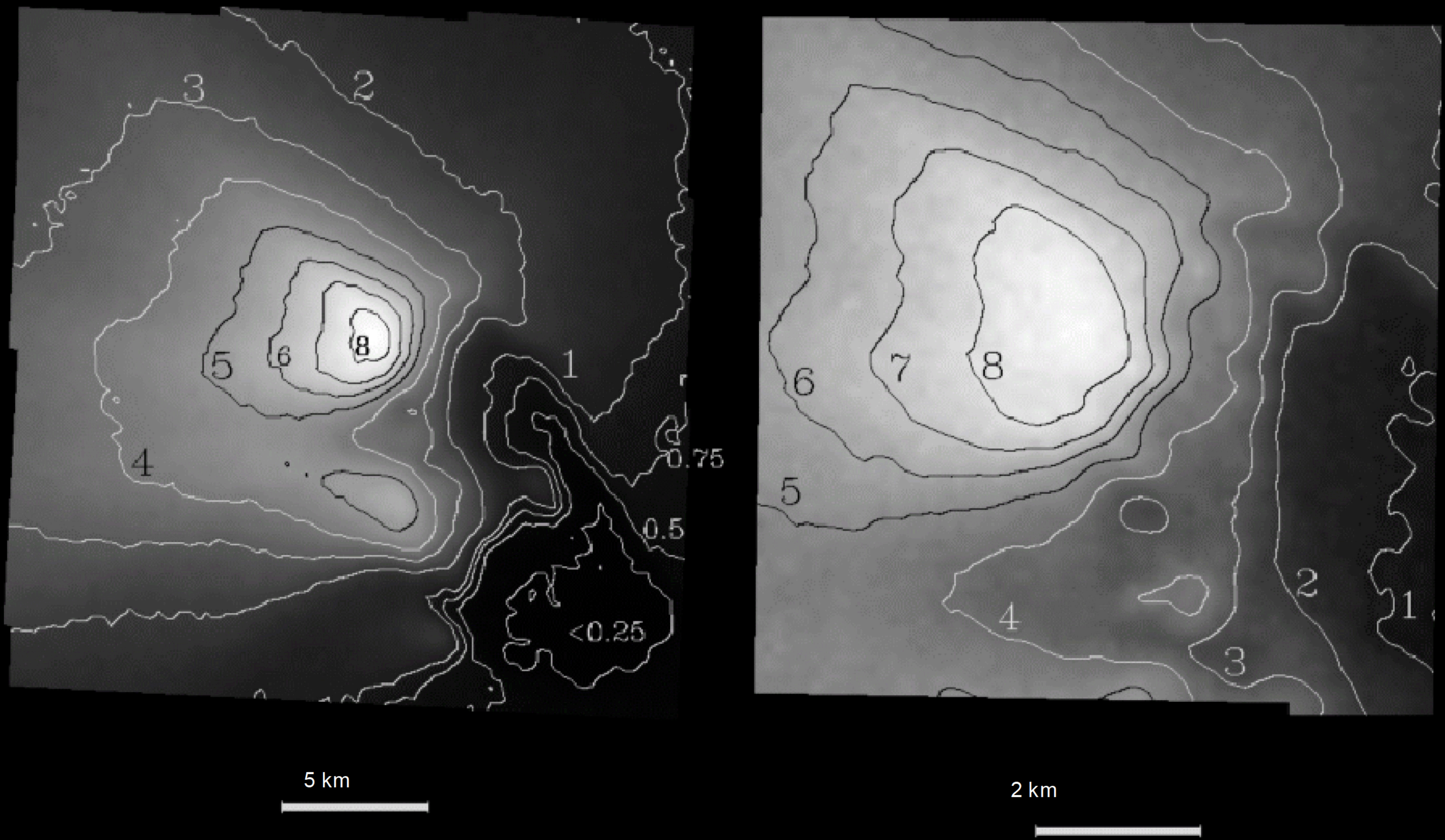
GIOTTO

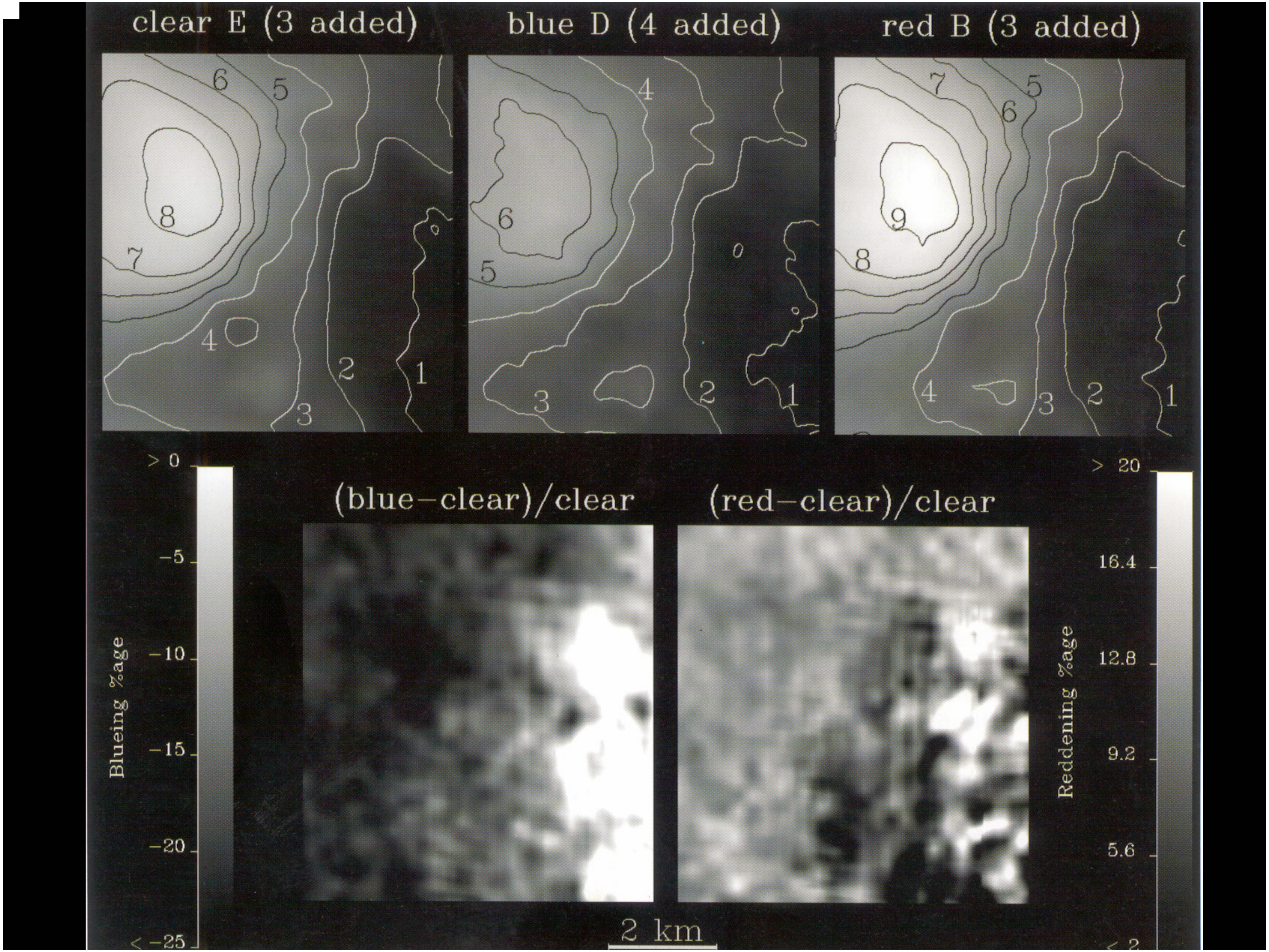
Physical Parameters of Comet Halley's Nucleus

	Comet Halley's Nucleus	
Projected shape (full outline)	max.. length 14.2±0.3 km	HMC
	max.. width 7.4±0.2 km	
Model body	15.3 x 7.2 x 7.22 km^3	E. Merényi et al. (1990)
Volume	420±80 km^3 tri-axial ellipsoid 365 km^3 model body	E. Merényi et al. (1990)
Surface	294 km^2	
Topography	mountains, ridges, terraces	HMC
Activity	concentrated in 3 major areas, ≤ 10% of surface	
Geometric albedo	0.04+0.02-0.01	R.Z. Sagdeev et al. (1986)
Colour (reddish)	reflectivity gradient: 6 ± 3% $(100nm)^{-1}$ from 440 to 810 nm	N. Thomas and H.U. Keller (1989)
Mass	1-3 · 10^{14} kg	from non-gravitational forces H. Rickman et al. (1987)
Density	550 ± 250 km m^3	H. Rickman et al. (1987)
Rotation (complex)	spin period 2.84 d 7.1 d around long axis 3.7 d nutation	M.J.S. Belton et al. (1991)

Clear filter images 3457 and 3491

Contour levels in units of reflectivity x 1000
Phase angle 107°

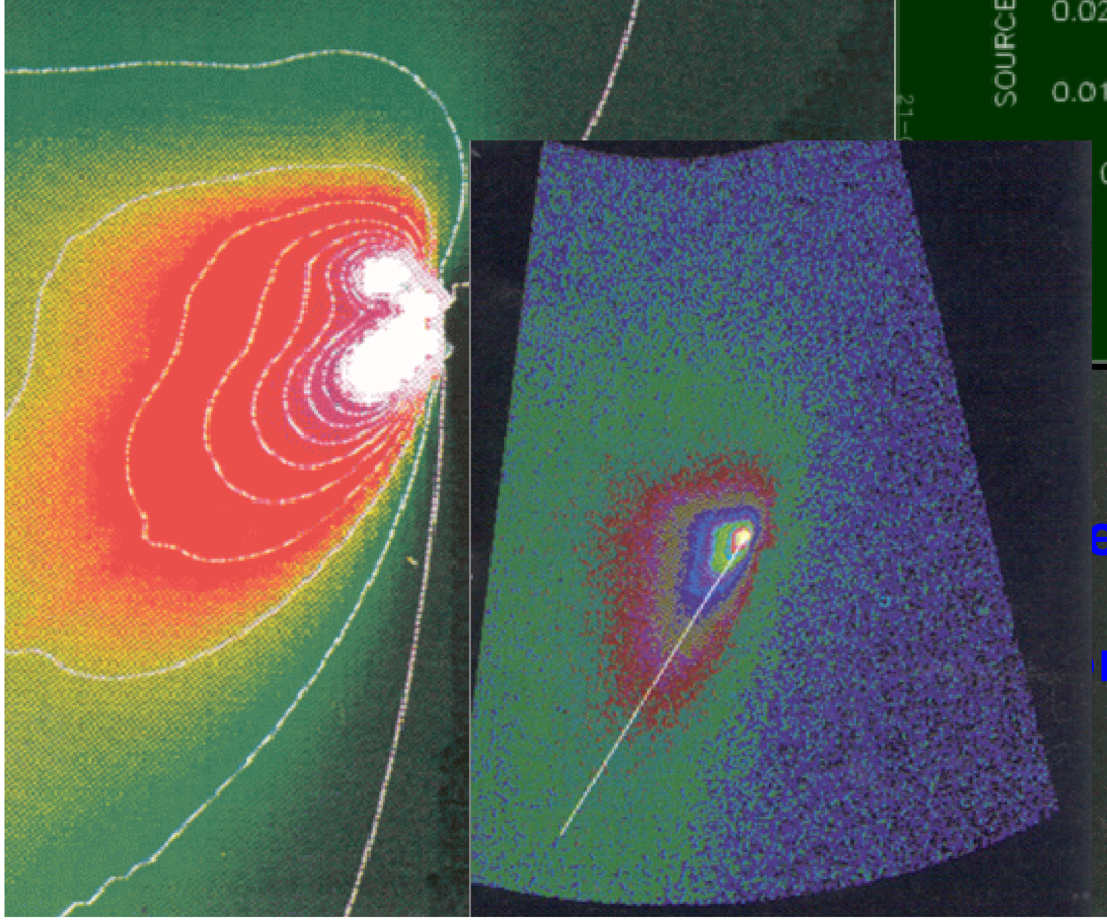


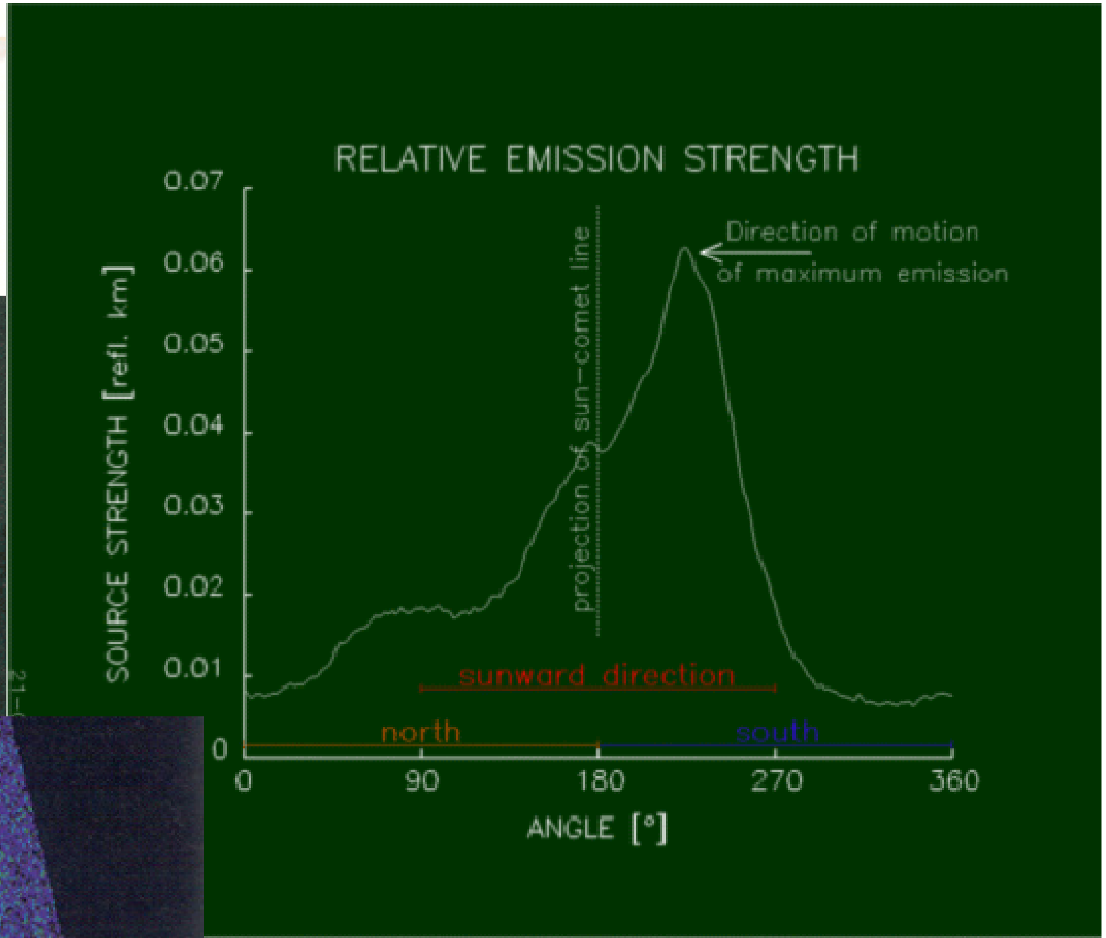


clear E (3 added)
blue D (4 added)
red B (3 added)
(blue−clear)/clear
(red−clear)/clear
Blueing %age
Reddening %age
> 0
−5
−10
−15
−20
< −25
> 20
16.4
12.8
9.2
5.6
2 km

Global dust distribution

Modelling the dust distribution around the nucleus with 3 jets of Gaussian cross sections



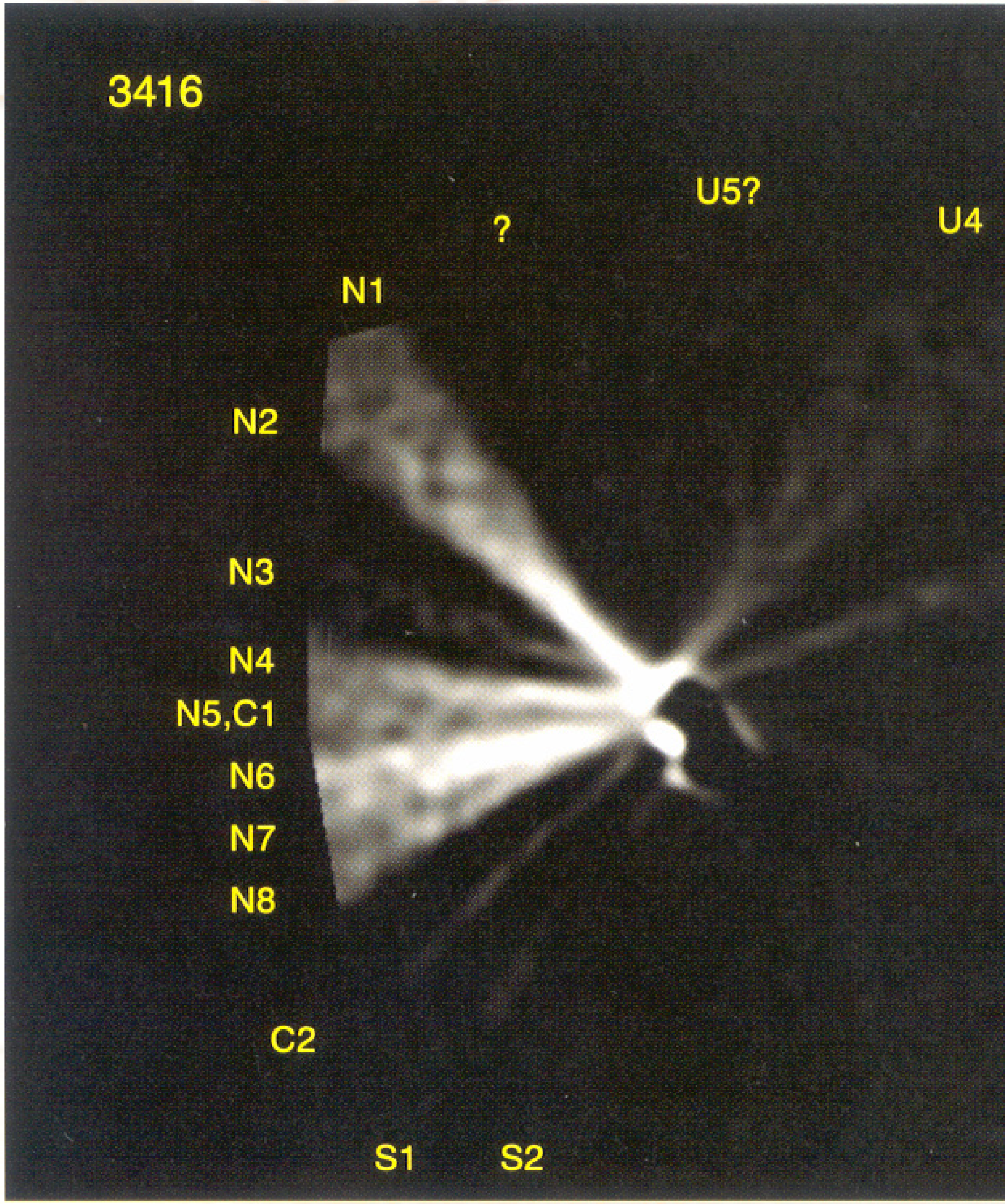


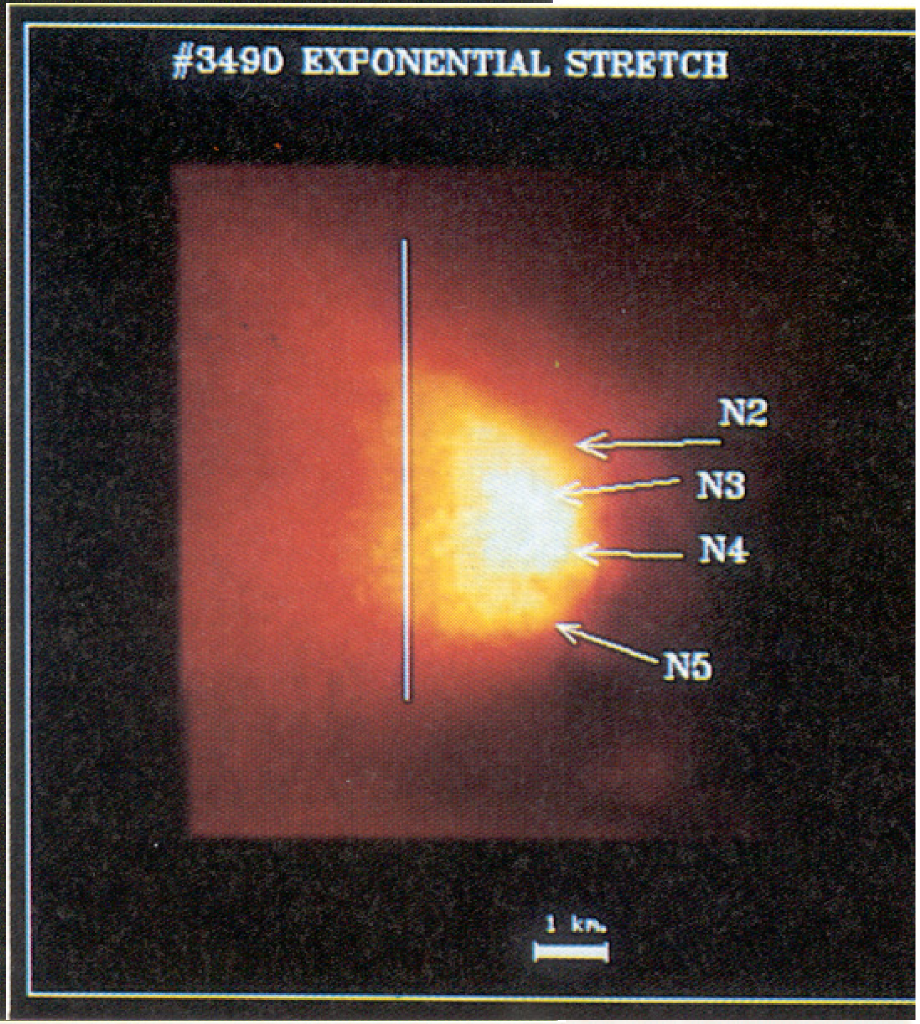
e

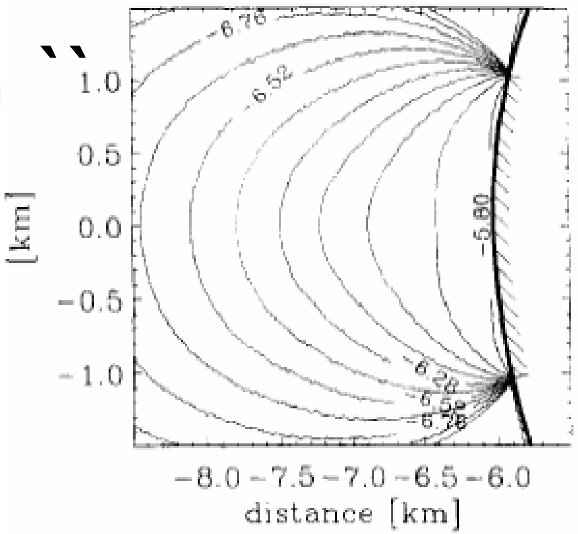
ns

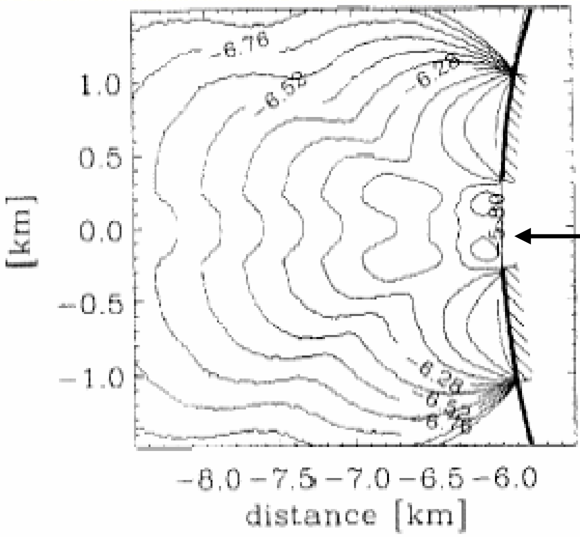
Direction (°)	Halfwidth (°)	Fraction (%)'
137	37	47
198	31	17
273	44	11

Jets and Filaments



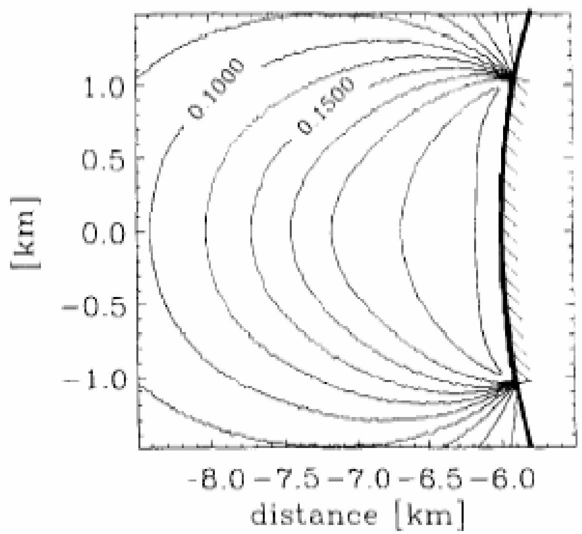


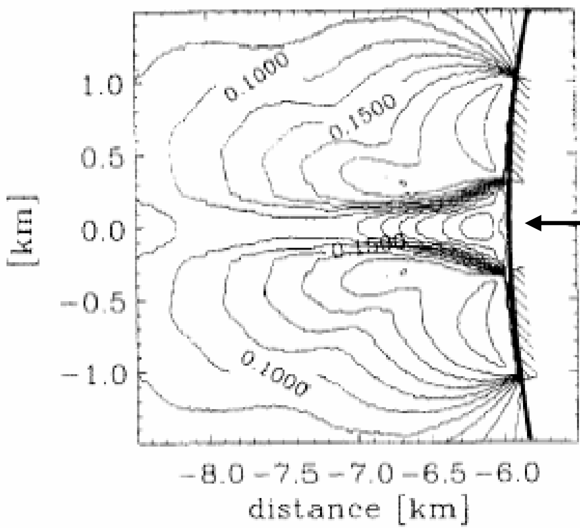




Gas density (log)

Non active patch

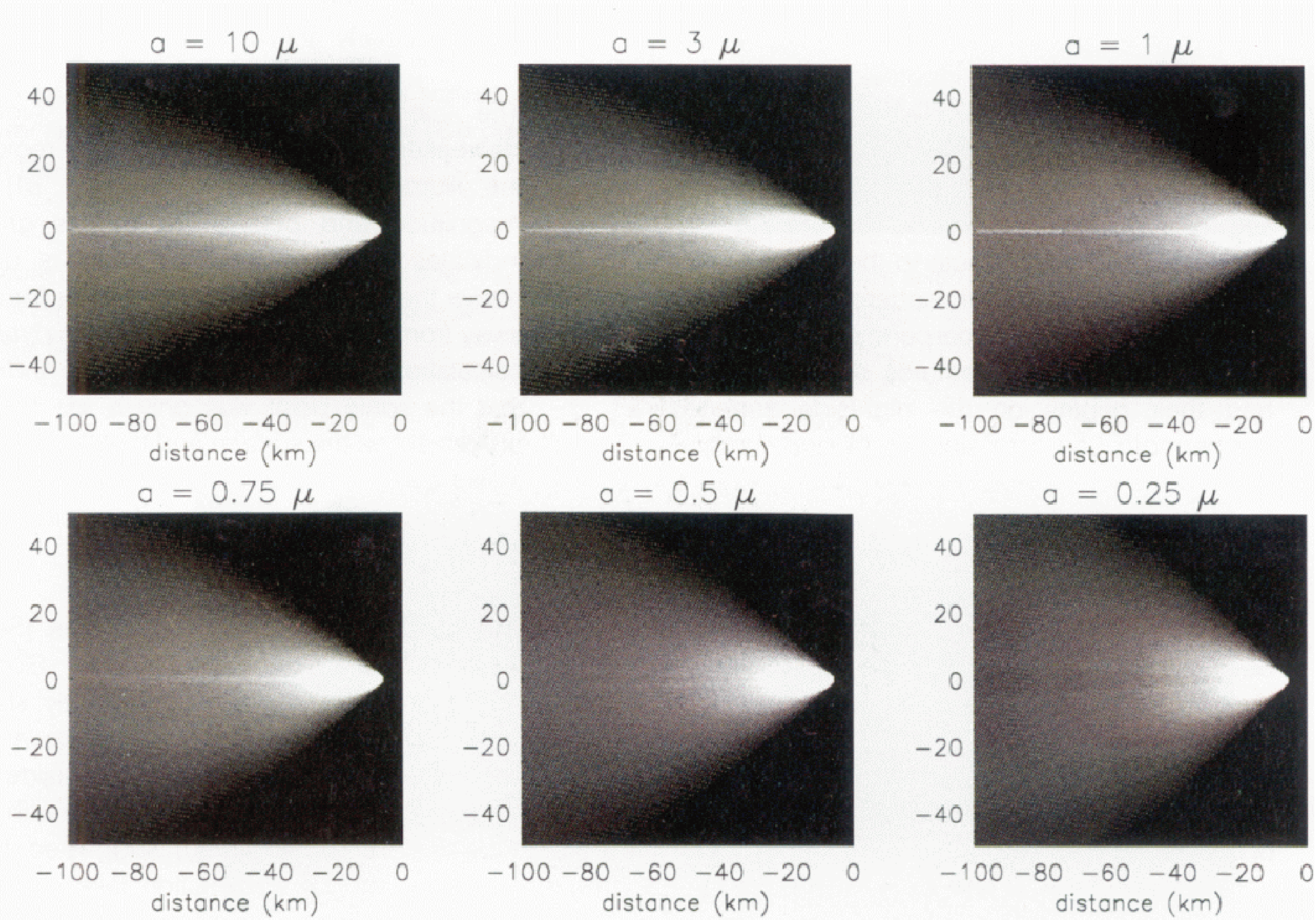




Gas momentum flux (log)

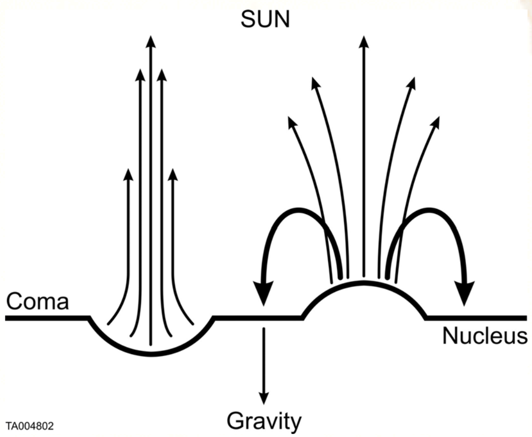
Non active patch

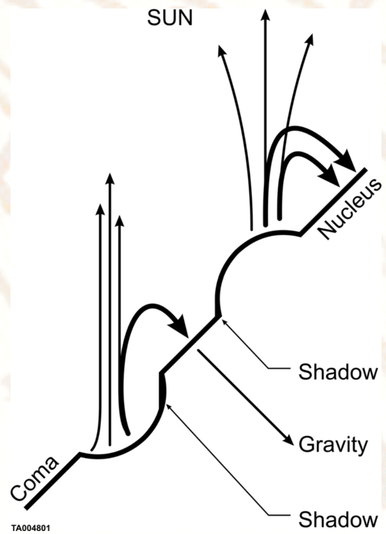
Modeling the filaments by putting inactive spots within an active area



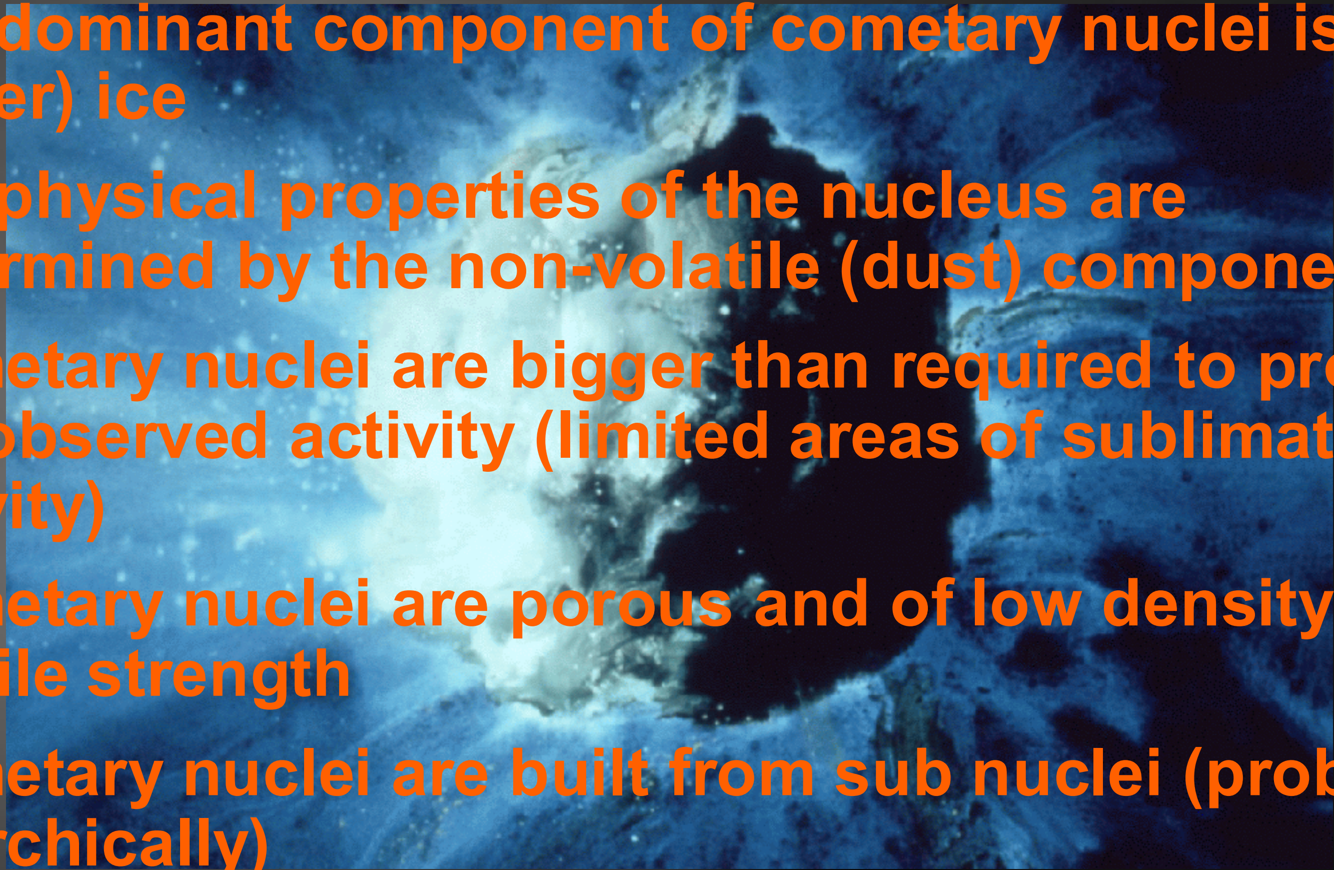
“Jet” and Mantle Formation

- Gas from valleys converges
  - It forms “jets” and entrains larger particles
- Gas from “hills” diverges
  - Larger particles fall back to surface





HMC images changed our perception of cometary nuclei to a new paradigm



- The dominant component of cometary nuclei is not (water) ice
- The physical properties of the nucleus are determined by the non-volatile (dust) component
- Cometary nuclei are bigger than required to produce the observed activity (limited areas of sublimation activity)
- Cometary nuclei are porous and of low density and tensile strength
- Cometary nuclei are built from sub nuclei (probably hirarchically)

Comets resemble icy dirt balls rather than dirty snowballs

Physical properties from VIS+IR measurements (HST, ISO ground based)

(Lamy, Groussin)

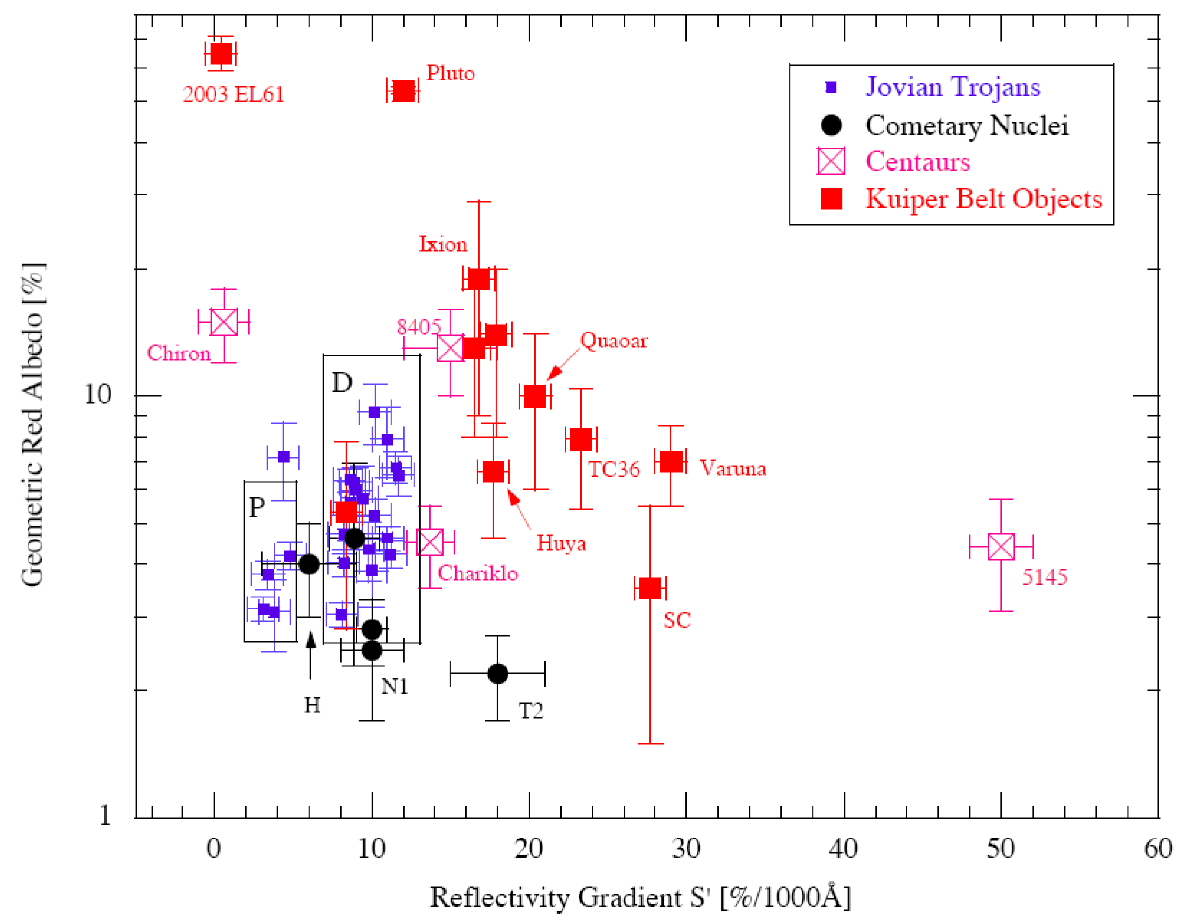
	Object	Radius (r_n)	Albedo (p_v)	Active fraction (x)
Oort Comets	Hale-Bopp (C/1995 O1)	38 ± 6	0.06 ± 0.03	0.13 ± 0.05
	IRAS-Araki-Alcock	3.0 ± 0.5	0.03 ± 0.01	0.06 ± 0.03
	55P/Tempel-Tuttle	1.84± 0.15	0.05 ± 0.01	-
	126P/IRAS	1.57 ± 0.14	0.04	0.11 ± 0.03
SPC	103P/Hartley 2	0.8 ± 0.1	0.04	~1
	22P/Kopff	2.29 ± 0.18	0.03 ± 0.01	0.53 ± 0.15
Centaurs	Chiron (2060)	71 ± 5	0.11 ± 0.02	-
	Chariklo (1997 CU26)	118 ± 6	0.07 ± 0.01	-
Sungrazing comets	Kreutz comets	< 110 m	0.04	-
	Non-Kreutz comets	< 26 m	0.04	-

More Nuclei

Comet	r_n[†] (km)	Axes ratio[‡]	A_p[¶]	Wavelength[§]	Technique(s) used[£]
1P/Halley	5.5	2.0	0.04	VIS	SPC/DNM/SCM
2P/Encke	3.0-4.1	1.8		VIS/RAD	DNM/SRE
4P/Faye	2.7	1.2		VIS	SCM
10P/Tempel 2	4.5	1.5	0.02-0.04	VIS/TIR	DNM/MSD/SCC
19P/Borrelly	2.8	2.5		VIS	SCM
28P/Neujmin 1	9.7	1.2	0.02-0.04	VIS/NIR	MSD
29P/Schwassmann-Wachmann 1	8.6-15	2.6	0.13[a]	VIS/TIR	SCM
31P/Schwassmann-Wachmann 2	3.4	1.6		VIS	MSD
45P/Honda-Mrkos-Pajdusakova	0.34	1.3		VIS	SCM
46P/Wirtanen	0.6	1.2		VIS	SCM
49P/Arend-Rigaux	4.7	1.6	0.02-0.06	NIR/TIR	DNM/MSD/SCC/SCM
55P/Tempel-Tuttle	1.8	1.5		VIS	DNM
95P/Chiron	90	1.1	0.13-0.14	VIS/TIR/RAD	DNM/OCC
107P/Wilson-Harrington	1.3-2.0[b]		0.05-0.10	NIR/TIR	DNM
81P/Wild 2	2.2				
C/1983 H1 (IRAS-Aracki-Alcock) 1.5	5			TIR/RAD	MSD/SRE
C/1995 O1 (Hale-Bopp)	30-40[c]			VIS[d]	SCM
C/1996 B2 (Hyakutake)	2-3			VIS[d]/TIR/RAD	SCM/SRE

Keller and Jorda (2001)

Albedos and Colours of Primitive Bodies

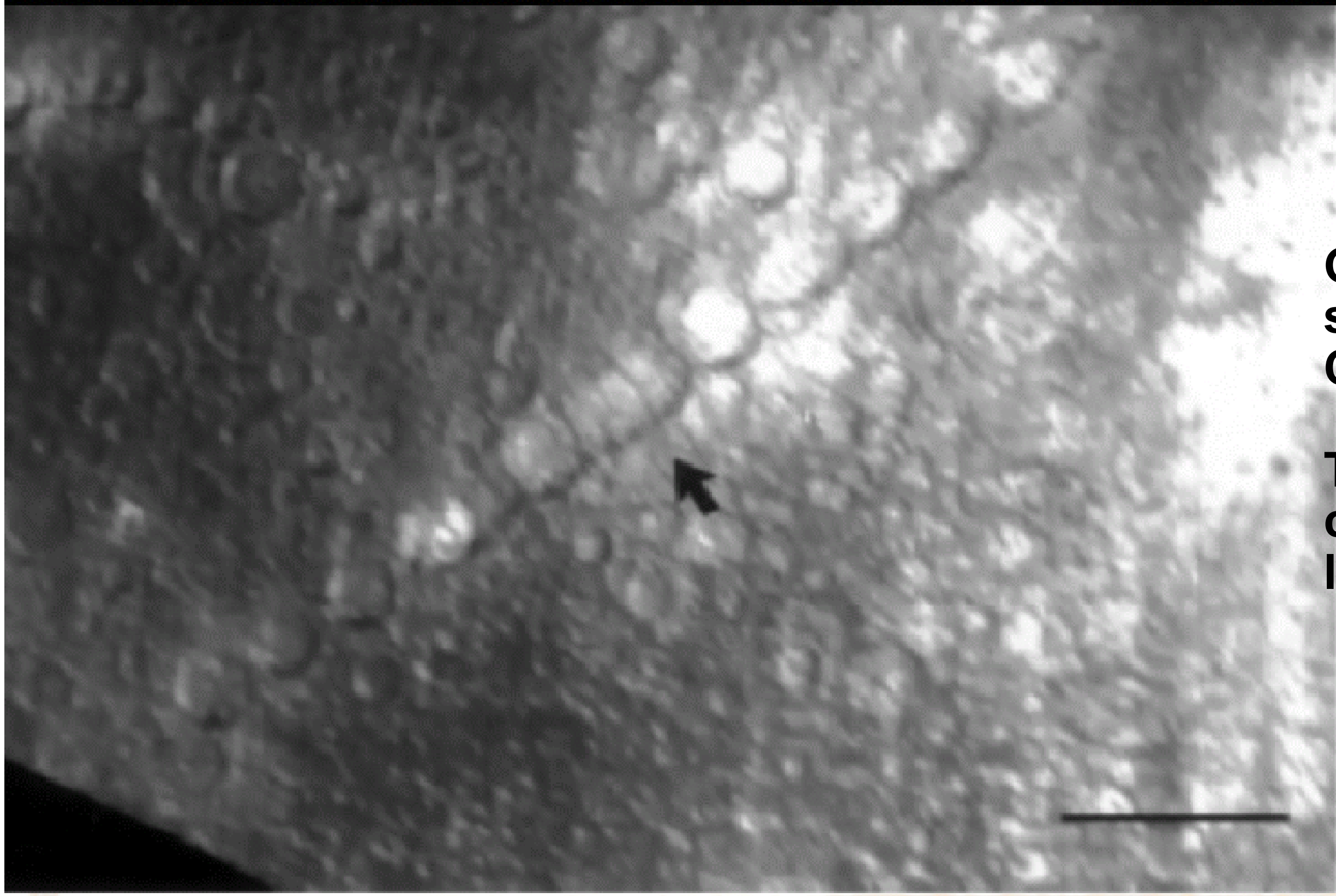


Jewitt, 2006
Saas Fee 35
Proceedings

Nucleus Fragmenation

- **Tensile strength of nuclei must be low**
- **Comets are often observed to split**
- **Comets shed small fragments**
  - **limited lifetime**
  - **therefore predominantly observed when comets are close to earth (resolution)**
- **Recent example of nucleus disruption is comet Shoemaker Levy**
- **Close encounter with Jupiter**
- **Other hints are crater chains (catenae)**

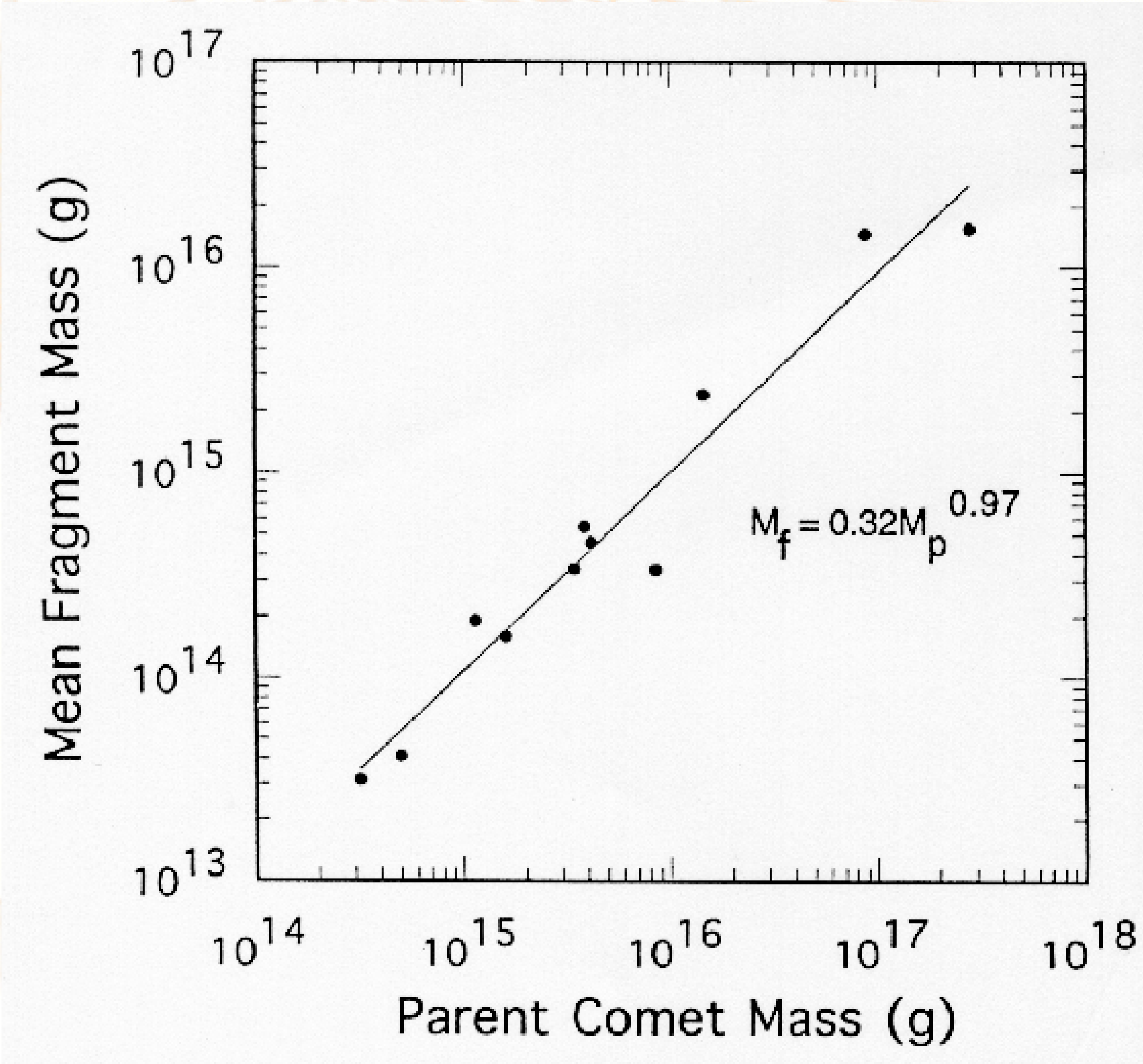
Comet Shoemaker-Levy



Gipul Catena on the surface of Jupiter's moon Callisto.

This chain of 18 impact craters is about 625 km long.

Catenae on Ganymed and Callisto

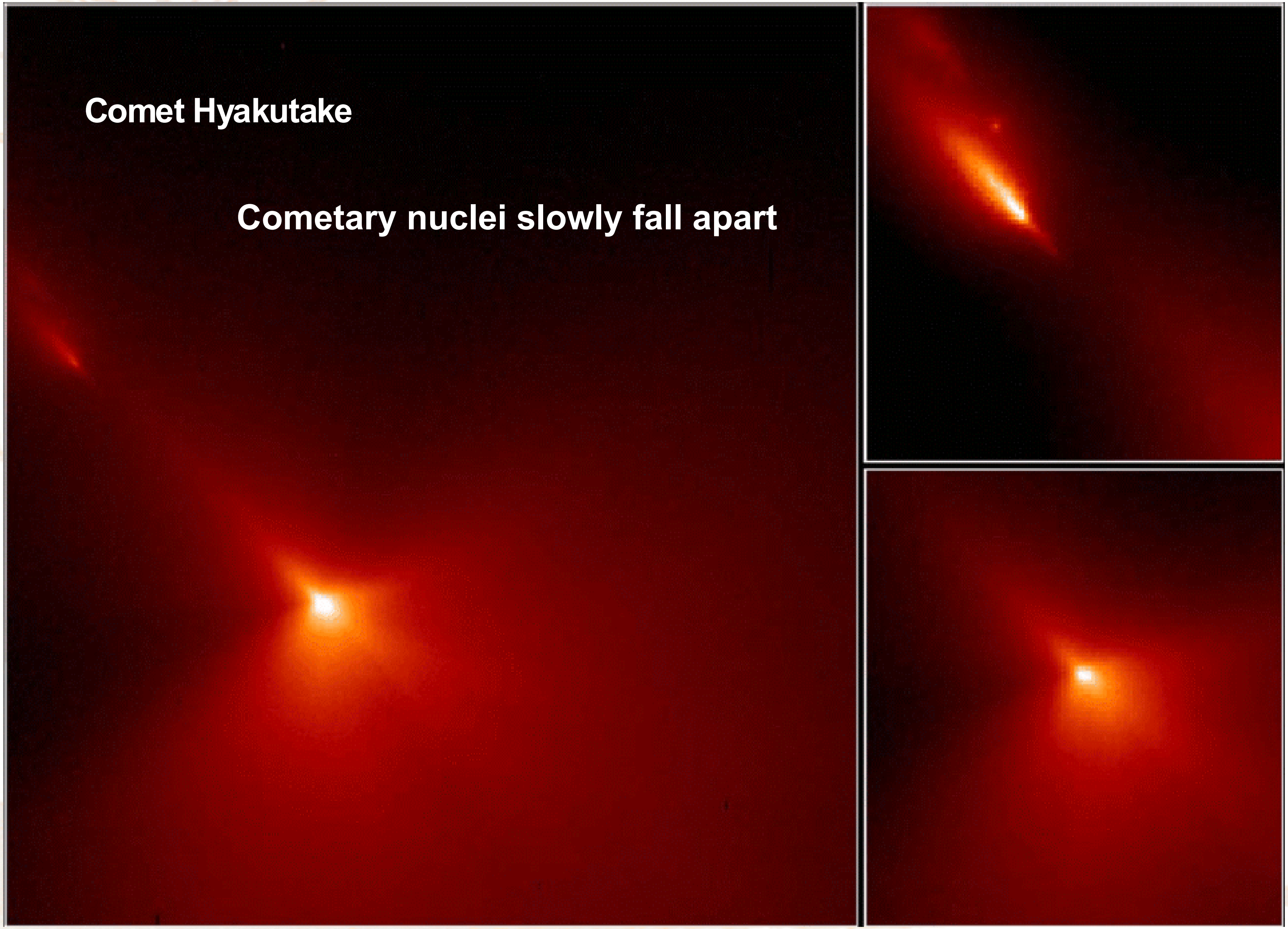


Correlation of mean fragment mass for individual crater chain comets and mass of the associated parent comet (Schenk et al 1996, data from McKinnon and Schenk 1995).

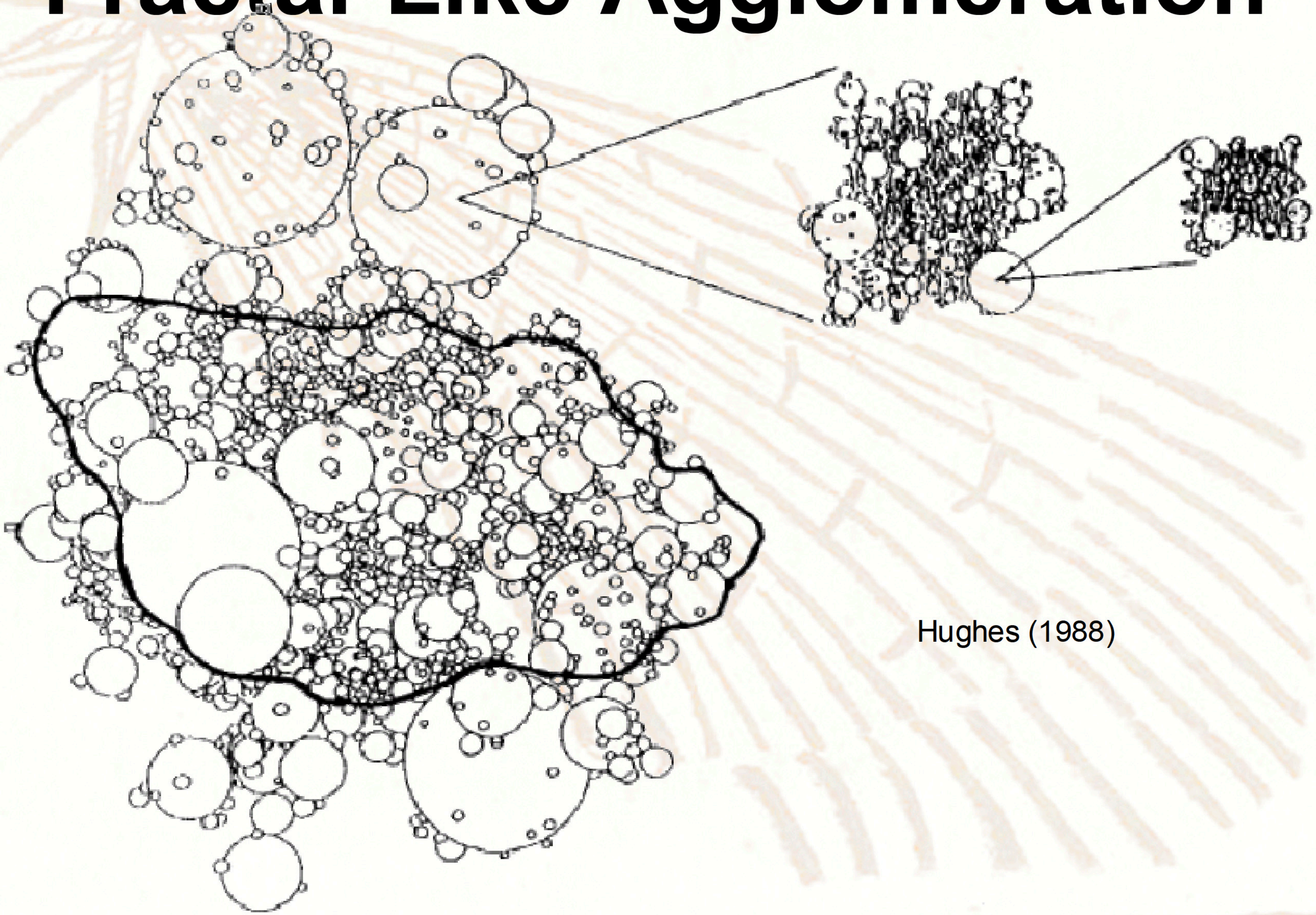
Bigger comets break up in bigger subnuclei.

No preferred size!
(Weidenschilling 1997, 2000)

Cometary Nuclei are of Low Tensile Strength



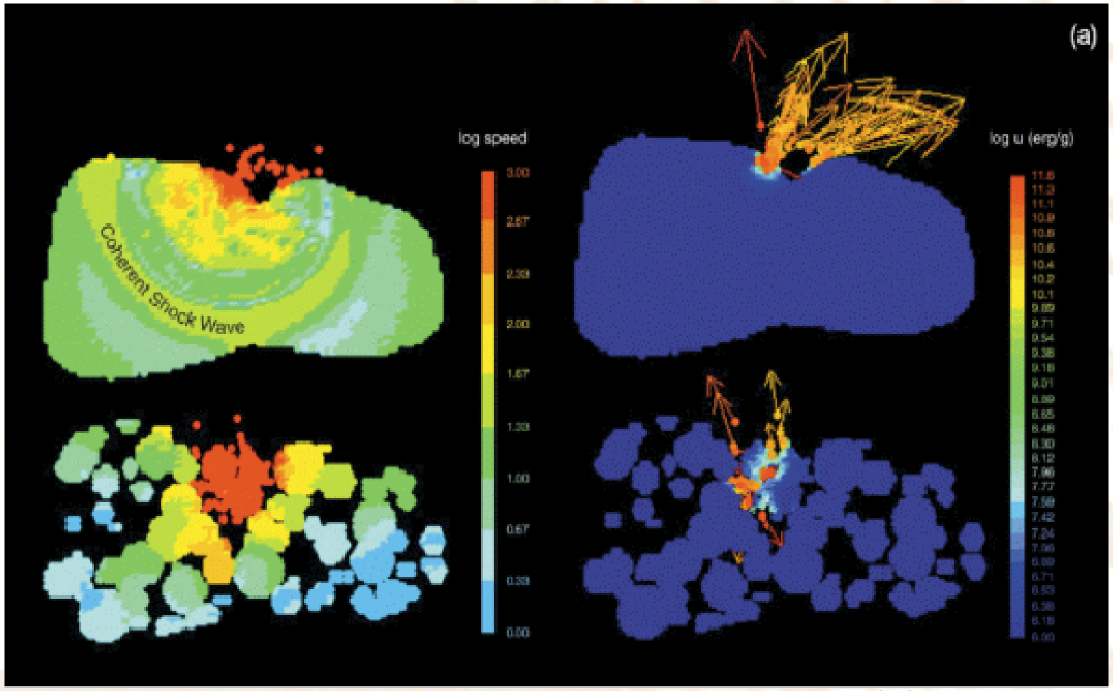
Fractal-Like Agglomeration



Hughes (1988)

Collisions

- Comets suffer collisions
- The Oort cloud comets formed inside the planetary system experience a rather hostile environment before they are thrown out while they are passed from planet to planet - many cometesimals end up as dust (Weissman)
- The KB comets suffer during their storage, however, less violent encounters

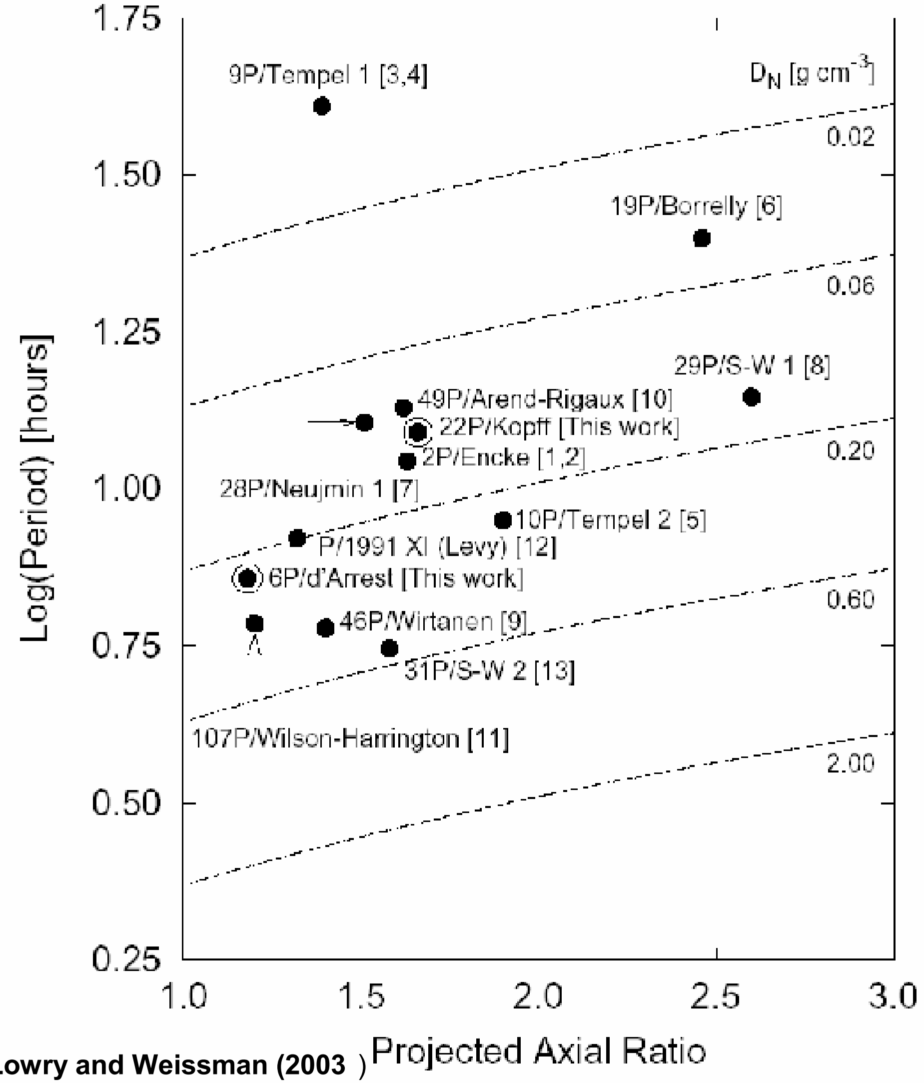


High impact energies can create shock fronts that penetrate and shatter the whole target body:

"rubble pile"

Asphaug et al. (2003)

Rubble Piles?



Lowry and Weissman (2003)

Cometary nucleus density lower limits derived from rotation periods

Faster rotators seem to have smaller axial ratios =>

loosely bound aggregates (?)

'under-dense' if compared to constituent material

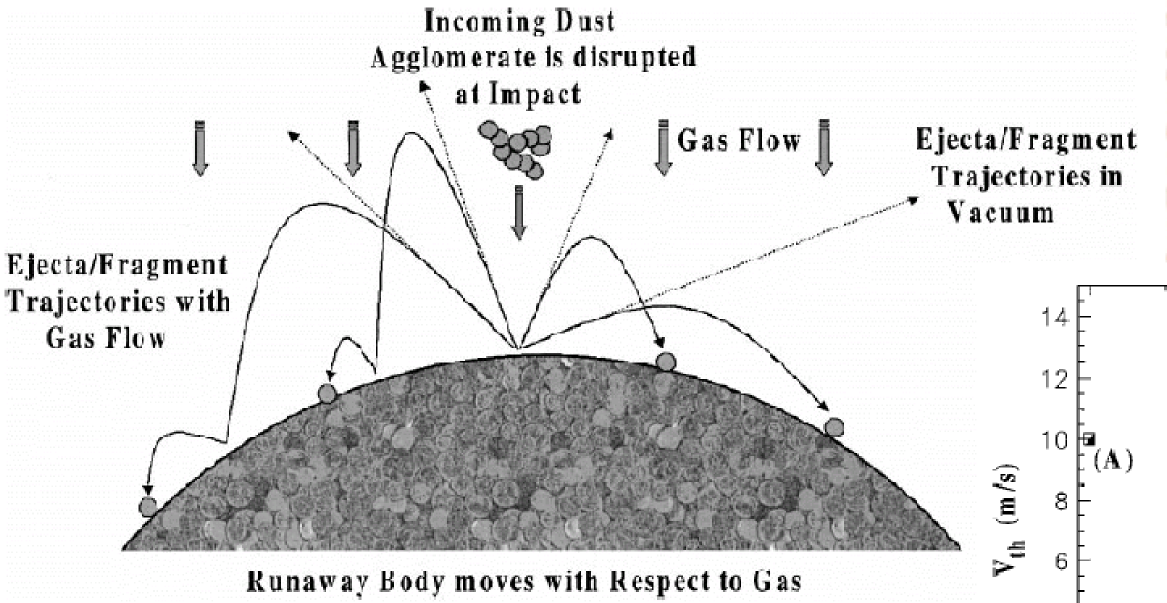
Formation

Standard picture: formation in the protosolar rotating dust disk as planetesimals (cometesimals)

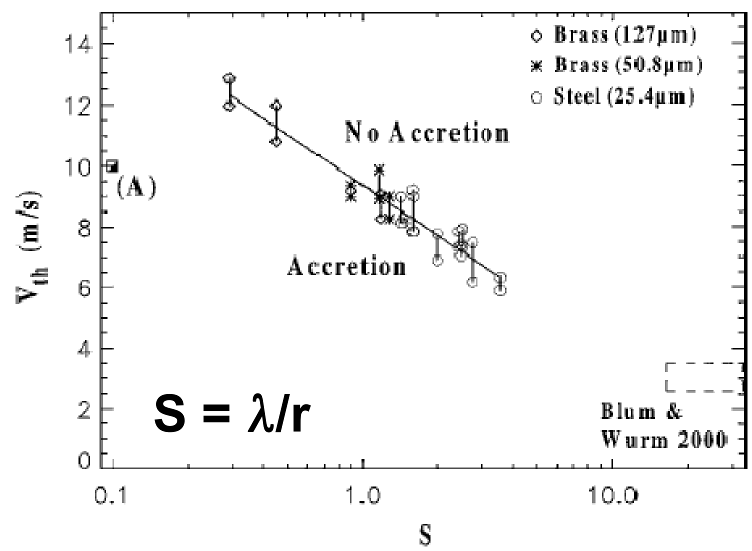
What are the steps?

- Coagulation and accretion from submicron sized grains supported by Brownian motion within the gas of the nebula
- Formation of extremely fluffy fractal-like particles (up to cm-size and speeds < 1 m s^{-1})
- Compaction at higher drift speeds, but still porous!
- Gas helps to grow meter-sized bodies (Wurm et al. 2001)
- Bodies of same or similar sizes collide with low velocities
- Radial mixing due to migration (typically 0.1 to 10 m bodies)

Effect of Gas Drag



Wurm et al. (2001)



Critical body sizes from 1 cm to 1 km
Gas density high enough around 1 AU, but at 30 AU?

Collisions of porous (m-sized) bodies

Roland Speith, Christoph Schäfer, Ralf Geretshauser, Willy Kley

Institute of Astronomy and Astrophysics University Tübingen

- So far: simulations of collisions of solid bodies
  - consisting of rocky materials,
  - consisting of rocky rubble piles.

⇒ Results: Erosion or fragmentation, no net growth.

- However, pre-planetesimals may consist of porous agglomerates with differing material properties

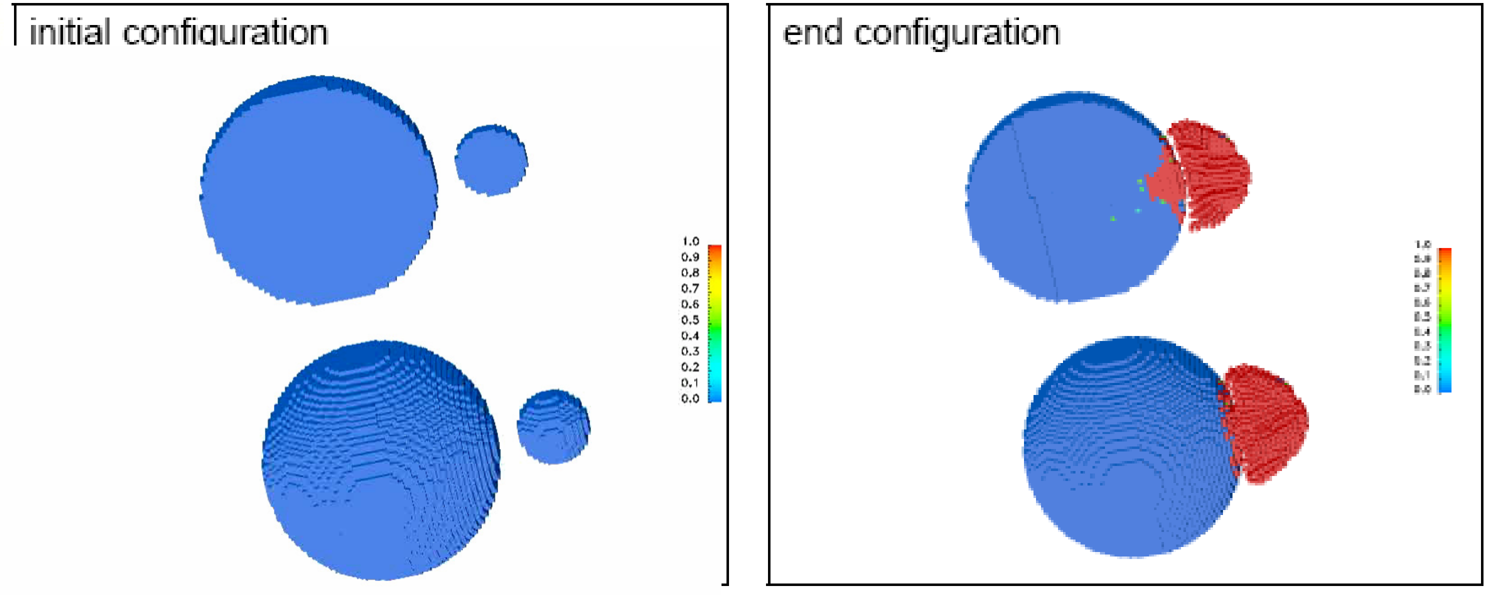
  (strongly indicated, e.g., by low density of asteroids and comets, by lab experiments of dust growth (Blum, Wurm), and theoretical simulations (Dominik, Tanaka)).

⇒ Next step: SPH simulations to study collisions of porous bodies. **SPH: Smooth Particle Hydrodynamics**

⇒ Porosity model in SPH: material parameters depend on filling factor of density (Sirono 2004)

Smooth Particle Hydrodynamics (SPH)

Collision with small impactor – solid rocky material



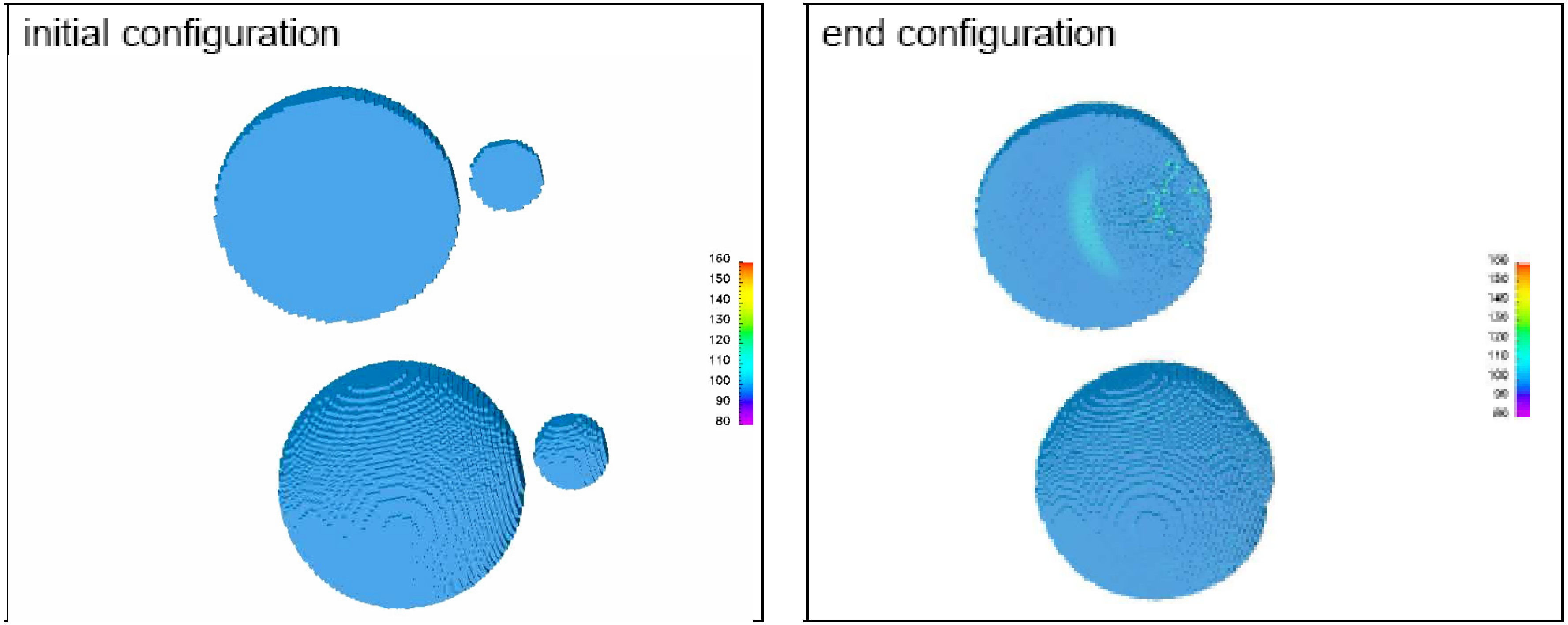
Colour-coded: damage

Target-radius: $1\,\mathrm{m}$, Impactor-radius: $1/3\,\mathrm{m}$, Initial density: $3\,\mathrm{g/cm^3}$,

Relative velocity: $20\,\mathrm{m/s}$

Smooth Particle Hydrodynamics (SPH)

Collision with small impactor – porous material



Colour-coded: density

Target-radius: $1\,\mathrm{m}$, Impactor-radius: $1/3\,\mathrm{m}$, Initial density: $0.1\,\mathrm{g/cm^3}$, Porous filling: 0.1,

Relative velocity: $20\,\mathrm{m/s}$

Nuclei - Subnuclei

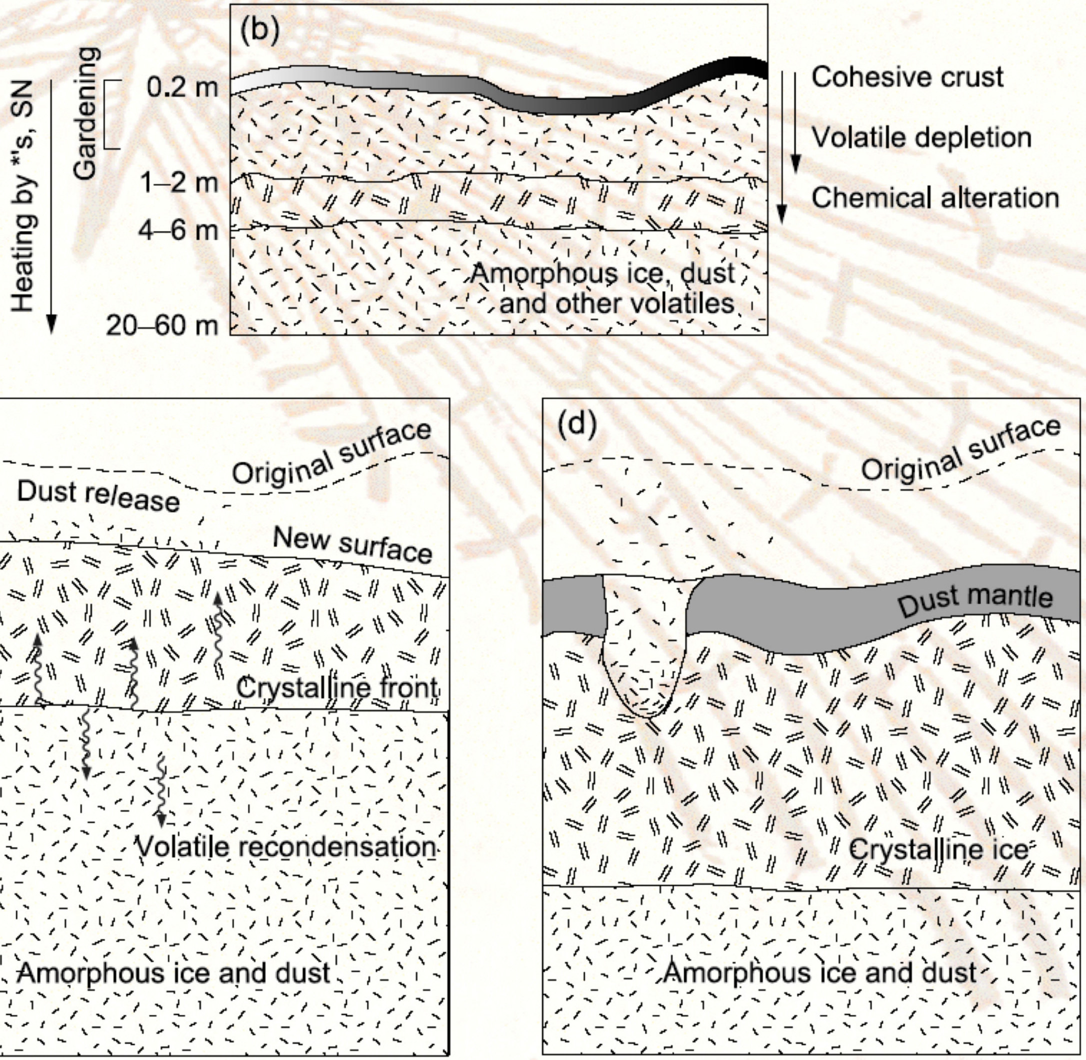
- **Both comets, Halley and Borrelly, suggest a hierarchical size distribution of their building blocks**
- **Interpretation of the catenae leads to the same conclusion**
- **Feeding the agglomeration by a monolithic size (100 m range) is not corroborated**
- **Shedding of pieces during activity (e. g. Hyakutake) and frequent splitting point to a very low tensile strength**
- **Collisions of porous bodies lead to partial compaction and hence to non- uniformity of physical properties (varying density and tensile strength)**
- **Collisions in KB anyhow not energetic enough to shatter whole nucleus into a rubble pile**

Activity

Key questions:

- **How does activity work?**
- **Why is most of the surface inactive?**
- **What localizes activity over several (many) orbits?**
- **Crust versus mantle**

Near Surface Layers



Meech and Svoren (2004)

Amorphous Water Ice

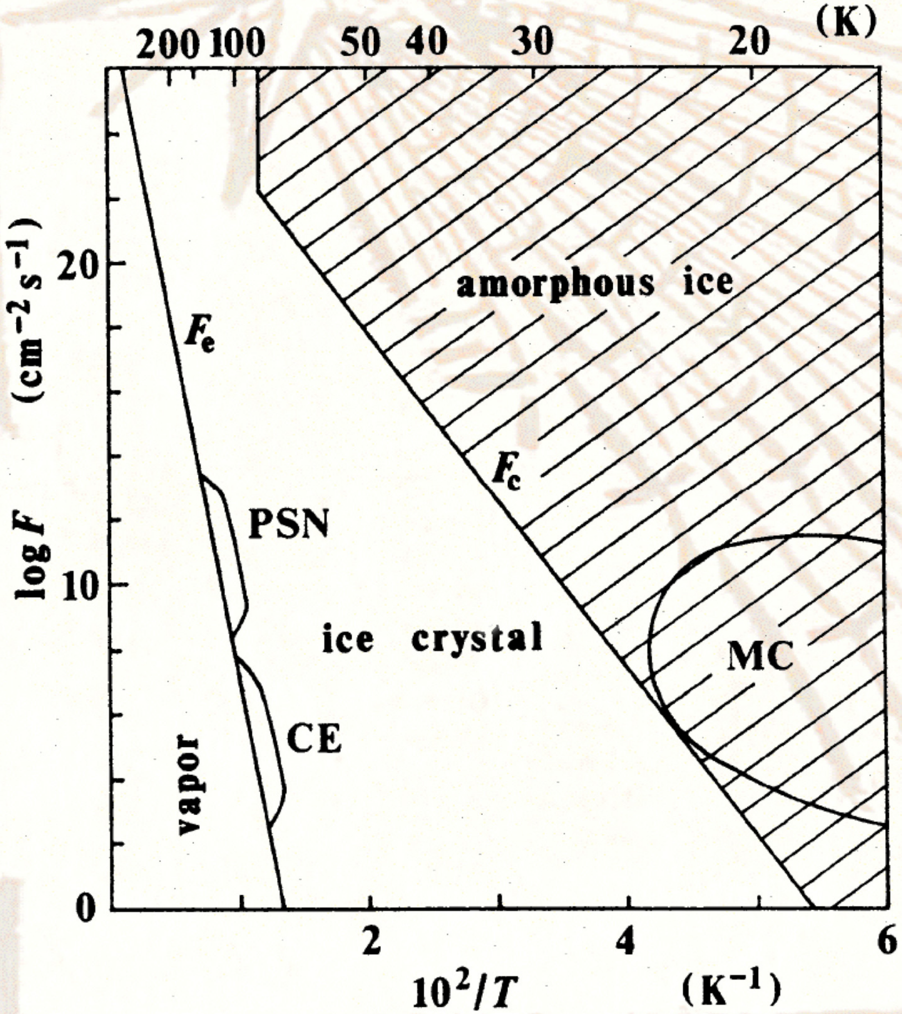
- **Has been produced in laboratory at:**
  - **Low temperature**
  - **Fast rate of condensation (no time for orientation of molecules as they condense)**
- **Has been suggested to exist in comet nuclei:**
  - **Low temperature of formation**
  - **Comet outbursts at large *r* (exothermic phase transition)**
  - **Trapped gases (but <u>not</u> clathrate hydrates)**

Amorphous Water Ice

Problems:

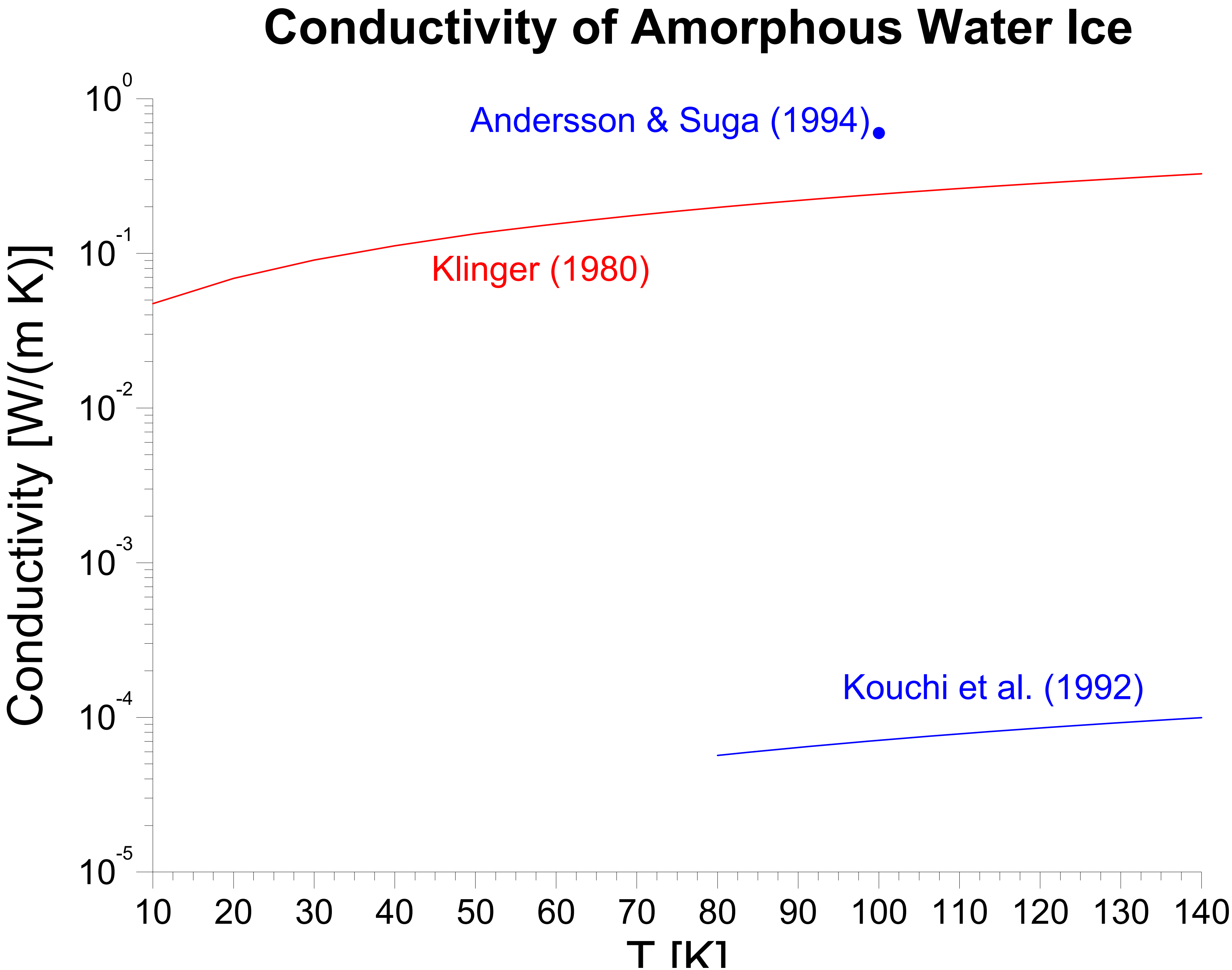
- Has <u>not</u> been identified directly in:
  - Interstellar clouds
  - Star-forming regions
  - Outer solar system objects
- N_2, CO, and Ar should have solar abundances
- Condensation in Solar Nebula too slow
- Conductivity poorly known

Amorphous Ice



Crystallinity of ices in astrophysical sites. F_c* is the critical flux, and t_c is assumed to be 10^7 years. PSN, CE and MC denote the primordial solar nebula, circumstellar envelope, and molecular cloud, respectively. Amorphous ice forms only if the condensing flux > *Fc (Kouchi et al. 1994).**

➔no amorphous ice



Conductivity of Amorphous Water Ice
Conductivity [W/(m K)]
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
Andersson & Suga (1994)
Klinger (1980)
Kouchi et al. (1992)
10
20
30
40
50
60
70
80
90
100
110
120
130
140
T [K]

Surface Heat Balance

$$\rho c \frac{dT}{dt} = \frac{F_o(1-A_0)}{r_h^2} - \varepsilon\sigma T^4 + LZ(t) + \kappa \frac{dT}{dz}$$

$$\delta = \frac{\kappa}{\rho c}$$ Thermal diffusivity

$$\sqrt{\kappa\rho c} = \Gamma$$ Thermal inertia (MKS)

$$x = \sqrt{\frac{2\delta}{\varpi}} = \sqrt{\frac{\tau\delta}{\pi}}$$ Scale length for wave to drop by 1/e, τ is period of heating

For Moon typically 5 cm, for Mars 10 to 20 cm

Thermal Scale Lengths

For Mars, x_1 is typically 10-20 cm.

Compact ice?

$\kappa = 1\ W\ m^{-1}\ K^{-1}$
$\rho = 600\ kg\ m^{-3}$
$c = 800\ J\ kg^{-1}\ K^{-1}$
$\tau = 6\ hours$
$d_t = 2\ 10^{-6}\ m^2\ s^{-1}$
$\Gamma = 700\ W\ m^{-2}\ s^{-1/2}\ K^{-1}$
$\delta = 12\ cm$

skin depth

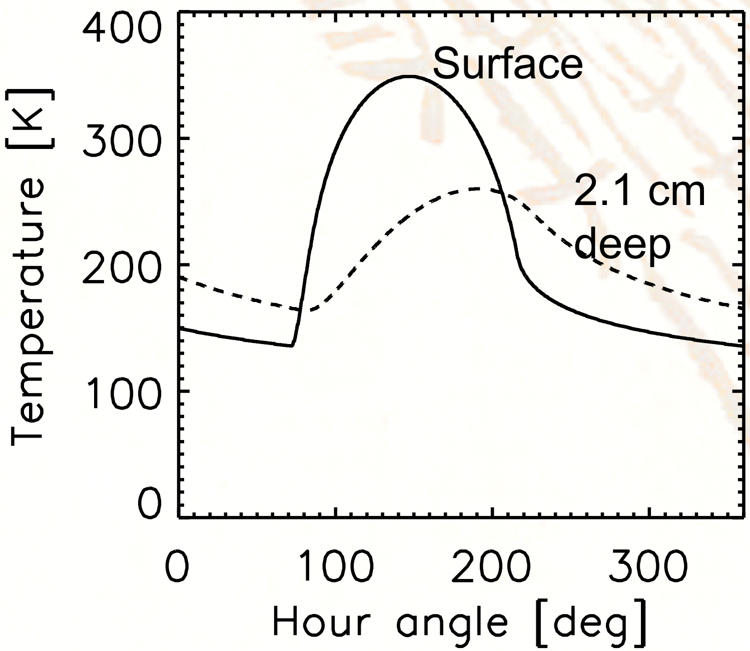
Highly porous material

$\kappa = 0.01\ W\ m^{-1}\ K^{-1}$
$\rho = 600\ kg\ m^{-3}$
$c = 400\ J\ kg^{-1}\ K^{-1}$
$\tau = 6\ hours$
$d_t = 4\ 10^{-8}\ m^2\ s^{-1}$
$\Gamma = 50\ W\ m^{-2}\ s^{-1/2}\ K^{-1}$
$\delta = 1.5\ cm$

DI gives
$\Gamma < 50\ W\ m^{-2}\ s^{-1/2}\ K^{-1}$

Steady-State Calculation

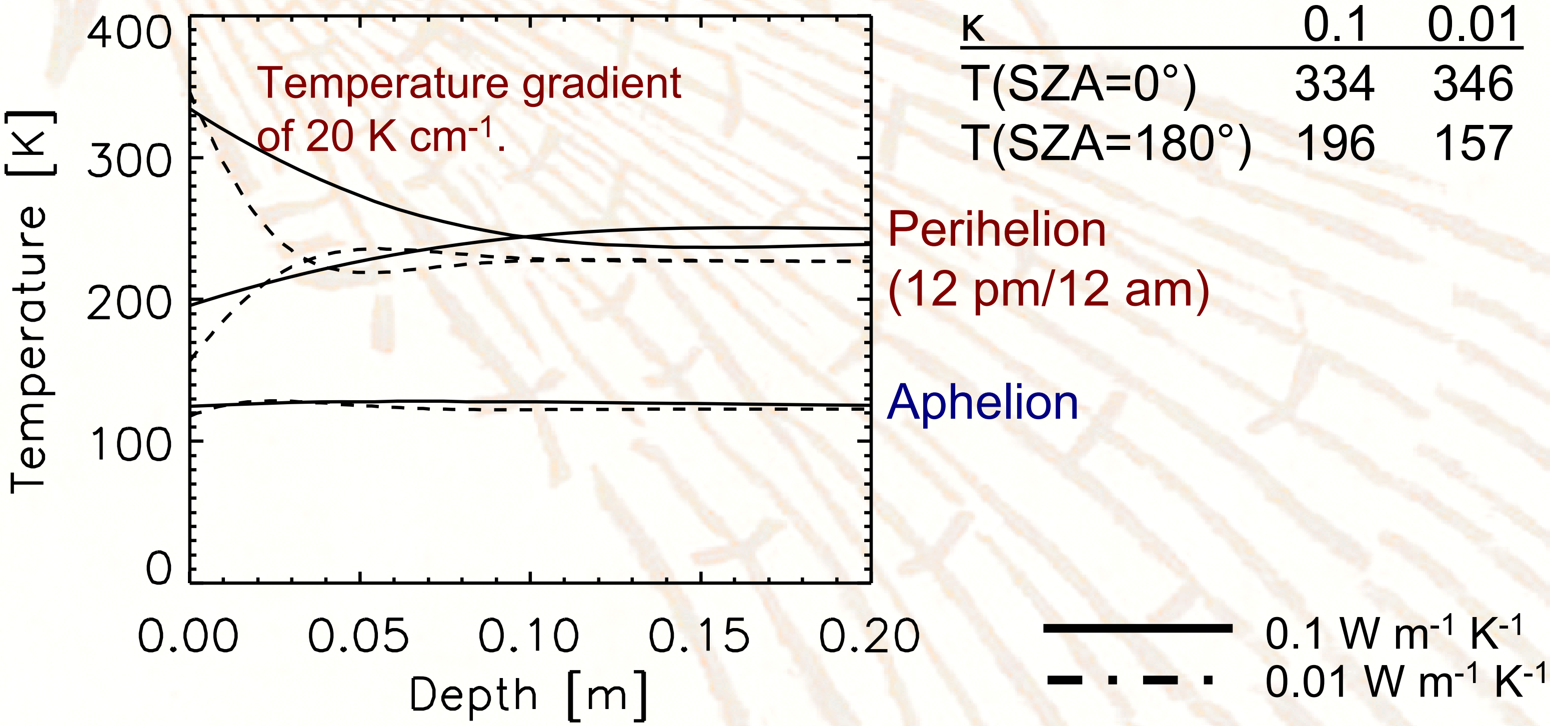
● Simple calculation shows that the temperature gradient is enormous.



R_h = 1.3 AU
A_H = 0.04
ε = 0.9
P = 12.3 h
T_{int} = 100 K

$$\Theta = \frac{\Gamma\sqrt{\omega}}{\varepsilon\sigma T^3}$$

Calculation Over 1 Orbit of C-G



κ	0.1	0.01
T(SZA=0°)	334	346
T(SZA=180°)	196	157

Temperature contrast is largest on nightside for determining Γ. (cf. Prialnik et al., 2004). Temperature at depth is strongly dependent upon the lower boundary condition.

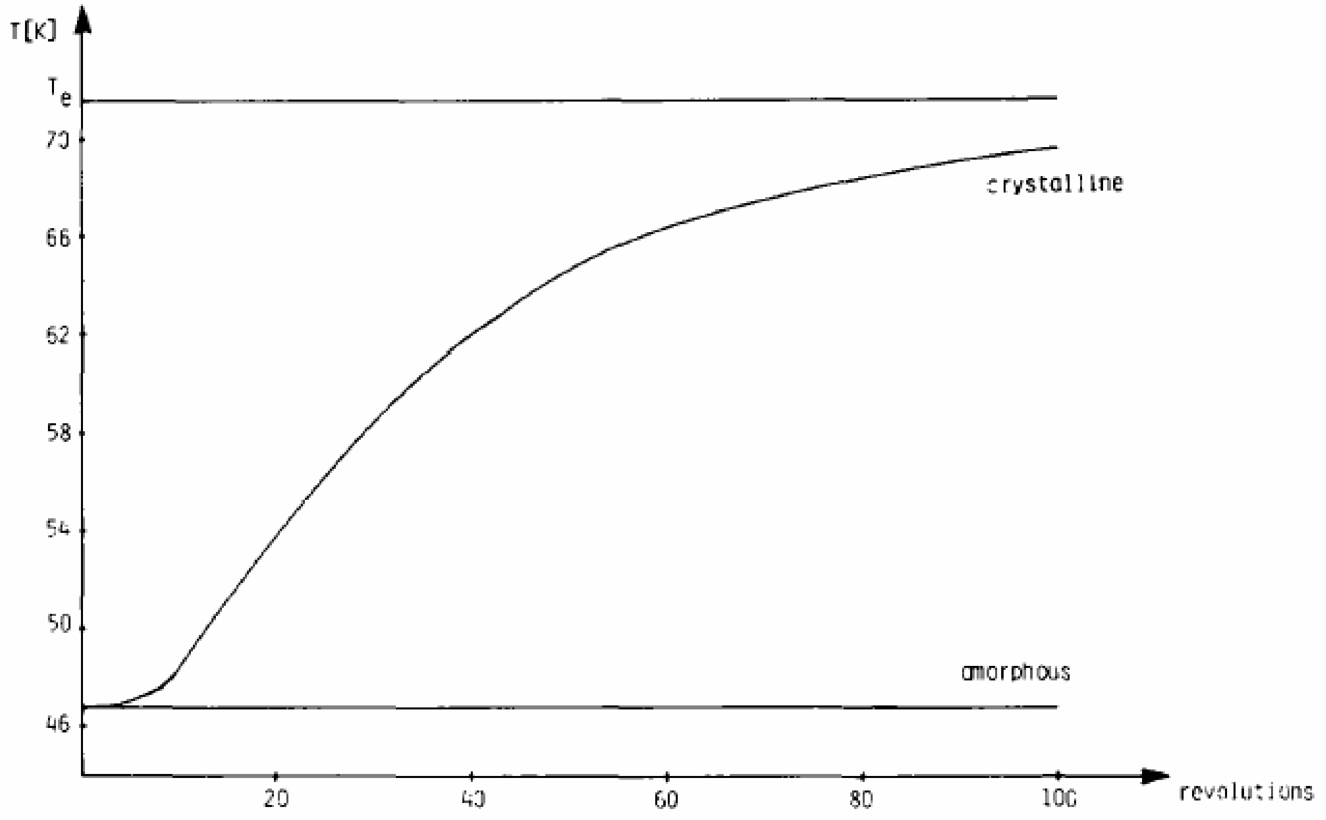
Nucleus Temperature

The interior of a cometary nucleus is only heated up after many revolutions around the sun. Amorphous ice prevents the nucleus from reaching its equilibrium temperature, T_e:

$$T_e = \frac{1}{\tau}\int_0^\tau T_s dt = \frac{1}{\varepsilon\sigma\tau}\int_0^\tau \left[\frac{C_s(1-A_s)}{4r_h(t)^2} - (1-f_d)LZ(T_s) - K\left.\frac{dT}{dr}\right|_{r=R} \right]^{1/4} dt$$

T_s surface temperature	**r_h heliocentric distance**
σ Stefan-Boltzmann constant	**f_d fraction of inactive area**
ε emissivity	**L latent heat of water sublimation**
C_s solar constant	**Z sublimation flux**
A_s surface albedo	**K thermal conductivity**

Temperature inside a nucleus



The temperalure in the center of the nucleus of crystalline and amorphous ice, respectively, versus number of revolutions. T_e is the equilibrium temperature. (Kührt 1984)

How fast is ice lost from the uppermost layer? (Or what is dm/dt?)

Hertz-Knudsen equation

$$Q(T) = P_s \sqrt{\frac{1}{2\pi mkT}}$$

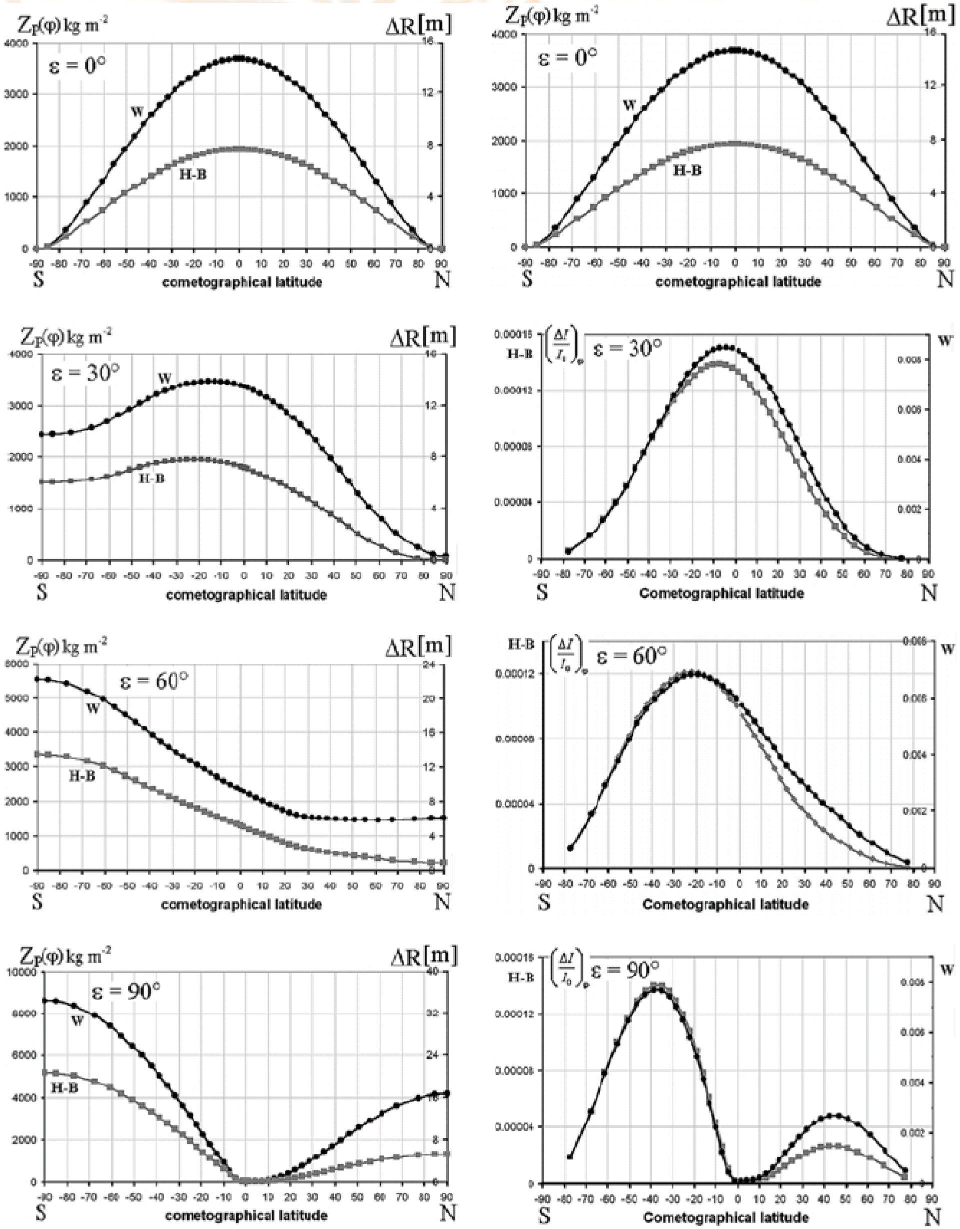
If applied to an ice surface, sublimation is rapid. Balancing energy input and latent heat, rates of 10^{22} molecule m^{-2} s^{-1} are typical leading to depth loss rates of 1 cm per few hours.

Consequence: Sublimation down to a skin depth occurs in, at most, a few rotations of the nucleus.

Consequence: Surface must be disrupted on a similar time scale to maintain observed constancy/repeatability of emission.

E.g. Halley observed by HMC to be constant to 1% over 3 hours.

Non-Uniform Sublimation



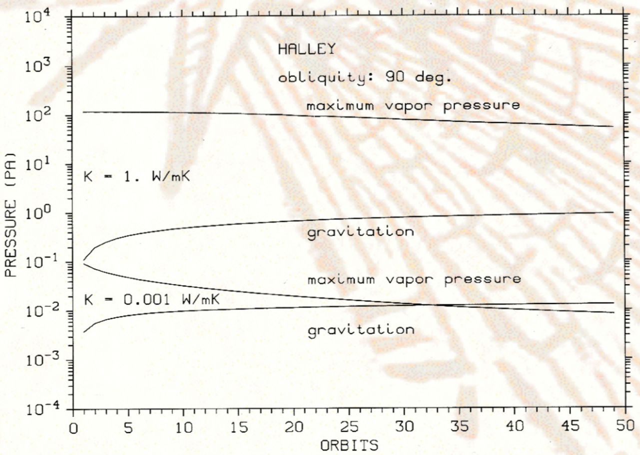
Dziak-Jankowska et al., EM&P, 2002.

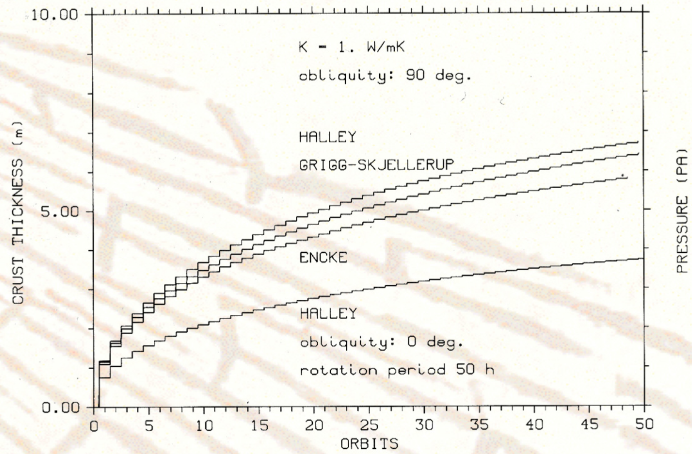
An initially spherical uniformly subliming nucleus will become aspherical naturally because of the orbital eccentricity combined with the obliquity.

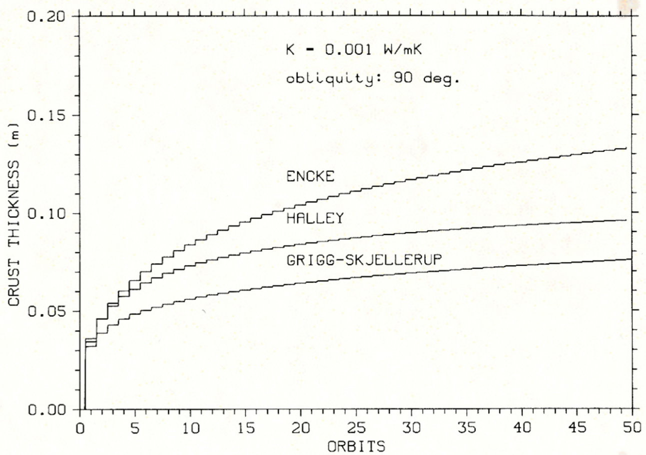
Gas “Pressure”

- **Gas transport as a heat transport mechanism is well established in models.**
- **But how significant is pressure in breaching the surface layer?**
- **Thermal conductivity dictates that the temperature must drop in the first cms so that sublimation sub-surface is lower.**
- **Furthermore, the surface layer is said to be porous**
- **Skin depth is small but still many pore sizes (μms)**

No Mantle but a Thin Crust







Parameter	Symbol	Value
Albedo	A	0.05
Specific heat	c	600 J kg^{1} K^{1}
Emissivity	ϵ	1
Latent heat	H	2.66 x 106 J kg^{1}
Crust porosity	p	0.5
Crust density	p	500 kg m^{3}
Effective pore size	l	1 mm
Crust heat conductifity	K	10^{3} or 1 W m^{1} K^{1}
Core heat conductivity	K_{core}	1 W m^{1} K^{1}
Dust-to-ice mass ratio	X	1

Local pressures (forces) in a cometary nucleus

Gravitational pressure on a layer with thickness Δ :

P_g [Pa] = 1.33 G π ρ^2 R Δ = 3 * 10^{-10} ρ [kg/m^3]^2 R[m] Δ [m]

G: grav. constant, R: radius of the nucleus, ρ: density

Vapor pressure

P_v [Pa] = 3.56 10^{12} exp(-6141/T_{ice} [K])

Minimum cohesive strength by Van der Waals forces

P_c [Pa] = 3 π α / r (Chokshi et al. AJ 1993)

α: material constant 0.01…1 N/m, r: grain size

Example nucleus:

R= 1 km, ρ = 1 g/cm^3 , α = 0.1 N/m (Graphite), T_{ice} = 220 K, r = 1 mm

P_g [Pa] = 0.3 Δ [m]

P_v = 3 Pa

P_c = 1000 Pa if porous, reduced by factor (1-$p^{2/3}$) ≈ 0.4 (Klinger et al. 1989)

Measured strengths:

Lunar regolith: $10^2 \ldots 10^3$ Pa (Mitchel et al. 1973 from Apollo experiments)

Filamentary sublimate residues: 10^4 Pa (Storrs et al. 1988 from lab experiments)

Fireballs: $10^3 \ldots 10^6$ Pa (Wetherill et al. 1982 from observations)

Snow: ca. 10^3 Pa

Conclusions:

Measured strength numbers support the modeled values

Cohesion of a dust matrix is the dominant force and controls the local structure of a nucleus !

Globally measured strength (e.g. SL9: 10 Pa) is lower than the local strength because of weaknesses between cometary building blocks

Reduction in Sublimation by a Surface Layer

● **If sublimation occurs at around 1 skin depth, the sublimation rate might be reduced by a factor of 8-10.**

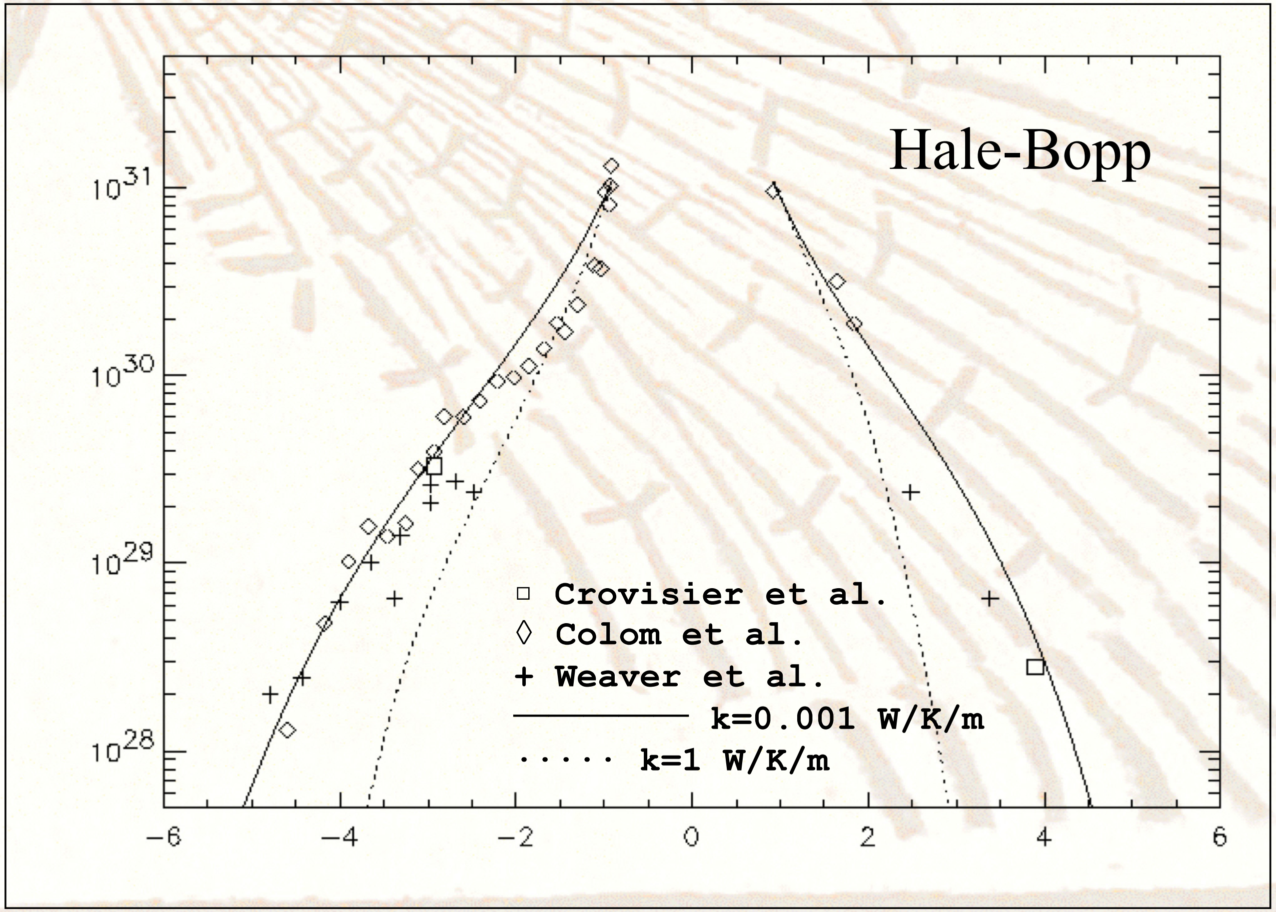
● **For C-G, the emission can be explained by unrestricted activity from 2-4% of the surface.**

● **If sublimation occurs from 2-3 cm below the surface, 20-40% of the surface area is required to be active - almost an entire hemisphere and without taking into account the solar zenith angle.**

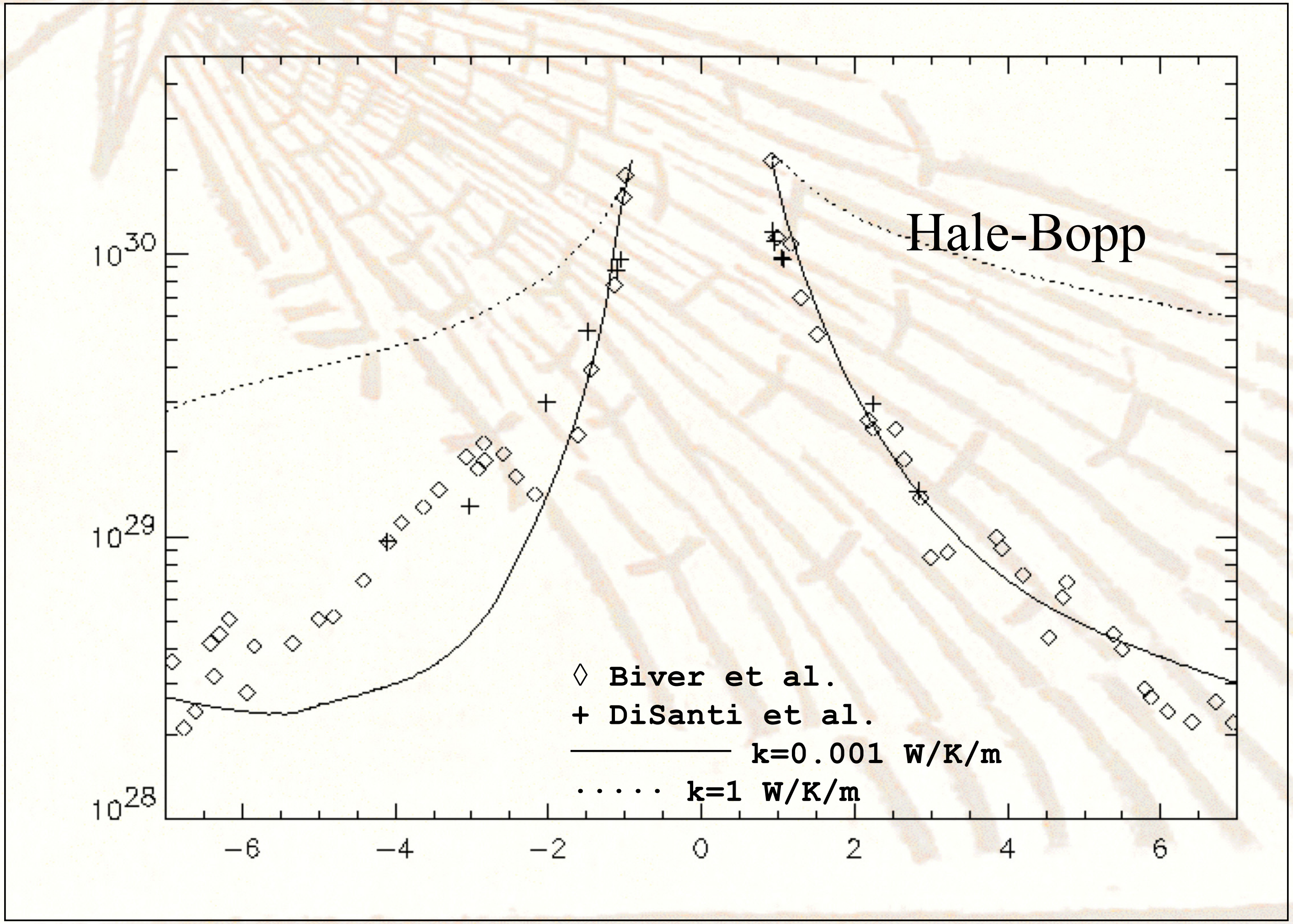
Sublimation from a sub-surface layer below 1 thermal skin depth cannot match cometary production rates.

Modeled and measured H_2O production rates

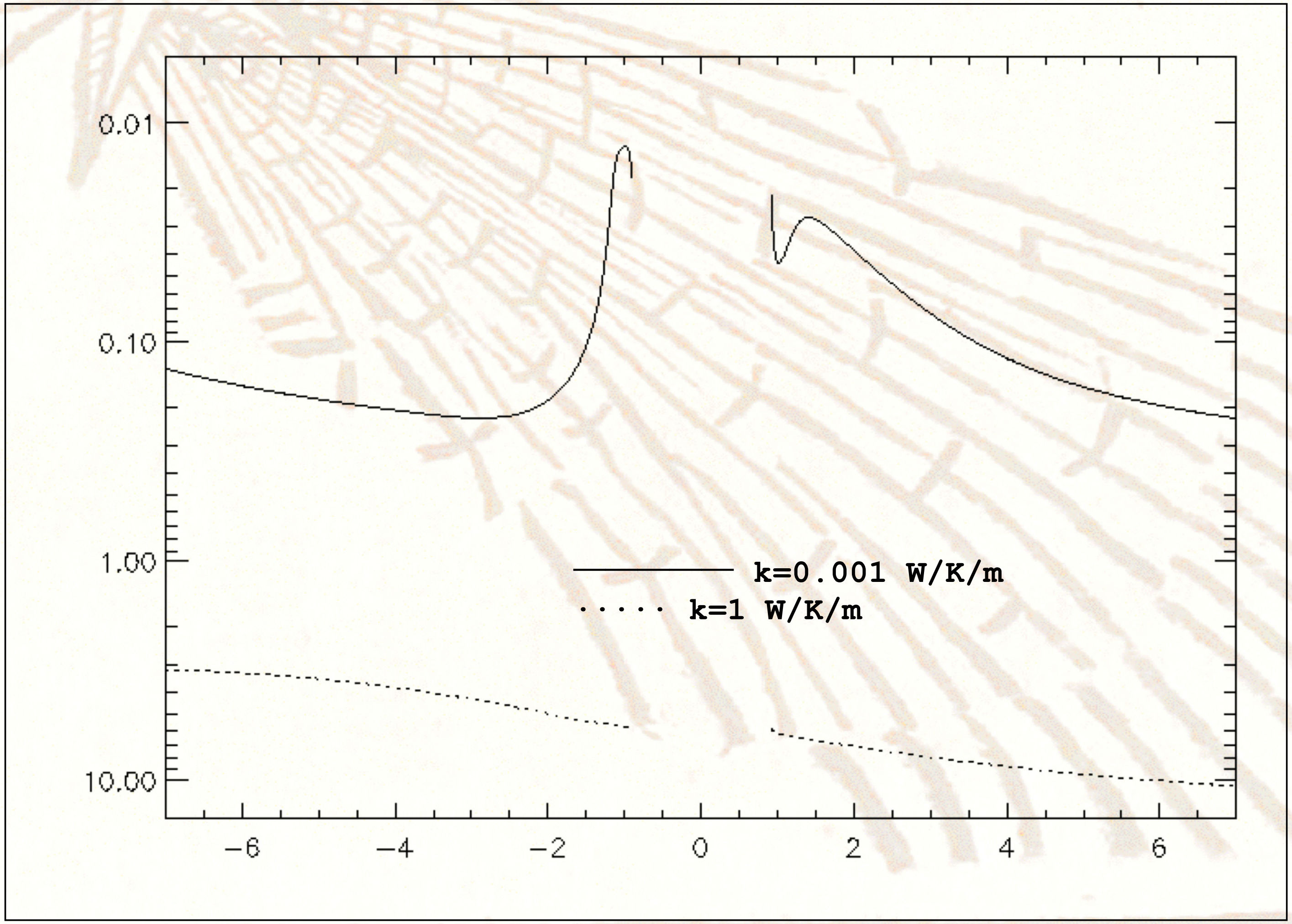
(Kührt, Knollenberg, Groussin)



Modeled and measured CO production rates



Depth of the CO sublimation front



Conclusions

- Surprisingly, the Hale-Bopp CO sublimation rates are nearly proportional to $1/r_h^2$ or to the solar energy input

  Hale-Bopp water and CO data strongly indicate a low thermal conductivity of the nucleus (k = 0.001 W/Km) and, therefore, a high porosity

  As a consequence the CO sublimation front in an active area is near the surface (some cm)

Cometary Encounters

What have we learned from the flybys?

Giotto

1P/Comet Halley

- retrograde orbit 76 y
- perihelion 0.84 AU
- Oort cloud

Stardust

81P/Comet Wild 2

- Jupiter family orbit
- perihelion 1.58 AU

Deep Space 1

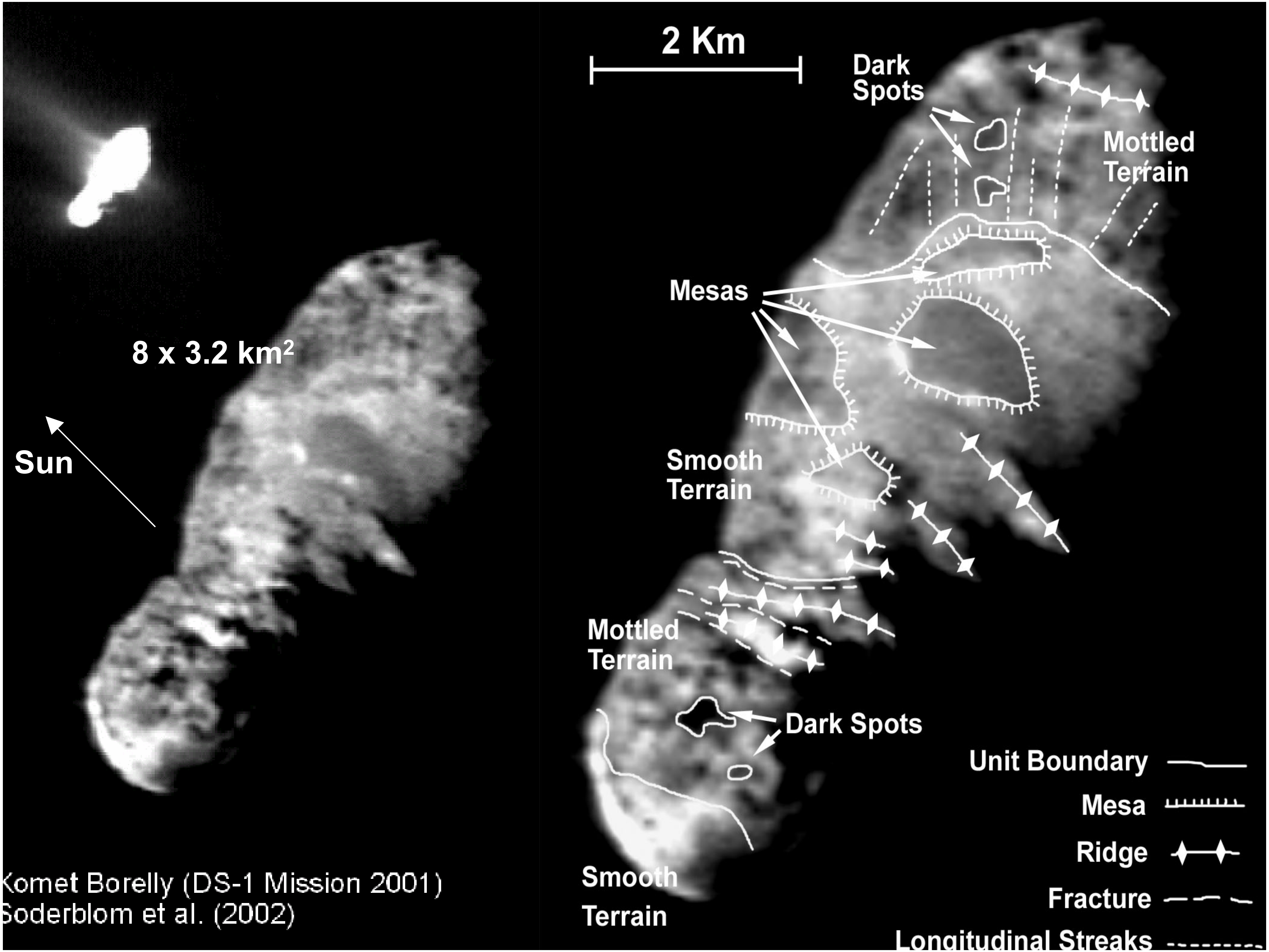
19P/Comet Borrelly

- Jupiter family orbit
- perihelion 1.36 AU

Deep Impact

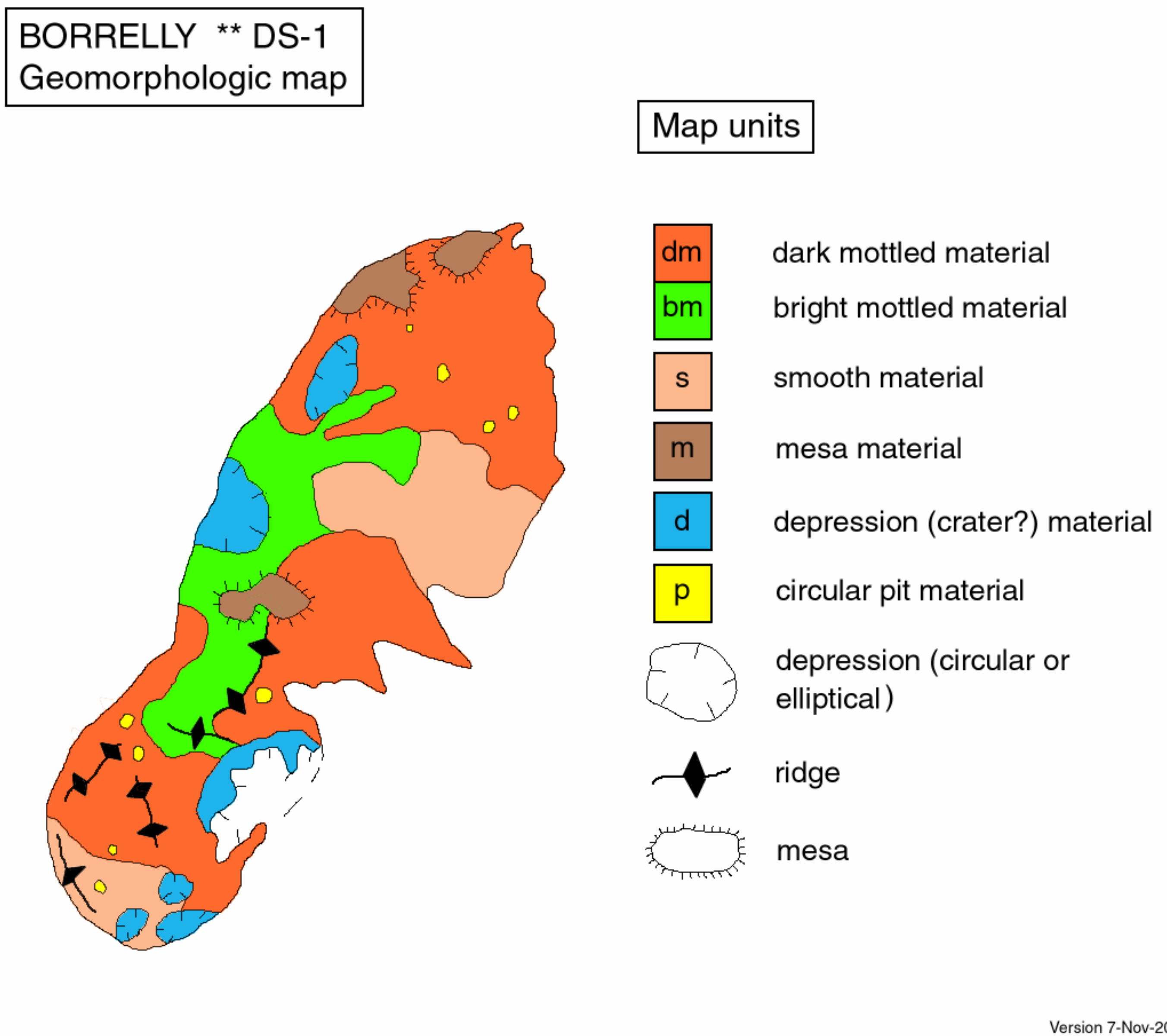
9P/Tempel 1

- Jupiter family orbit
- perihelion 1.32 AU



Komet Borelly (DS-1 Mission 2001)
Soderblom et al. (2002)

Comet Borrelly Surface Units

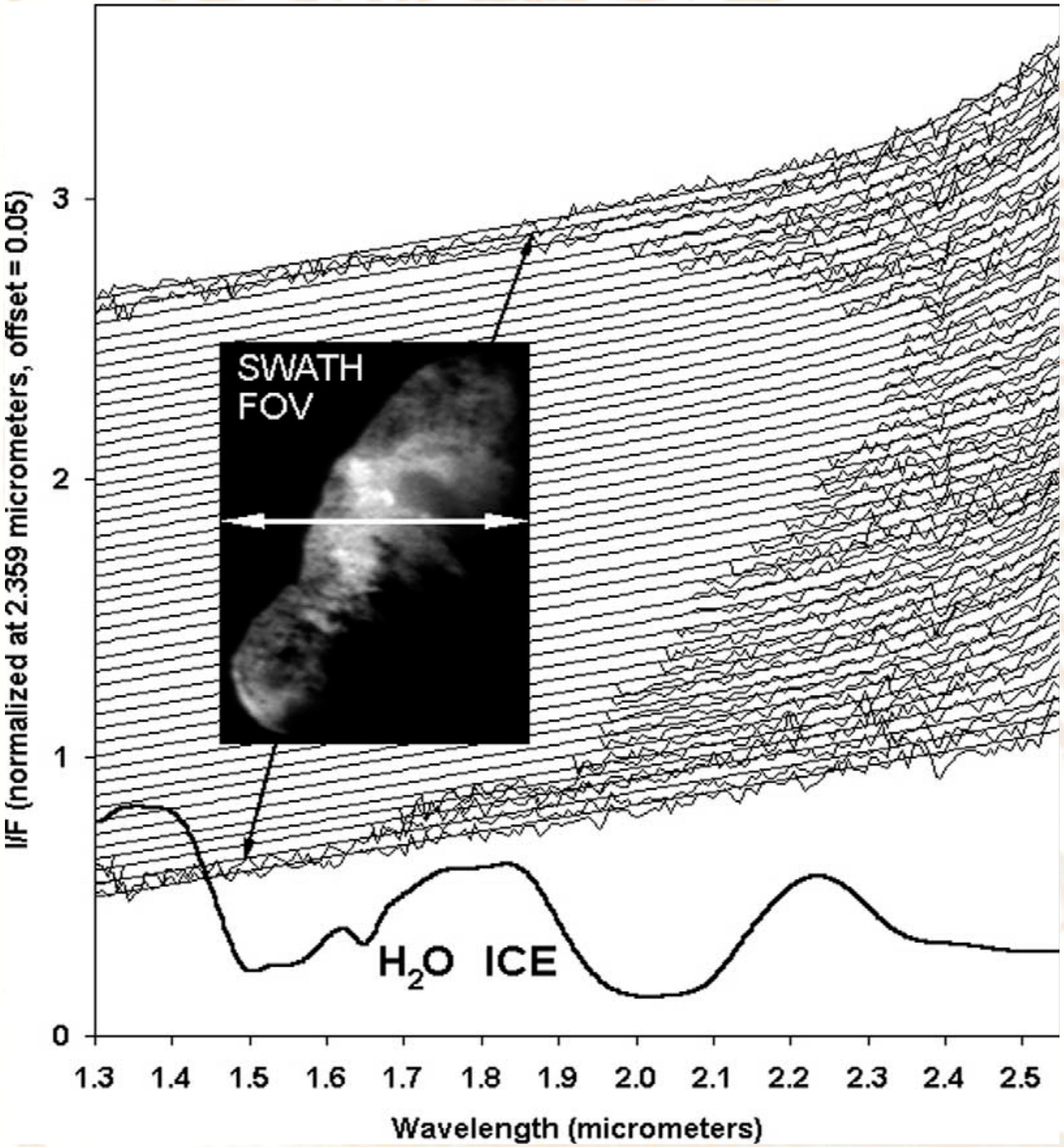


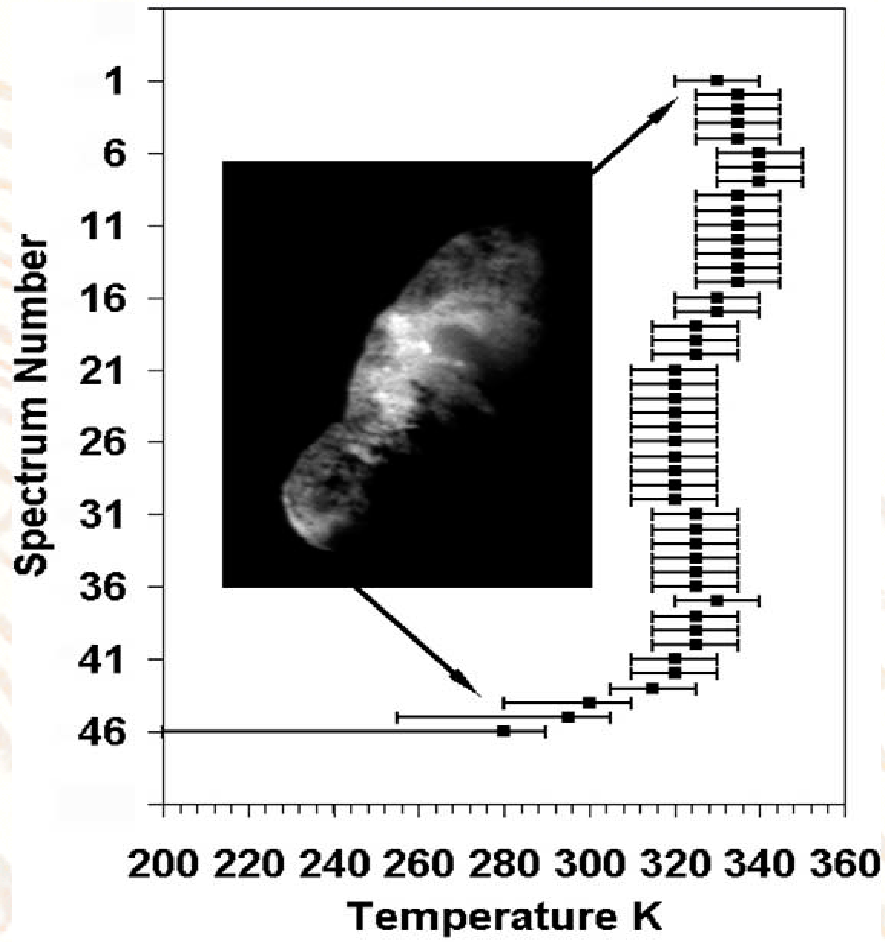
Surface albedo:

0.02 and strong variations (Buratti et al. 2004)

0.056 and little variation (Kirk et al. 2004)

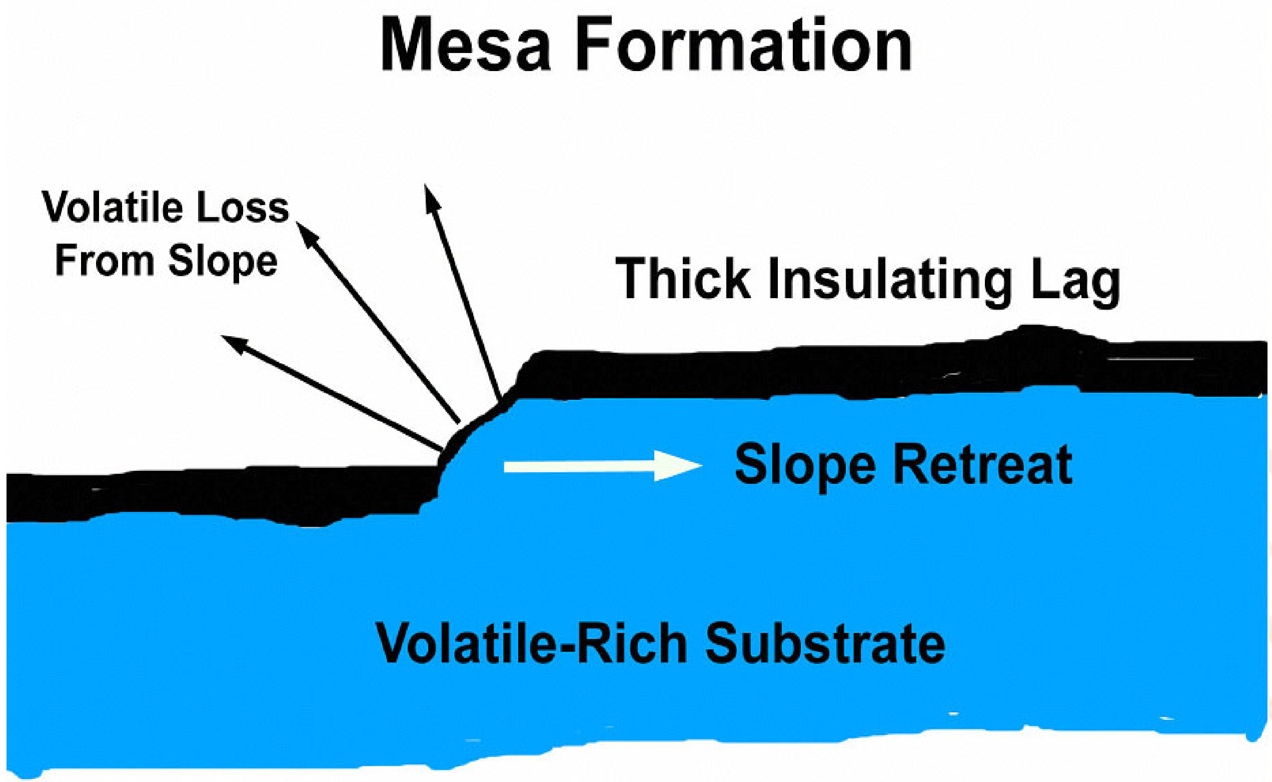
IR Spectra of 19P/Borrelly





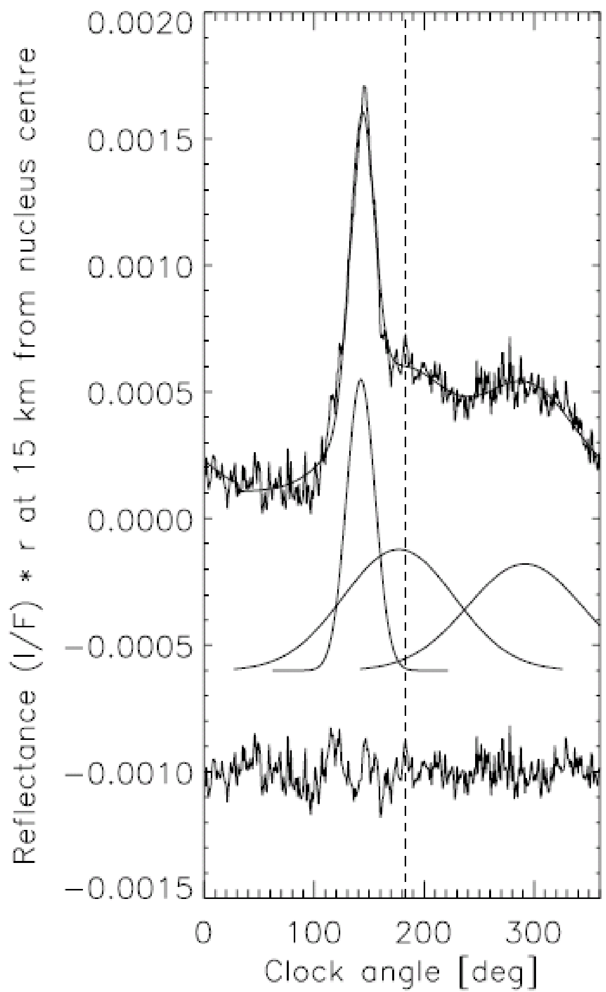
Soderblom et al. (2004)

Does this explain activity?

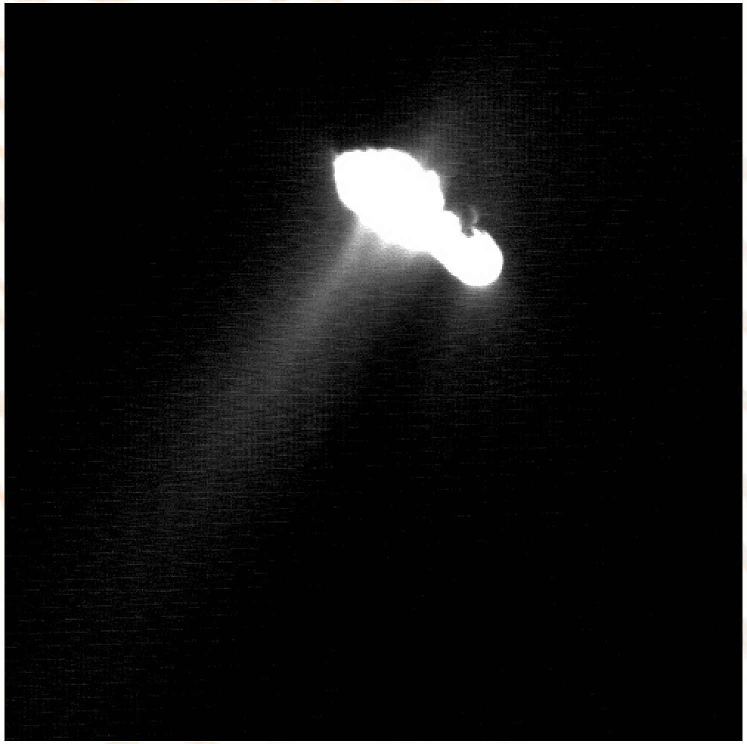


Volatile loss undermines the mesa tops and collapses the lag material down to the "Smooth Terrain" valley floor.

Jet Distribution in Borrelly's Inner Coma



Main jet contributes 19-24% to the inner dust coma. FWHM is only 18°.

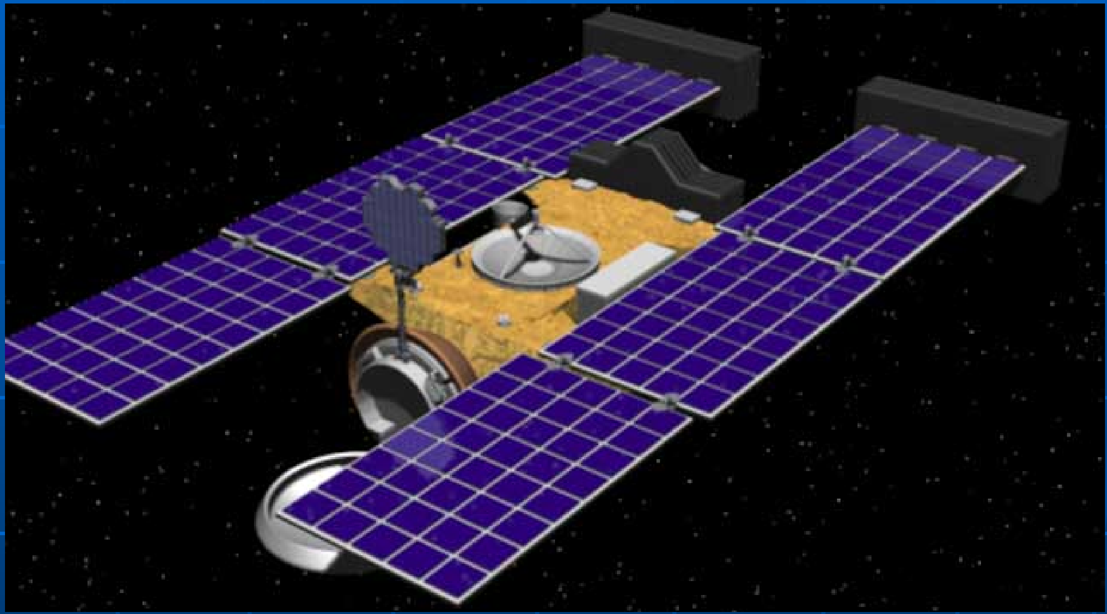


Ho et al., 2002

19P/Borrelly Summary

- Bimodal surface slopes => 2 gravitational aggregates (?)
- Single scattering albedo:
  - Either extremely small and highly variable 0.008 to 0.024
  - Or “normal” 0.056 (Kirk et al. 2004)
- Localized activity in narrow jets (α an β)
- High surface temperature (330 K)
- No sign of water

STARDUST



81P/Wild 2

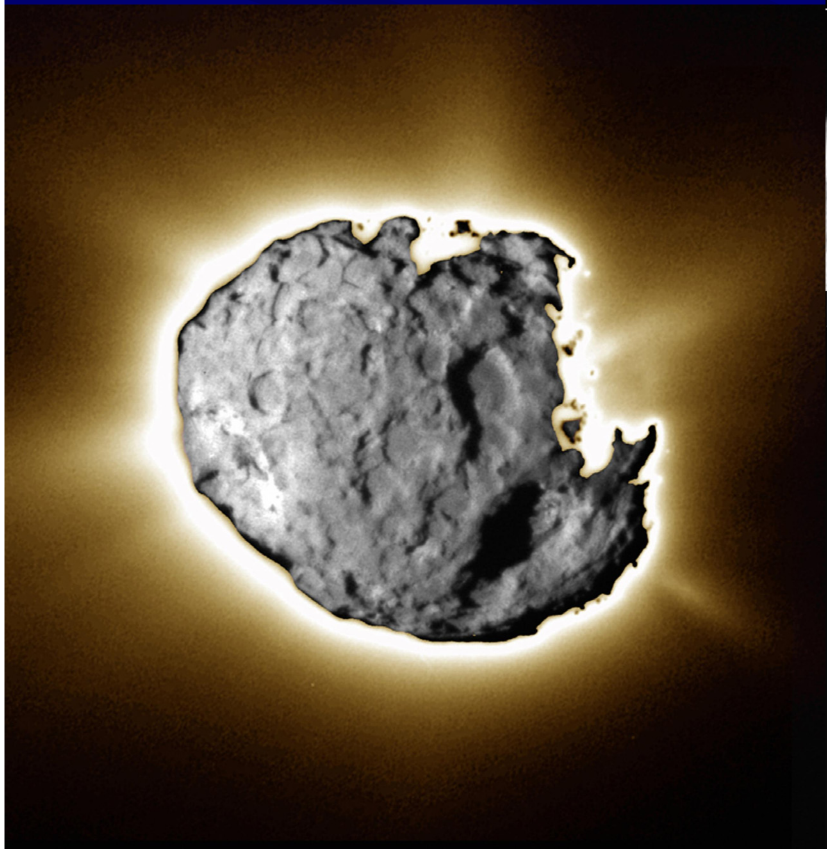
Stardust flyby of 81P/Wild 2 at 236km on 2 jan. 2004 (6.1km/s)

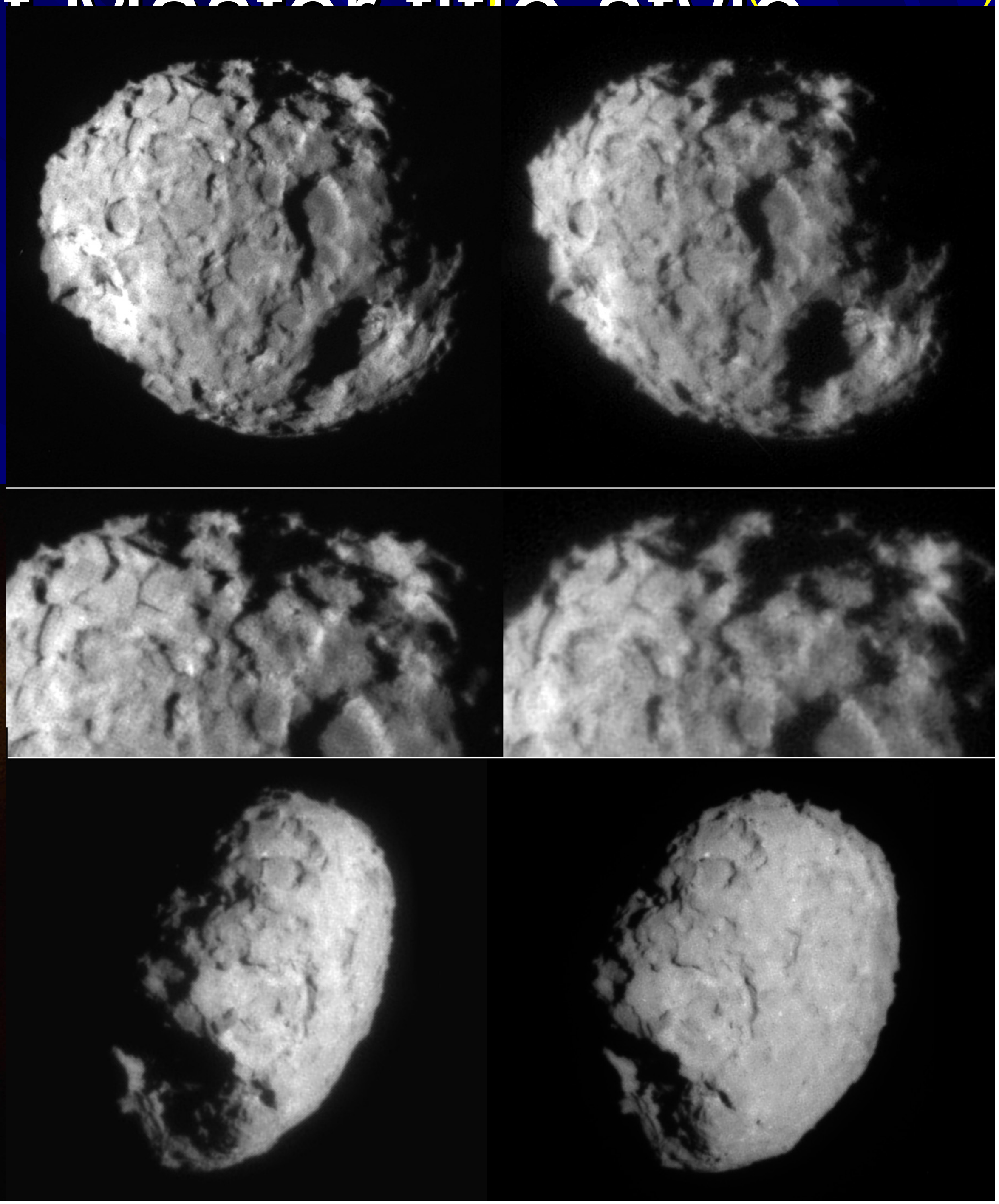
Nucleus

5.5 × 4.0 × 3.3 km

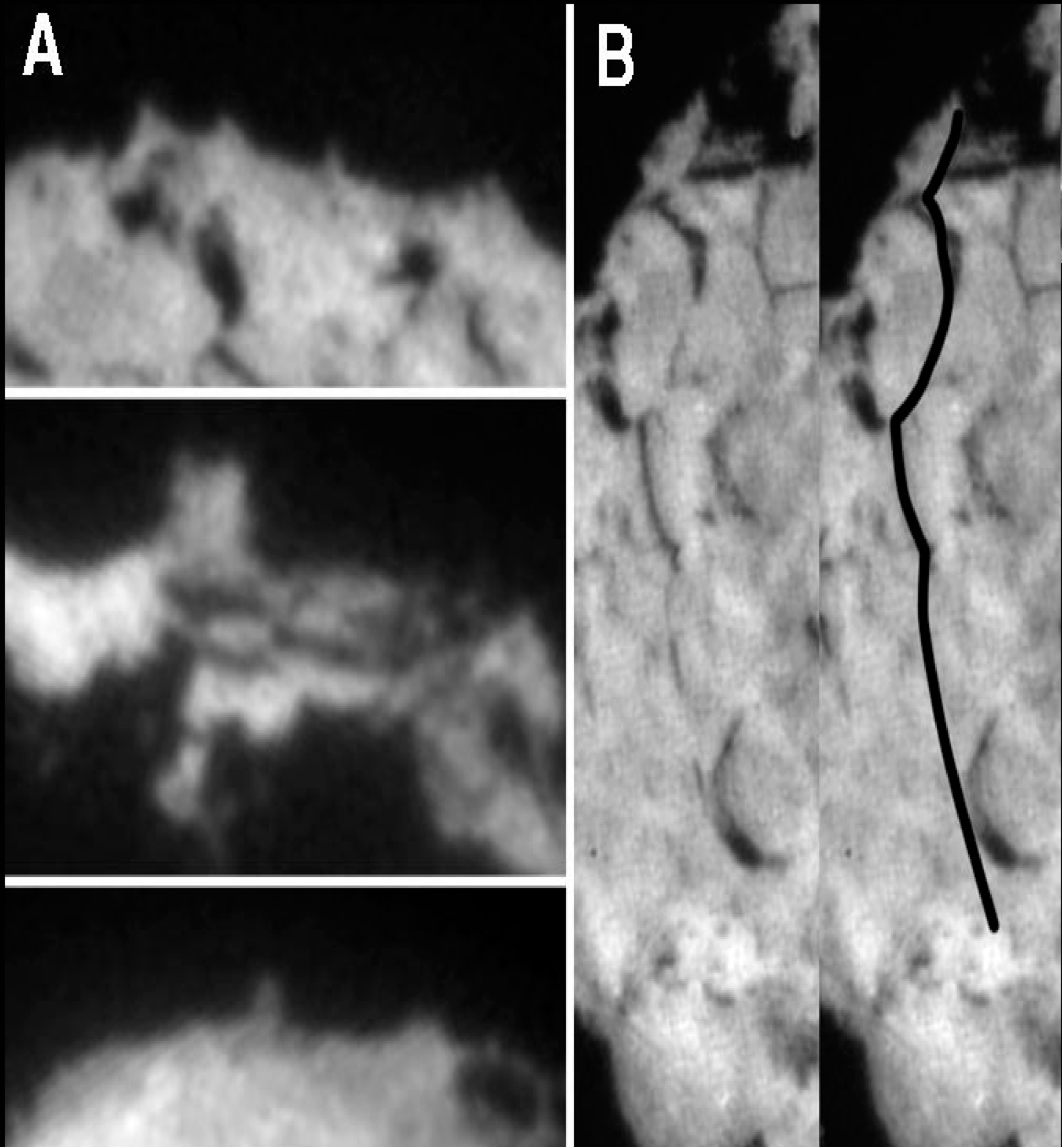
Albedo = 3%

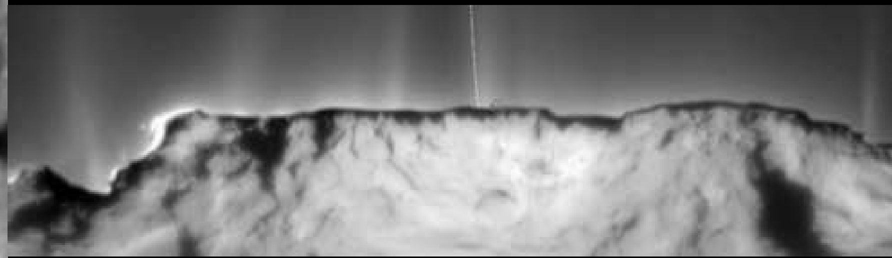
r_h=1.86 UA Q_{H2O}=0.2 t/s





81P/Wild 2 (Stardust)





The jets appear to be normal to the limb rather than be radial from the nucleus center. The white line near the center above the limb indicates the direction to the sun.

(A) A variety of small pinnacles and mesas seen on the limb of Wild 2. (B) The location of a 2-km series of aligned scarps that are best seen in the stereo images.

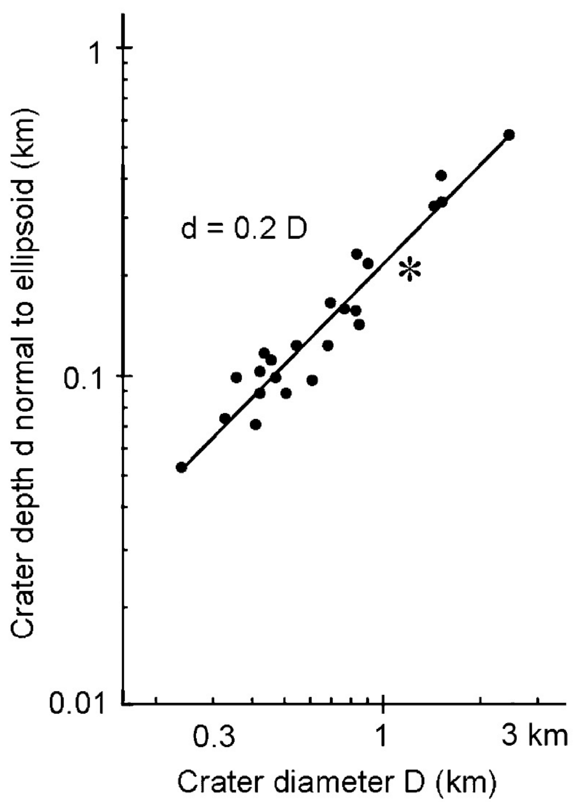
Wild 2 surface <u>is not similar</u> to asteroid, satellite or other comet surfaces!

Wild 2

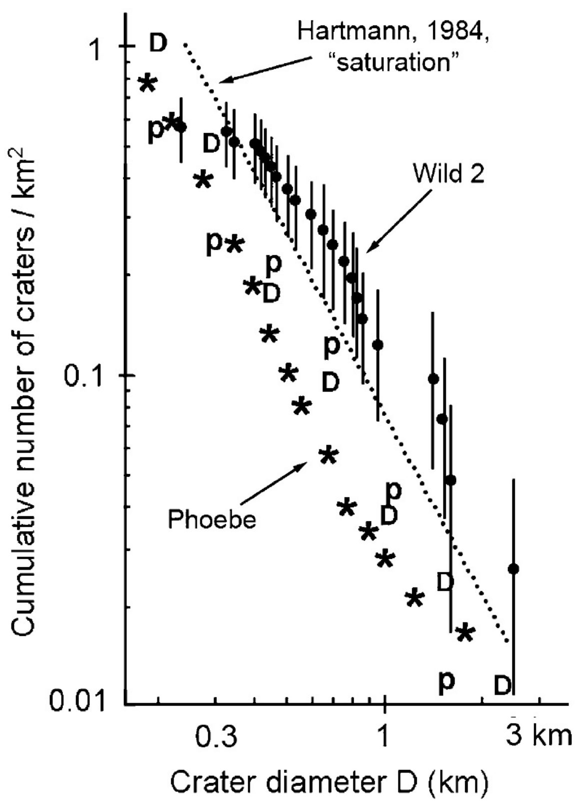
Ida

Dactyl

Wild 2 Craters



Kirk et al. (2005)



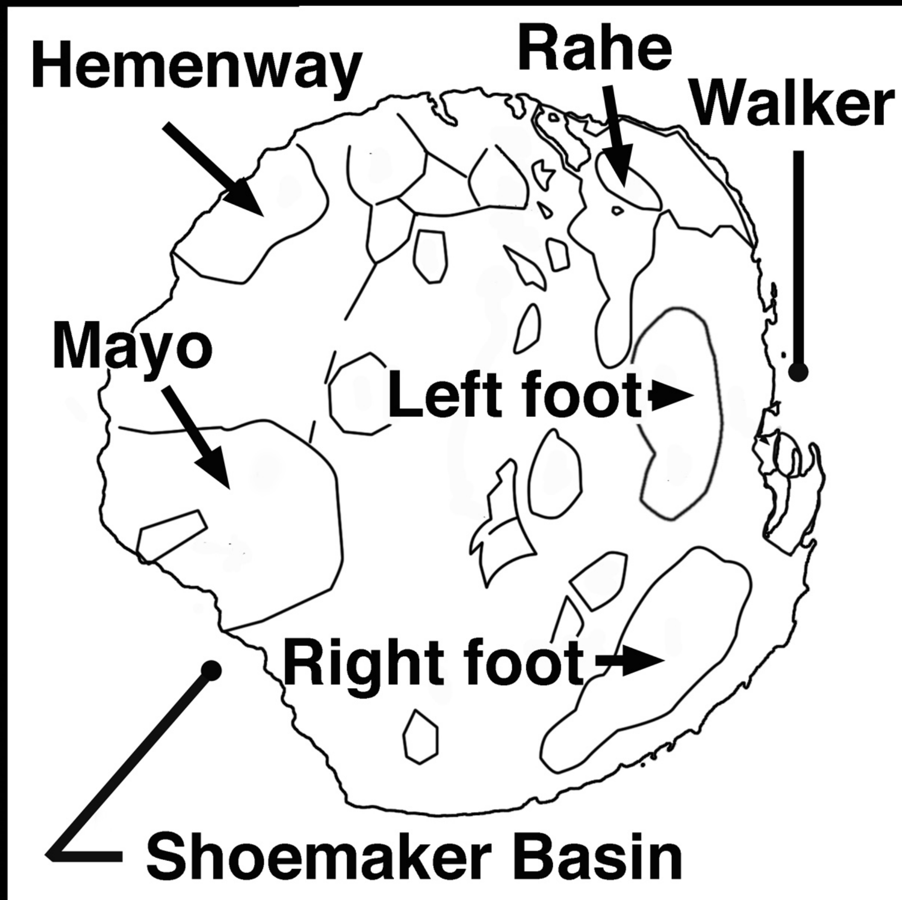
Basilevsky and Keller (2006)

Surface densely cratered

Beyond saturation line => diameters increased by sublimation

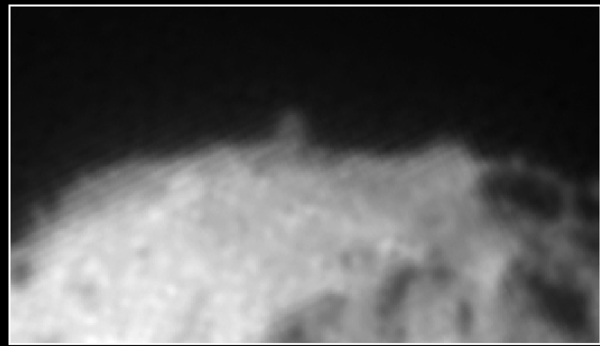
Cratering occurred early in the life of the comet

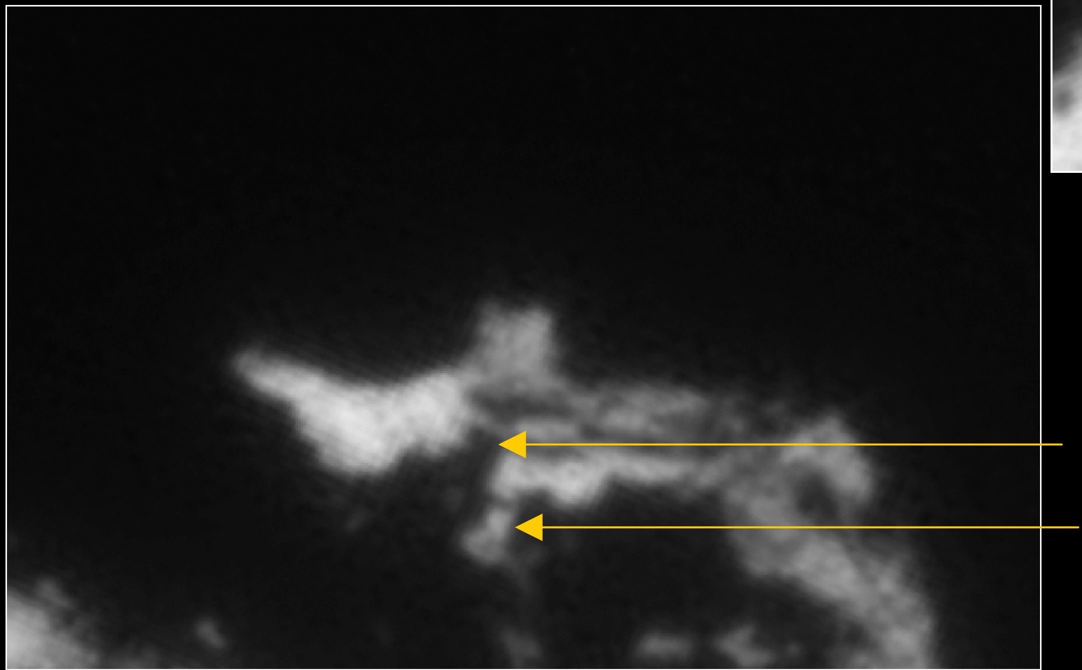
Wild 2 Map


Hemenway
Rahe
Walker
Mayo
Left foot
Right foot
Shoemaker Basin

Wild 2's pinnacles

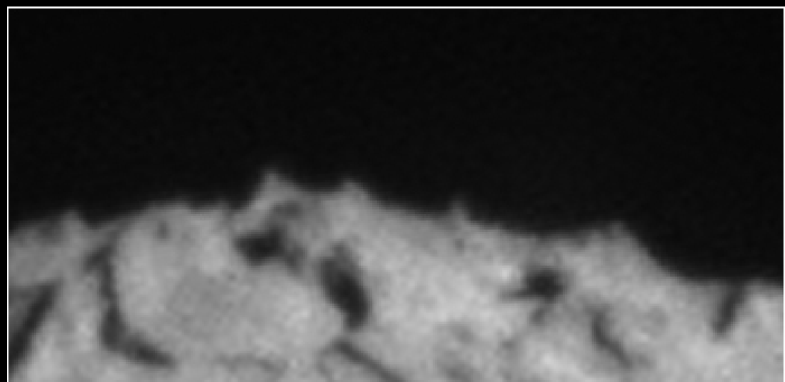
(Monument Valley in dirty ice)





pinnacle shadow

pinnacle

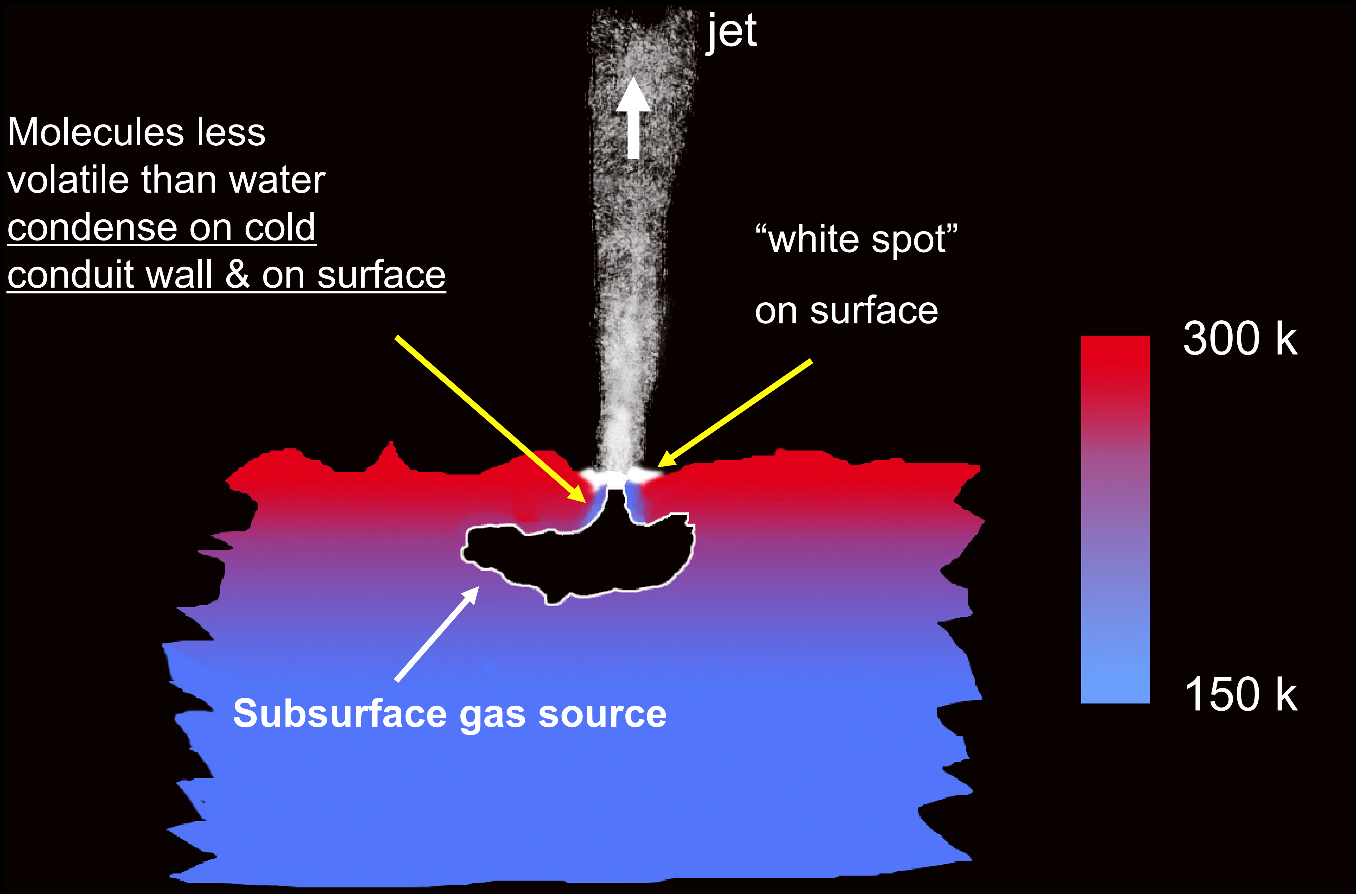


Bright spot

Cold Spot?

Condensed material?

Possible origin of "white spots" & pinnacles



81P/Wild 2

- Higher resolution reveals very rough surface on all scales
  - **Deep craters with steep walls (some depth to diameter ratio: > 0.3!)**
  - **Craters formed in strength regime (Brownlee et al. 2004)**
  - **Cliffs and overhangs**
  - **Pinnacles and spires (100 m high)**
- Localized activity in narrow jets, filaments (perpendicular to topographic relief)
- Uniform and “normal” albedo: 0.03 ± 0.015
- Active areas cannot be discerned
- Elongated oblate nucleus (1.65 x 2.00 x 2.75 km^3)
- Eroded surface features (craters)
- No surge in brightness near zero phase => no regolith of small grains (Duxbury et al. 2004)

Some Conclusions

Not a rubble pile

Cliffs, pinnacles & overhangs $\Rightarrow$some strength
Long (> 2 km) features (scarps)

Very rugged surface with many depressions

No classic impact craters, surface is older than that of previous comets

Crater density saturated (old!)

Mesas, pinnacles, and other erosional remnants

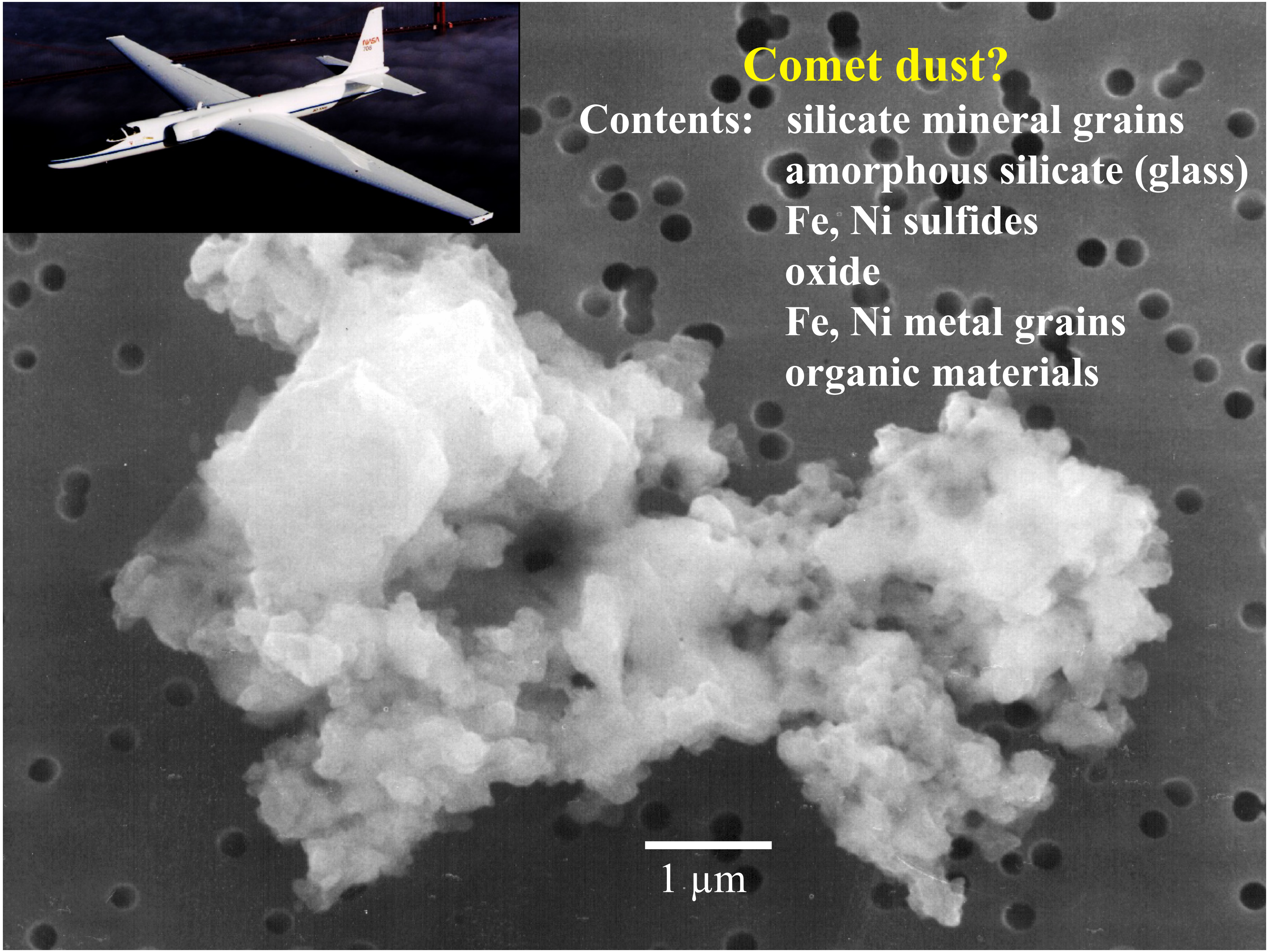
Suggest >100m loss of original surface, earlier visit(s) into the inner solar system

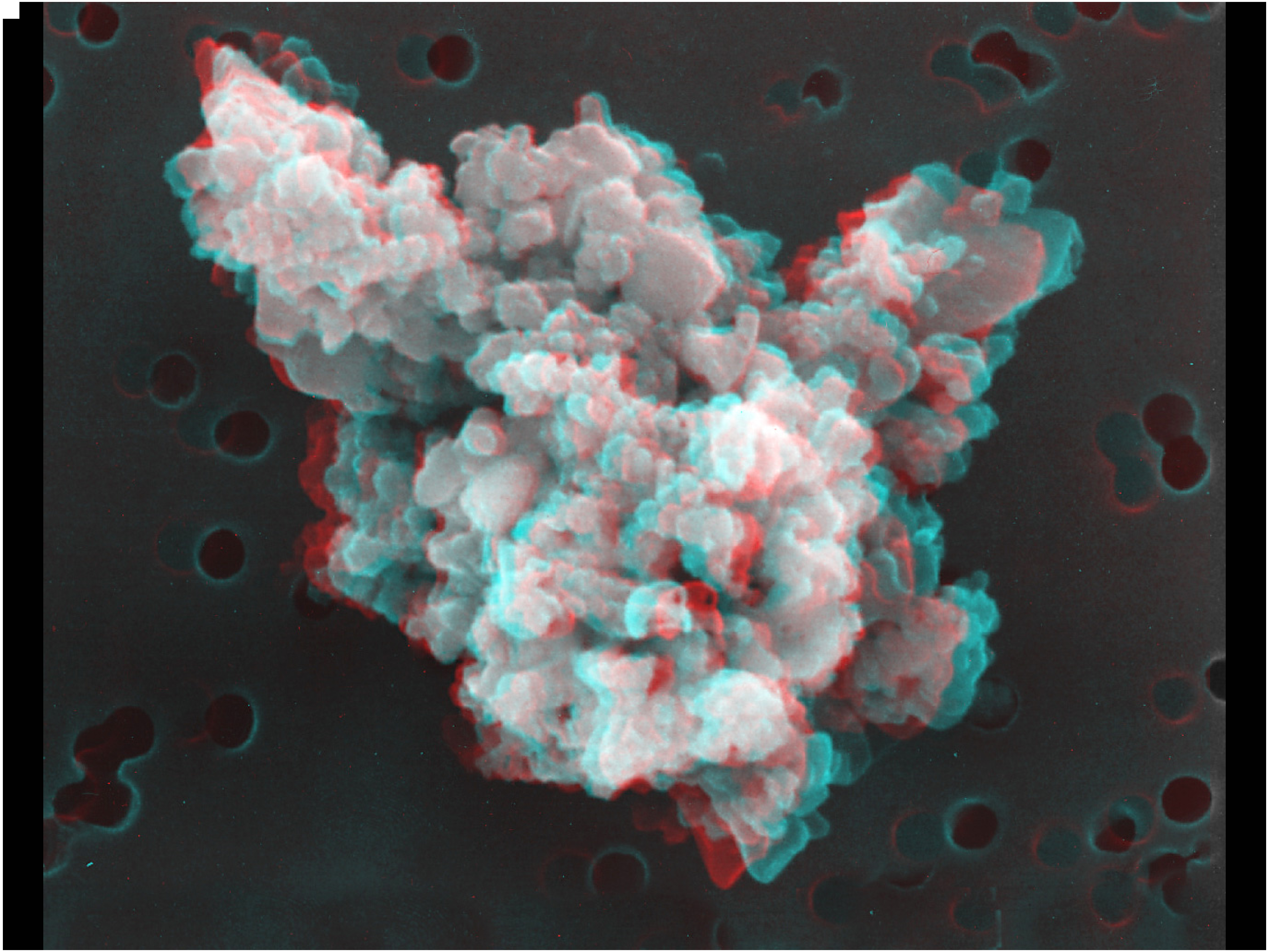
Jet sources are small, numerous, and highly collimated

Some active in the shade
Illuminated pole region appears to be inactive

Are the observations consistent with the properties of Chondritic Porous (CP) IDPs

?


Comet dust?
Contents: silicate mineral grains
amorphous silicate (glass)
Fe, Ni sulfides
oxide
Fe, Ni metal grains
organic materials
1 μm



Grain size

- The 10µm silicate feature requires the presence of submicron silicates.
- Submicron silicates cannot be made during the ejection process…they must be original accreted grains
- CP IDPs are aggregates of submicron grains

Porosity

- **Wild 2 surface appears to be a rigid freeze-dried material with relatively uniform albedo**

- **CP IDPs are a weak, porous, uniform material that is weak but strong enough to produce pinnacles, mesas and overhangs**

Structure

The open porous structure of CP IDPs is (probably) a natural result of

A) gentle accretion of submicron silicates, organics and ice

B) gentle sublimation of the ice

CP IDPs are the most porous, fragile and primitive meteoritic materials

Fragmentation of Dust

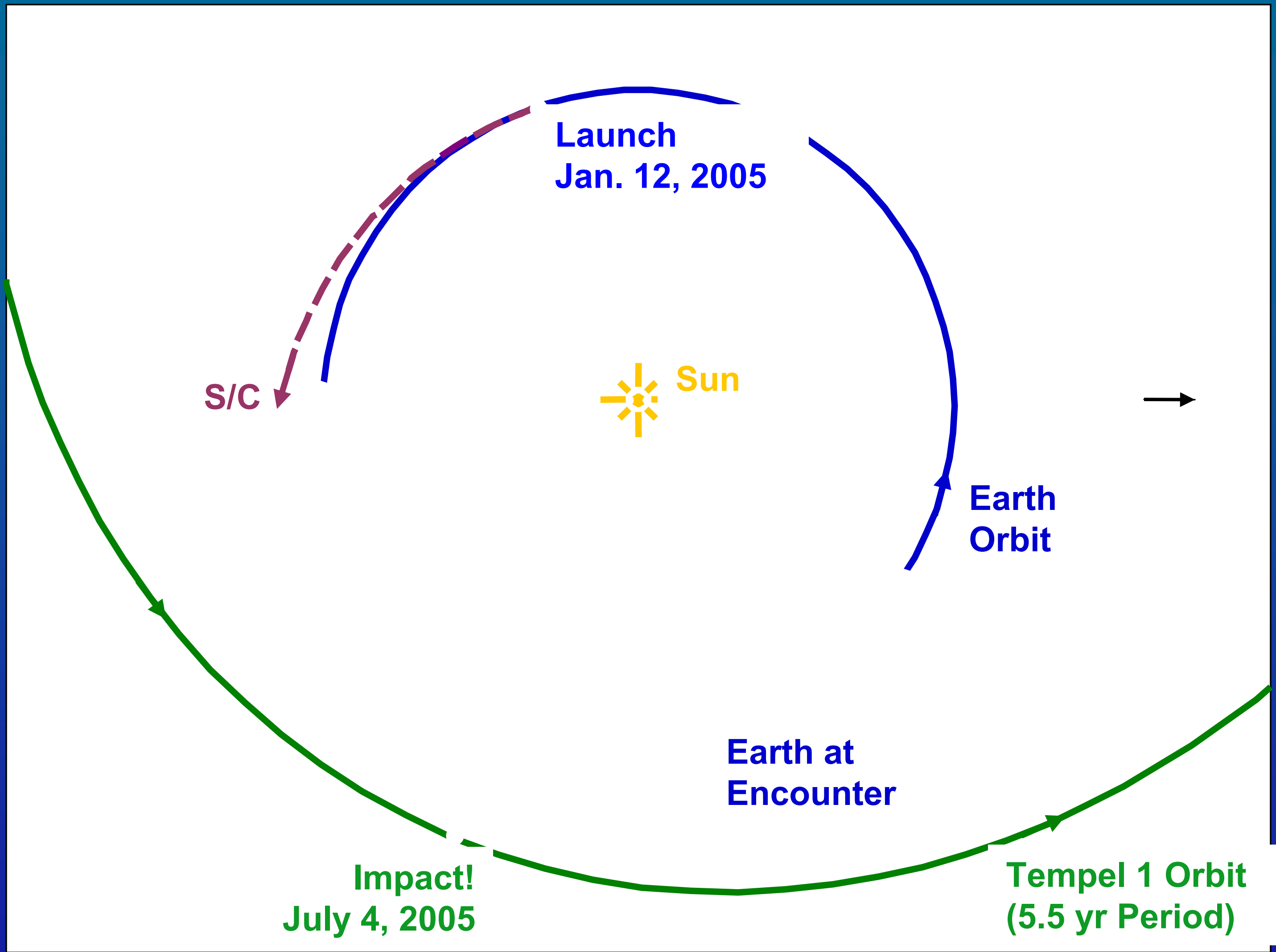
- Stardust dust measurements and other observations indicate that comet dust fragments after ejection

- Highly porous aggregates fragment easily

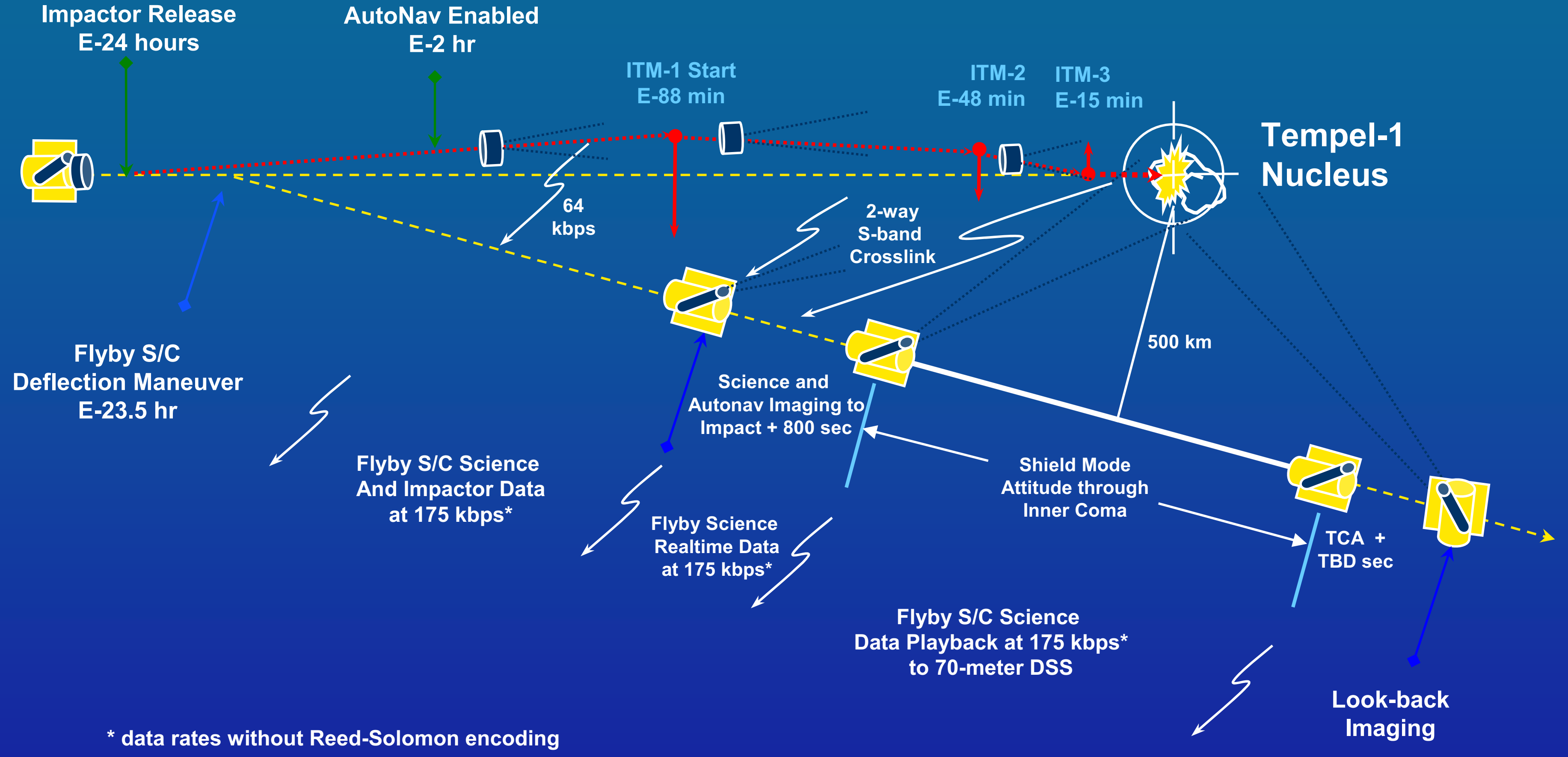
Deep Impact

- **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

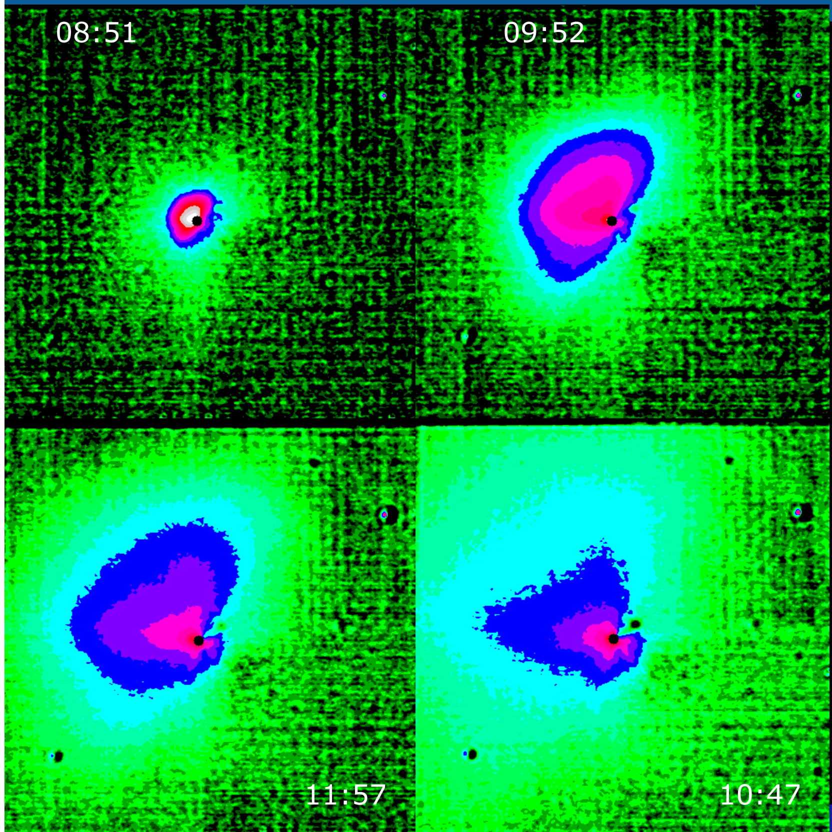


Encounter Schematic

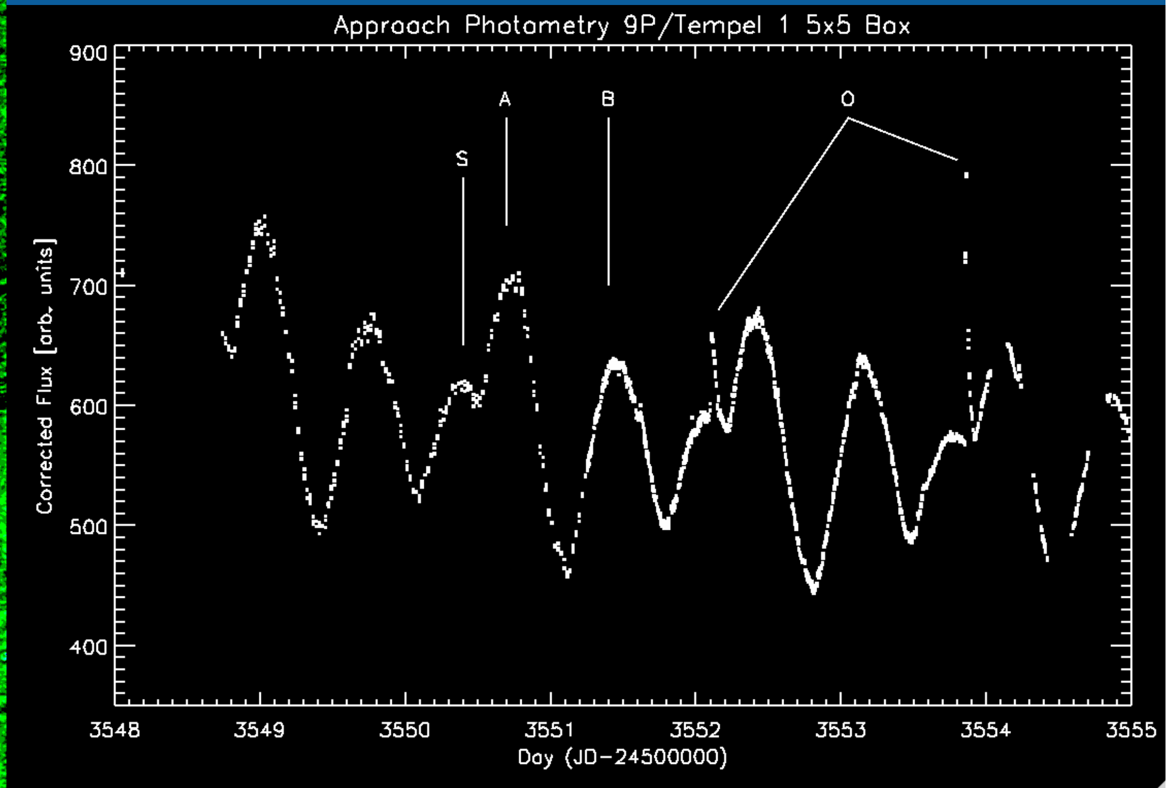


Approach Photometry

~~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

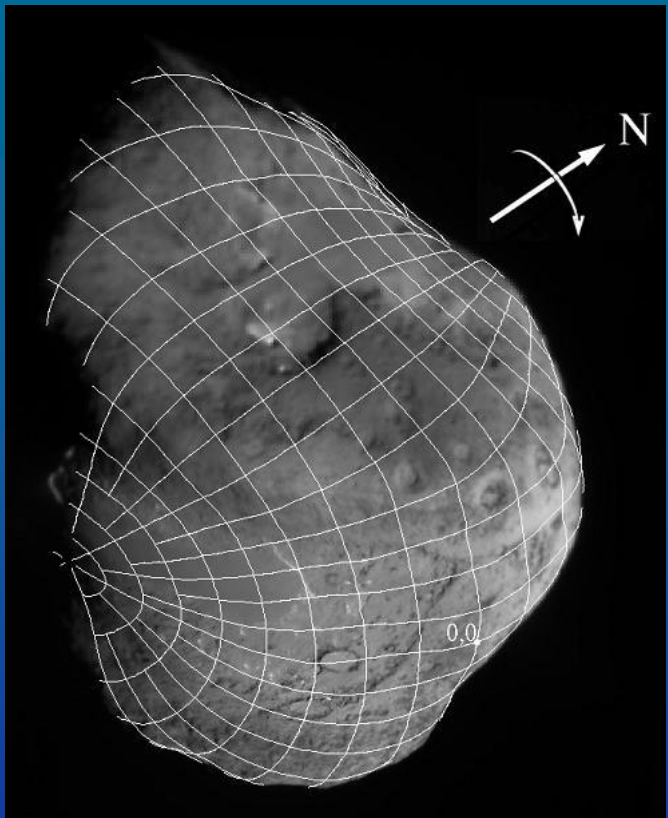


2 July Outburst by *D. Lindler*



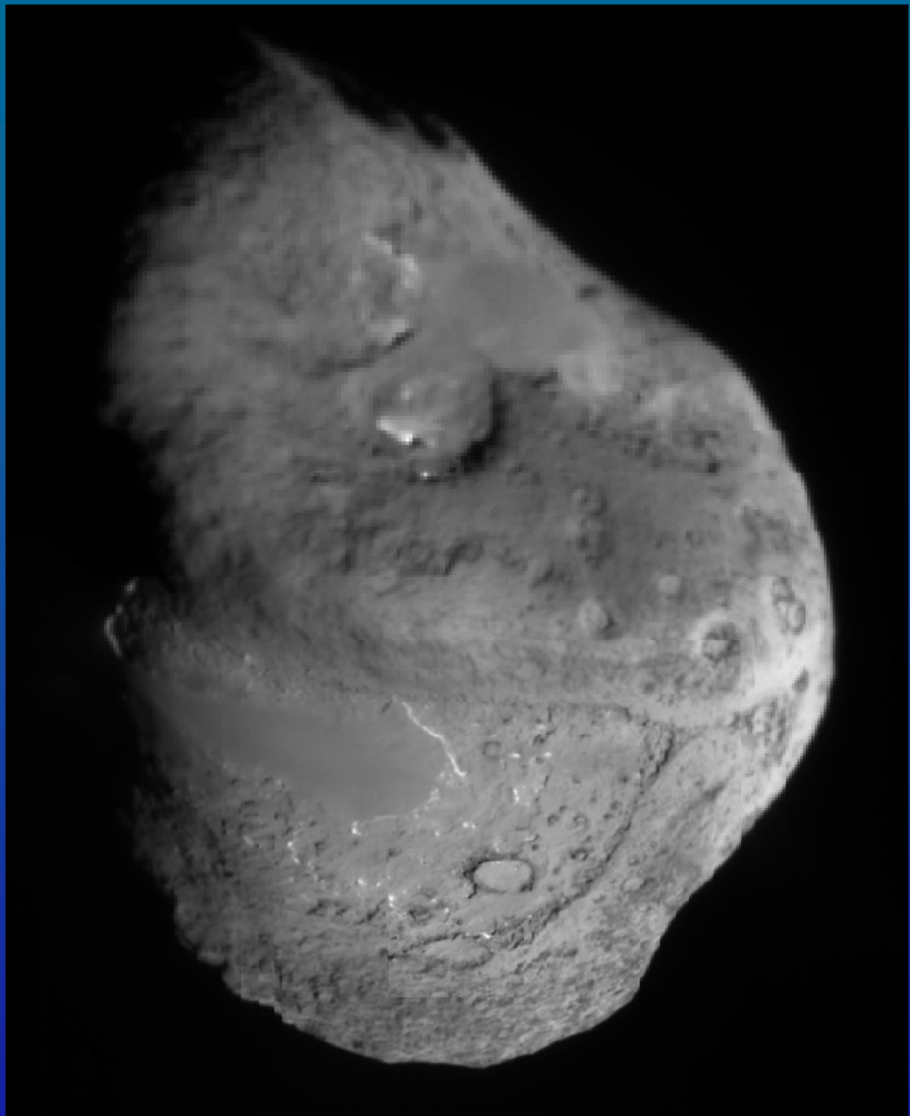
A'Hearn *et al.* 2005 *Science* **310**, 258

ITS Sequence

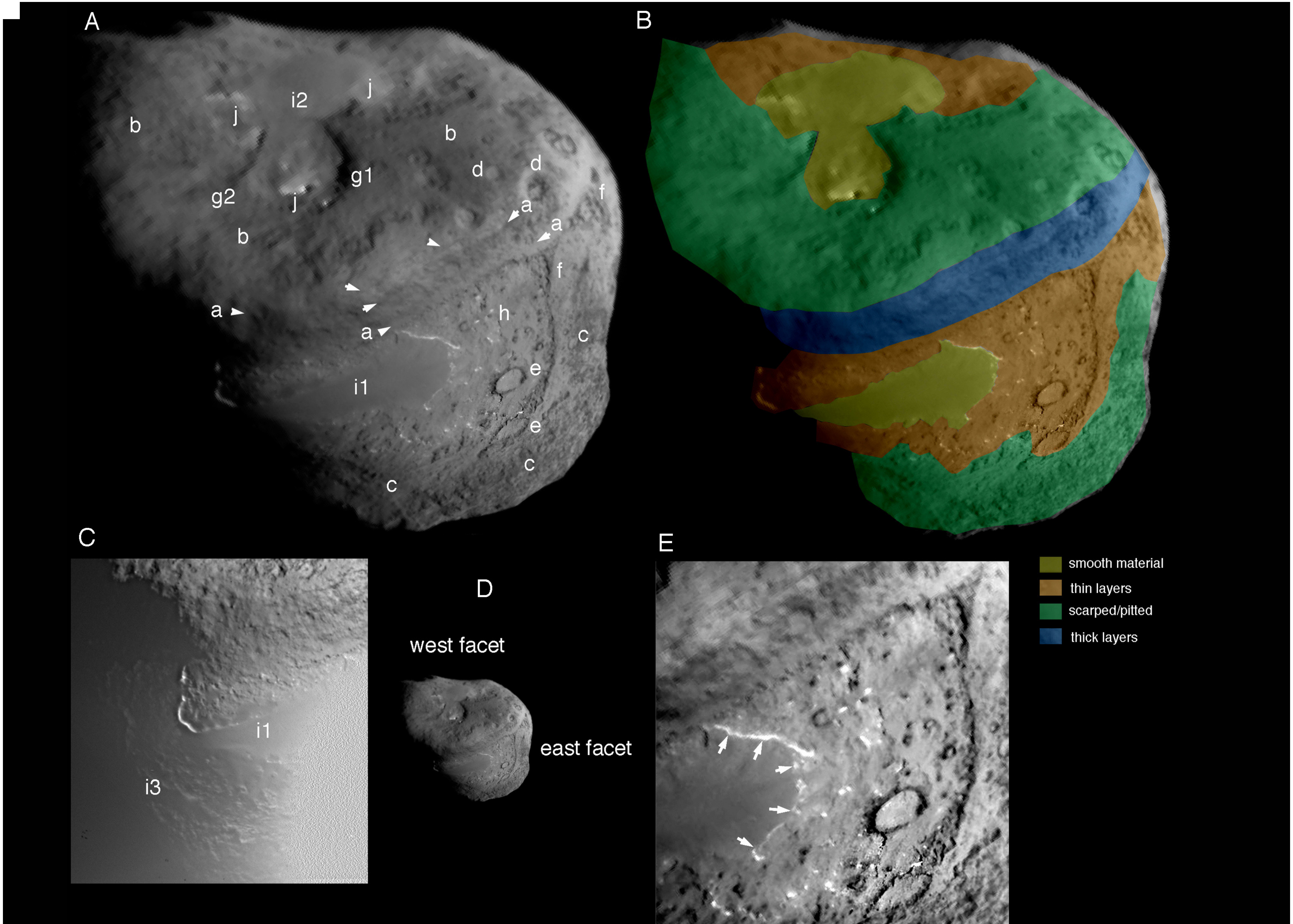


- ITS images - impact site indicated by arrows (now right side up - ecliptic north in upper right quadrant, sun to right)
- Sense of rotation - top is approaching
- Oblique impact - 36° from horizontal by shape model but 20 to 35° from assuming circular craters

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.

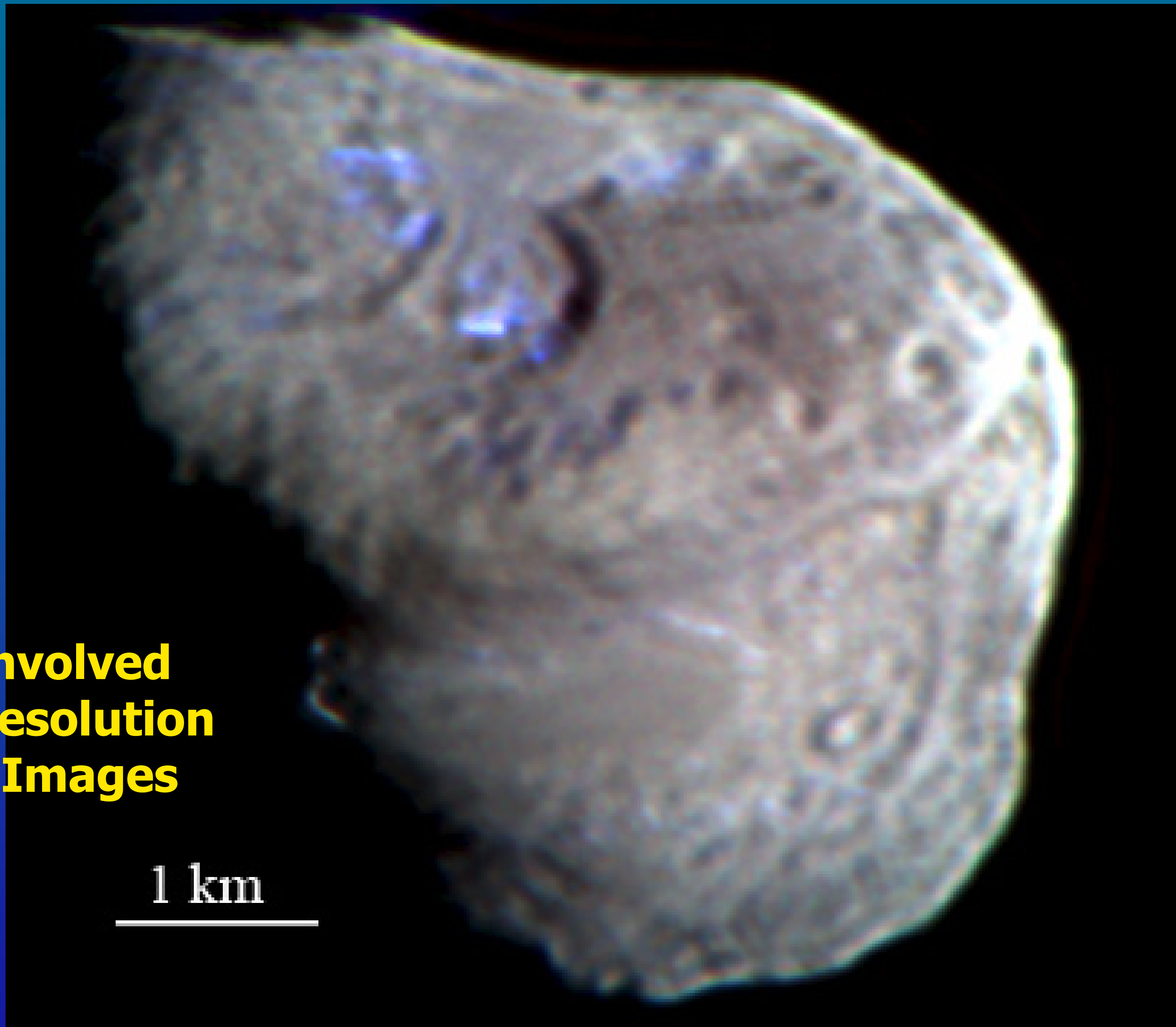


Thomas et al. (2006)

Tempel 1 Parameters

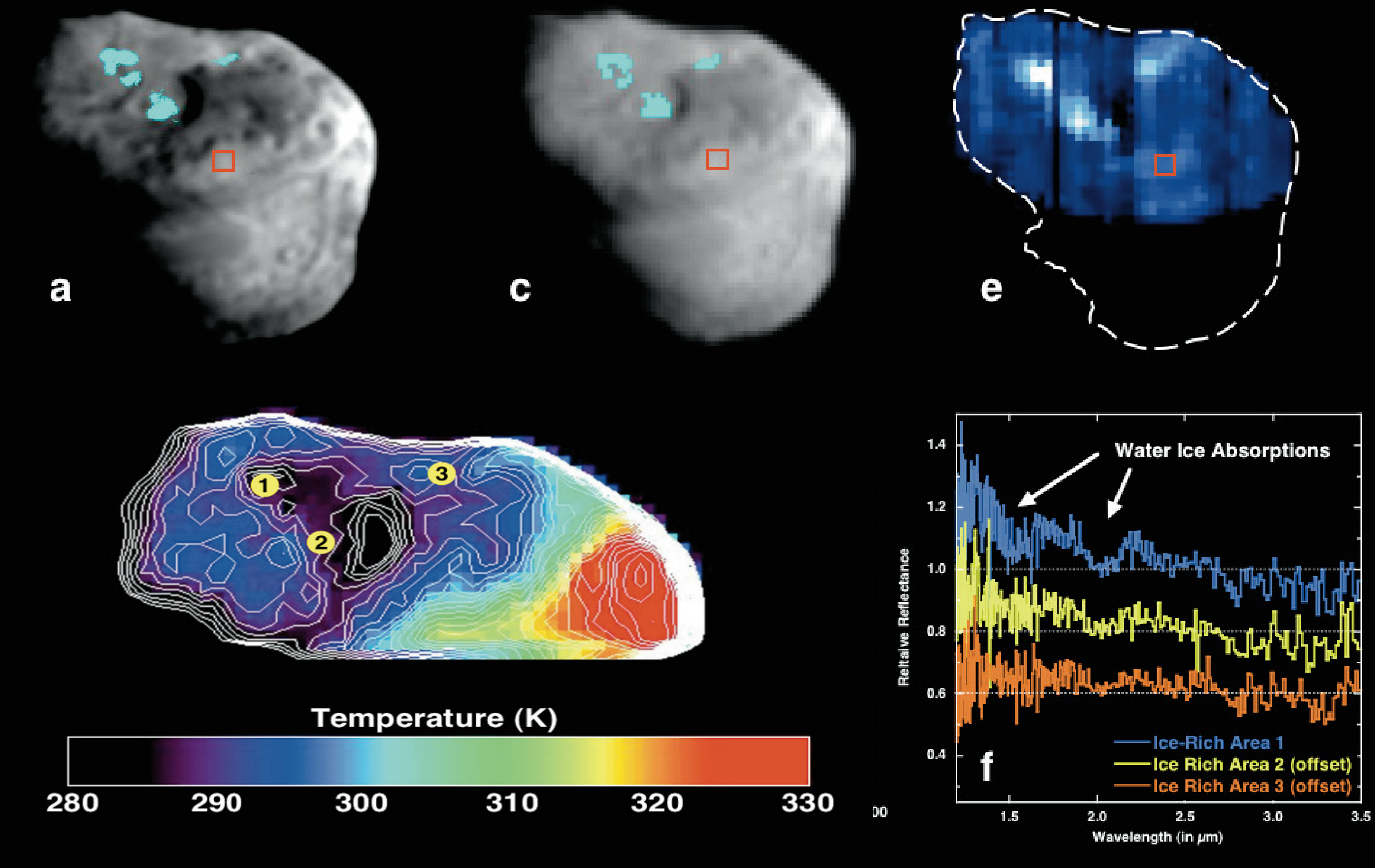
Mean radius: 3.0 ± 0.1 km
Diameter range: 5.0 - 7.5 km
Gravity: 0.024 - 0.030 cm $/s^2$
Area: 119 km^2
Range of gravitational heights: 0.73 km
Mean Density: 0.3 ± 0 .2 gm $/cm^3$

Anomalously Colored Regions



Deconvolved High Resolution Color Images

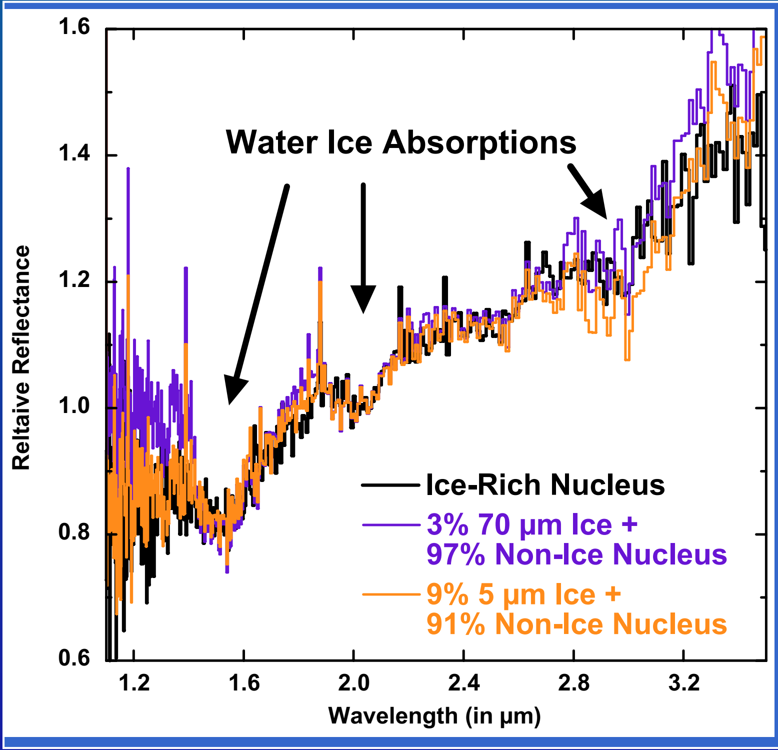
Sunshine et al. 2006, Science ***311****, 1453*

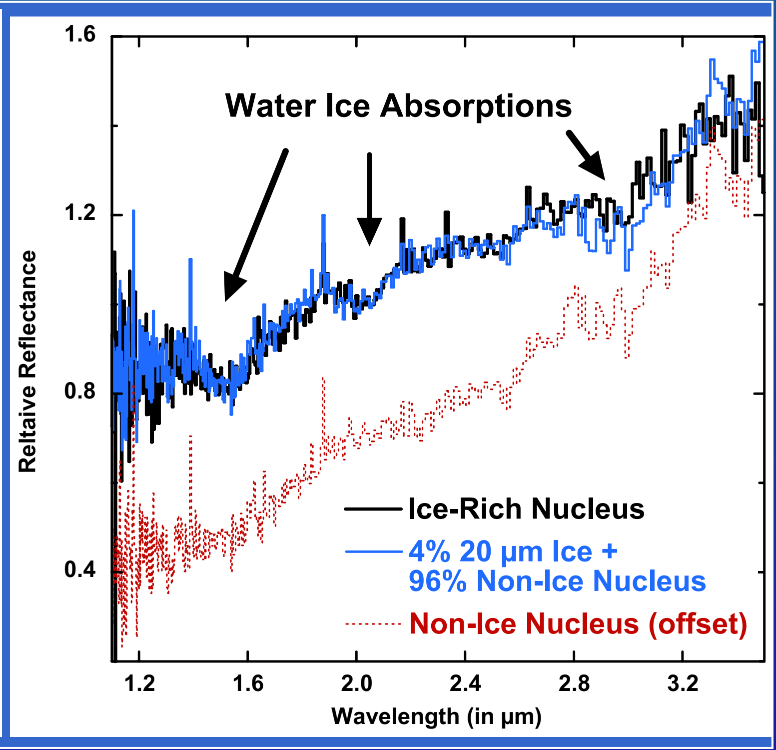


Sunshine et al. (2006)

Modeling Surface Water Ice

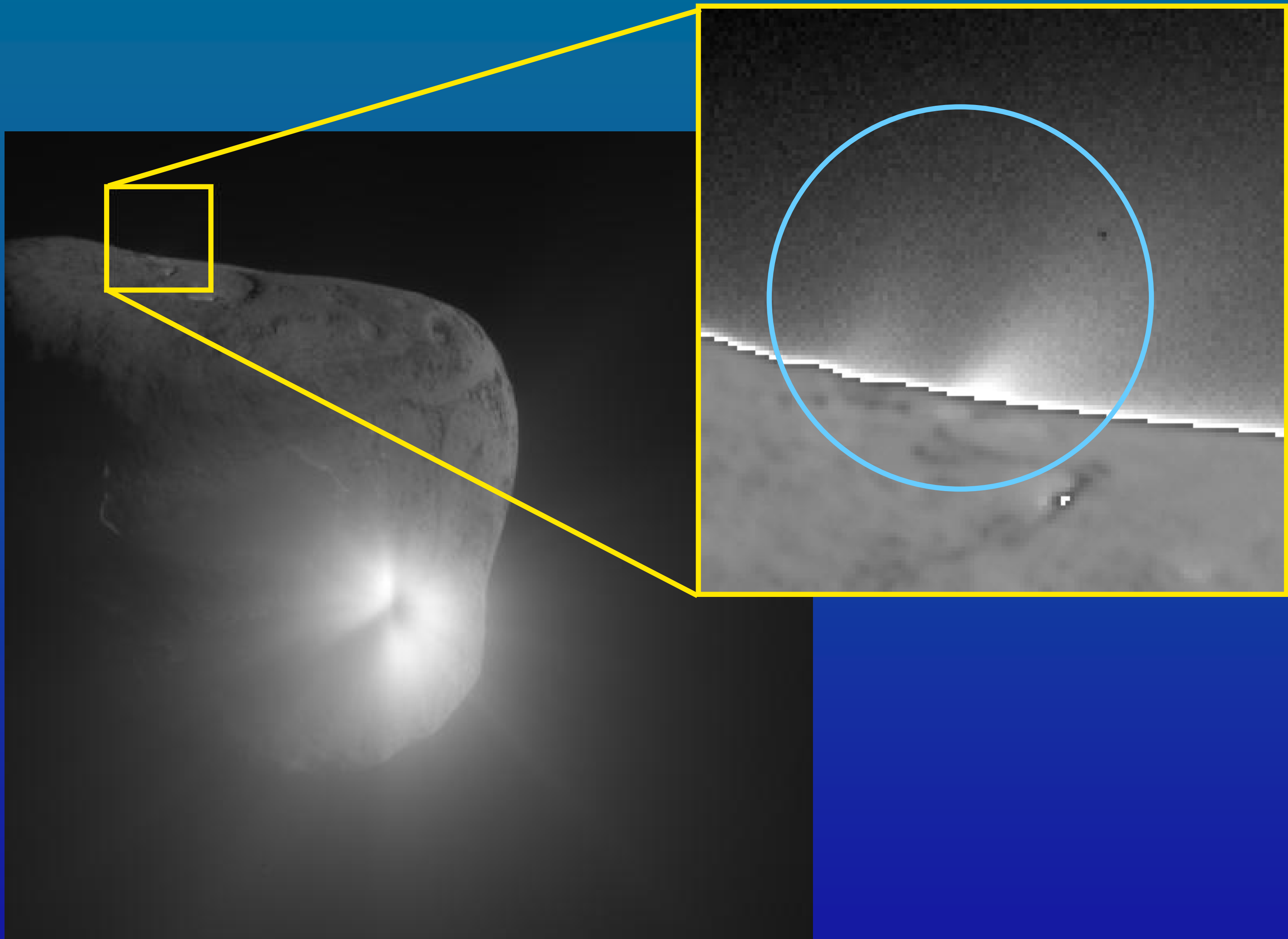
- Nominal (non-ice) nucleus + laboratory water ice
  - 3-6% water ice
  - 30 ± 10 μm size particles
- Not enough surface to be significant in overall outgassing
- Frost from source of outbursts on shoulder?

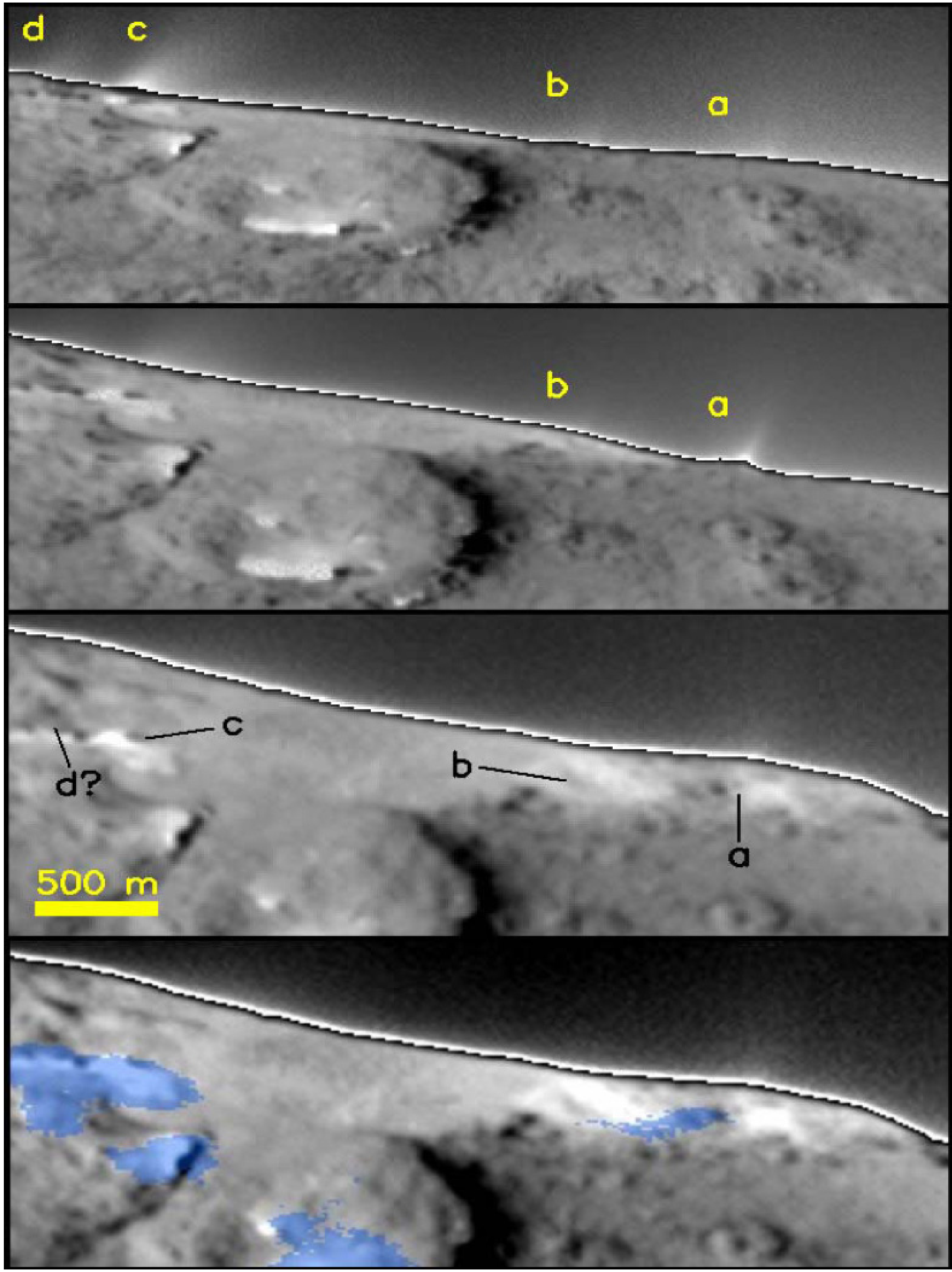




Sunshine et al. 2006 Science ***311****, 1453*

Activity off Limb

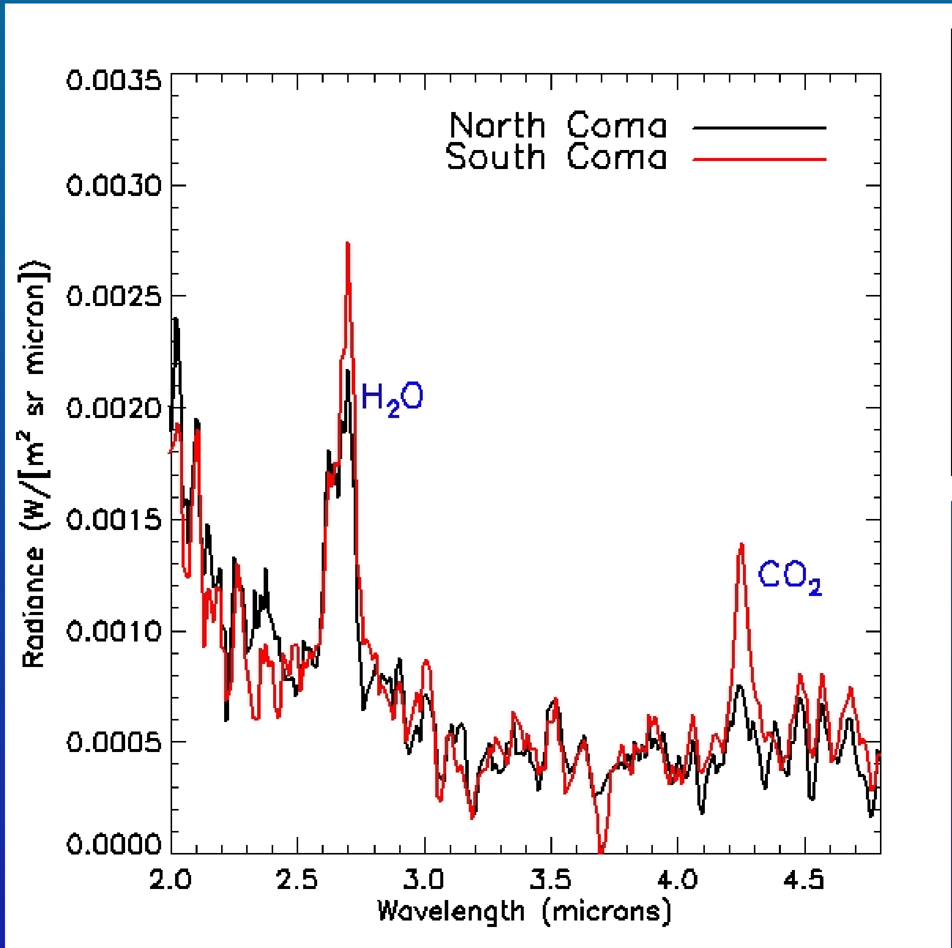


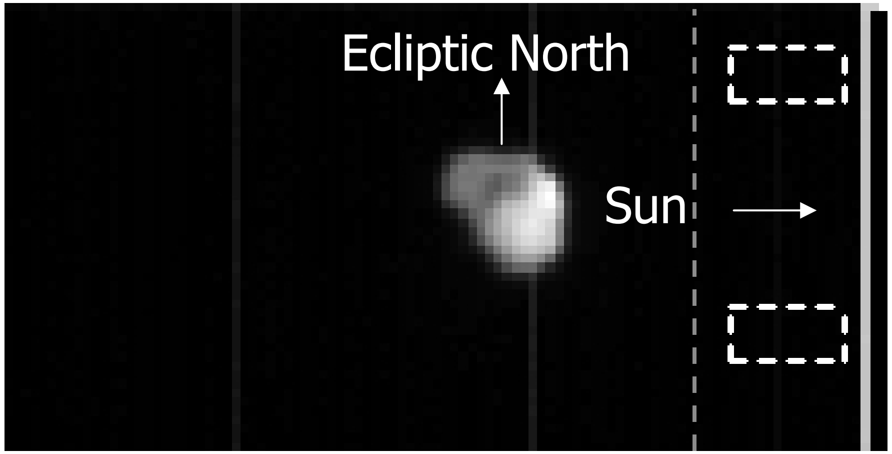


Sequence of Deep Impact images of the limb of the nucleus of comet Tempel 1, showing at least four small jets coming from the surface (“a”-“d”). As the horizon shifts with time (3 top panels), the jets pass through the plane of the sky where they are highlighted and can be traced back to their source 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



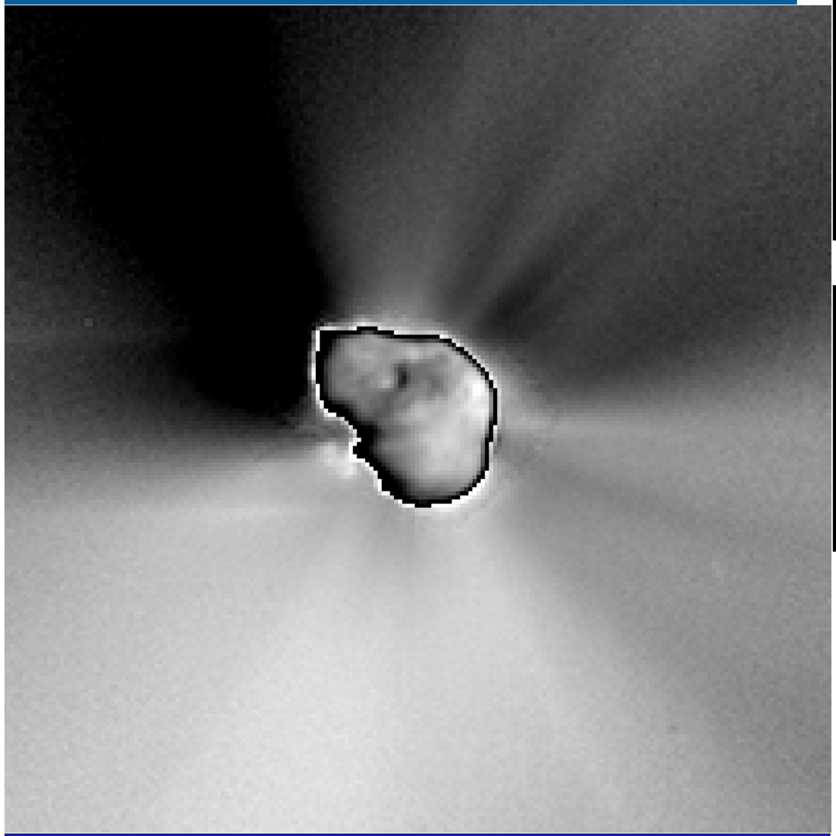


- 1 hour before impact
- ~440 m/pixel resolution
- Northern and southern regions examined
- **Spectra show comparable H_2O but factor of 2 increase in CO_2 relative to H_2O in the south**

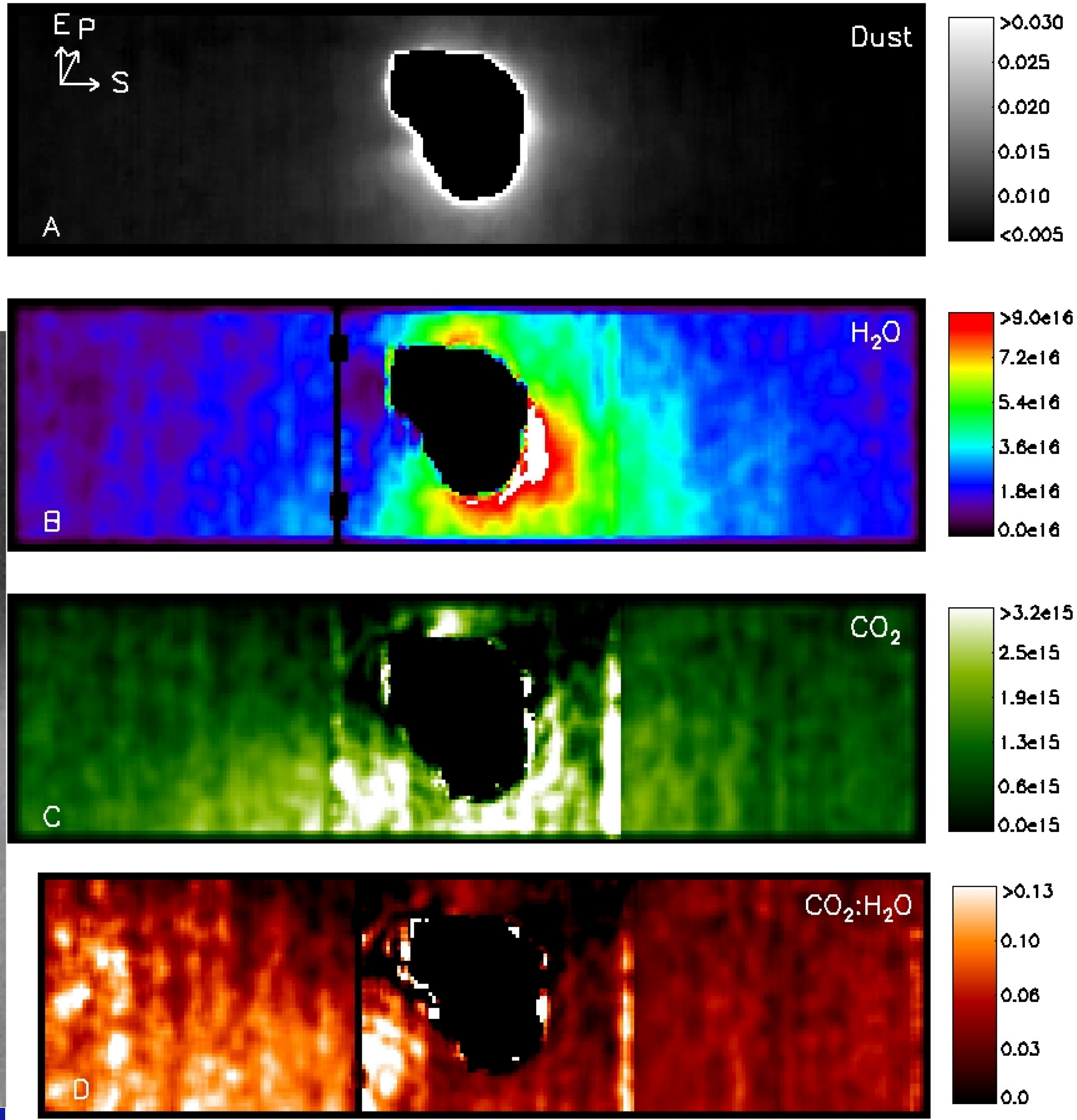
Spatial Distributions Vary by Species

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

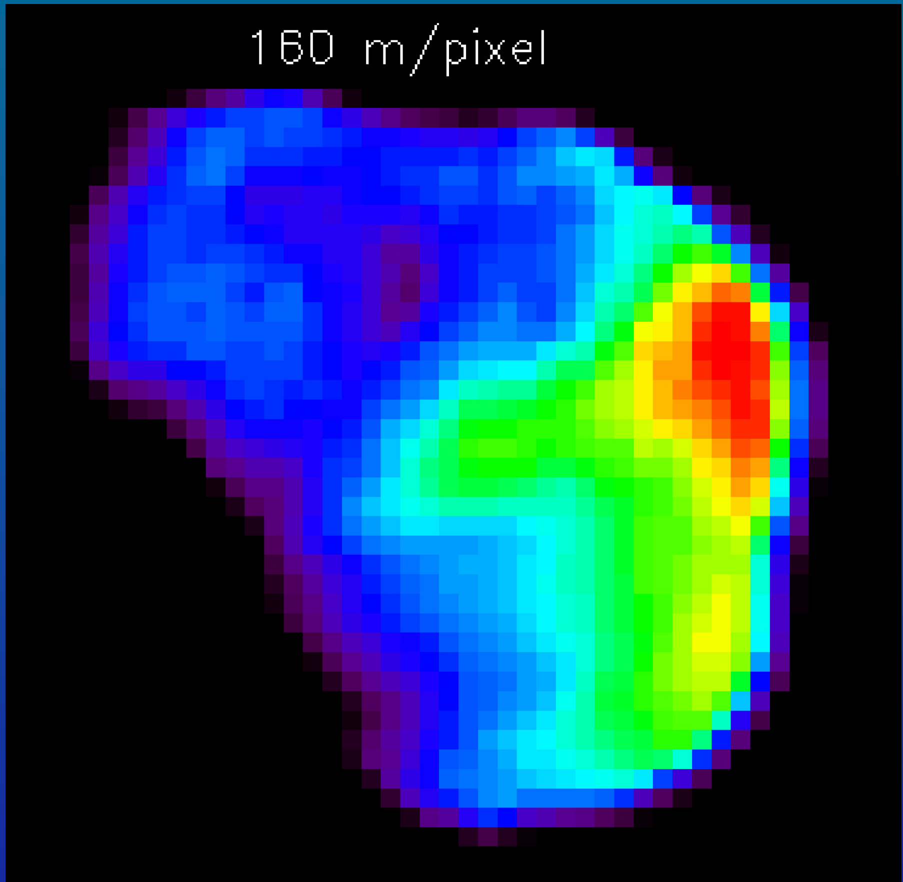


Farnham et al. 2006. Icarus, submitted



Feaga et al. 2006. Icarus, submitted

Thermal Map of Nucleus

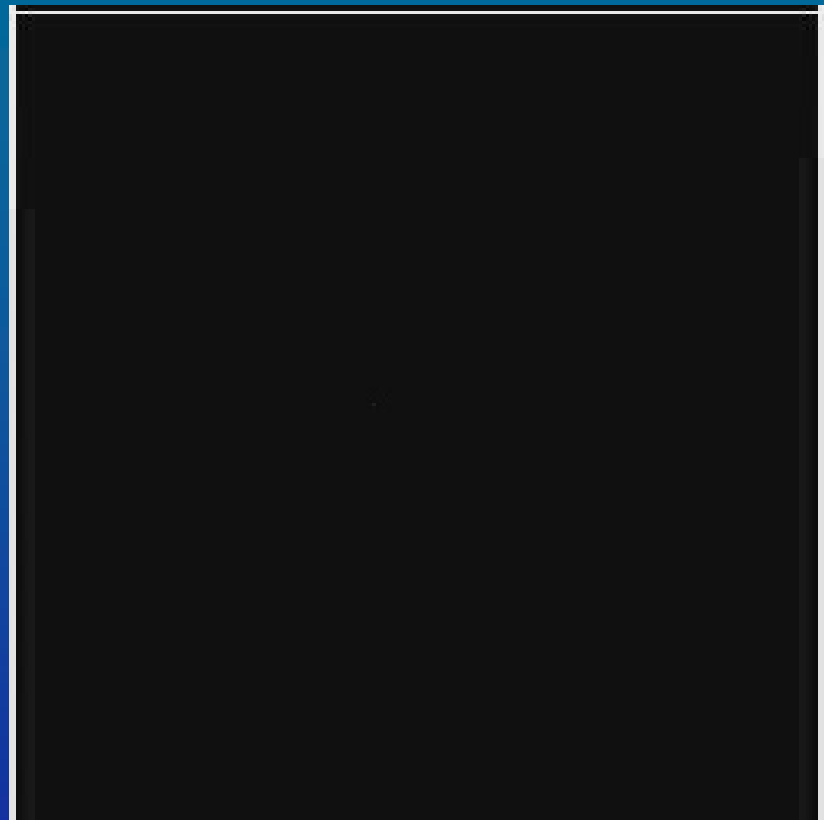


Groussin *et al.* 2006 *Icarus*, submitted

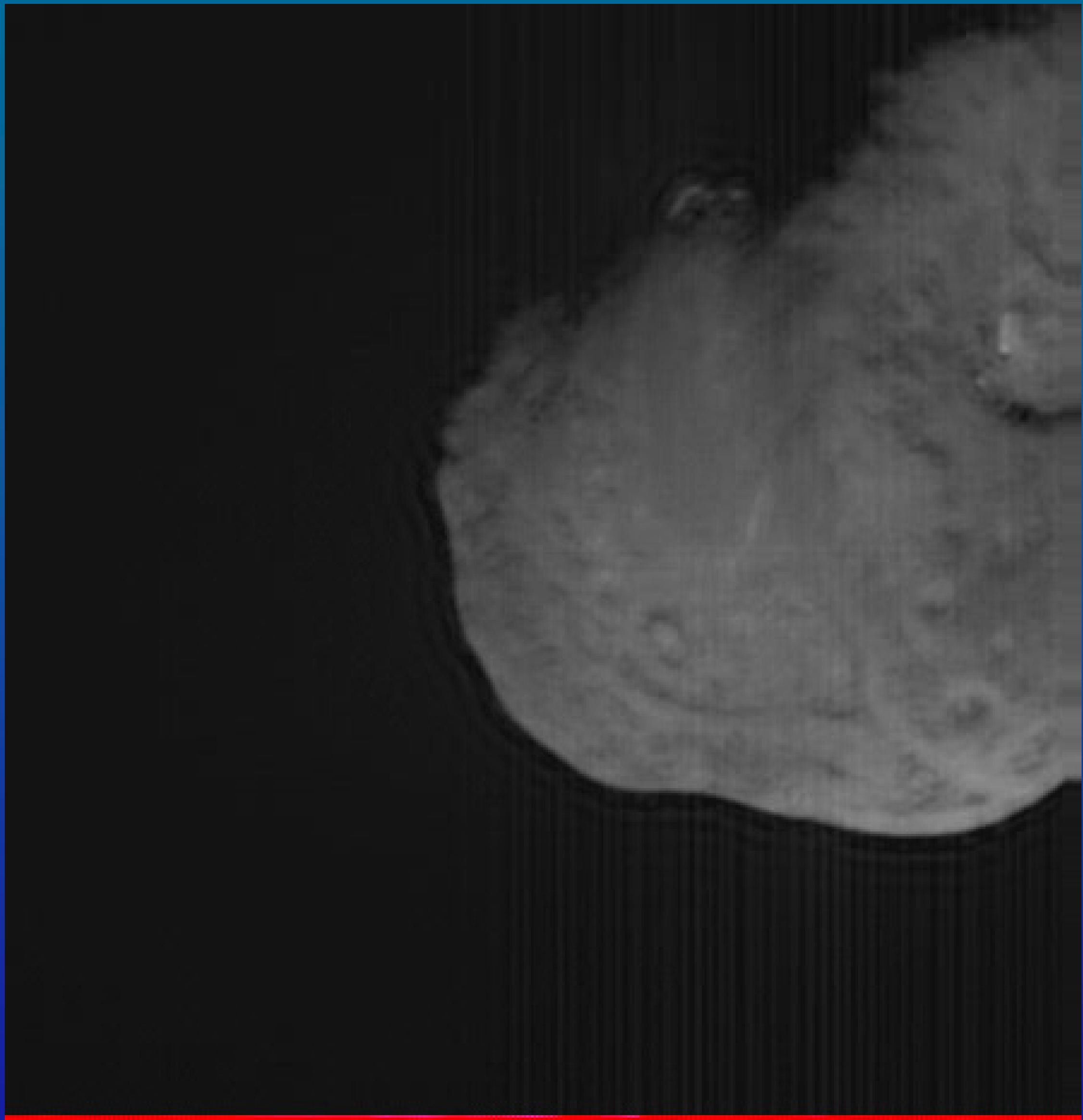
- First real thermal map of a nucleus
- Consistent with STM plus roughness to warm areas near terminator; I~<20 W K^{-1} m^2 $s^{0.5}$
- No locations as cold as sublimation temperature of H_2O ice
- Therefore ice must be below the surface but “not far” below
- Diurnal skin depth 3 cm, annual skin depth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



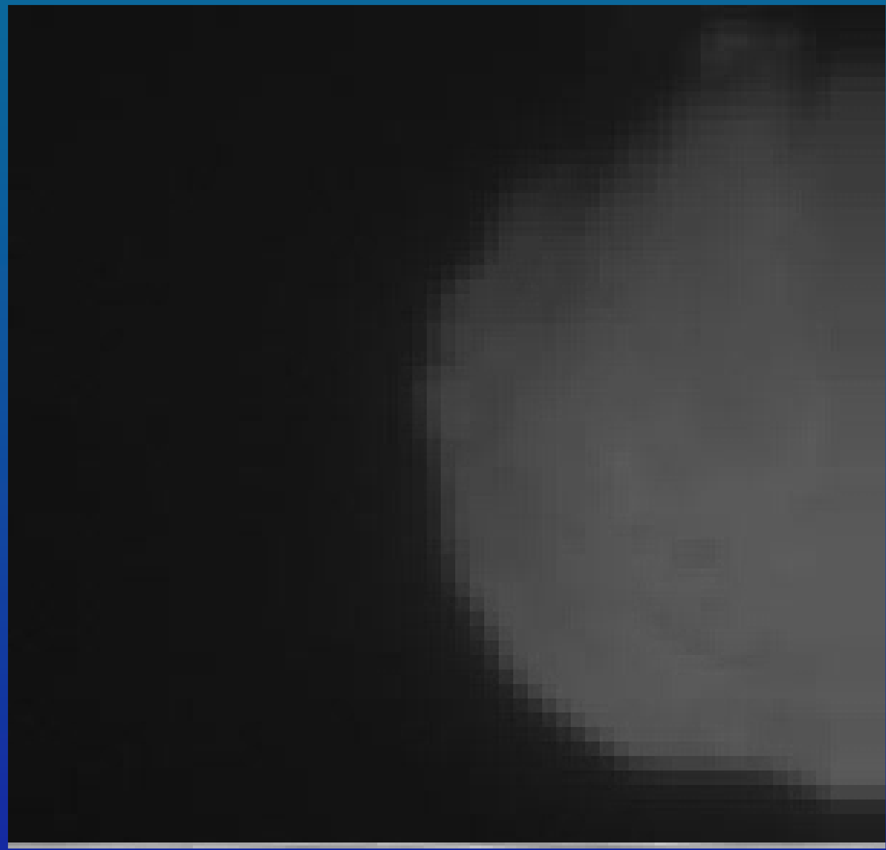
HRI Movie



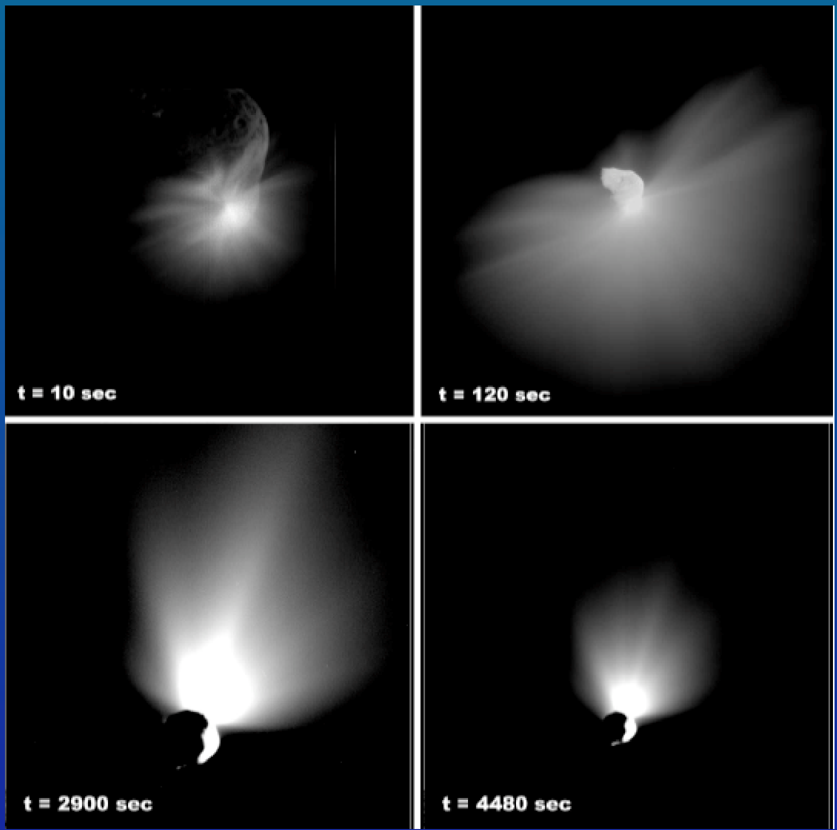
- Much slower frame speed than with MRI
- Longer period included in movie
- “Vertical bar” immediately after impact is bleeding of the saturated CCD, not real ejecta
- Note shadow cast by optically thick ejecta

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

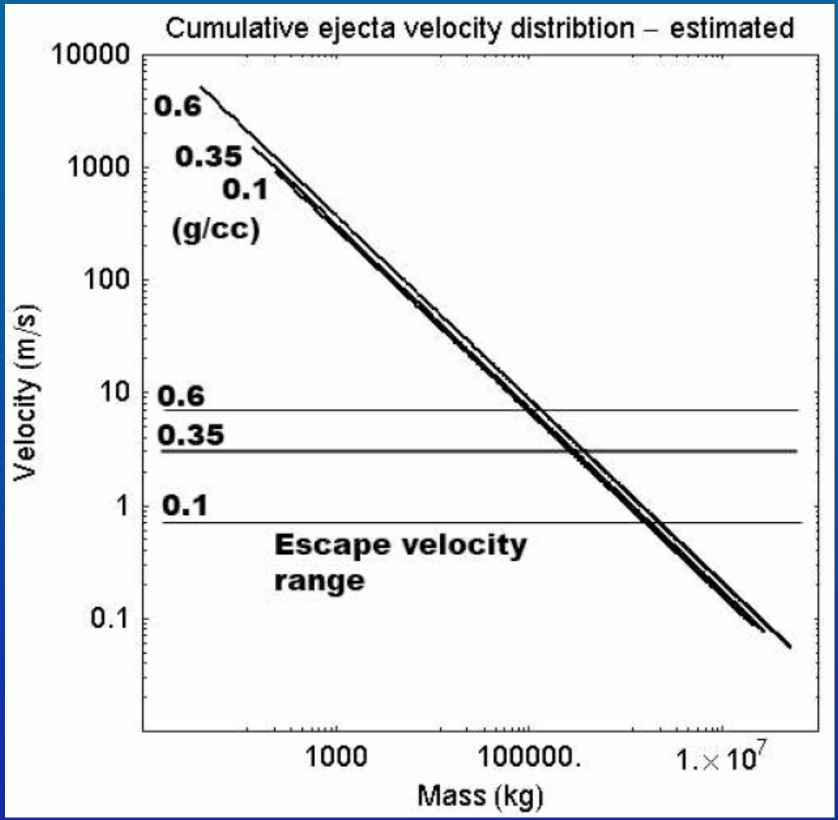


Richardson & Melosh 2007, *Icarus*, submitted

- 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



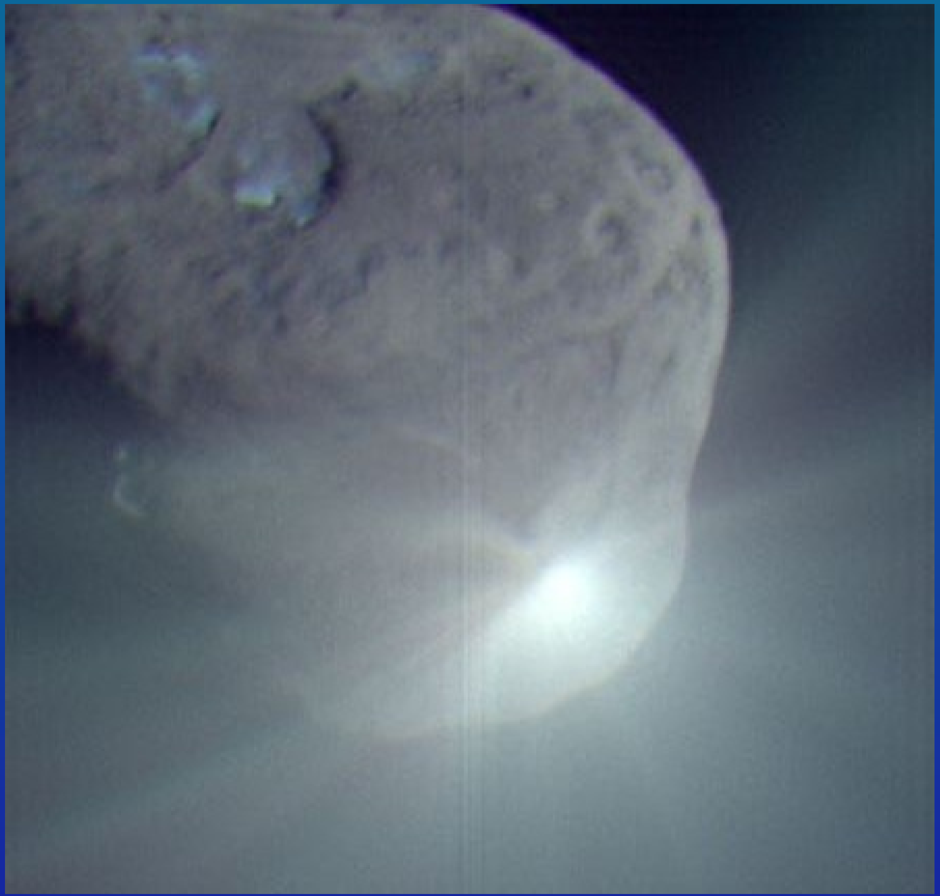
Richardson & Melosh 2007, *Icarus*, submitted

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

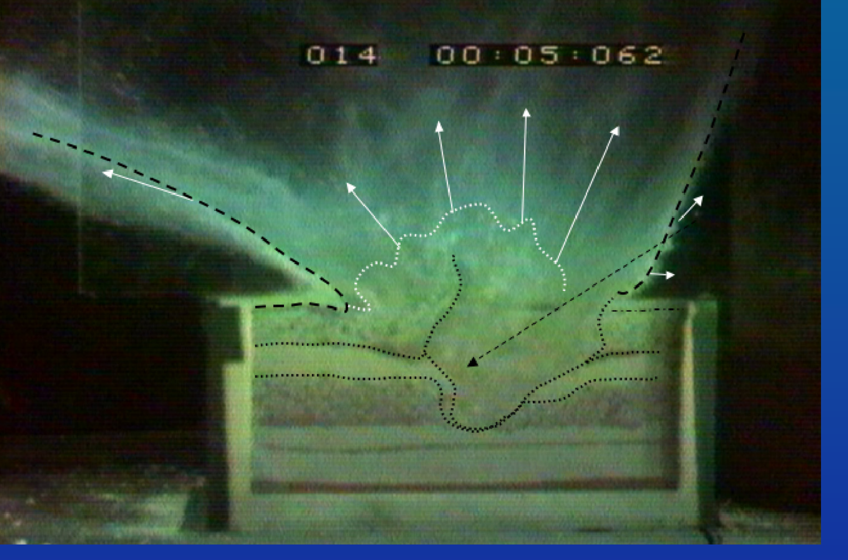
Deconvolved HRI Image

- 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



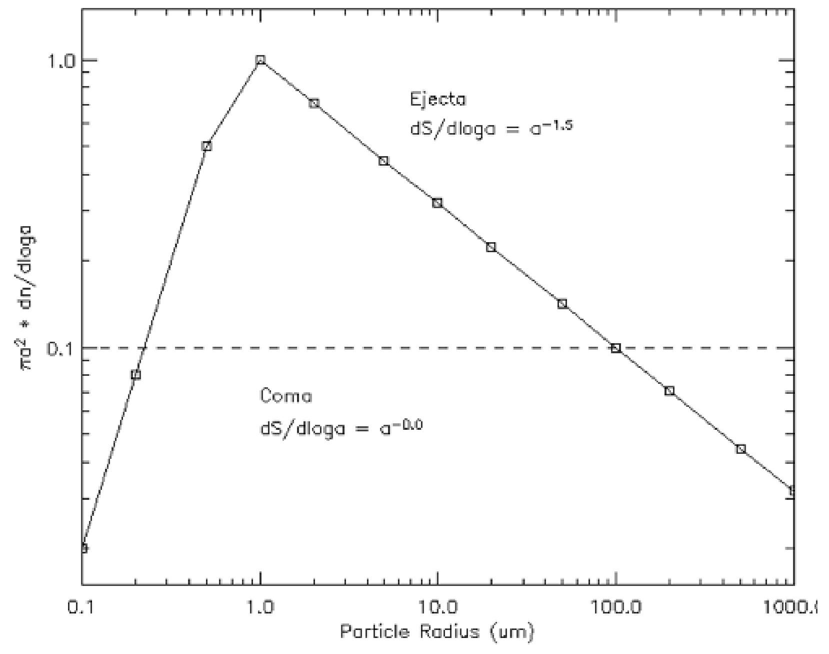
Structure Summary

- **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



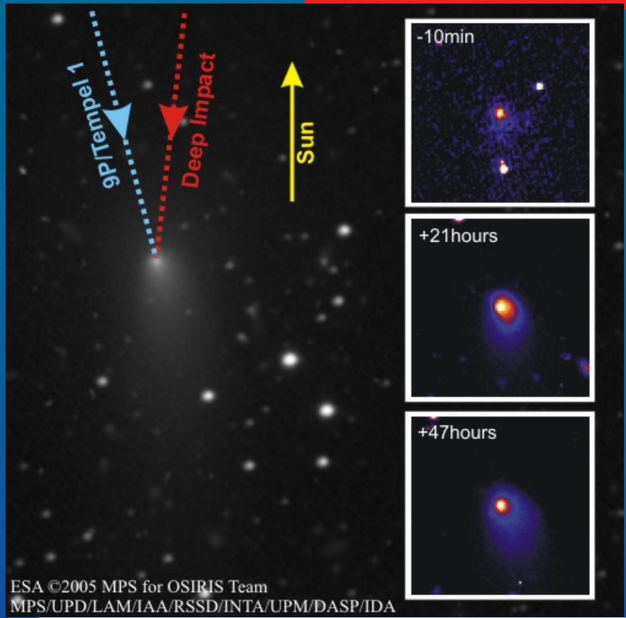
Lisse et al. 2006. Science, on-line

- 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

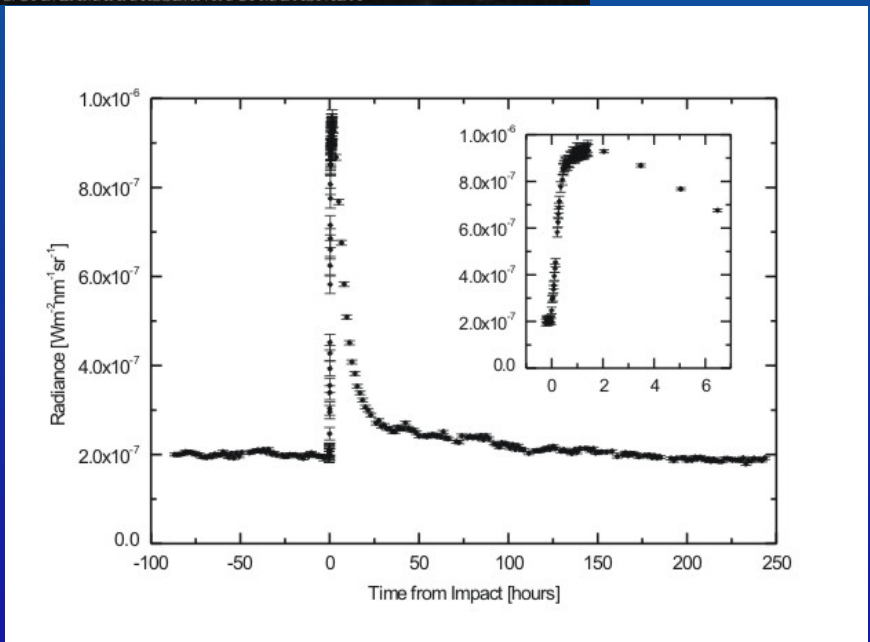


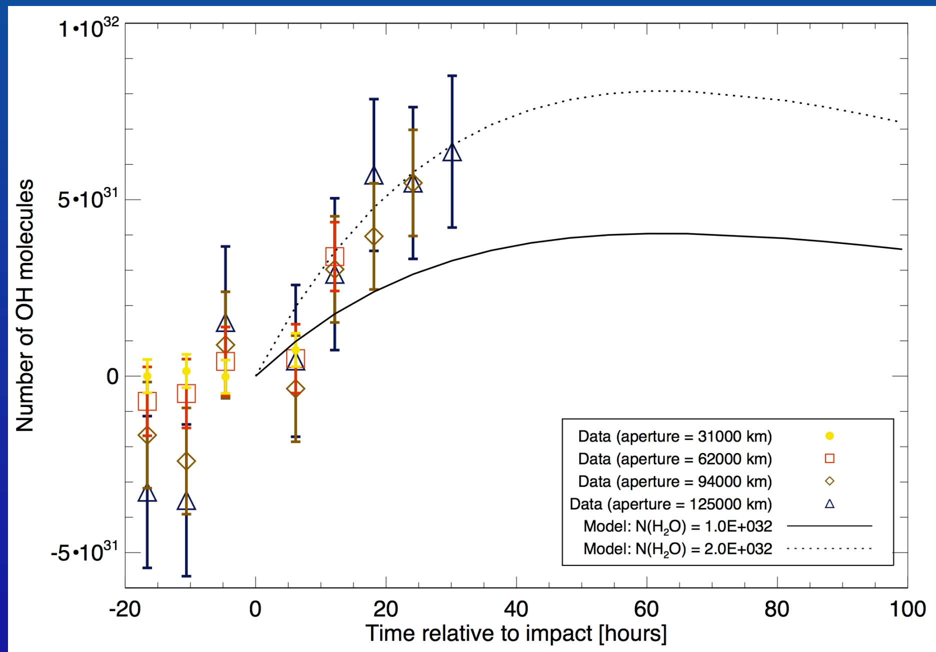
Küppers et al., 2005 Nature **437**, 987
Observations with OSIRIS on Rosetta

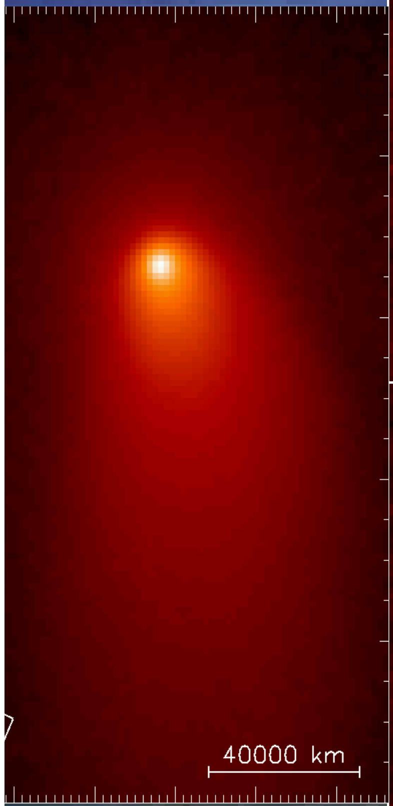
Enables determination of total water released in impact ~ 4000 tons original estimate, revised upward (4500 - 9000 tons) with better calibration

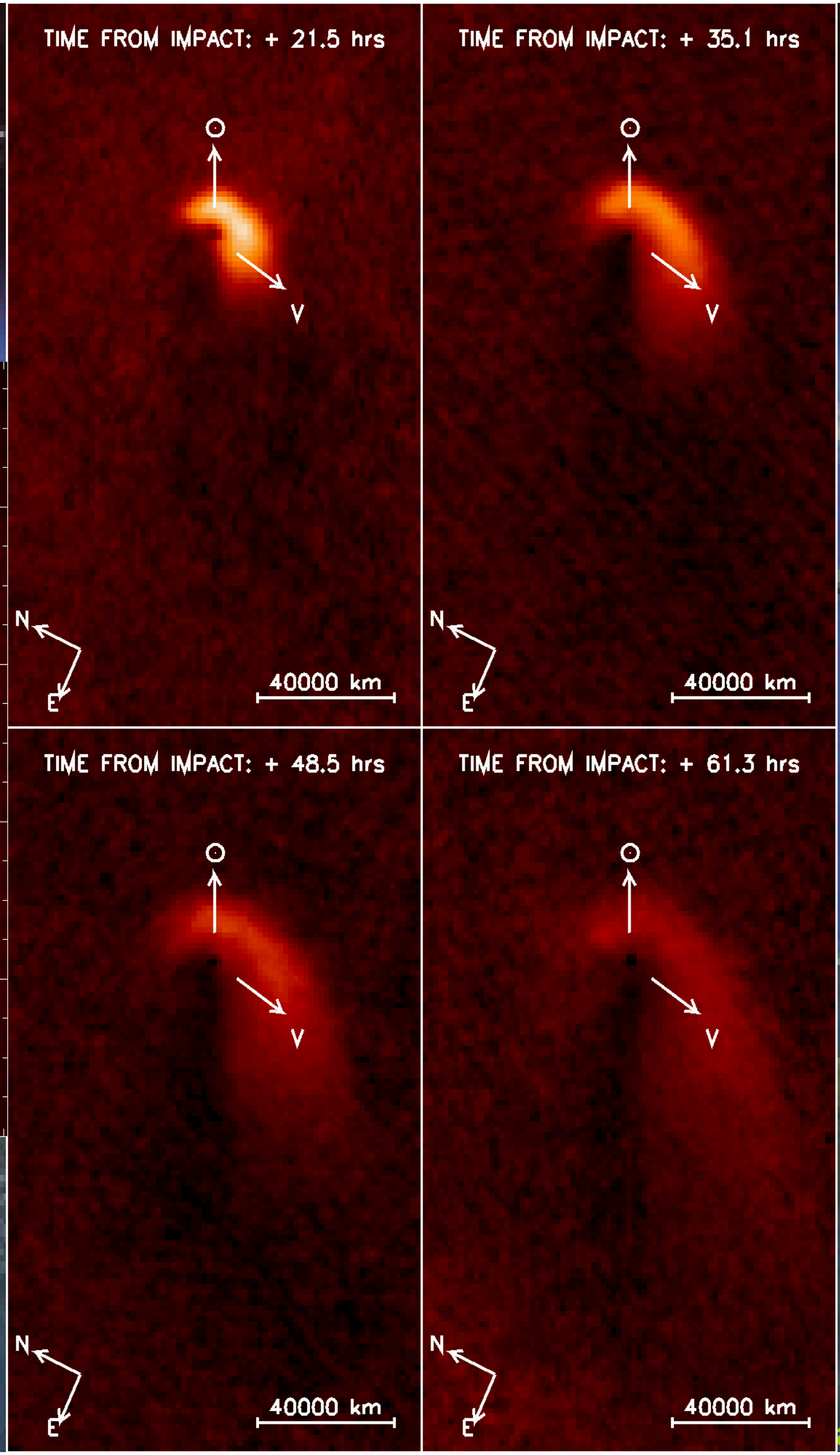
Many observers (incl. ODIN, ground-based OH) find 4 to 10x10^3 tons of water

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









Dust from impact

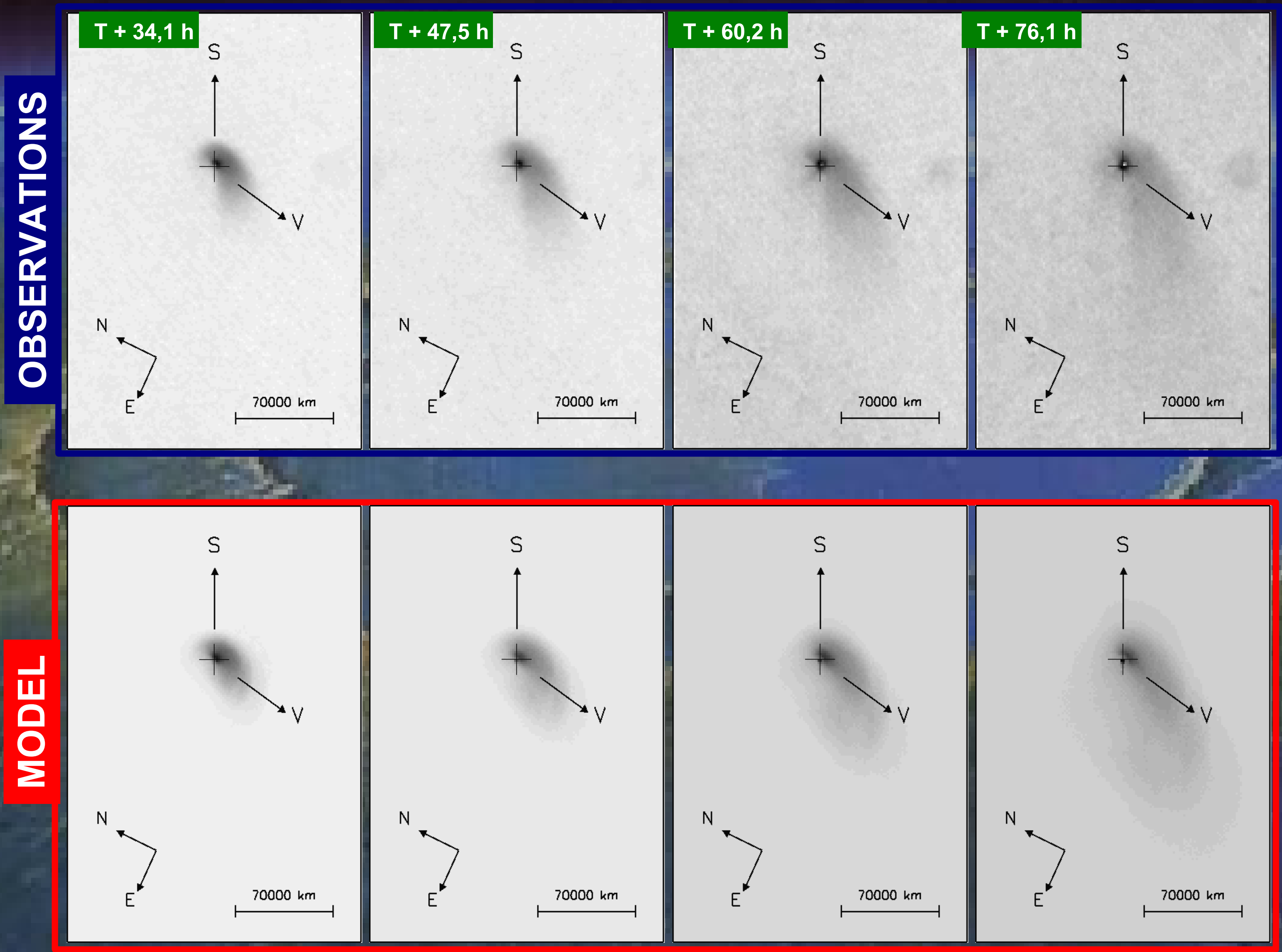
Post impact images minus pre impact image

OSIRIS images contain information about particle velocity and size distribution

L. Jorda et al.

DUST MODELING

COMPARISON MODEL – OBSERVATIONS

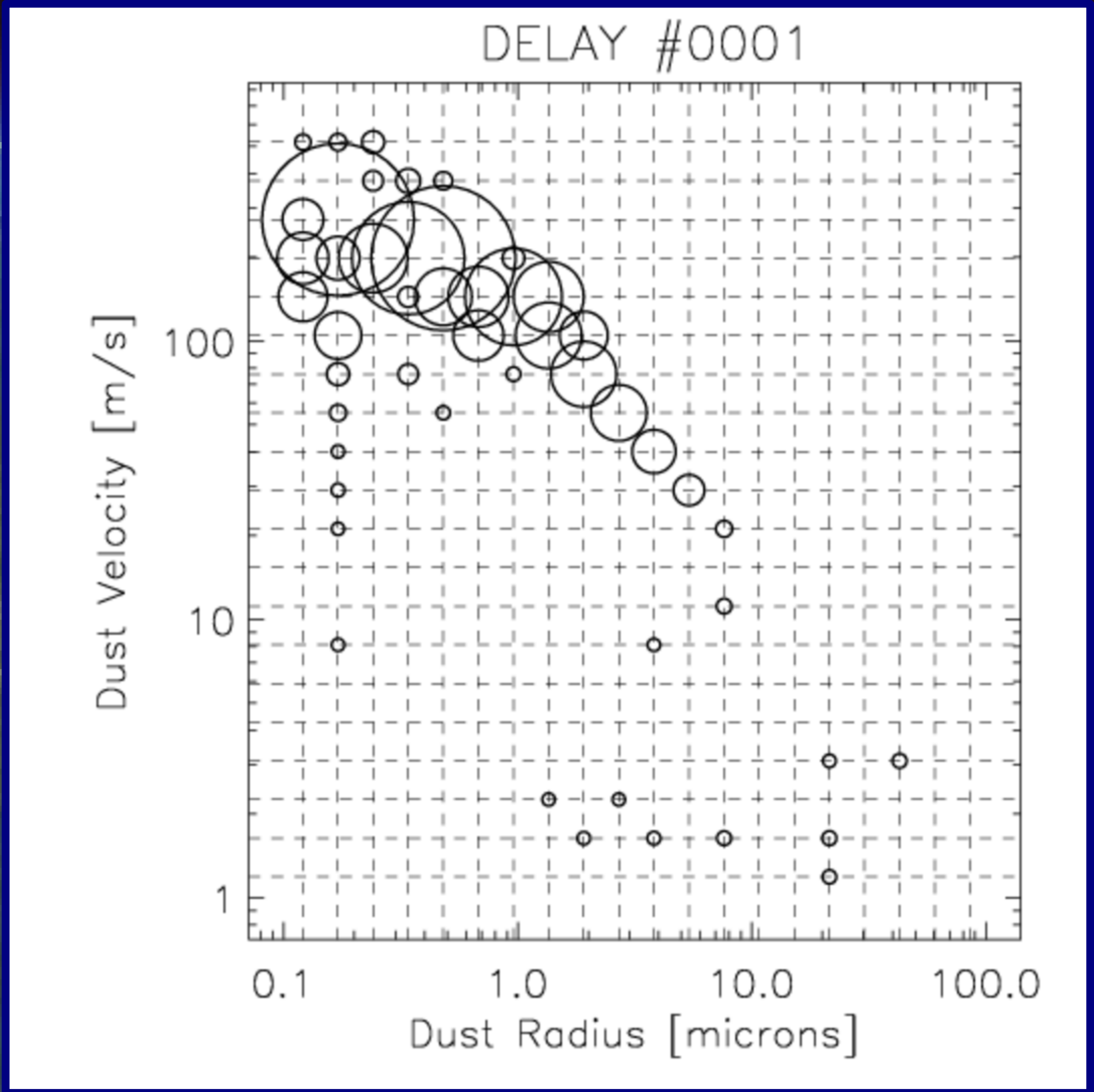


COSPAR 2006

OSIRIS observations during Deep Impact

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

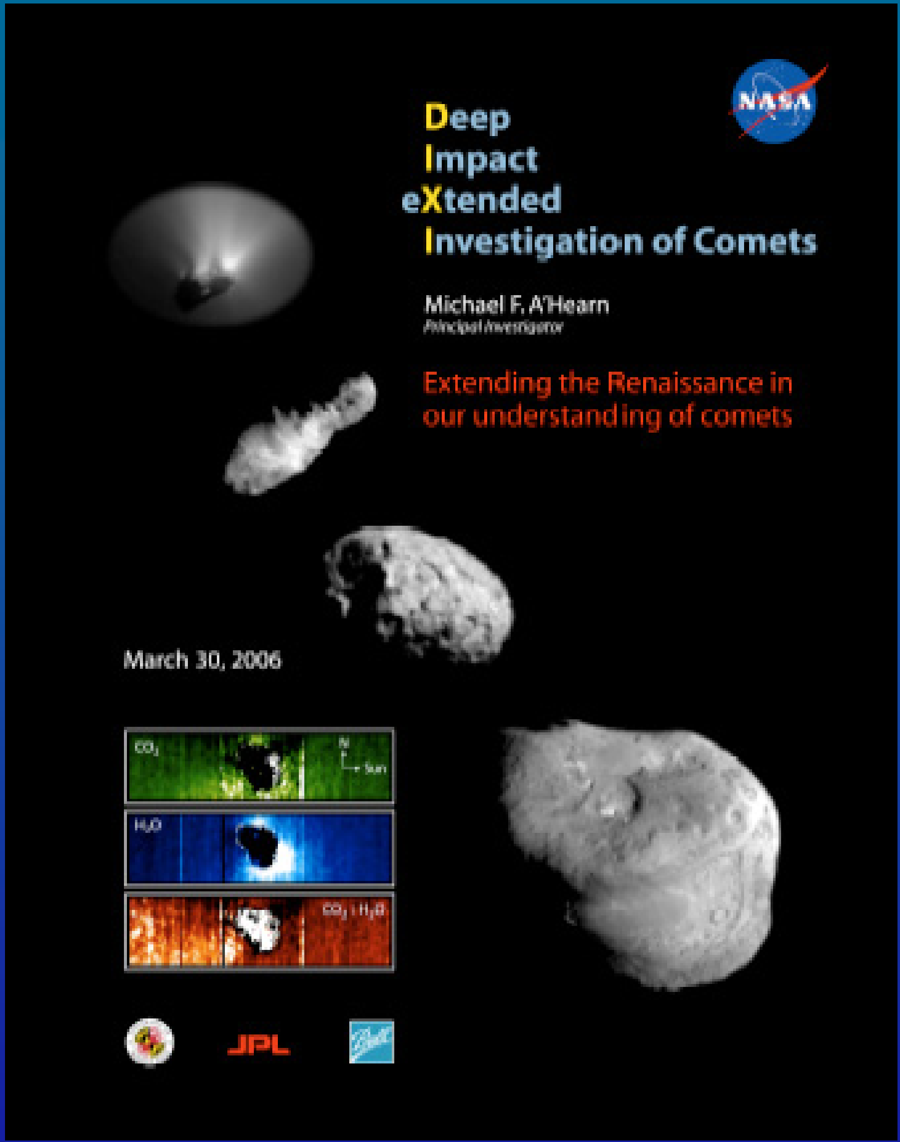
➔ cross section dominated by *sub-micron grains*

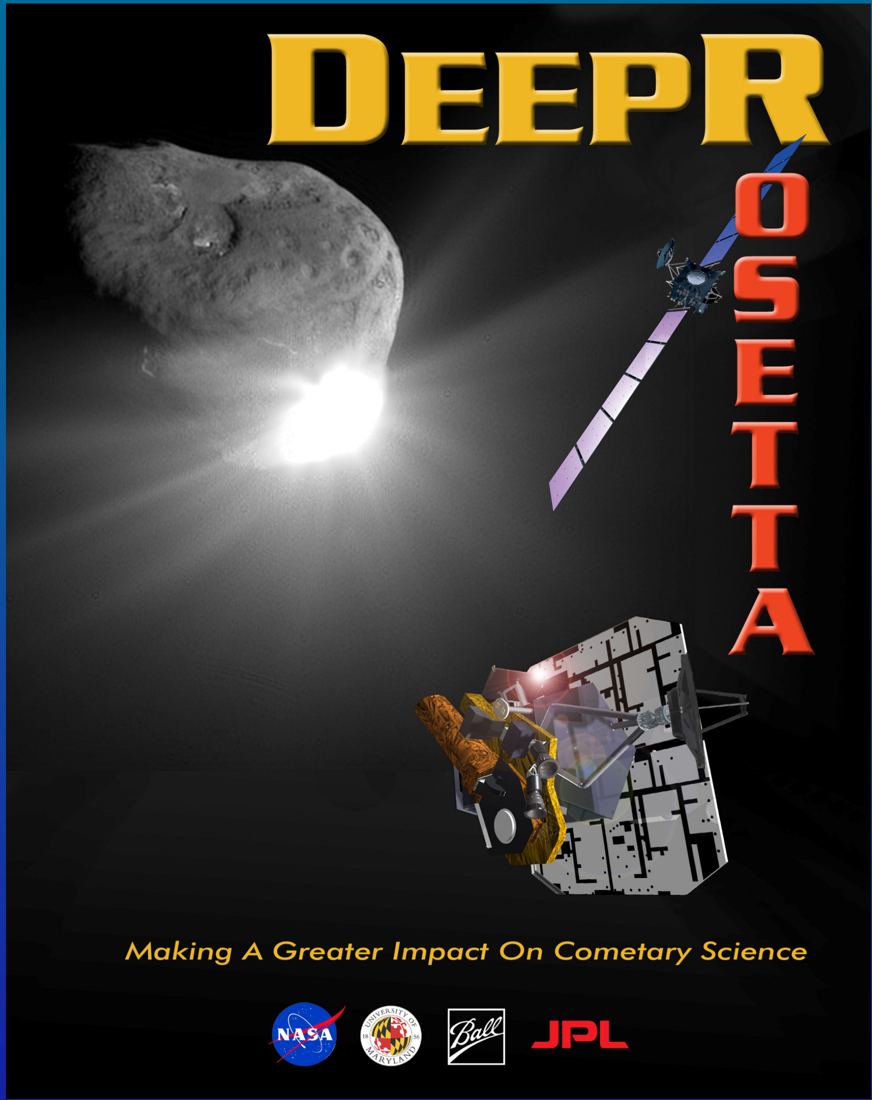
Deep Impact

- 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

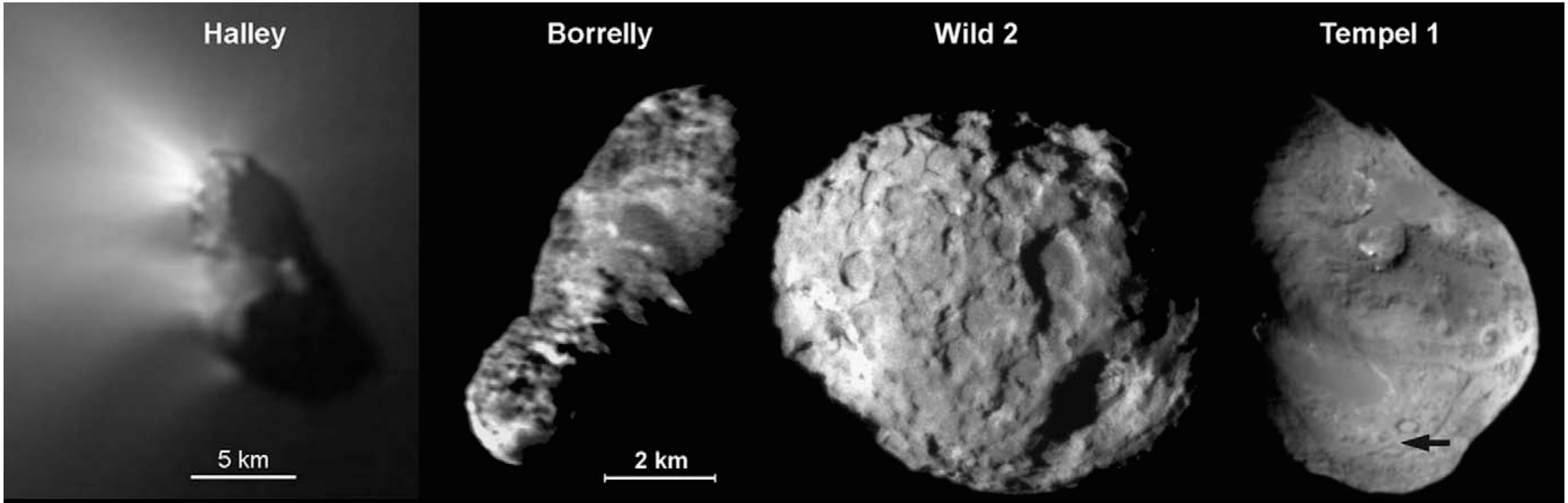
- Second "cratered" nucleus
  - Nature of craters?
    - 2 distinct populations
- Layers – primordial
  - Different from previous comets?
- Smooth and hammocky terrains
  - Smooth: avalanche-like, activity, formed recently
  - Erosion rates of terrains have varied, slope retreats
- Spots of activity 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
JPL

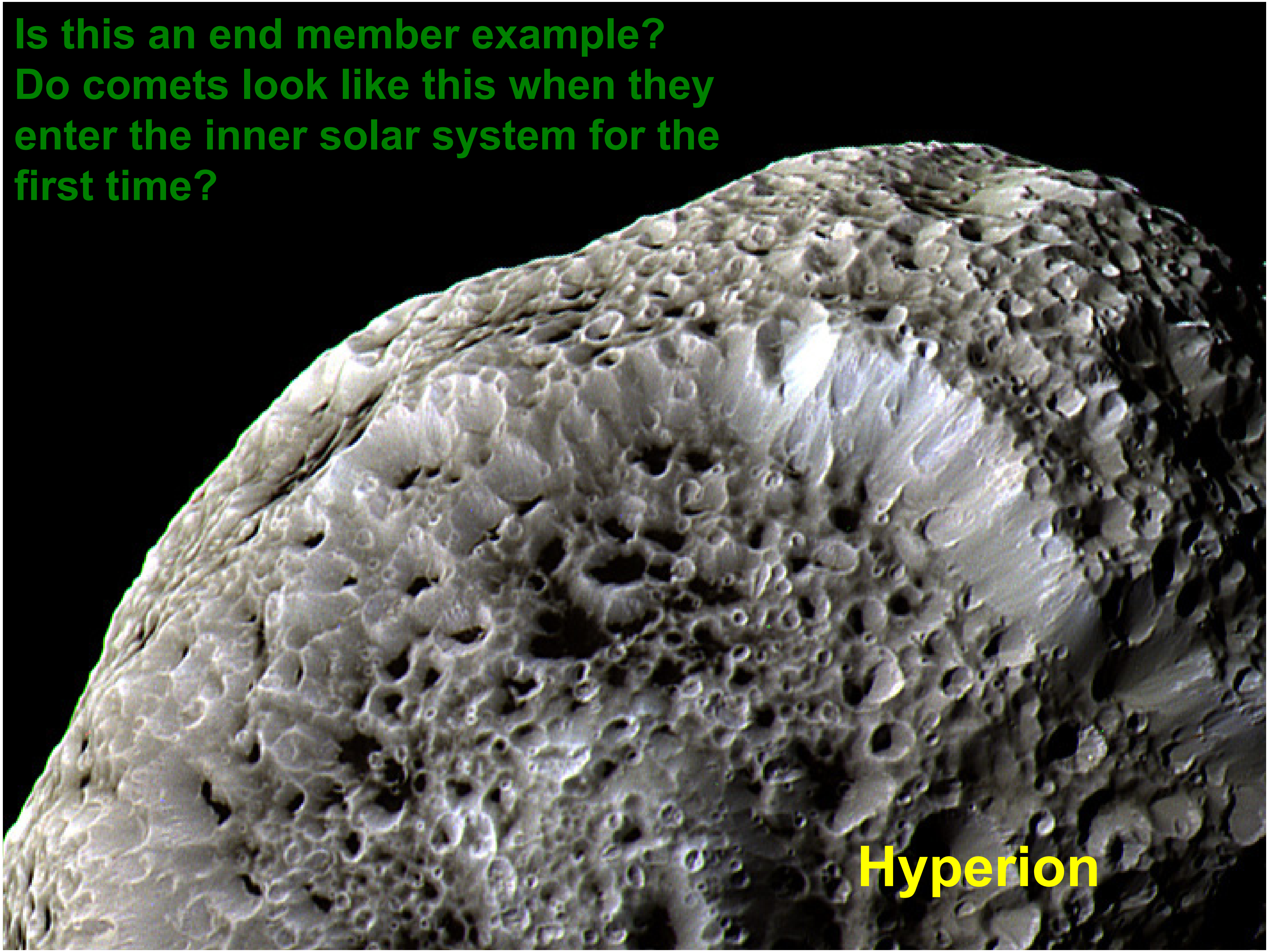
Comets - Asteroids

- **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**



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?
Hyperion

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

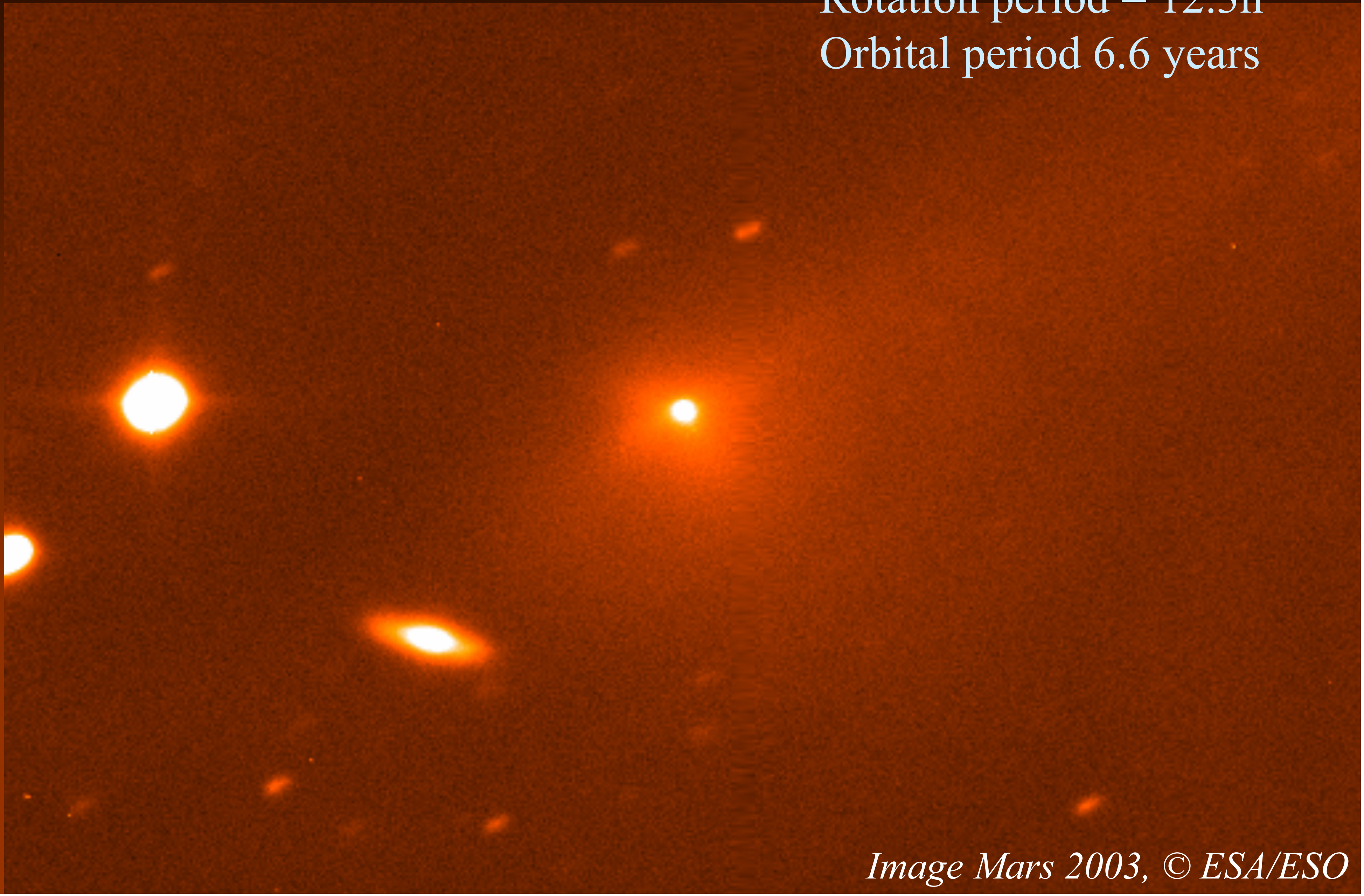
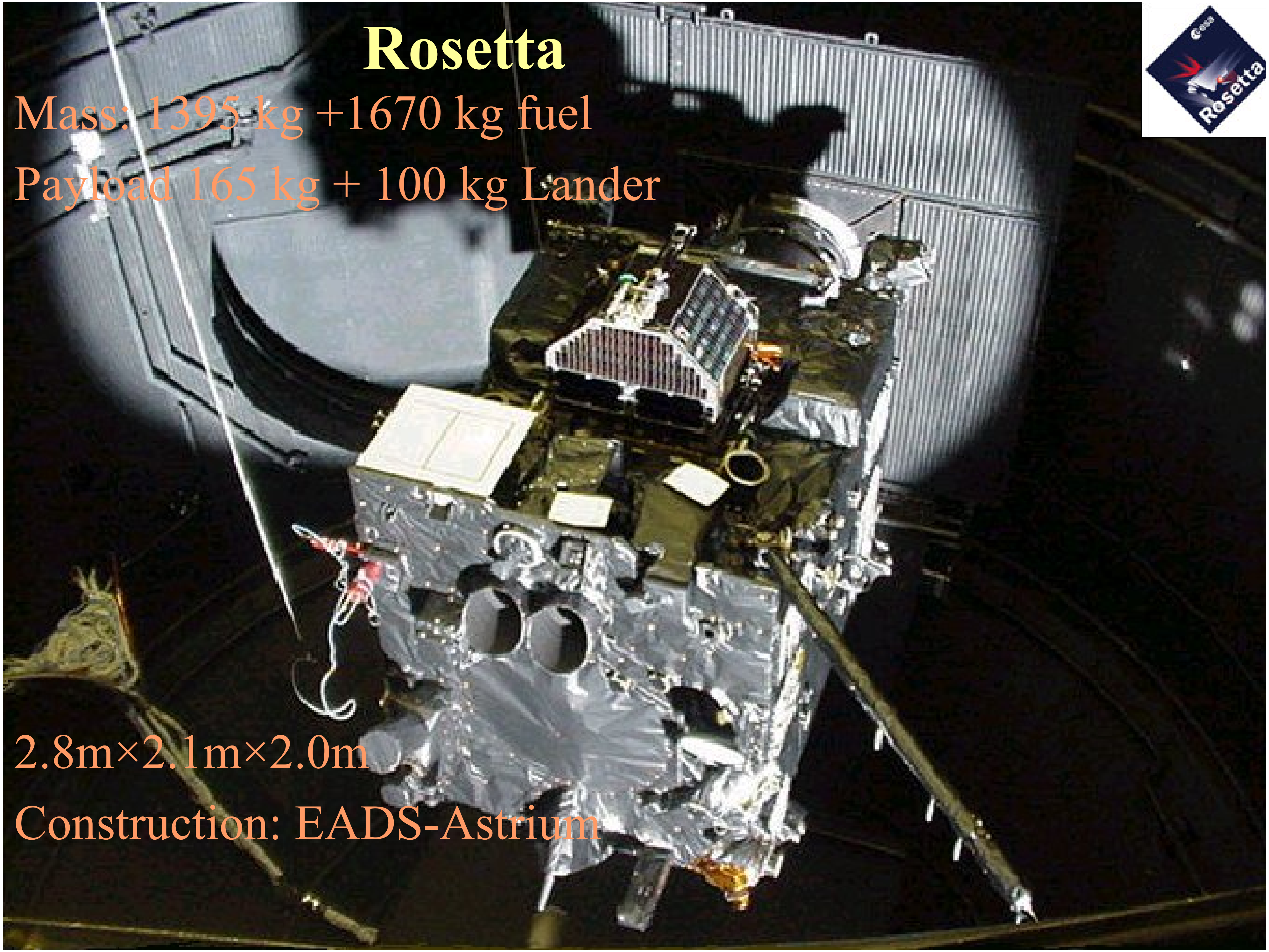


Image Mars 2003, © ESA/ESO

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)*

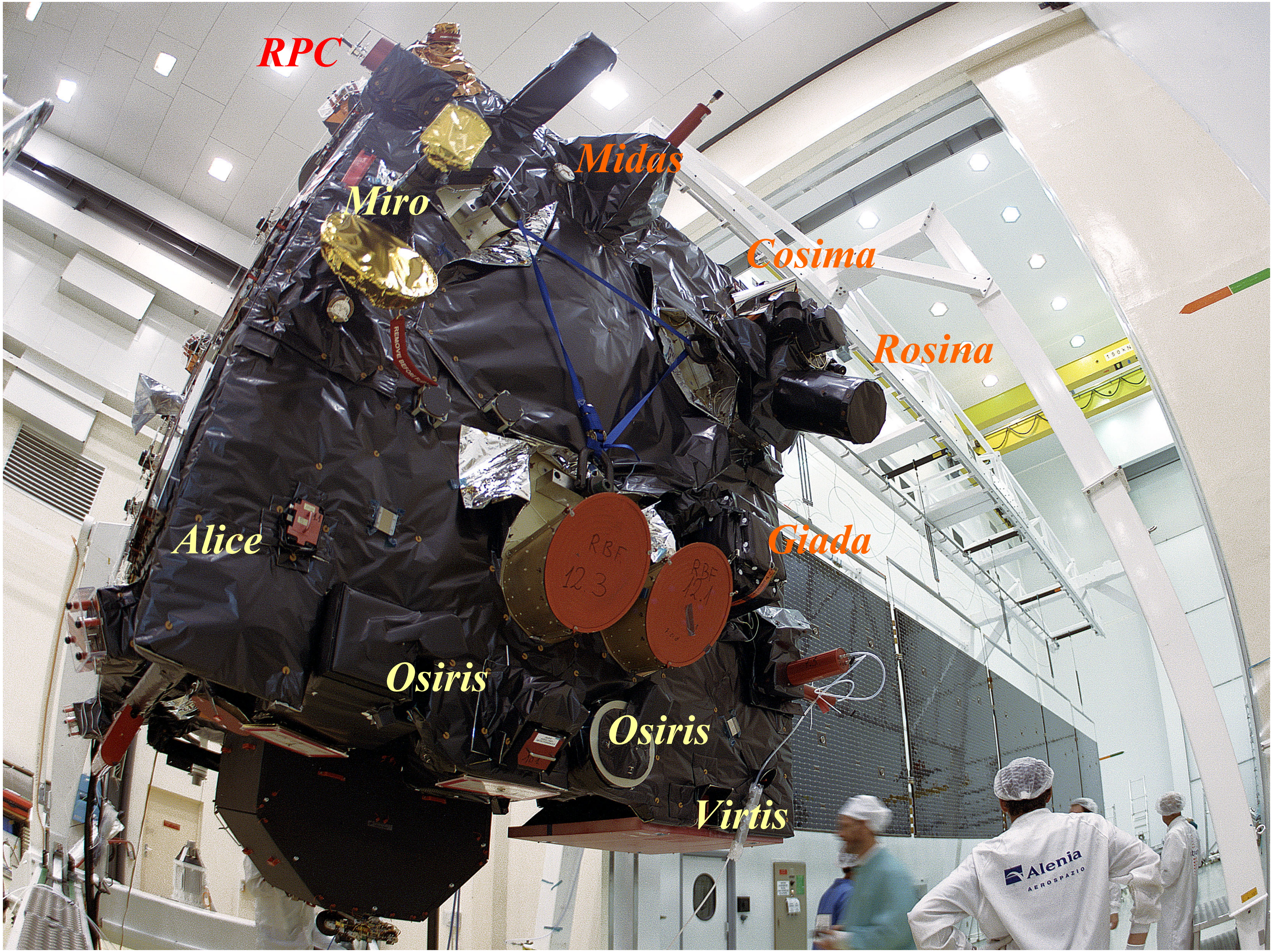
OSIRIS: Camera Visible (CCD 2k×2k 14bit 250 – 1000 nm):
Large FOV: WAC 140mm:12°
Narrow FOV: NAC 700mm: 2.4° *PI: H.U Keller (Germany)*

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
REMOVE BEFORE
RBF 12.3
RBF 12.1
Alenia
AEROSPAZIO

Instruments to measure the nucleus environment

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

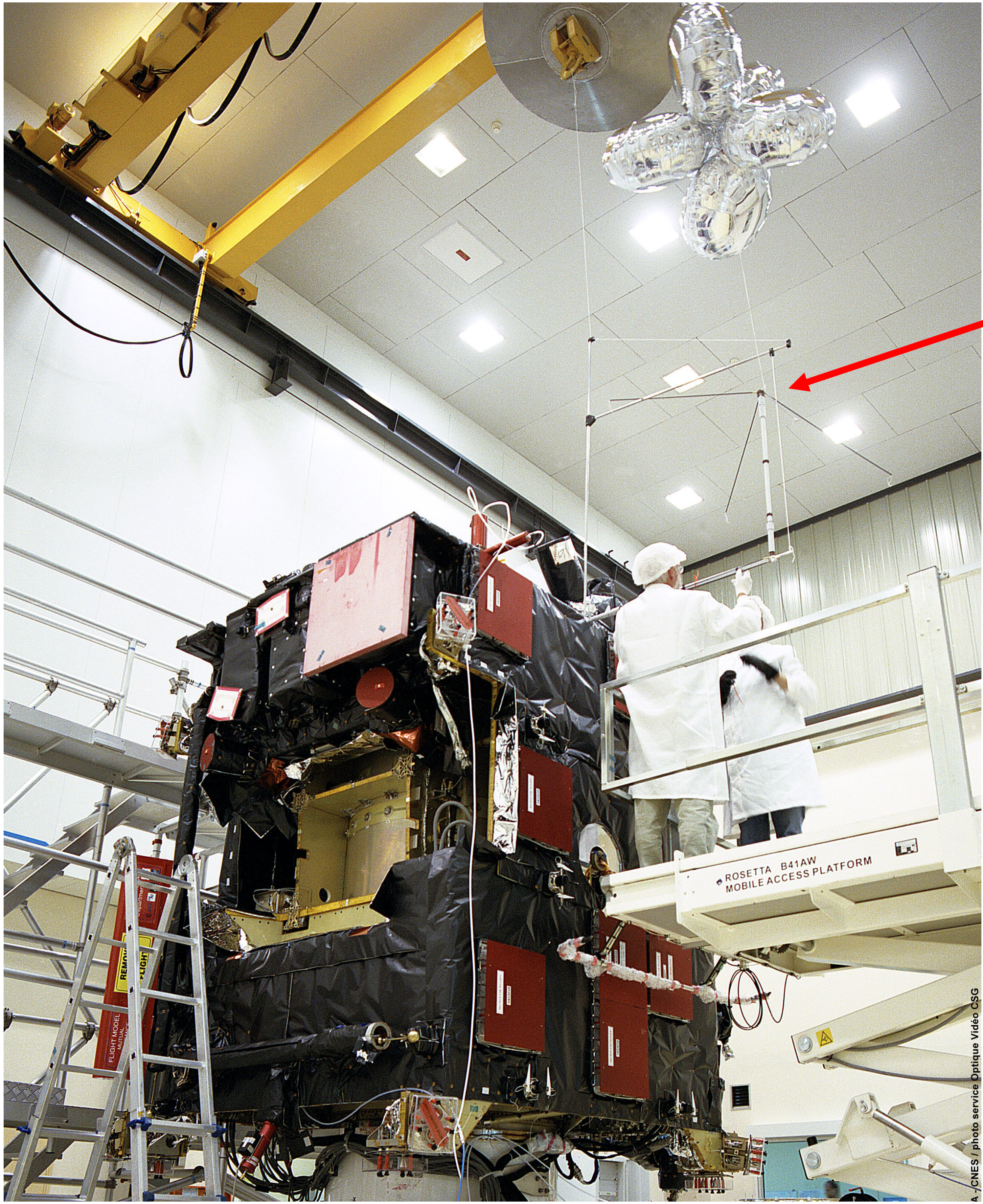
MIDAS: Dust microscopic analyser. *PI: W. Riedler (Austria)*

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

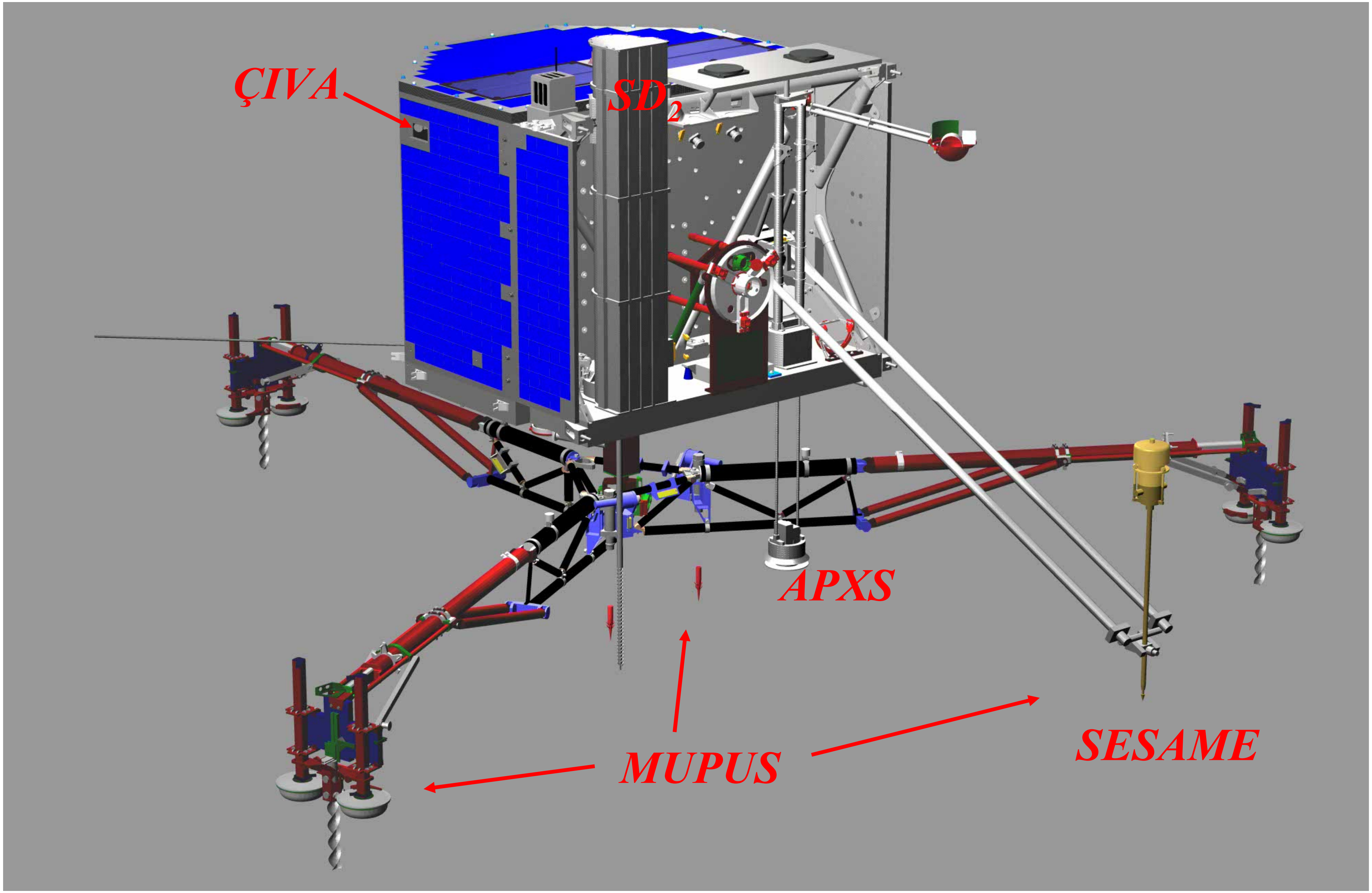


Antenna deployment test at ESTEC

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)

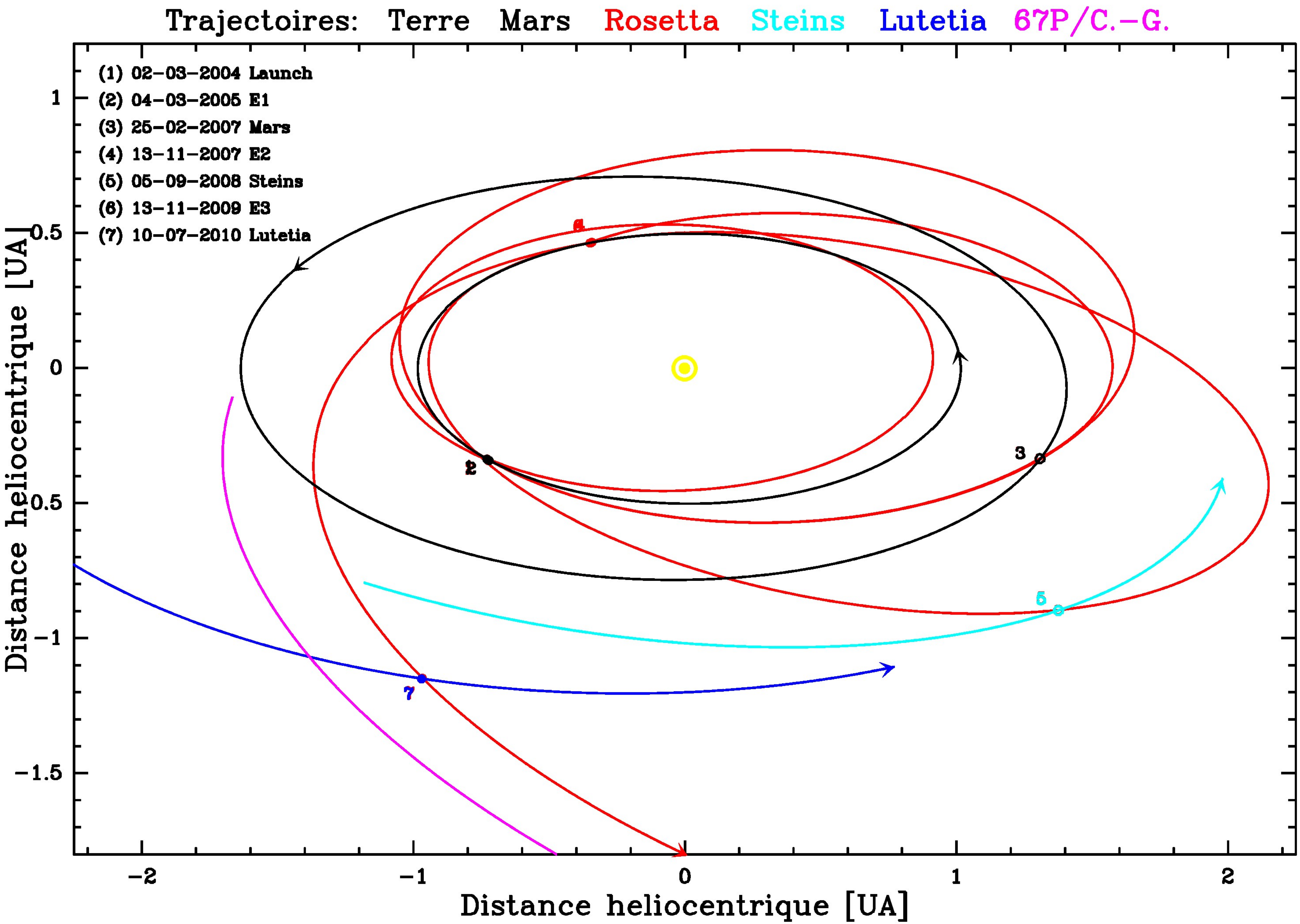
MUPUS: Mesuring the mechanical and thermal properties of the nucleus (part of the anchoring system) *PI: T. Spohn (Germany)*

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

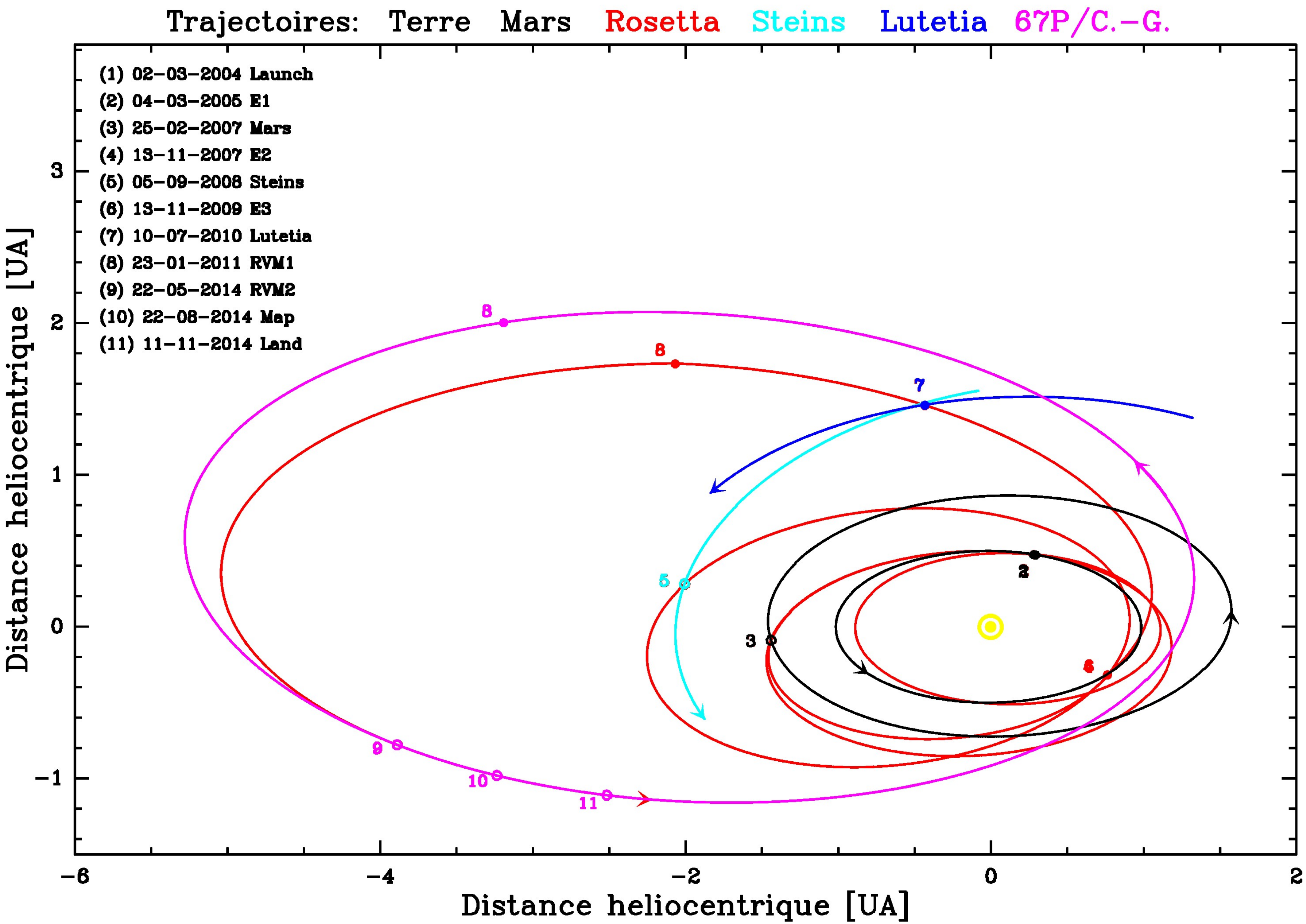
PHILAE

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
(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
(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

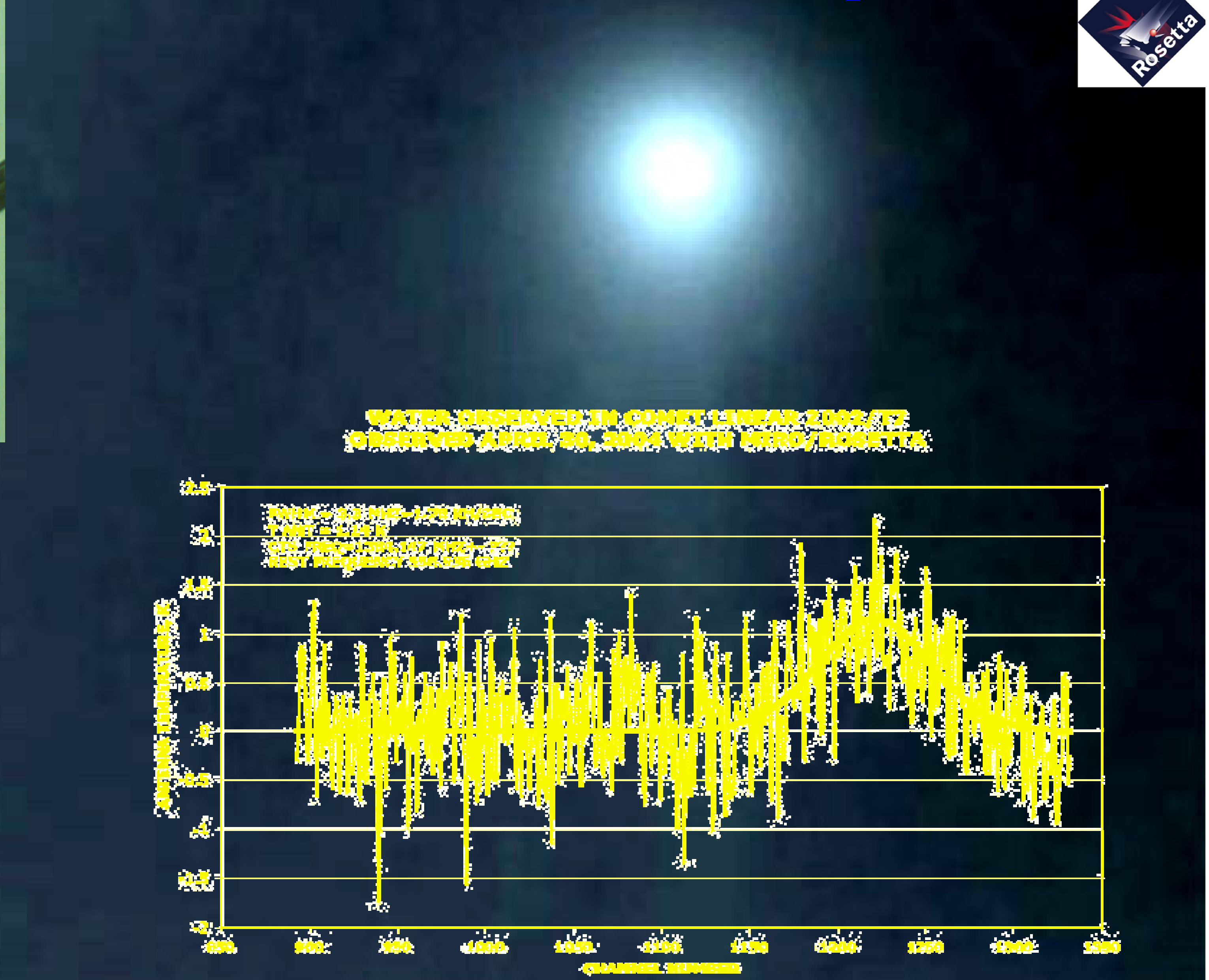
Images (enhanced) taken by the panoramic lander cameras

Images by CIVA-P of the solar pannelsof Rosetta

First comet observations by Rosetta

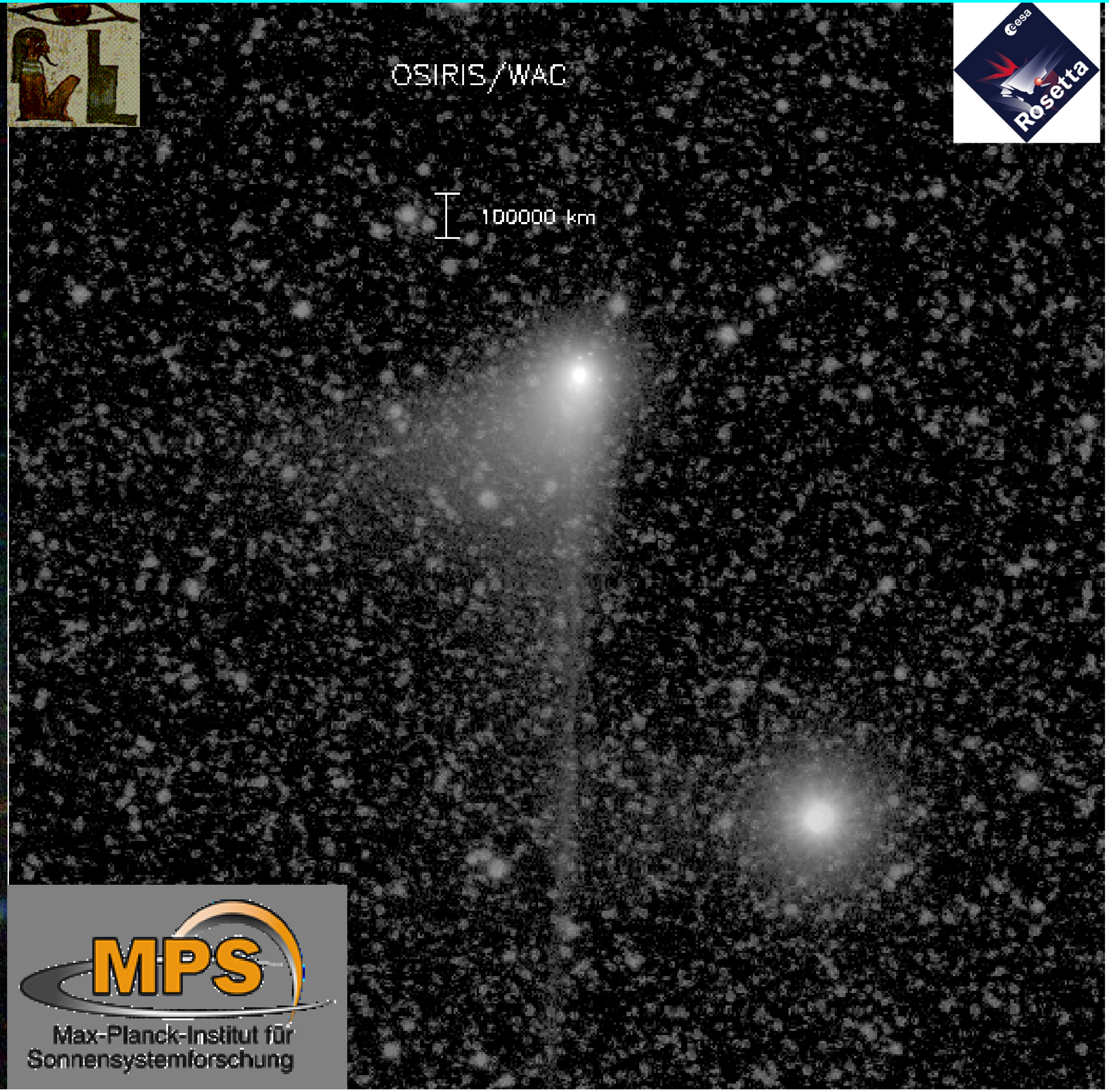
C/2002 T7 (LINEAR) on 30 April 2004

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

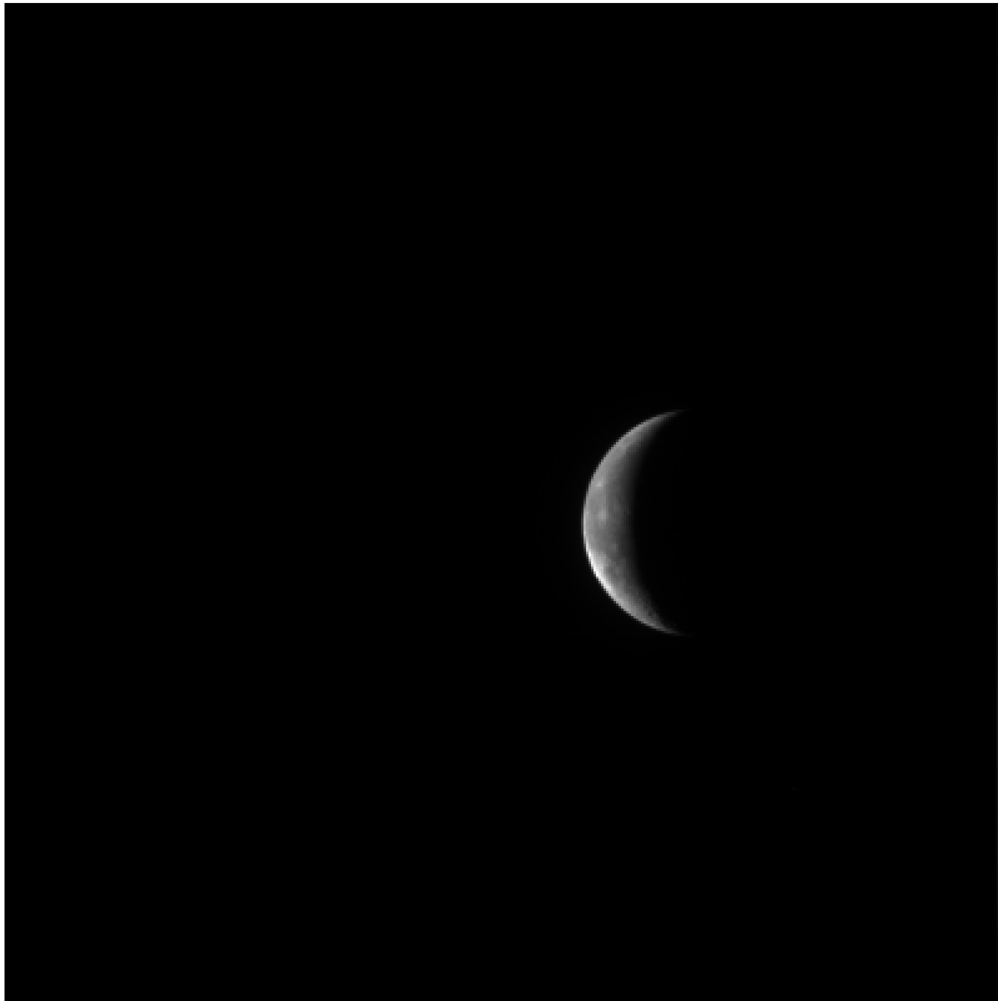


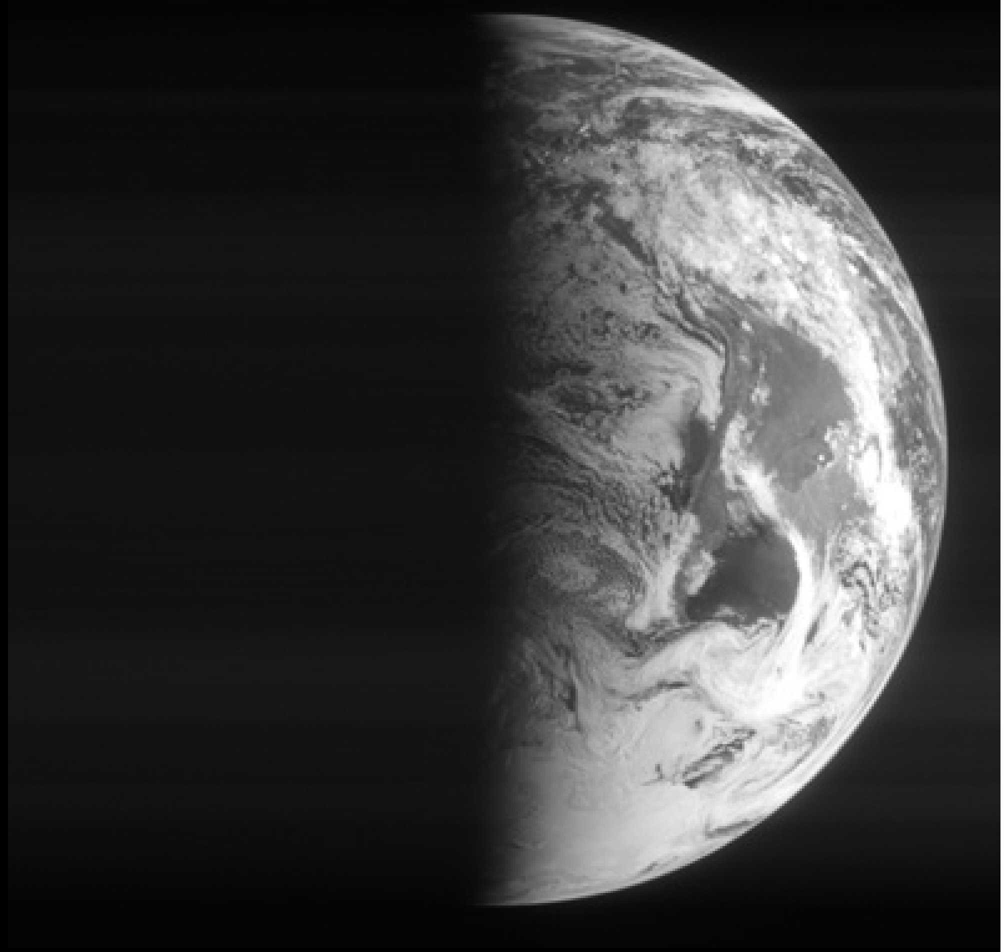
C/2002 T7: MIRO © JPL/NASA/ESA - OSIRIS © ESA/MPG/Keller

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



OSIRIS NAC 28. Sept. 2004





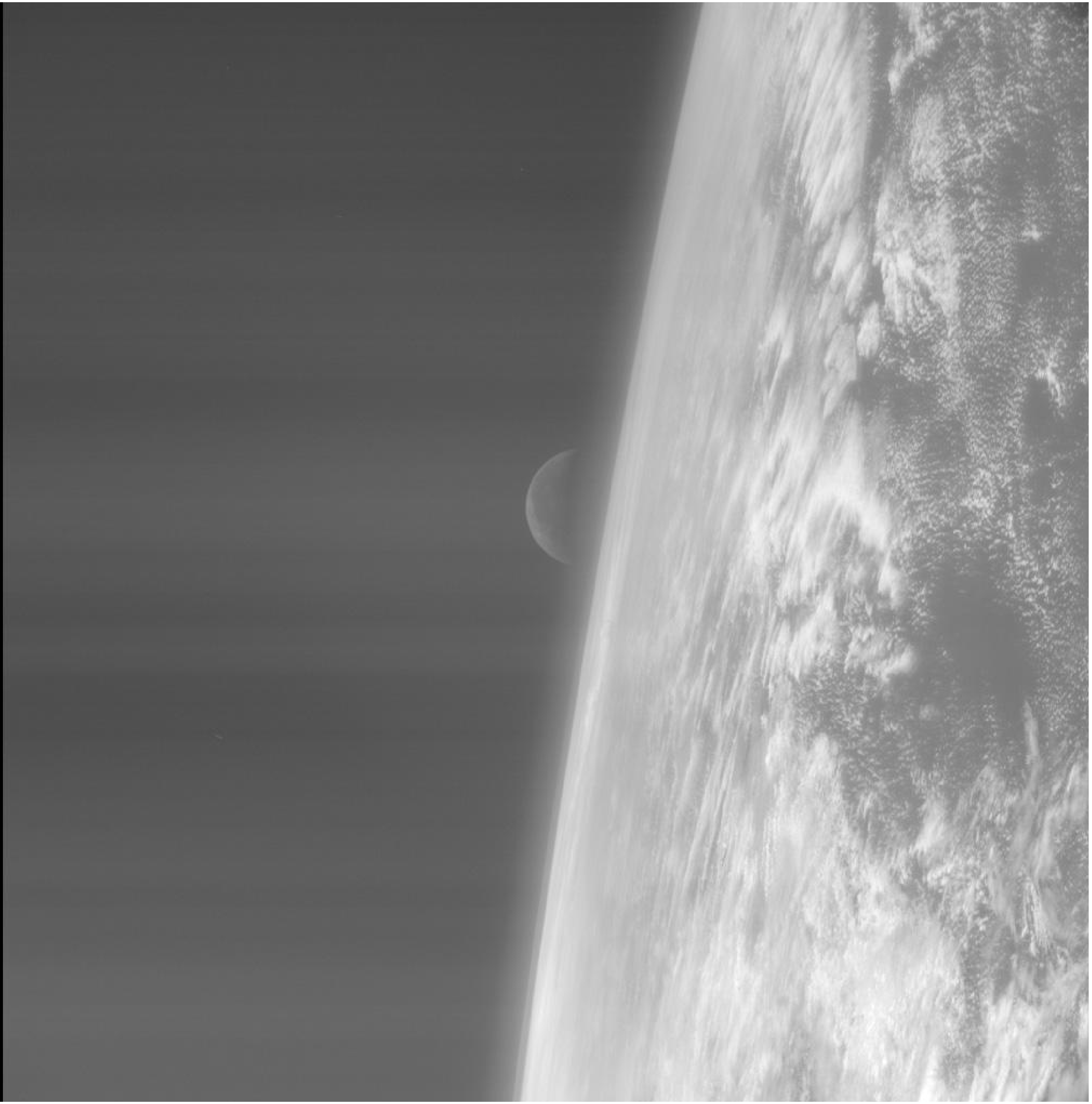
Images taken by the navigation cameras on 4 March 2005:

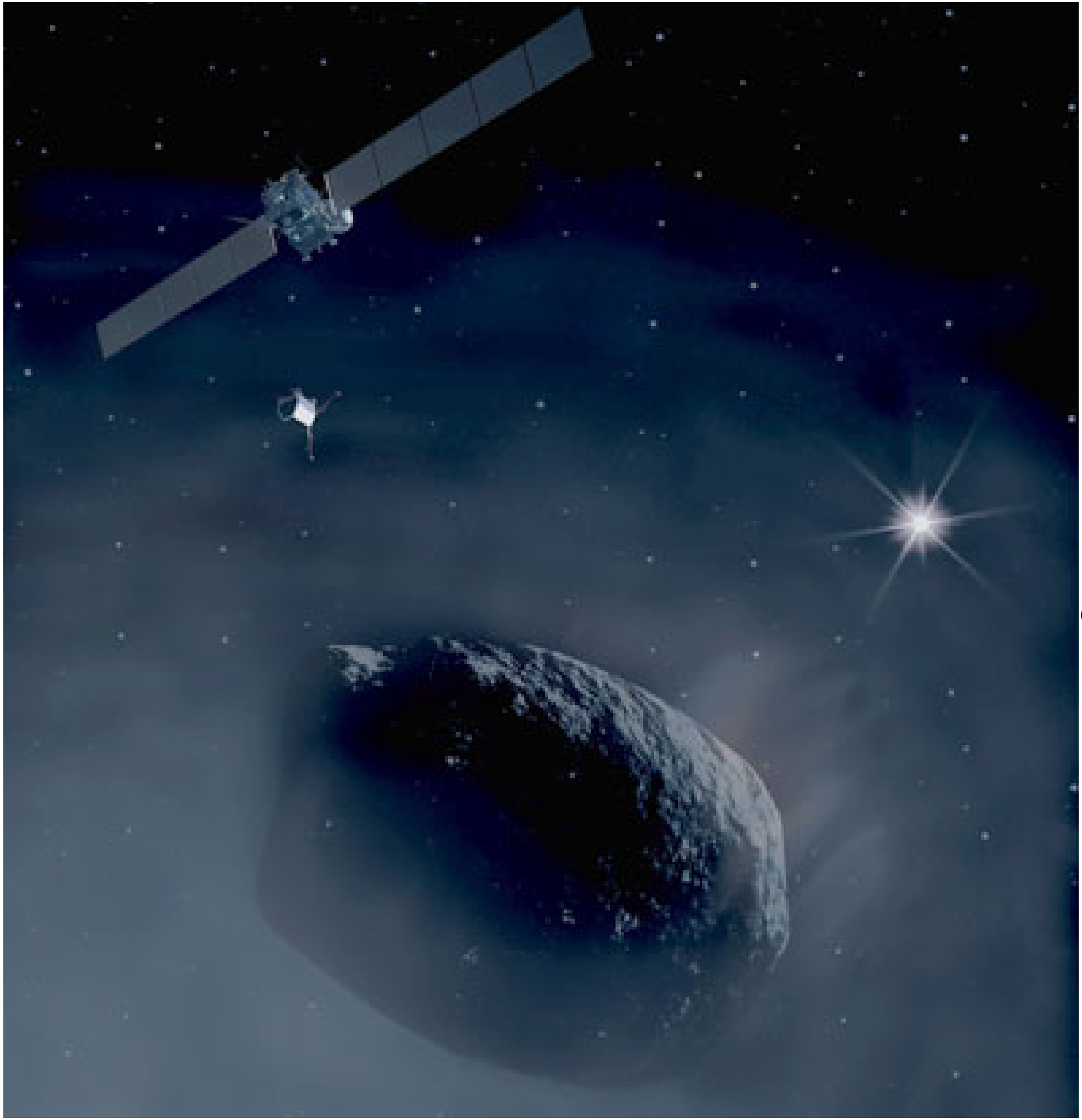
Moon (at 428061 km), before the flyby of Earth on 4 March at 15h10

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