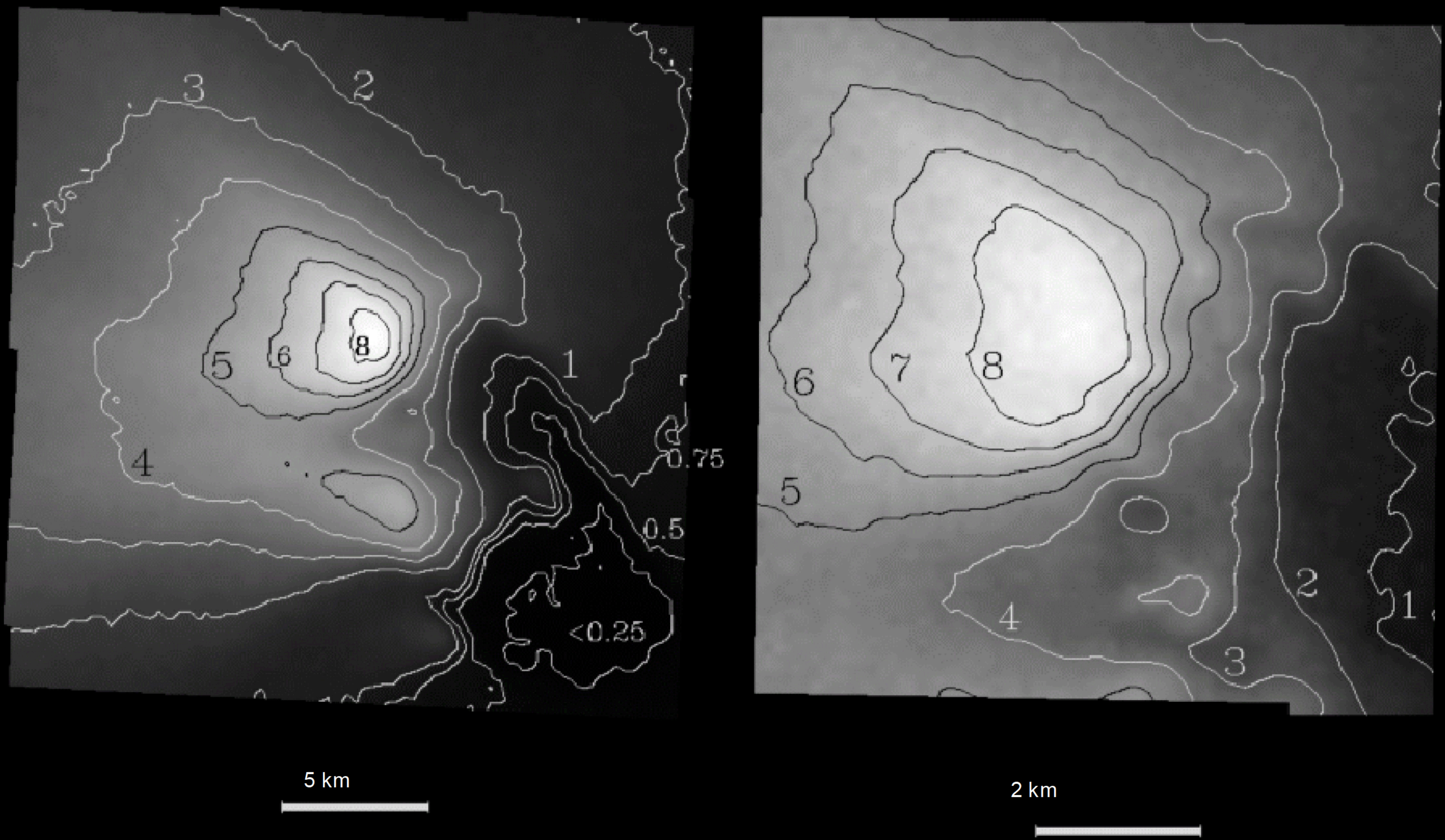
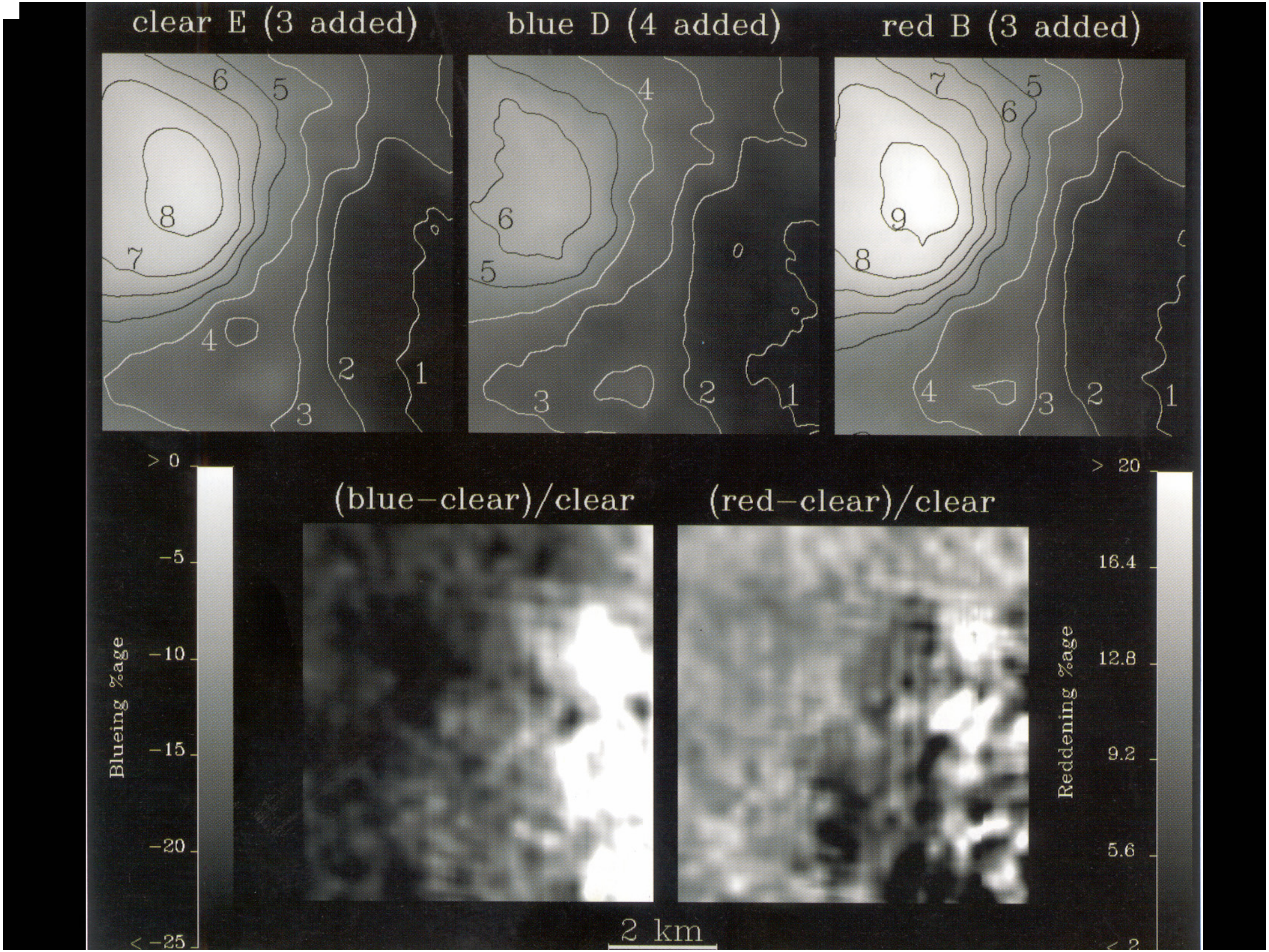
Clear filter images 3457 and 3491

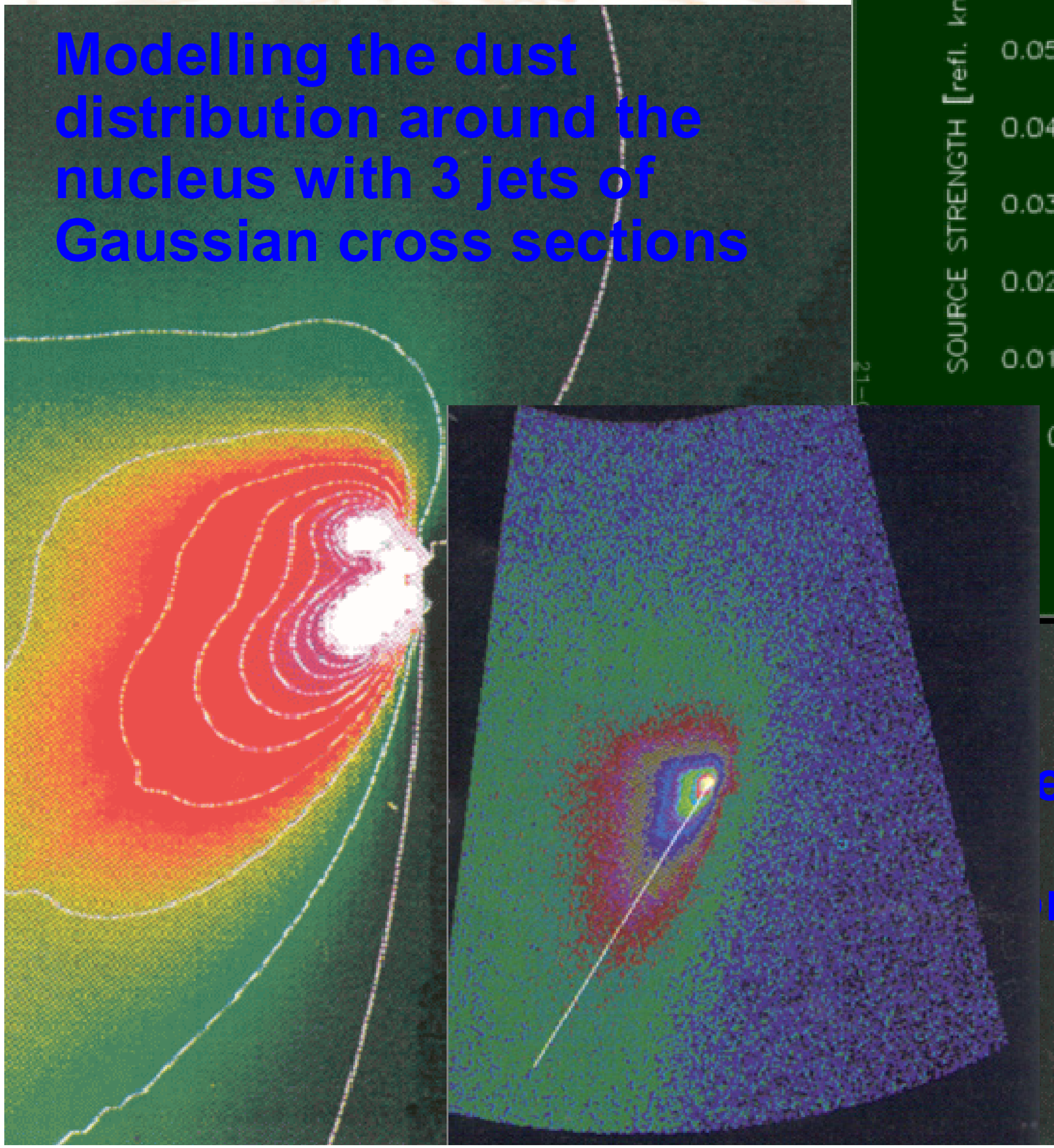
Contour levels in units of reflectivity x 1000
Phase angle 107°

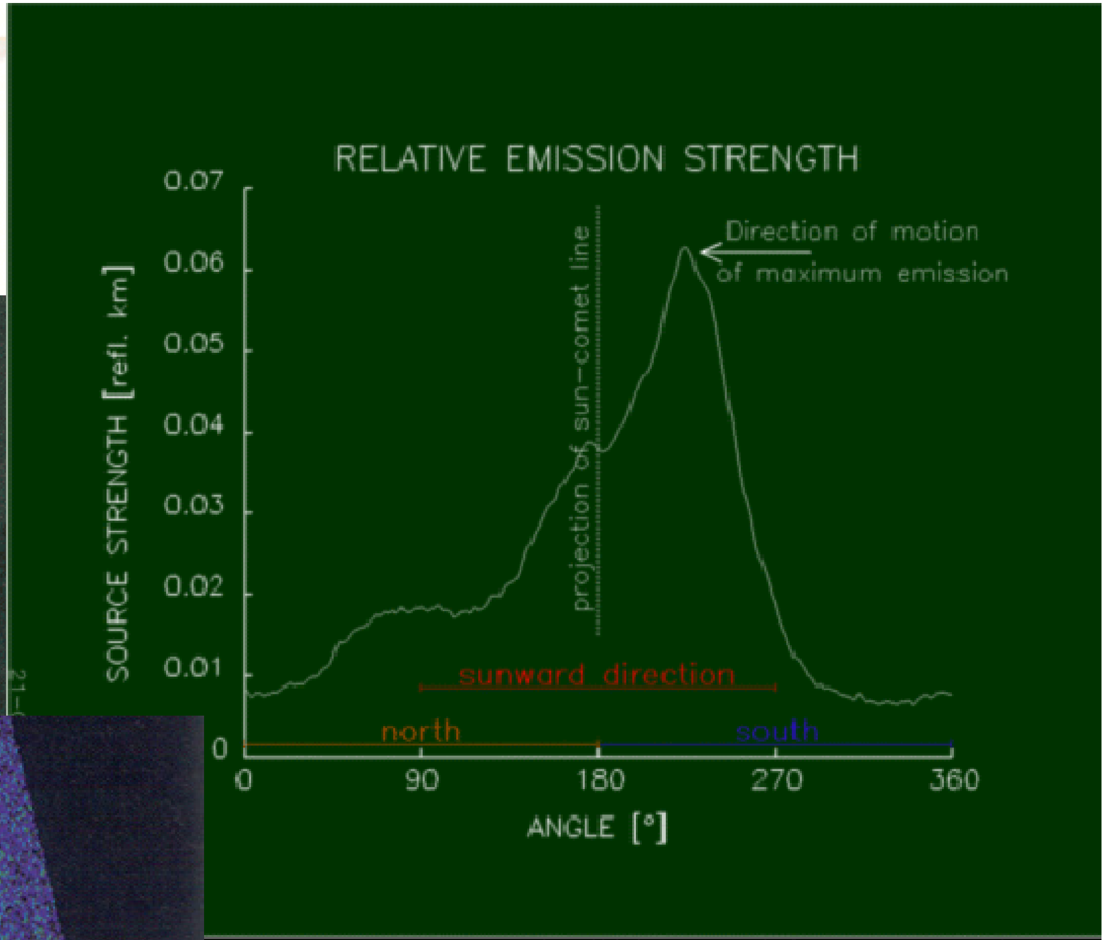



clear E (3 added)
blue D (4 added)
red B (3 added)
(blue−clear)/clear
(red−clear)/clear
Blueing %age
Reddening %age
> 0
−5
−10
−15
−20
< −25
> 20
16.4
12.8
9.2
5.6
< 2
2 km

Global dust distribution

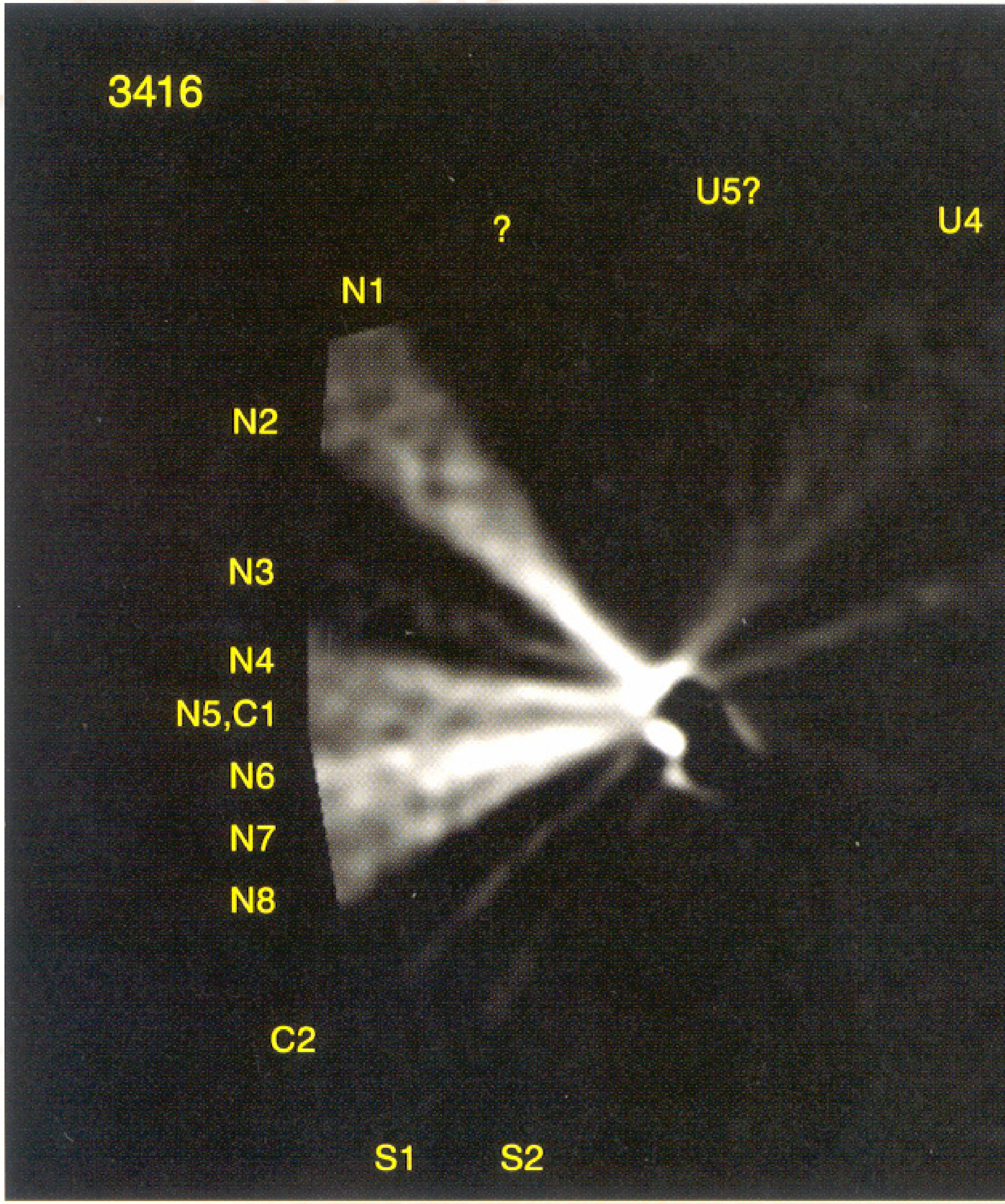
Modelling the dust distribution around the nucleus with 3 jets of Gaussian cross sections

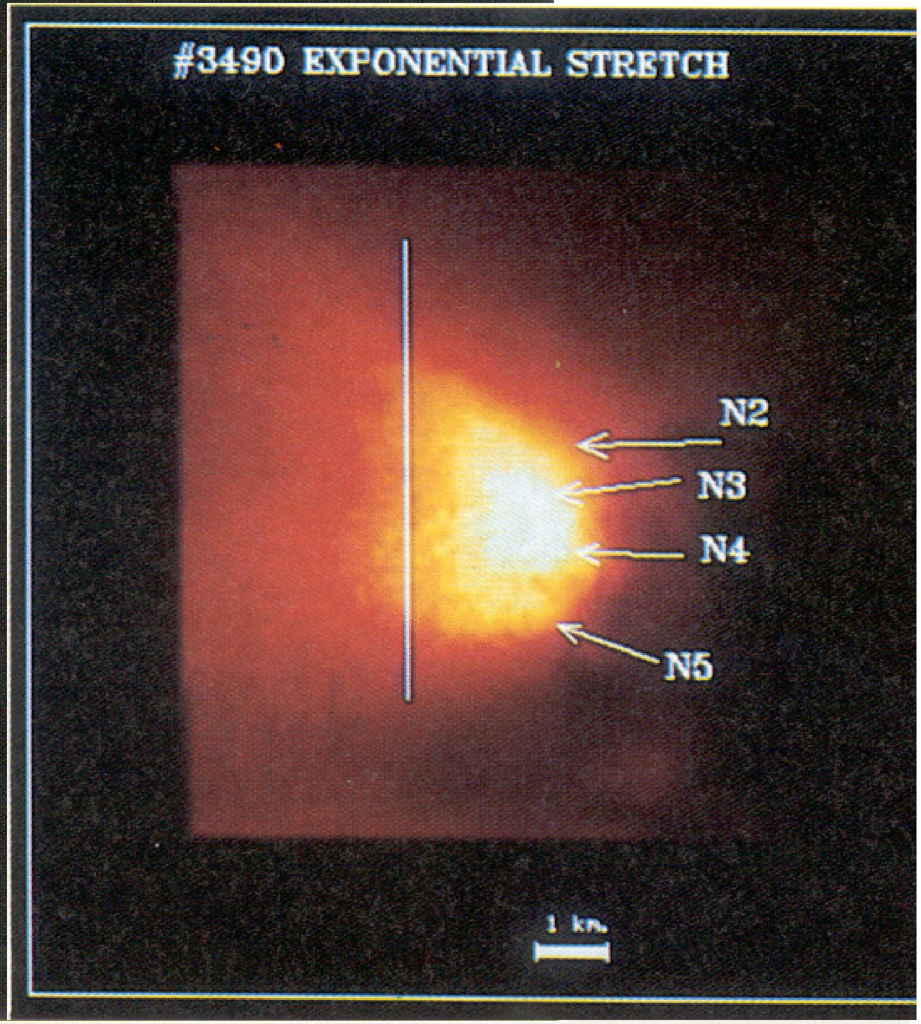


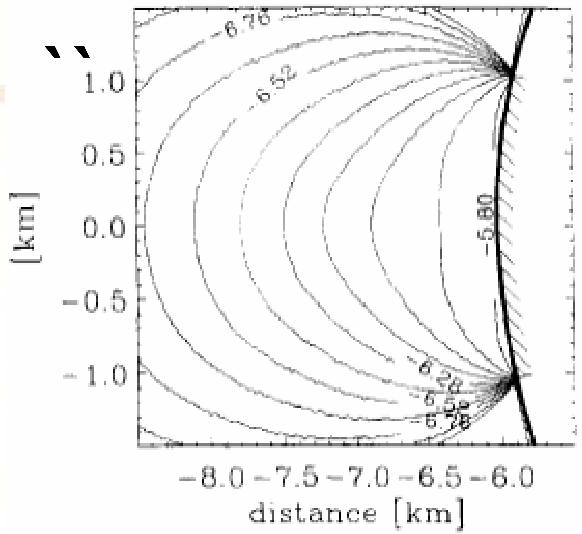


Direction (°)	Halfwidth (°)	Fraction (%)
137	37	47
198	31	17
273	44	11

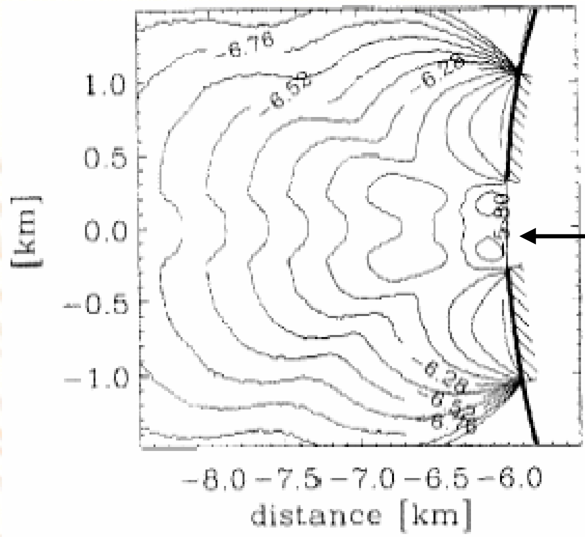
Jets and Filaments



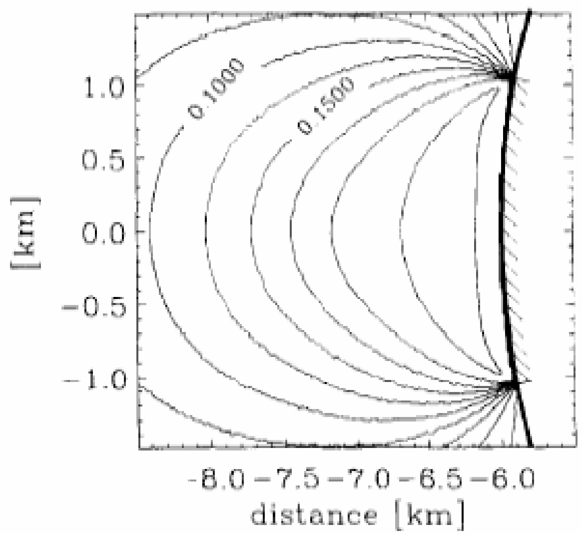




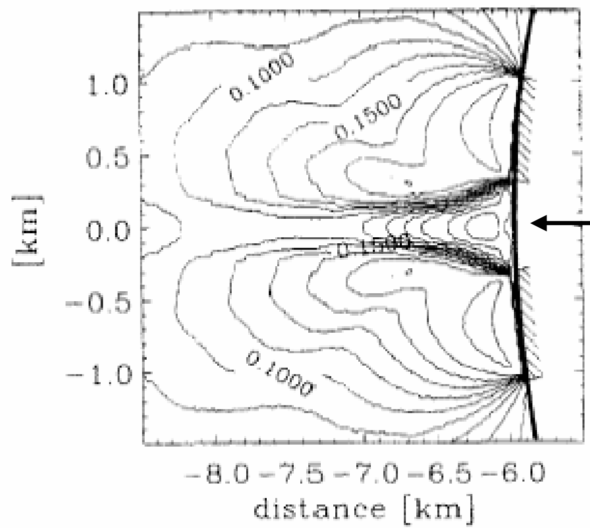
Gas density (log)



Non active patch

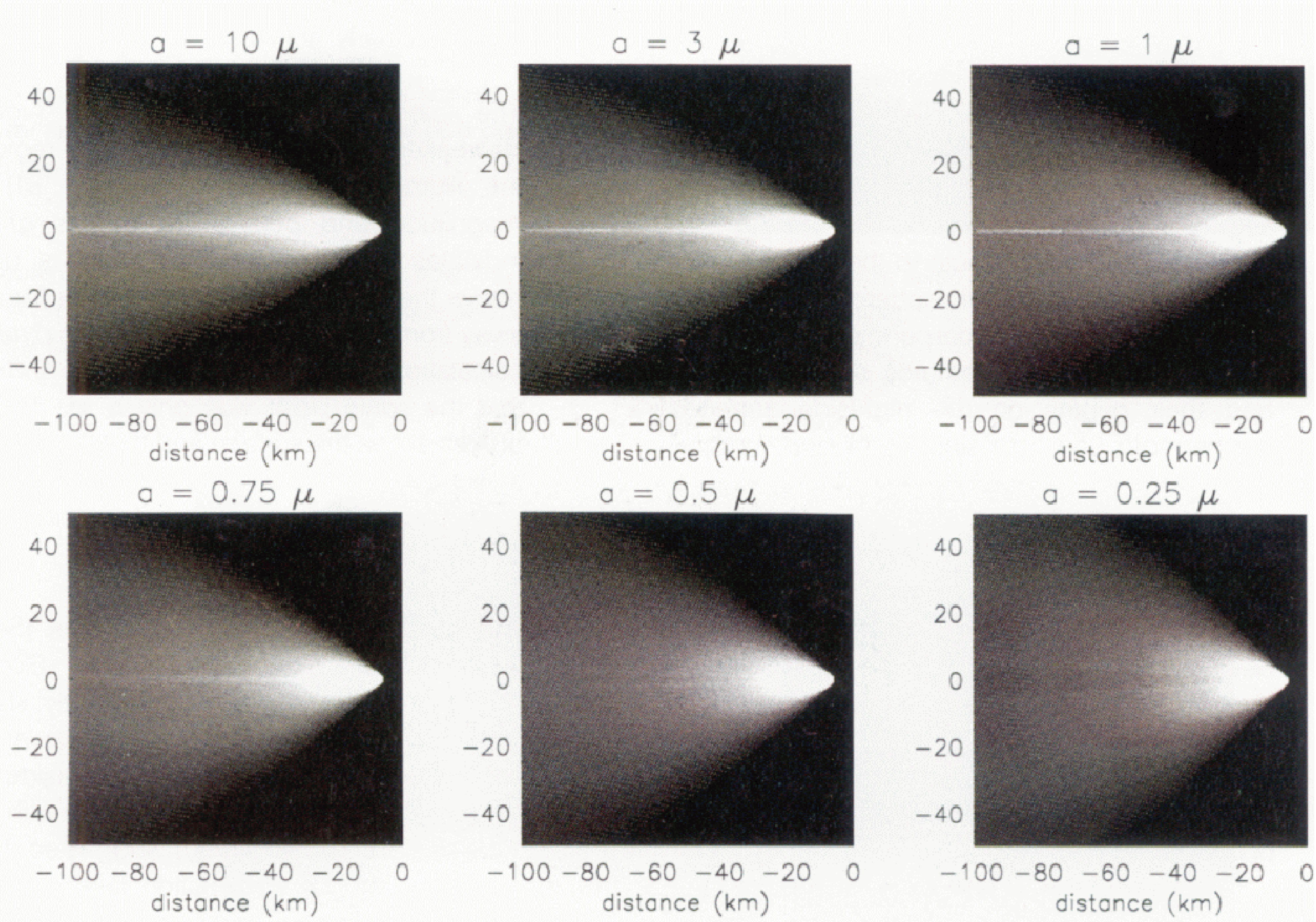


Gas momentum flux (log)



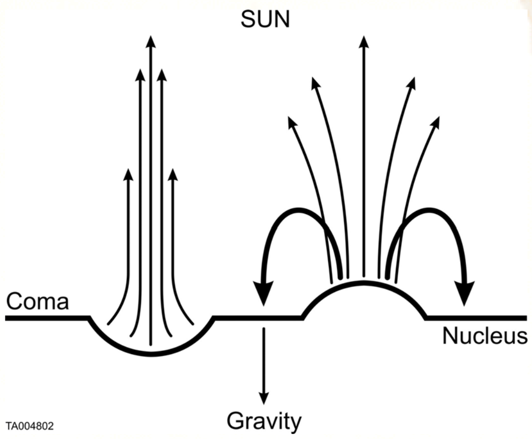
Non active patch

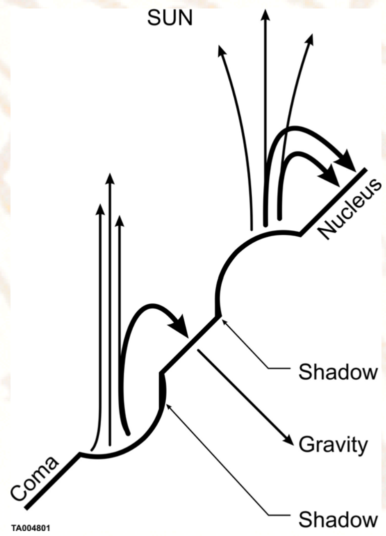
Modeling the filaments by putting inactive spots within an active area



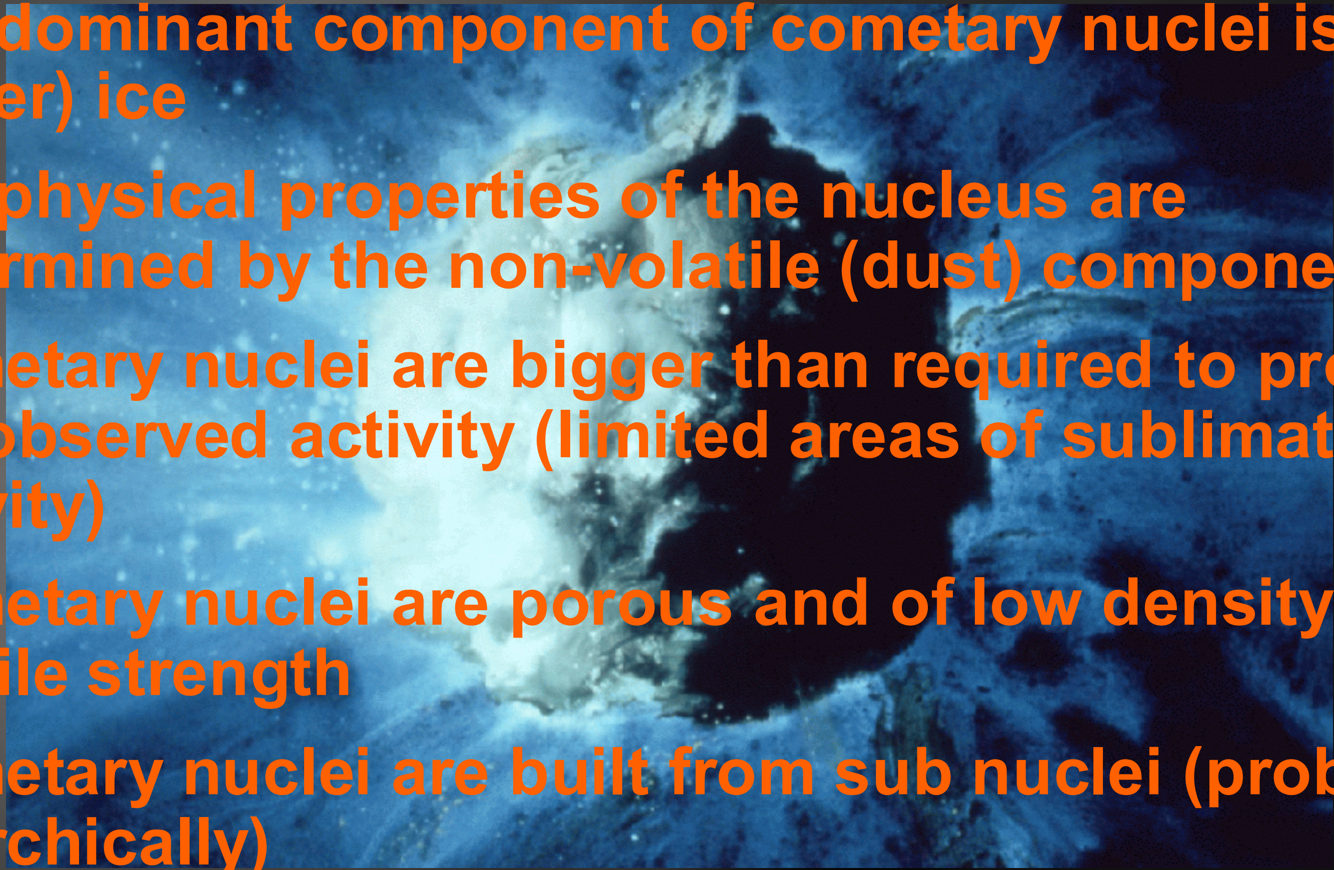
“Jet” and Mantle Formation

- 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)

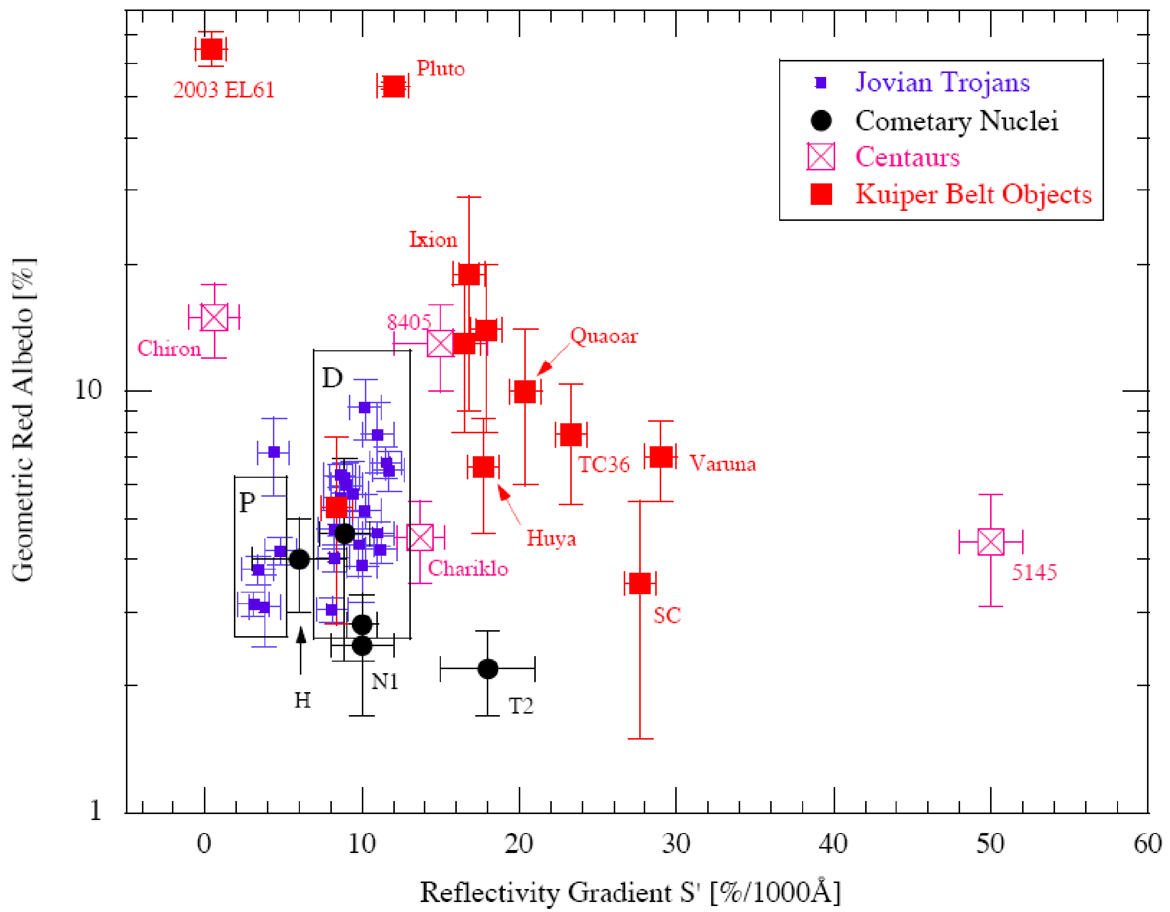
	Object	*Radius (r_n)*	*Albedo (p_v)*	*Active fraction (x)*
Oort Comets	**Hale-Bopp (C/1995 O1)**	**38 ± 6**	**0.06 ± 0.03**	**0.13 ± 0.05**
	IRAS-Araki-Alcock	**3.0 ± 0.5**	**0.03 ± 0.01**	**0.06 ± 0.03**
	55P/Tempel-Tuttle	**1.84± 0.15**	**0.05 ± 0.01**	**-**
	126P/IRAS	**1.57 ± 0.14**	**0.04**	**0.11 ± 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	1.5			
C/1983 H1 (IRAS-Aracki-Alcock)	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

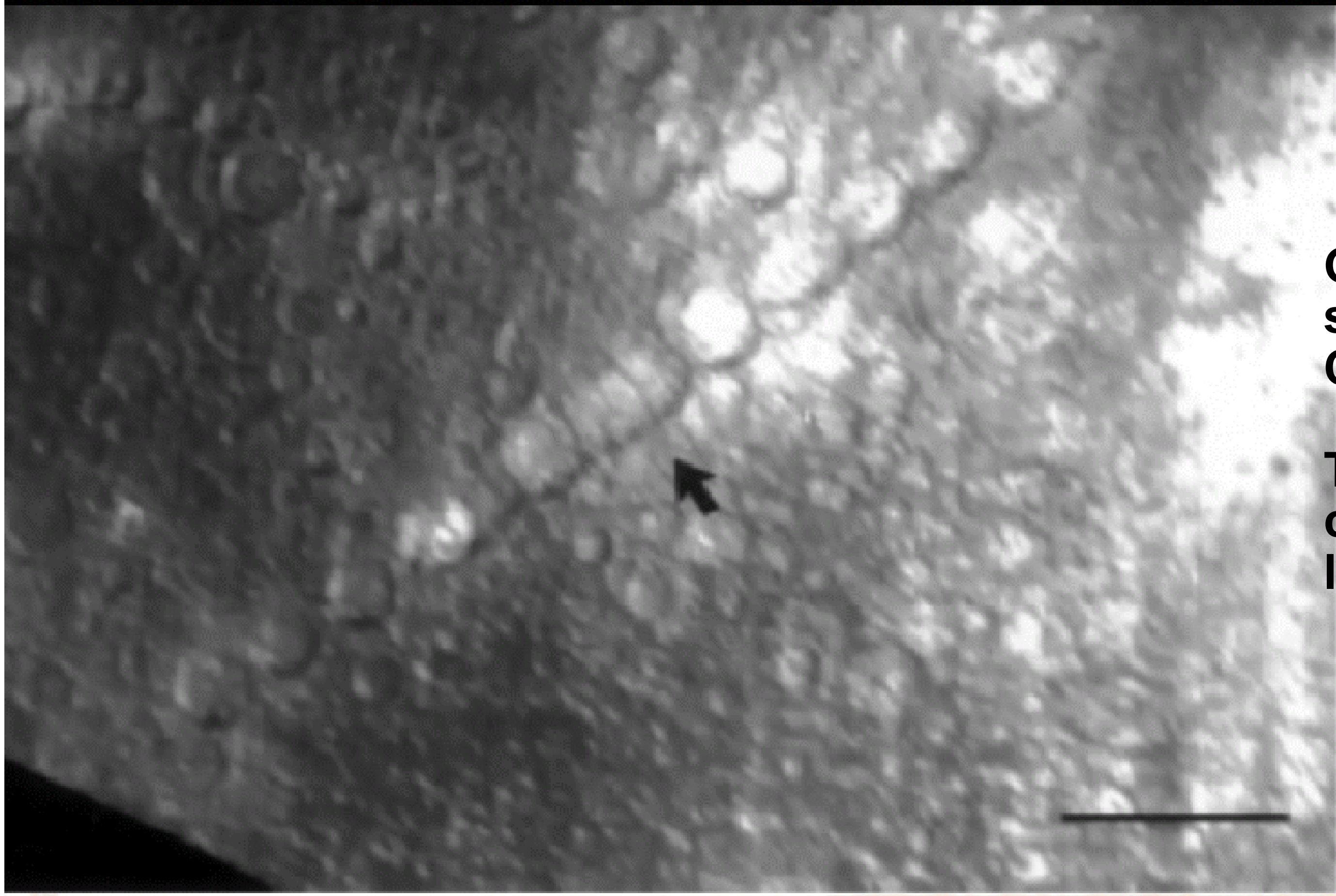


Jewitt, 2006
Saas Fee 35
Proceedings

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)

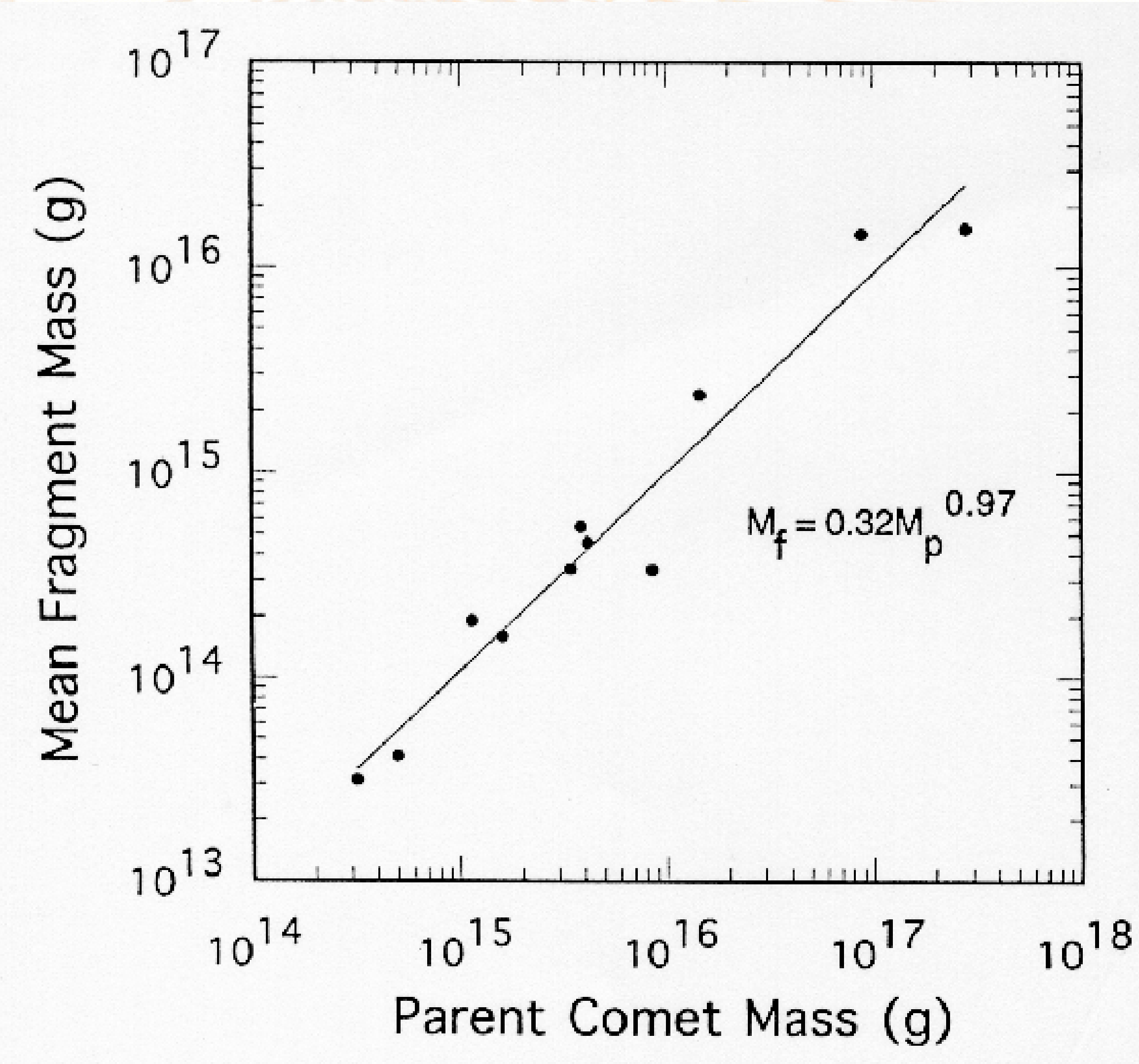
Comet Shoemaker-Levy



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

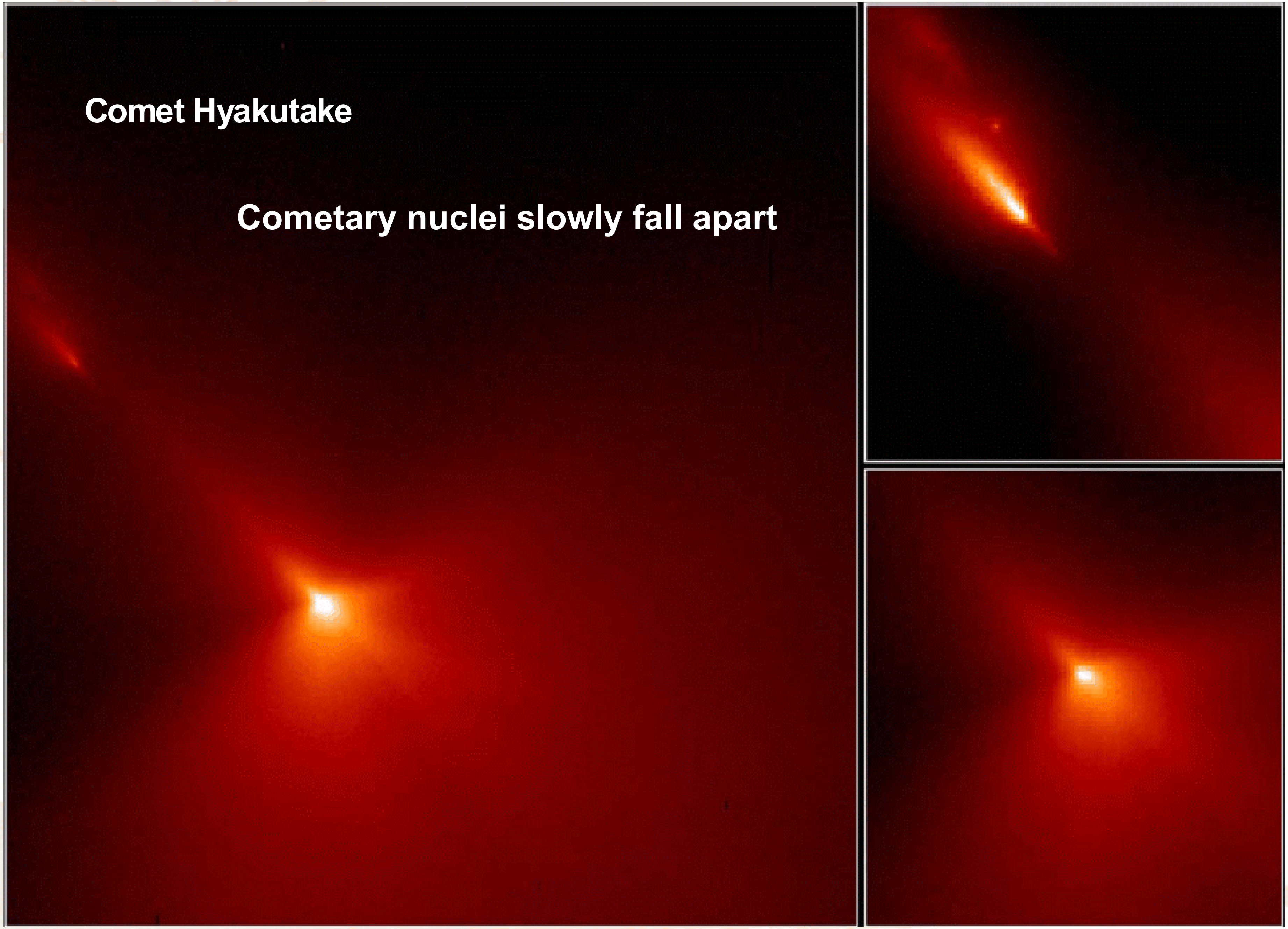


Correlation of mean fragment mass for individual crater chain comets and mass of the associated parent comet (Schenk et al 1996, data from McKinnon and Schenk 1995).

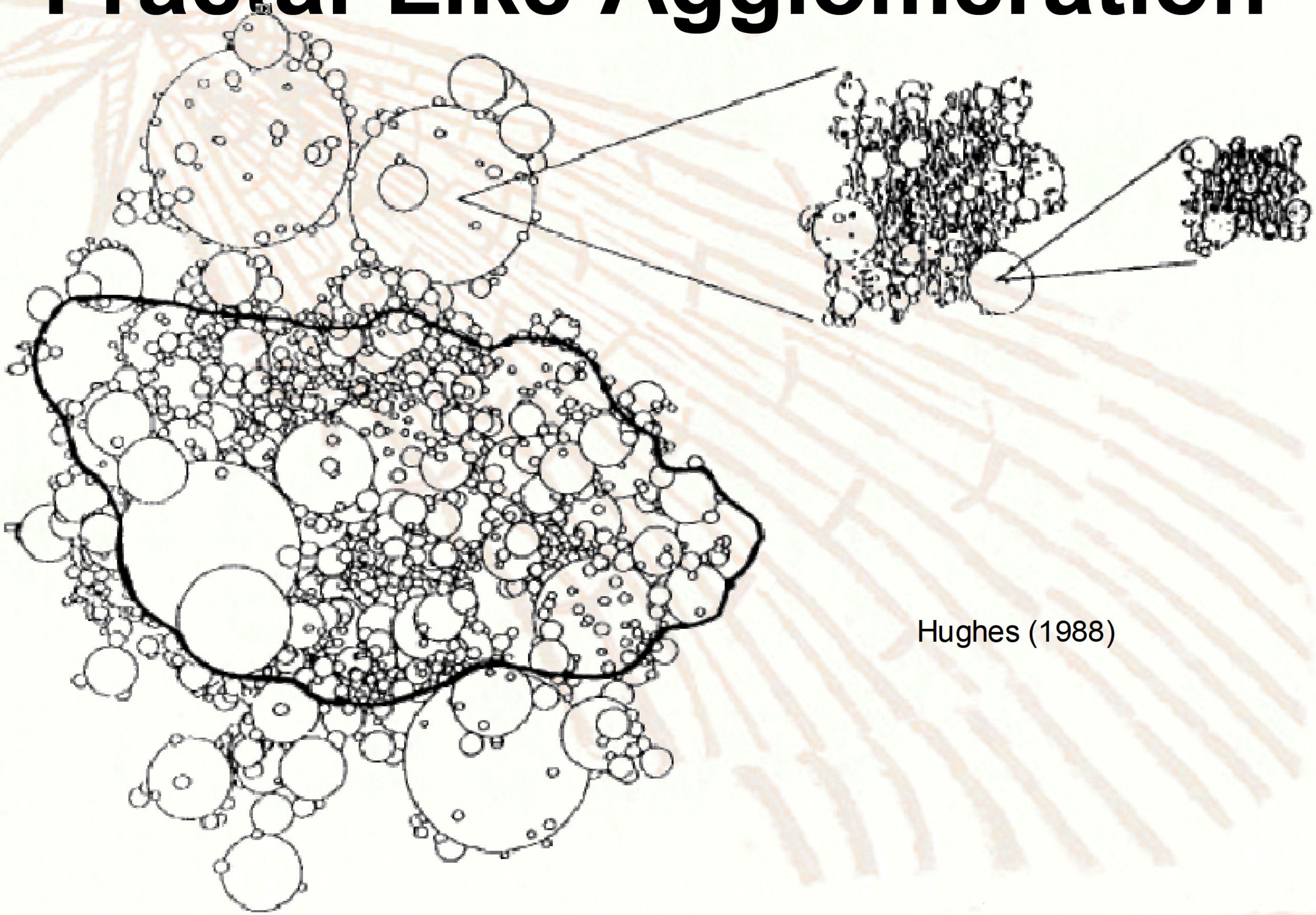
Bigger comets break up in bigger subnuclei.

No preferred size!
(Weidenschilling 1997, 2000)

Cometary Nuclei are of Low Tensile Strength



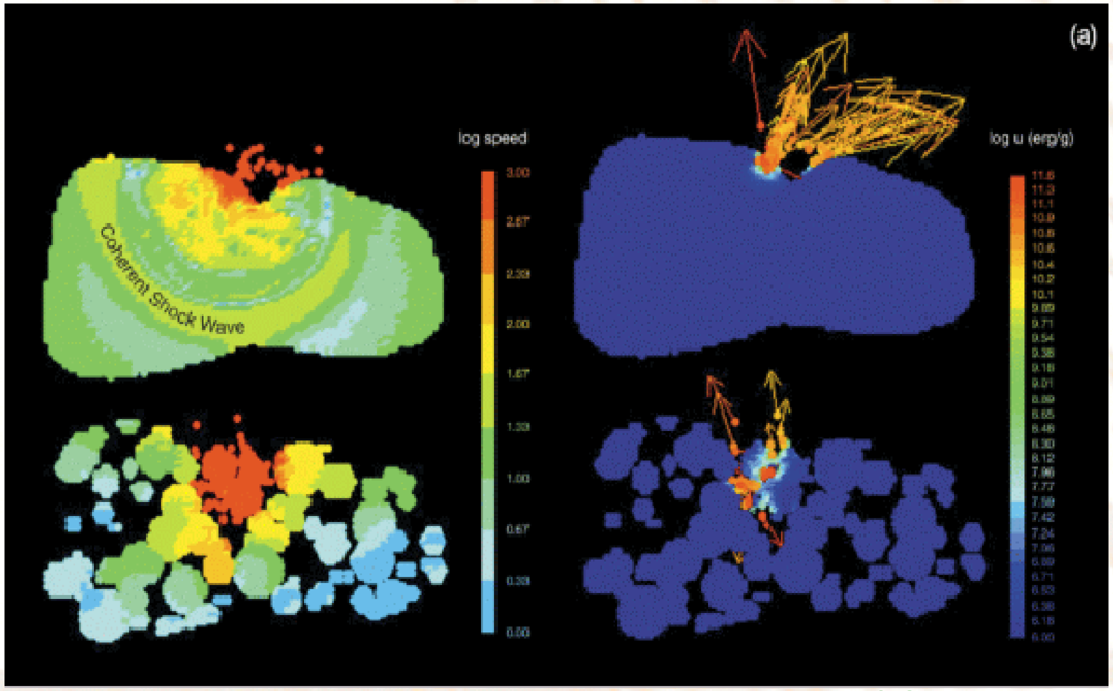
Fractal-Like Agglomeration



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

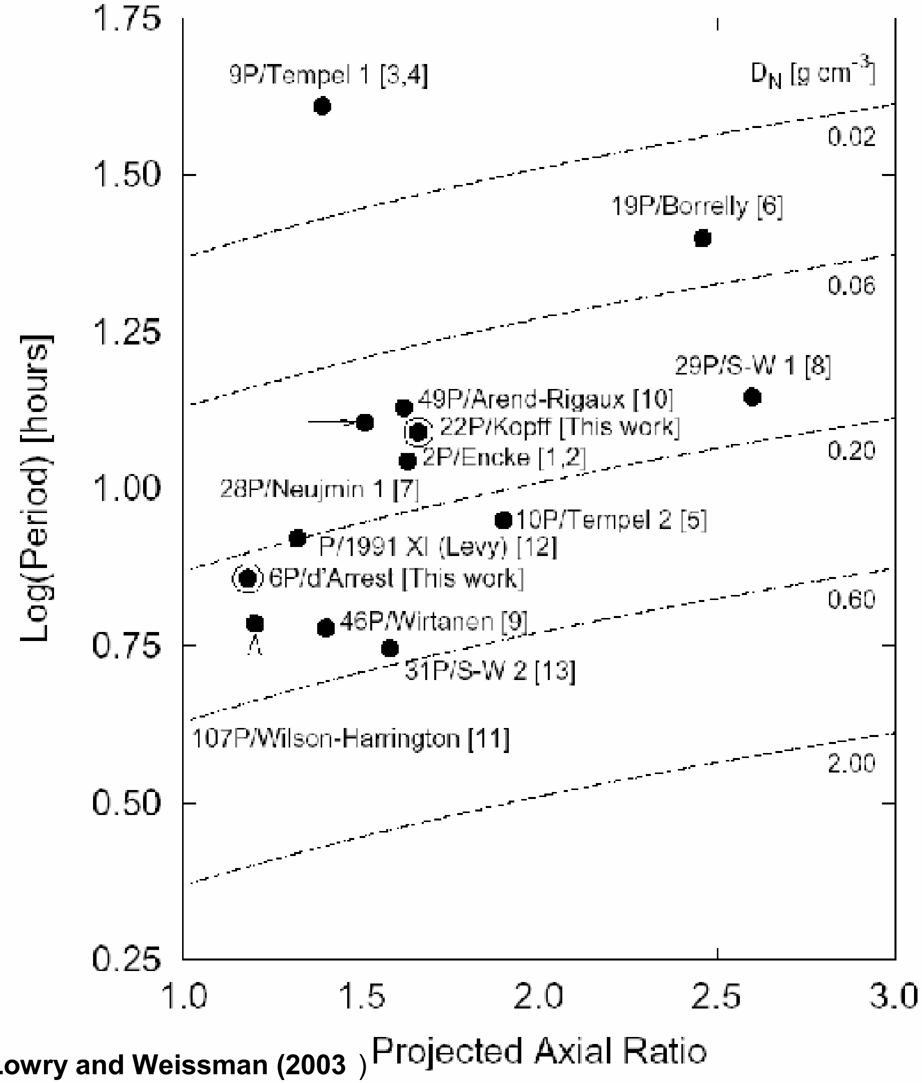


High impact energies can create shock fronts that penetrate and shatter the whole target body:

"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

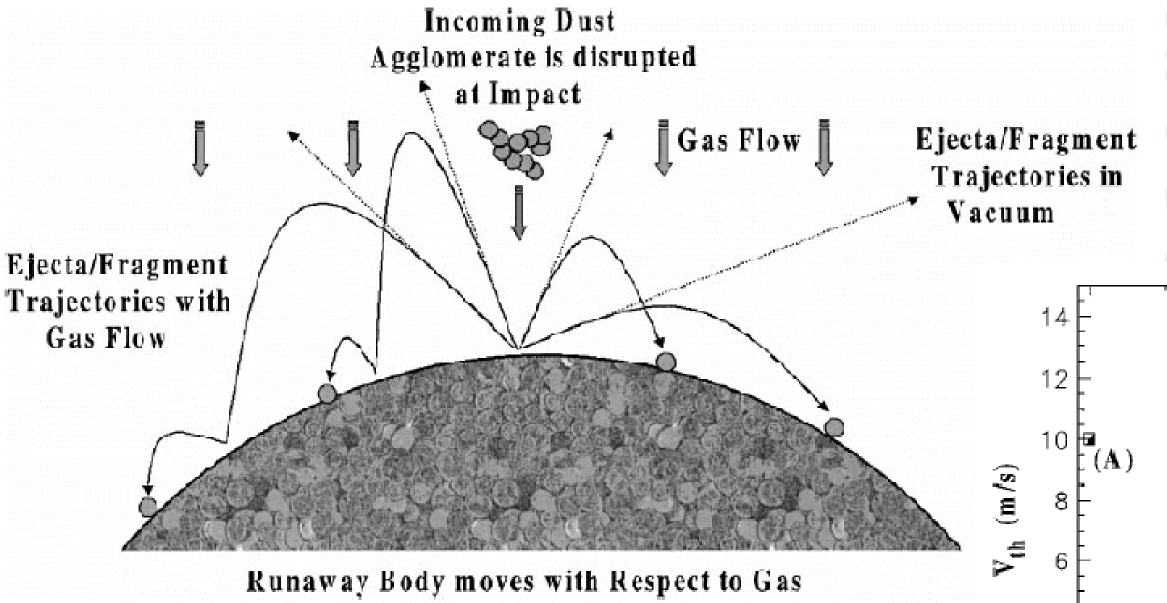
Formation

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

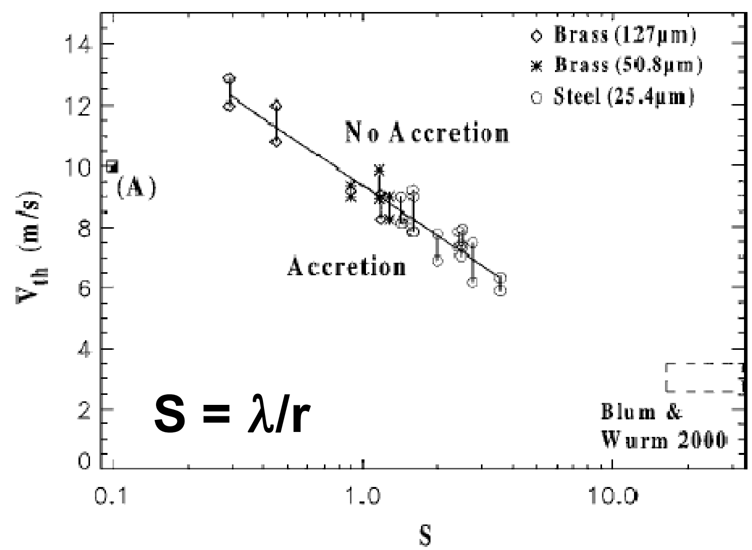
What are the steps?

- 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)



$S = \lambda / r$

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

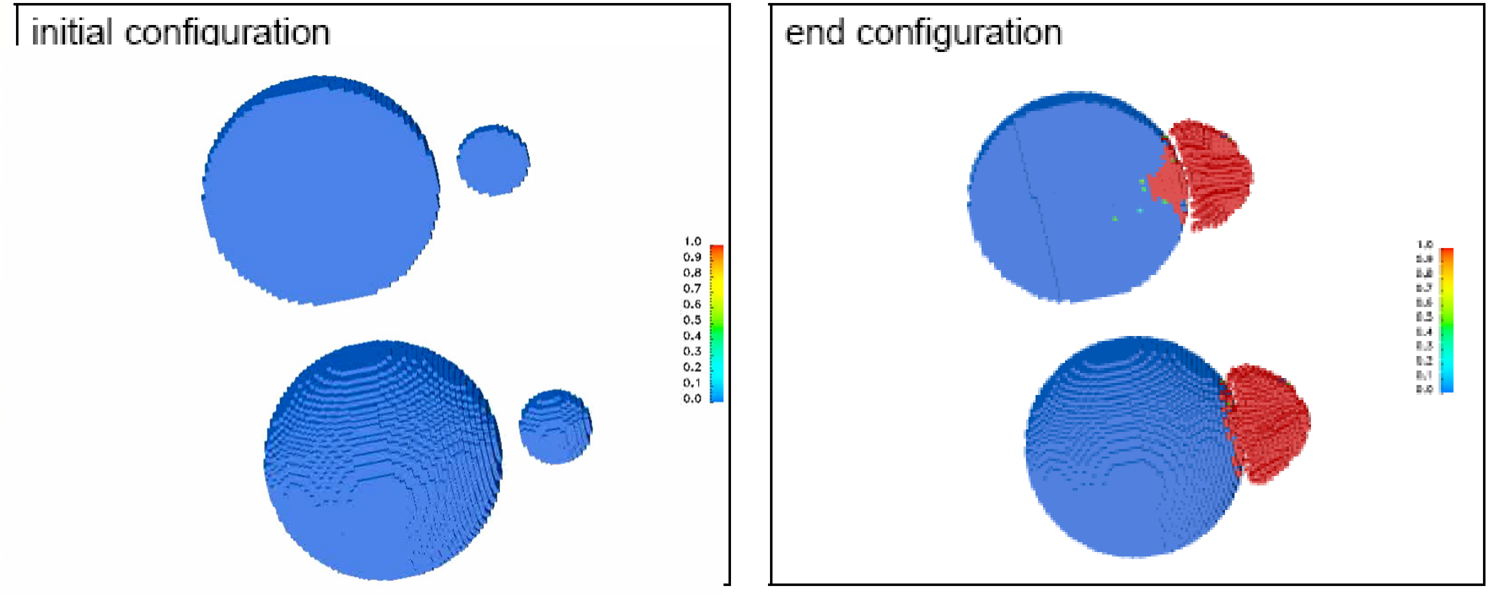
  (strongly indicated, e.g., by low density of asteroids and comets, by lab experiments of dust growth (Blum, Wurm), and theoretical simulations (Dominik, Tanaka)).

⇒ 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



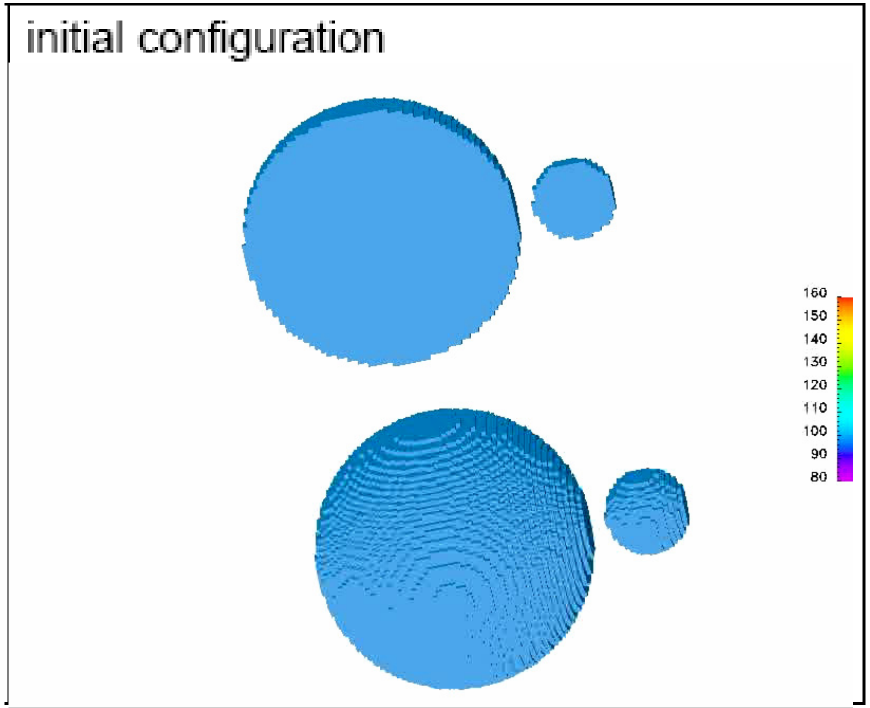
Colour-coded: damage

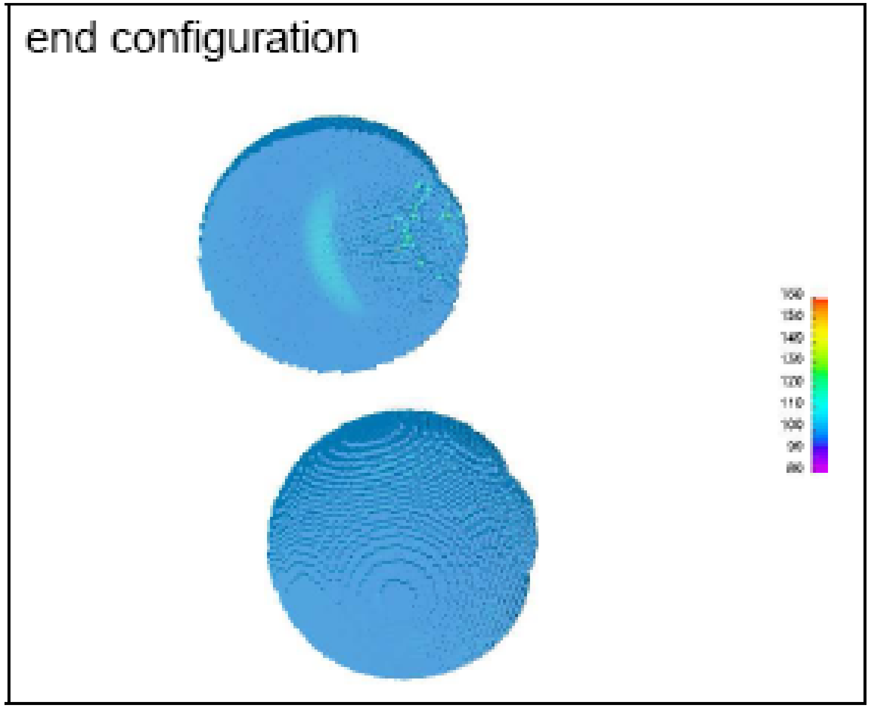
Target-radius: $1\,\mathrm{m}$, Impactor-radius: $1/3\,\mathrm{m}$, Initial density: $3\,\mathrm{g/cm^3}$,

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

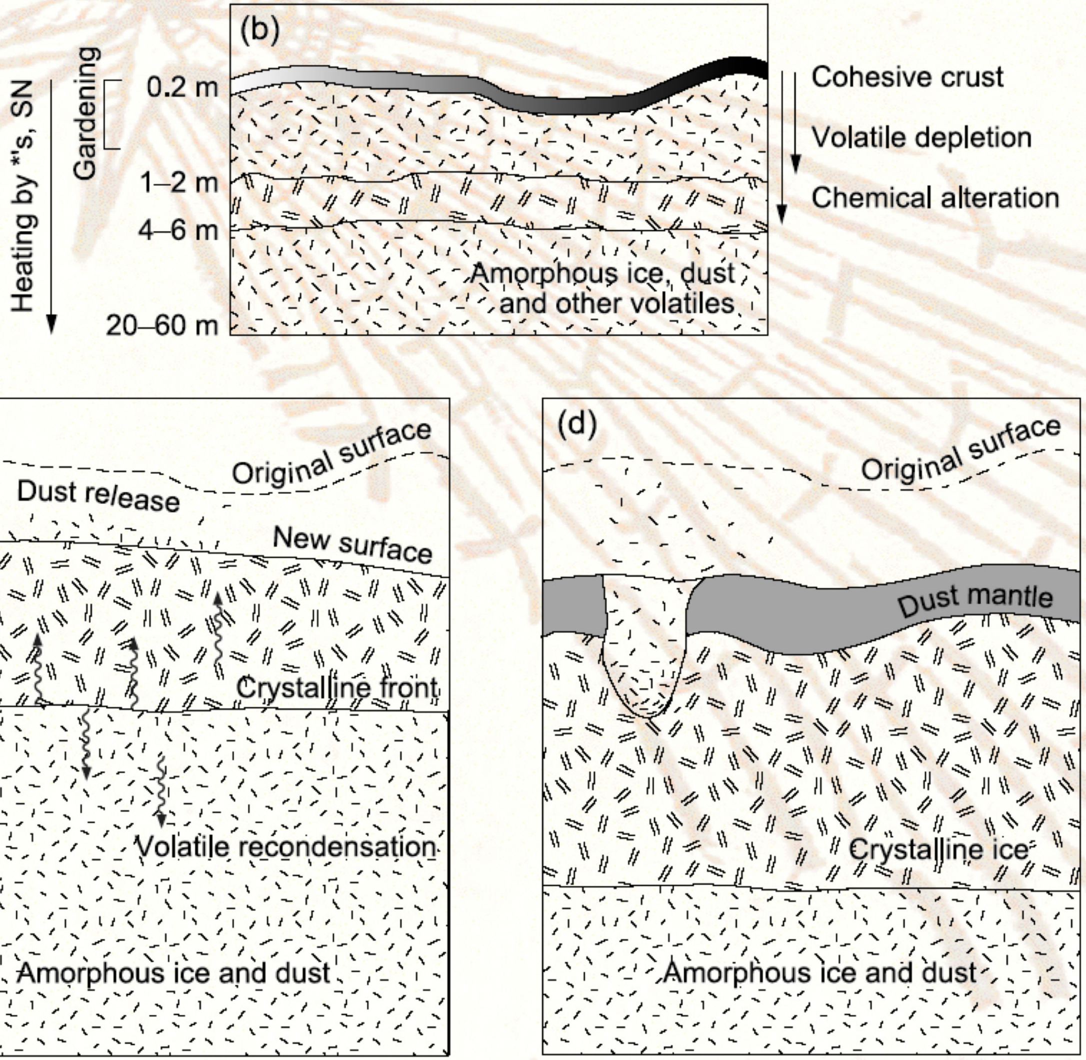
- Both comets, Halley and Borrelly, suggest a hierarchical size distribution of their building blocks
- Interpretation of the catenae leads to the same conclusion
- Feeding the agglomeration by a monolithic size (100 m range) is not corroborated
- Shedding of pieces during activity (e. g. Hyakutake) 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

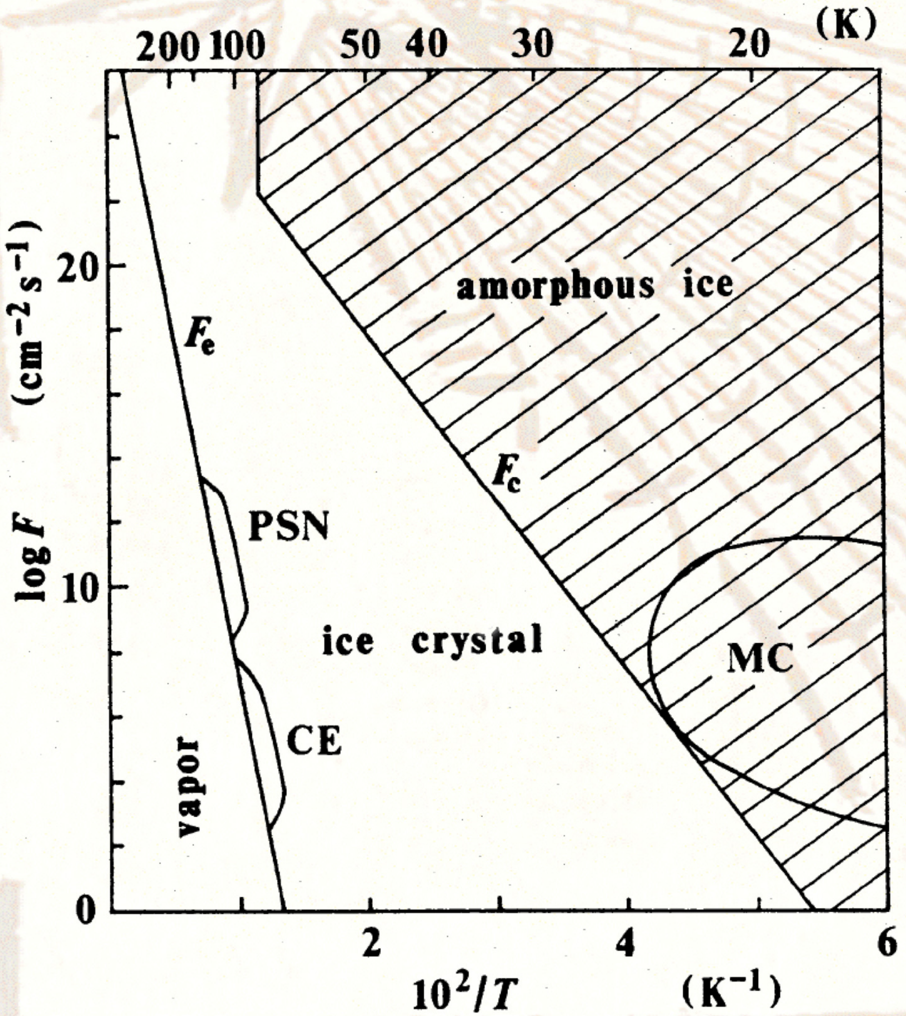
- **Has been produced in laboratory at:**
  - **Low temperature**
  - **Fast rate of condensation (no time for orientation of molecules as they condense)**
- **Has been suggested to exist in comet nuclei:**
  - **Low temperature of formation**
  - **Comet outbursts at large *r* (exothermic phase transition)**
  - **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

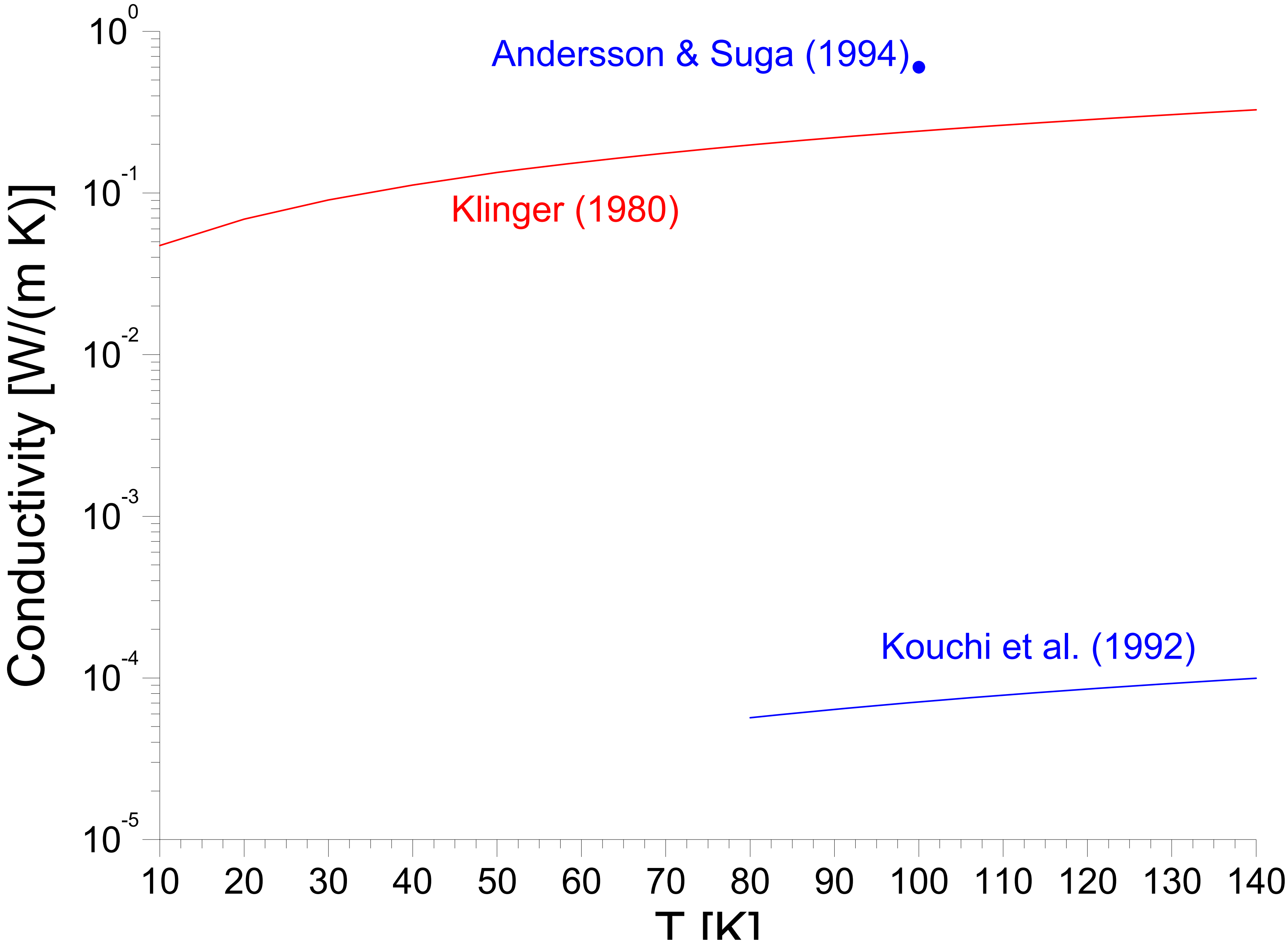
Amorphous Ice



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



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?

κ = 1 W m^{-1} K^{-1}
ρ = 600 kg m^{-3}
c = 800 J kg^{-1} K^{-1}
τ = 6 hours
d_t= 2 10^{-6} m^2 s^{-1}
Γ = 700 W m^{-2} $s^{-1/2}$ K^{-1}
δ = 12 cm

skin depth

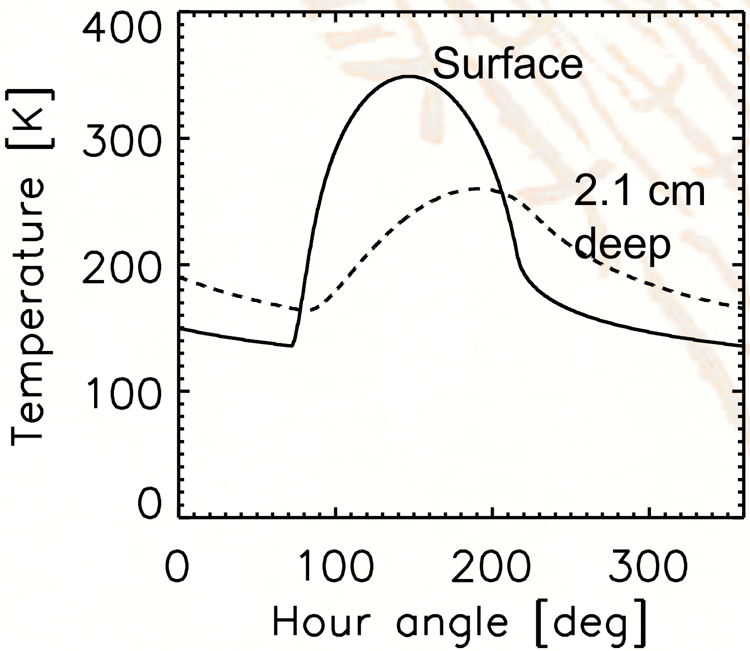
Highly porous material

κ = 0.01 W m^{-1} K^{-1}
ρ = 600 kg m^{-3}
c = 400 J kg^{-1} K^{-1}
τ = 6 hours
d_t= 4 10^{-8} m^2 s^{-1}
Γ = 50 W m^{-2} $s^{-1/2}$ K^{-1}
δ = 1.5 cm

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

Steady-State Calculation

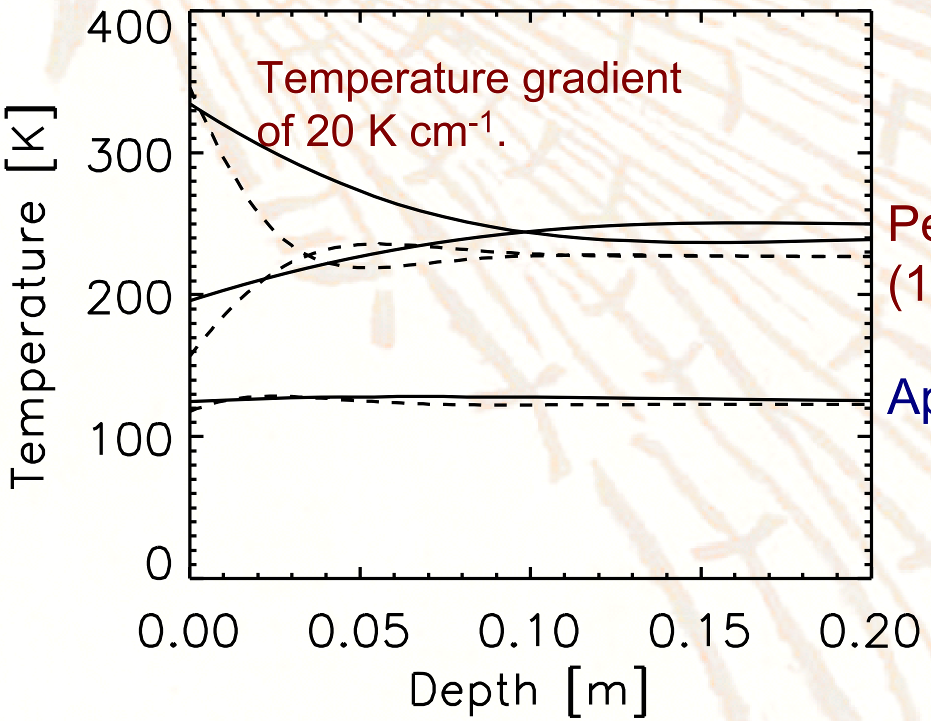
● Simple calculation shows that the temperature gradient is enormous.



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.

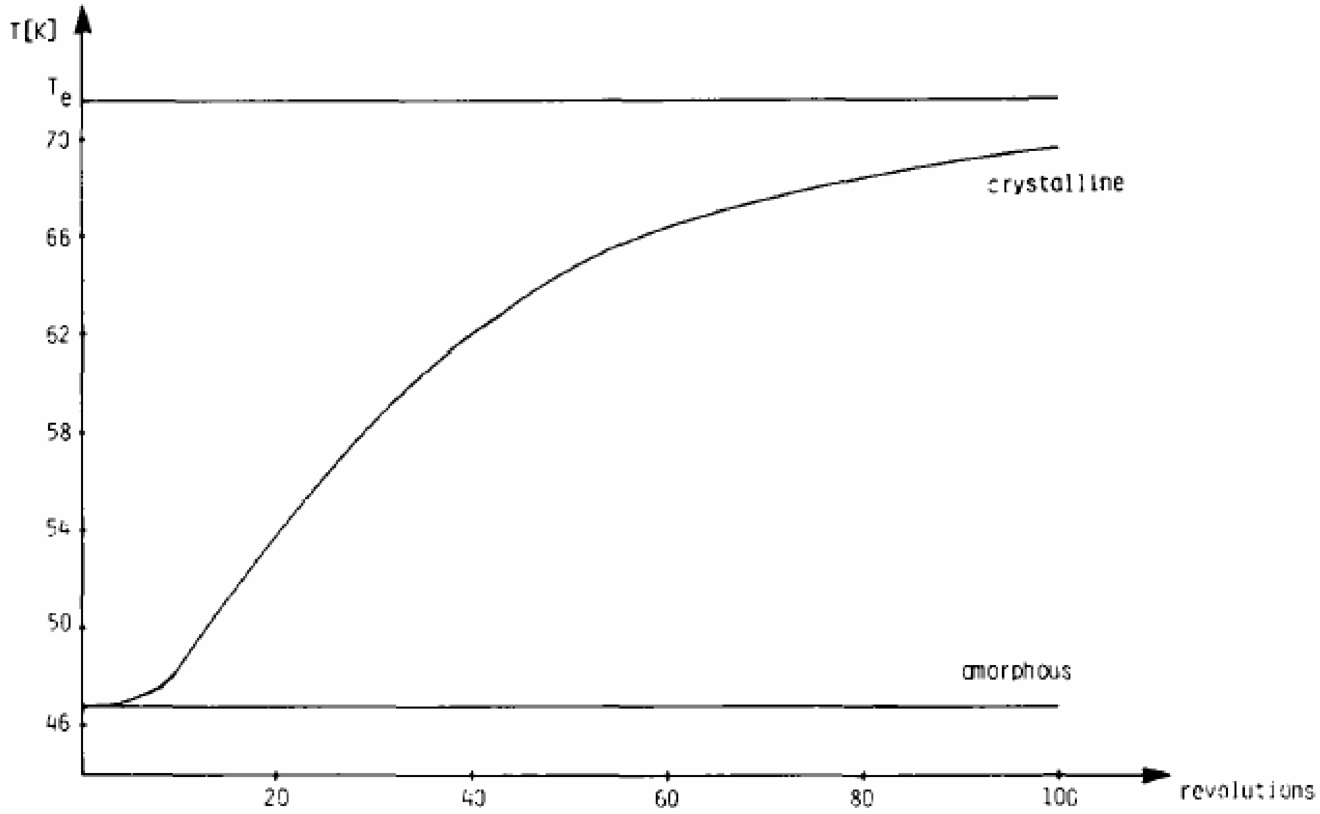
Nucleus Temperature

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

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

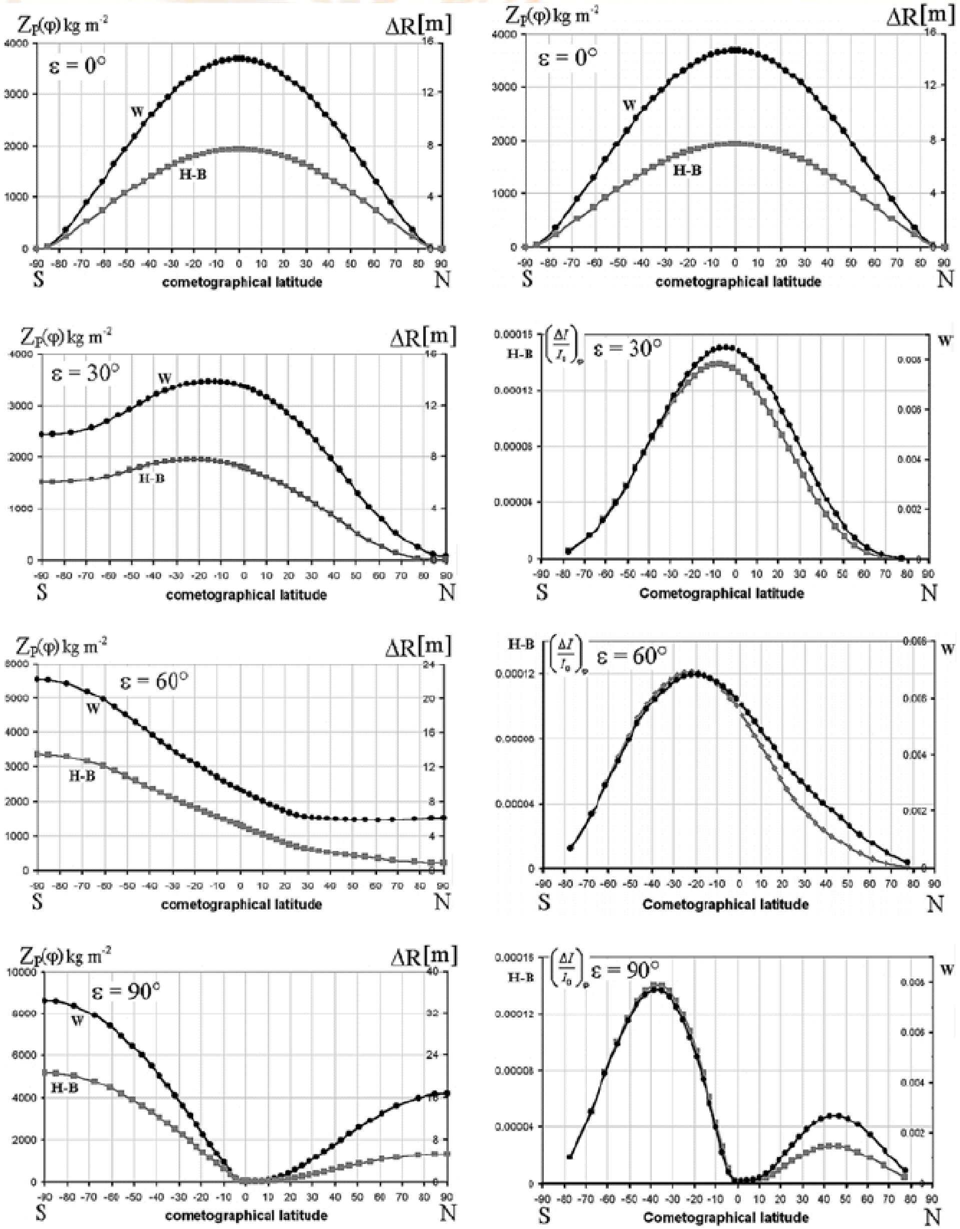
If applied to an ice surface, sublimation is rapid. Balancing energy input and latent heat, rates of 10^{22} molecule m^{-2} s^{-1} are typical leading to depth loss rates of 1 cm per few hours.

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



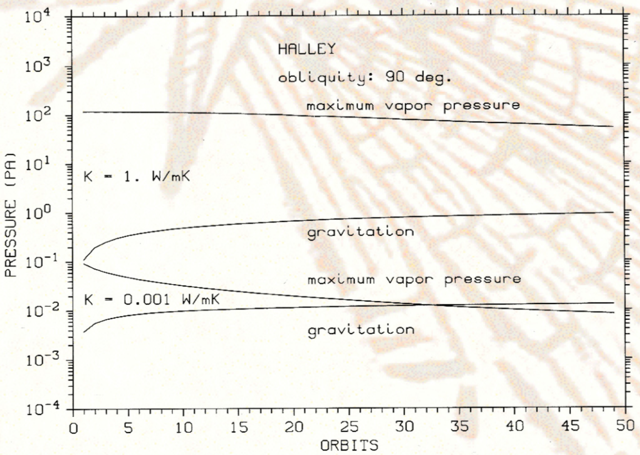
Dziak-Jankowska et al., EM&P, 2002.

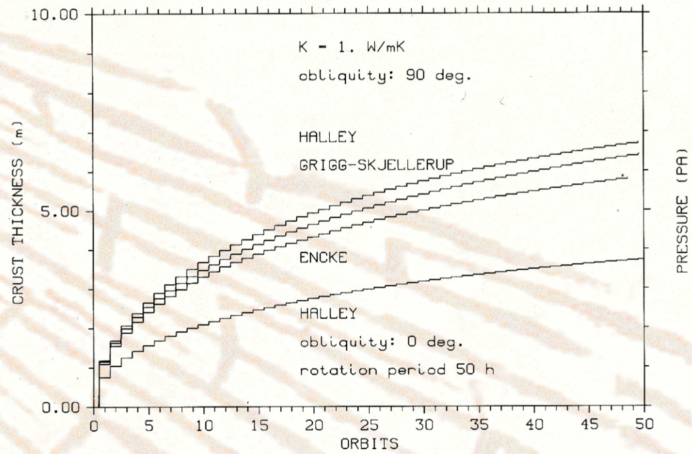
An initially spherical uniformly subliming nucleus will become aspherical naturally because of the orbital eccentricity combined with the obliquity.

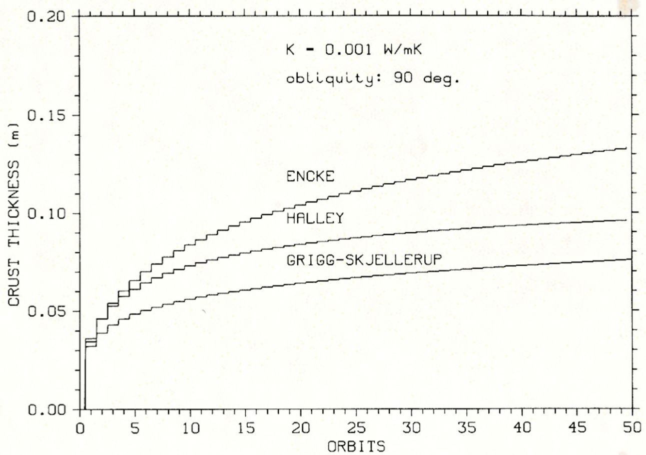
Gas "Pressure"

- **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

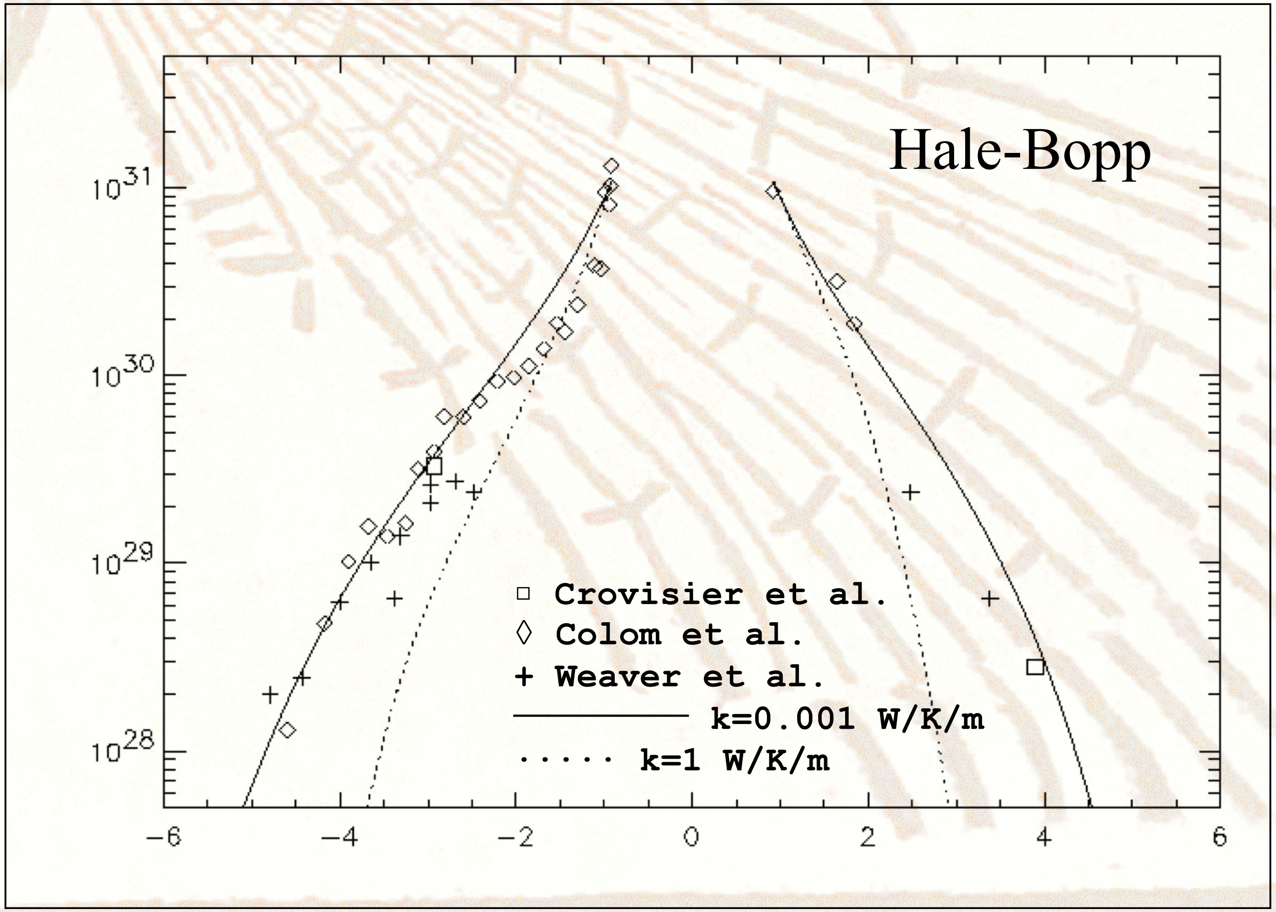
Reduction in Sublimation by a Surface Layer

- **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.**

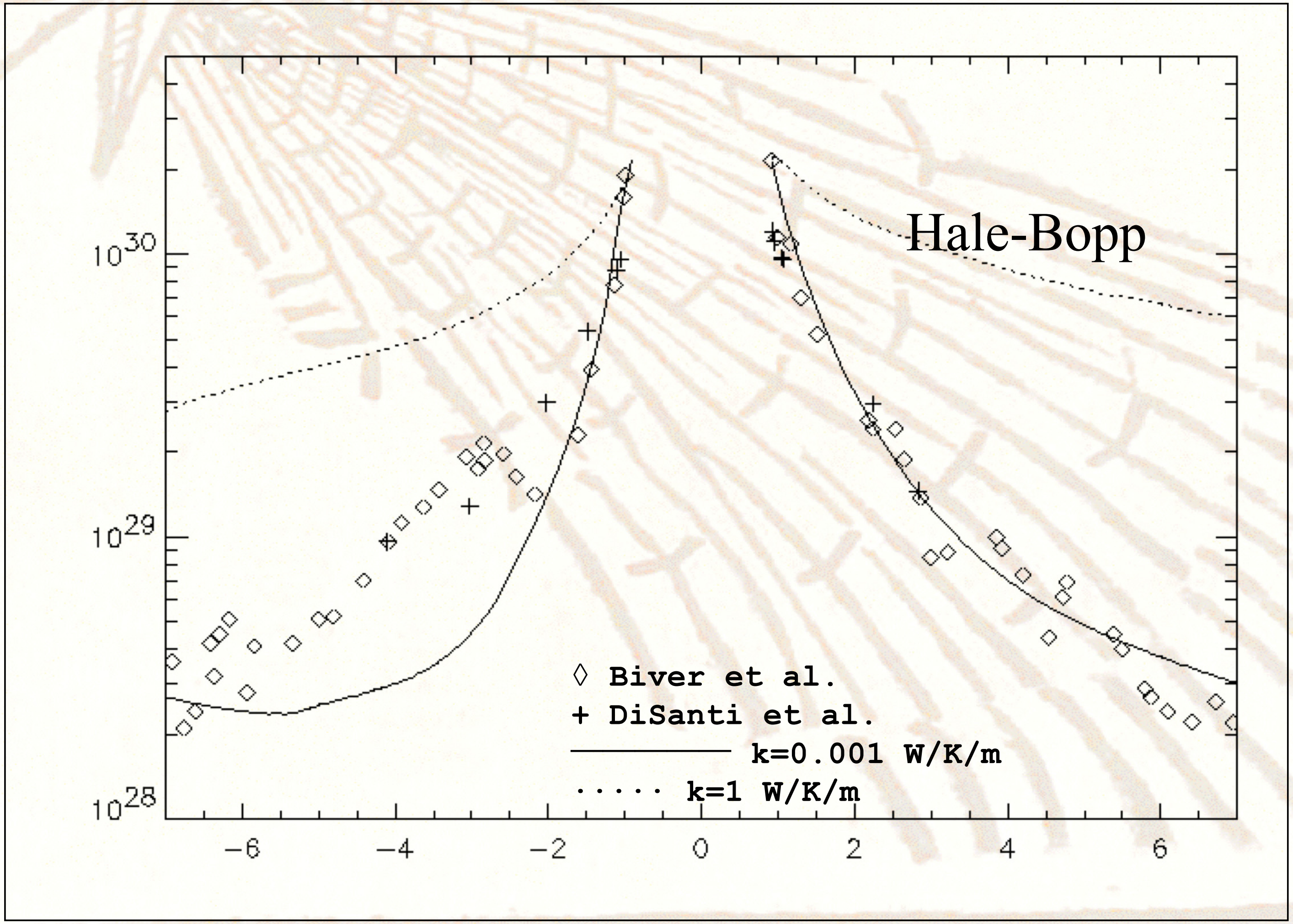
Sublimation from a sub-surface layer below 1 thermal skin depth cannot match cometary production rates.

Modeled and measured H_2O production rates

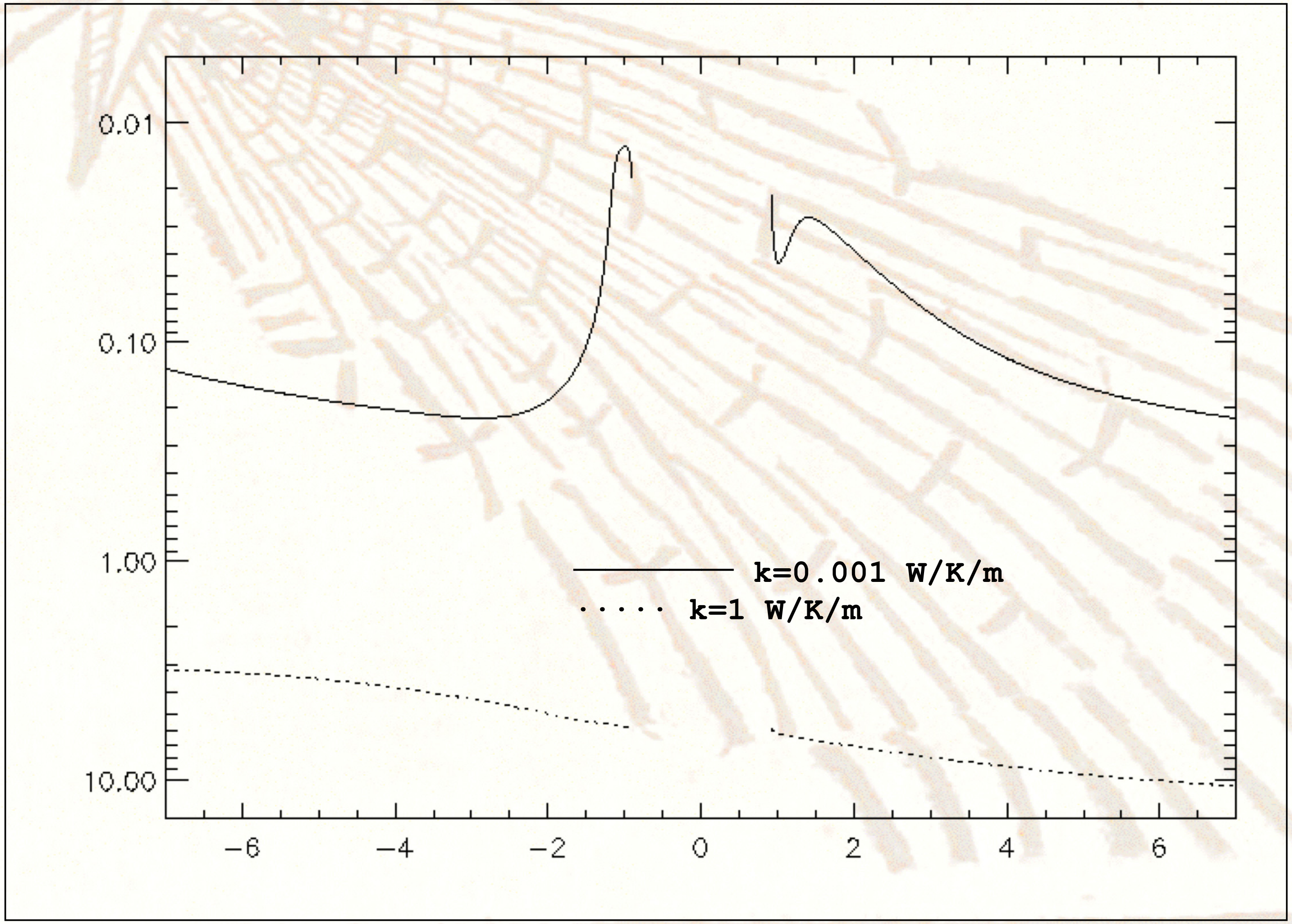
(Kührt, Knollenberg, Groussin)



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

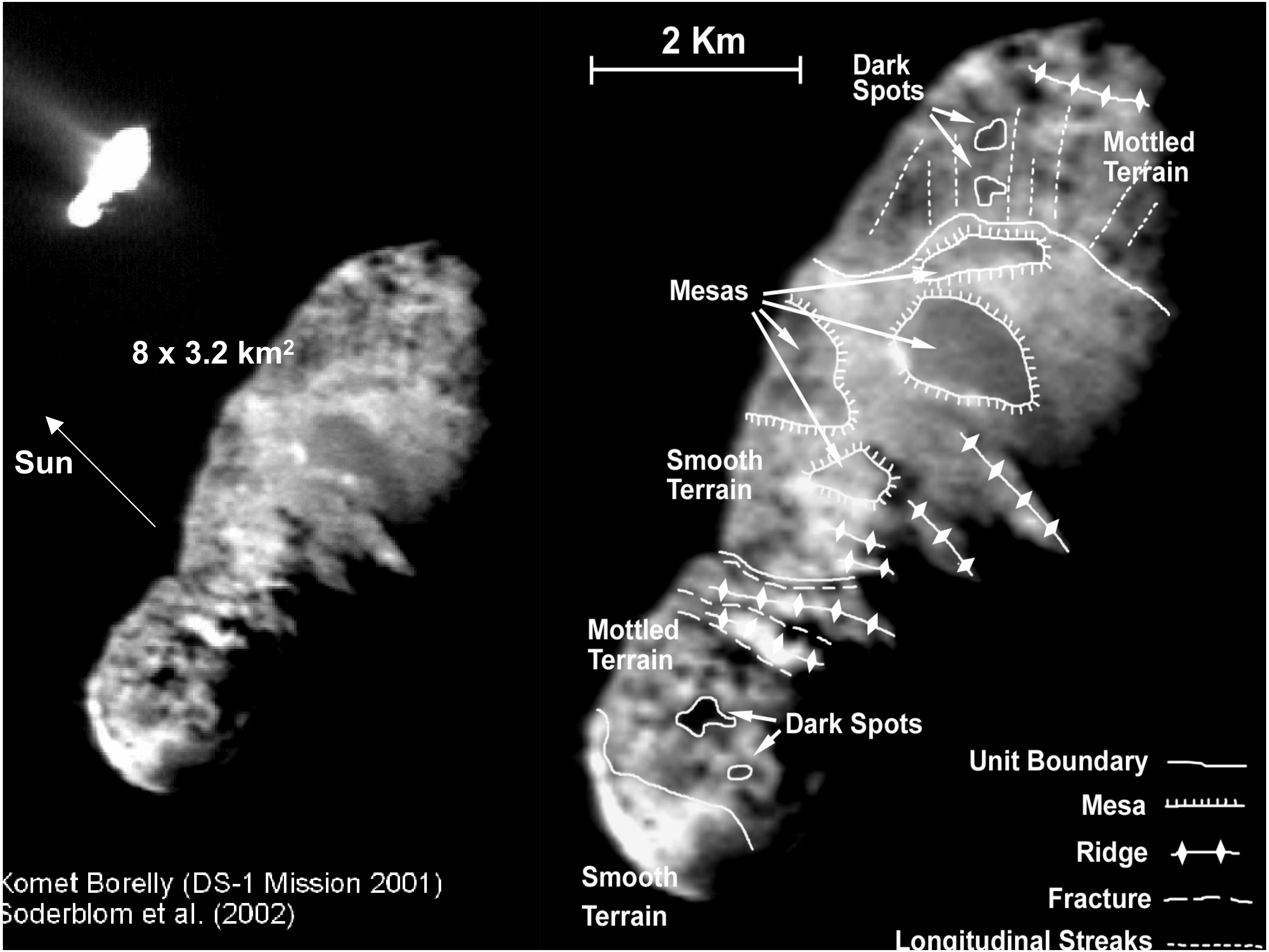
19P/Comet Borrelly

- Jupiter family orbit
- perihelion 1.36 AU

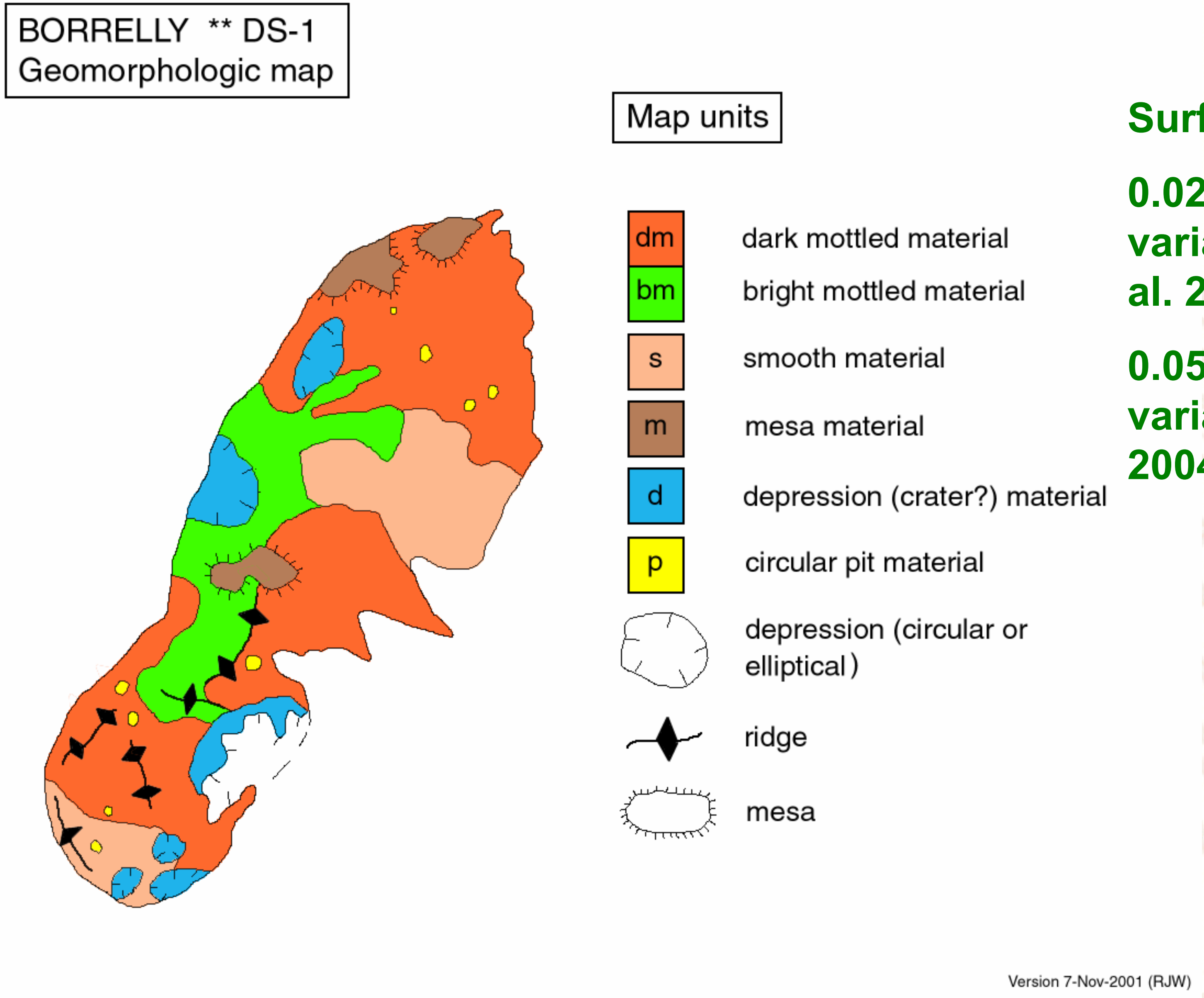
Deep Impact

9P/Tempel 1

- Jupiter family orbit
- perihelion 1.32 AU


8 x 3.2 km²
Sun
Komet Borelly (DS-1 Mission 2001)
Soderblom et al. (2002)
2 Km
Dark Spots
Mottled Terrain
Mesas
Smooth Terrain
Mottled Terrain
Dark Spots
Smooth Terrain
Unit Boundary
Mesa
Ridge
Fracture
Longitudinal Streaks

Comet Borrelly Surface Units

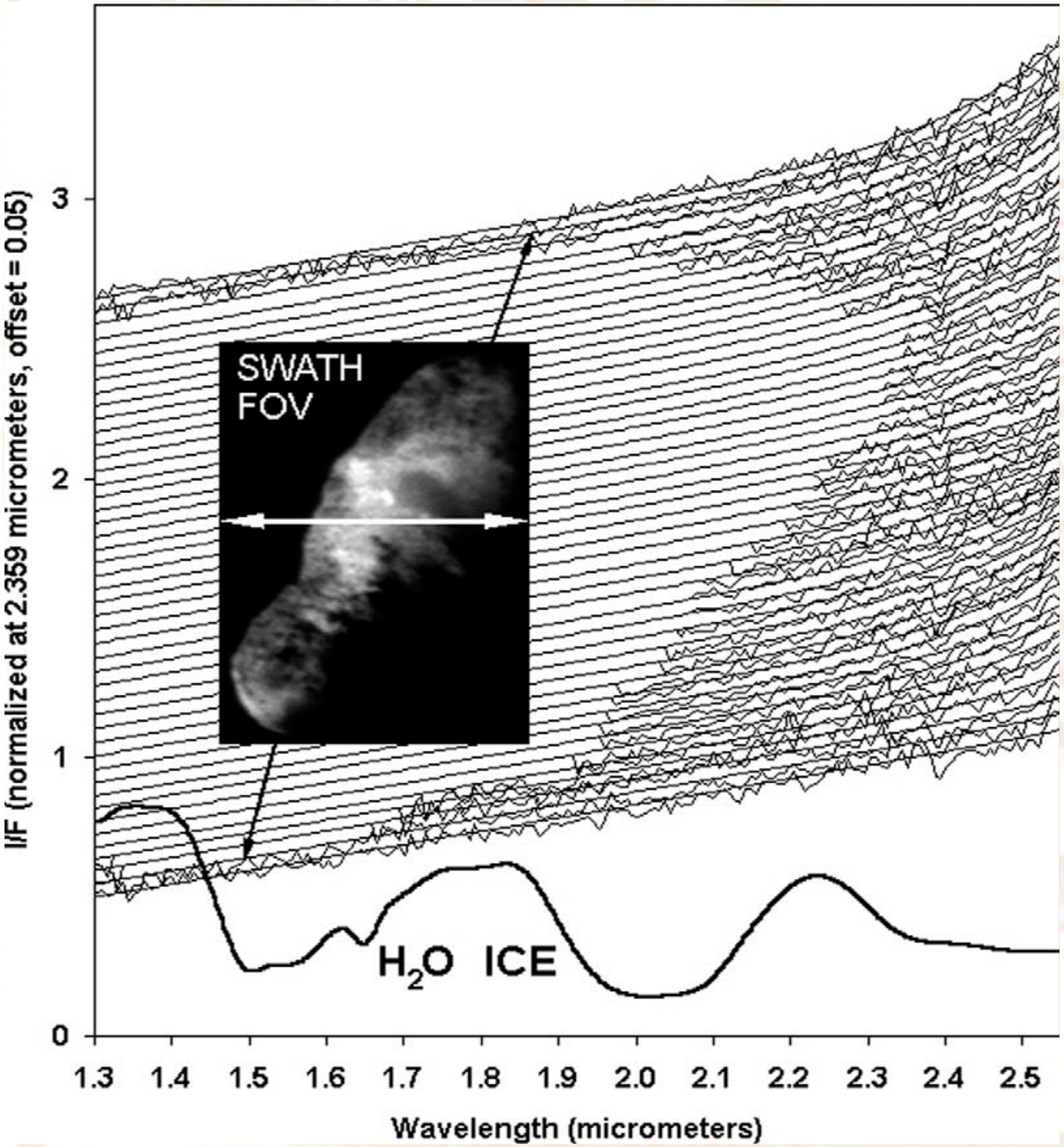


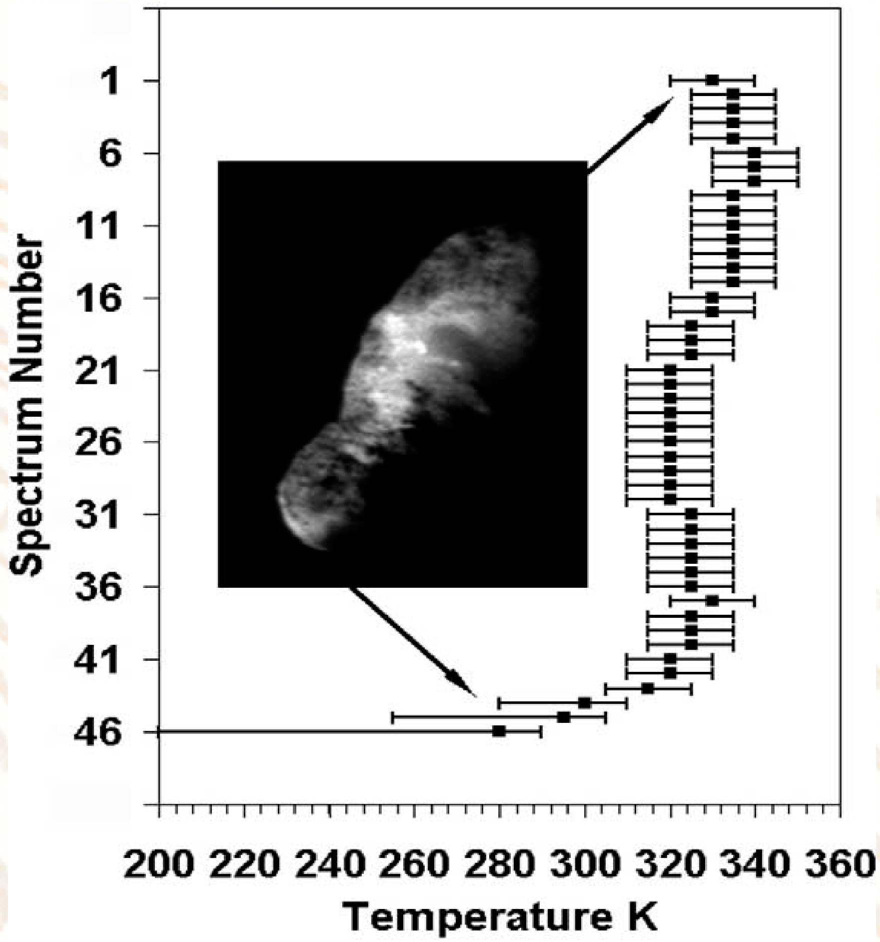
Surface albedo:

0.02 and strong variations (Buratti et al. 2004)

0.056 and little variation (Kirk et al. 2004)

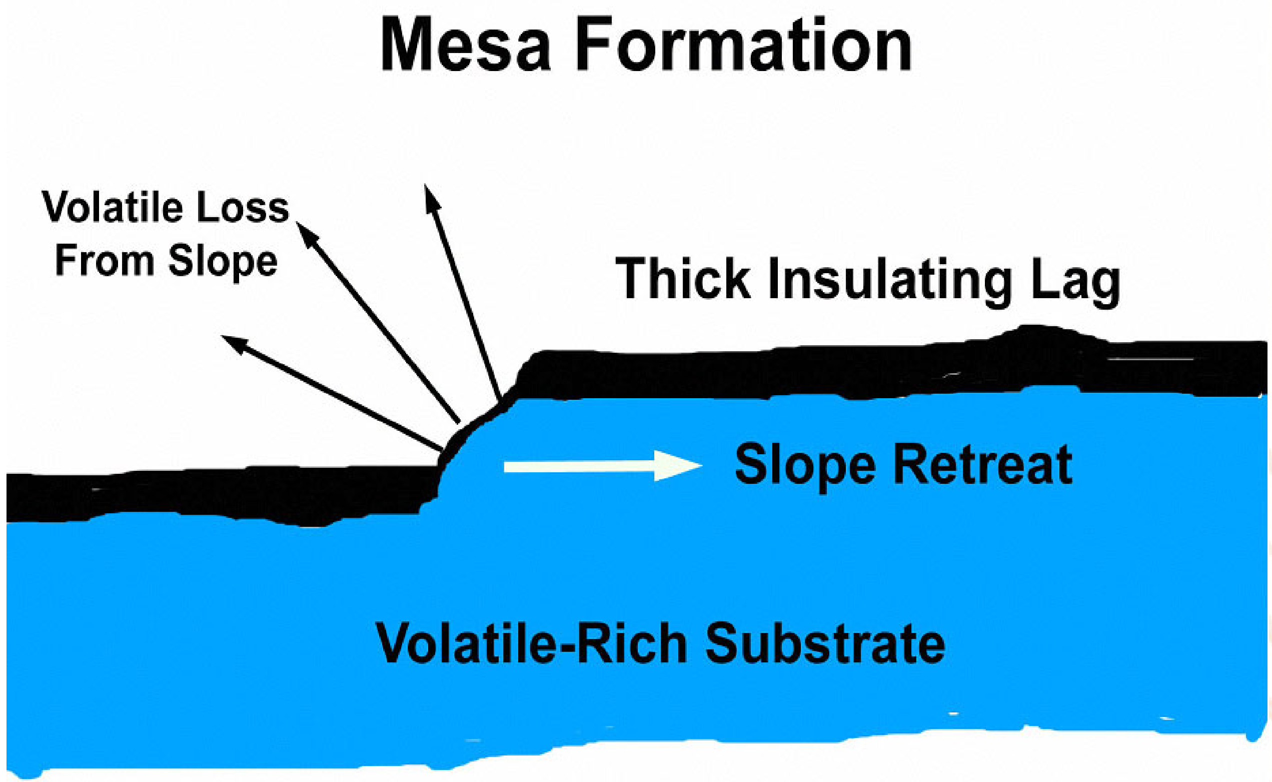
IR Spectra of 19P/Borrelly





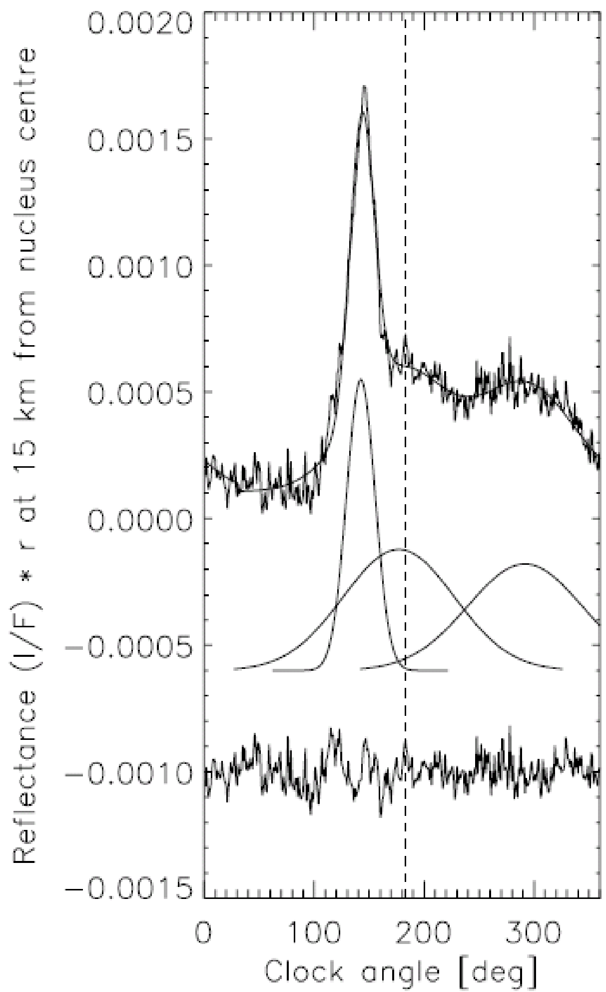
Soderblom et al. (2004)

Does this explain activity?

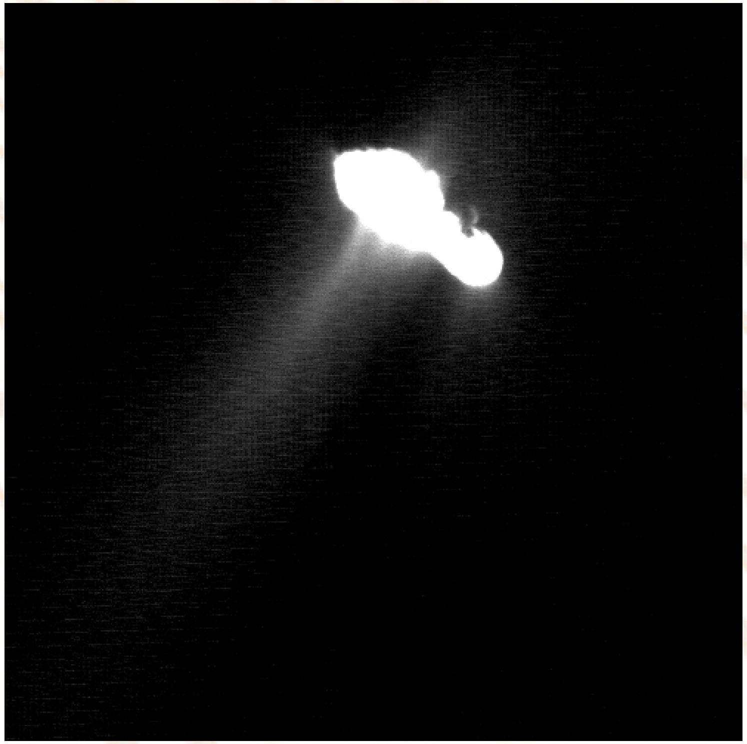


Volatile loss undermines the mesa tops and collapses the lag material down to the "Smooth Terrain" valley floor.

Jet Distribution in Borrelly's Inner Coma



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

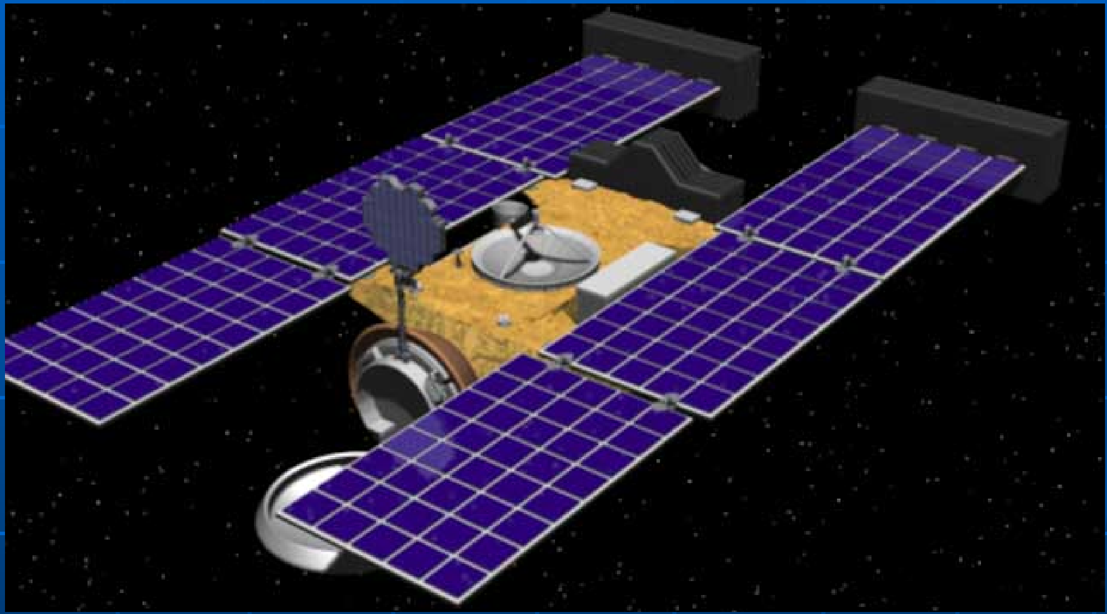


Ho et al., 2002

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

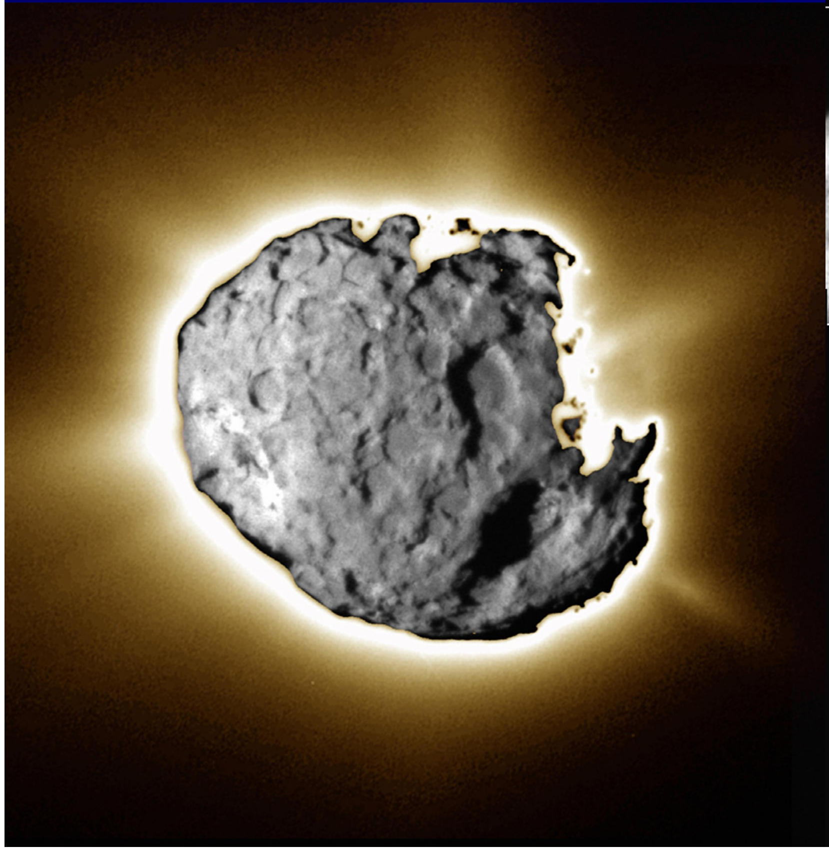
Stardust flyby of 81P/Wild 2 at 236km on 2 jan. 2004 (6.1km/s)

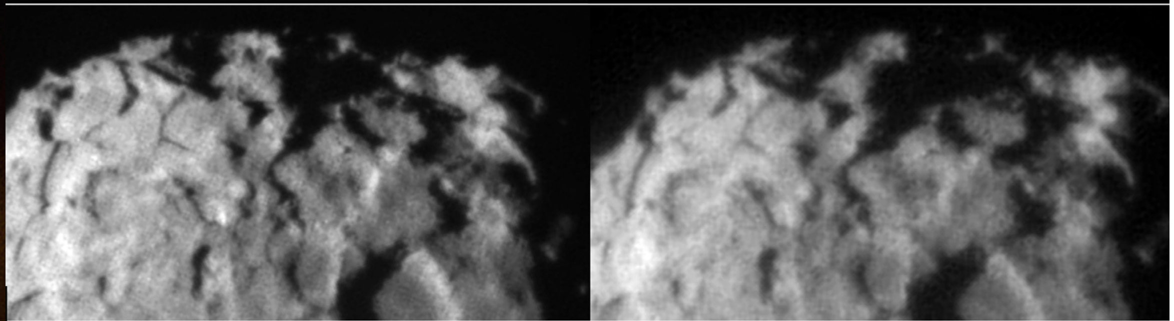
Nucleus

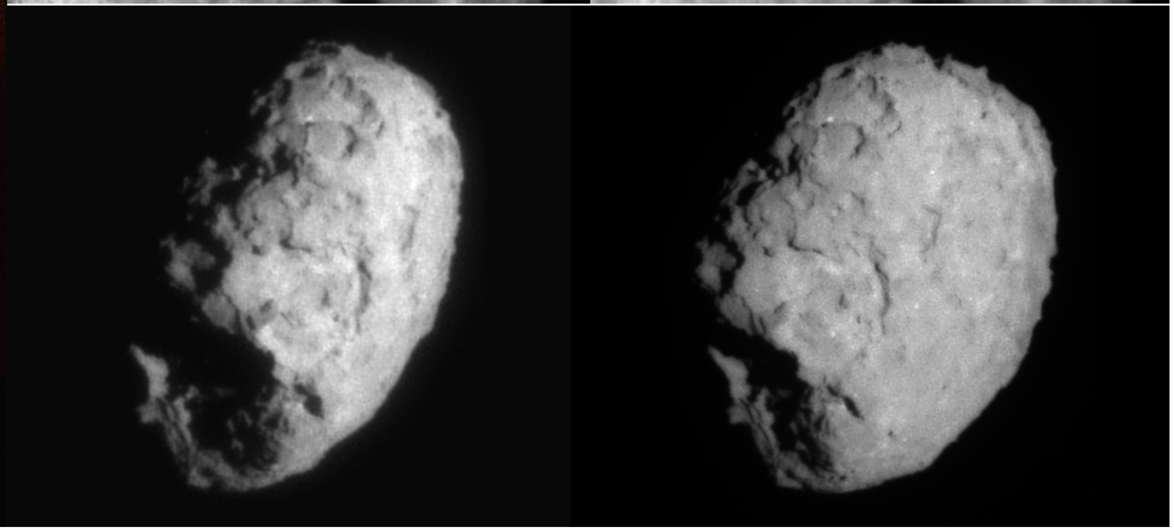
5.5 × 4.0 × 3.3 km

Albedo = 3%

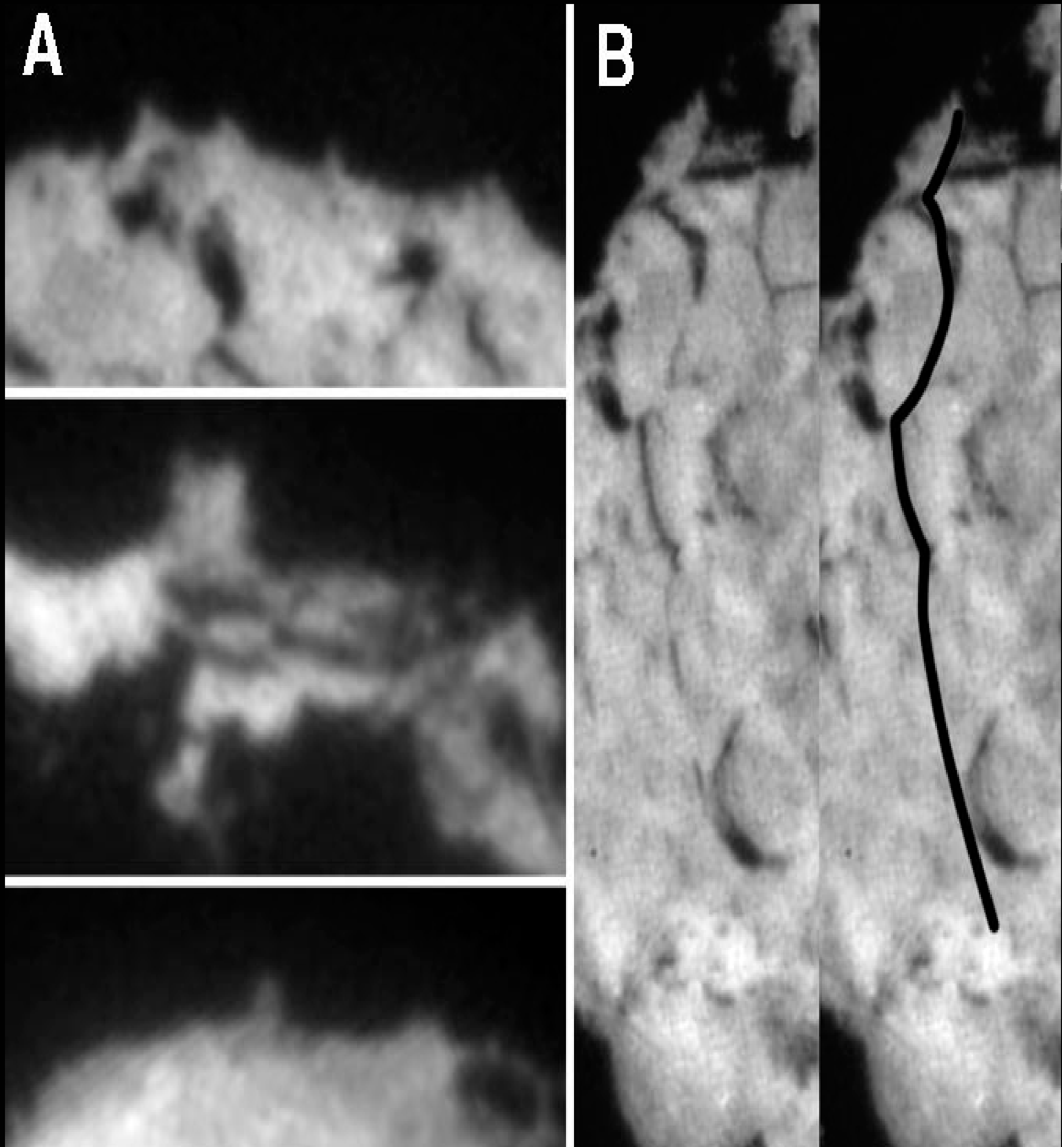
r_h=1.86 UA Q_{H2O}=0.2 t/s

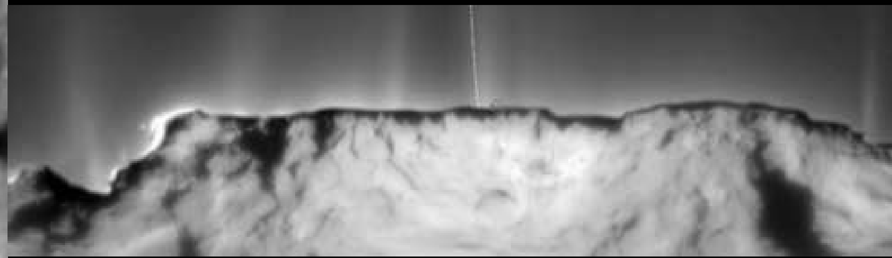






81P/Wild 2 (Stardust)





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.

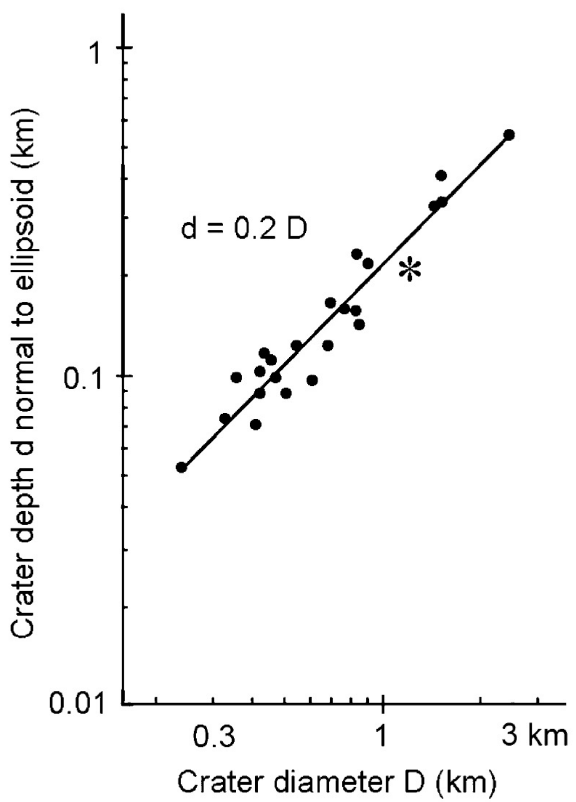
Wild 2 surface is not similar to asteroid, satellite or other comet surfaces!

Wild 2

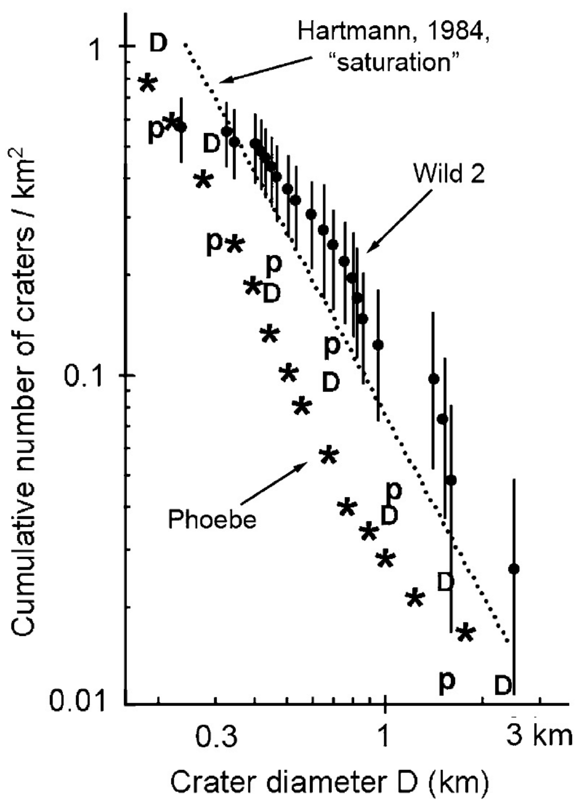
Ida

Dactyl

Wild 2 Craters



Kirk et al. (2005)



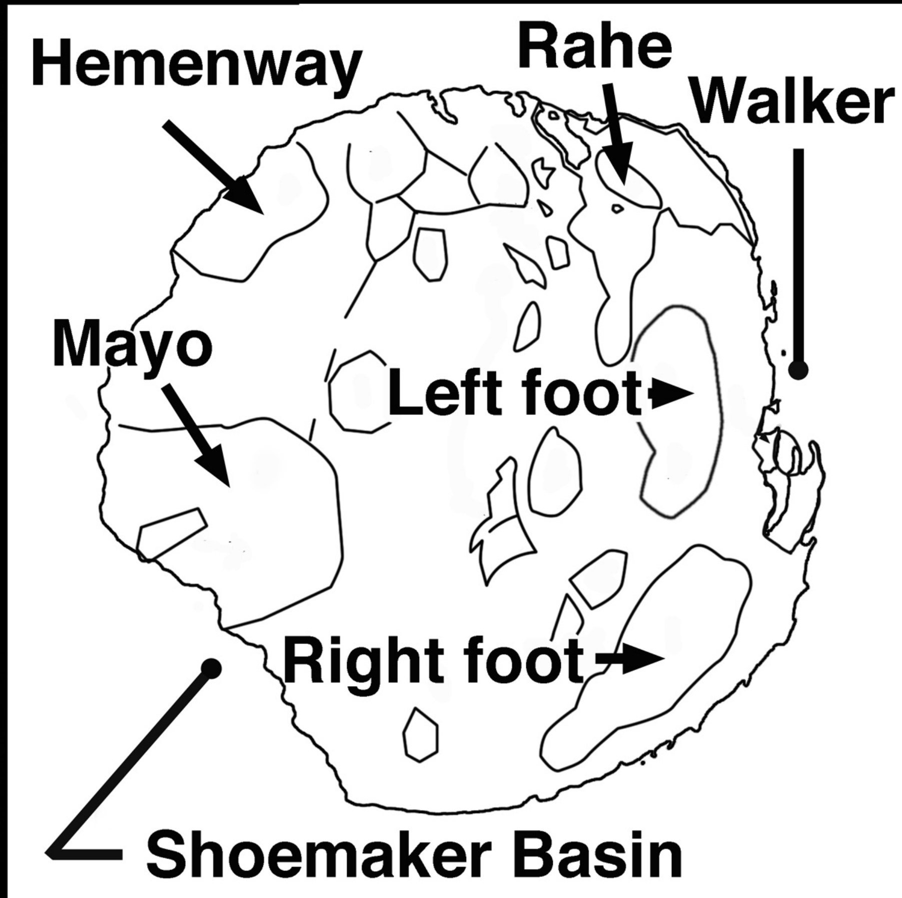
Basilevsky and Keller (2006)

Surface densely cratered

Beyond saturation line => diameters increased by sublimation

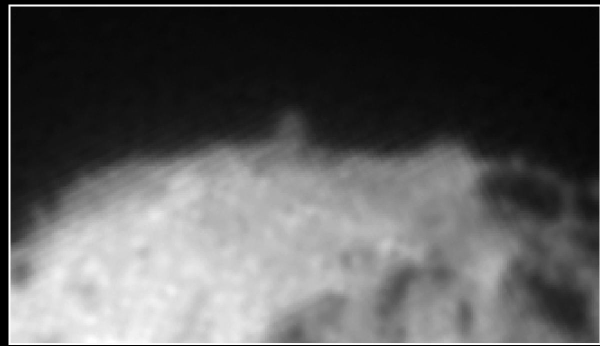
Cratering occurred early in the life of the comet

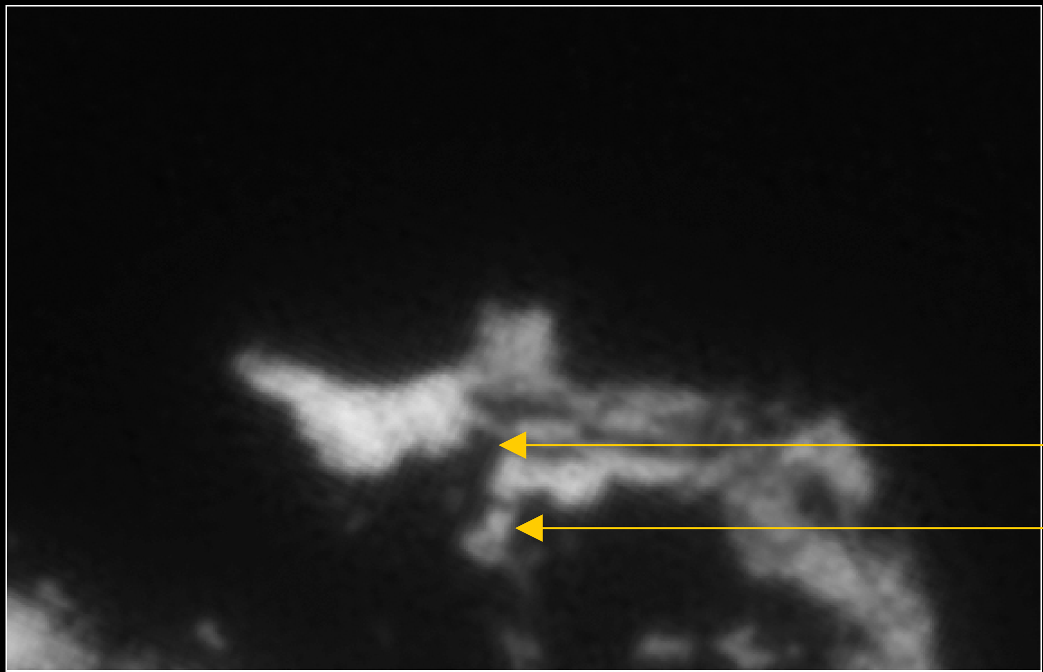
Wild 2 Map

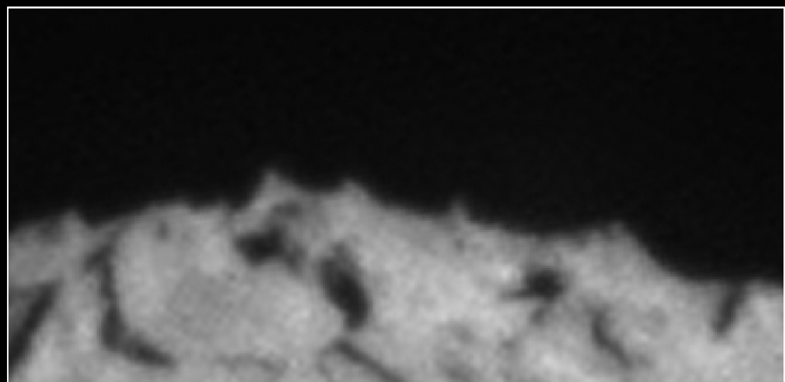

Hemenway
Rahe
Walker
Mayo
Left foot
Right foot
Shoemaker Basin

Wild 2’s pinnacles

(Monument Valley in dirty ice)





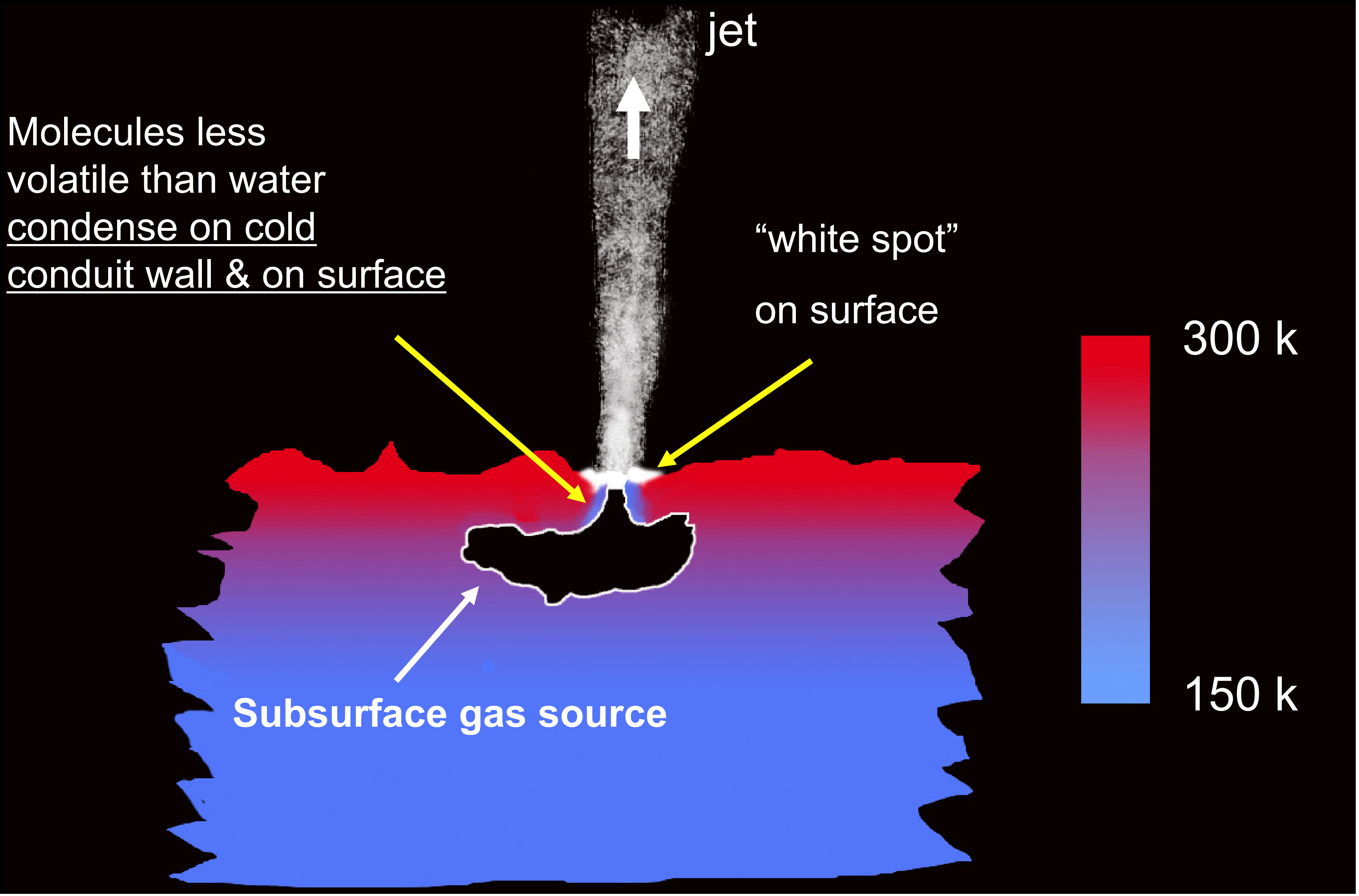


Bright spot

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 ⇒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

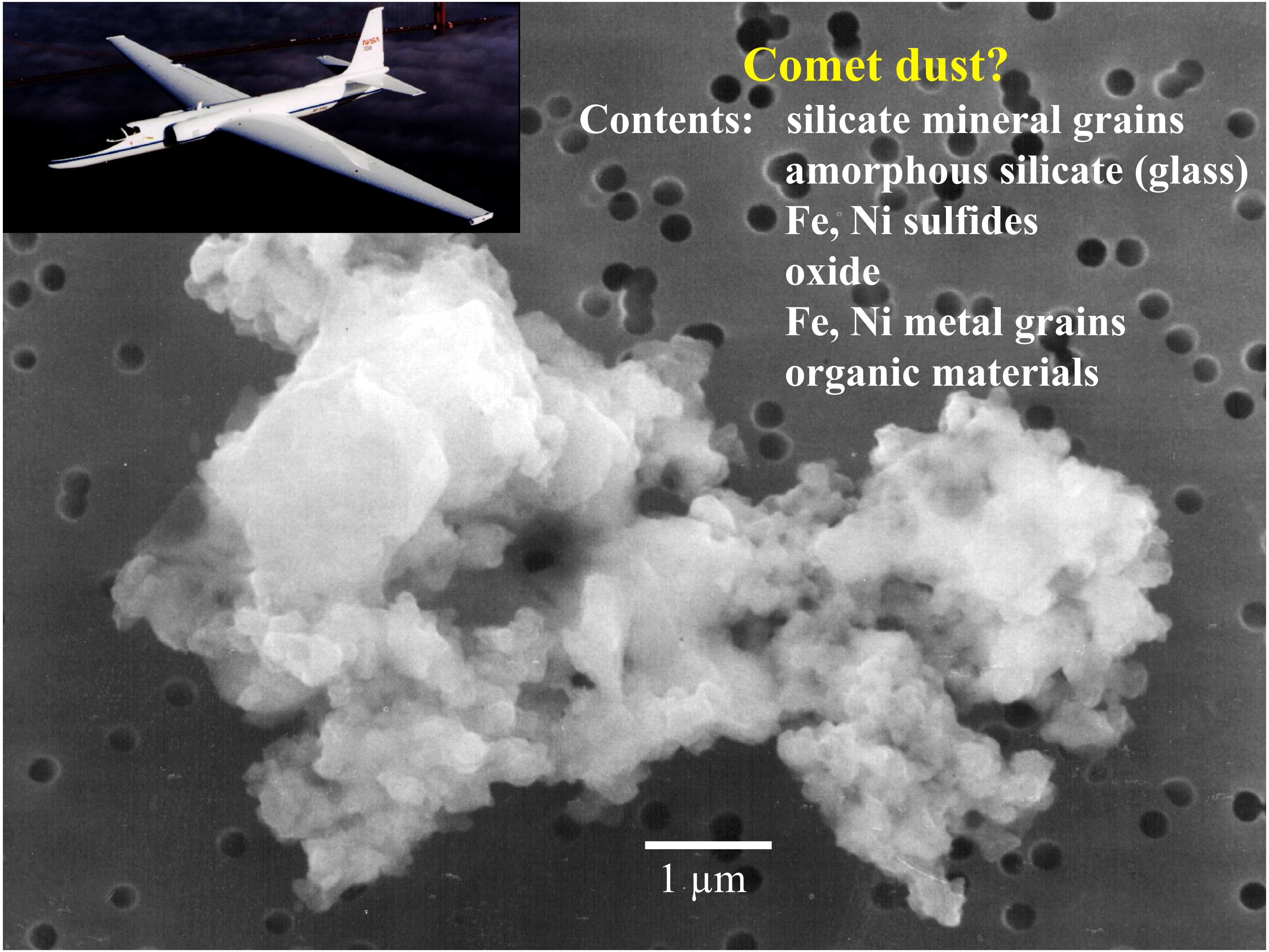
Jet sources are small, numerous, and highly collimated

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

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

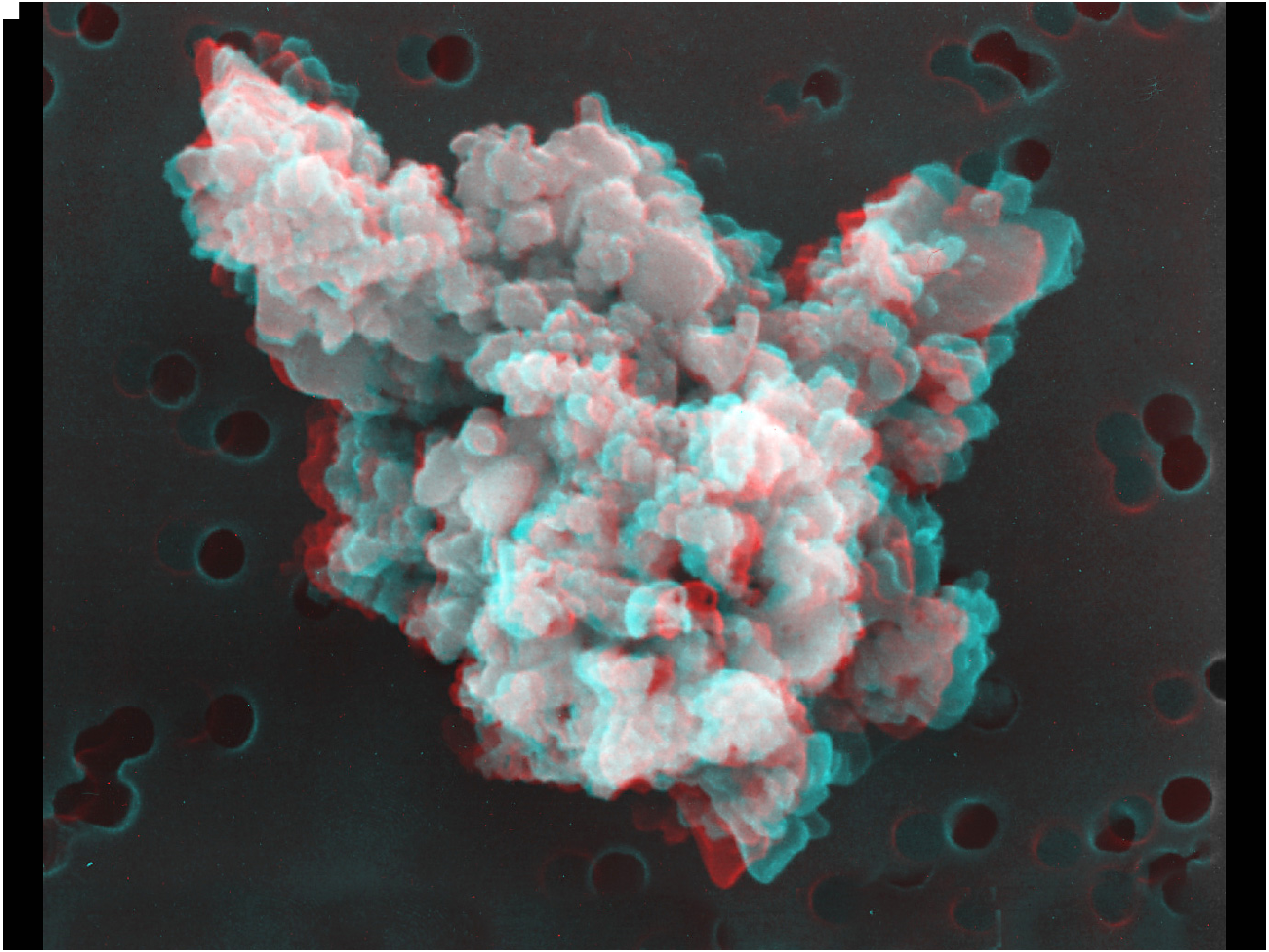
?

Comet dust?



Contents:

- silicate mineral grains
- amorphous silicate (glass)
- Fe, Ni sulfides
- oxide
- Fe, Ni metal grains
- organic materials



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**