Cometary Research from Space - the Past, Present, and Future

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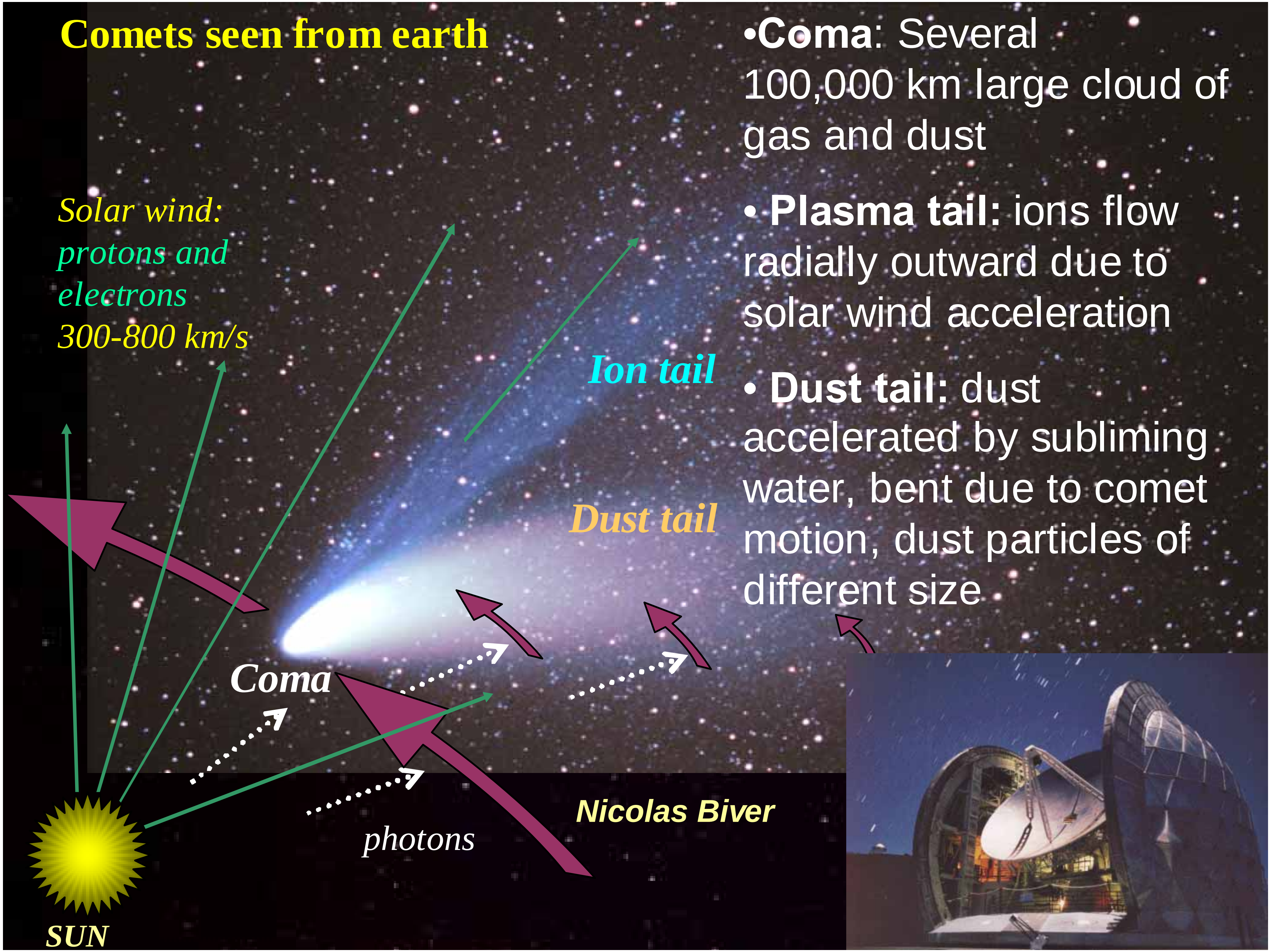
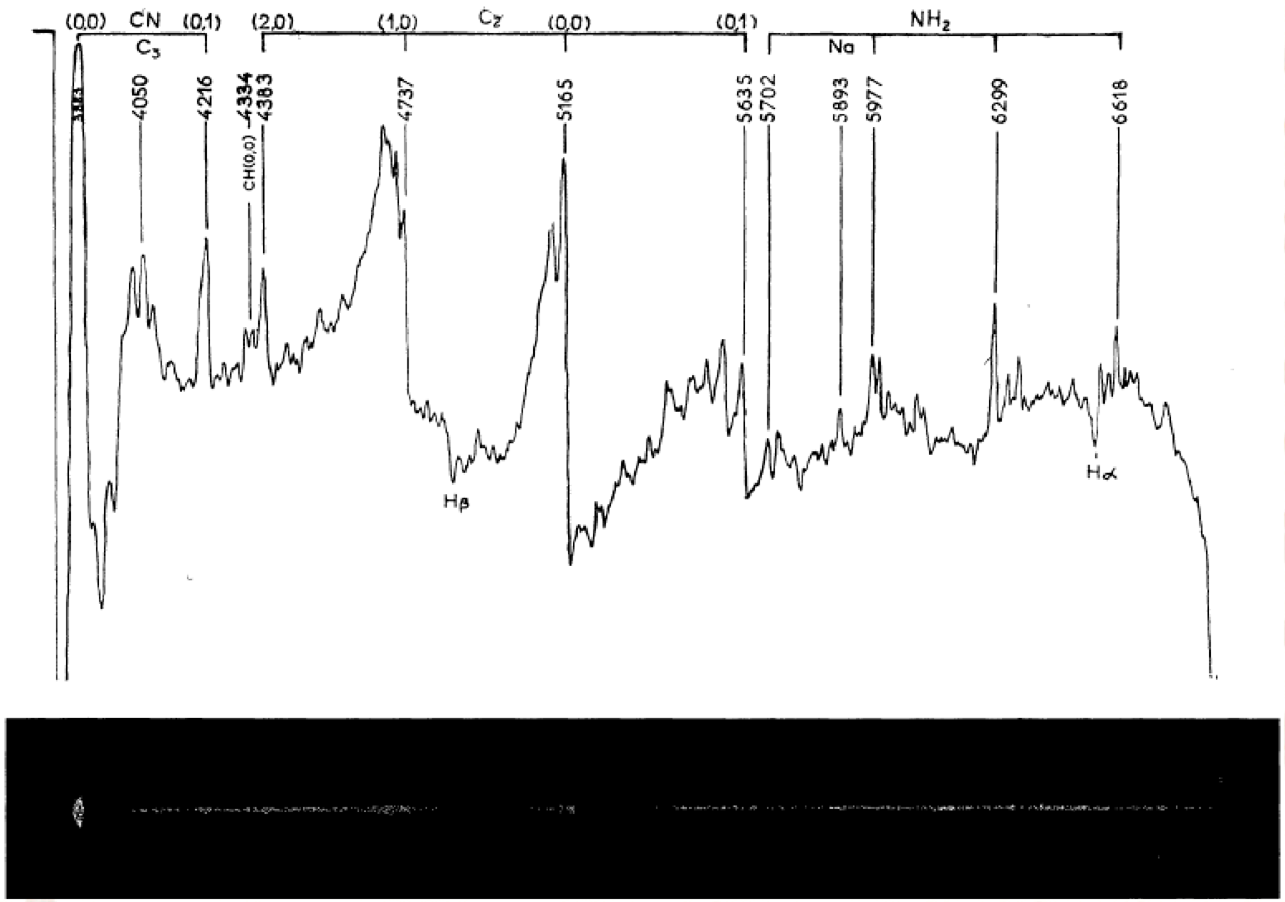

Comets seen from earth
•Coma: Several 100,000 km large cloud of gas and dust
• Plasma tail: ions flow radially outward due to solar wind acceleration
• Dust tail: dust accelerated by subliming water, bent due to comet motion, dust particles of different size
Solar wind:
protons and
electrons
300-800 km/s
Ion tail
Dust tail
Coma
photons
Nicolas Biver
SUN

Visible Coma Spectrum

- **What are comets made of?**

AREND-ROLAND (1956 *h*)



All species are short lived radicals

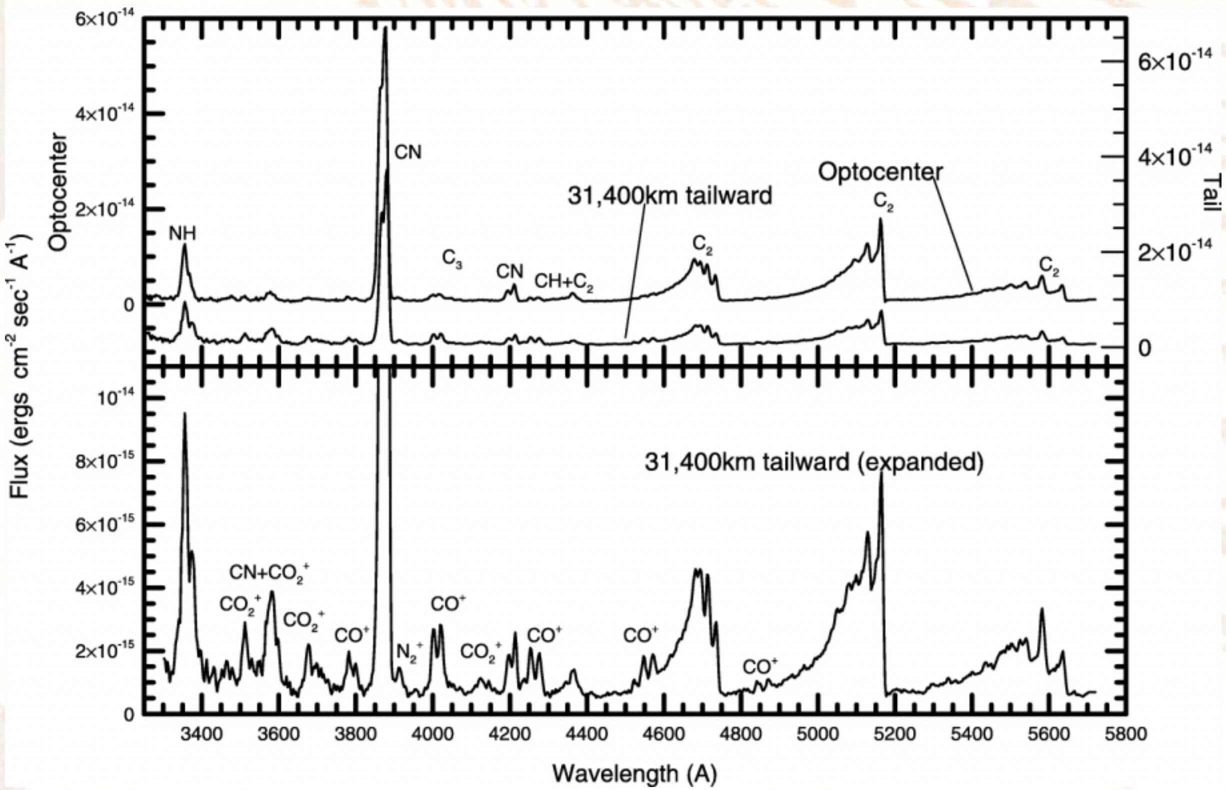
=> concept of parent molecules (Wurm 1934,1935)

Fehrenbach et al. 1957

Visible Coma Spectrum

- **What are comets made of?**

Ikea - Zhang



All species are short lived radicals

=> concept of parent molecules (Wurm 1934,1935)

Cochran et al. 2002

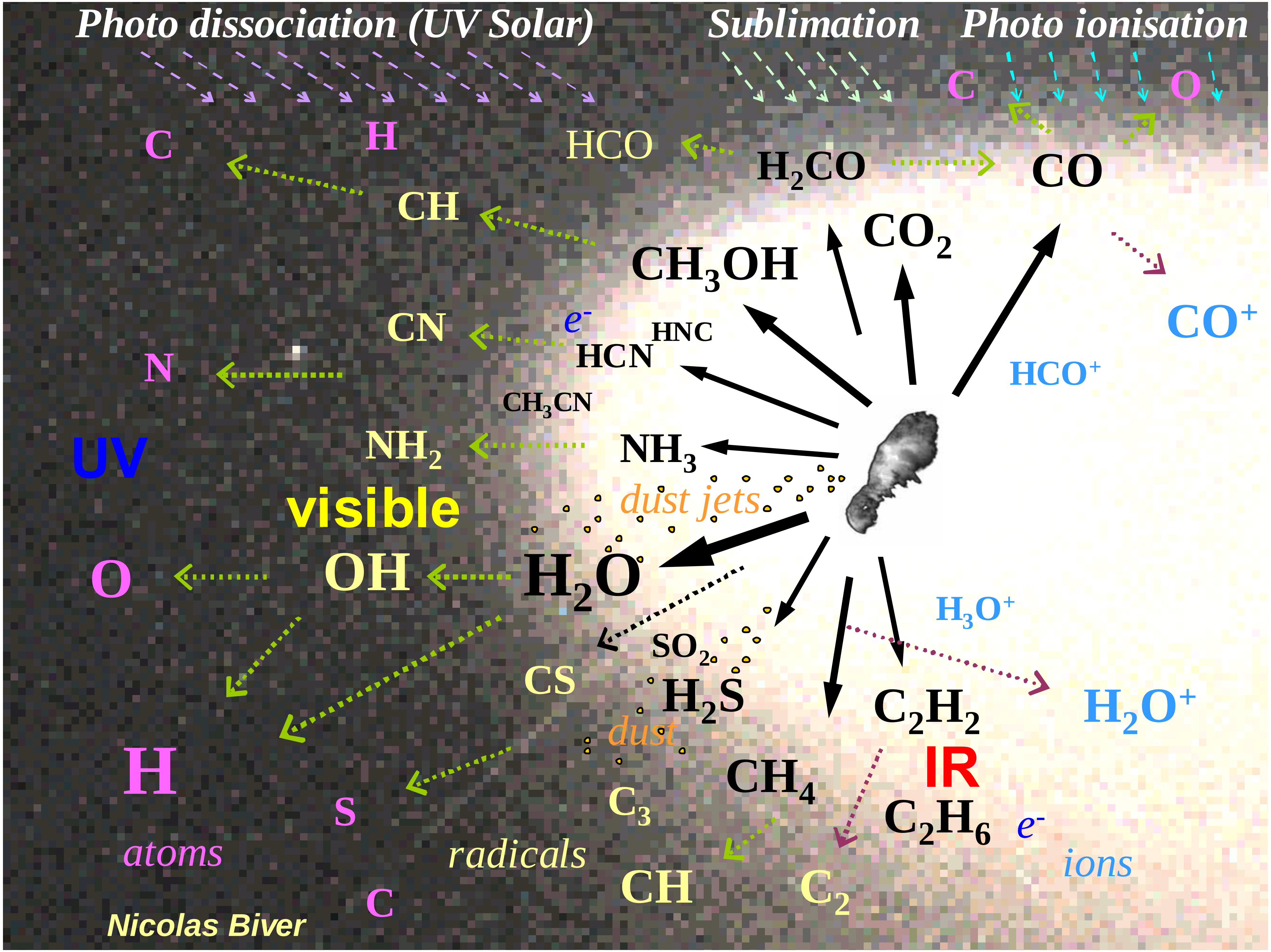
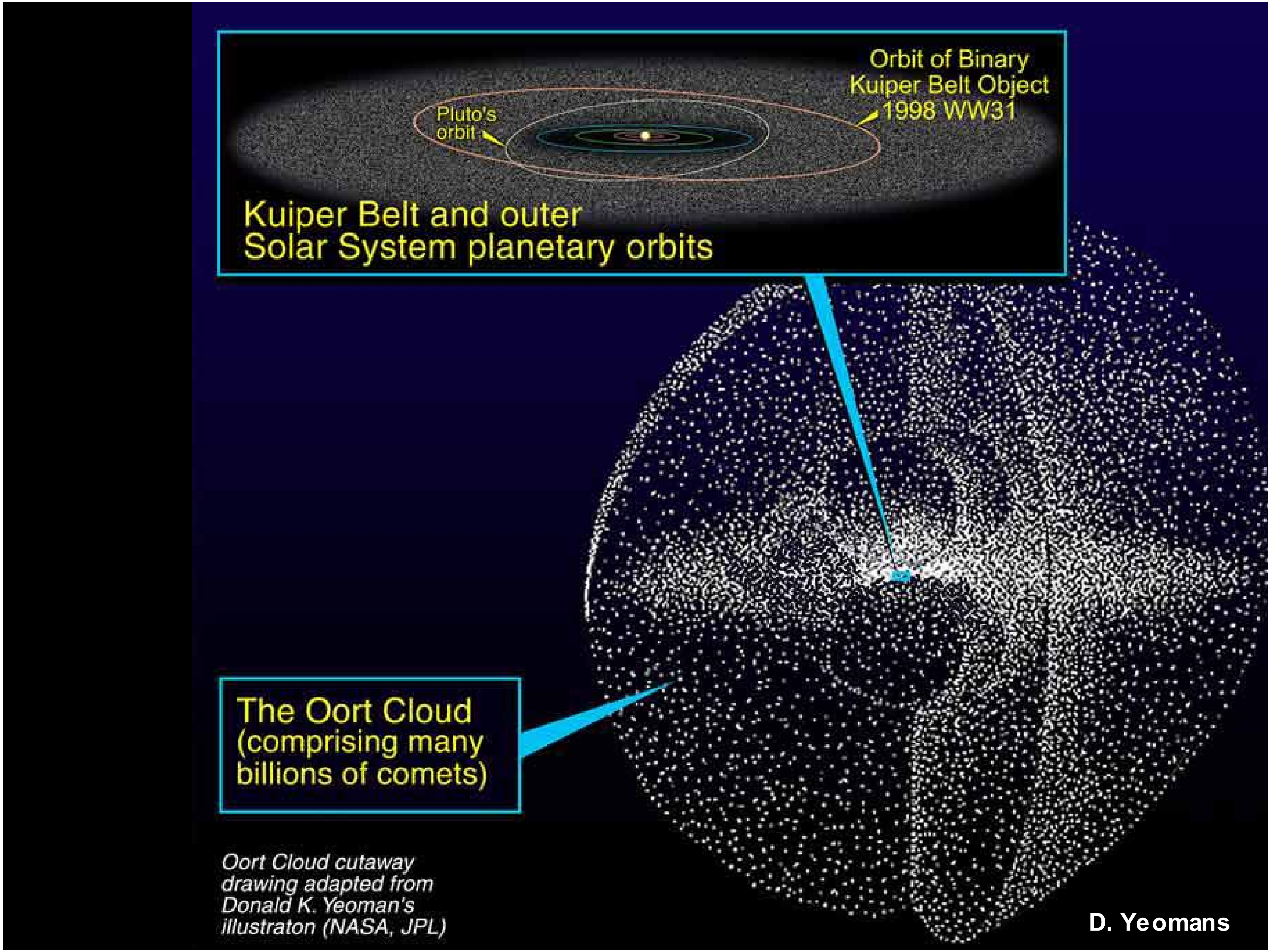
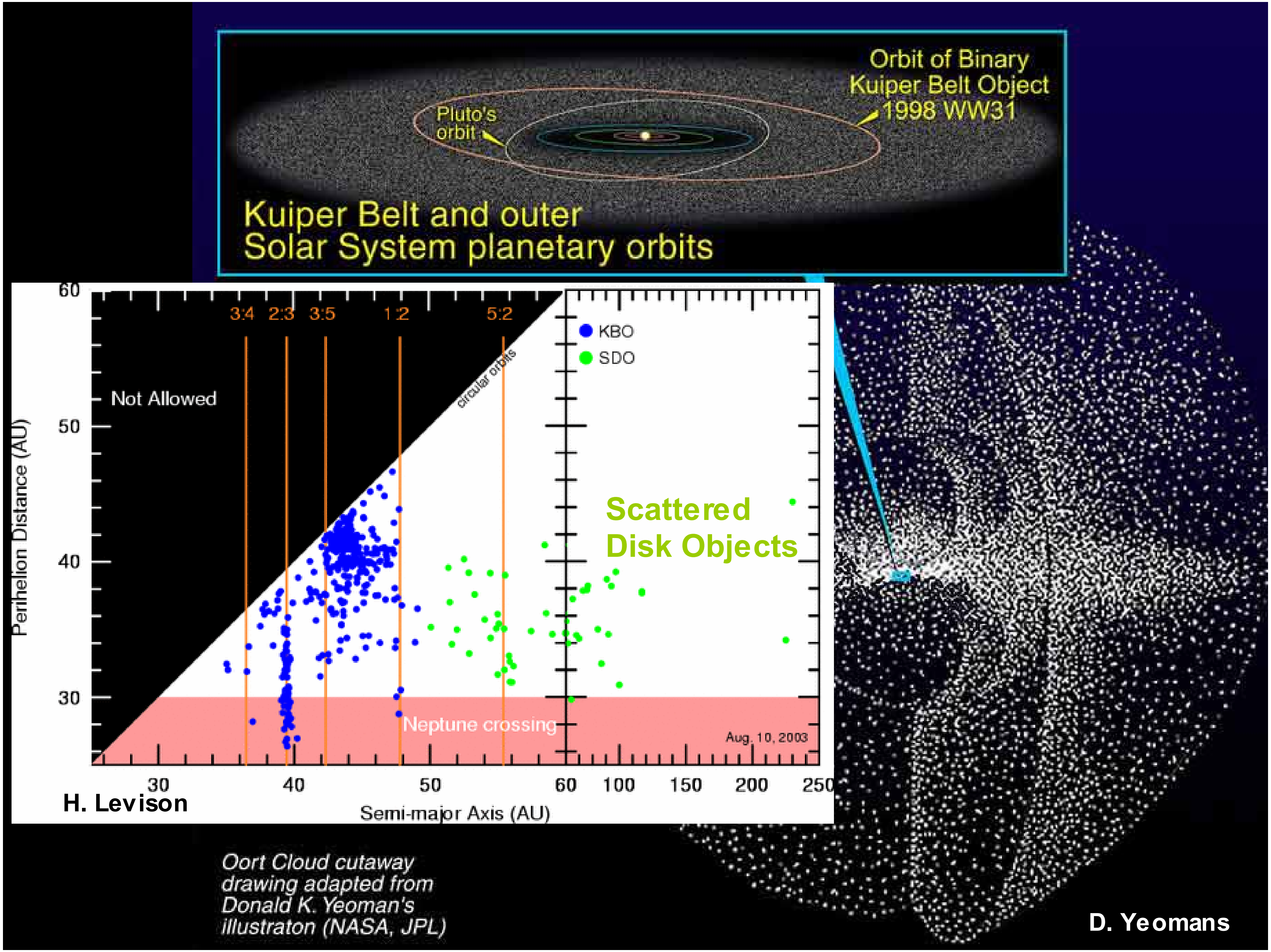


Photo dissociation (UV Solar)
Sublimation
Photo ionisation
C
H
HCO
H_2CO
CO
C
O
CH
CH_3OH
CO_2
CO^+
CN
e^-
HNC
HCN
N
HCO^+
CH_3CN
UV
NH_2
NH_3
dust jets
visible
O
OH
H_2O
H_3O^+
SO_2
CS
H_2S
C_2H_2
H_2O^+
dust
H
CH_4
IR
S
C_3
C_2H_6
e^-
atoms
radicals
ions
C
CH
C_2
Nicolas Biver


Orbit of Binary
Kuiper Belt Object
1998 WW31
Pluto's
orbit
Kuiper Belt and outer
Solar System planetary orbits
The Oort Cloud
(comprising many
billions of comets)
Oort Cloud cutaway
drawing adapted from
Donald K. Yeoman's
illustraton (NASA, JPL)
D. Yeomans


Orbit of Binary
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Pluto's
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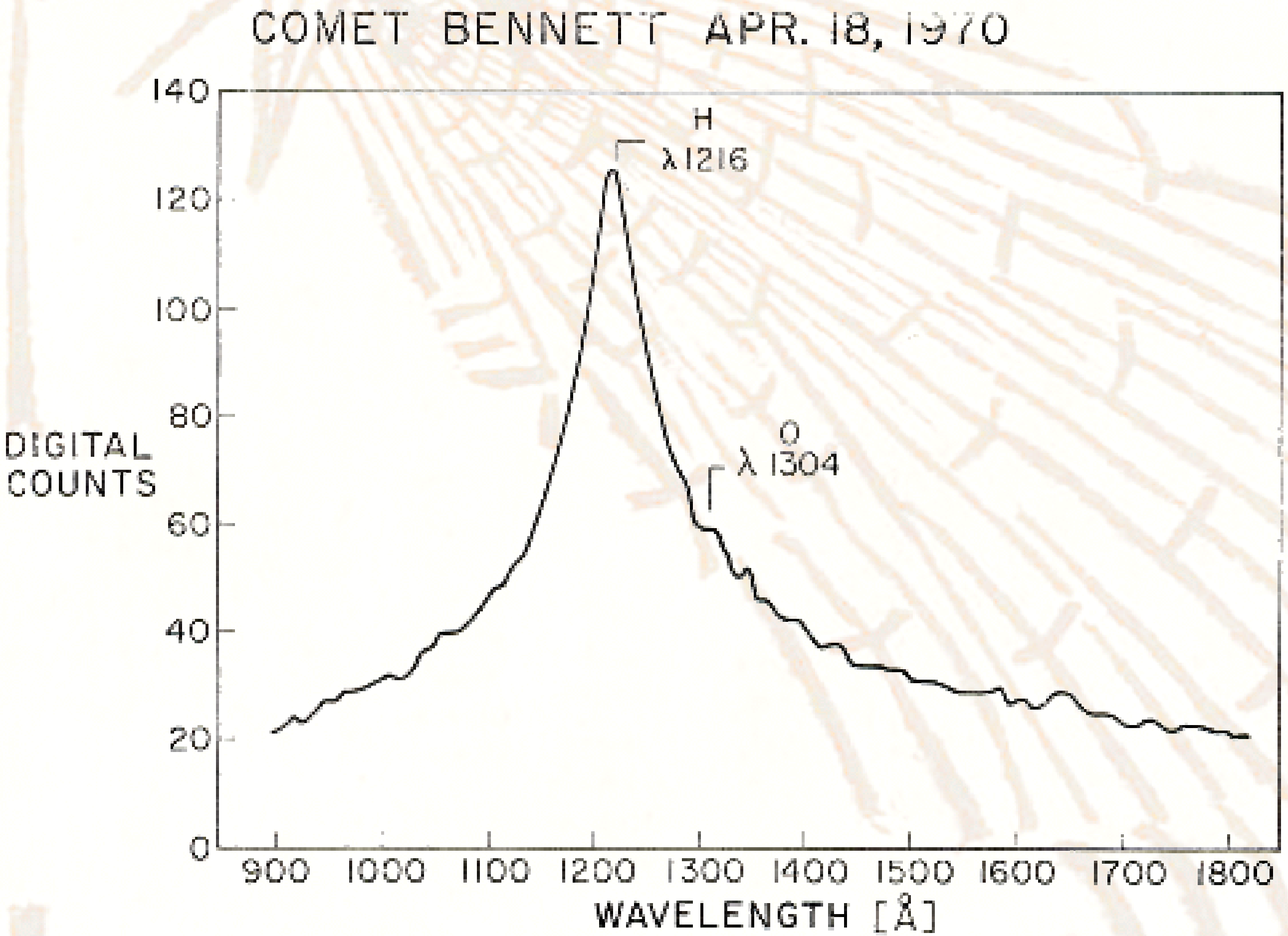
Kuiper Belt and outer
Solar System planetary orbits
3:4
2:3
3:5
1:2
5:2
Not Allowed
circular orbits
KBO
SDO
Scattered
Disk Objects
Neptune crossing
Aug. 10, 2003
Perihelion Distance (AU)
Semi-major Axis (AU)
30
40
50
60
100
150
200
250
H. Levison
Oort Cloud cutaway
drawing adapted from
Donald K. Yeoman's
illustraton (NASA, JPL)
D. Yeomans

UV Photometry and Spectra

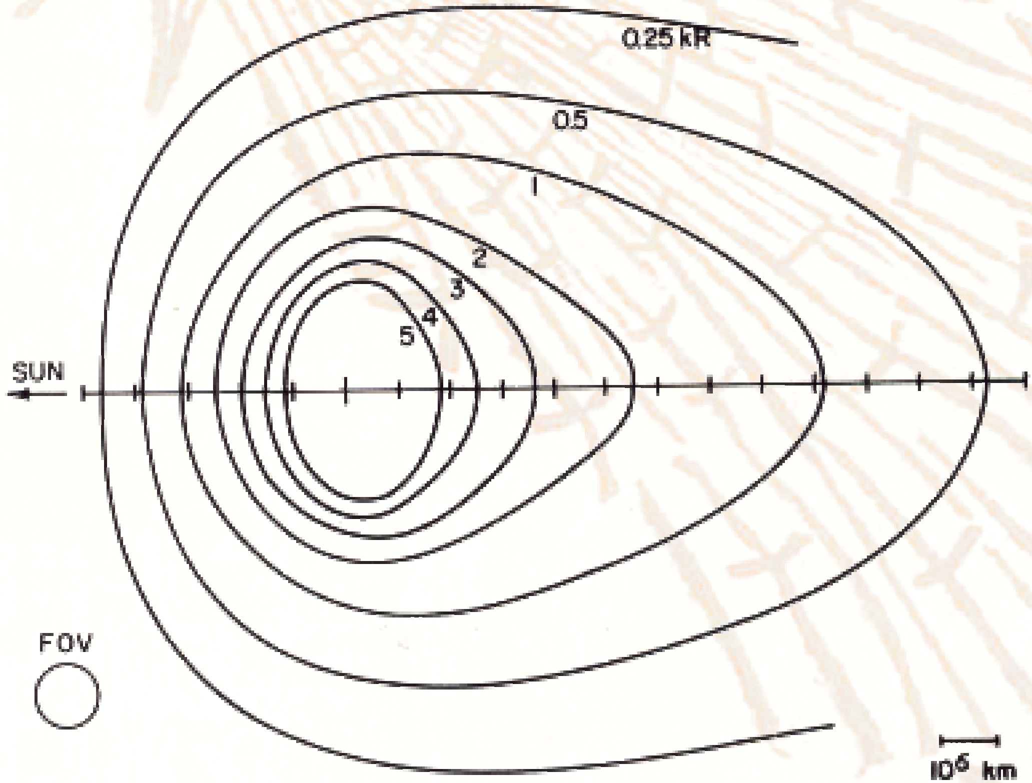


Hydrogen Coma

- predicted in 1963 by Biermann

- detected around comet TSK in Jan. 1970 by Code et al. with OAO-2

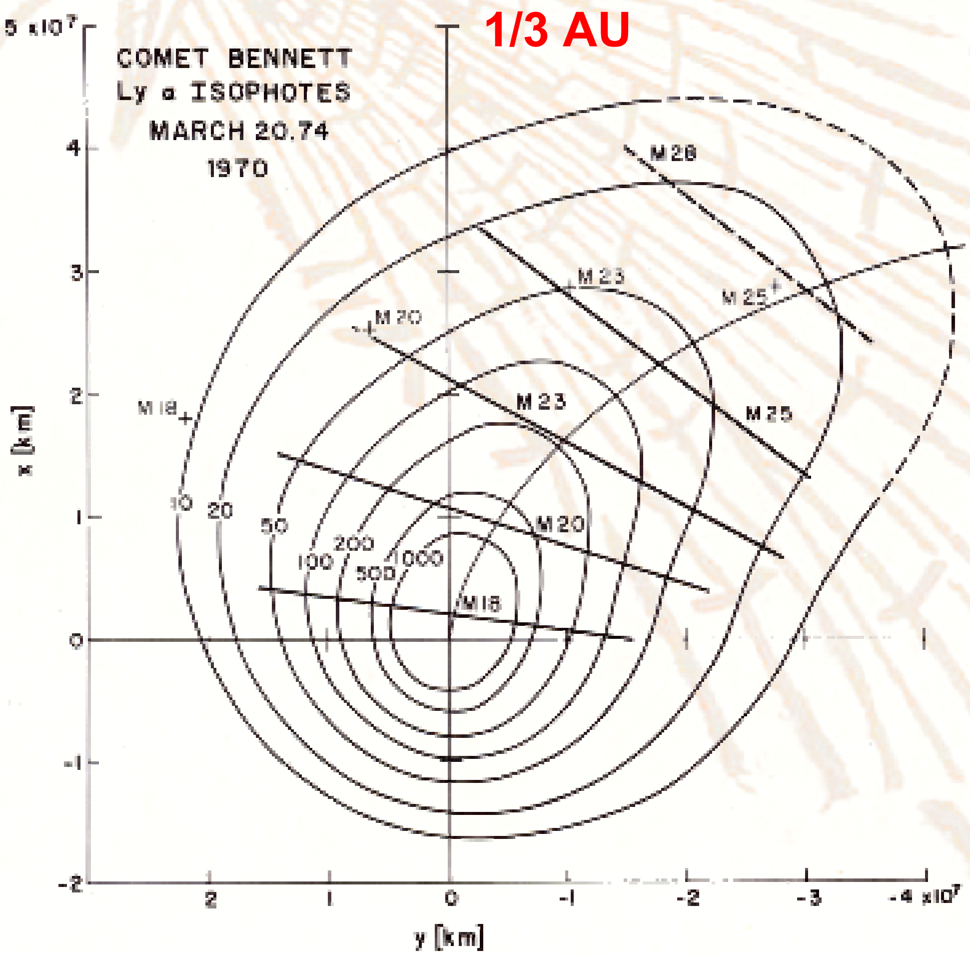
Lyman α Isophotes



Comet Bennett (1970 II)

Bertaux *et al.* (1973) on April 1, 1970 (r=0.61 AU) during spin-up mode of the OGO-5 satellite.

The Largest Object



OGO-5 U. Colorado photometer (Keller and Thomas (1975))

Radiation pressure

Curvature due to cometary orbit (after perihelion)

Extension due to fast outflow velocity of hydrogen atoms.

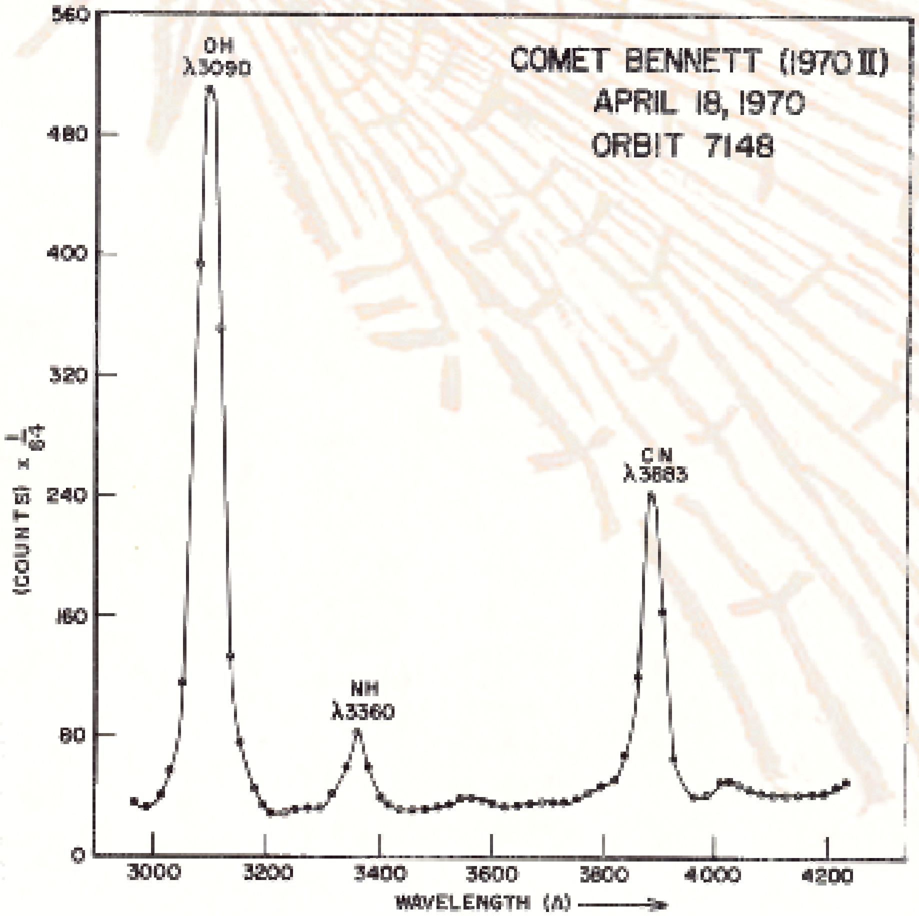
Bimodal distribution with 7 km s^{-1} and 21 km s^{-1}

Photo dissociation of water provides excess energy

H_2O -> H + OH

OH -> H + O

UV Spectra



OH the brightest emission line

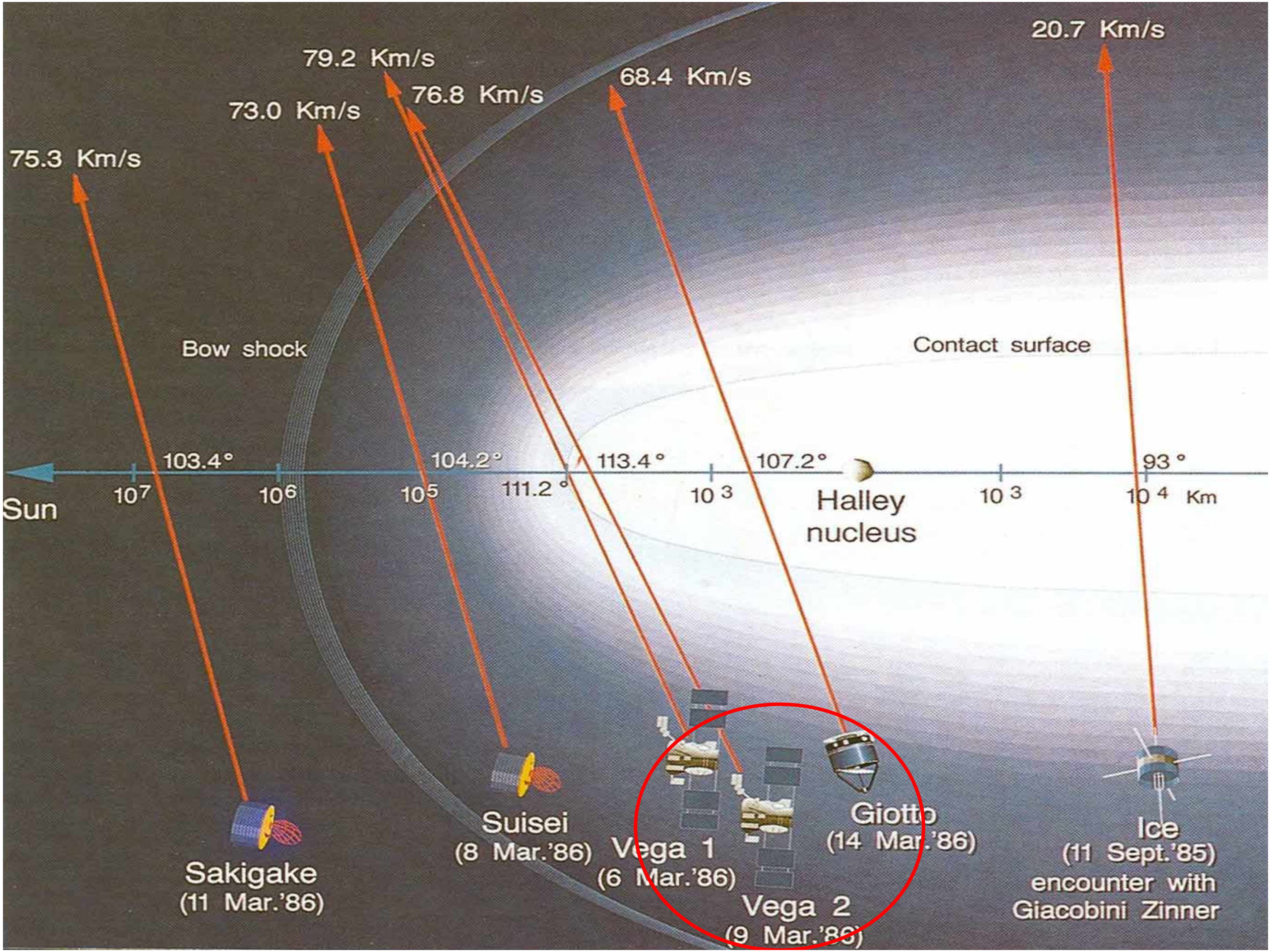
Strongly underestimated in ground based spectra (ozone absorption!)

=> water is the dominant volatile of comets

In the 70ties

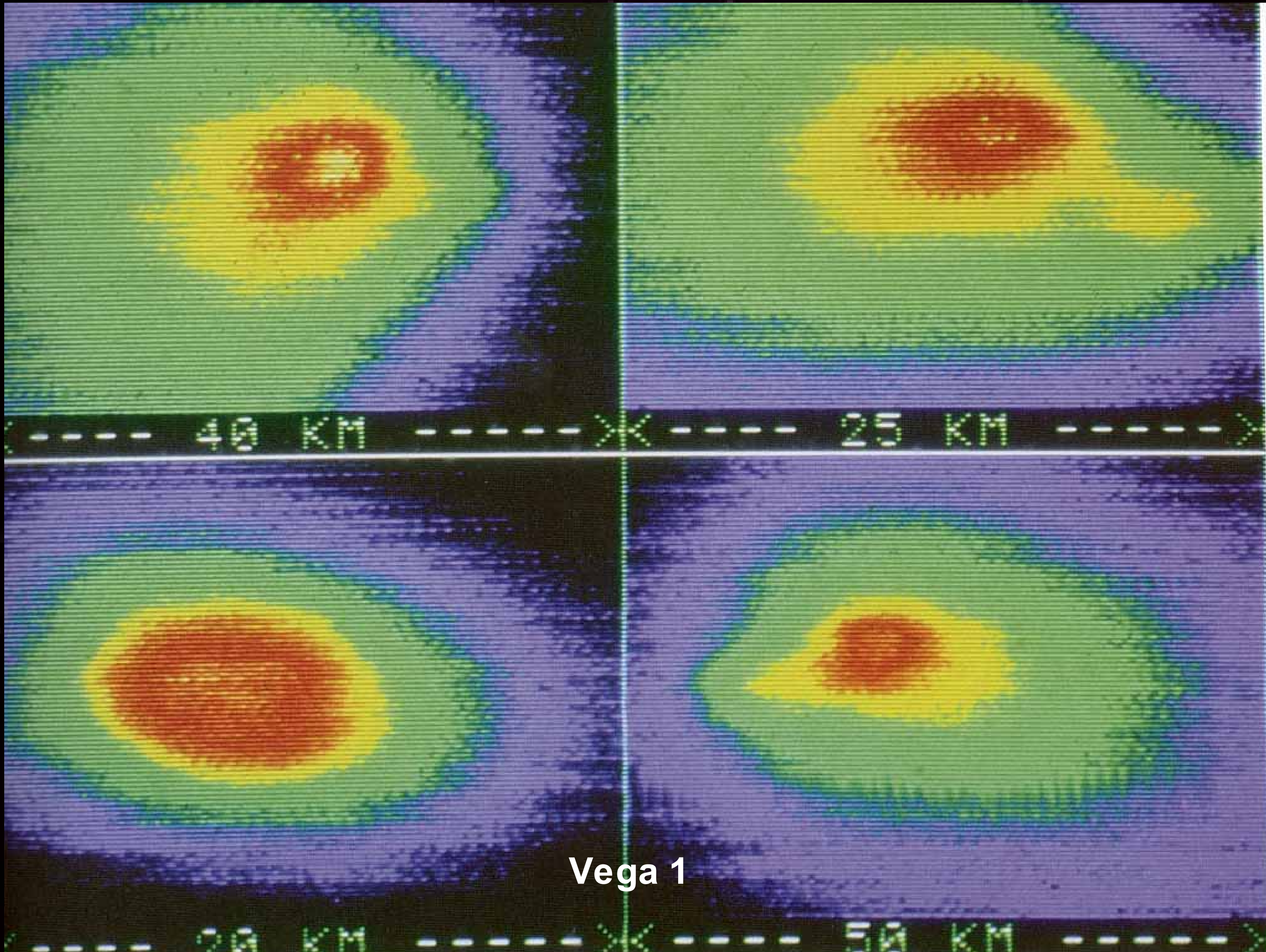
- Cometary nucleus is solid icy conglomerate body
  - contains large fraction of volatiles (H_2O, CH_4, NH_3 etc) as ices and dust (Whipple 1950)
  - the most pristine material
- Water is the dominant volatile of comets (UV observations!)
- Comets were formed and then stored in Oort cloud (Oort 1950)
  - Material is primordial (pre-solar)
- The highly active comet Halley was about to re-appear after 75 years

Unique chance to confirm concept by *in situ* observations using a spacecraft



20.7 Km/s
79.2 Km/s
68.4 Km/s
76.8 Km/s
73.0 Km/s
75.3 Km/s
Bow shock
Contact surface
103.4°
104.2°
113.4°
107.2°
93°
111.2°
Sun
10^7
10^6
10^5
10^3
Halley nucleus
10^3
10^4 Km
Suisei
(8 Mar.'86)
Vega 1
(6 Mar.'86)
Giotto
(14 Mar.'86)
Ice
(11 Sept.'85)
encounter with
Giacobini Zinner
Sakigake
(11 Mar.'86)
Vega 2
(9 Mar.'86)

The Vega Encounters



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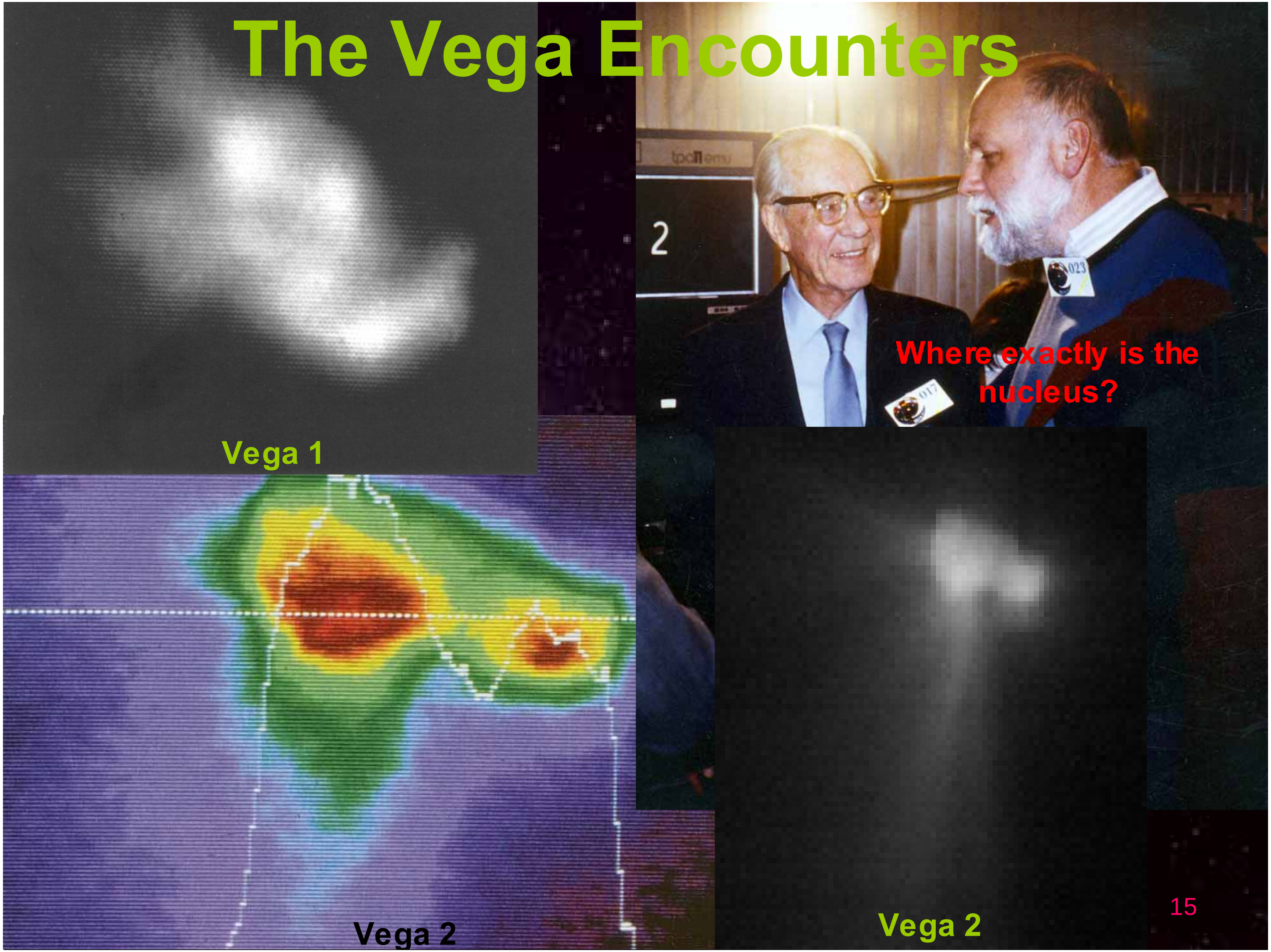
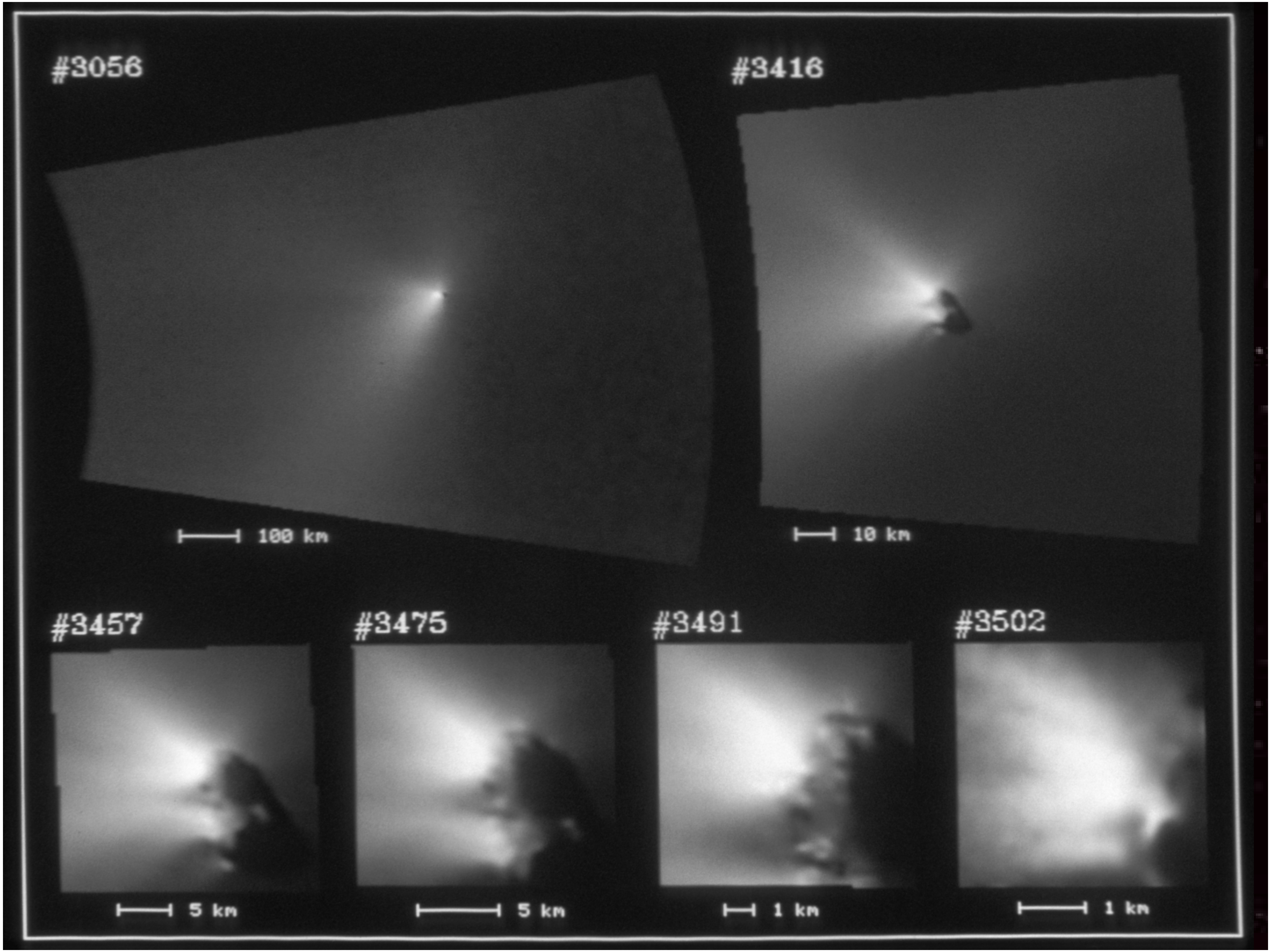




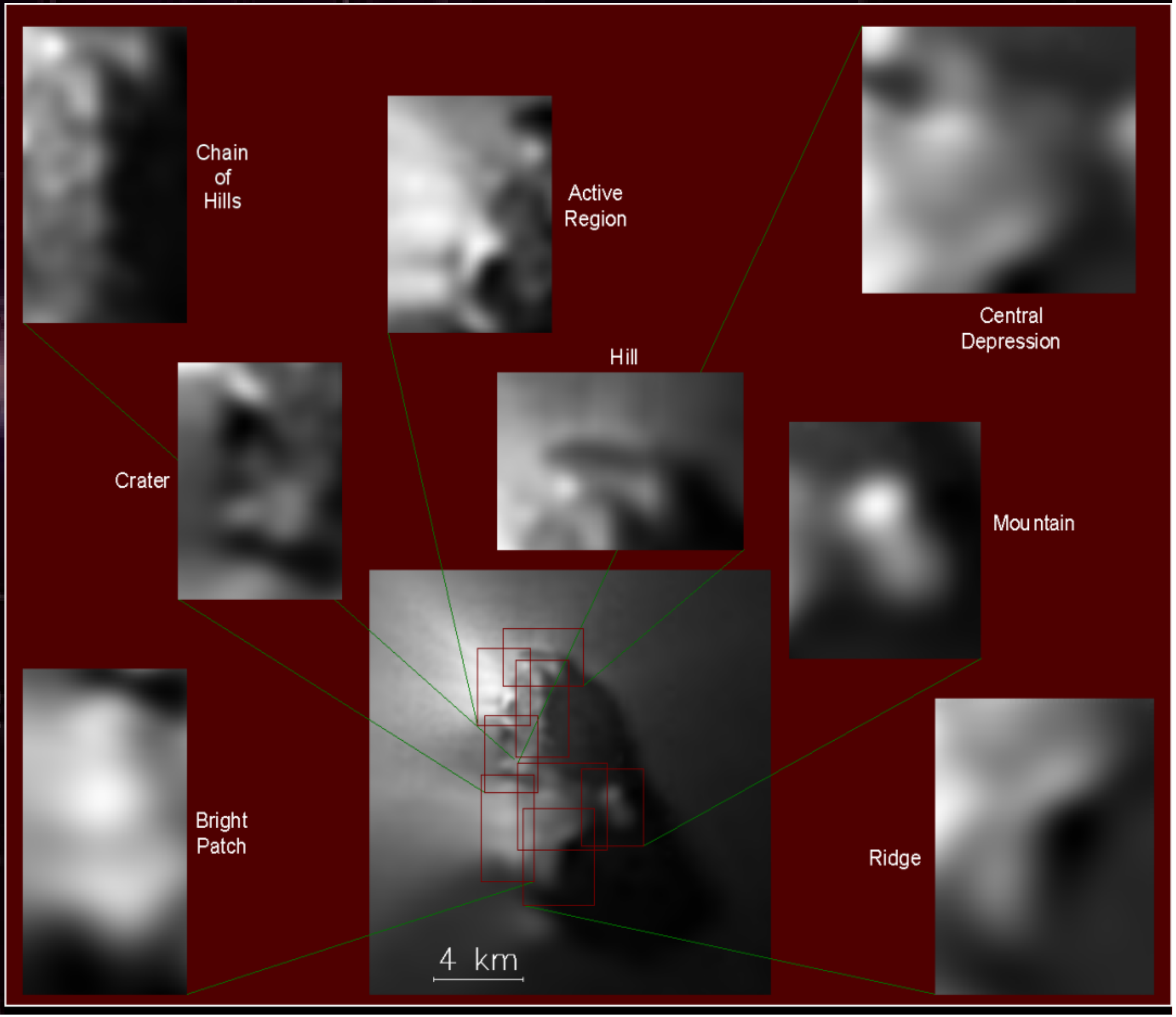
#3056
100 km
#3416
10 km
#3457
5 km
#3475
5 km
#3491
1 km
#3502
1 km

Comet Halley

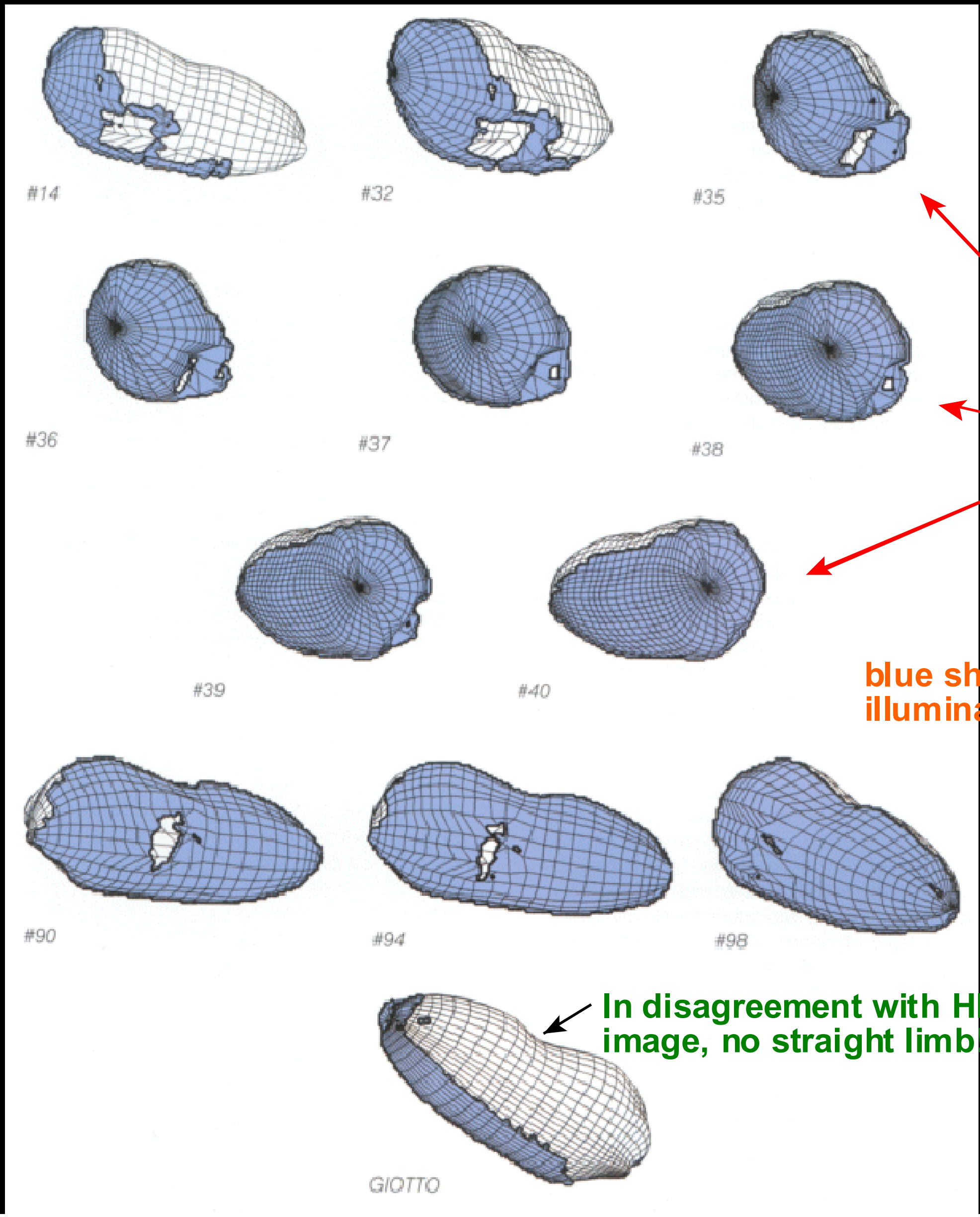
Elongated
15.3 x 7.2 x 7.2 km^3
Very dark albedo
No impact craters
Activity limited

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

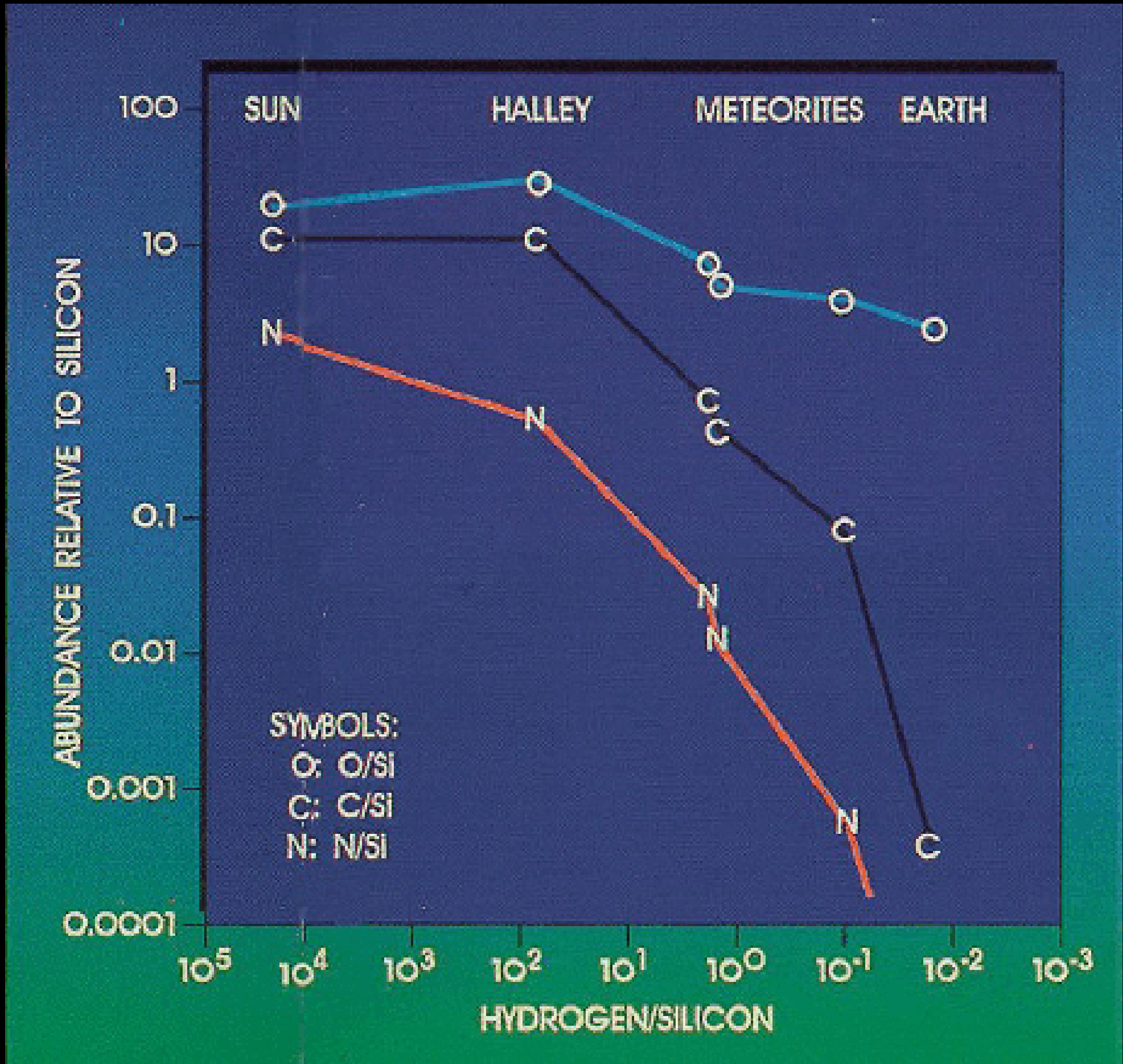
Comet Halley images changed our perception of cometary nuclei to a new paradigm

Comet Halley 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)

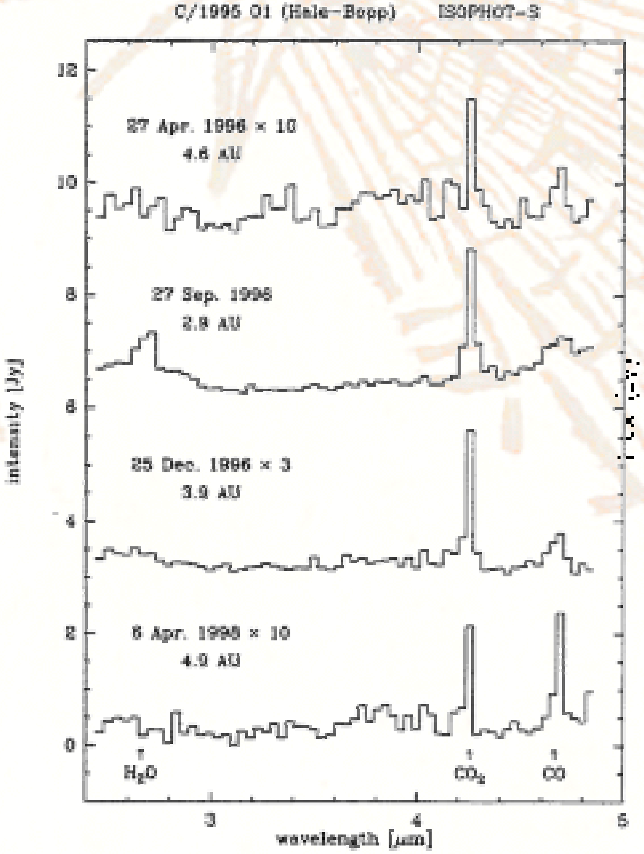
Comets resemble icy dirt balls rather than dirty snowballs

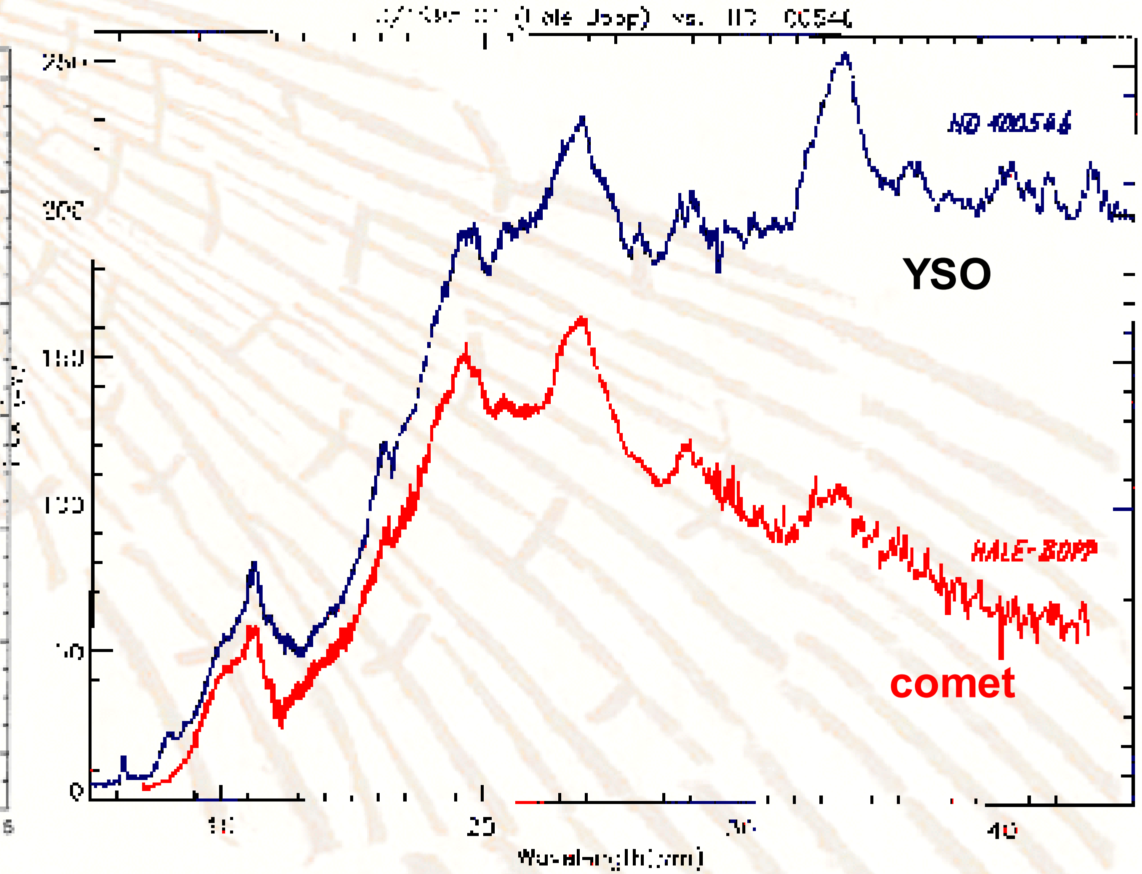
Comets – the most volatile minor bodies



IR Observations

H_2O, CO_2, CO





Crovisier et al. (1999)

C. WAELKENS ET AL. (1997)

Why are comets so exciting?

- Nearly solar abundances (high fraction of volatiles)
- Gas phase molecules similar to interstellar abundances
- Temperatures during formation similar to interstellar environment ($T \leq 30$ K)
- Temperatures during storage low enough to sustain original condensates ($T_{max} < 50$ K)
- Cometary material reflects the composition of the pre-planetary nebula
- Most pristine material – large organic molecules expected

Cometary Encounters

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

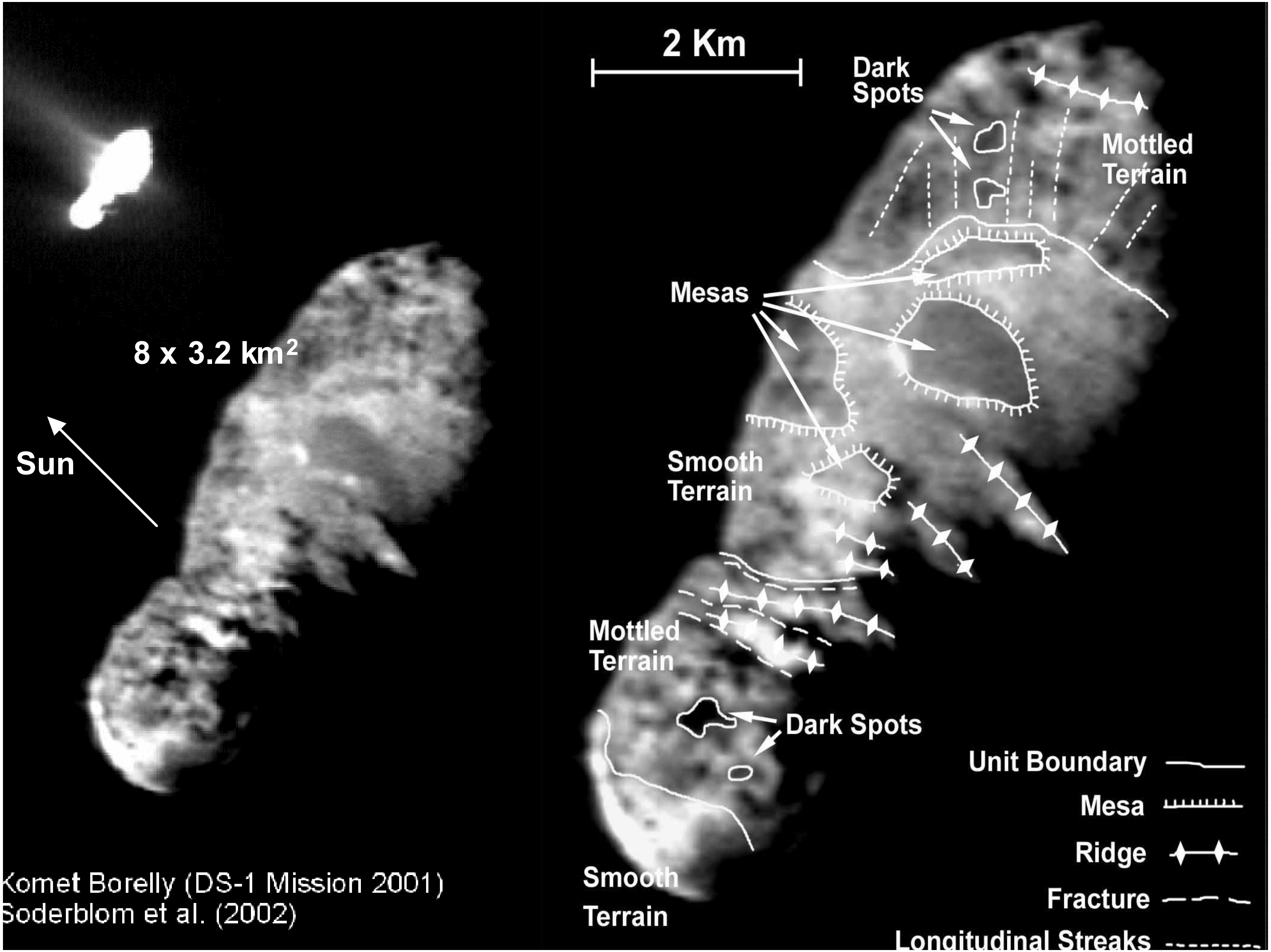
19P/Comet Borrelly

- Jupiter family orbit
- perihelion 1.36 AU

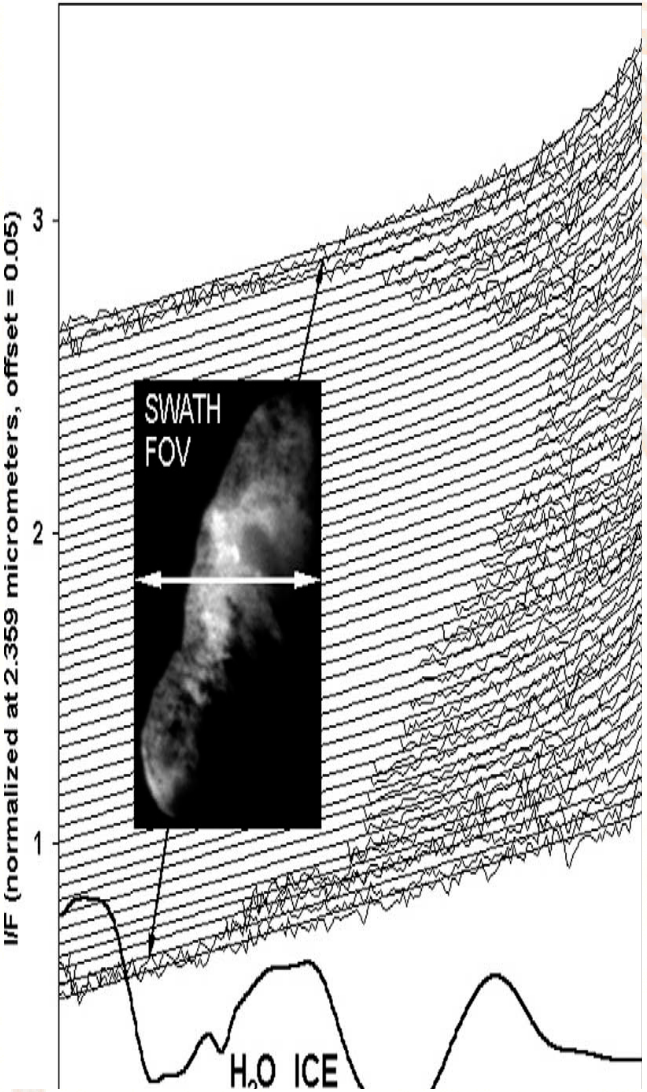
Deep Impact

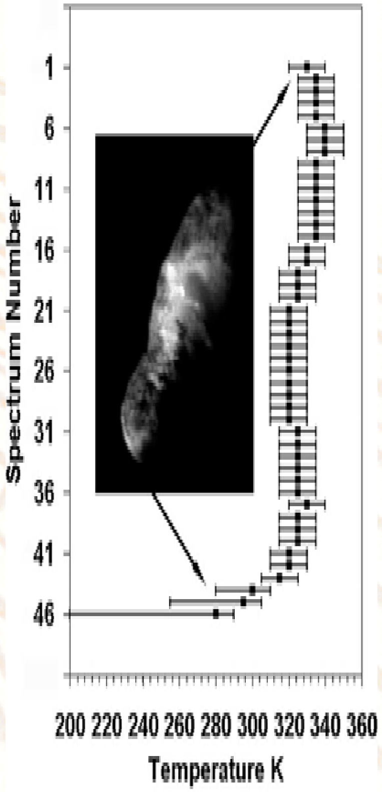
9P/Tempel 1

- 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

IR Spectra of 19P/Borrelly

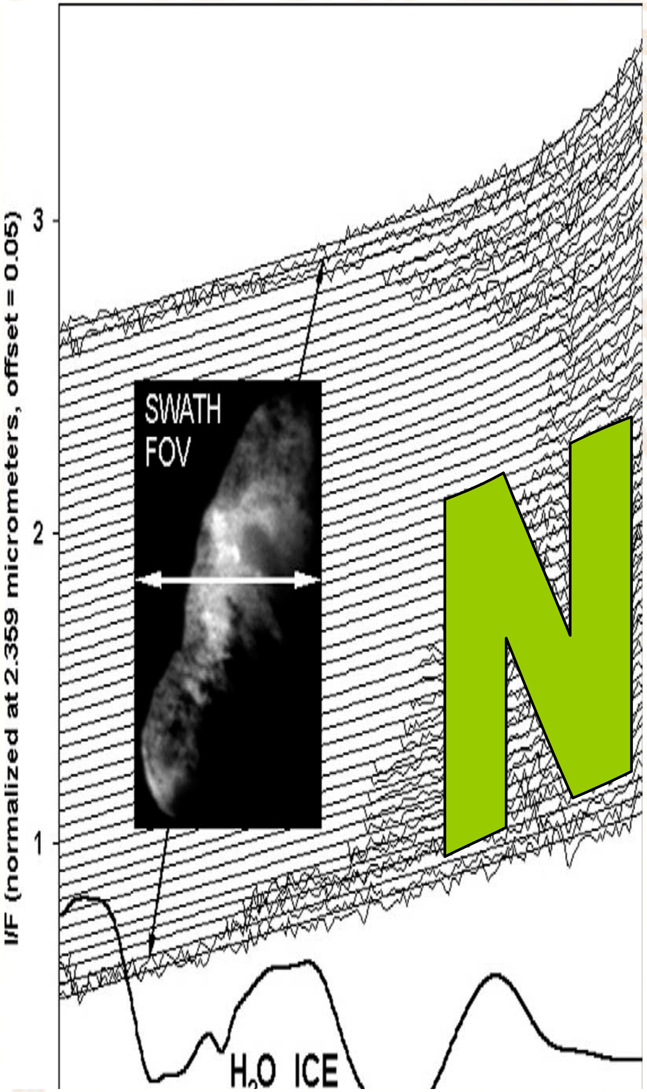




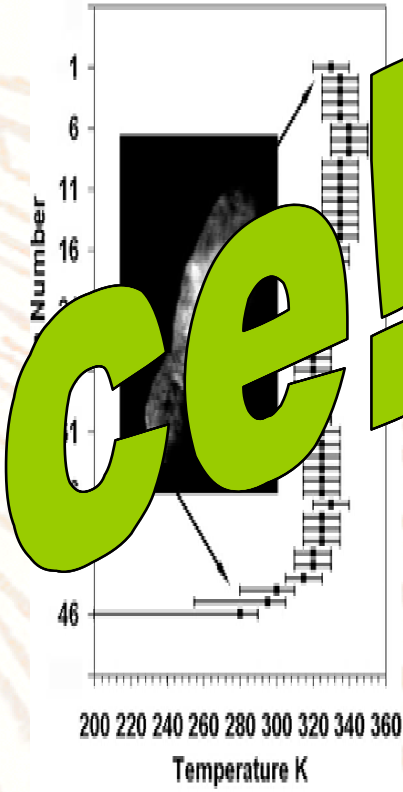
Soderblom et al. (2004)

Confirmation of VEGA results!

IR Spectra of 19P/Borrelly



No ice!



Soderblom et al. (2004)

Confirmation of VEGA results!

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

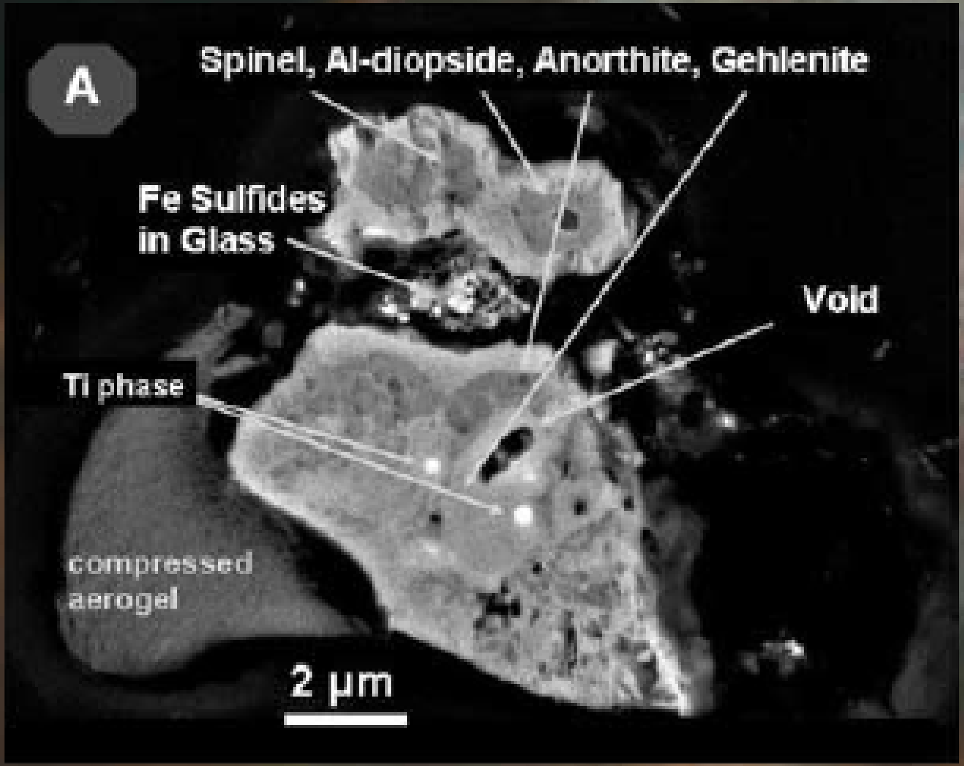
Nucleus

$5.5 \times 4.0 \times 3.3$ km

Albedo = 3%

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

Stardust results from comet Wild 2
Sampling the coma (not the nucleus!)



CAI-like grain
Zolensky et al. (2006)

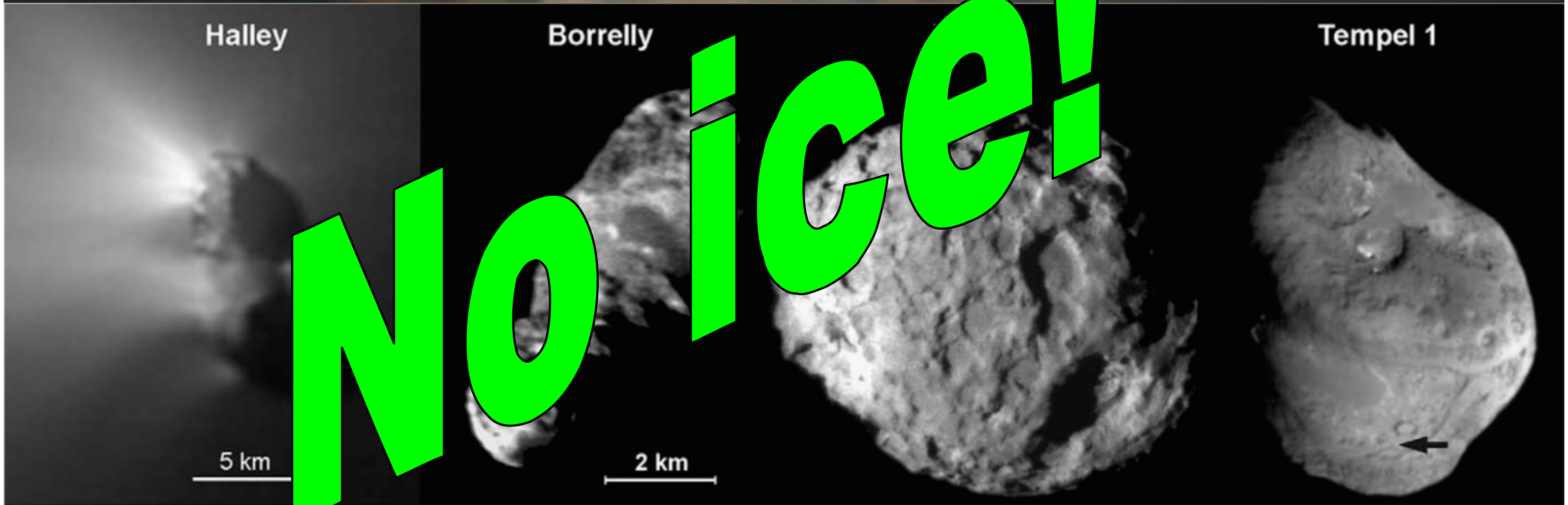
Minerals within the CAI-like particle require high temperature for formation (> 2000 K)

⇒radial mixing

Organics:
Polymeric-heterocyclic aromates (CIDA, Kissel et al)
Amine-rich organic polymers
Nitrogen rich organic compounds (methylamine and ethylamine)
Proto stellar origin (Sandford et al. 2006)

Total mass < 1 mg, therefore chronology not possible!

Physical nature of cometary nuclei



Cometary nuclei are kilometre sized bodies of low density

Show localized activity

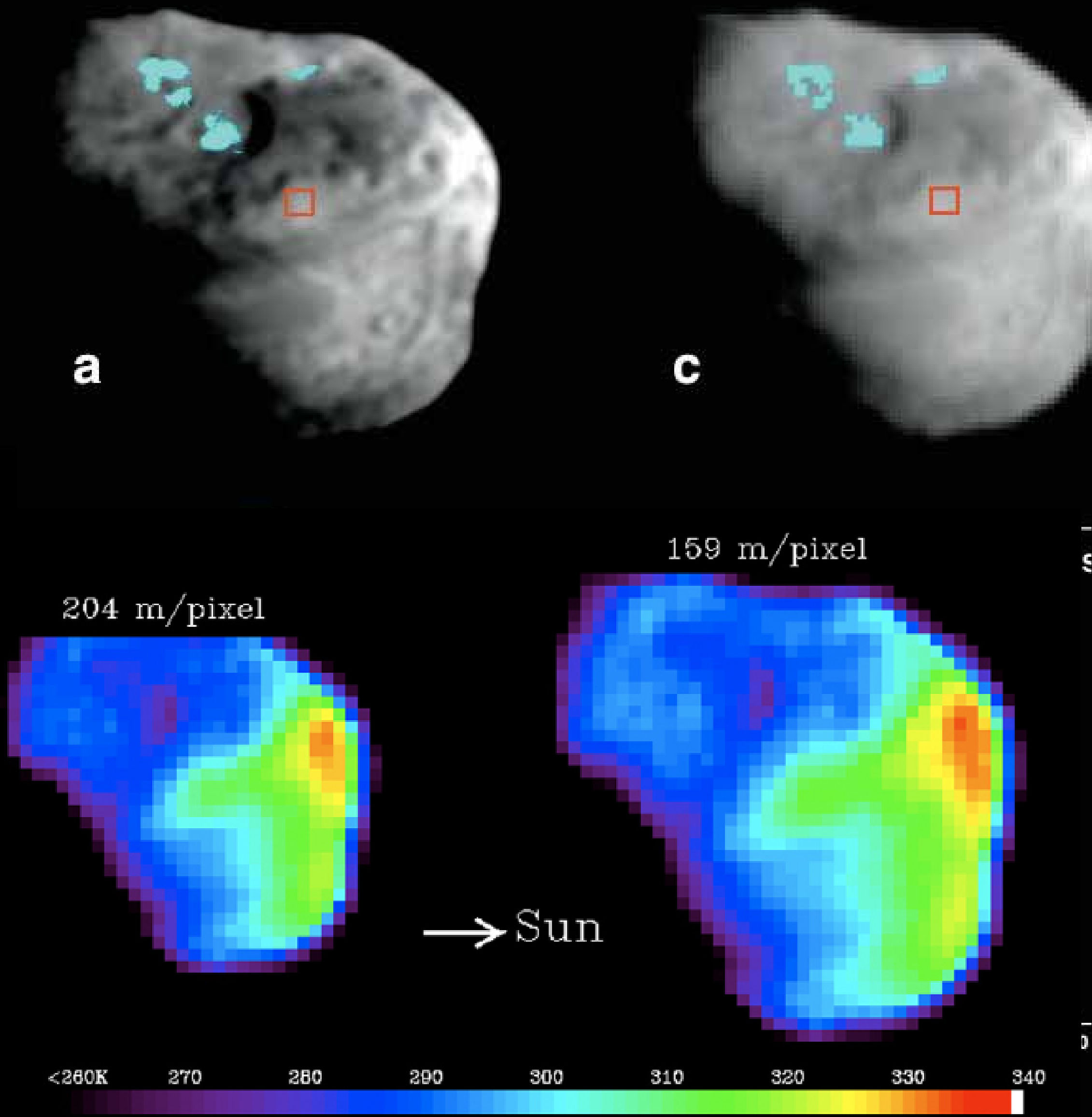
Dark albedo (0.04), no (water) ice visible

Very rough surface

Fragile with low tensile strength

These paradigms were fully confirmed by Deep Impact

Deep Impact



Very low thermal inertia:

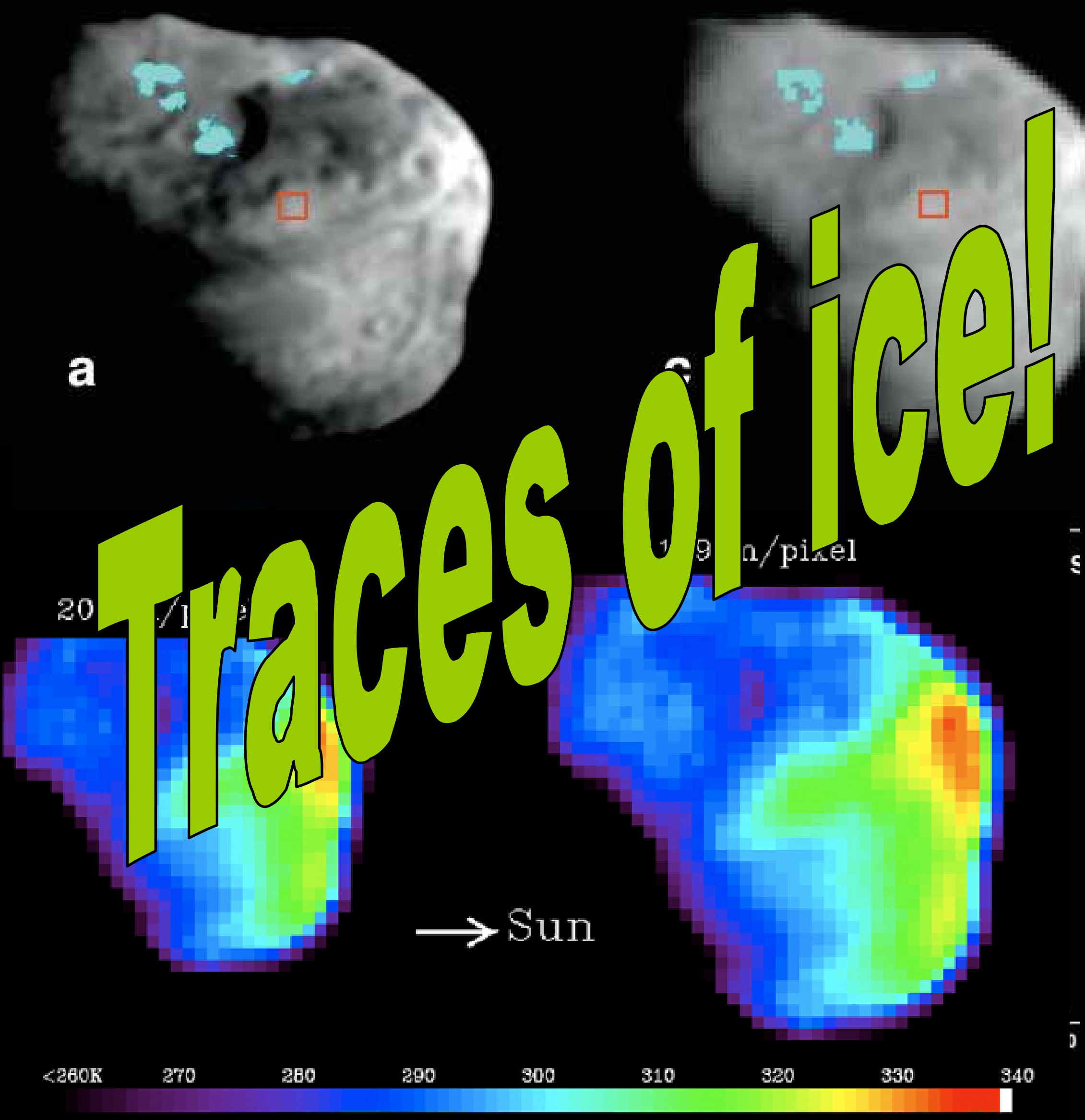
$\Gamma < 50 \text{ W m}^{-2} \text{ s}^{-1/2} \text{ K}^{-1}$

consequently very low heat conductivity:

$\kappa \approx 0.01 \text{ W m}^{-1} \text{ K}^{-1}$

(Groussin et al. 2007)

Deep Impact



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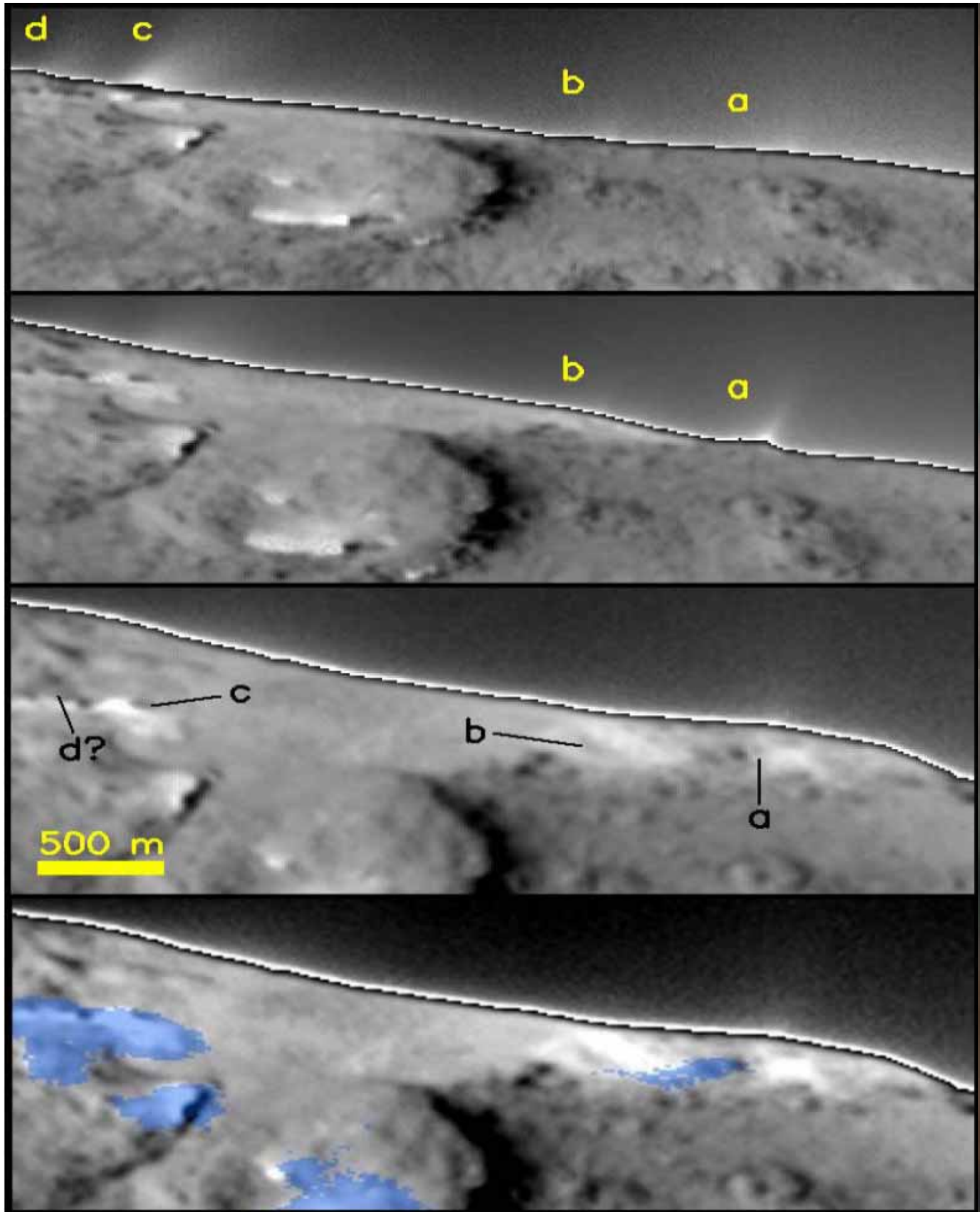


Sequence of Deep Impact images of the limb of the nucleus of comet Tempel 1, showing at least four small jets coming from the surface (“a”-“d”).

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. (Farnham et al. 2006)

Outstanding question:

How does cometary activity work?

Answer expected from Rosetta rendezvous

Conclusions from Deep Impact

Cometary nuclei:

- of low density
- very weak tensile strength
- very low thermal inertia
- very low heat conductivity
- ice not visible

Question: How thick is the dust layer on top of the ice?

Surface Heat Balance

$$\frac{\partial T}{\partial t} = \frac{\kappa}{\rho c}\frac{\partial^2 T}{\partial^2 z}$$ Thermal conductivity equation

$$0 = \frac{F_o(1-A_0)}{r_h^2} - \varepsilon\sigma T^4 + LZ(T) + \kappa\frac{dT}{dz}$$ Surface boundary condition

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

κ thermal conductivity

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

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

Thermal Skin Depths

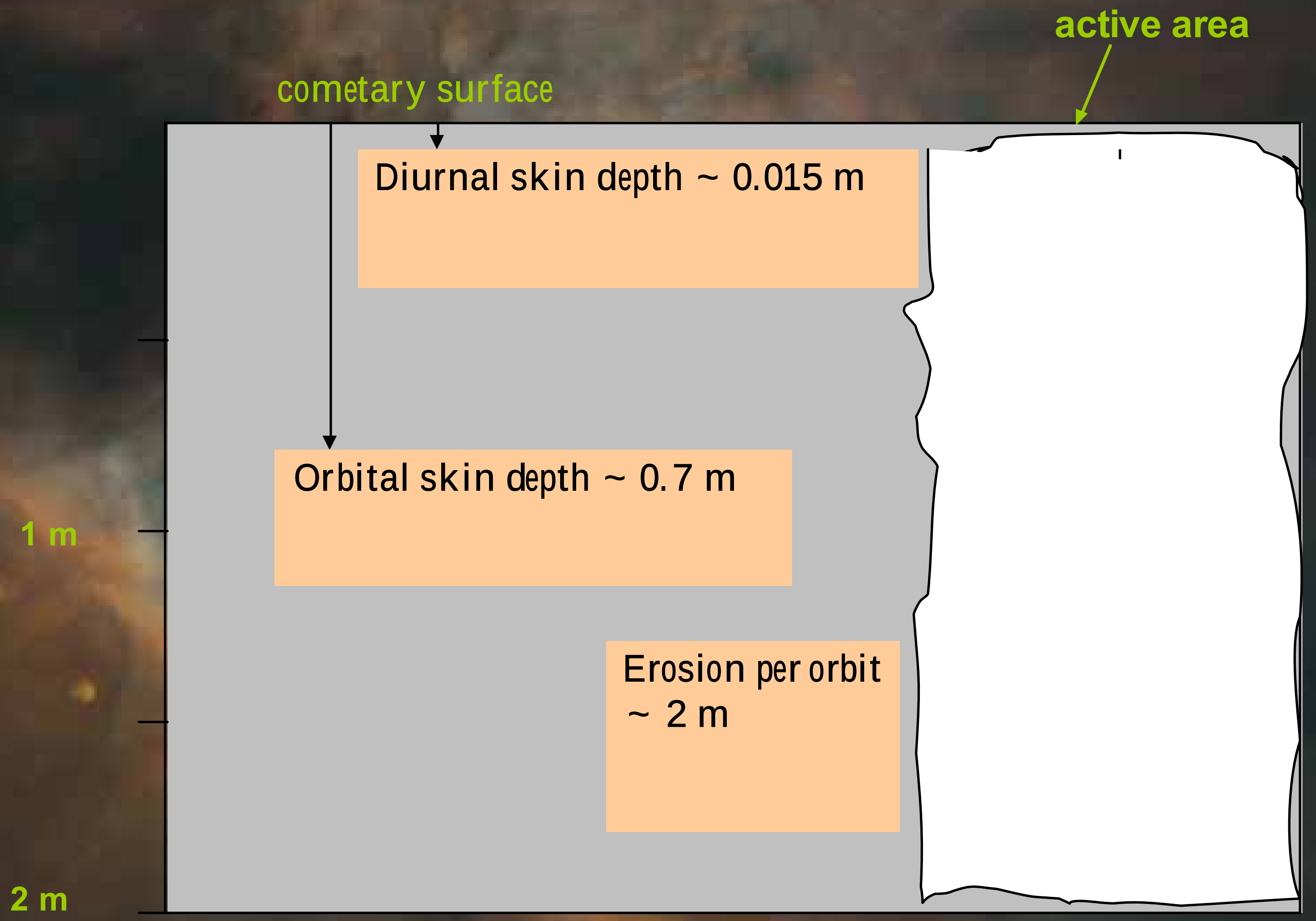
$$x = \sqrt{\frac{\tau d}{\pi}}$$ **Skin depth**

$\tau_{diurnal} = 10^5$ s => $x_{diurnal} = 1.5$ cm

$\tau_{orbital} = 2\ 10^8$ s => $x_{orbital} = 44\ x_{diurnal} \approx$ 70 cm

Orbital skin depth is only 70 cm, smaller than the thickness of the surface layer that is removed by sublimation activity

Schematics



Around perihelion the surface of an active area recedes faster than the heat wave penetrates!

Conclusion

=> Material, a few centimetres below an active surface, was covered in previous orbits by metres of essentially unaltered nucleus material and is not affected by insolation

How to get hold of the pristine material?

- Take a sample of the nucleus from an active area after perihelion
- 50 cm depth should suffice (> 25 times the diurnal skin depth)
- A comet nucleus sample return (CNSR) mission is proposed to ESA:

Triple F

in collaboration with ROSCOSMOS

Triple F

Comet Nucleus Sample Return Mission

will answer key questions:

- What were the conditions during the formation of the solar nebula from its parent molecular cloud (e.g. Orion-like versus T Tauri-like conditions)?
- To which extent are comets composed of pristine interstellar grains? Do they carry prebiotic complex molecules?
- What are the formation processes and chronology of cometary refractories?
- What was the role of comets in the origin of atmosphere, water, organic chemistry, and life on Earth?

A proposal in response to ESA's Cosmic Vision Call
in joint collaboration with ROSCOSMOS

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kueppers@mps.mpg.de

for the Triple F Team

Triple F

Comet Nucleus Sample Return Mission

Conclusions

- Stardust and Deep Impact confirmed essential cometary nucleus parameters to facilitate a CNSR mission – the time is ripe!
- Comets contain interstellar matter, organics, and matter processed in the solar nebula
- Pristine material can be found close to the surface because erosion is faster than heat penetration
- Sampling is easy because of the low tensile strength
- Triple F will deliver highly pristine material including complex organic molecules to Earth
- Triple F will provide ground truth for the planetary nebula composition

A proposal in response to ESA's Cosmic Vision Call
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Triple F
Comet Nucleus Sample Return Mission
Fresh From the Fridge
Comet Nucleus Sample Return Mission
A proposal in response to ESA's Cosmic Vision Call
in joint collaboration with ROSCOSMOS
First flyby – First rendezvous – First sample return
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for the Triple F Team