Nature and Physics of Cometary Nuclei

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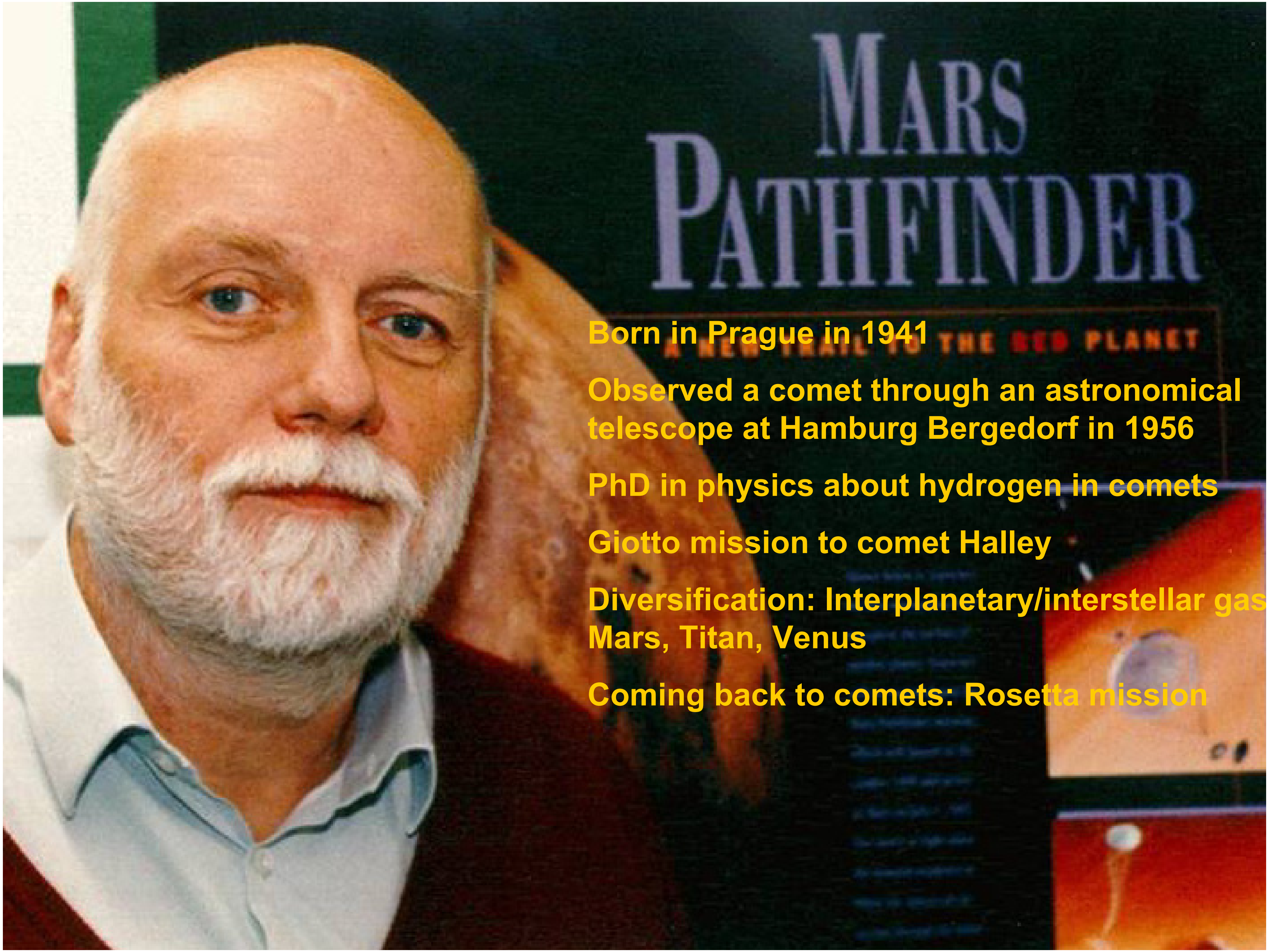


Born in Prague in 1941

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

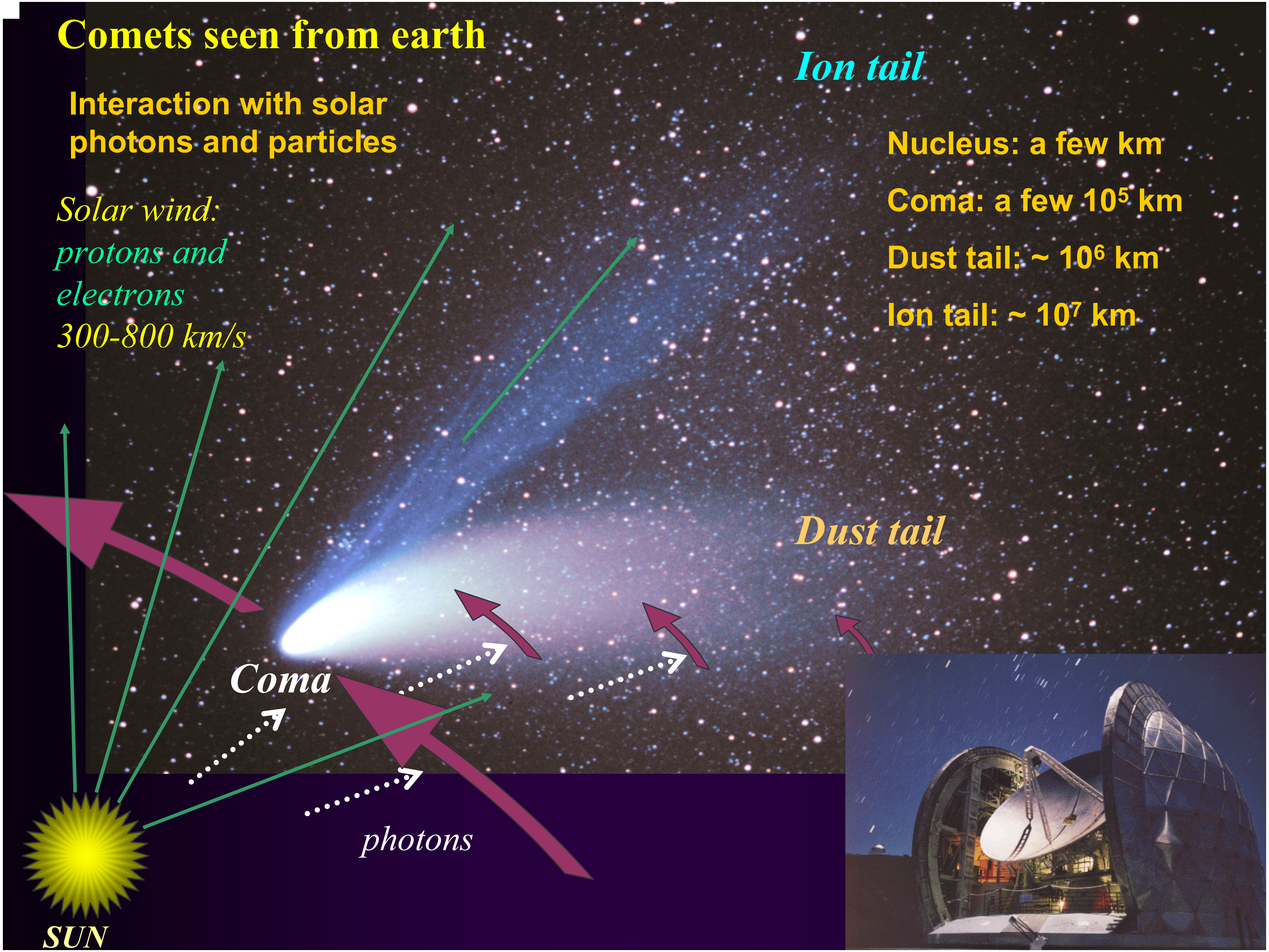
Rosetta OSIRIS observations of DI and results

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 10^5 km
Dust tail: ~ 10^6 km
Ion tail: ~ 10^7 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

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)

Leonid shower early 19th century

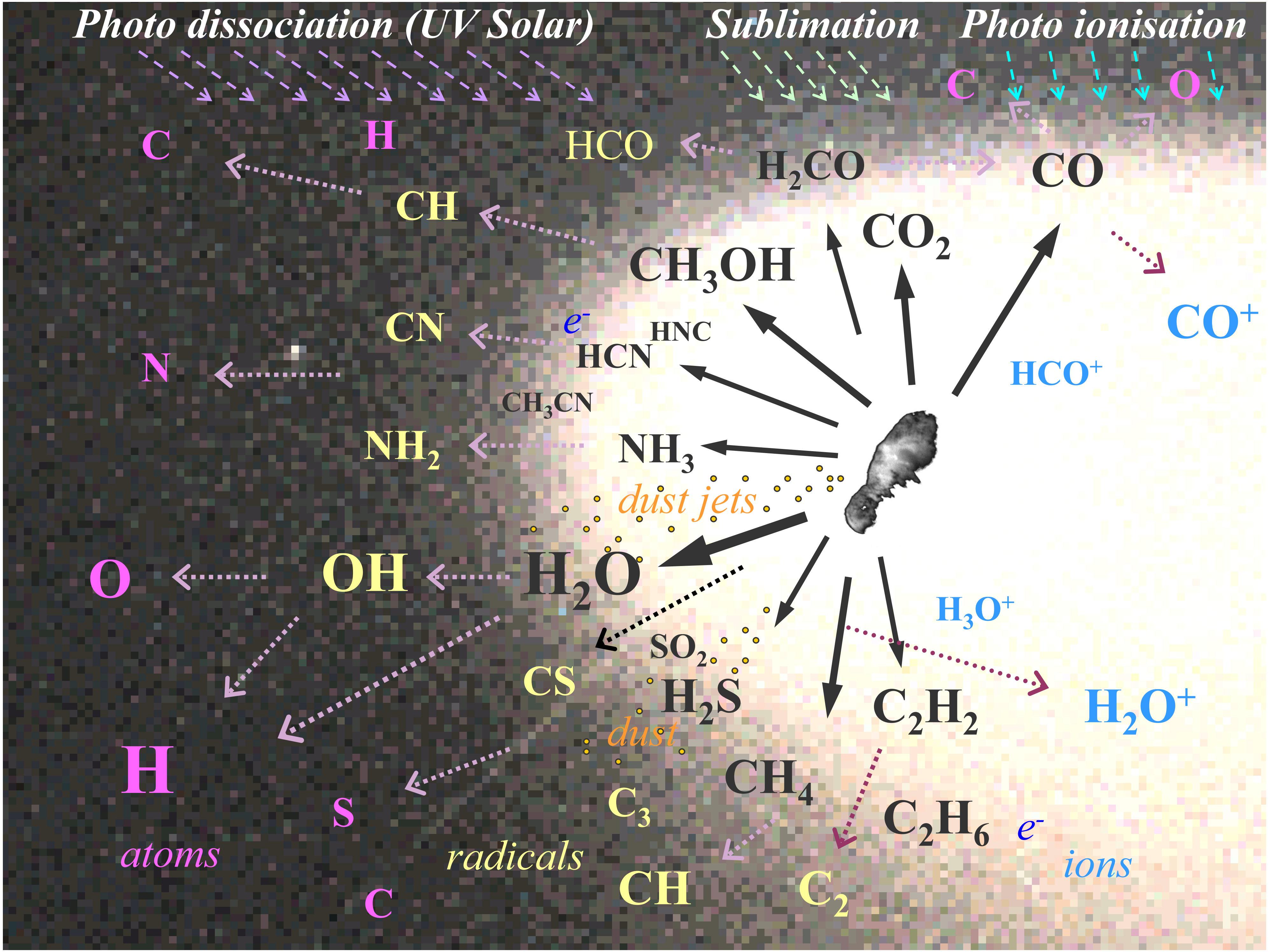
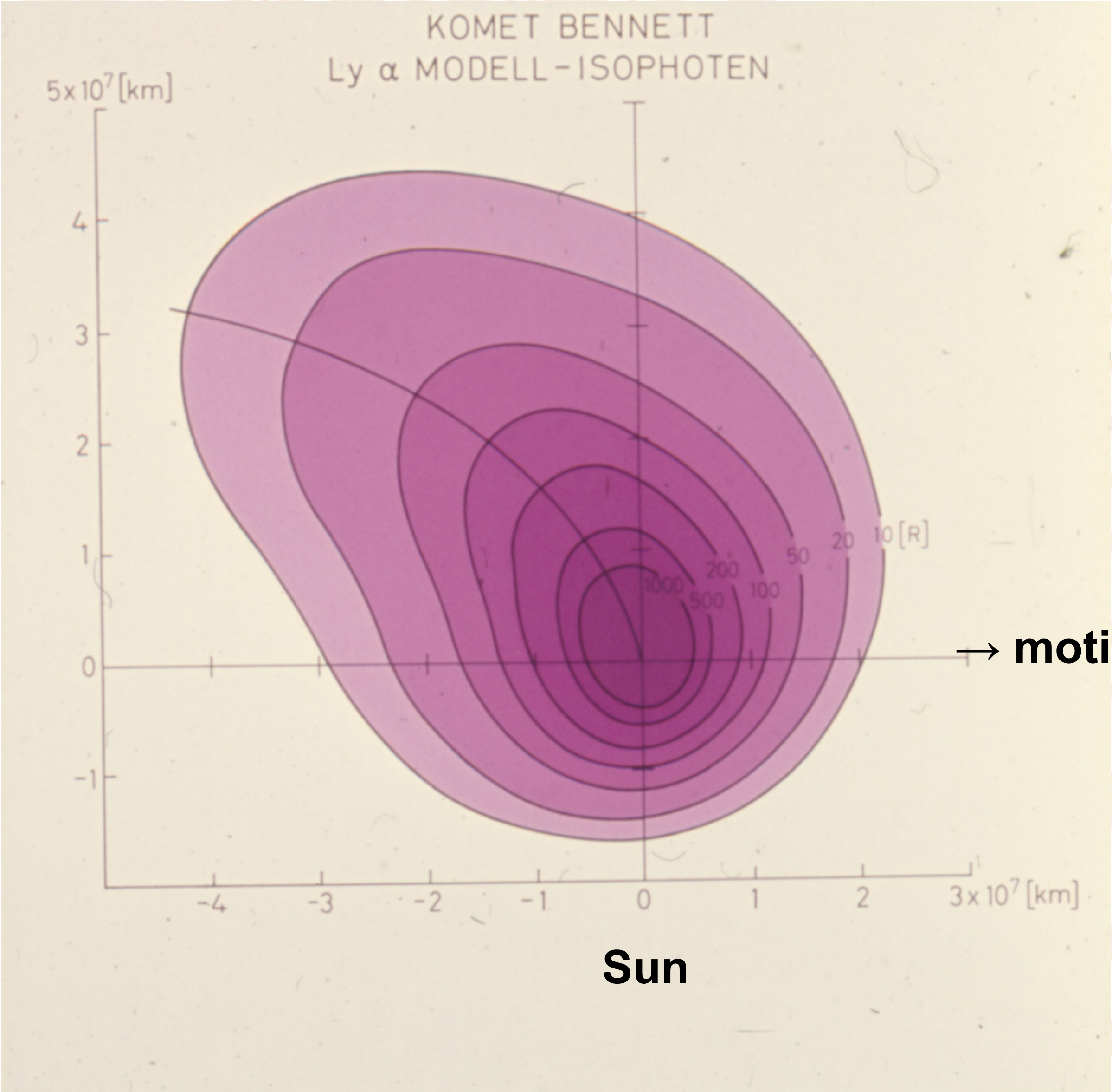


Photo dissociation (UV Solar)
Sublimation
Photo ionisation
C
O
C
H
HCO
H2CO
CO
CH
CO2
CH3OH
CO+
CN
e-
HNC
HCN
N
HCO+
CH3CN
NH2
NH3
dust jets
O
OH
H2O
H3O+
SO2
CS
H2S
C2H2
H2O+
dust
H
CH4
S
C3
C2H6
e-
atoms
radicals
ions
C
CH
C2

Ly α Isophotes - Model

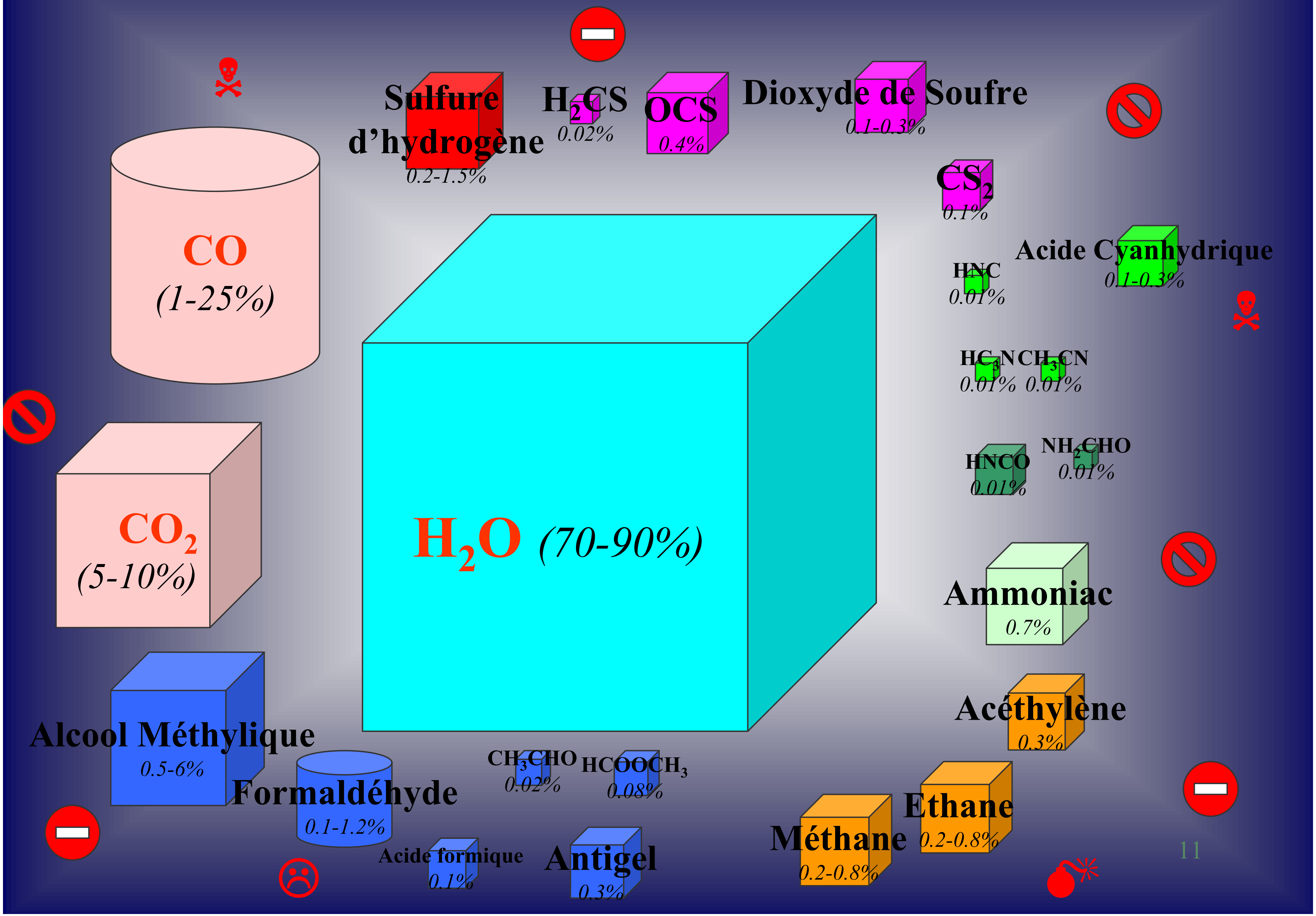


Hydrogen Coma of Comet Bennett

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

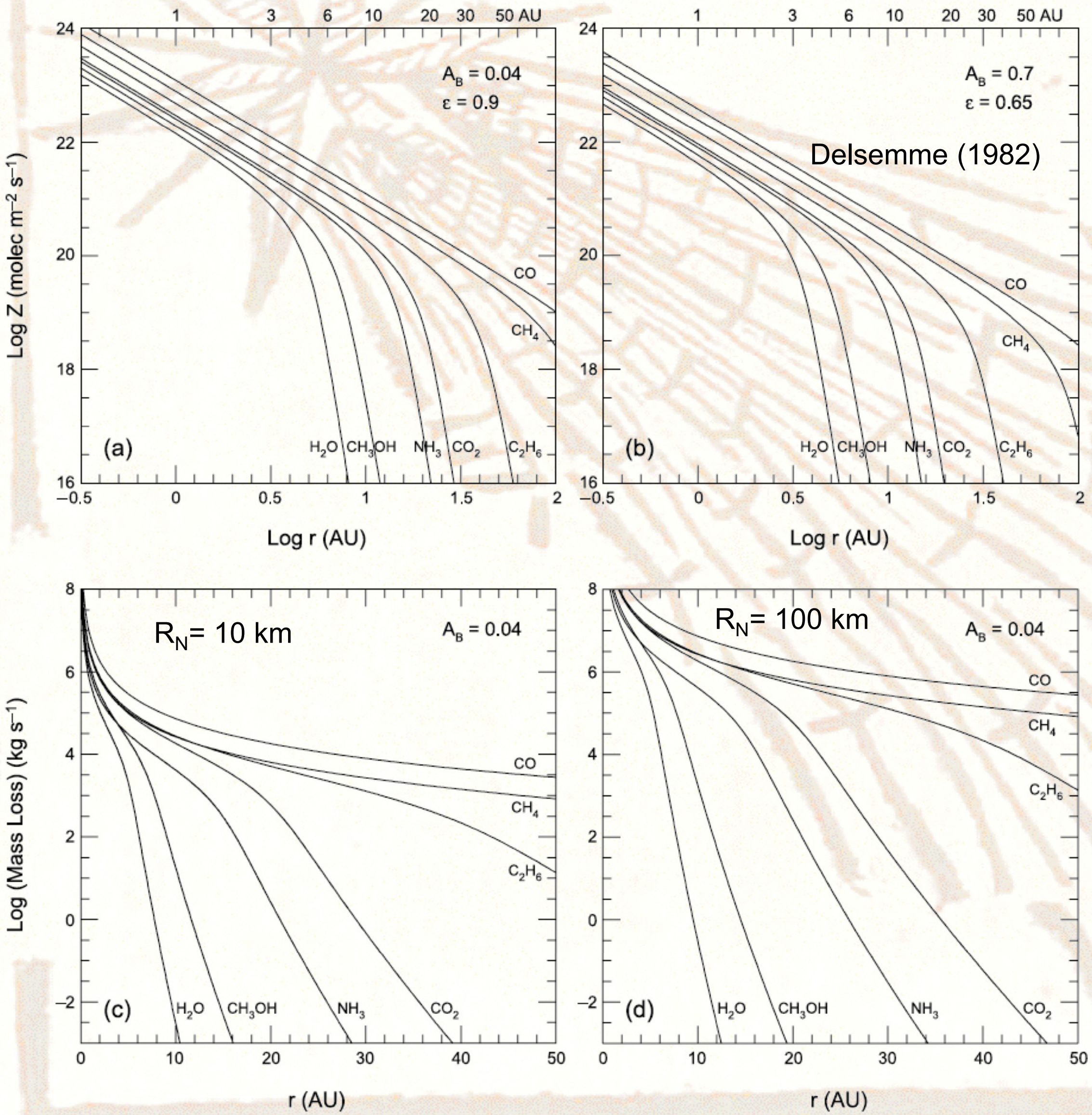
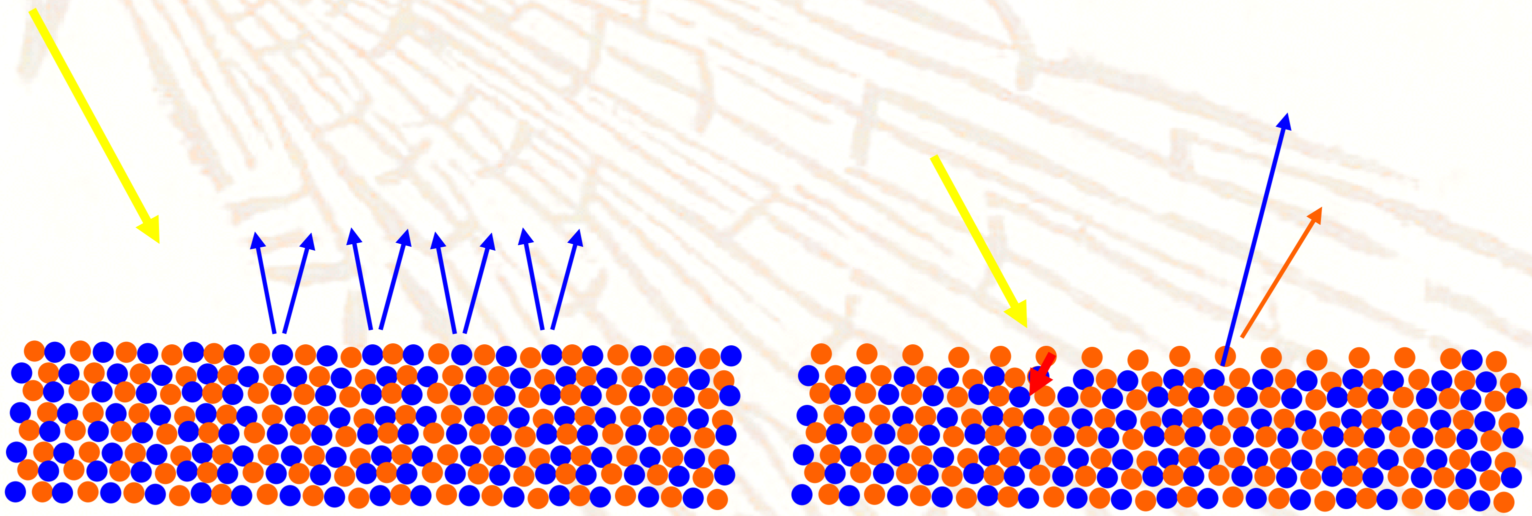


TABLE 1. Temperature regimes for onset of comet activity.

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)
=> $0.5 \text{ km} < R_N < 10 \text{ km}$ ($B \alpha A R_N^2$)

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

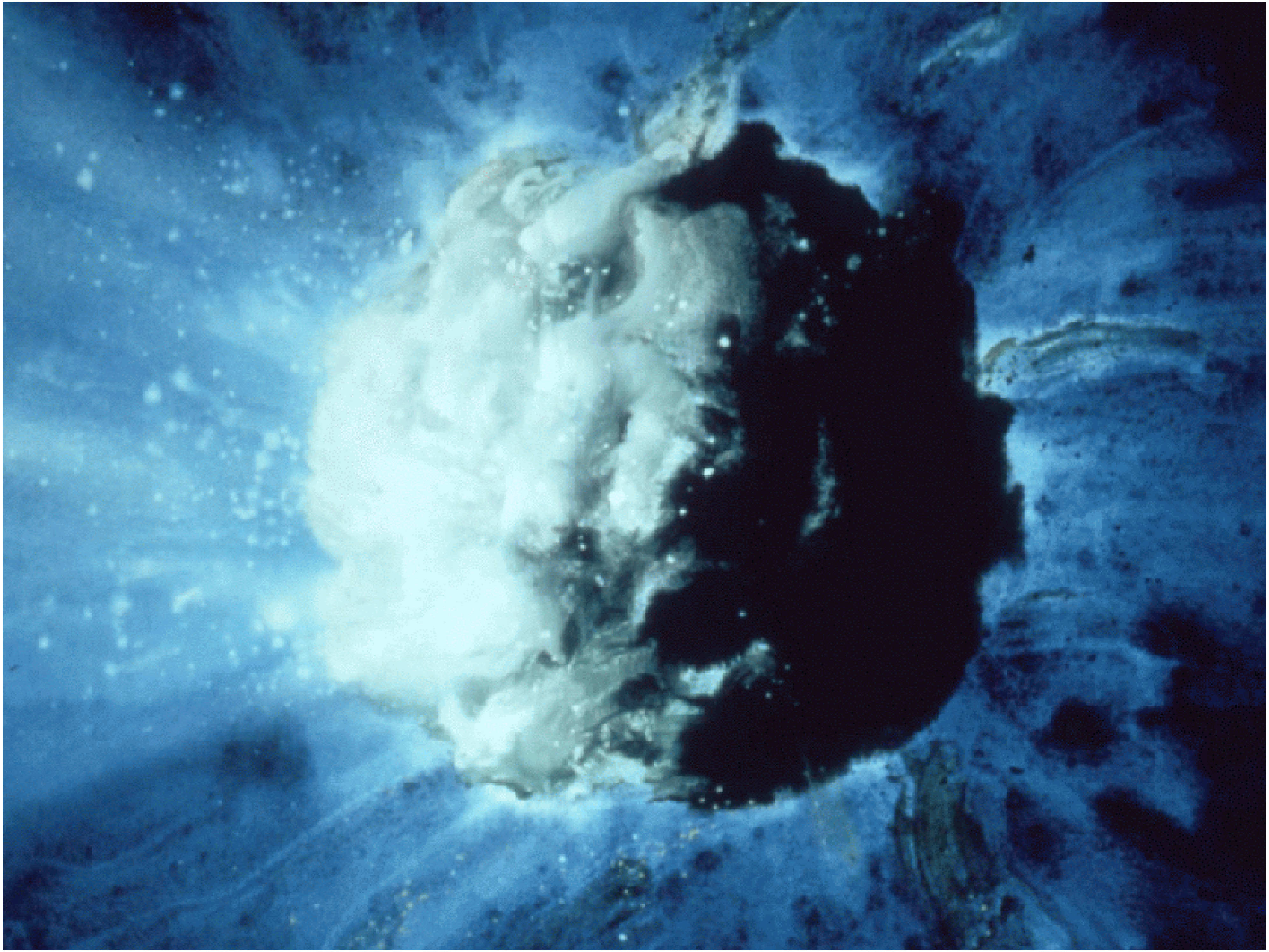
Second observational method is required to separate A from R:

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

Albedo and Nuclear Radius for Two Comets

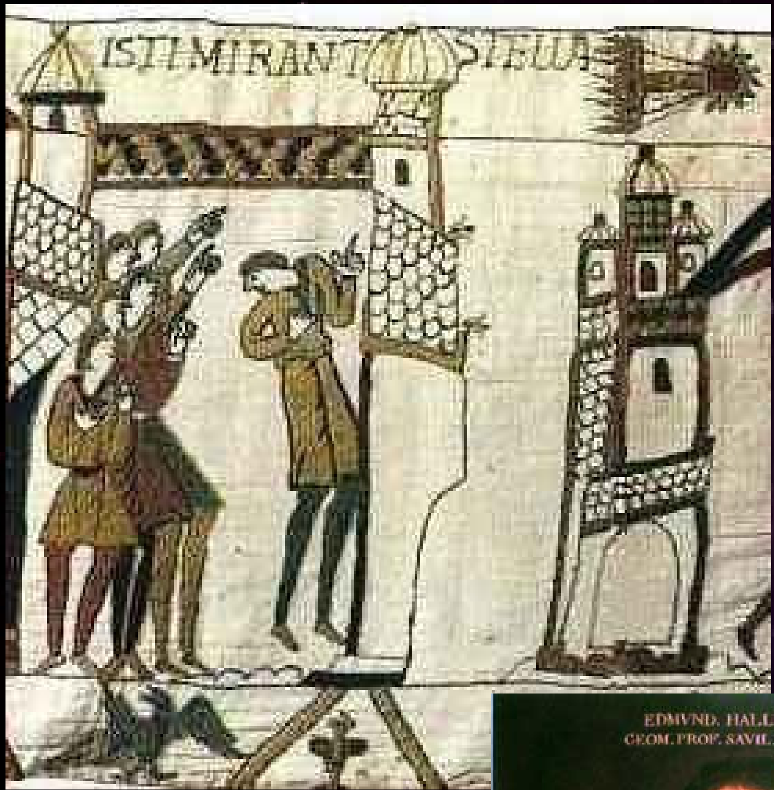
Comet	Bond Albedo *A*	Nuclear Radius *R*
Tago Sato Kosaka	0.63 ± 0.13	2.20 ± 0.27 km
Bennett	0.66 ± 0.13	3.76 ±0.46 km

Delsemme and Rudd (1973)



Halley's Comet,

First observed in China 240 BC

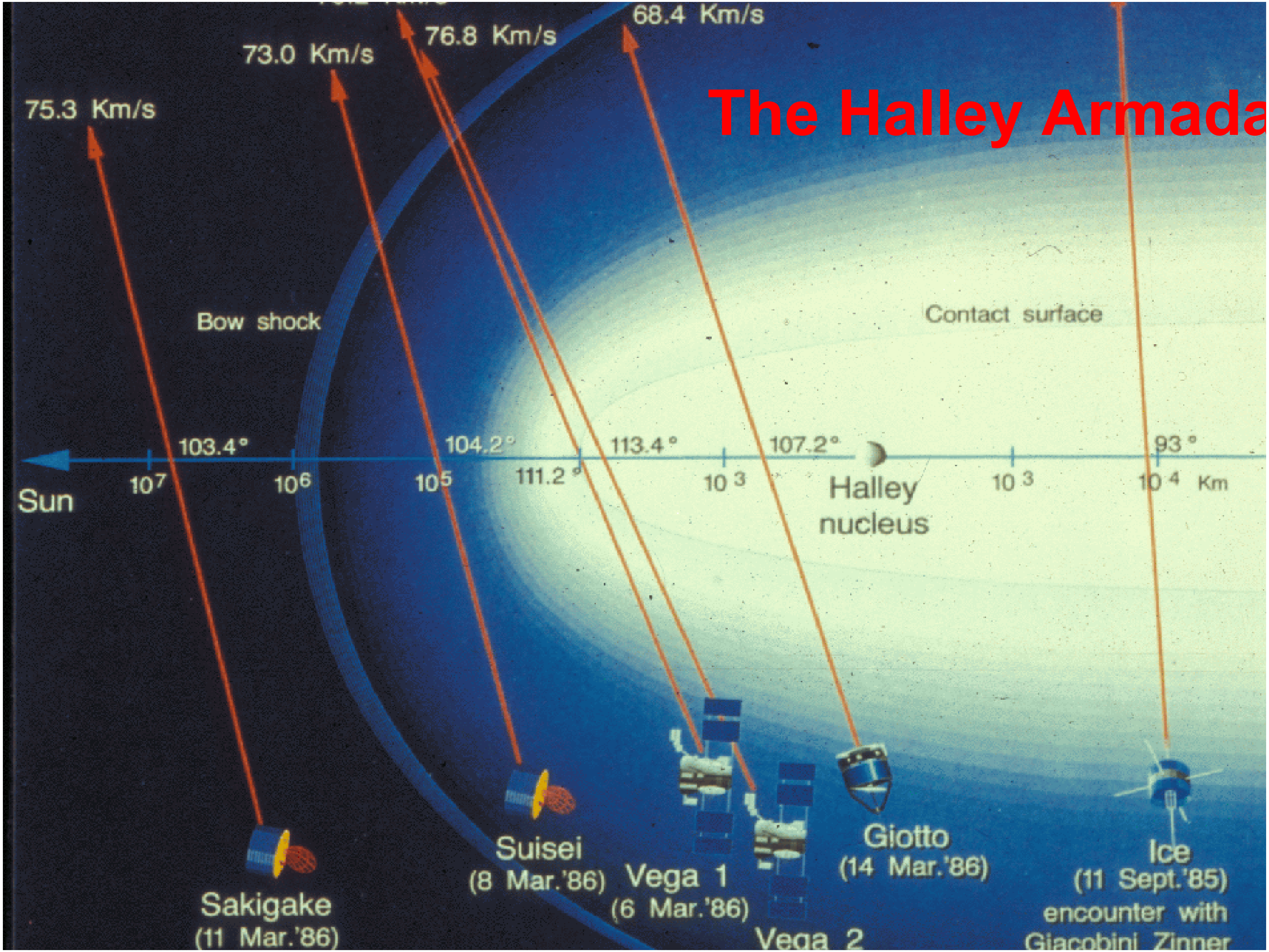


1066 Bayeux Tapestry

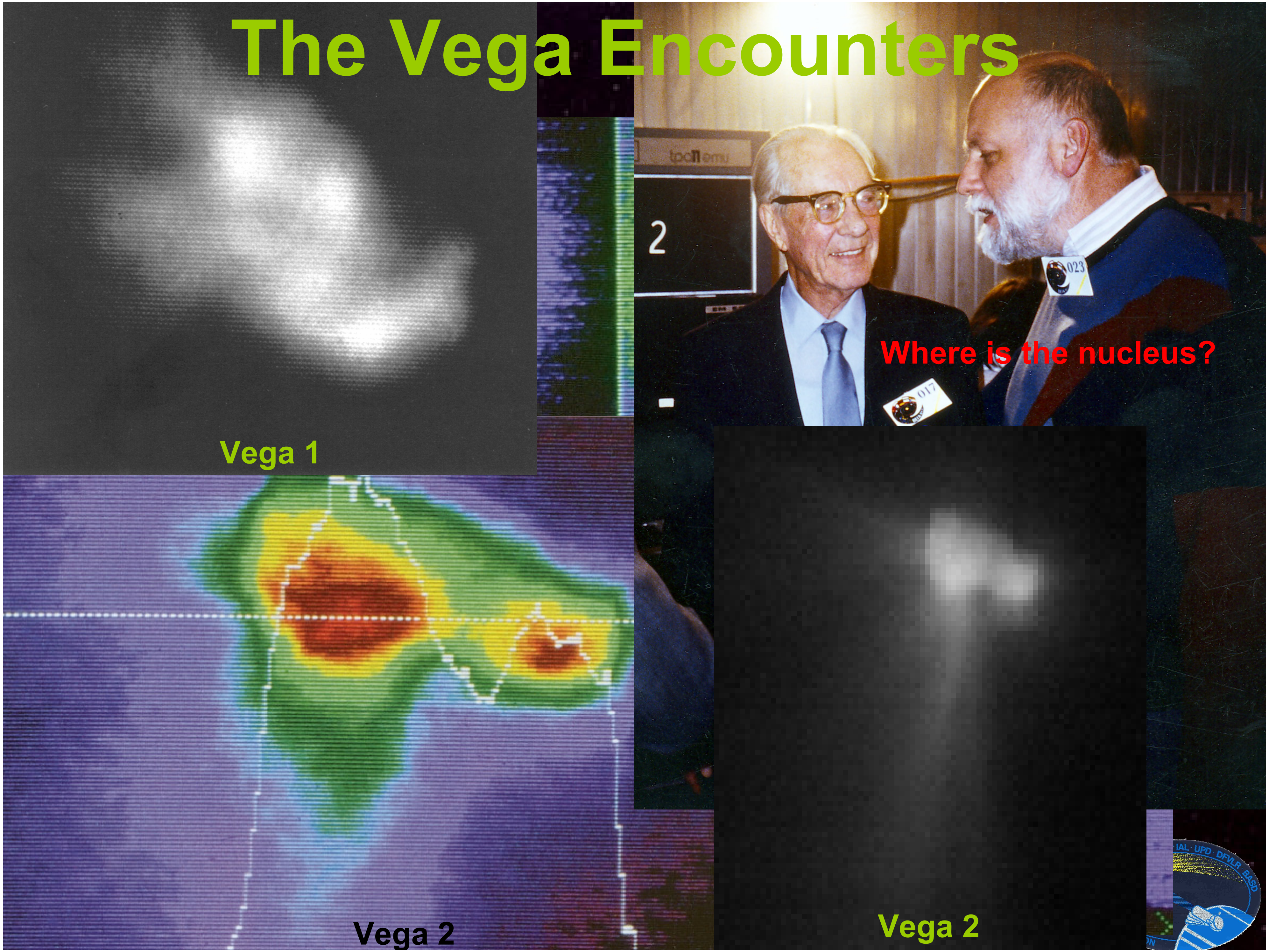
1305, Giotto di Bondone

1705, Edmond Halley

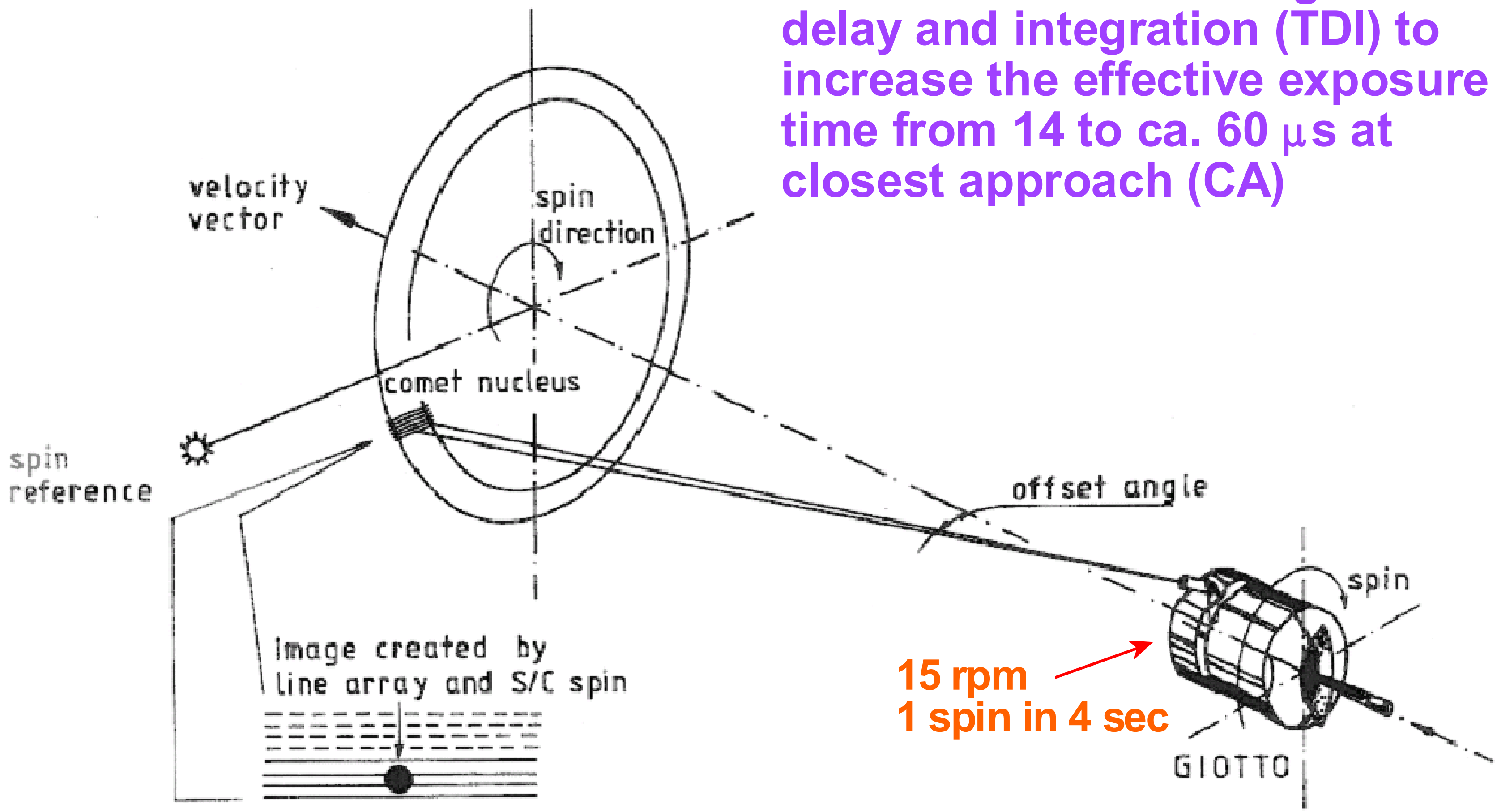
The Halley Armada



The Vega Encounters



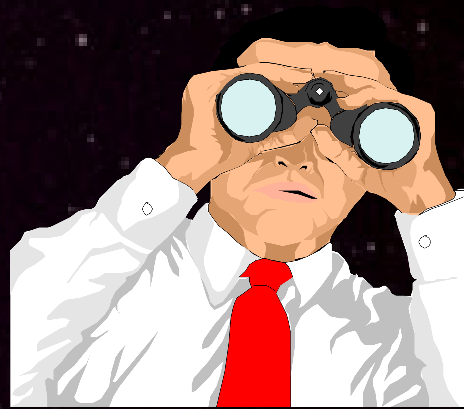
Line scan camera using time delay and integration (TDI) to increase the effective exposure time from 14 to ca. 60 μs at closest approach (CA)



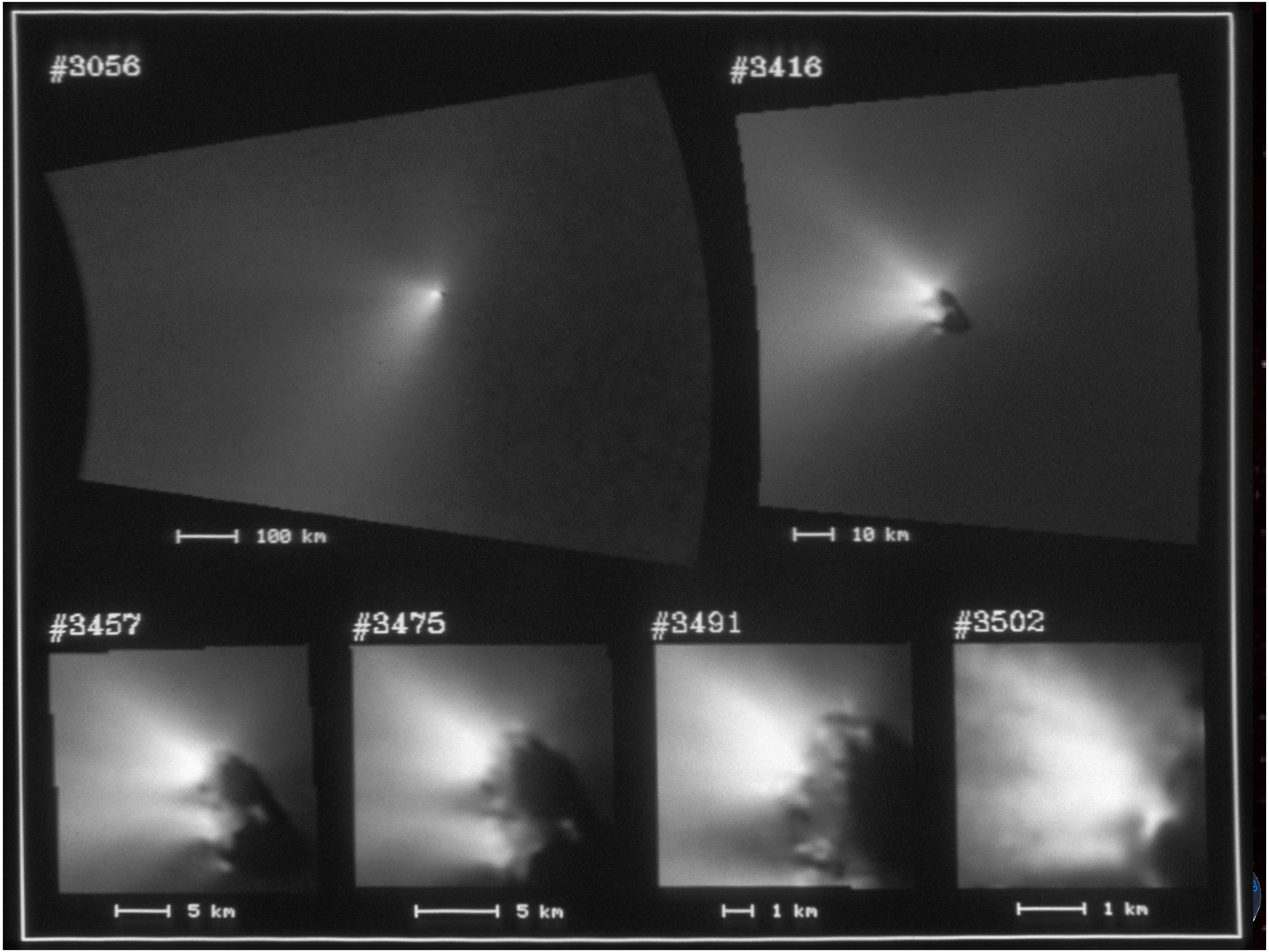
15 rpm
1 spin in 4 sec

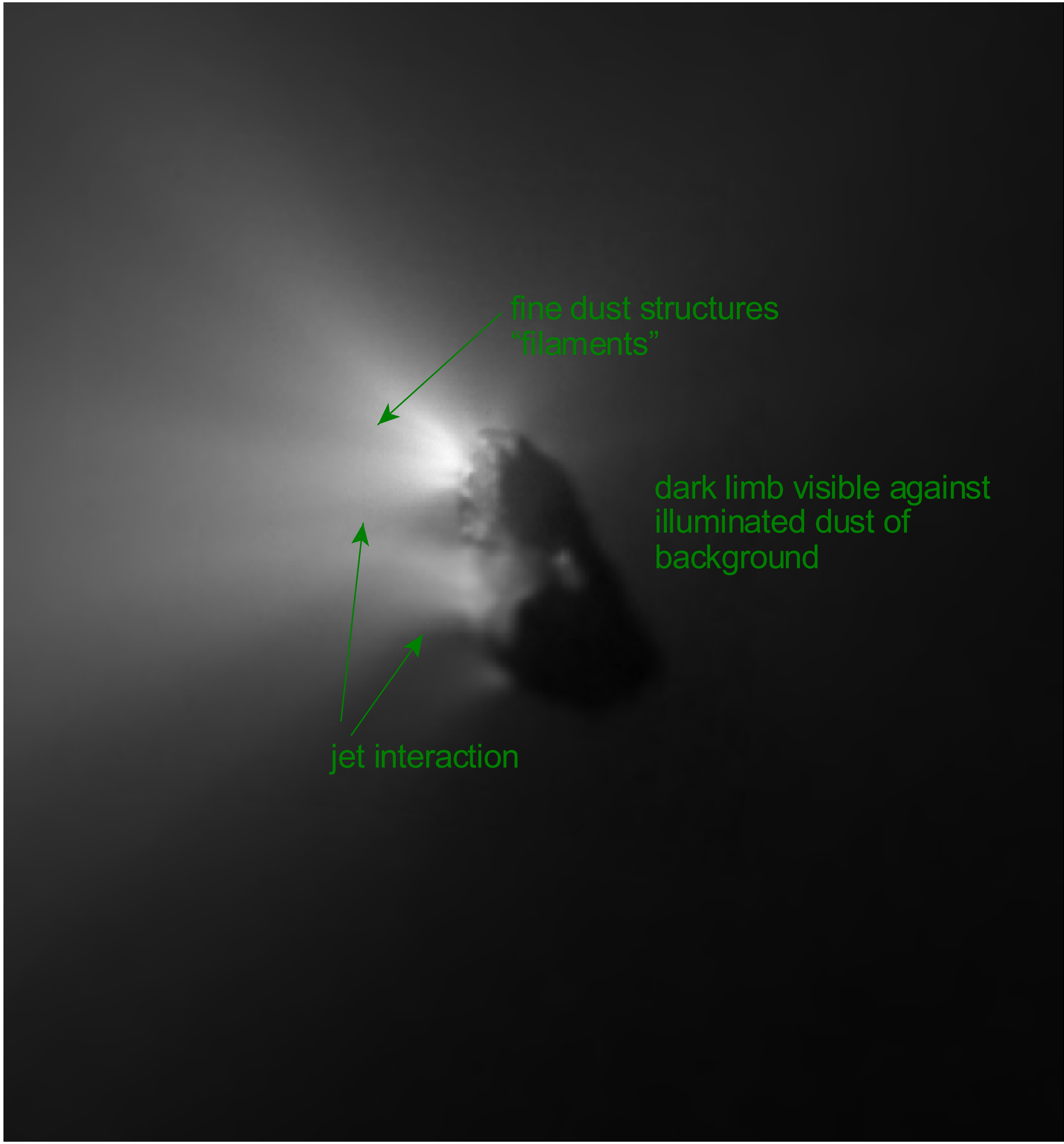
HMC Capabilities

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

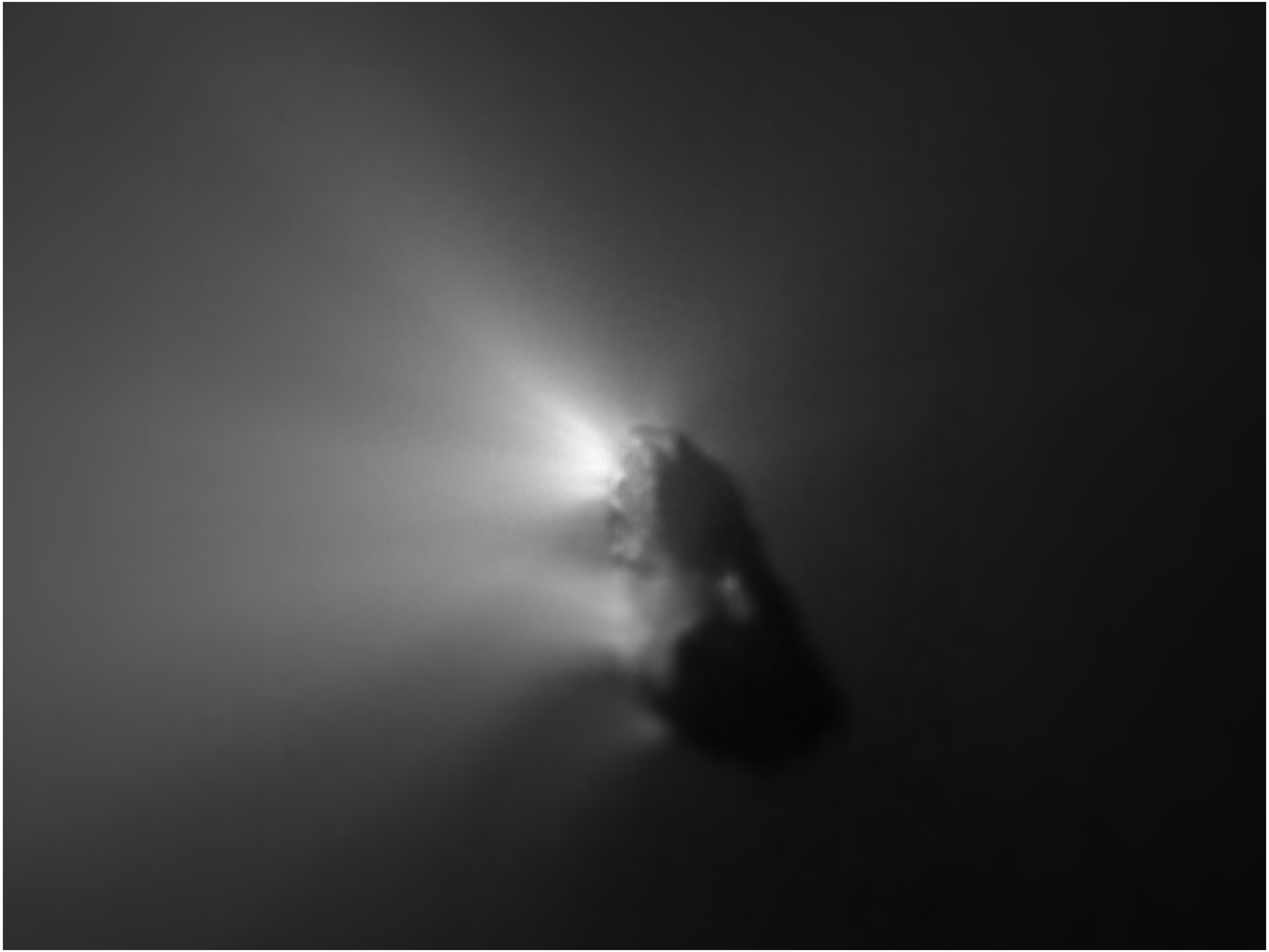


Composite image of comet Halley

68 images are combined

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

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

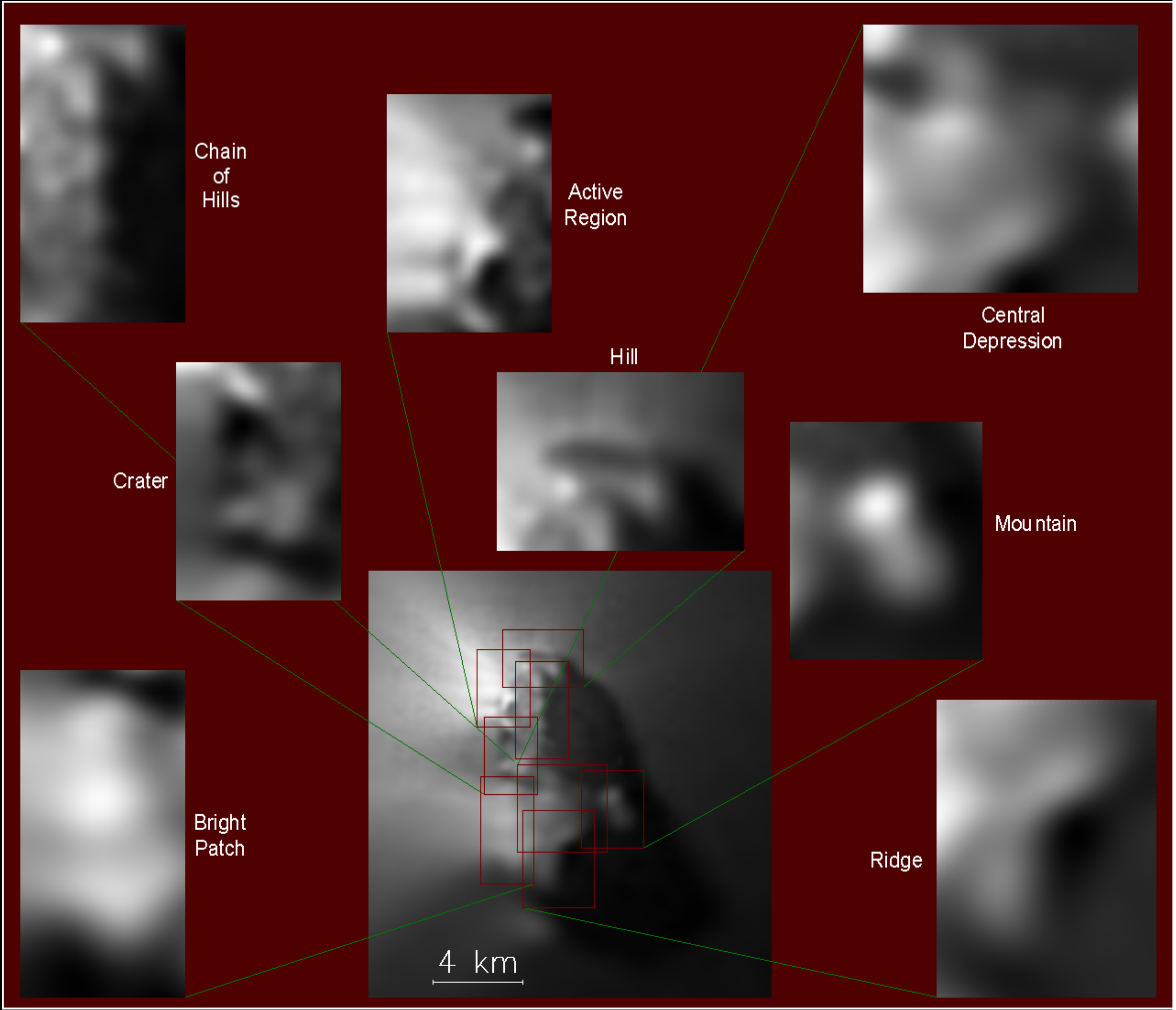


Comet Halley

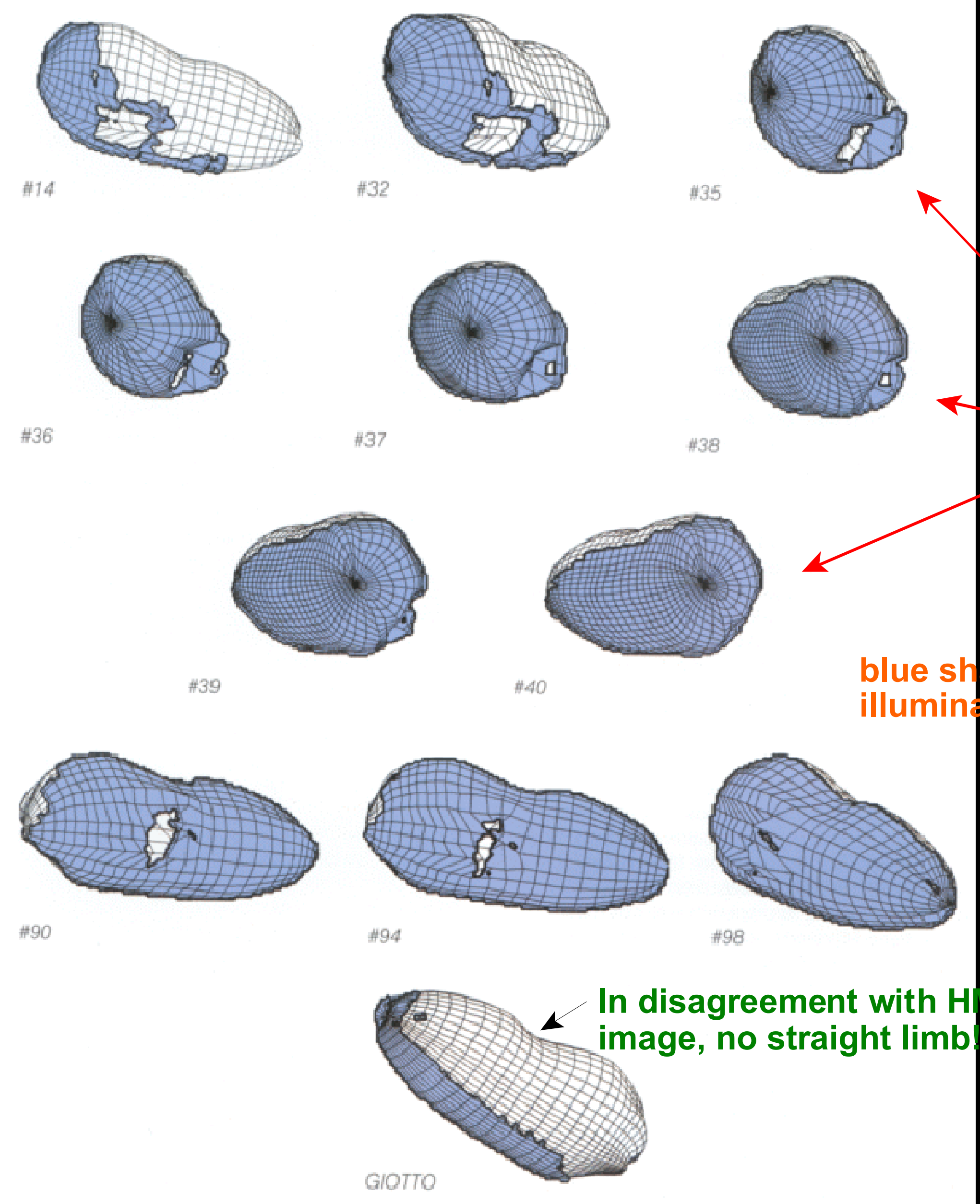
Elongated
15.3 x 7.2 x 7.2 km^3
Very dark albedo
No impact craters
Activity limited

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

VEGA 2

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)