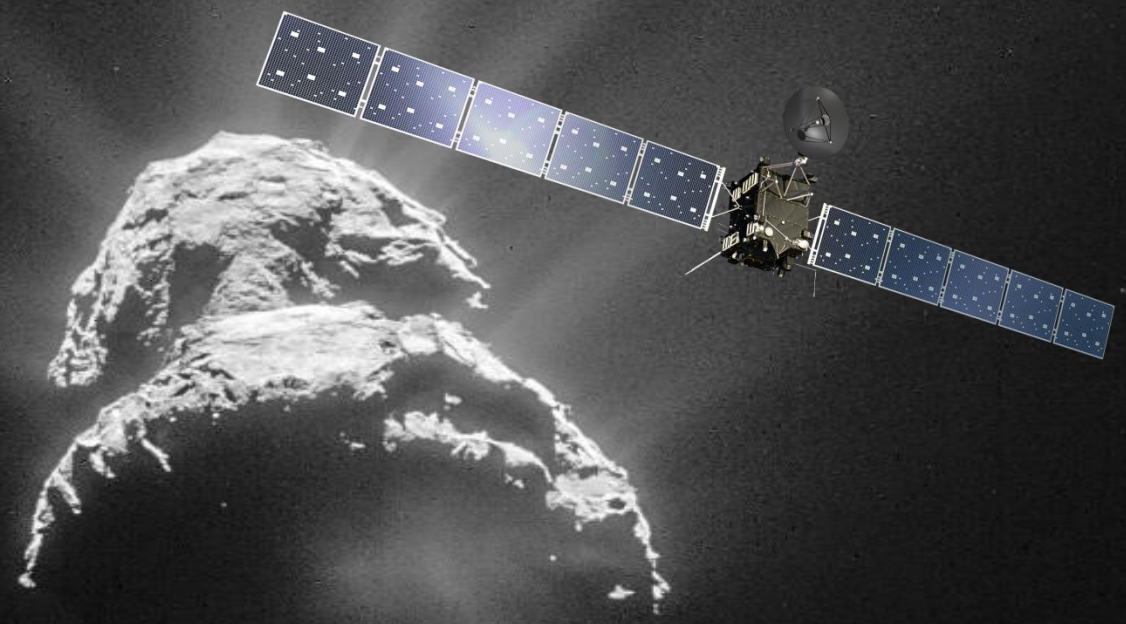
New challenges for cometary dust modeling after Rosetta

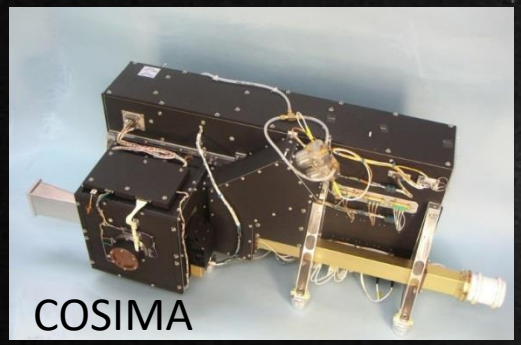


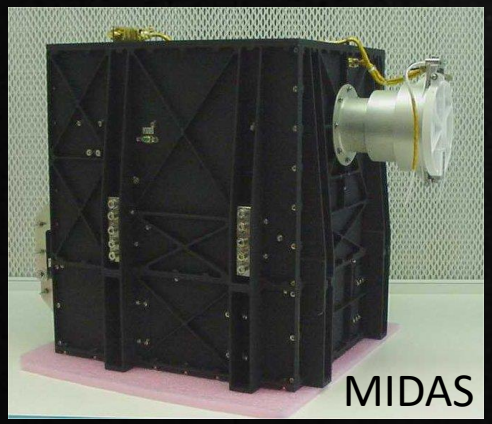
Ludmilla Kolokolova, ***University of Maryland, USA***

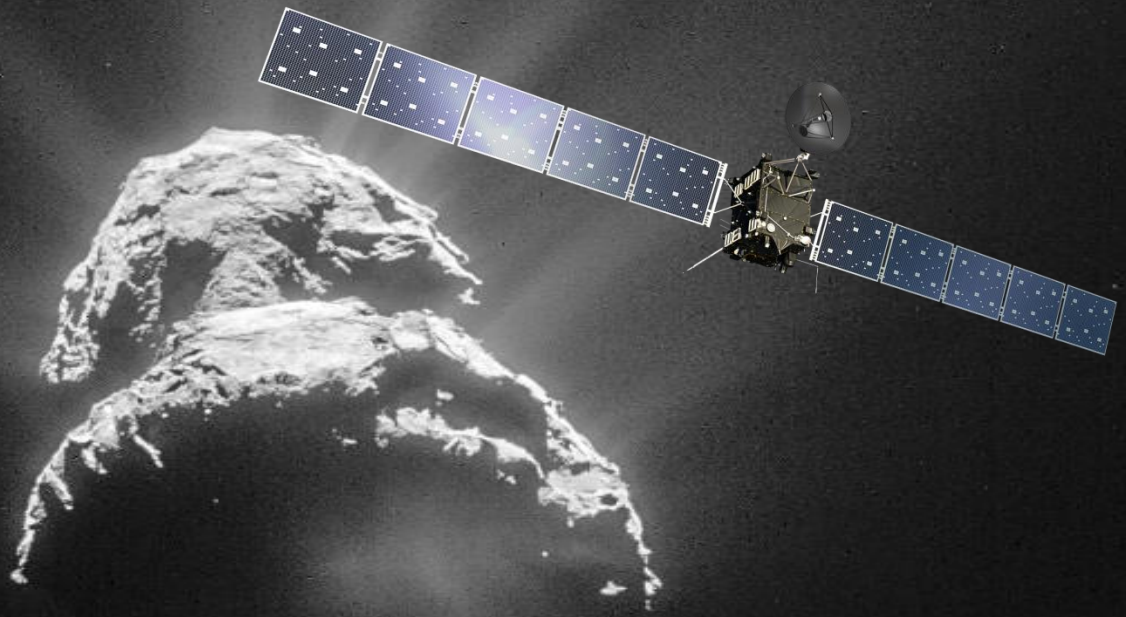
Hiroshi Kimura, ***Chiba Institute of Technology, Japan***

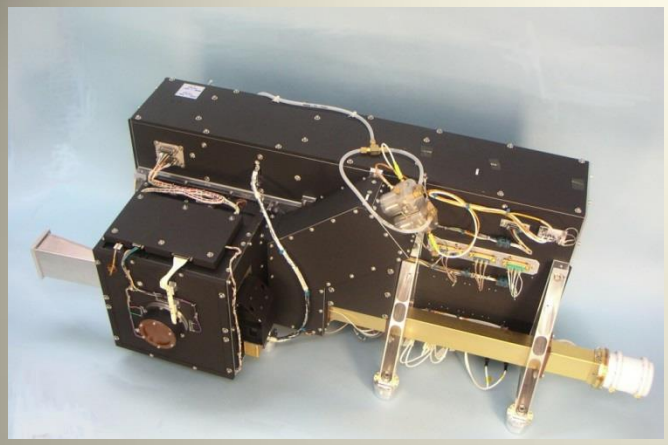
Thanks to the COSIMA team for discussions


GIADA


COSIMA

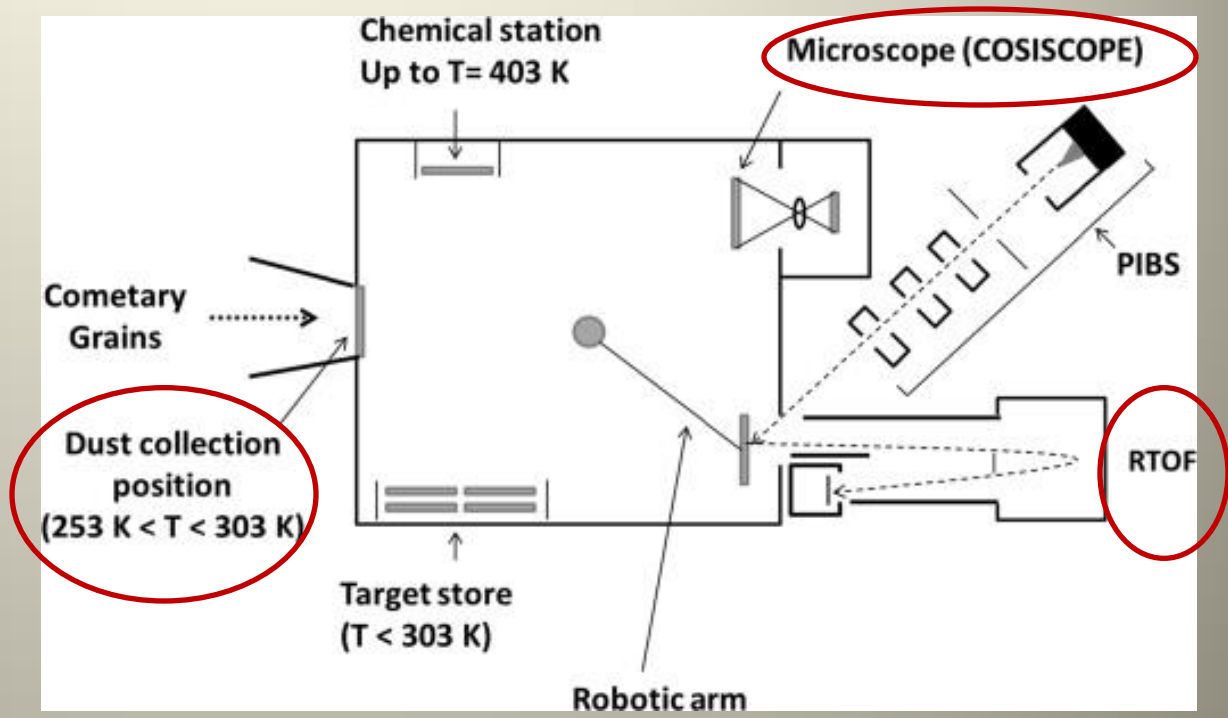

MIDAS





COSIMA

COmetary Secondary Ion Mass Analyser



Microscope **(COSISCOPE)** in front of which exposed targets placed to detect the location of any grains

Analysis position where grains will be bombarded with the Primary Ion Beam System (PIBS) and from which secondary ions will be accelerated and focalized into the Reflectron Time Of Flight **(RTOF)** mass spectrometer.

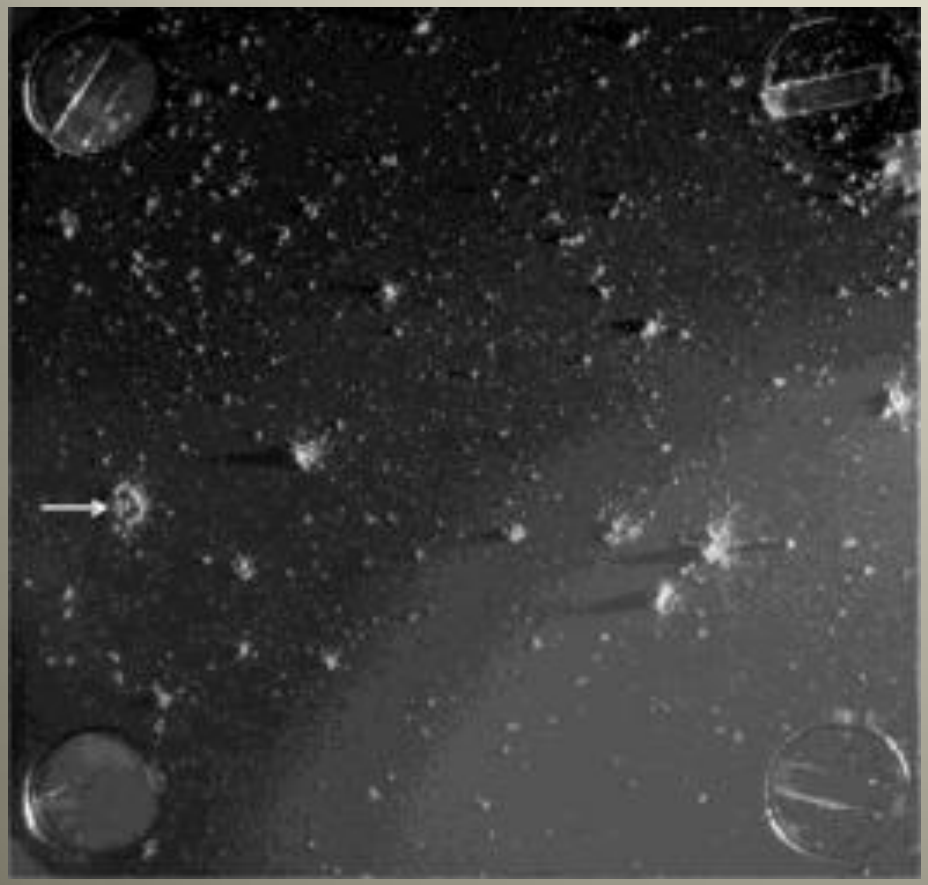
Kissel et al. (2007)

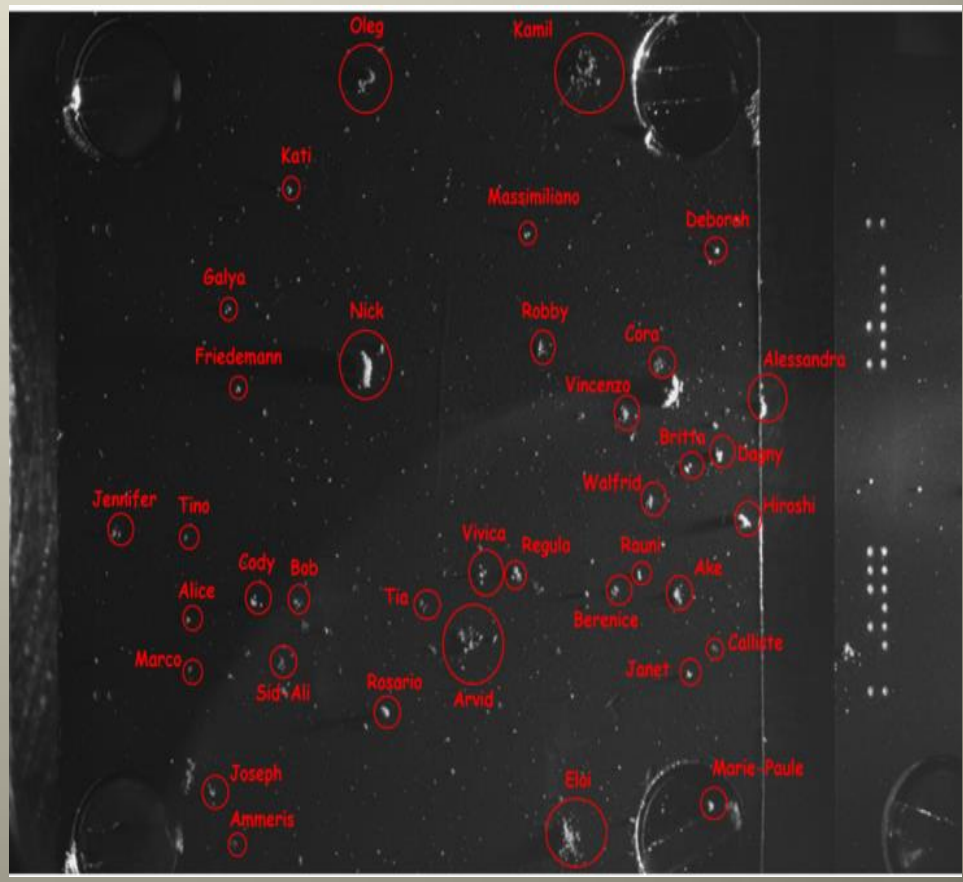
COSIMA -COSISCOPE

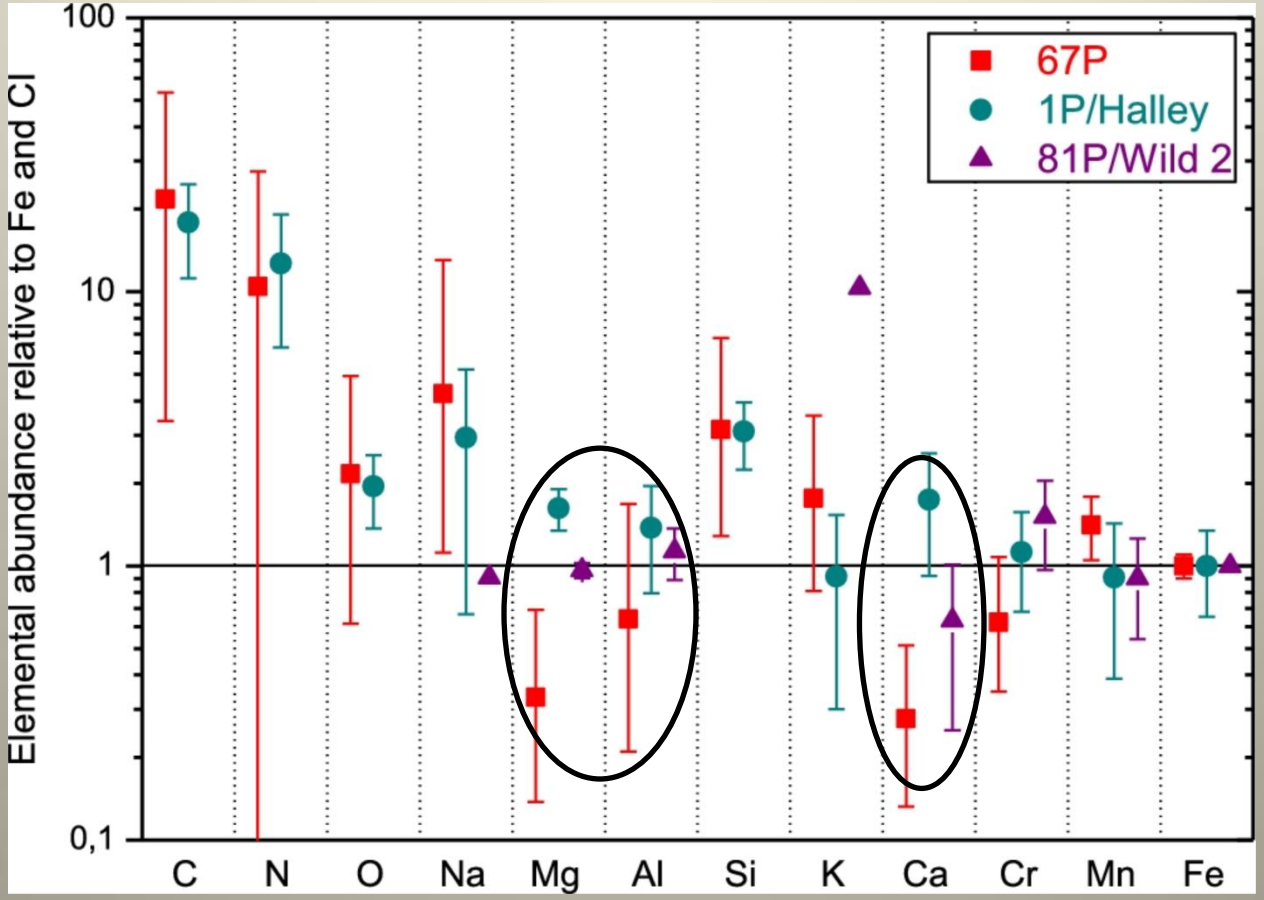
More than 10,000 cometary particles have been collected and imaged by COSIMA.

The collected particles exhibit a complex typology, dominated by clusters (shattered clusters, glued clusters and rubble piles)

The collected particles present similarities with micrometeorites and IDP's.







From: Carbon-rich dust in comet 67P/Churyumov-Gerasimenko measured by COSIMA/Rosetta

Mon Not R Astron Soc. 2017;469(Suppl_2):S712-S722. doi:10.1093/mnras/stx2640

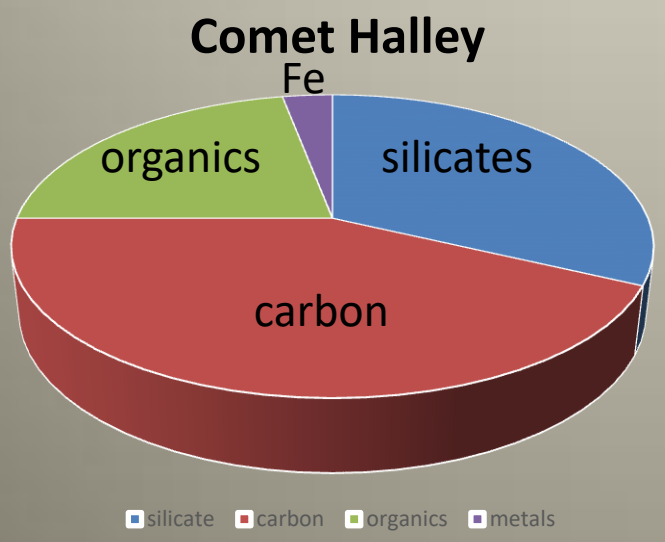
Elemental abundances in the dust of comets 67P and Halley
normalized to Fe

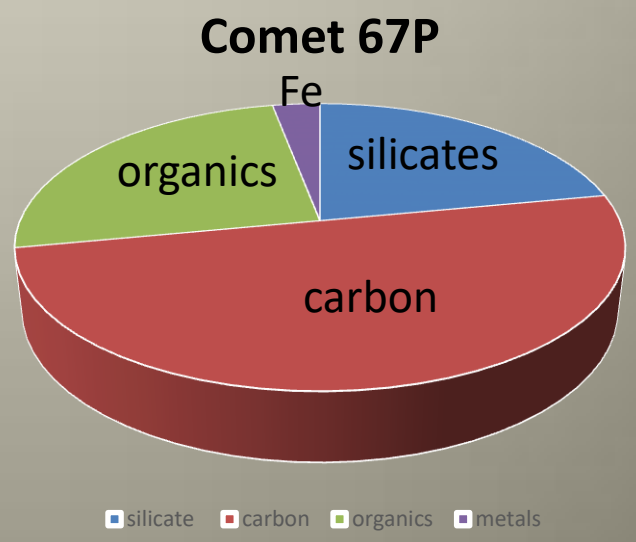
Element	Atomic weight	Abundance 67P	Abundance Halley
C	12.011	19	15.65
N	14.007	0.66	0.81
O	15.999	19	17.1
Mg	24.305	0.4	1.92
Si	28.086	3.5	3.56
Fe	55.845	1	1

Reference for comet 67P: Bardyn et al., MNRAS, 469, S712–S722, 2017
Reference for comet Halley: Mann et al. Journal of Quantitative Spectroscopy & Radiative Transfer 89 (2004) 291–301

Ratio of the constituents in the cometary dust by volume

	Comet Halley	Comet 67P
Silicates	0.318	0.221
Organics	0.219	0.252
Carbon	0.438	0.504
Fe	0.026	0.023

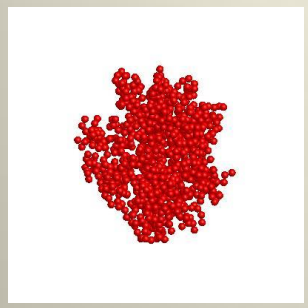




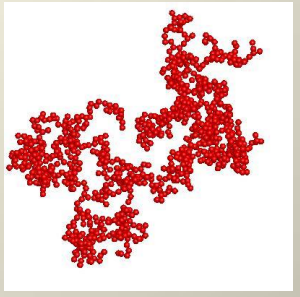
Refractive indices and volume fractions for 67P

Material name	Wavelength		Volume fraction in 67P	Volume fraction in Halley	Ref.
	450 nm	650 nm			
Amorphous carbon	1.95+0.786i	2.14+0.805i	0.5042	0.4379	Rouleau and Martin, 1991
Organic refractory	1.69+0.150i	1.71+0.149i	0.2521	0.2189	Li and Greenberg, 1997
Astronomical silicate	1.69+0.0299i	1.68+0.0302i	0.2208	0.3176	Laor and Draine, 1993
Amorphous olivine (enstatite)	1.85+0.004i	1.825+0.0023i	0.2208	0.3176	Scott and Duley, 1996
Iron	2.59+2.77i	2.90+3.02i	0.0228	0.0256	Johnson and Christy, 1974
Comet 67P (astron. silicate)	1.901+0.526i	2.015+0.532i			
Comet 67P (amorph. olivine)	1.942+0.5186i	2.051+0.5233i			
Comet Halley	1.88+0.47i	1.98+0.48i			Kimura et al. 2003

Parameters of modeling



BPCA (Ballistic Particle-Cluster Aggregate)



BCCA (Ballistic Custer Cluster Aggregate)

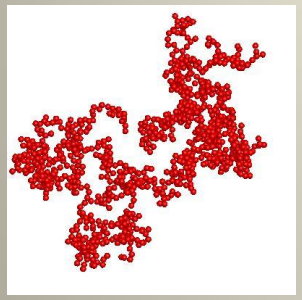
The radius of monomers: **a_m=0.1 μm**
The number of monomers: **N=1024**
The refractive index
for the dust Halley
1.88+0.47i at 0.45 μm
1.98+0.48i at 0.65 μm
for 67P dust
1.942+0.5186i at 0.45 μm
2.051+0.5233i at 0.65 μm

Mackowski's T-matrix code for parallel computing MSTM3
http://eng.auburn.edu/users/dmckwski/scatcodes/

Computations were performed using NASA HEC supercomputer cluster Pleiades

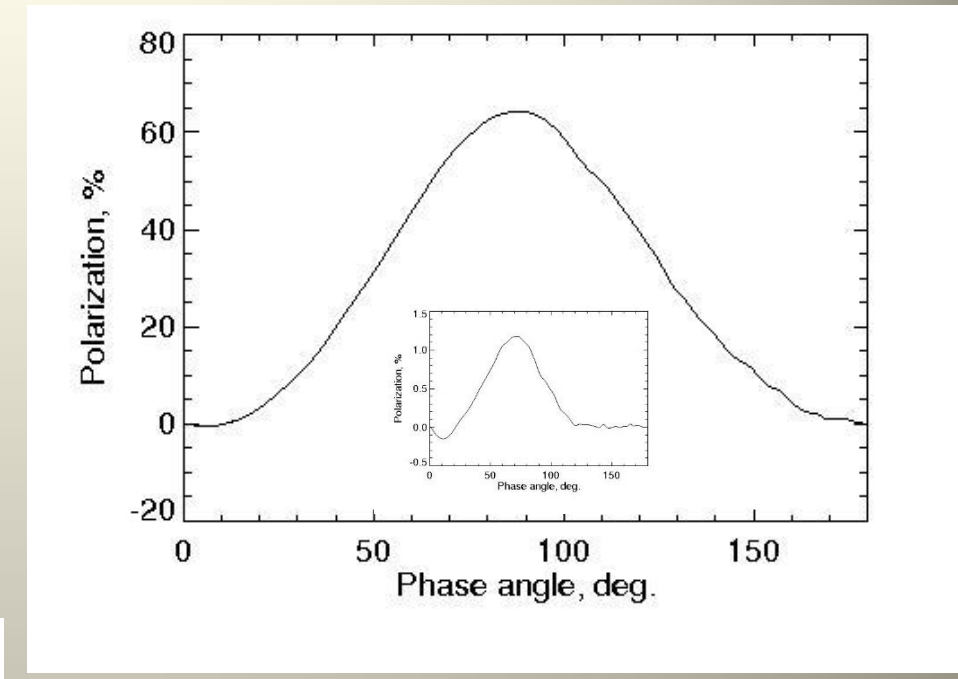
BCCA aggregate: 1P/Halley and 67P refractive indexes

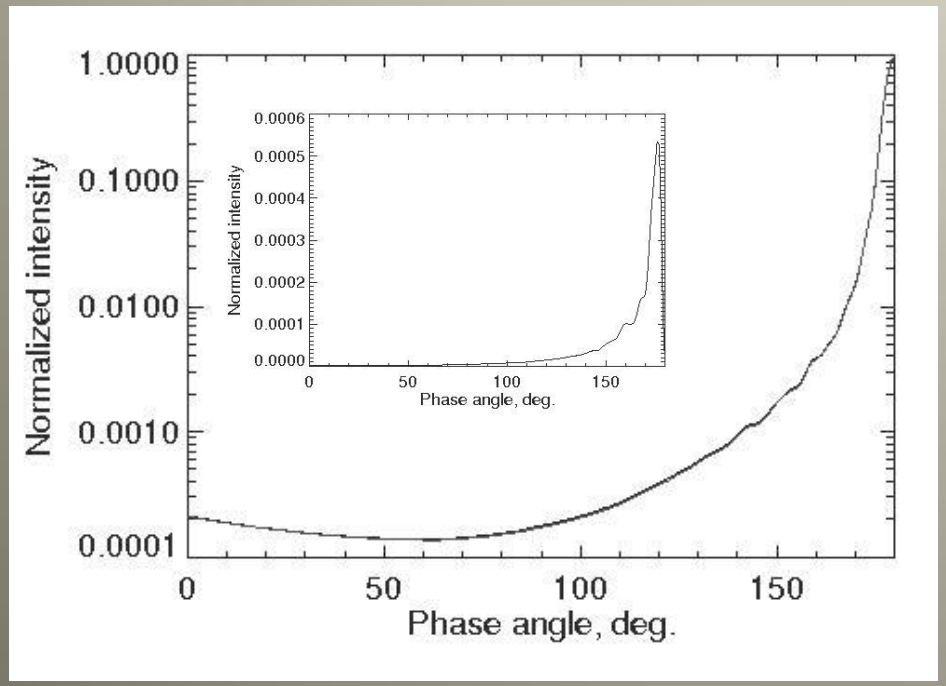
Red filter, albedo 3.08% (67P), 3.12%(1P)

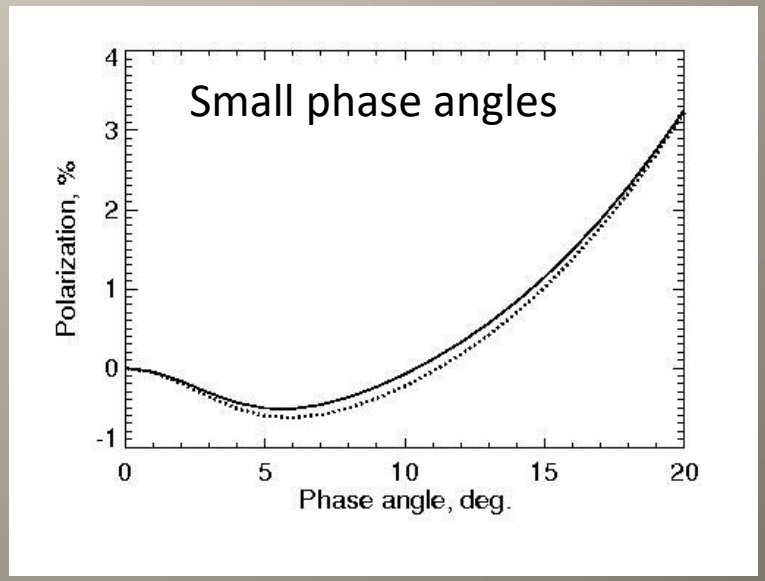


Solid line – 67P
Dotted line – Halley dust

Inserts show the difference between 67P and Halley dust

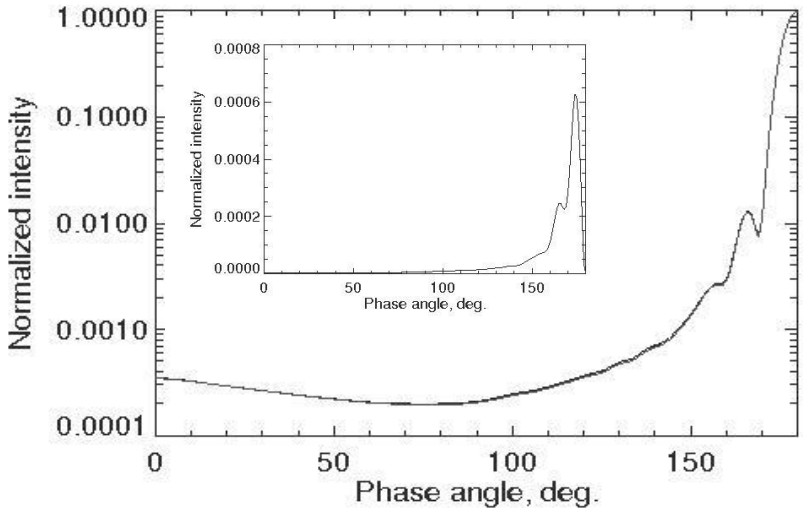




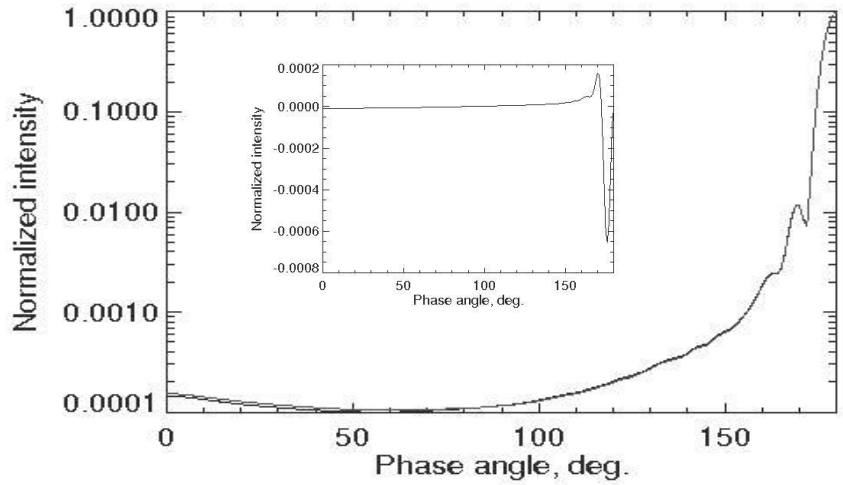


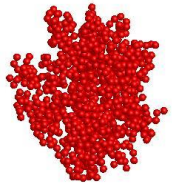
BPCA aggregate: 1P/Halley and 67P refractive indexes

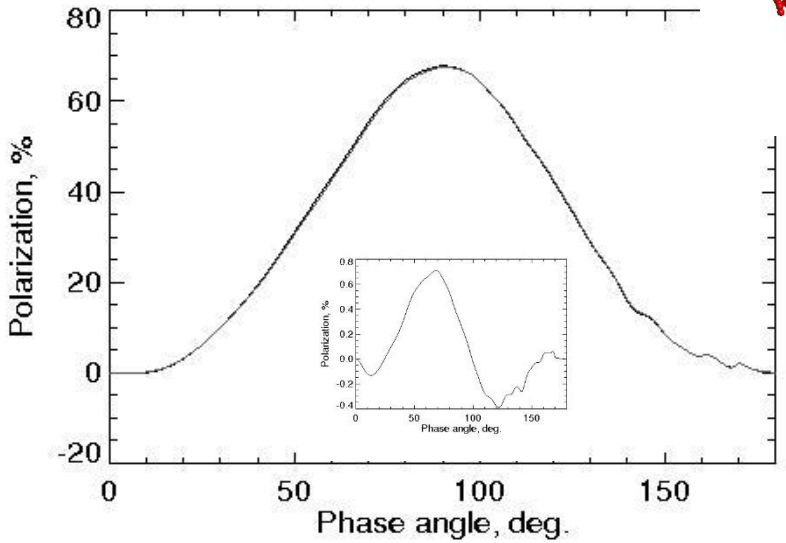
Red filter, albedo 6.53%(67P); 6.61%(1P)

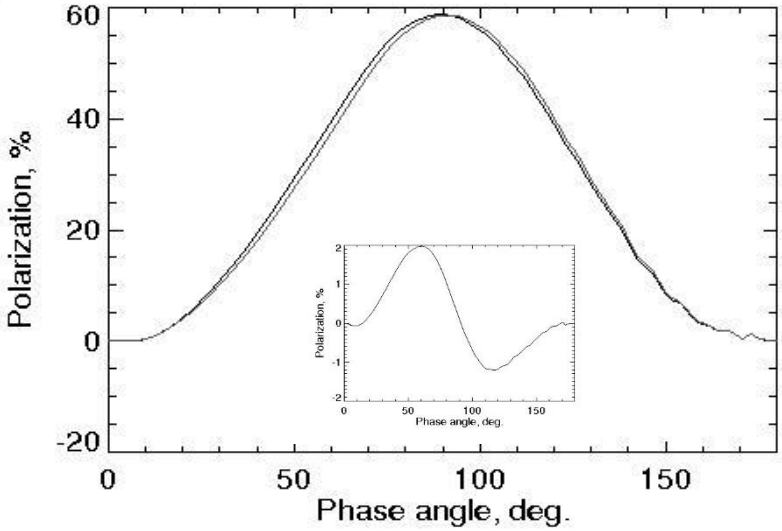


Blue filter, **albedo 4.69%(67P), 4.89%(1P)**







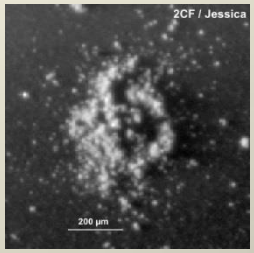


COSIMA-COSISCOPE, particle types

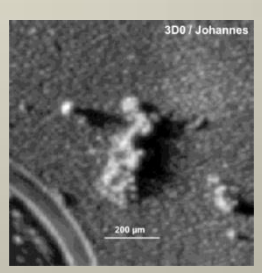
http://blogs.esa.int/rosetta/2016/03/02/profiling-cosimas-dust-grain-family/

Clustered particles exhibit well-defined sub-components, and can be further sub-divided into three sub-classes: **shattered, glued and rubble piles**

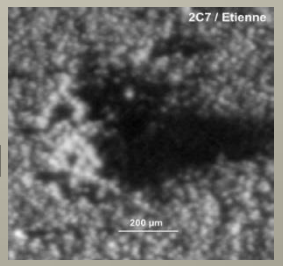
Shattered clusters form a close group with no well-defined principal component.



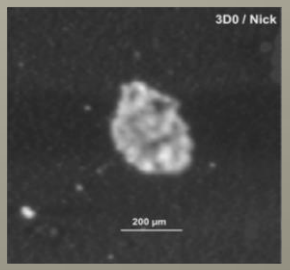
Glued clusters: particles with sub-components which are linked together by a fine-grained matrix.



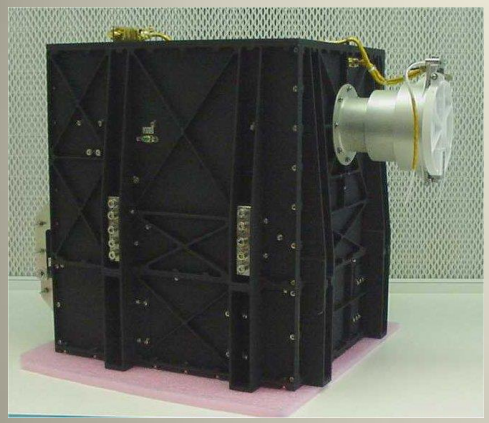
Rubble piles typically have a flattened conical pile appearance with small outliers indicating that, contrary to glued clusters, the constituents are not strongly connected to a matrix.

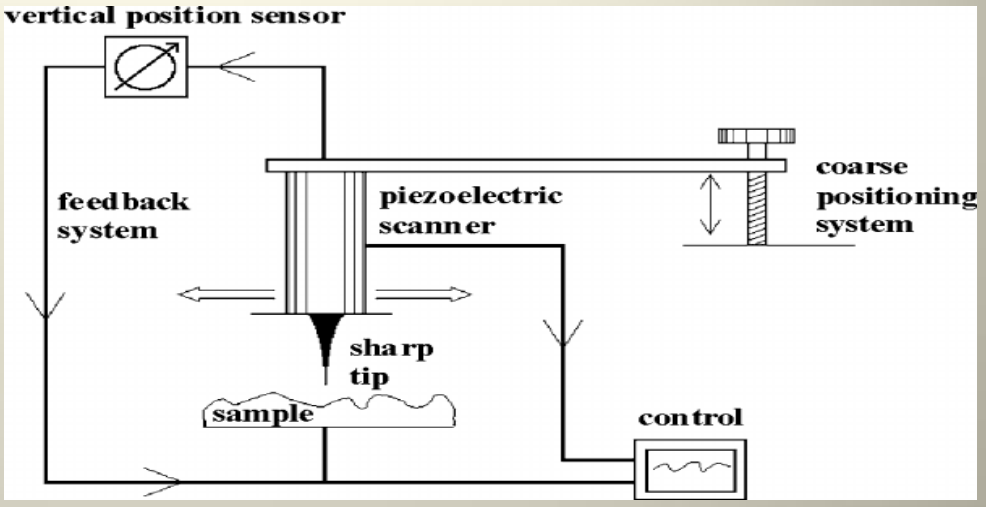


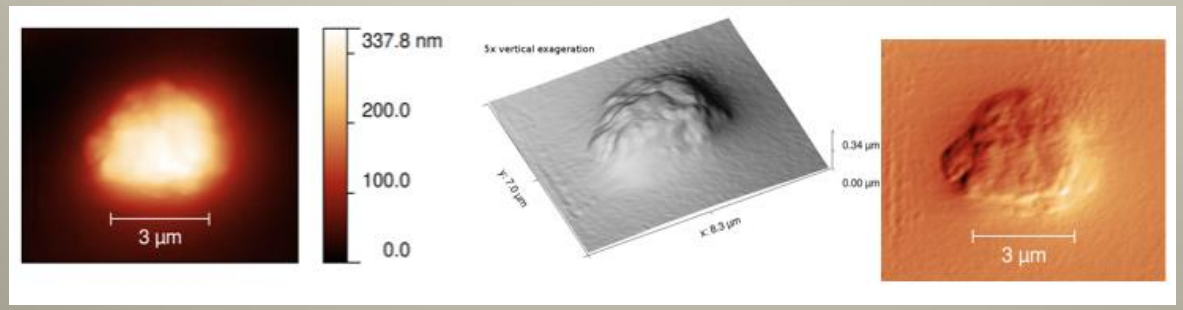
Compact particles have well-defined boundaries, without any related smaller ‘satellite’ particles (break into pieces under ion beam)

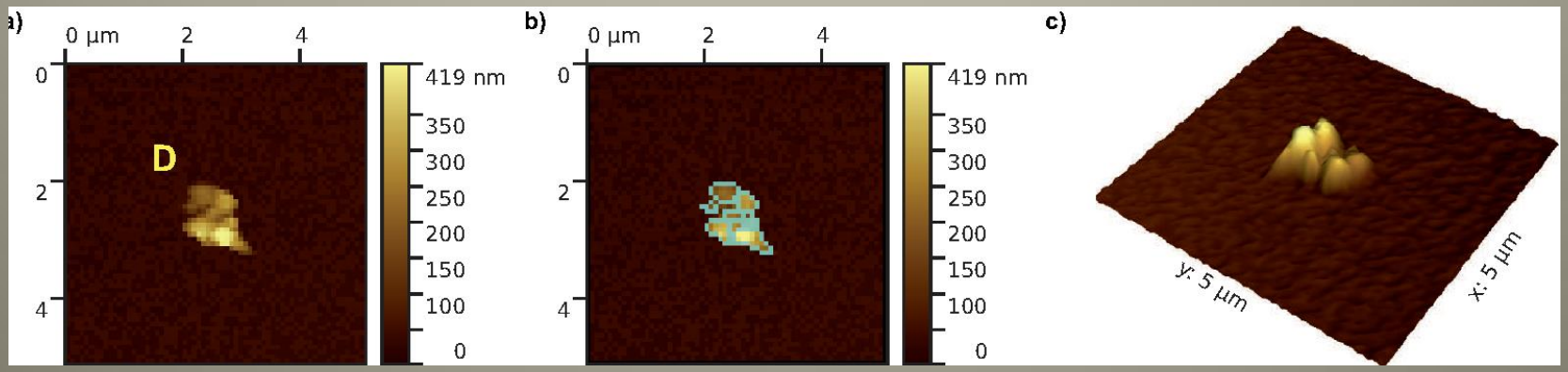


MIDAS: Micro-Imaging Dust Analysis System

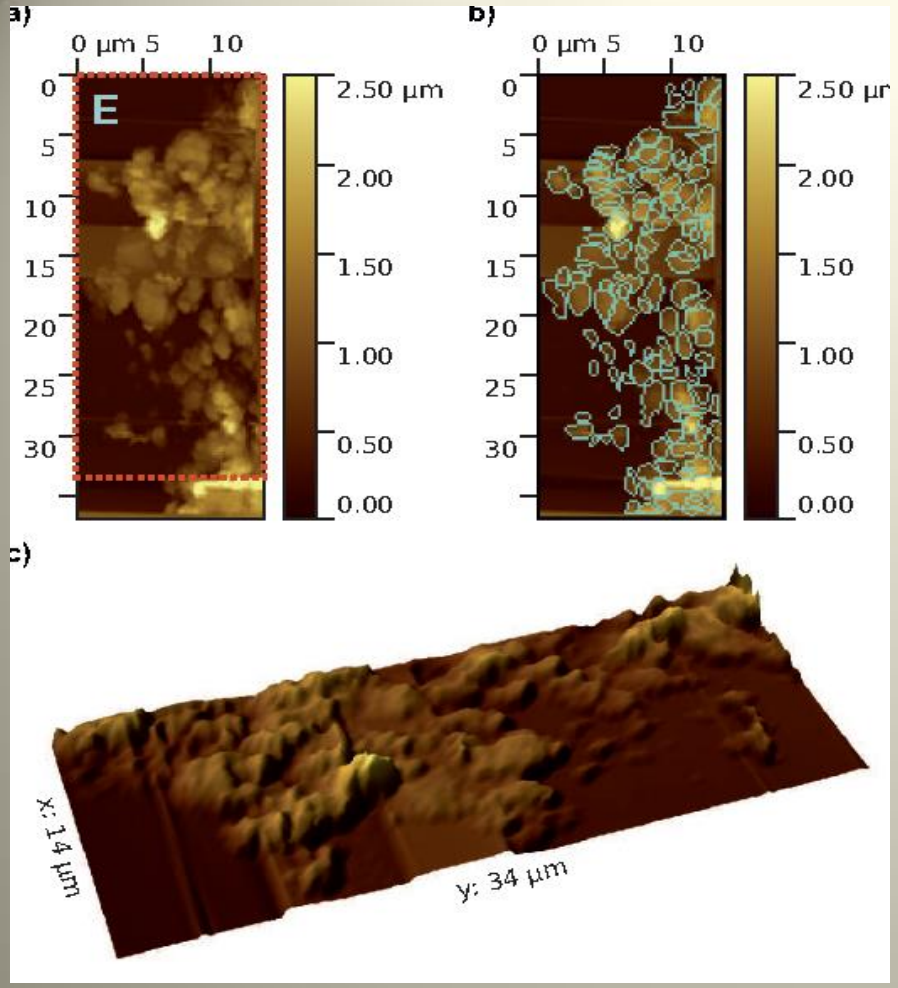




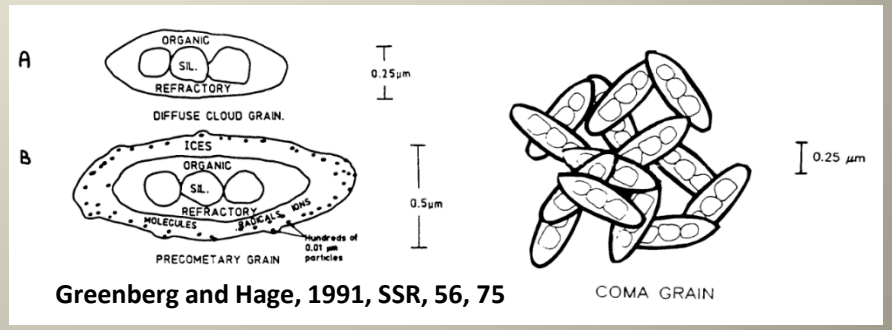




MIDAS results



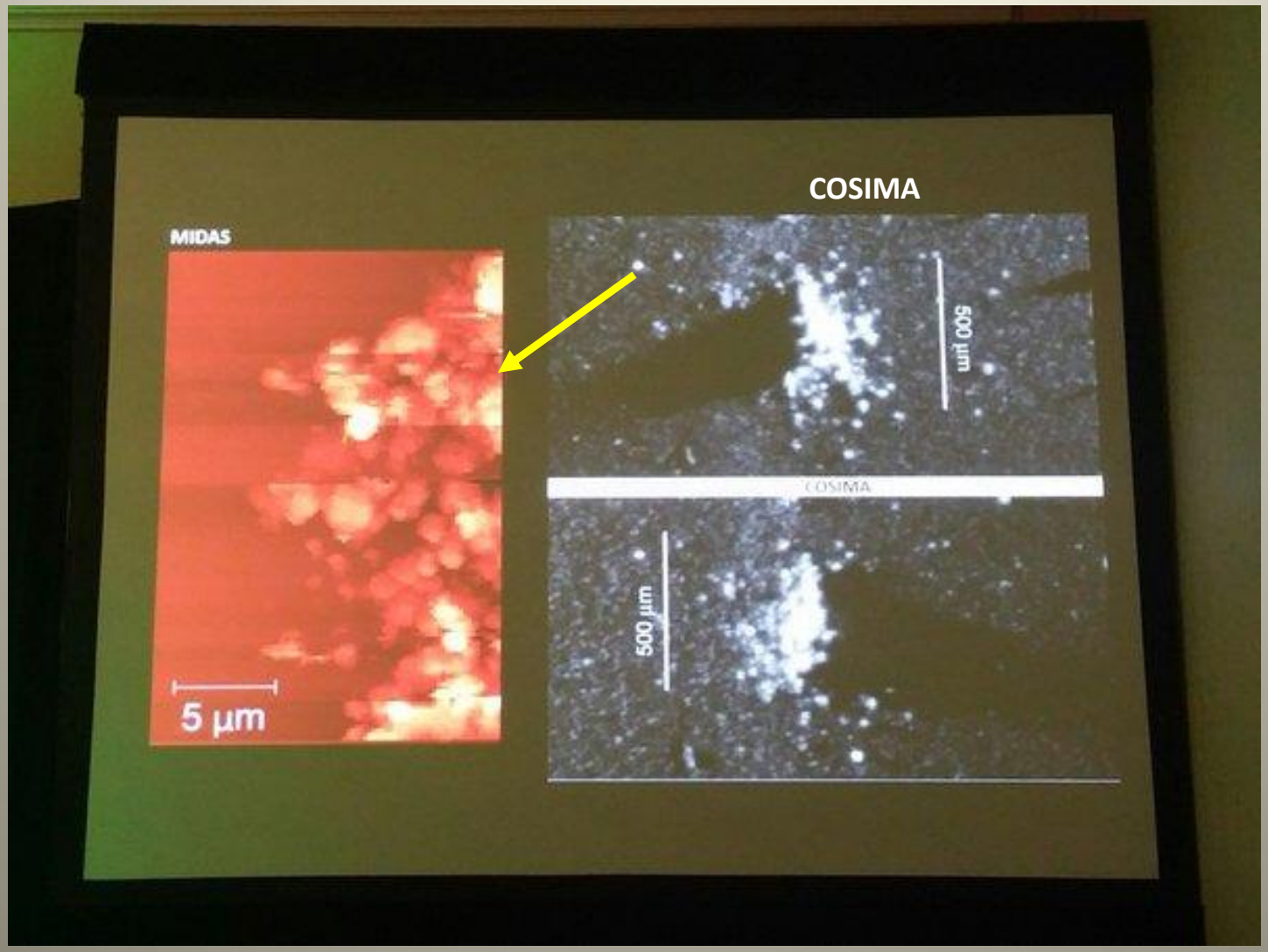
Bentley et al. Nature, 31,8, 2016
Mannel et al. MNRAS 462, S304-S311

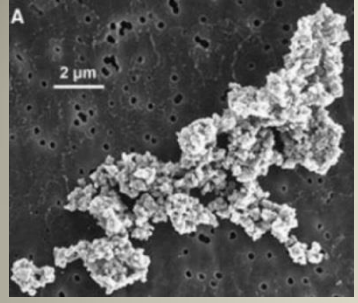


Greenberg and Hage, 1991, SSR, 56, 75

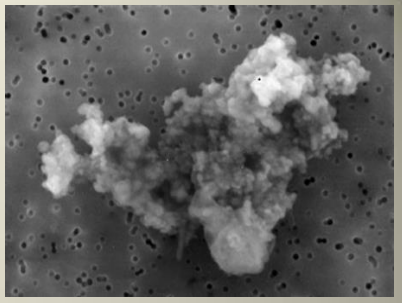
	type	diameter	height	elongation
grain 1	dust grain	$0.26^{+0.05}_{-0.12}$	0.17	$1.89^{+0.19}_{-0.36}$
grain 2	dust grain	$0.48^{+0.03}_{-0.16}$	0.22	$2.52^{+0.20}_{-0.47}$
grain 3	dust grain	$0.41^{+0.03}_{-0.14}$	0.31	$1.62^{+0.11}_{-0.27}$
grain 4	dust grain	$0.33^{+0.04}_{-0.13}$	0.25	$1.74^{+2.51}_{-0.71}$
grain 5	dust grain	$0.46^{+0.03}_{-0.17}$	0.37	$1.53^{+0.09}_{-0.28}$
grain 6	dust grain	$0.54^{+0.02}_{-0.25}$	0.42	$2.00^{+5.07}_{-0.82}$
grain 7	dust grain	$0.26^{+0.05}_{-0.15}$	0.32	$2.00^{+8.03}_{-0.97}$

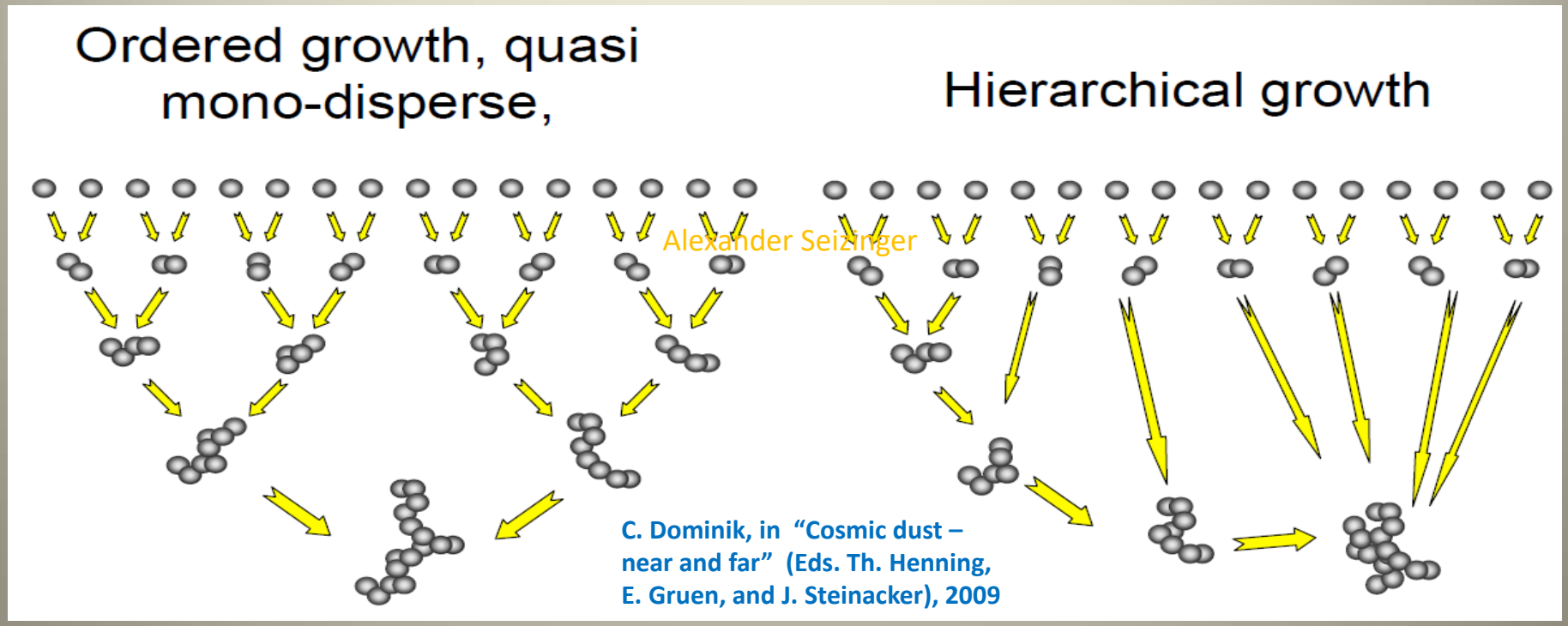
Combined model of cometary aggregates

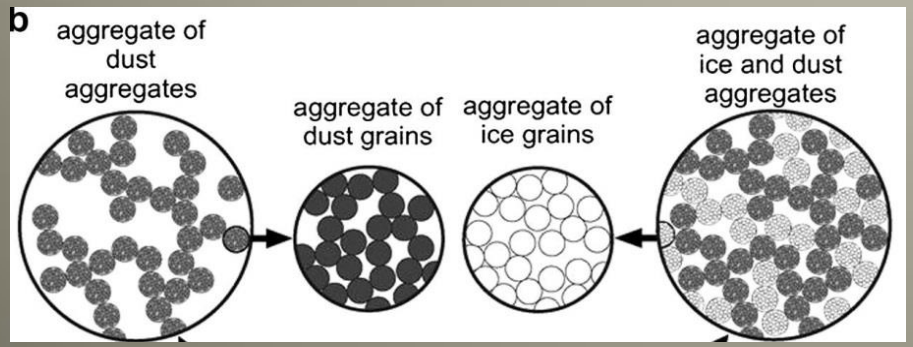




Hierarchical aggregates!



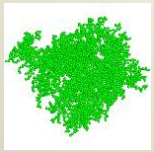


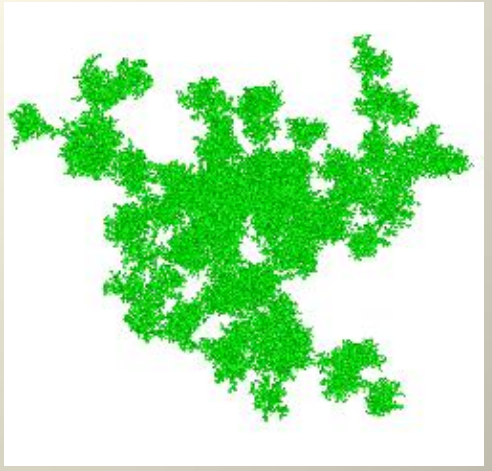


Yu. Skorvov and J. Blum
(Icarus, 221, 1-11, 2012)
modeled upper layers of a cometary nucleus which consist of hierarchical aggregates (BPCA aggregates made of BPCA aggregates).

Code for building hierarchical aggregates (Lev Nagdimunov)

Starts with building BPCAs (level 1 clusters)





Builds level 2 clusters as ballistic aggregates of level 1 clusters

Builds next level clusters as ballistic aggregates of the clusters of the previous level

Parameters of Modeling

The radius of monomers: **a_m=0.1 μm**

The number of monomers: **N=1024**

The refractive index for the dust

1.88-*i*0.47 at λ=0.45 μm

1.98-*i*0.48 at λ=0.65 μm

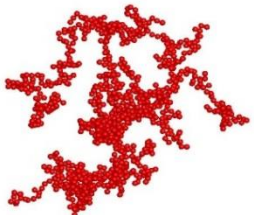
Mackowski's T-matrix code for parallel computing MSTM3

http://eng.auburn.edu/users/dmckwski/scatcodes/

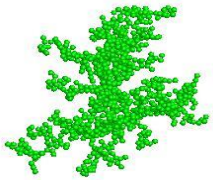
Computations were performed using NASA HEC supercomputer cluster Pleiades

Hierarchical aggregates of 1024 monomers

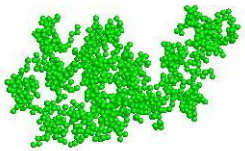
BCCA
r = 3.83μm
V_v/V = 98.6%



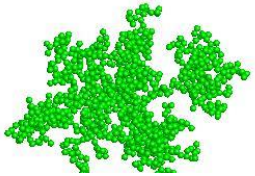
16x64
r = 2.67μm
V_v/V = 94.6%



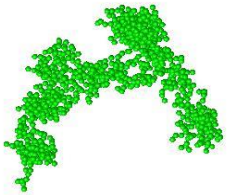
64x16
r = 3.43μm
V_v/V = 97.5%



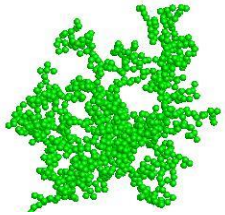
8x128
r = 2.83μm
V_v/V = 95.5%



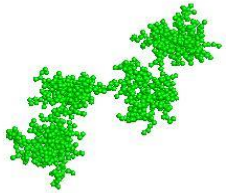
128x8
r = 3.36μm
V_v/V = 97.3%



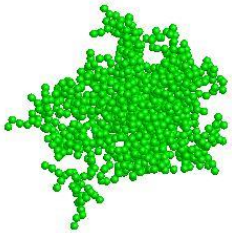
4x256
r = 2.42μm
V_v/V = 92.8%



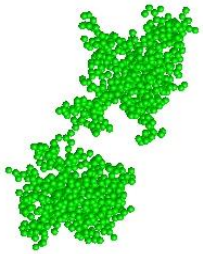
256x4
r = 3.34μm
V_v/V = 97.2%



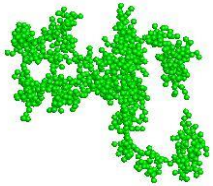
2x512
r = 2.23μm
V_v/V = 90.7%



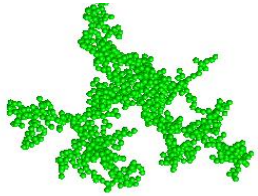
512x2
r = 2.75μm
V_v/V = 95.1%



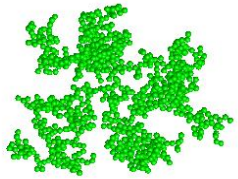
32x32
r = 3.26μm
V_v/V = 97.0%



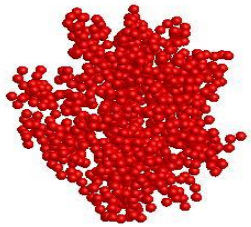
2x32x16
r = 3.35μm
V_v/V = 97.3%



2x16x32
r = 3.19μm
V_v/V = 96.8%

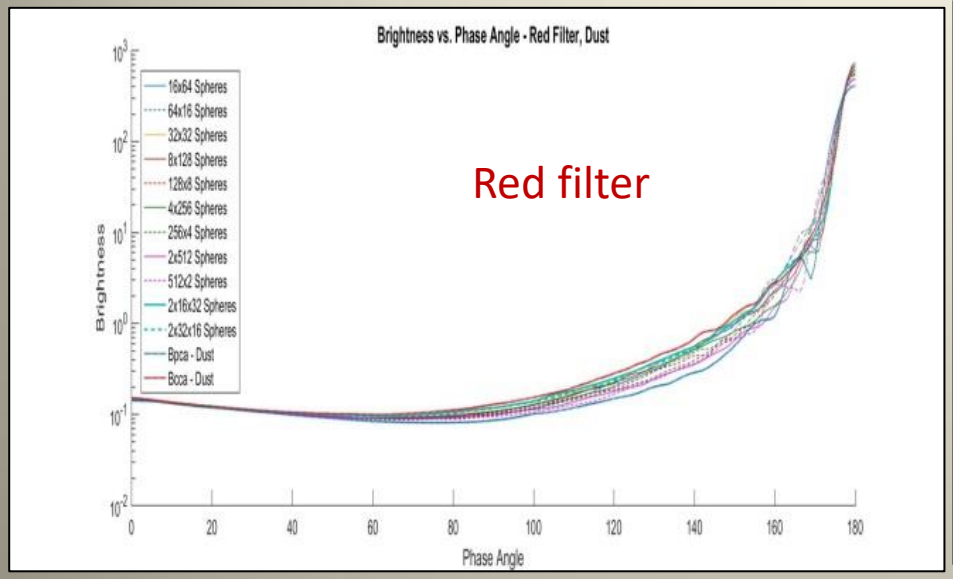


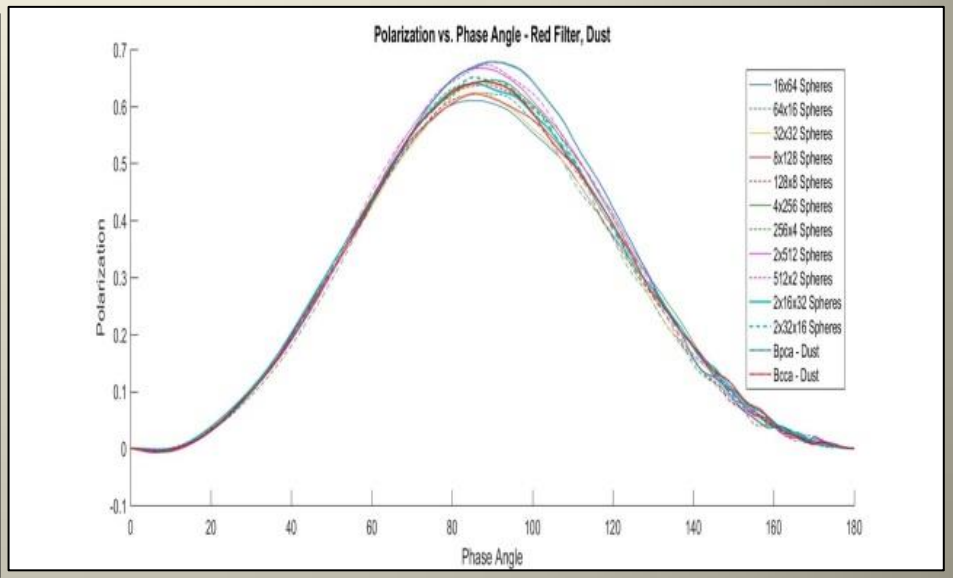
BPCA
r = 1.92μm
V_v/V = 85.5%

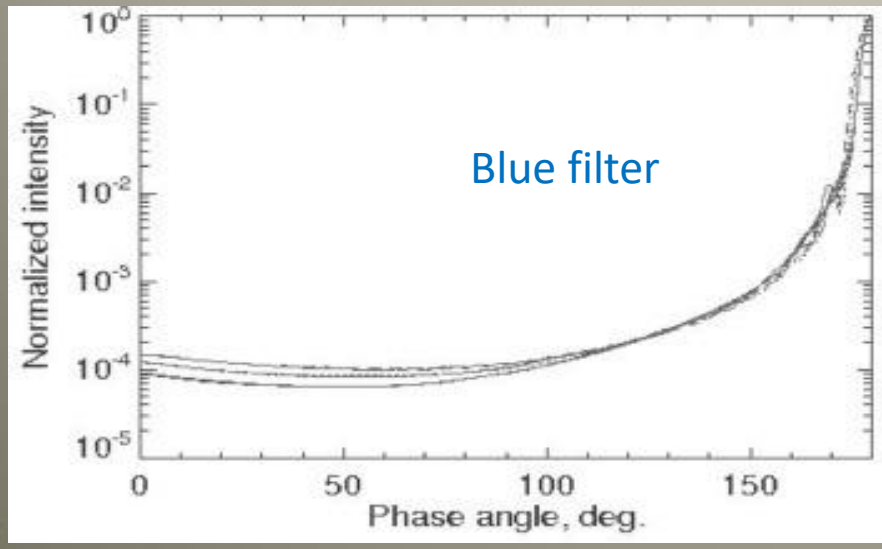


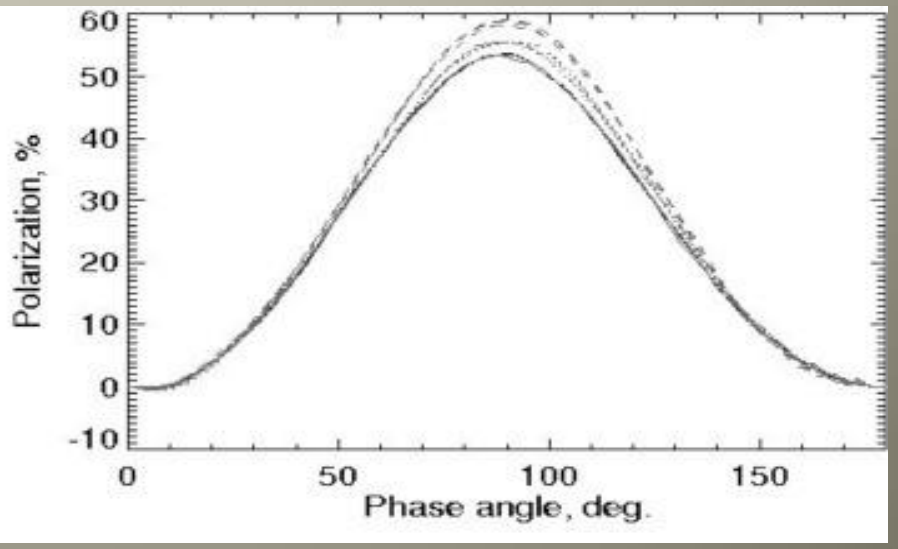
Results of the modeling

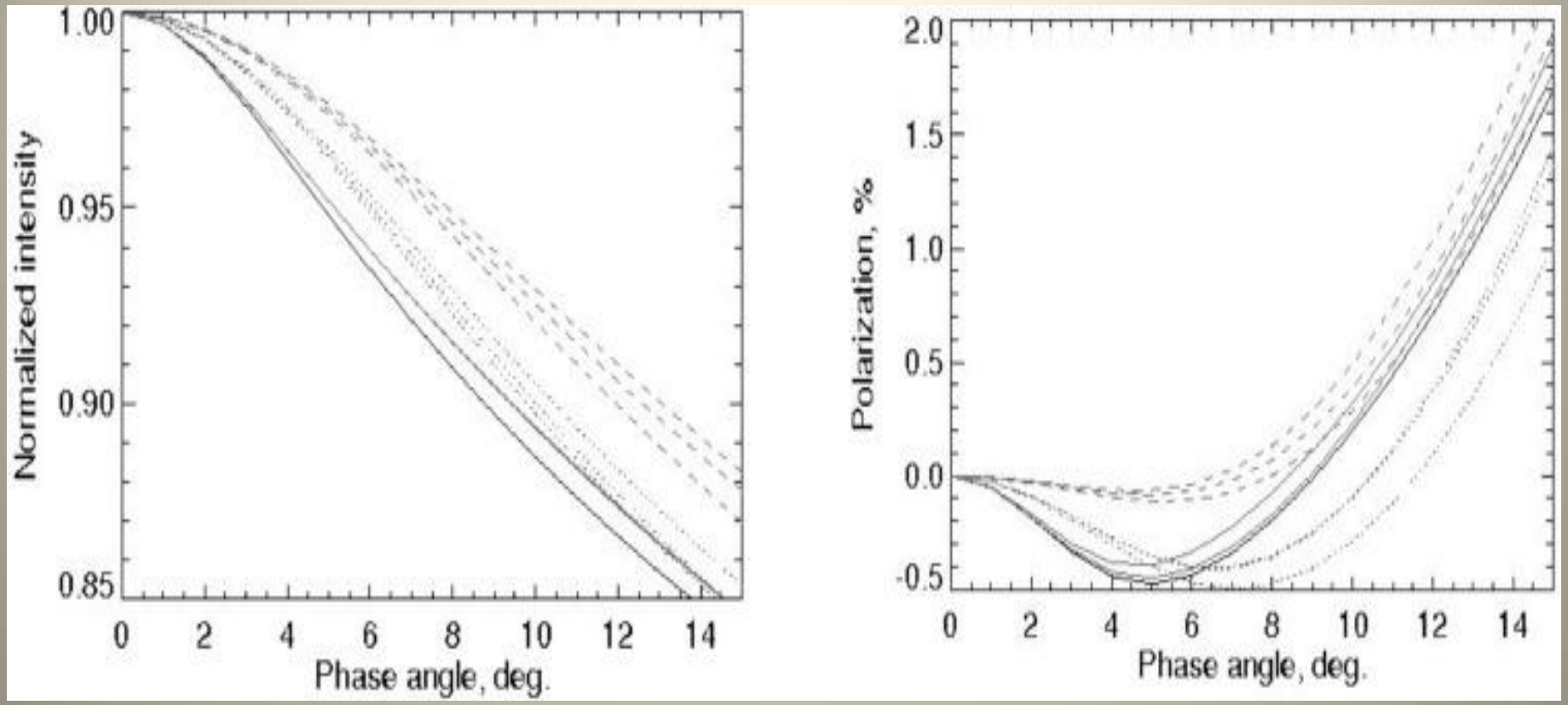
Brightness and polarization for aggregates of 1024 spheres of radius 0.1 micron, Halley dust







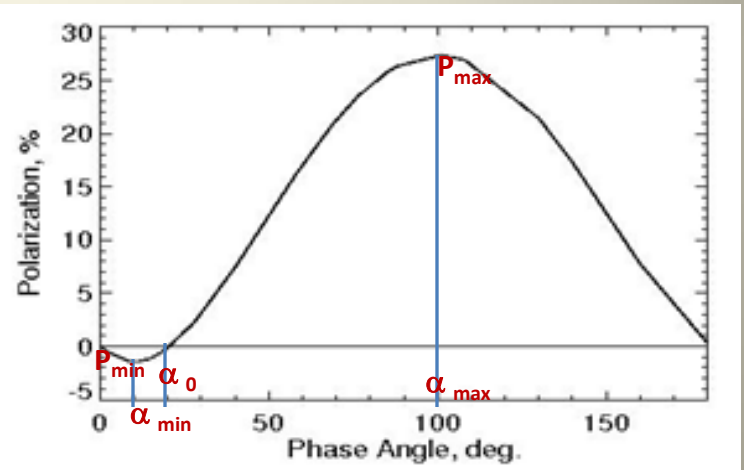




The results for three configurations of each aggregate: solid line is for 2 × 16 × 32 aggregate, dotted line is for 2 × 512 aggregate, and dashed line is for BPCA. Blur filter.

Halley dust, red filter

P_{min}	-0.19 - -0.88
α_{min}	6 - 8
α_0	10 - 13
P_{max}	61.0 - 67.3
α_{max}	85 – 91
Albedo	0.01 - 0.038
Pol. Color	6.3 - 11.3
Color	0.003 - 0.01



Hierarchical structure of aggregates noticeably affects their light-scattering properties

Conclusions

- Based on the COSIMA measurements, composition of the dust in 67P characterized by a larger amount of carbonaceous materials and smaller amount of silicates than in comet Halley. Besides, silicates in 67P are not Mg-reach ones.

An updated refractive index for two most popular cometary continuum filters in the visible is not affecting noticeably the modeling results of computations of the intensity and polarization.

- COSIMA and MIDAS results show that the dust particles in 67P are hierarchical aggregates with 100 micron particles consist of 10 micron grains, which, in turn, consist of submicron grains.

The hierarchical structure of the particles affects the computed intensity and polarization, although not dramatically.

- Future updates of the models required based on the Rosetta findings:

Larger particles! - larger number of constituent grains.

The shape of the monomers is spheroidal with the aspect ratio about ~2.87

The sizes of the based monomers range from 0.5 to 2.5 micron (large dimension) and 0.15 – 0.87 micron (small dimension).