Contribution of super-micron dust particles into light scattering by comets or Why the Rosetta samples are irrelevant to analysis of the ground-based observations

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Rosetta (Orbiter) Payload Factsheet

ALICE	Ultraviolet Imaging Spectrometer
CONSERT	Comet Nucleus Sounding
COSIMA	Cometary Secondary Ion Mass Analyser
GIADA	Grain Impact Analyser and Dust Accumulator
MIDAS	Micro-Imaging Analysis System
MIRO	Microwave Instrument for the Rosetta Orbiter
OSIRIS	Rosetta Orbiter Imaging System
ROSINA	Rosetta Orbiter Spectrometer for Ion and Neutral Analysis
RPC	Rosetta Plasma Consortium
RSI	Radio Science Investigation
VIRTIS	Visible and Infrared Mapping Spectrometer

https://www.esa.int/Our_Activities/Space_Science/Rosetta/Rosetta_factsheet

The Rosetta Facilities Applicable to Dust Particles

Direct sampling

1. COSIMA:

Analysis of mass spectra of particles with sizes >14 μm [1].

2. GIADA:

Sensitive to particle momentum being $>6.5\times10^{-10}$ kg m/s [2].
At v=10 m/s and ρ=1 g/cm^3, particle size should be >50 μm.

3. MIDAS:

Images of few micron-sized particles were obtained [3].

Remote sensing

4. OSIRIS:

Measurements of color [4] and phase function [5] in distant particles, whose size is unknown; presumably, it is >10 μm.

[1] Langevin et al. 2016: Icarus, 271, 76; [2] Fulle et al. 2015: ApJ, 802, L12; [3] Bentley et al. 2016: Nature, 537, 73; [4] Cremonese et al. 2016: A&A, 588, A59; [5] Bertini et al. 2017: MNRAS, 469, 404

Rosetta vs. Other Space Missions to Comets

Rosetta was mainly sensitive to particles larger than 10 µm. Although such super-micron particles may play an important role for understanding evolution of the Solar System, they are practically useless for interpretation of the ground-based observations of comets, at least in the visible and NIR because the light-scattering response is predominantly governed by submicron and micron-sized grains.*

In this sense, Rosetta did not make much progress in understanding of interrelation between light-scattering characteristics measured in the ground-based observations of comets and true microphysical properties of cometary dust particles.

* This will be demonstrated below through modeling of light scattering by dust in comets

Rosetta vs. Other Space Missions to Comets

Two the most comprehensive investigations of the micron-sized particles were conducted by VeGa-1,2 and Giotto space probes in Comet 1P/Halley and by Stardust in 81P/Wild 2.

It was figured out that cometary dust particles obey a quasi power-law size distribution r^{-n}, where the power index n tends to grow with the particle size from <u>n = 1.5–3 in submicron and micron-sized particles</u> to <u>$n \geq 3.4$ in super-micron particles</u> [1,2].

It also was found that the power index n significantly varies throughout the coma [3].

[1] Mazets et al 1986: Nature, 321, 276; [2] Price et al. 2010: M&PS, 45, 1409; [3] Mazets et al. 1987: A&A, 187, 699

Rosetta vs. Other Space Missions to Comets

Two of the most comprehensive investigations of cometary particles were conducted by VeGa-1,2 and Giotto space probes in Comet 1P/Halley and by Stardust in 81P/Wild 2.

The bulk material density in small dust particles was first constrained from the analysis of micro-craters in Al foil of the Stardust return module. It yields a wide range, from 0.3 g/cm^3 to 3 g/cm^3 [1]. This is in accordance with a previous study of interplanetary dust particles (IDPs), revealing two distinct density groups with 0.6 g/cm^3 and 1.9 g/cm^3 [2].

[1] Hörz 2006: Science, 314, 1716; [2] Flynn & Sutton 1991: LPSC, 21, 541

Modeling Light Scattering by Dust in Comets

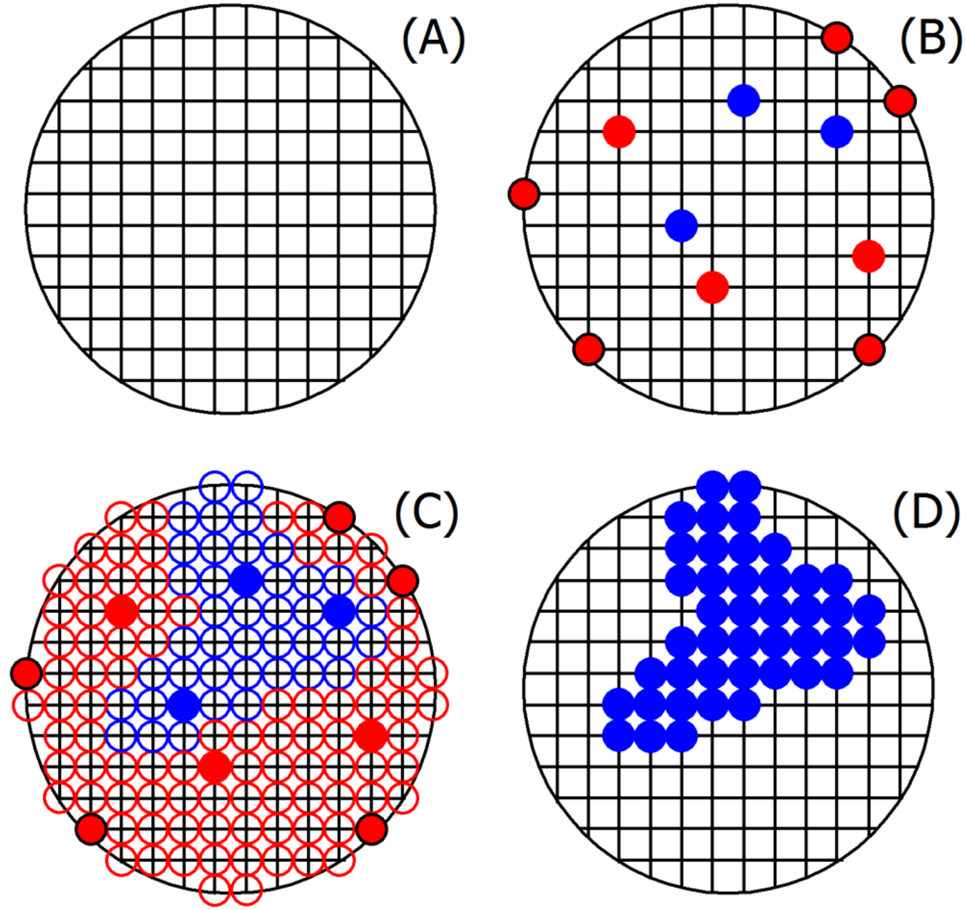
We have developed a model of dust particles that is consistent with the bulk material density and size distribution found in situ in comets. The model particles have highly irregular aggregate morphology. We label them agglomerated debris particles.

Modeling Light Scattering by Dust in Comets

Agglomerated debris particles are built up by small-volume elements, using the following algorithm.

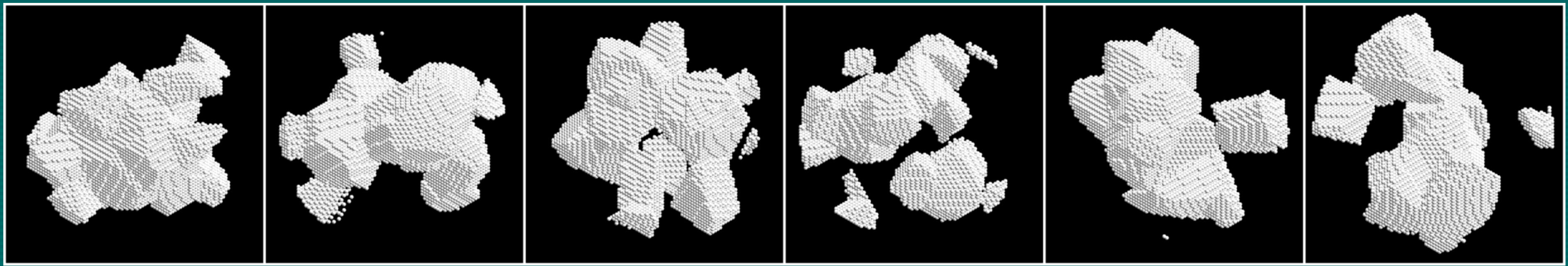
Input parameters

(1) surface seed cells
for empty space – 100
(2) depth of surface layer – 0.5%
(3) internal seed cells
for empty space – 20
(4) internal seed cells
for a material – 21

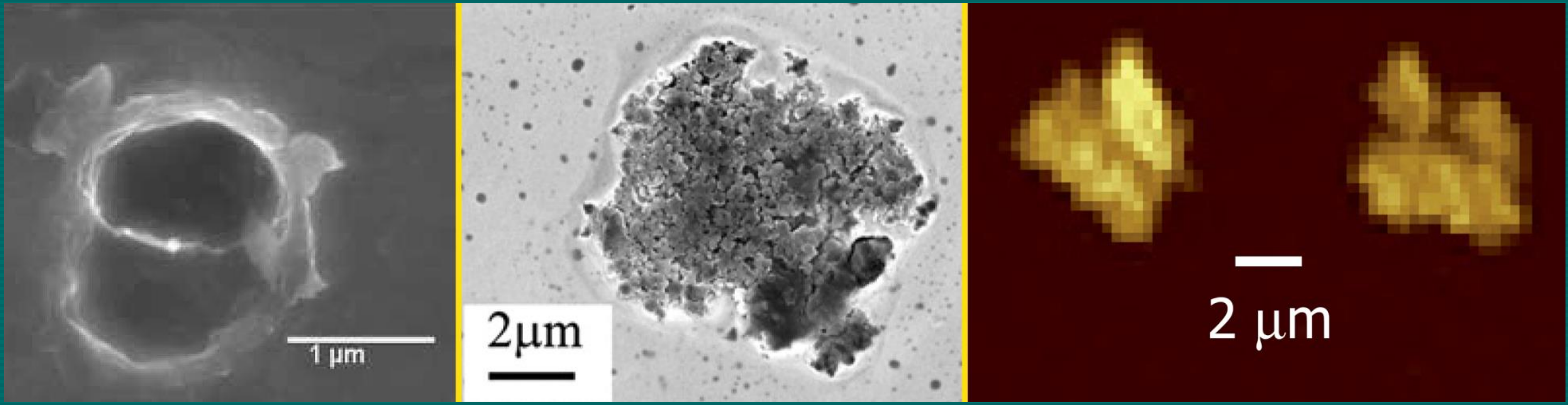


Modeling Light Scattering by Dust in Comets

Agglomerated debris particles is a realistic model of cometary dust due to highly irregular aggregate morphology.

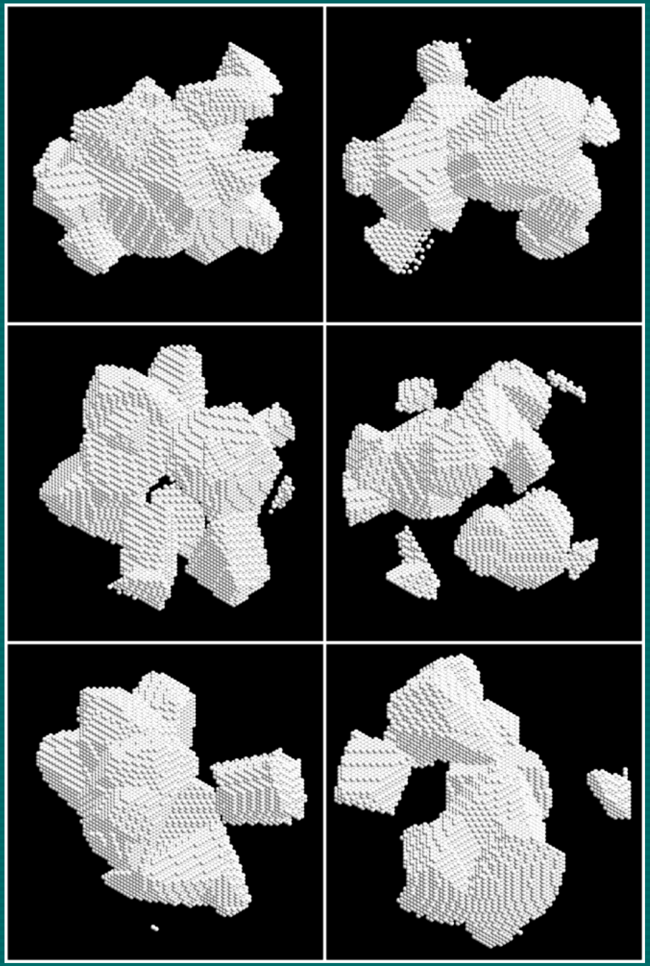


Images of micron-sized cometary dust particles.



81P/Wild 2 26P/G-S 67P/C-G

Modeling Light Scattering by Dust in Comets



Features of agglomerated debris particles

(1) Irregular and equi-dimensional shape;

(2) Material packing density = 23.6%;

(3) Bulk material density = 0.35–0.83 g/cm3;

(4) Capable of reproducing laboratory optical measurements of cosmic dust analogs (e.g., [1–4]).

[1] Zubko et al. 2013: JQSRT, 131, 175; [2] Zubko 2015: Opt. Lett., 40, 1204; [3] Zubko et al. 2016: LPSC, 47, 2111; [4] Videen et al. 2018: JQSRT, 211, 123

Modeling Light Scattering by Dust in Comets

Light scattering by agglomerated debris particles is computed with the discrete dipole approximation (DDA). We use a well-tested implementation of the DDA.

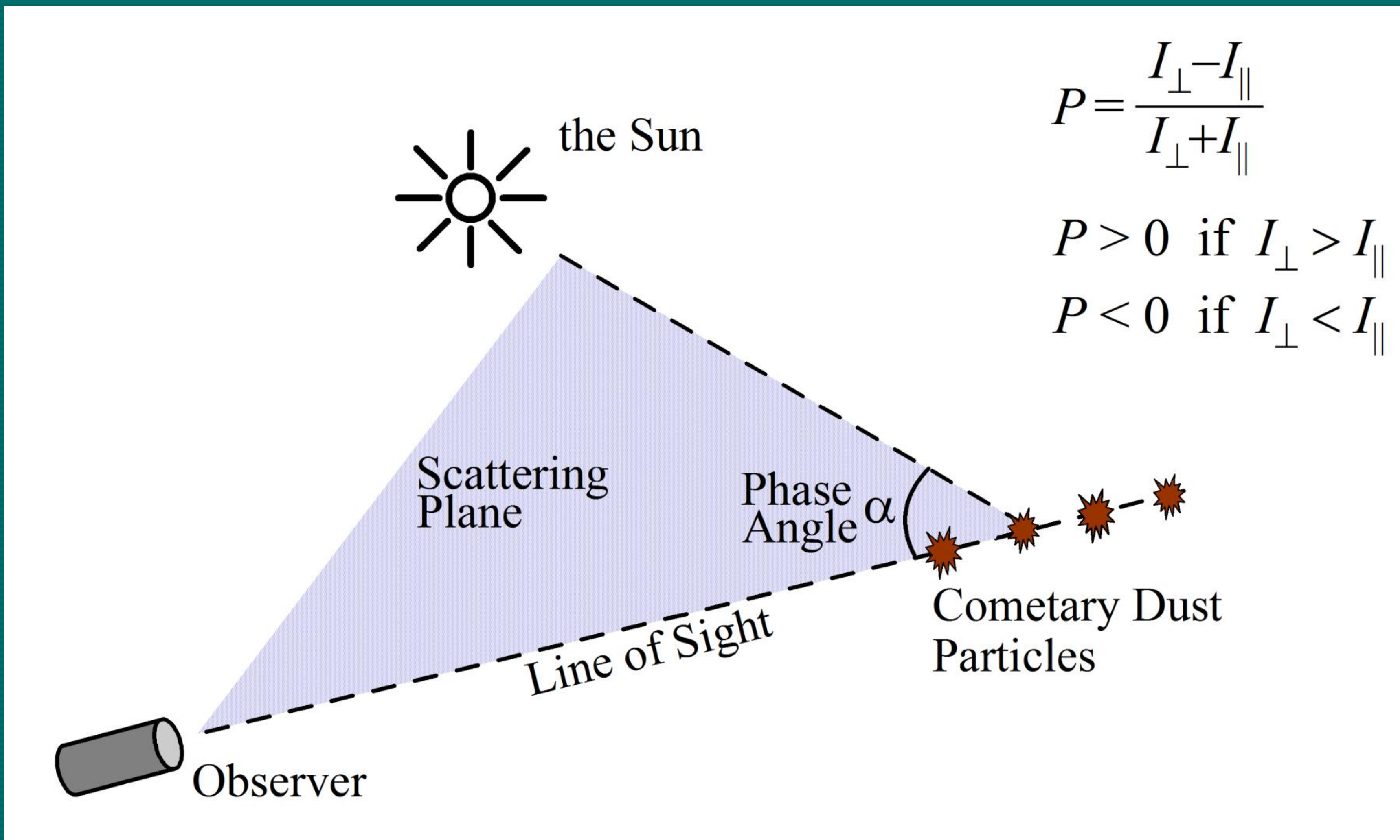
Agglomerated debris particles were studied at 50 different refractive indices m: Re(m)=1.1–2.5 and Im(m)=0-1.

Light scattering is dependent on the ratio of the particle radius r and wavelength λ of the incident light, described with the size parameter $x=2\pi r/\lambda$. Each m was studied at x=1-32 (50). In 35 cases, we compute a secondary set x=0.7-22.3(34.9) aimed for studying photo-polarimetric color.

At each pair of x and m, result is averaged over 500+ shapes.

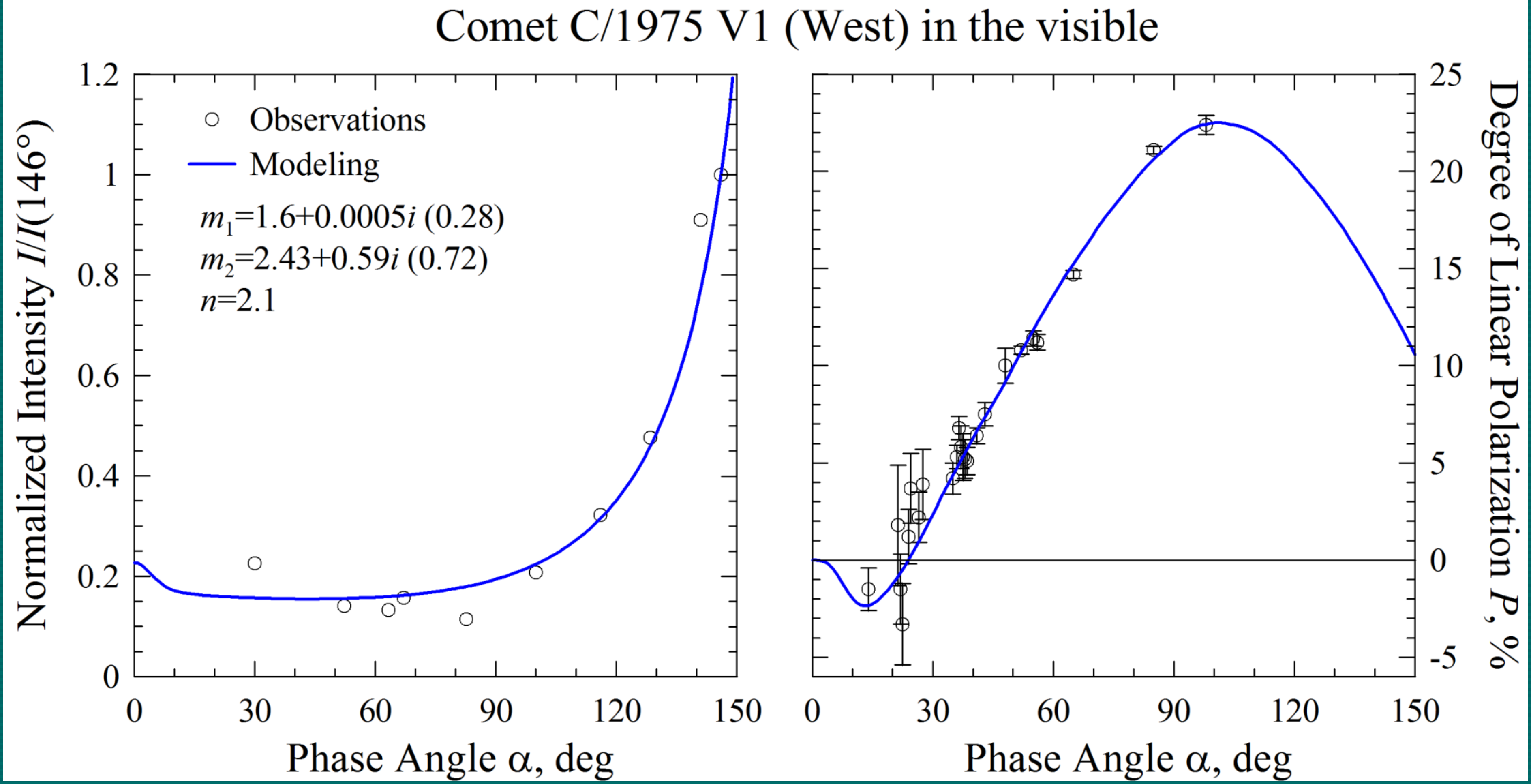
Geometry and Characteristics of Light Scattering by Comets

Two light-scattering characteristics are available in the visible and NIR: flux I and degree of linear polarization P.



How Well Agglomerated Debris Particles Fit Observations?

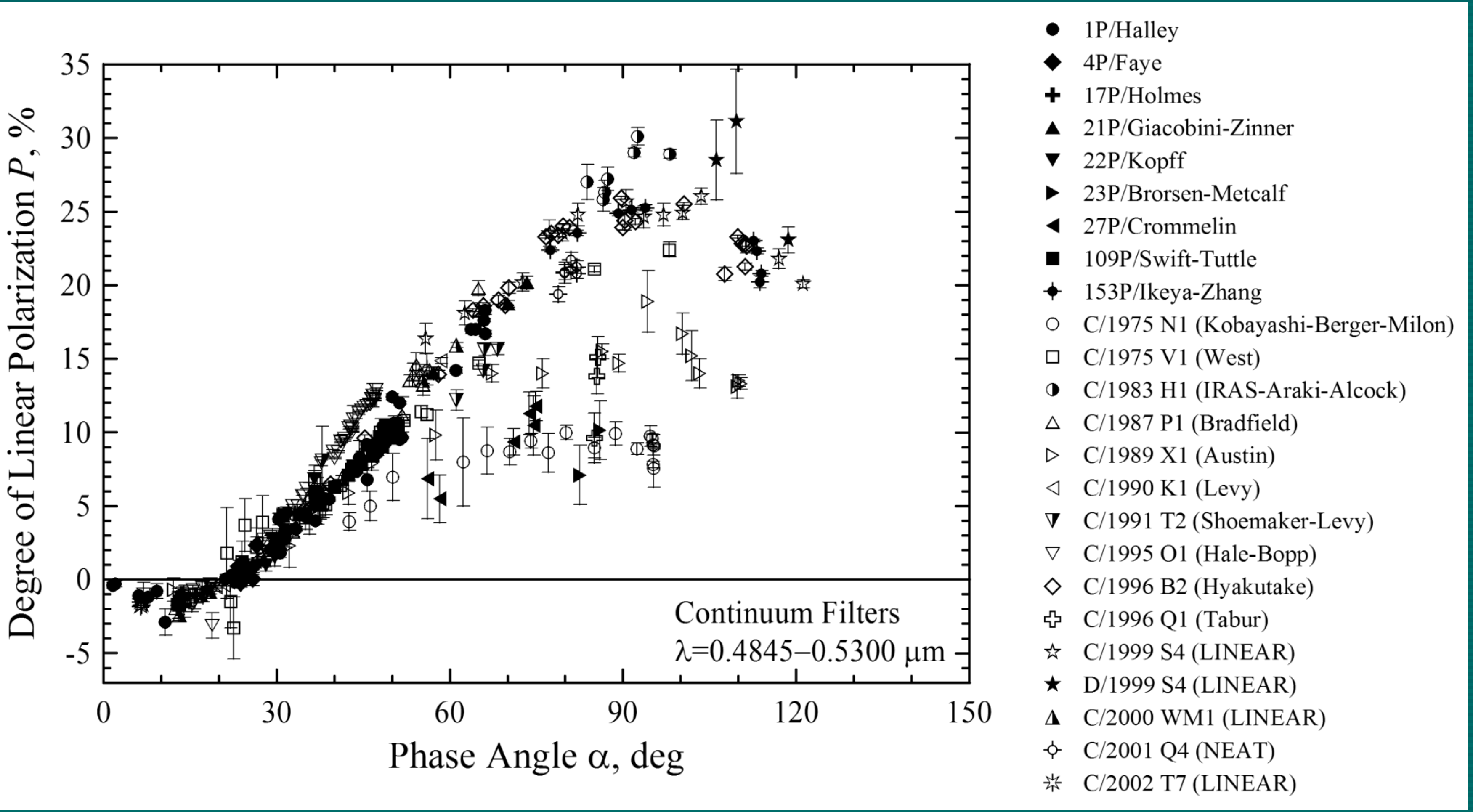
Observations can be satisfactorily reproduced with a mixture of particles having two distinct refractive indices.



More details in Zubko et al. 2014: MNRAS, 440, 2928

How Well Agglomerated Debris Particles Fit Observations?

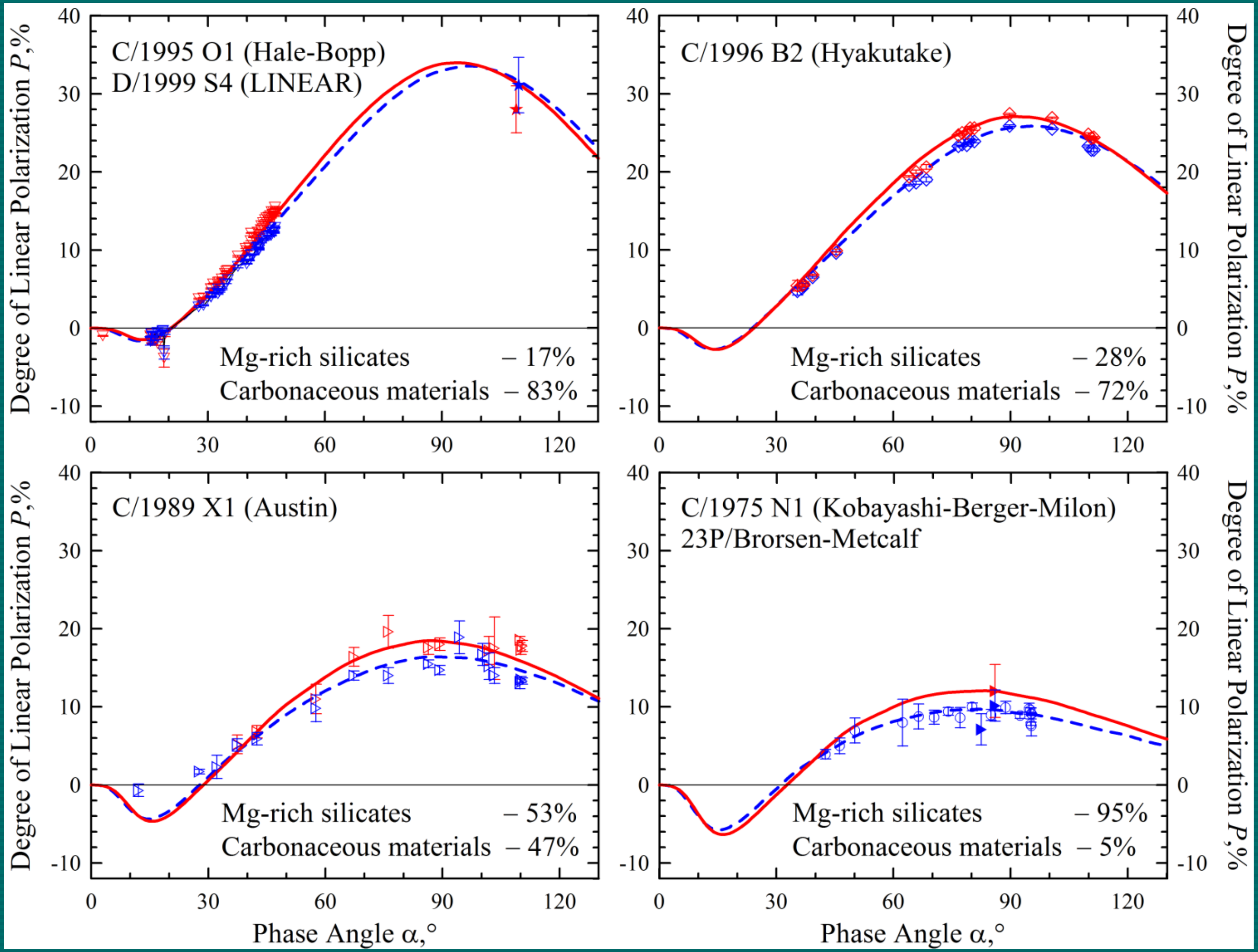
The two-component framework can explain dispersion of the positive-polarization amplitude observed in comets.



More details in Zubko et al. 2016: PSS, 123, 63

How Well Agglomerated Debris Particles Fit Observations?

The dispersion can be explained by varying a sole parameter!



More details in Zubko et al. 2016: PSS, 123, 63

How Well Agglomerated Debris Particles Fit Observations?

A few other examples of success:

1. Explanation of odd wavelength dependence of the negative polarization in Comet 17P/Holmes [1];
2. Explanation of the lack of carbonaceous materials in the Stardust samples of Comet 81P/Wild 2 [2];
3. Interpretation of the Giotto polarimetric measurements of Comets 1P/Halley and 26/Grigg-Skjellerup [3];
4. Interpretation of the HST photometric and polarimetric observations of Comet C/2012 S1 (ISON) [4];
5. Interpretation of fast and significant color variations in Comets C/2013 UQ4 (Catalina) [5].

[1] Zubko et al. 2011: JQSRT, 112, 1848; [2] Zubko et al. 2012: A&A, 544, L8; [3] Zubko et al. 2013: MNRAS, 430, 1118; [4] Zubko et al. 2015: PSS, 118, 138; [5] Ivanova et al. 2017: MNRAS, 469, 2695

Role of Super-Micron Particles in Light Scattering by Comets

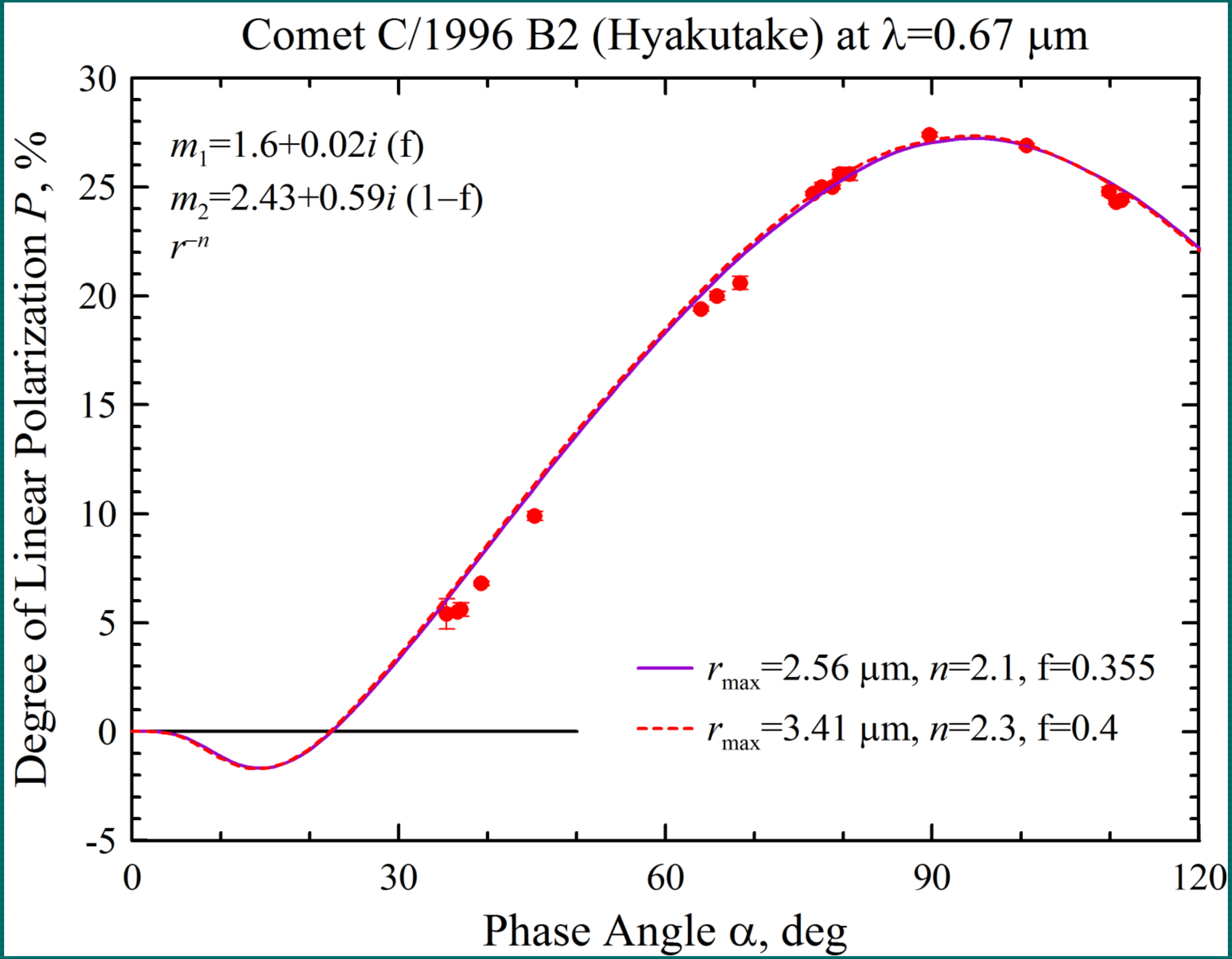
We assess the effect of large dust particles on the light-scattering response using the two-component framework and model of the agglomerated debris particles.

We model polarization in Comet C.1996 B2 (Hyakutake) measured by Kikuchi in red light at λ=0.67 μm [1]. However, we consider different upper values of the size parameter x.

[1] Kikuchi 2006: JQSRT, 100, 179

Role of Super-Micron Particles in Light Scattering by Comets

We compare modeling results obtained at x_{max}=24 and 32.



Role of Super-Micron Particles in Light Scattering by Comets

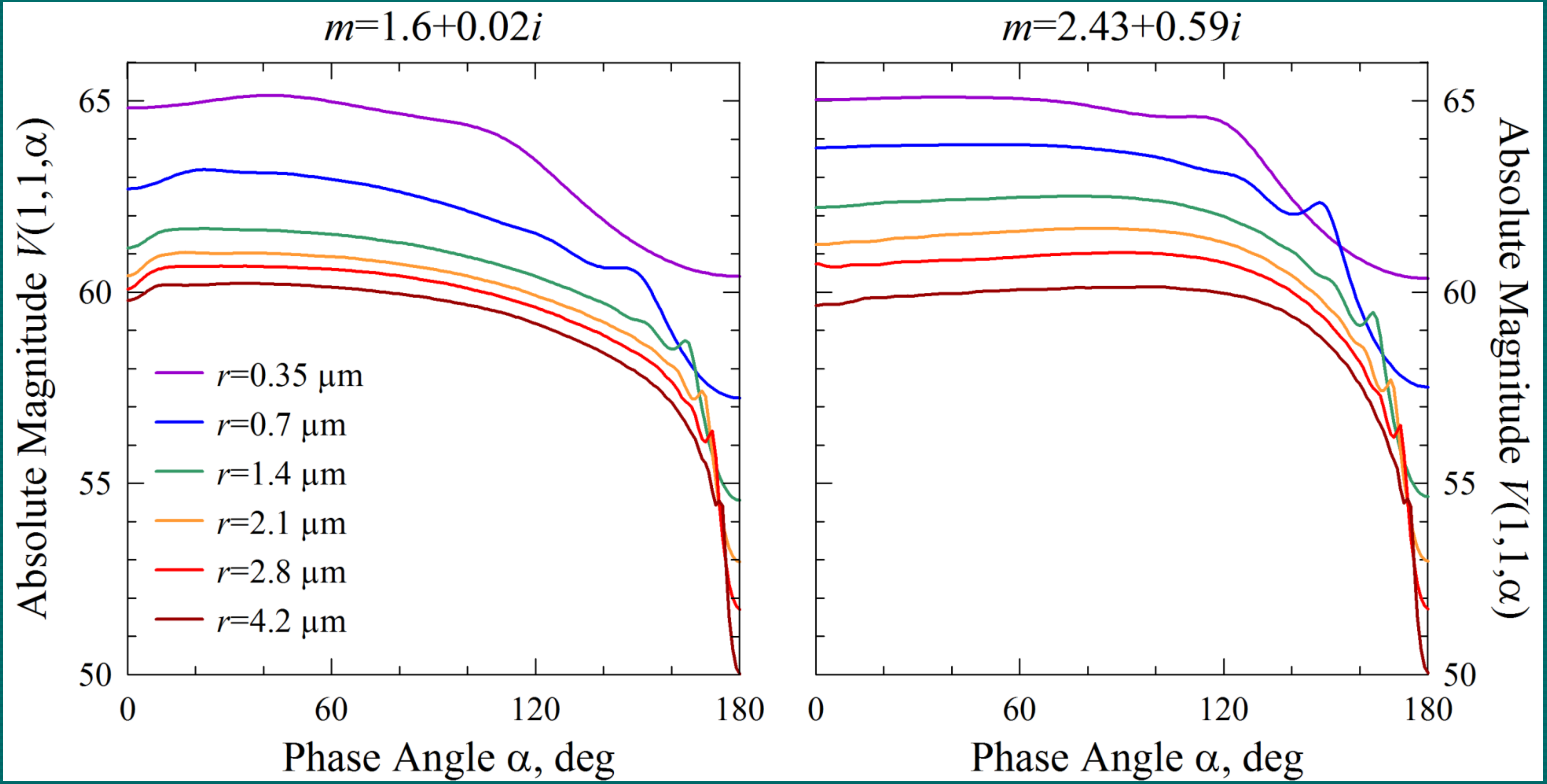
The light-scattering response in comets is predominantly governed by submicron and micron-sized dust particles.

10-μm particles only slightly affect the total signal, somewhat increasing uncertainty in retrieved microphysical properties. Such uncertainty appears to be much less than temporal and spatial variations of microphysical properties of dust often observed in cometary coma.

However, involving super-micron dust particles into analysis tremendously increases constraints on mass of ejecta.

Role of Super-Micron Particles in Light Scattering by Comets

We compute the absolute magnitude $V(1,1,\alpha)$ of the agglomerated debris particles having six different radii.



Role of Super-Micron Particles in Light Scattering by Comets

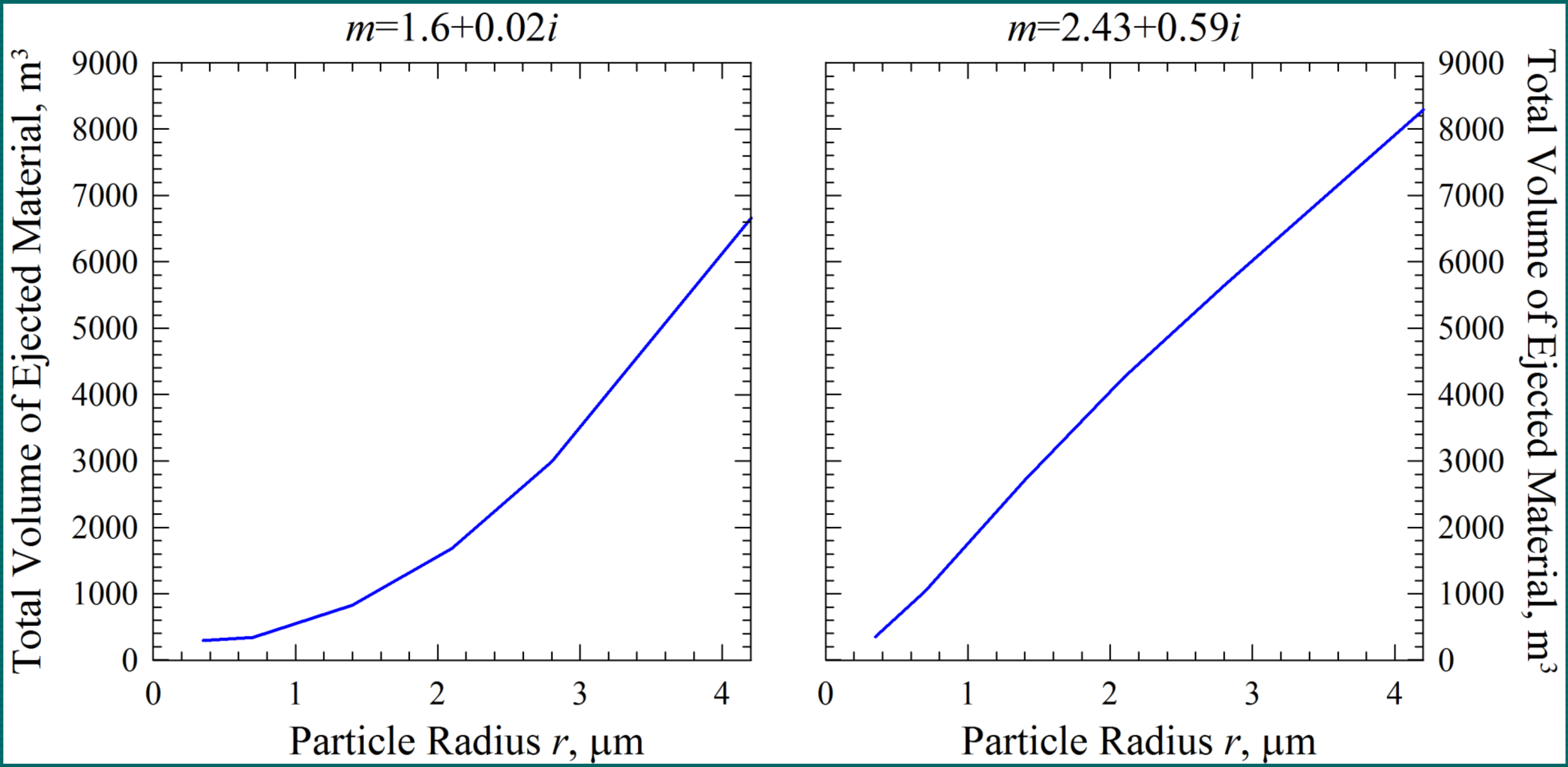
Using the $V(1,1,\alpha)$ diagrams, one can interpret apparent magnitude of Comet C/1996 B2 (Hyakutake) in terms of the total volume of its material.

We adapt the apparent magnitude of Comet Hyakutake $V = 5.4^m$ that it has on March 27, 1996.* On this epoch, the comet was at $r = 1$ au, $\Delta = 0.121$ au, and $\alpha = 85.7°$.

* http://www.minorplanetcenter.net/iau/MPEph/MPEph.html

Role of Super-Micron Particles in Light Scattering by Comets

While 0.35-μm particles suggest total volume of material in the Hyakutake coma to be ~290-350 m^3, 4.2-μm particles would require ~6653-8287 m^3; i.e., ~23 times larger volume.



Conclusion Remarks

Light scattering by comets is mainly produced by submicron and micron-sized dust particles. Unfortunately, such particles were beyond the limits of the Rosetta space probe.

This suggests the Rosetta findings are hardly applicable in analyses of the ground-based observations of comets in the visible and NIR.

Therefore, the next space mission to a comet should consider small dust particles as they provide clues to understanding ground-based observations. However, this task is difficult to accomplish in practice due to the slow encounter and electrostatic forces.