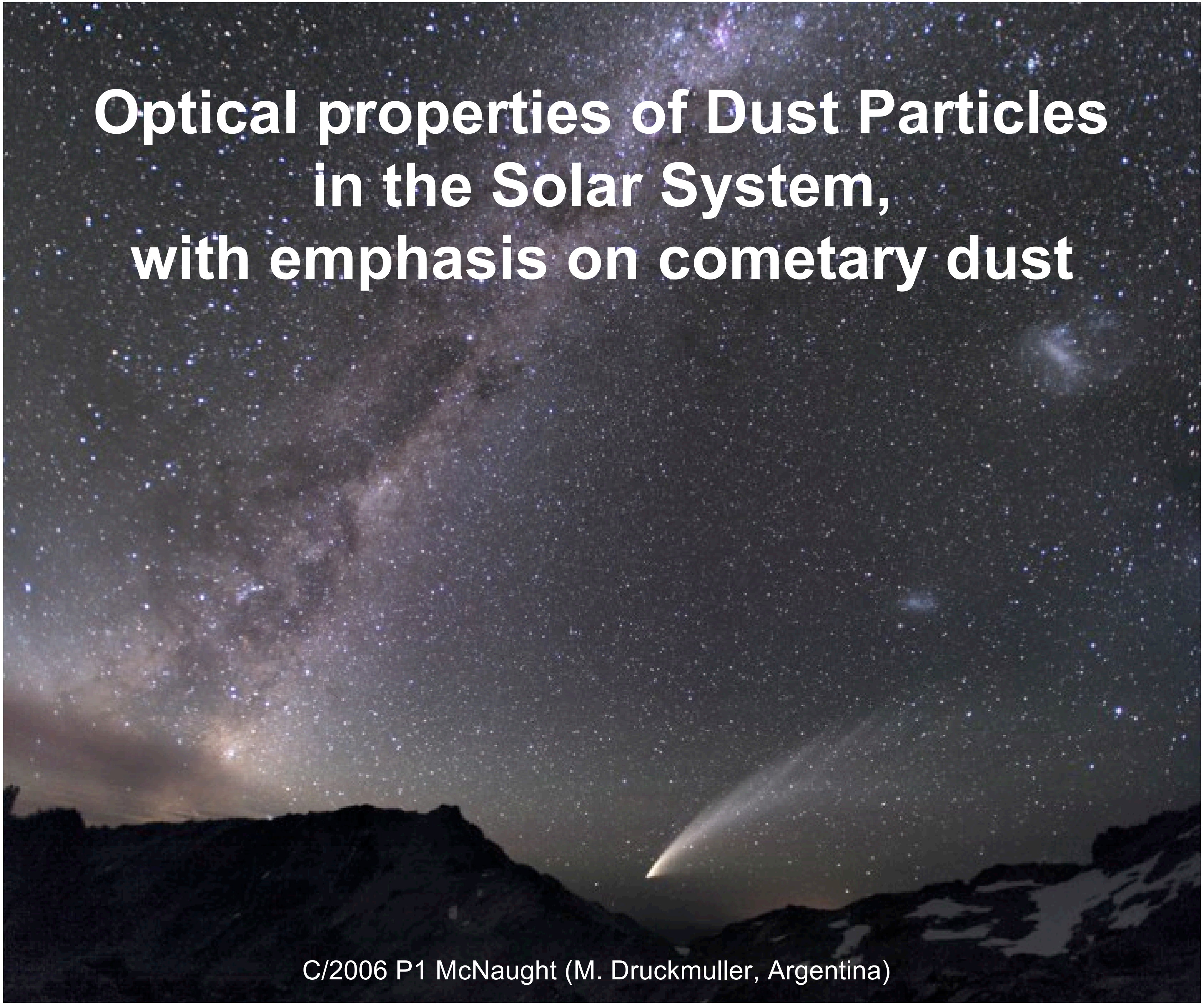

Optical properties of Dust Particles
in the Solar System,
with emphasis on cometary dust
C/2006 P1 McNaught (M. Druckmuller, Argentina)

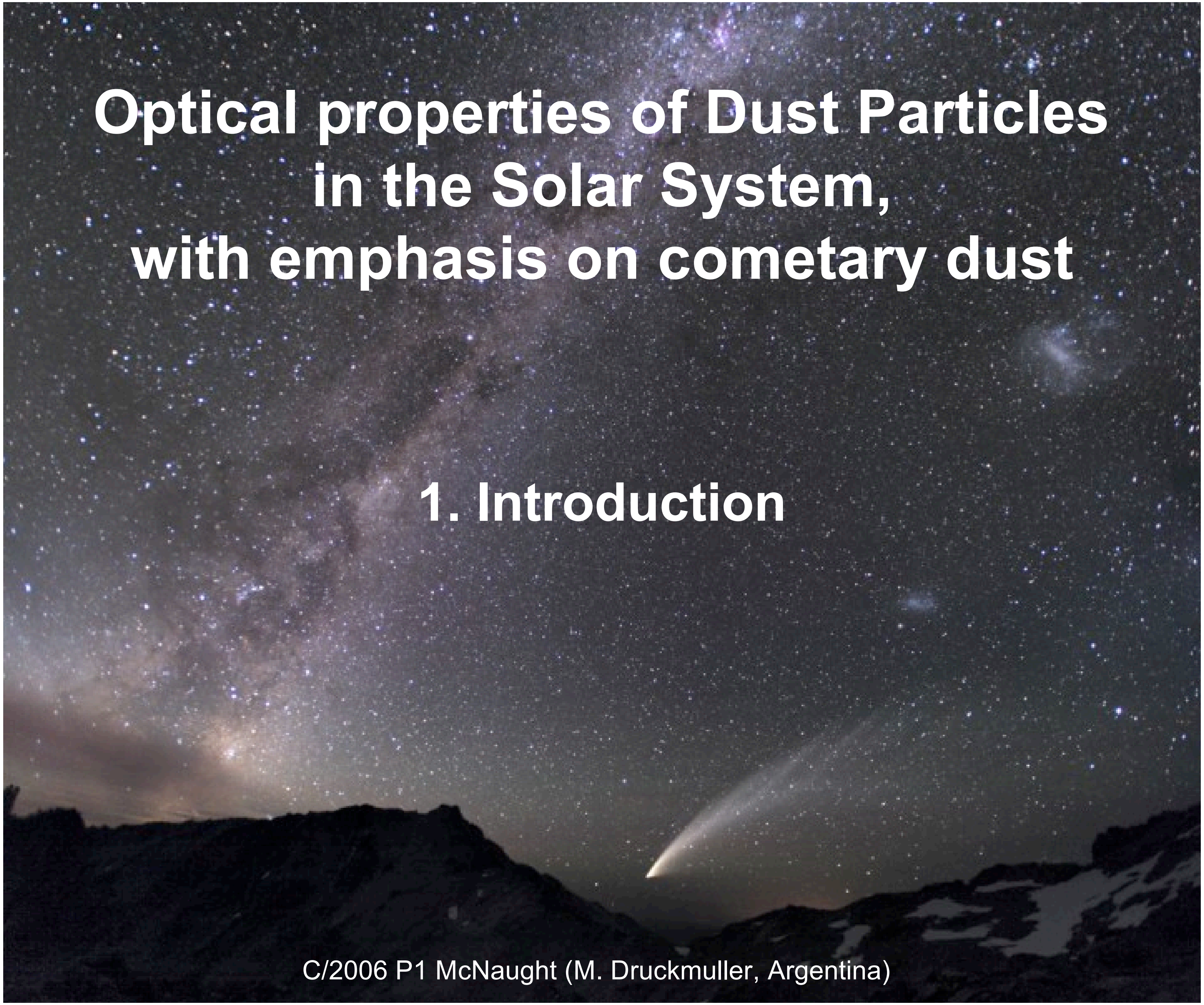
# Optical properties of Dust Particles in the Solar System, with emphasis on cometary dust


**A.Chantal Levasseur-Regourd**

**UPMC Univ Paris 6 / IPSL-CNRS, France**


**Outline**

1. Introduction
2. Key facts about cometary dust
3. Polarization of solar light scattered by dust
4. Cometary dust polarimetric observations
5. Interpretation through numerical simulations
6. Interpretation through laboratory simulations
7. Optical properties, interplanetary & asteroidal dust
8. Perspectives and conclusions


Optical properties of Dust Particles
in the Solar System,
with emphasis on cometary dust
1. Introduction
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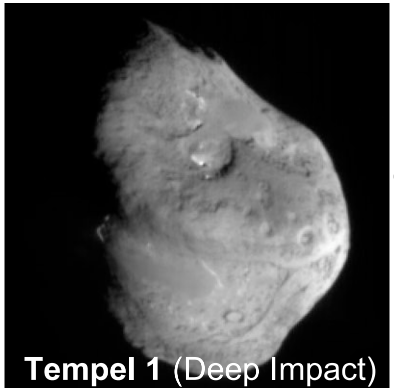
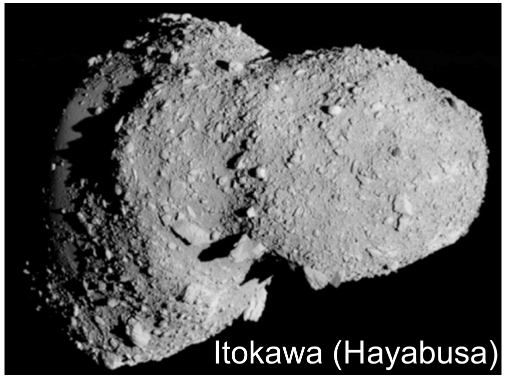
# 1. Introduction: Dust in small bodies



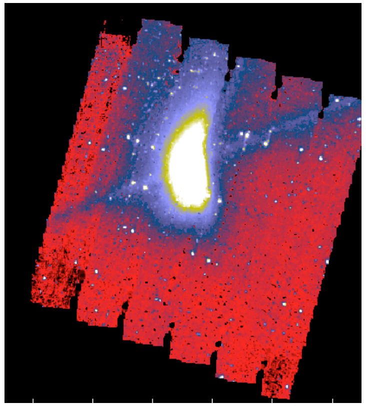
**Tempel 1** (Deep Impact)

**Cometary nuclei**

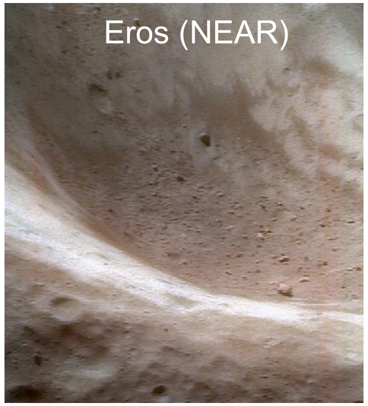


Itokawa (Hayabusa)

**Asteroids**



**Dust trails** (W. Reach)



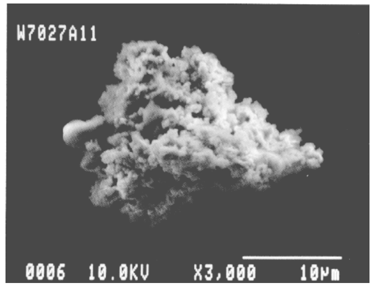
Eros (NEAR)

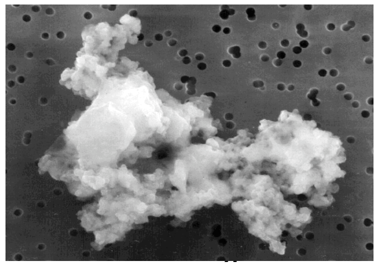
**Regolith**

**Hale-Bopp** (N. Biver)

**Comae and dust tails**
Optically thin media

**Interplanetary dust** (M. Fulle)
Optically thin dust cloud



**IDPs** (Nasa)
Irregular, >1 μm

# 1. Introduction: Motivation

• Dust partly revealed to the naked eye by the **solar scattered light**

• Limited amount of information from a few unique **in-situ missions**

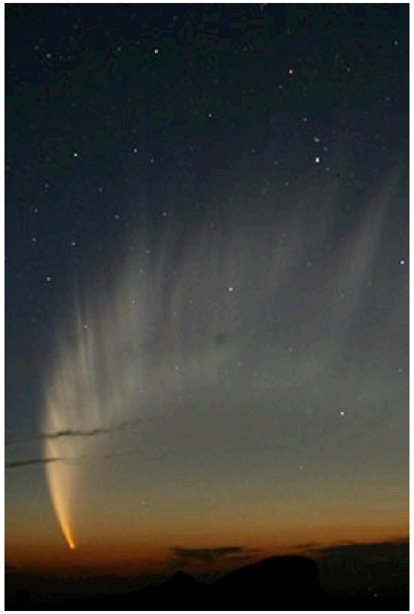
• “Ground truth” from **sample return** missions, up to now limited to dust particles collected in the coma of comet Wild 2

⇨ Numerous clues to the bulk properties of the dust from remote observations

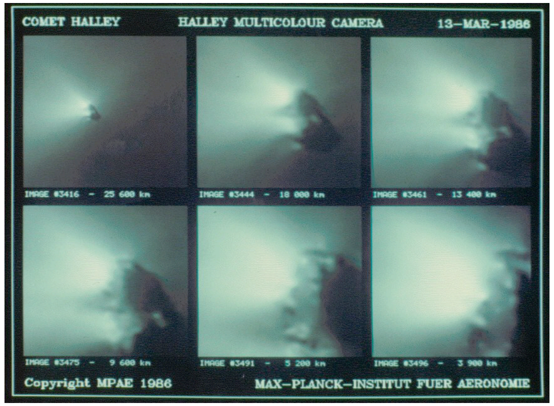
• **Spectroscopy** providing information on composition

• **Optical properties** for classification and bulk properties

**Holmes** (© M. Jäger)

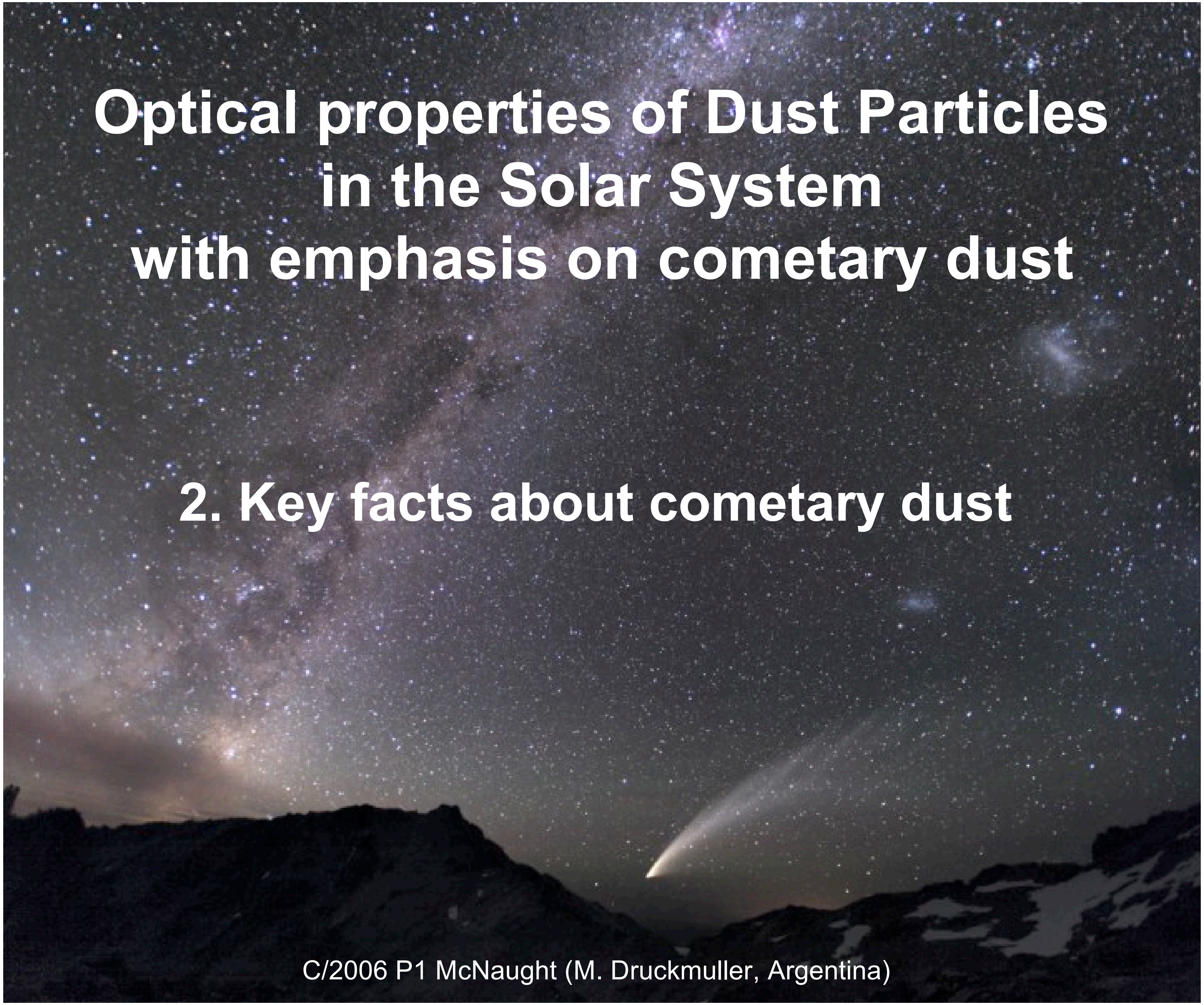


**McNaught** (McNaught)




**Halley** (Giotto)

**Wild 2 dust container** (Stardust)

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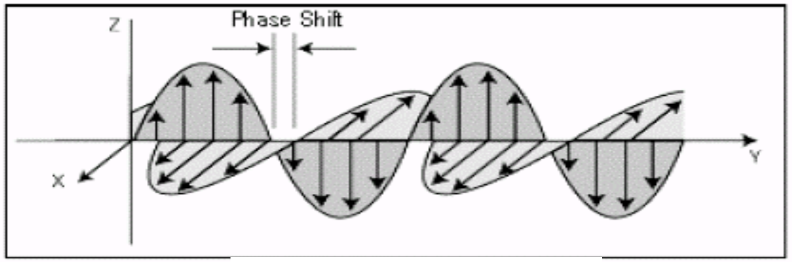
# 2. Key facts about cometary dust: Evidence for dust

**Un-polarized solar light scattered by particles partially linearly polarized by scattering**

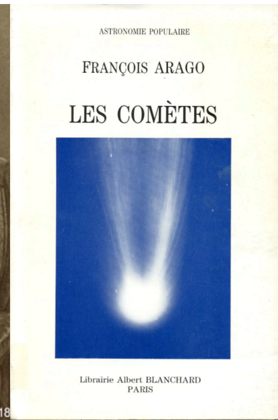
An old “technique”, already used by:

• Arthropods (e.g. honeybees) to navigate, with their “eyes” (ommatidia) sensitive to polarisation by Rayleigh scattering on atmospheric molecules

• Arago to establish the presence of dust in cometary tails, through observations of a bright comet in 1819 and of comet Halley in 1835 (with a ‘polariscope’)







# 2. Key facts about cometary dust: Composition

**1P/Halley flyby**

• Vega 1 and Giotto dust mass spectrometers

⇨ **Dust ≈ 50% rocky silicates and 50 % light elements "CHON"**

• Vega 2 spectrometer ⇨ Tentative identification of PAHs

• Giotto plasma analyzers ⇨ Heavy CHON ions (possibly POM)

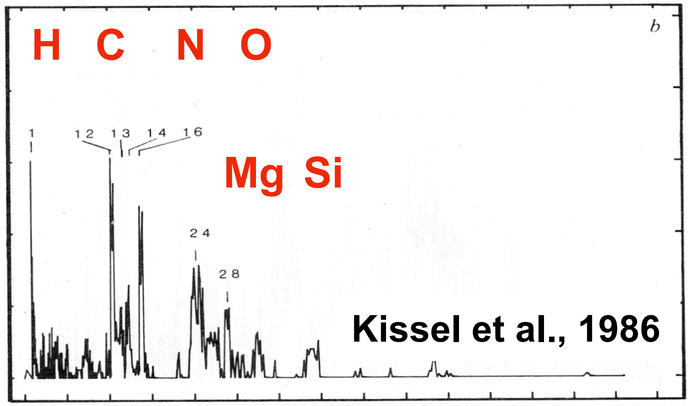
**Remote observations in the infrared domain**

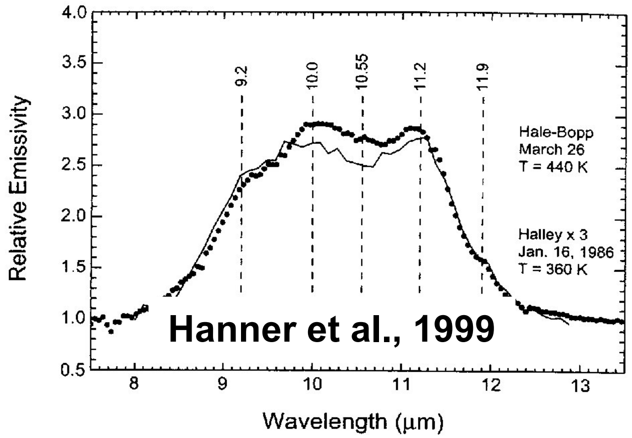
⇨ Silicate emission feature for some comets (very structured for Hale-Bopp)

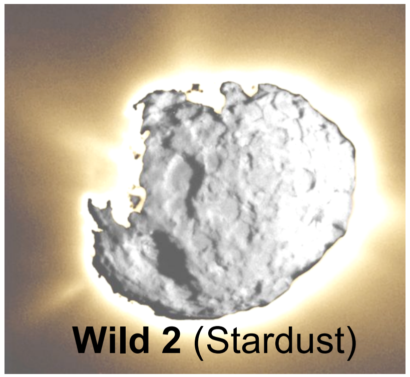
⇨ Fits requesting amorphous and crystalline silicates (Crovisier et al., 2000)

**81P/Wild 2** (Stardust flyby and samples analysis)

⇨ Dust also rich in CHON; heterogeneous distribution of organics; amorphous & crystalline silicates (Sandford et al., 2006; Zolensky et al., 2006, 2008)



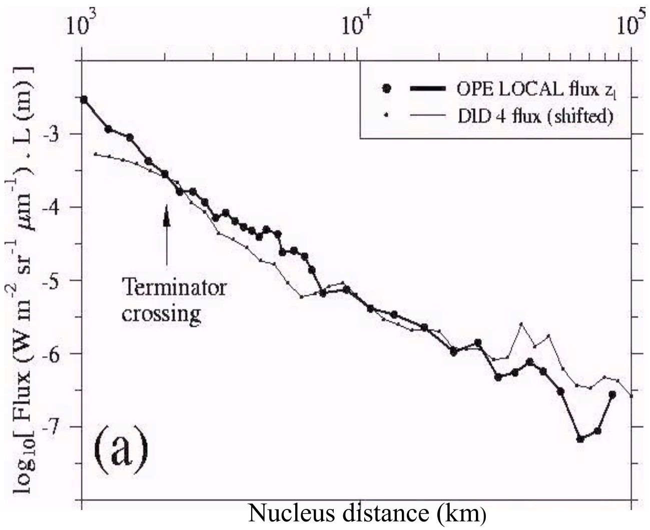



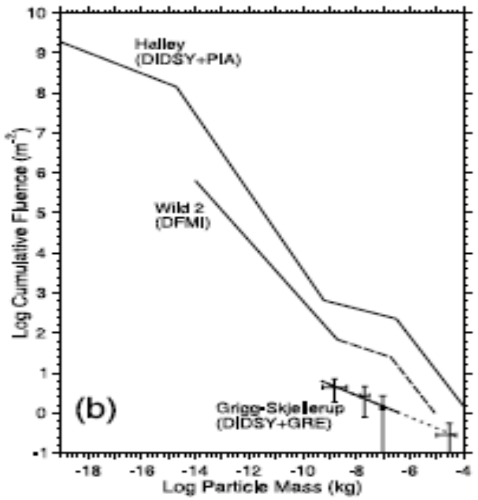
# 2. Key facts about cometary dust: Bulk properties

**1P/Halley** (Giotto)
⇨ Dust fluence versus mass
⇨ Local brightness & polarization showing significant changes within coma
⇨ Dynamical model best fit of a dynamical model (Fulle et al., 2000)
**Albedo ≈ 0.04**, dust size distribution ≈ $s^{-2.6}$, **density ≈ 100 kg m$^{-3}$**
⇨ **Very fluffy dust particles**

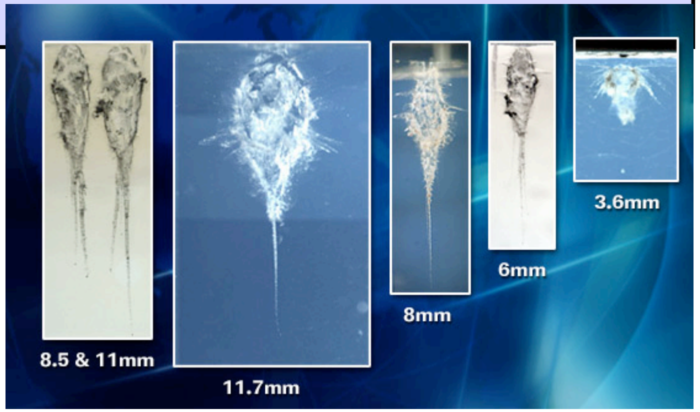
**81P/Wild 2** (Stardust flyby, samples tracks and impacts)
⇨ Fragmentation in the coma; evidence for aggregates
(Burchell et al., 2006, 2008; Hörz et al., 2006)

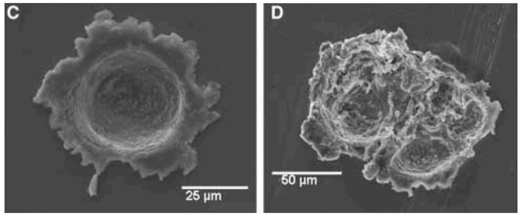



Levasseur-Regourd et al., 1999




Green et al, 2004

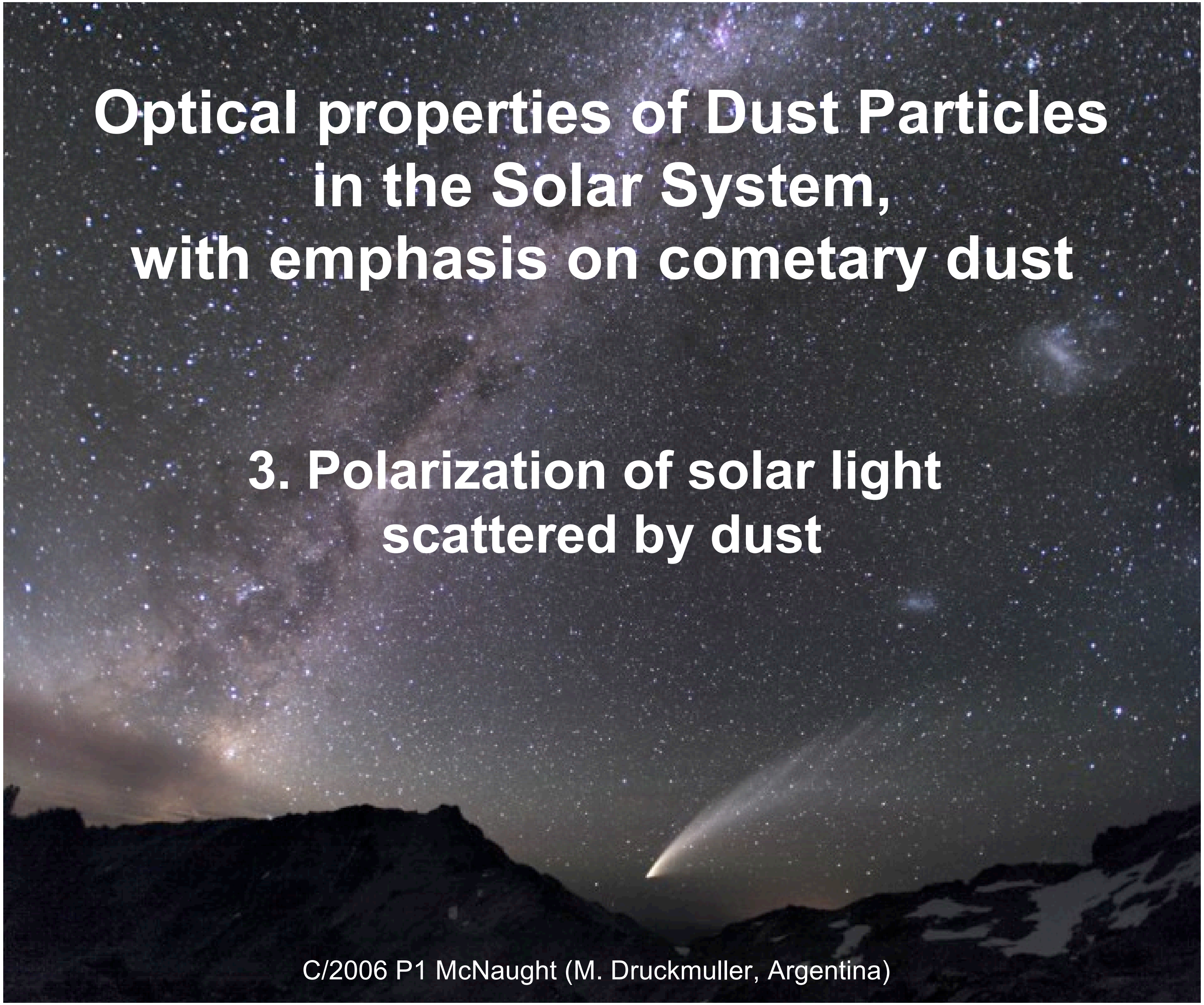



Hölz et al, 2006

# Optical properties of Dust Particles in the Solar System, with emphasis on cometary dust

## 3. Polarization of solar light scattered by dust



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# 3. Polarization of light scattered by dust: Definitions

• For randomly oriented particles, solar light scattered by an optically thin media linearly polarized, with the electromagnetic wave predominantly oscillating perpendicular or parallel to the scattering plane.

• Linear polarisation P, **dimensionless ratio**, allowing comparisons for objects at different distances to the Sun and the observer
⇨Noticed by Lyot for lunar regions
⇨Of major importance for comets, whose intensity is not proportional to $1/R^{2}$, but (normalized light-curve variations) nor to $1/\Delta^2$ (development of a bright coma)

• P varying only with
- phase angle $\alpha$
- wavelength $\lambda$
- **properties of the scattering medium**

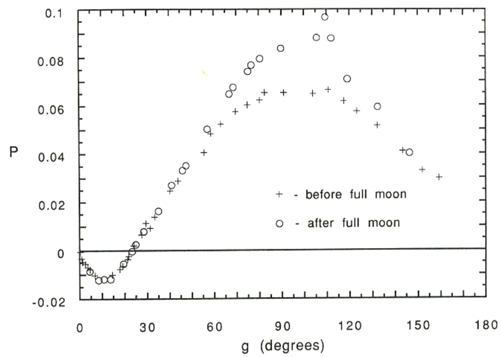
Intensity

$$I = I_p + I_{np}$$
$$I = (I_\perp + I_{//})$$

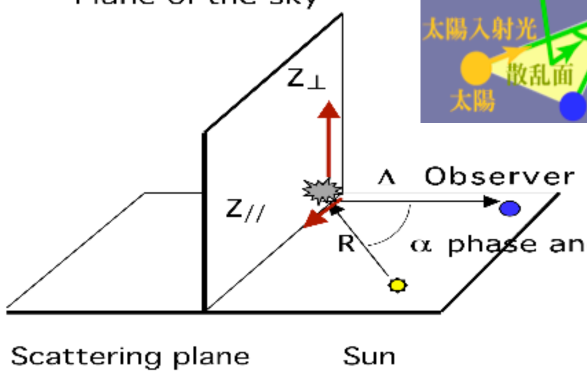
Linear polarisation

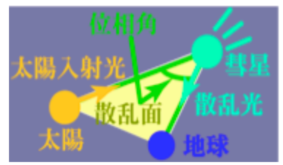
$$P = (I_\perp - I_{//})\,/(I_\perp + I_{//})$$
$$P = -\,Q/I$$

$\alpha = \pi - \theta$ ($\theta$ scattering angle)




**Moon**
**Lyot 1929**



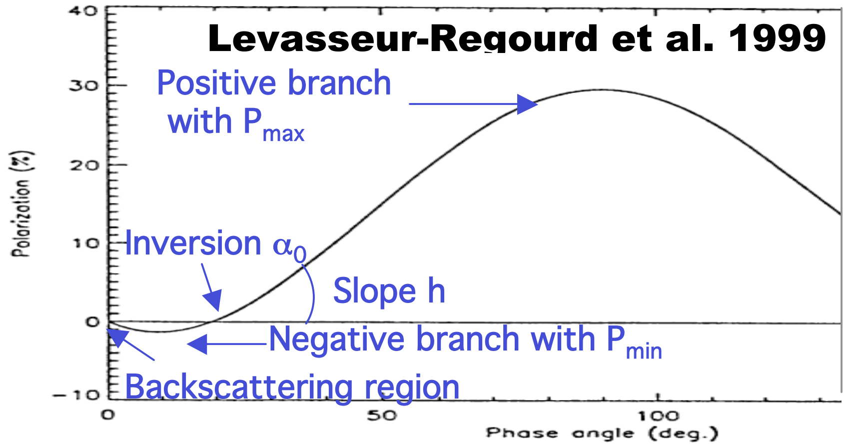
# 3. Polarization of light scattered by dust: Small bodies

• Phase angle $\alpha$ changing with time (observations' geometry), providing $P_\lambda(\alpha)$
⇨**'Smooth' polarization phase curves**, typical of scattering by irregular particles with sizes greater than observational wavelength, i.e. a few $\mu$m
⇨Mie solutions to Maxwell equations not acceptable here

• Empirical laws, e.g. albedo - slope at inversion, not necessarily acceptable (possibly only derived for one given class of objects)

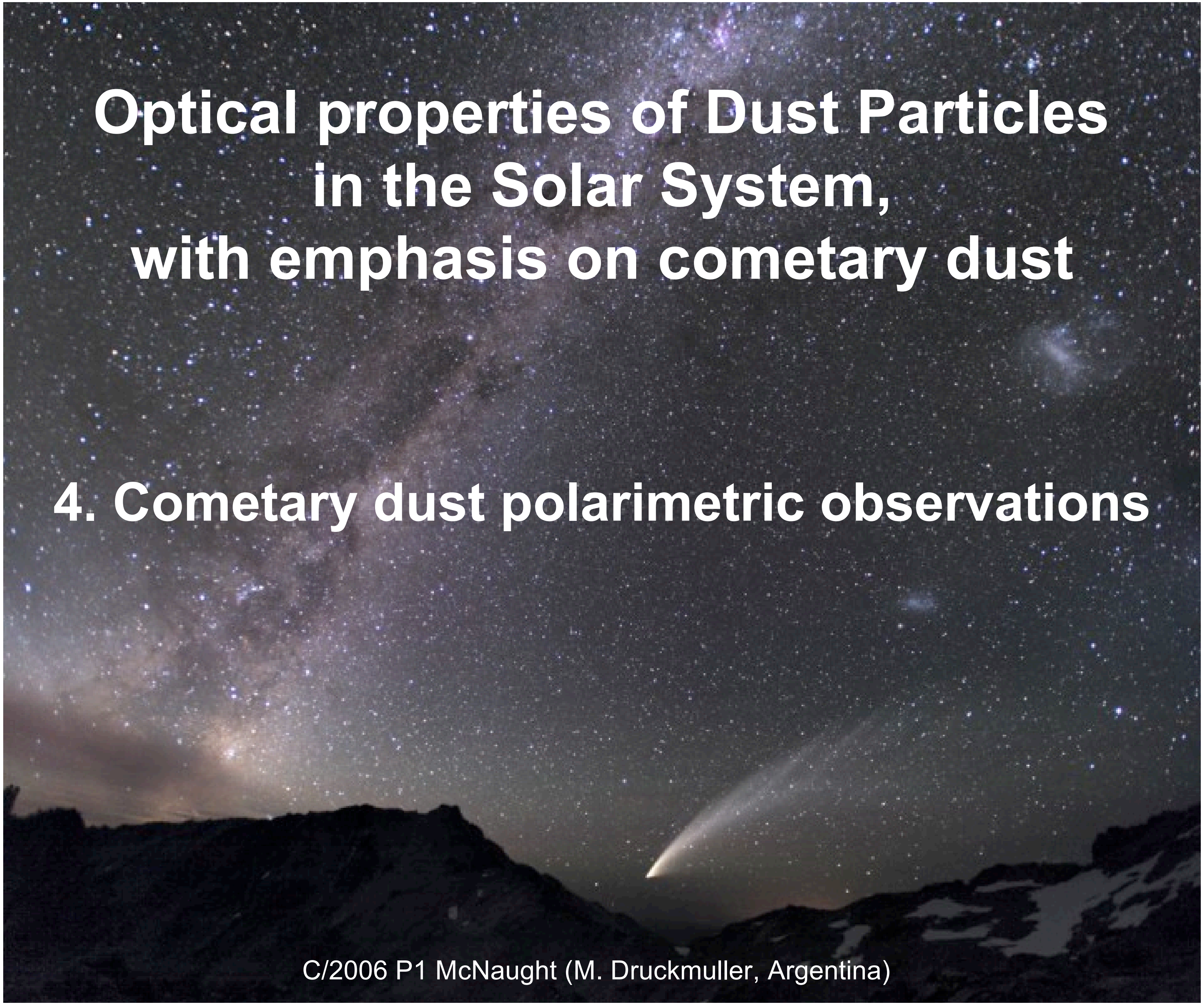
• Tentative interpretation of the observed variations of $P_\lambda(\alpha)$
(e.g. $\alpha_{min}$, $P_{min}$, $\alpha_0$, h, $\alpha_{max}$) and $P_\alpha(\lambda)$ in terms of physical properties,
from **experimental and numerical simulations** with realistic (?) particles

**Observational constraints**
• Moving objects in a fixed star-field
• Narrow interference filters mandatory for comets (to avoid depolarization from gaseous emissions)
• Interplanetary data needing inversion
• Asteroids usually at small $\alpha$



# Optical properties of Dust Particles in the Solar System, with emphasis on cometary dust

## 4. Cometary dust polarimetric observations



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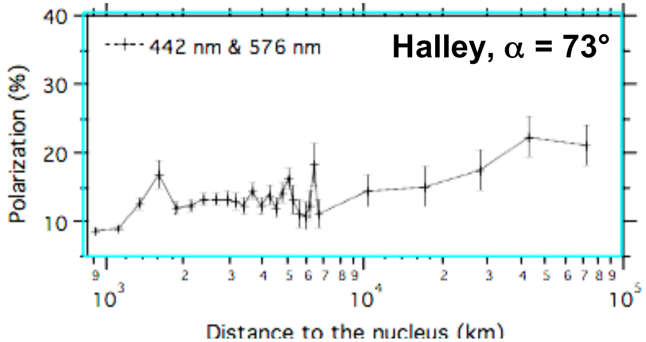
# 4. Cometary dust polarimetric observations: Spatial changes within the coma

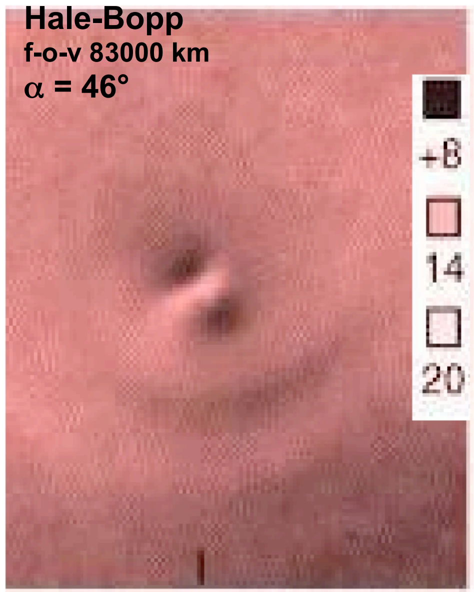
- In situ measurements (OPE/Giotto)
⇨ Significant variations of P in inner coma

- Remote P imaging technique (since 1990)
⇨Circumnucleus 'halo' and jet-like features (specially for active comets)

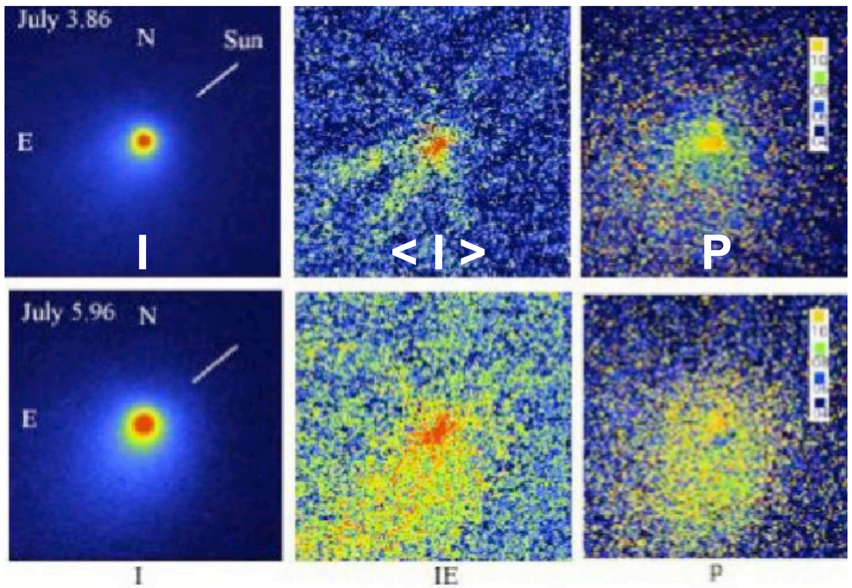
- P reaching an asymptote for increasing aperture
⇨ Significance of whole coma polarisation data




Levasseur-Regourd et al, 1999



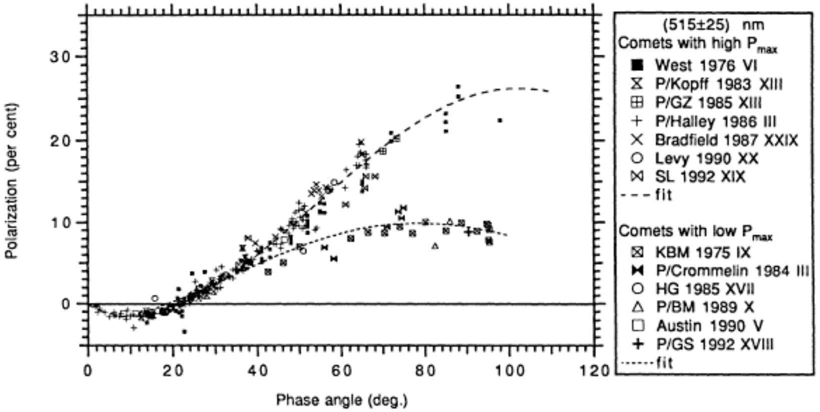

Hadamcik & L-R, 2003



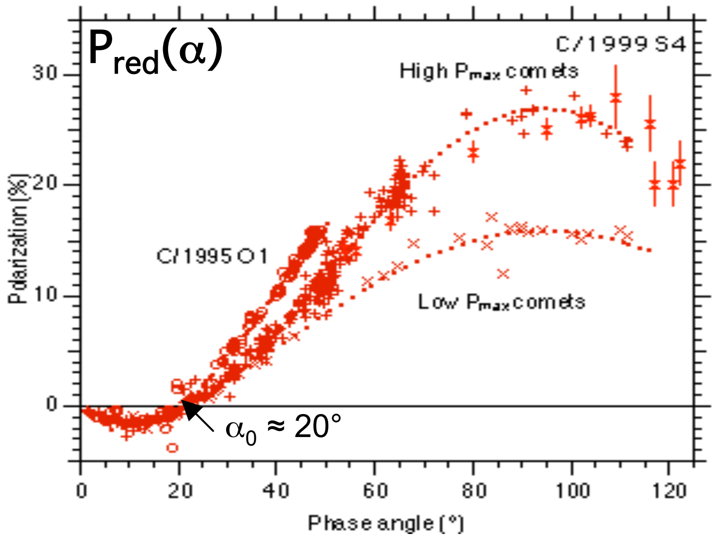

**Tempel 1**
**f-o-v 70000 km**
**$\alpha \approx$ 41°**

**Adapted from Hadamcik et al, 2007**

# 4. Cometary dust polarimetric observations: $\alpha$ dependence (whole coma)



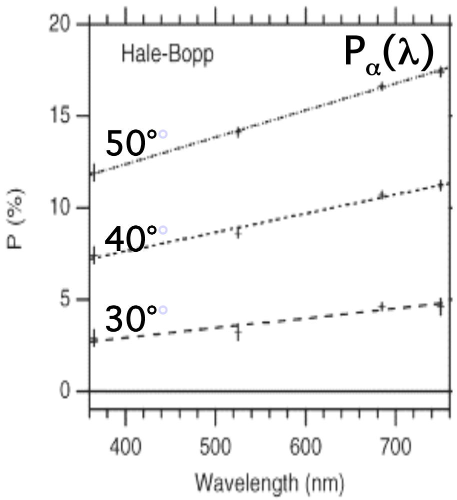

**Levasseur-Regourd et al, 1996**



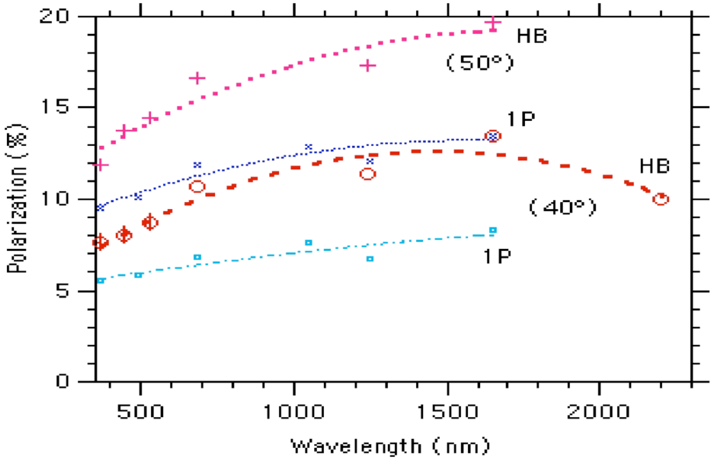

**Hadamcik & Levasseur-Regourd 2003**

- Smooth polarisation phase curves,
suggesting 2 (or 3) classes of comets from their dust properties
- $P_{max}$ higher whenever silicate emission feature
- P possibly increasing in jet-like features or after an outburst

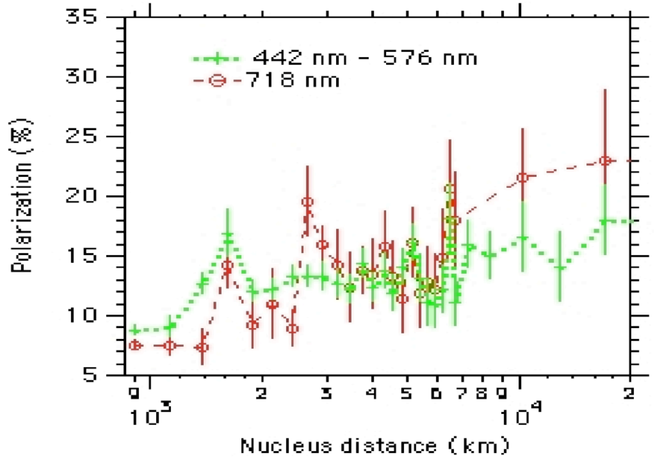
# 4. Cometary dust polarimetric observations: $\lambda$ dependence (whole coma)




Levasseur-Regourd & Hadamcik, 2003




Hadamcik et al, 2003




Levasseur-Regourd et al, 2005

- P usually **increasing with $\lambda$** for $\alpha > \approx 30°$, at least in the visible domain
- Some exceptions

- innermost coma (e.g. 1P/Halley)
- disruption events, tentatively due to different dust properties inside the nucleus (e.g. C/1999 S4 LINEAR)

# 4. Cometary dust polarimetric observations: Need for simulations

- Significant amount of observational data for JCF comets, as well as from comets probably originating from the Oort cloud
- Existence of empirical laws (mostly deduced from asteroidal data, e.g. slope at inversion - albedo relation)
- Interpretation of the observed variations of the polarization properties in terms of physical properties, requesting both numerical and experimental simulations, with tentatively realistic dust particles

In-situ observations
and samples
↓
Changes in the dust properties
Presence of aggregates

Remote light scattering polarimetric
observations
↓
Irregular particles
Estimation of the albedo

↓

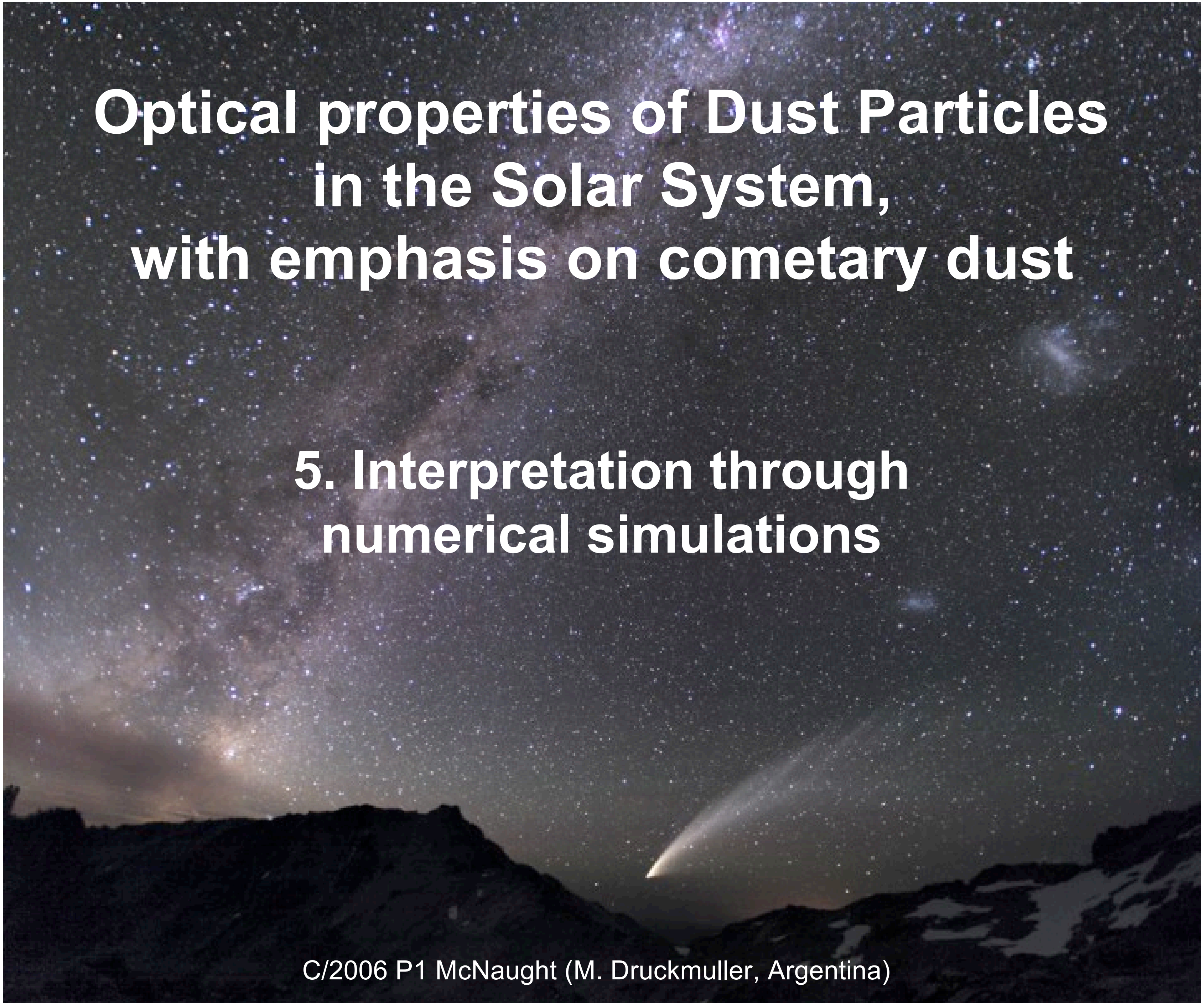
Light scattering numerical and experimental simulations
on irregular particles and aggregates
(Realistic particles? Realistic light scattering? )

↓

Clues to the physical properties of different dust media

# Optical properties of Dust Particles in the Solar System, with emphasis on cometary dust

## 5. Interpretation through numerical simulations



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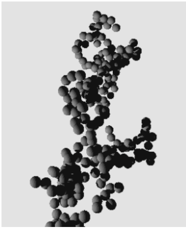
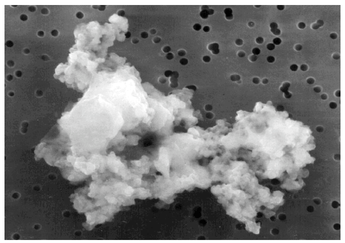


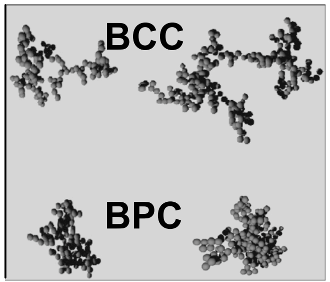
# 5. Interpretation through numerical simulations: principles

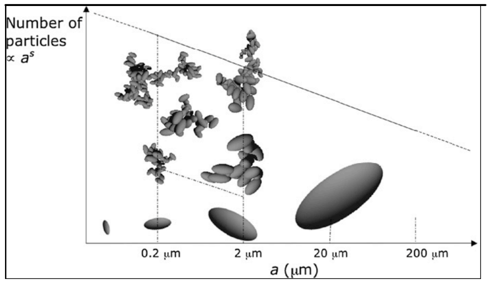
• **First light scattering simulations by Mukai et al** (1987), on 1P/Halley observations, by applying Mie theory to spheres with Vega size distribution
⇨ Complex refractive index, 1.385 + 0.035 i
Also simulations with spheroids, polyhedrons… (Lumme, 2000)

• From the late 90s, simulations with fractal aggregates of grains with **DDA codes** (Xing & Hanner, 1997; Levasseur-Regourd et al, 1997; Nakamura & Okamoto, 1999; Haudebourg et al, 1999; Petrova et al, 2000; Tiskovets et al, 2000, Kimura et al, 2003, Mann et al, 2004… ) or **ray tracing** for large grains (Okada et al, 2006…)

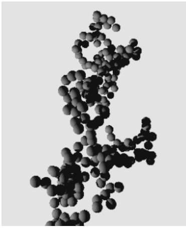
• Example: Light scattering simulations (T-matrix, ray-tracing, DDA codes) for **spheroids of astronomical silicates and more absorbing organics** (equivalent radius a) **and fractal aggregates thereof** (BCCA & BPCA, 500 dipoles per grain, 1500 orientations, up to 256 grains)



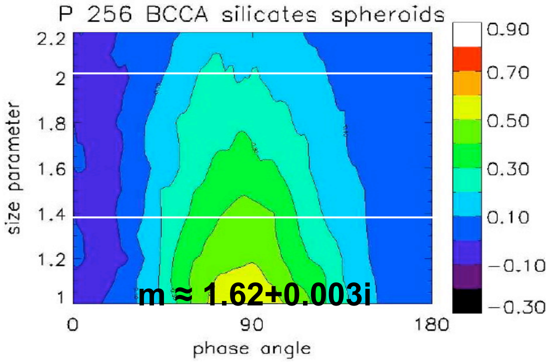


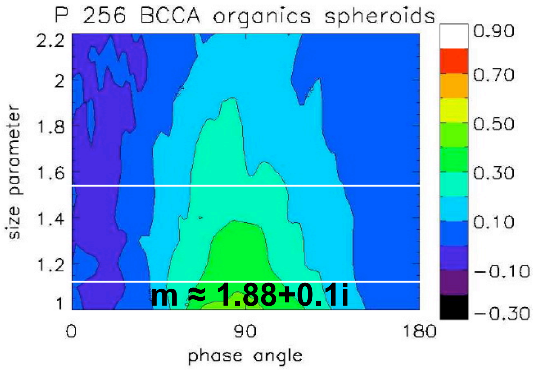



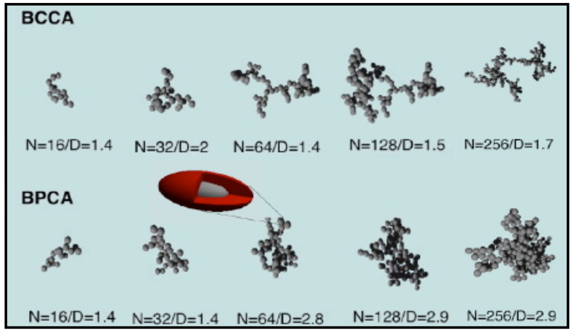

Lasue et al, 2009



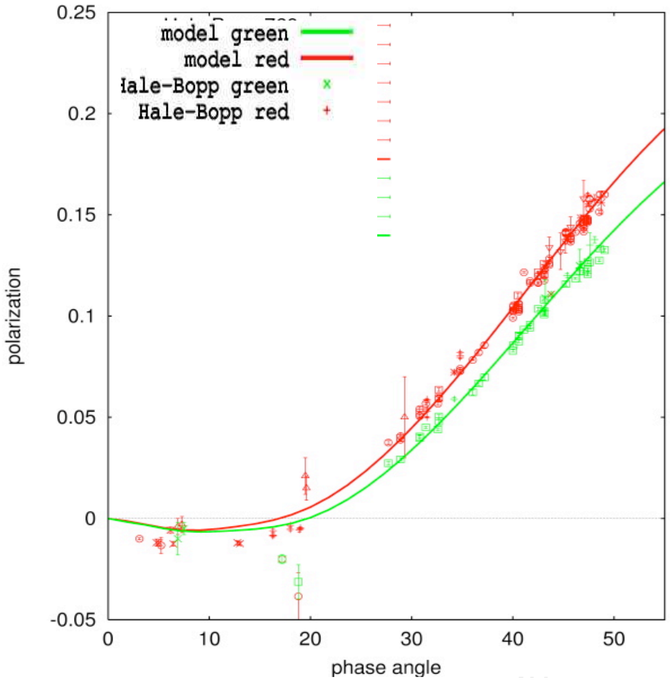
# 5. Interpretation through numerical simulations: Hale-Bopp in two colors



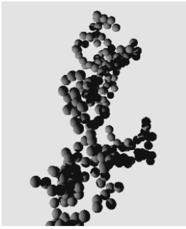



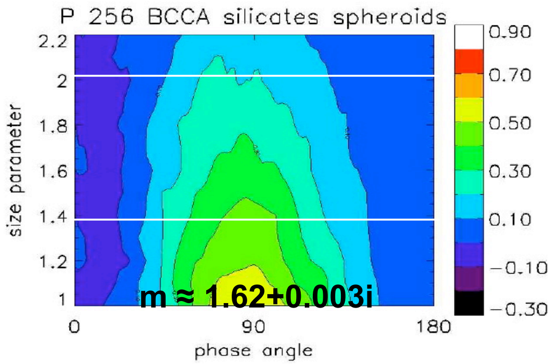

- Observations fitted for **only a few free parameters** (e.g. slope s of the size distribution $a^s$, minimal a, maximal a, silicates /organics ratio)
- For Hale-Bopp, from fits in two colors
  Size distribution ≈ $\mathbf{a^{-3}}$
  **0.1 μm < a < 20 μm**
  In mass ≈ **40% silicates & 60% organics**
  (up to 65% silicates, down to 35% organics)

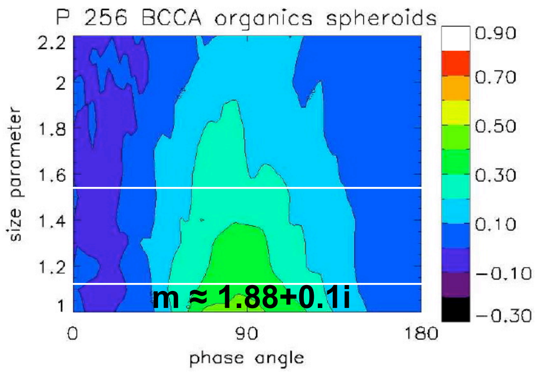


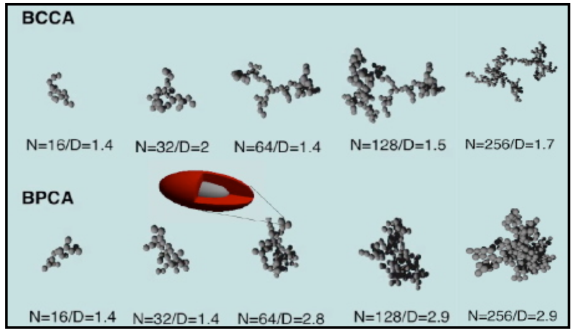

**Lasue et al. 2009**



# 5. Interpretation through numerical simulations: ‘predictions’ for other colors

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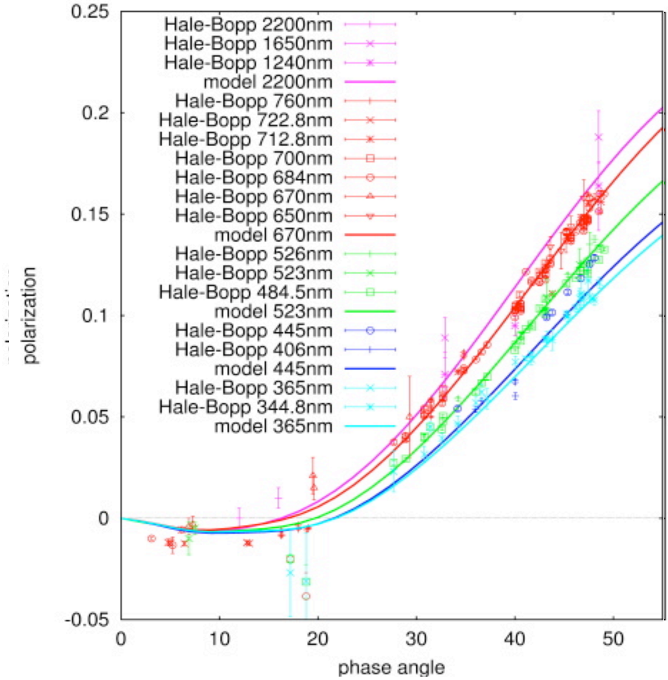
  Size distribution ≈ $\mathbf{a^{-3}}$
  **0.1 μm < a < 20 μm**
  In mass ≈ **40% silicates & 60% organics**
  (up to 65% silicates, down to 35% organics)
- With identical parameters,
  also excellent agreement in UV and near IR




**Lasue et al. 2009**

# 5. Interpretation through numerical simulations: summary

• In Hale-Bopp, significant amounts of **compact grains and aggregates** (more than ≈ 20%)**, as well as of silicates** (indices comparable to astronomical silicates) **and organics** (absorbing material), in agreement with Stardust results on Wild 2 (loosely-bound tiny-grains aggregates & cohesive-compact grains)

• Similar approach possible for other comets observed on a large enough range of $\alpha$ and $\lambda$, e.g. 1P/Halley Size distribution ≈ $a^{-2.8}$

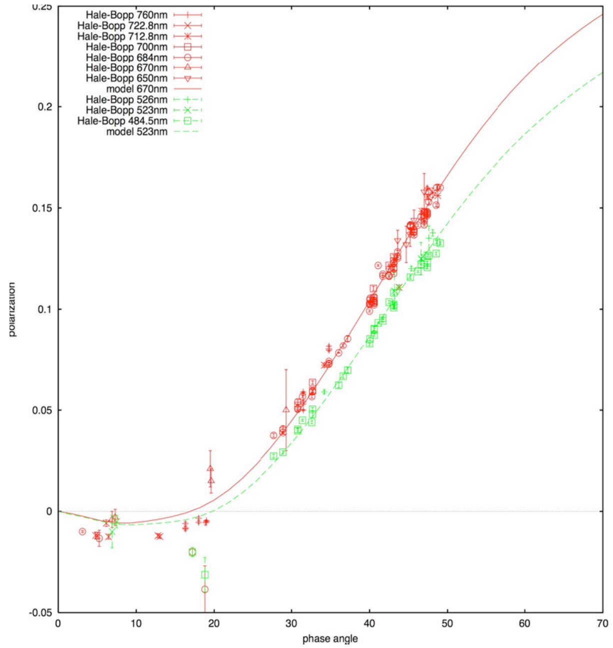
0.13 $\mu$m < a < 19 $\mu$m,

Similar silicates/organics ratio

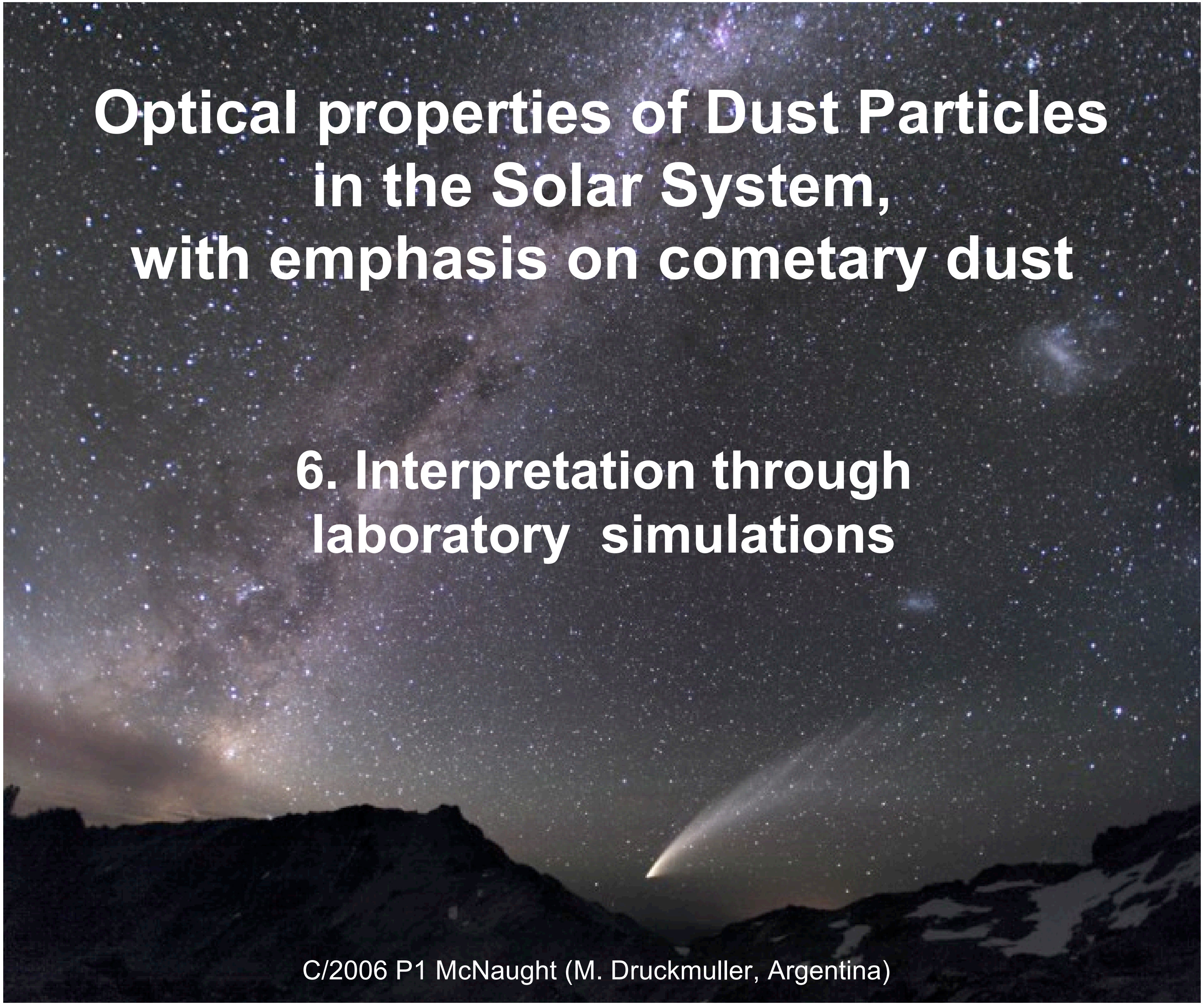
Less satisfactory fit on the negative branch

- larger aggregates ?
- different refractive indices ?
- more compact aggregates ?

• Need also for experimental simulations, with measurements on quite realistic particles



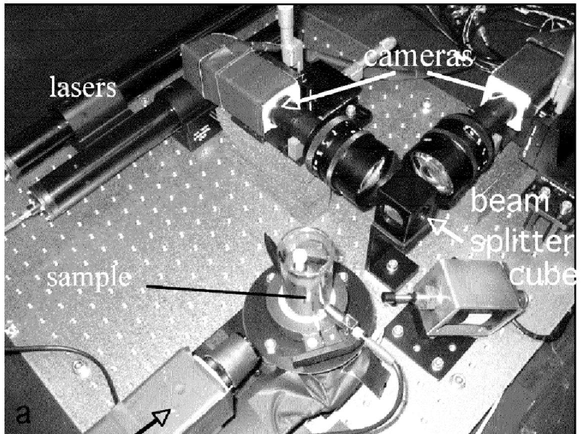

Lasue et al. 2009

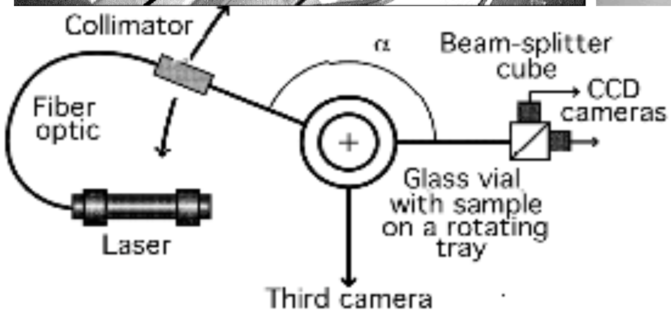

Optical properties of Dust Particles
in the Solar System,
with emphasis on cometary dust
6. Interpretation through
laboratory simulations
C/2006 P1 McNaught (M. Druckmuller, Argentina)

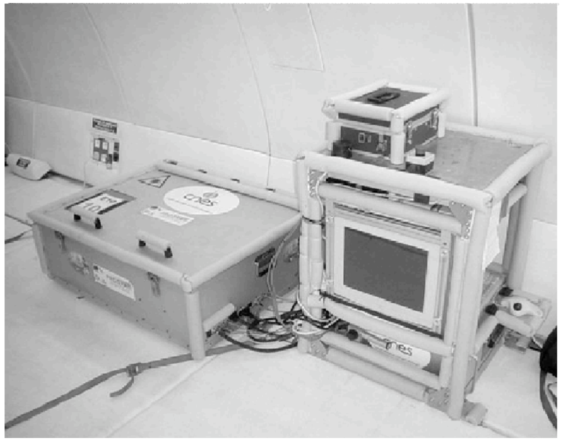

# 5. Interpretation through experimental simulations: principle

• Measurements with **PROGRA²-vis** experiment (at 543.5 & 632.8 nm) in the laboratory and during **parabolic flights campaigns,** avoiding sedimentation and multiple scattering on gravity packed layers (Worms et al, 1999, Renard et al. 2002)

• Calibration with spheres through Mie computations



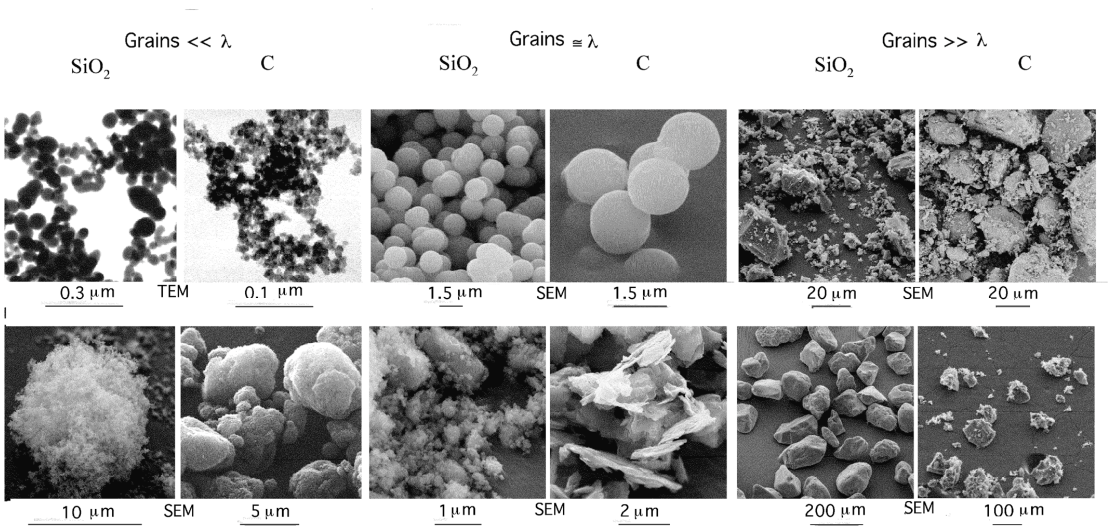



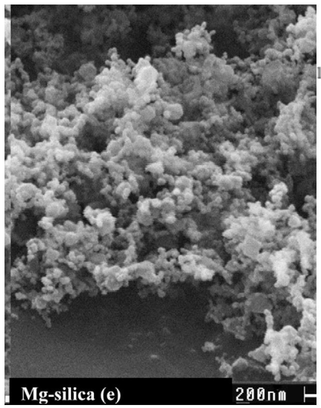
Hadamcik et al, 2008

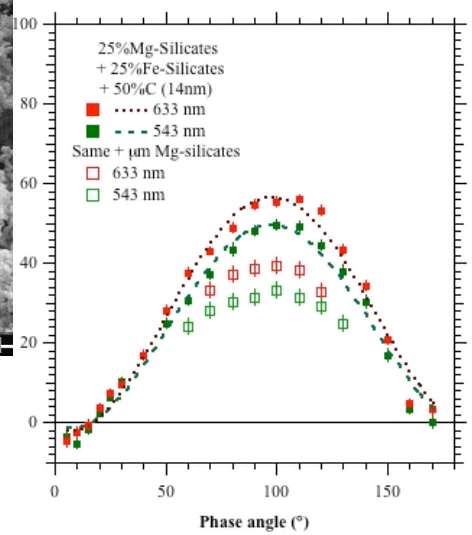
# 5. Interpretation through experimental simulations: main results

- Good match for mixtures of **fluffy** Mg-silicates, Fe-silicates and C aggregates, with some **compact** Mg-silicates grains
(fluffy chains = negative branch, C compounds = polarization colour)

- Excellent match with new sets of NASA samples, e.g. porous aggregates of subμm (MgSiO + FeSiO + C) grains, and compact Mg-silicates



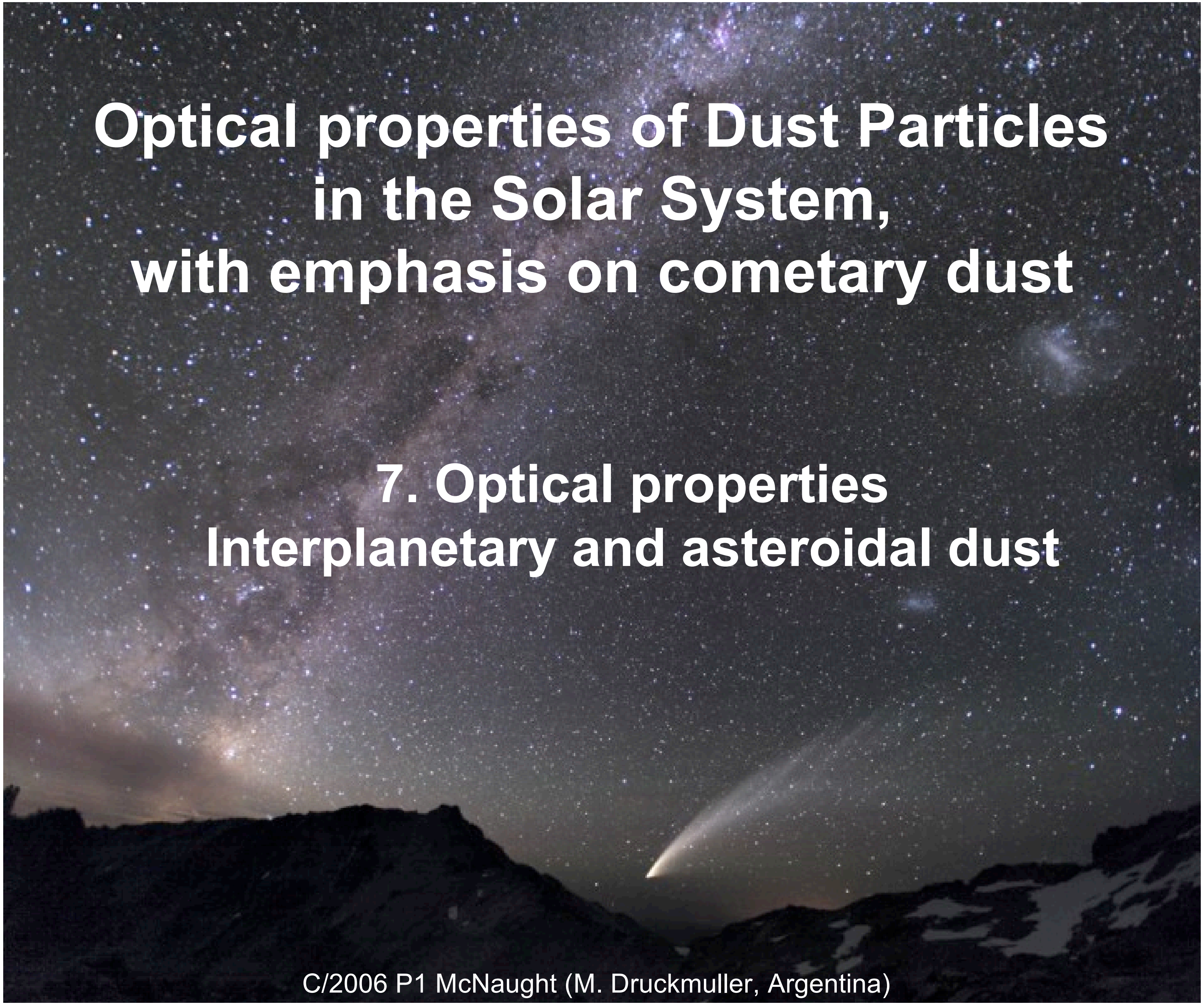




Hadamcik et al., 2007 and 2008

# Optical properties of Dust Particles in the Solar System, with emphasis on cometary dust

## 7. Optical properties
## Interplanetary and asteroidal dust



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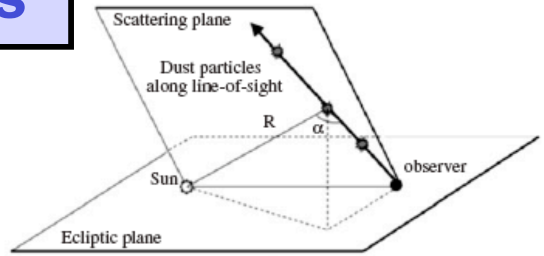
# 7. Optical properties: Zodiacal light observations

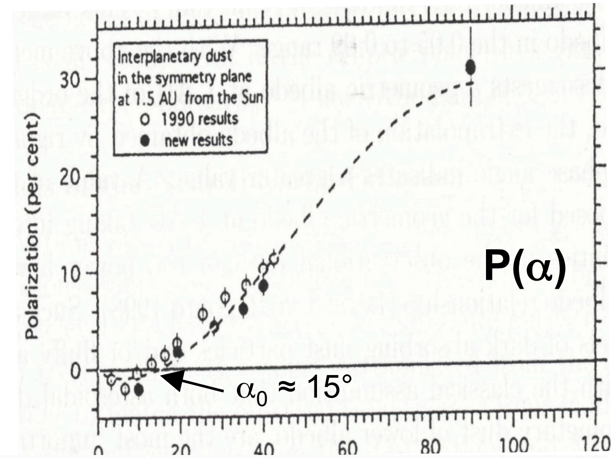
- Interplanetary data needing an inversion

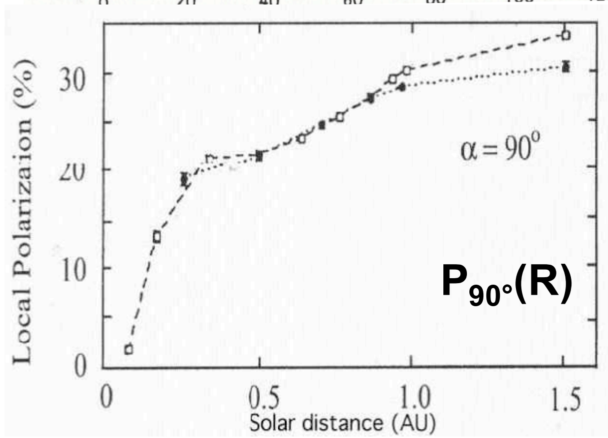
$$I_\lambda(\varepsilon, R) = F(\lambda) \int [n(r)\, \sigma_\lambda(r, \theta) / r^2]\, dl$$

- Local polarisation P retrieved
  - rigorously for l-o-s tangent to the direction of motion of the observer and for the section of the l-o-s where he is located (Dumont, 1973)
  - through inversion techniques, in the near-ecliptic symmetry plane of the cloud (Dumont and Levasseur-Regourd, 1985; Levasseur-Regourd et al., 1991; Lumme, 2000)
- From thermal emission, local temperature T(R) $\approx T_0\, R^{-0.45}$, i.e. non blackbody (Lasue et al, 2007)
- **Smooth P($\alpha$) phase curve**
  (at R = 1.5 AU near the ecliptic plane)
- **Decrease of P(90°) with decreasing solar distance R**




Levasseur-Regourd et al, 2007




Levasseur-Regourd et al, 1991

# 7. Optical properties: Interplanetary dust simulations

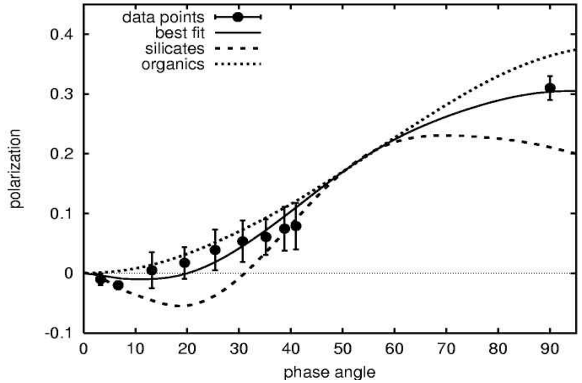
• Phase curve fits requesting both transparent and **absorbing** materials, with some **aggregates**

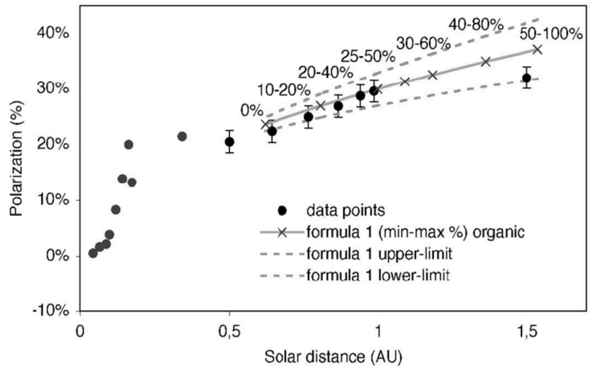
• At R = 1.5 AU near the ecliptic plane
size distribution $a^{-3}$, $0.11 < a < \approx 10\ \mu m$
$a^{-4.4}$, $a > \approx 10\ \mu m$
in mass, 40-80% silicates, 60-20% organics

• Un-fragmented aggregates likely to be of **cometary origin**: at least 20% in mass at 1.5 AU

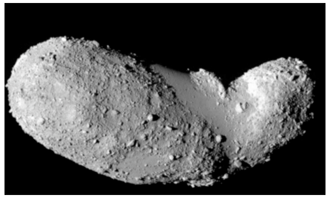
• P(R) decrease with decreasing R possibly due to a progressive thermal degradation of organics (HCN polymers and other solid carbonaceous compounds)

• Drastic change below ≈ 0.3 UA possibly due to degradation of silicates with smaller particles



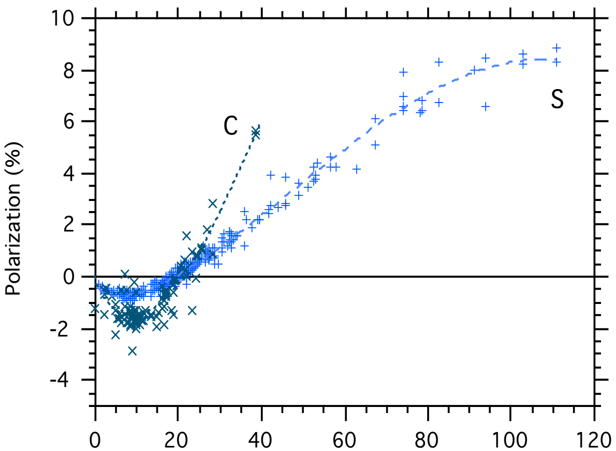

**Lasue et al., 2007**



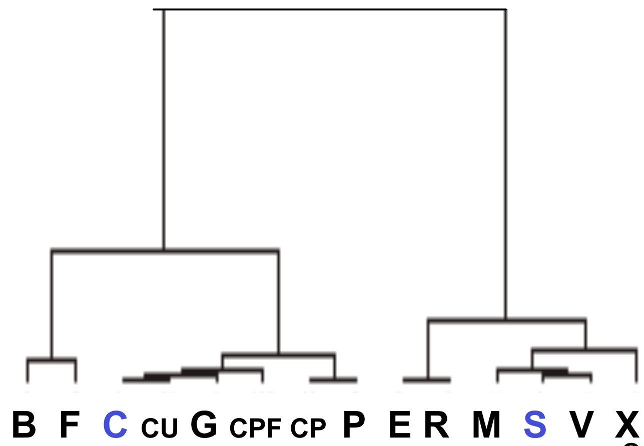
# 7. Optical properties: Observations of asteroids ($\alpha$)

- Observations mostly documented for S and C types and at small phase angles (mostly negative branch), except for NEA
- Slope at inversion h increasing with decreasing albedo
- Trend of the positive branch providing information about **taxonomic type** (principal component analysis)
- Example of application: 2667 **Steins**, first Rosetta target in Sept. 2008

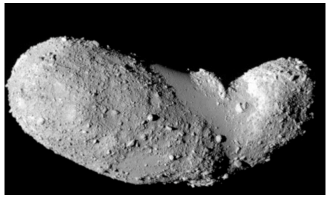
⇨ Albedo ≈ 0.45 and E-type (Fornasier et al. 2006)




**Levasseur-Regourd & Hadamcik 2003**




**Pentillä et al. 2005**

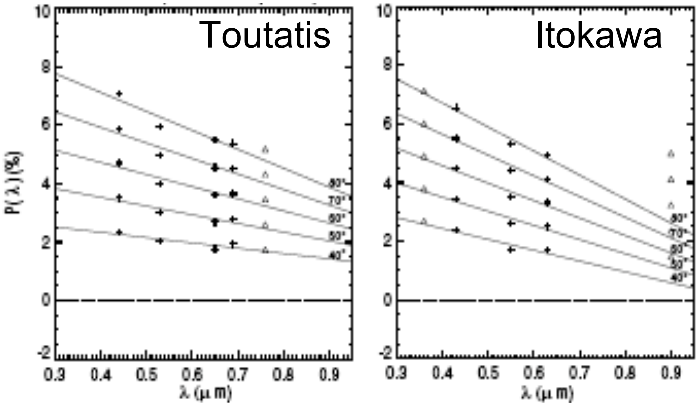


# 7. Optical properties: Observations of asteroids (λ)

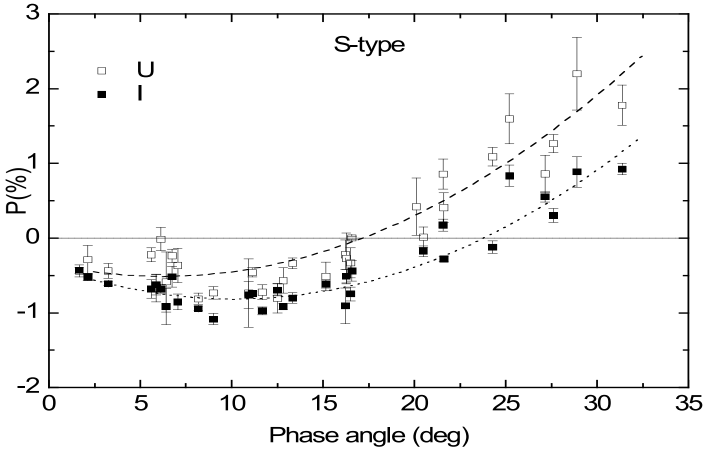
• Well documented for 4179 Toutatis (Lupishko et al. 1995, Mukai et al. 1997, Ishiguro et al. 1997) & 25143 Itokawa (Cellino et al. 2005)

• Polarisation significantly **decreasing with increasing** **λ** for S-type

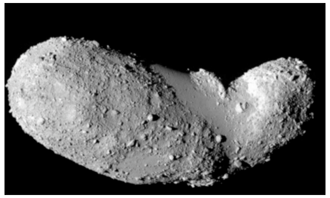
• However, from ongoing polarimetric observations (e.g. from OHP observatory), polarisation likely to increase with increasing λ for C-type




**Levasseur-Regourd et al. 2003**

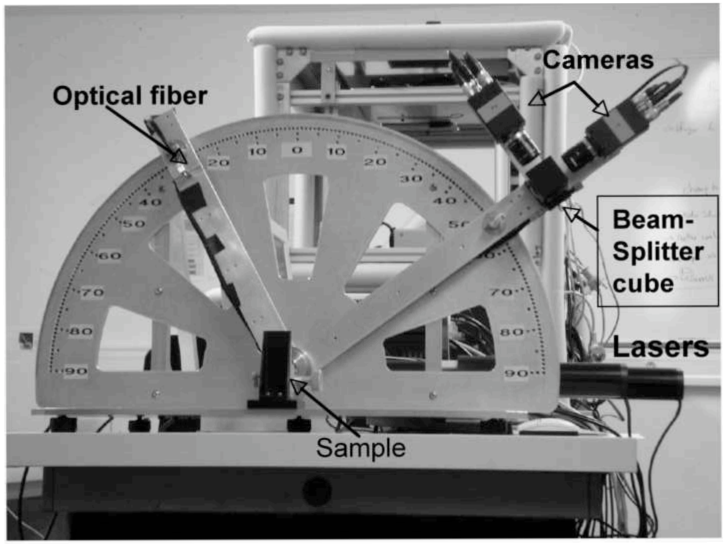



**Belskaya et al. 2008**

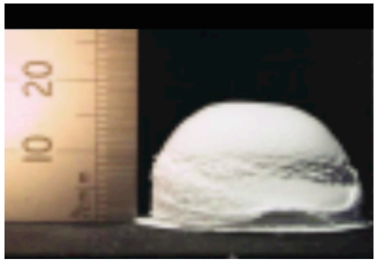


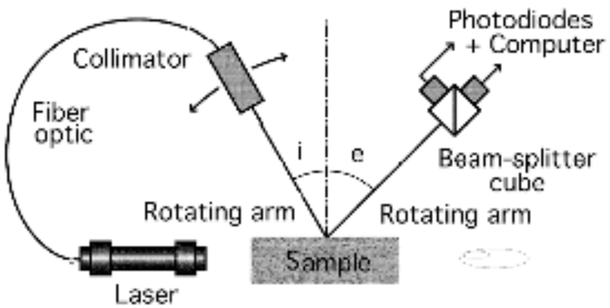
# 7. Optical properties: Asteroidal regoliths simulations

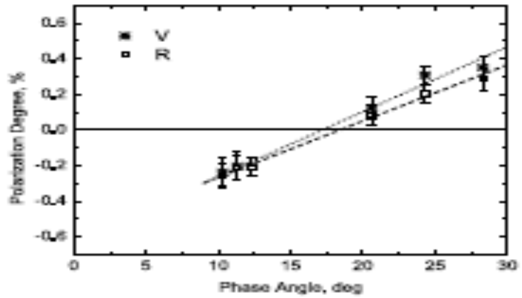

- Numerical simulations on irregular regolith layers not (yet?) feasible
- Measurements with **PROGRA²-surf** on dust layers (Hadamcik et al. 2008)
- Tests with huge agglomerates (filling factors of about 0.15) prepared by Braunschweig University
- Tentative confirmation of the faint polarization color trend observed for Steins on aubrites samples (expected to originate from E-type objects)




Hadamcik et al, 2008



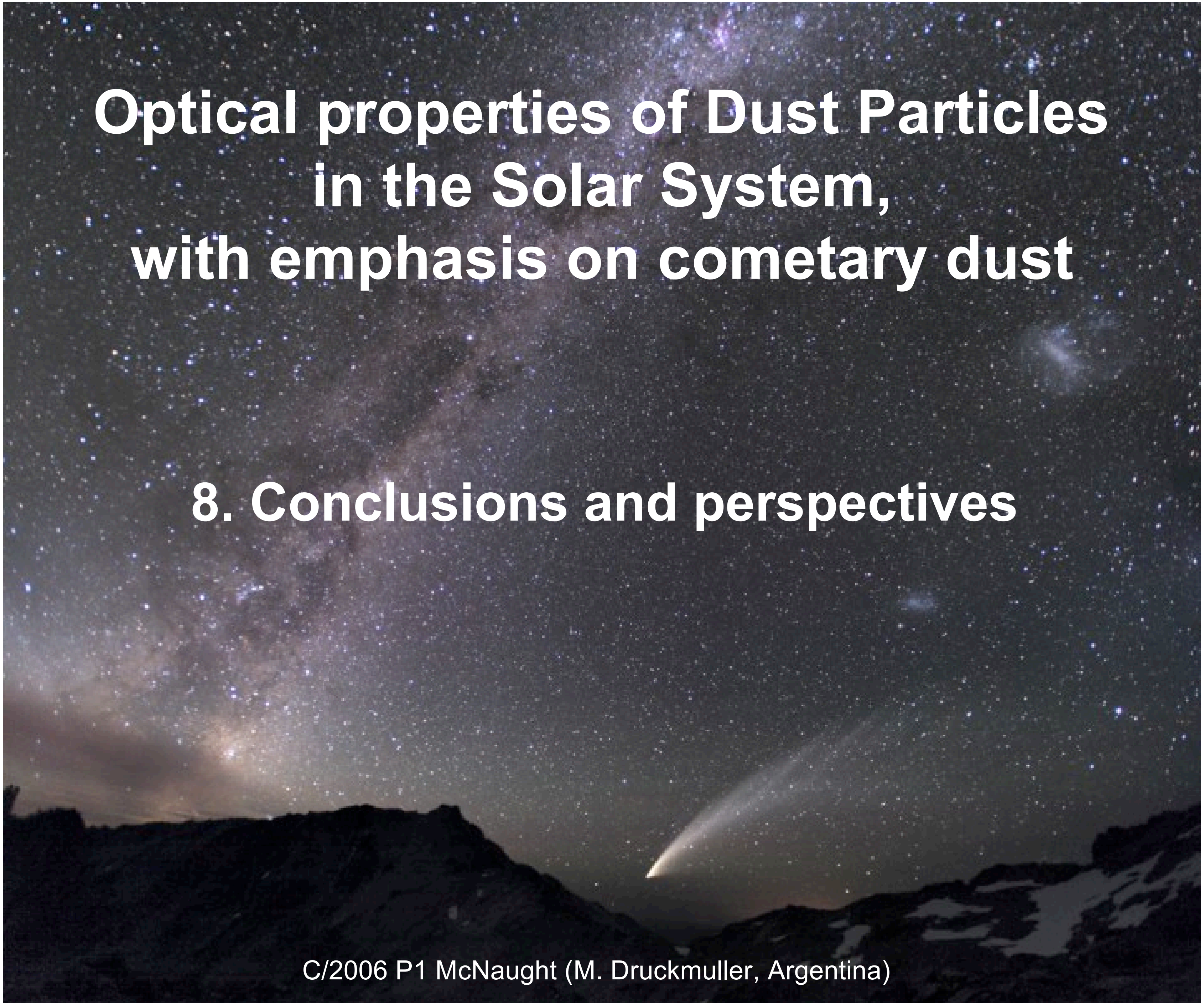



Fornasier et al, 2006

# Optical properties of Dust Particles in the Solar System, with emphasis on cometary dust

## 8. Conclusions and perspectives



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# 8. Conclusions

• Space missions, and specially sample return missions, present unique opportunities to reveal the dust properties of a few solar system bodies

• The analysis of (remote) observations of the linear polarization of the solar light they scatter gives clues to the properties of these various media

• Heterogeneities in terms of dust properties are found between
- innermost comae and comae
- different comets (high and low $P_{max}$ comets)
- dust in the coma and “fresh” dust from the subsurface

• Comparisons between the shapes of the polarimetric phase curves provide a classification with respect to the dust properties

• Extensive programmes of numerical and laboratory simulations with various irregular compact grains and aggregates are being developed by various teams…

# 8. Conclusions

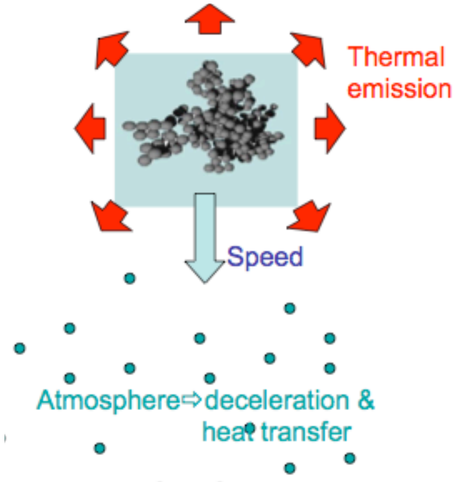
• The programmes of numerical and laboratory simulations with various irregular compact grains and aggregates have already established that

- cometary dust particles are built of both very fluffy aggregates and more compact grains, with a significant proportions of both rather transparent silicates and absorbing materials
- a significant proportion of interplanetary dust is rich in absorbing organics (evaporating close to the Sun), of cometary origin

• Such properties might suggest

- significantly **high micro-porosity of low-density nuclei** (Levasseur-Regourd et al., 2008)
- possible **survival of cometary organics** embedded in fluffy aggregates in terrestrial planets atmospheres, **by LHB time**

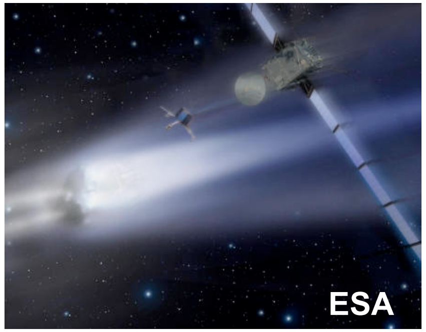
**Lasue et al. 2009**

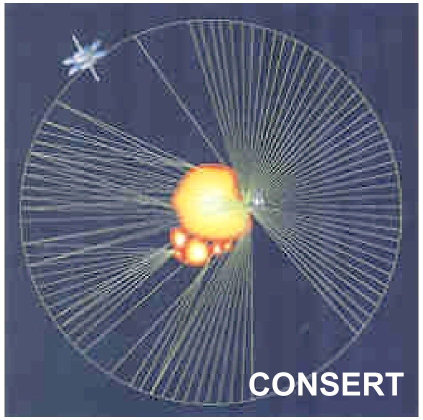


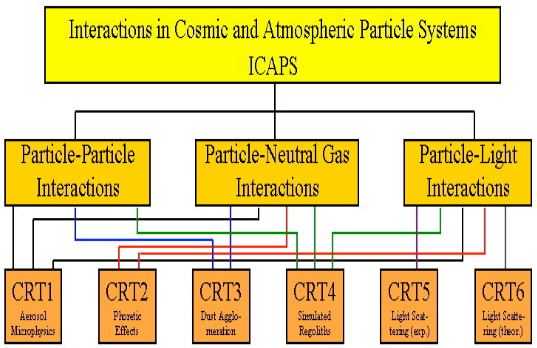

Atmospheric ablation for fluffy aggregates

# 8. Perspectives…

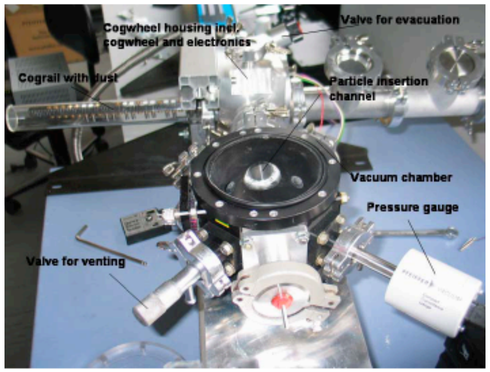
- More on-going remote observations of comets
- More zodiacal light remote observations with Akari
  Also in-situ observations, parallel to Planet C trajectory
- In 2014-2015, **Rosetta** rendezvous with and landing on 67P/Churyumov-Gerasimenko
  - dust in the coma (MIDAS, GIADA, OSIRIS…)
  - nucleus structure (CONSERT)
- More experimental simulations to take place in the lab
  Also possibly on board the ISS with **ICAPS** precursor?
- Marco-Polo mission to a primitive body (ESA-JAXA) ?




ICAPS



# 8. Perspectives

Some important aims for future studies

- **Numerical simulation of light scattering through irregular dust particles layers (i.e. multiple scattering)**
- **Laboratory simulations on realistic ices and dust mixture, possibly in low gravity conditions**
- **Better links with interstellar dust and dust debris studies**

⇨ Useful information on formation and physical processes, e.g.
accretion and agglomeration,
dust ejection and fragmentation,
sublimation of organics, collisions,
gravitational and non-gravitational effects

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# Thank you for your attention

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