Astrophysical light scattering problems (PAP316)

Lectures 5a & 5b

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Introduction (1/2)

- Physical characterization of astronomical objects (e.g., surfaces of airless planetary objects)
- Direct problem of light scattering by particles with varying particle size, shape, refractive index, and spatial distribution
- Inverse problem based on astronomical observations and/or experimental measurements
- Plane of scattering, scattering angle, solar phase angle, degree of linear polarization

Introduction (2/2)

- Comets
  - low-density km-sized objects of ices (mostly H_2O, CO_2, CO) and dust (silicates, carbon, organics)
  - nucleus, coma, tails
  - “dirty iceballs” or “icy dustballs”
- Polarimetry
  - single scattering in cometary comae
  - powerful, relevant computational techniques available (Discrete-Dipole Approximation, Superposition T-Matrix Method)
  - Experimental measurements using particle flows and microgravity environments

- Polarimetry
  - major role in cometary science
  - nearly full phase-angle coverage
  - negative and positive polarization
  - classification
  - spectral dependence in visible and near-IR
  - polarization for forward scattering using Sun-grazers
  - nonzero circular polarization with predominantly left-handed helicity
  - possibility of combining remote spectrophotometric and polarimetric data with in situ data

Methods of modern observations

- Aperture polarimetry
  - dominant before the CCD era
  - broadband filters bring up dust component
  - narrow-band cometary filters allow for separating dust and gas signals
- Imaging polarimetry
  - detailed distribution in the comae
  - works well for comets at small geocentric distances
  - broadband filters needed for distant comets
- Spectro-polarimetry
  - long-slit polarimetry rare for comets
  - allows to identify continuum and emission bands
- Near-IR polarimetry
  - gas contamination negligible in J, H, K filters
  - many comets observed
- Spaceborne and in situ polarimetry
  - SOHO LASCO coronagraph in H-alpha for 96P/Machholz 1
  - Giotto for 1P/Halley and 26P/Grigg-Skjellerup

Main trends in linear polarization

- Phase-angle-dependence of linear polarization in the visible
  - high-polarization vs. low-polarization comets
  - high-polarization comets show similar dependences
  - coma dust particles likely to be similar
  - exceptions: see Fig. 22.1
  - slight dependence on aperture

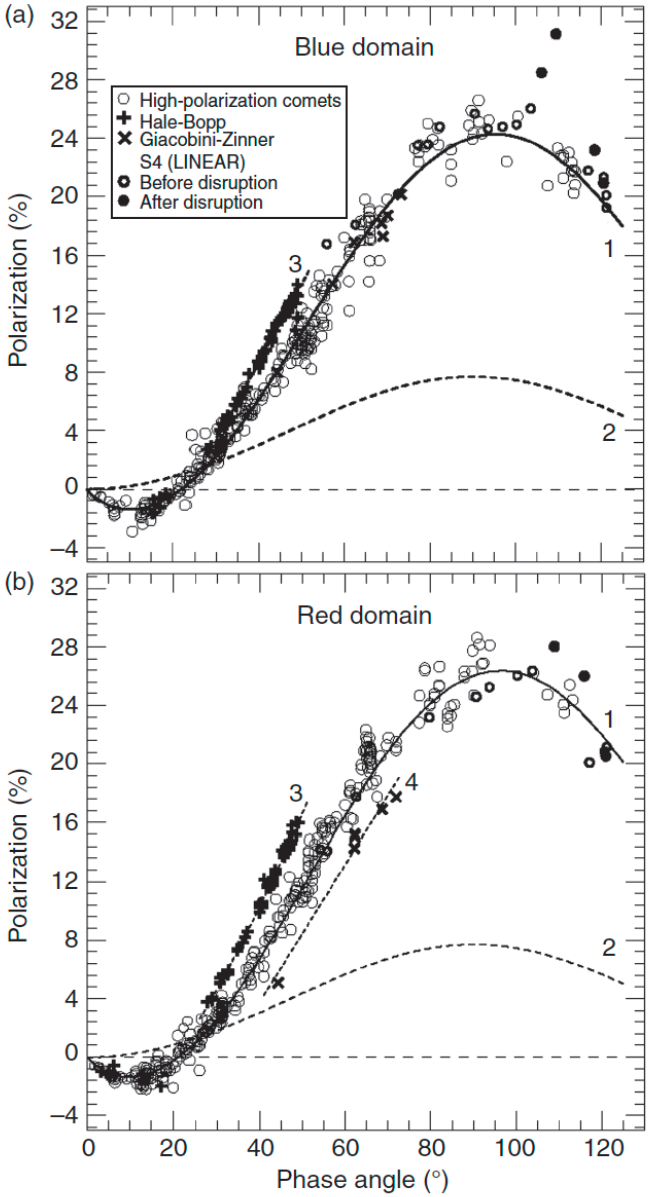

FIGURE 22.1 The phase-angle dependence of polarization for comets in the blue (a) and red (b) continuum. Curve 1 is the fit to data for high-P_{max} comets; curve 2 shows theoretical results for diatomic molecules according to Eq. (1); curve 3 is the fit to the comet Hale–Bopp data; curve 4 is the fit to the comet Giacobini–Zinner data.

- Phase-angle dependences continued
  - large variations in polarization for low-polarization comets, in particular, for >40°
  - low-polarization comets show large dependence on aperture: polarization increases with decreasing field of view

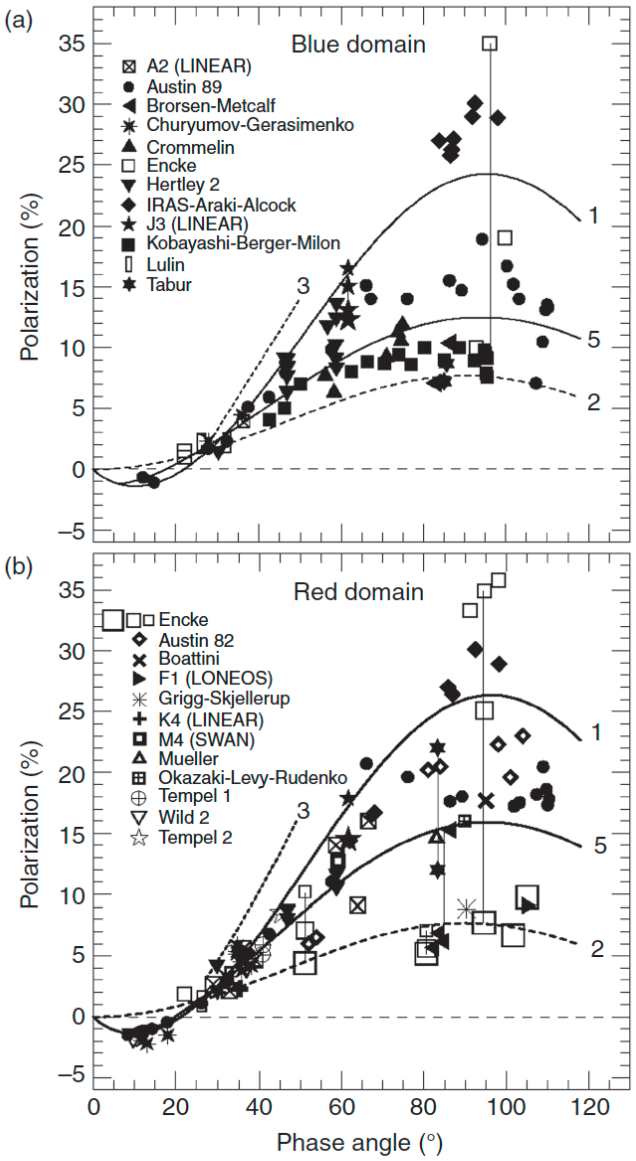

FIGURE 22.2 The polarization vs. phase angle for the low-P_{max} comets in the blue (a) and red (b) continuum. The curves 1, 2, and 3 are the same as in Fig. 22.1. Curves 5 are the fits to all polarization data for low-P_{max} comets with large apertures in the blue and the red. The vertical lines show the dependence of the polarization on aperture size for comets 2P/Encke, D/1996 Q1 (Tabur), and C/1999 J3 (LINEAR) as well as on the bandpass of the red filter for comet 23P/Brorsen–Metcalf.

- Phase-angle dependence in the near-IR
  - for Hale-Bopp, negative polarization branch virtually absent: Rayleigh domain

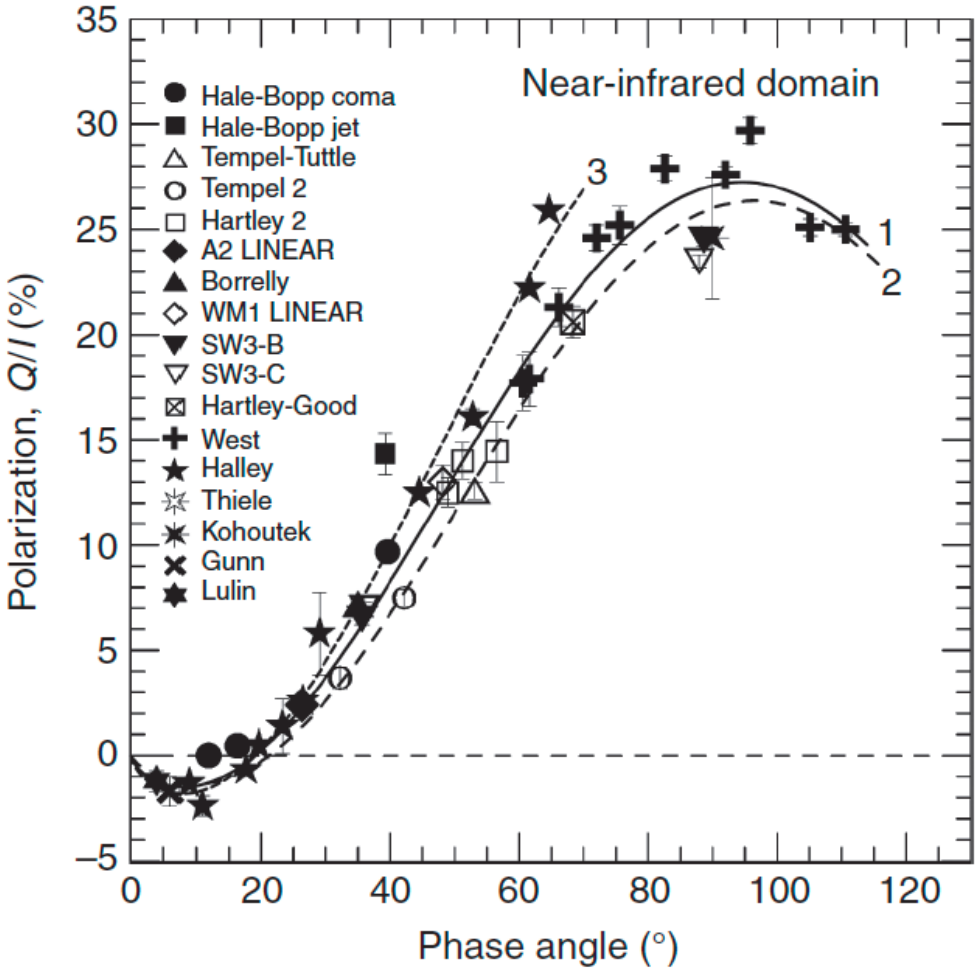

FIGURE 22.3 Phase-angle dependence of polarization for comets in the near-IR. Curve 1 is the average polarization curve for comets in the near-IR; curve 2 is the mean phase dependence of polarization taken from Fig. 22.1(b) for the high-P_{max} comets in the red; curve 3 is the fit to the polarization data of comet Halley in the K band.

- Spectral dependences of polarization
  - in the visible, most comets exhibit increase of polarization with wavelength at 30-80^{o}
  - positive, red polarimetric color
  - the negative branch becomes shallower in the near-IR (again, red polarimetric color)

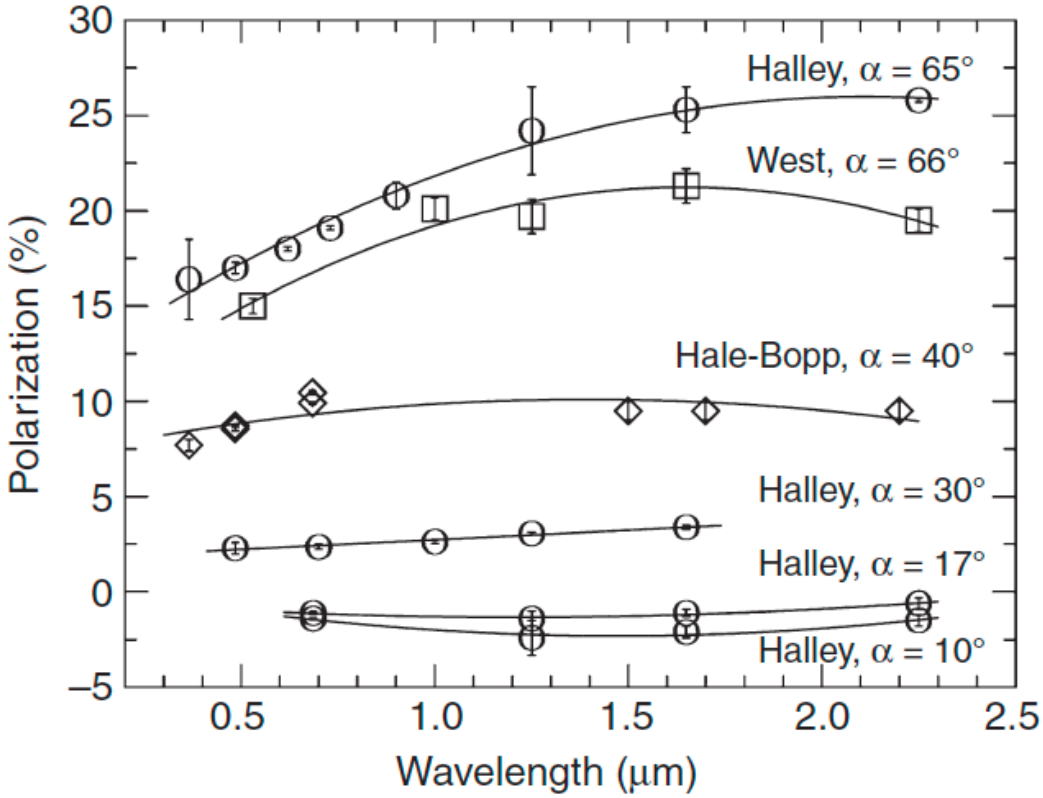

FIGURE 22.4 Typical spectral dependences of polarization for comets C/1975 V1 (West), C/1995 O1 (Hale–Bopp), and 1P/Halley at different phase angles. The curves are polynomial fits.

- Spectral dependences of polarization, exceptions
  - decreasing polarization with wavelength for 38-60° for five comets

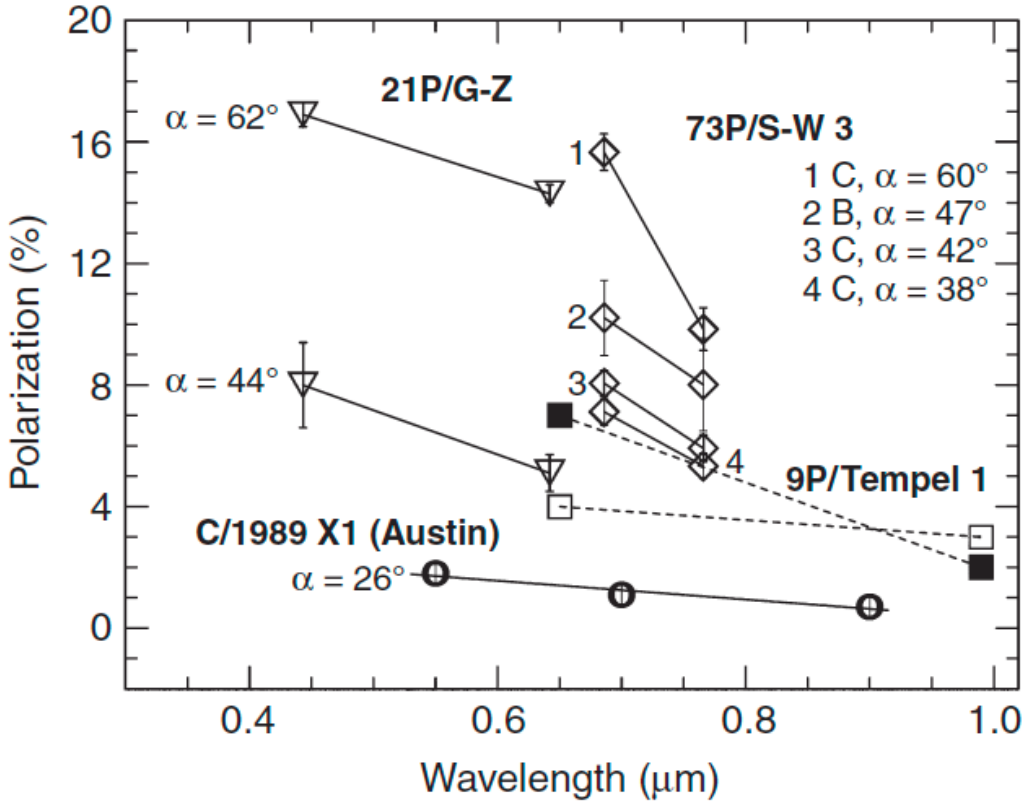

FIGURE 22.5 Non-typical spectral dependences of polarization for comets C/1989 X1 (Austin), 21P/Giacobini–Zinner, B and C fragments of 73P/Schwassmann–Wachmann 3, and 9P/Tempel 1 at a variety of phase angles. Open and filled squares show polarimetric color of comet 9P/Tempel 1, 40 minutes and 1.5 hours after the Deep Impact event, respectively.

TABLE 22.1 Comets with non-typical polarization color

Comet	$\Delta P/\Delta\lambda$ %/μm	Organic comp./ dyn. class, family
GZ	–15	atypical /SP, KB
73P/SW 3	–28	atypical /SP, KB
Tempel 1	–9 ± 2÷–23 ± 3	atypical /SP, KB
Austin 89	–7	atypical/DN, OC
S4	–14	atypical/DN, OC

In situ measurements

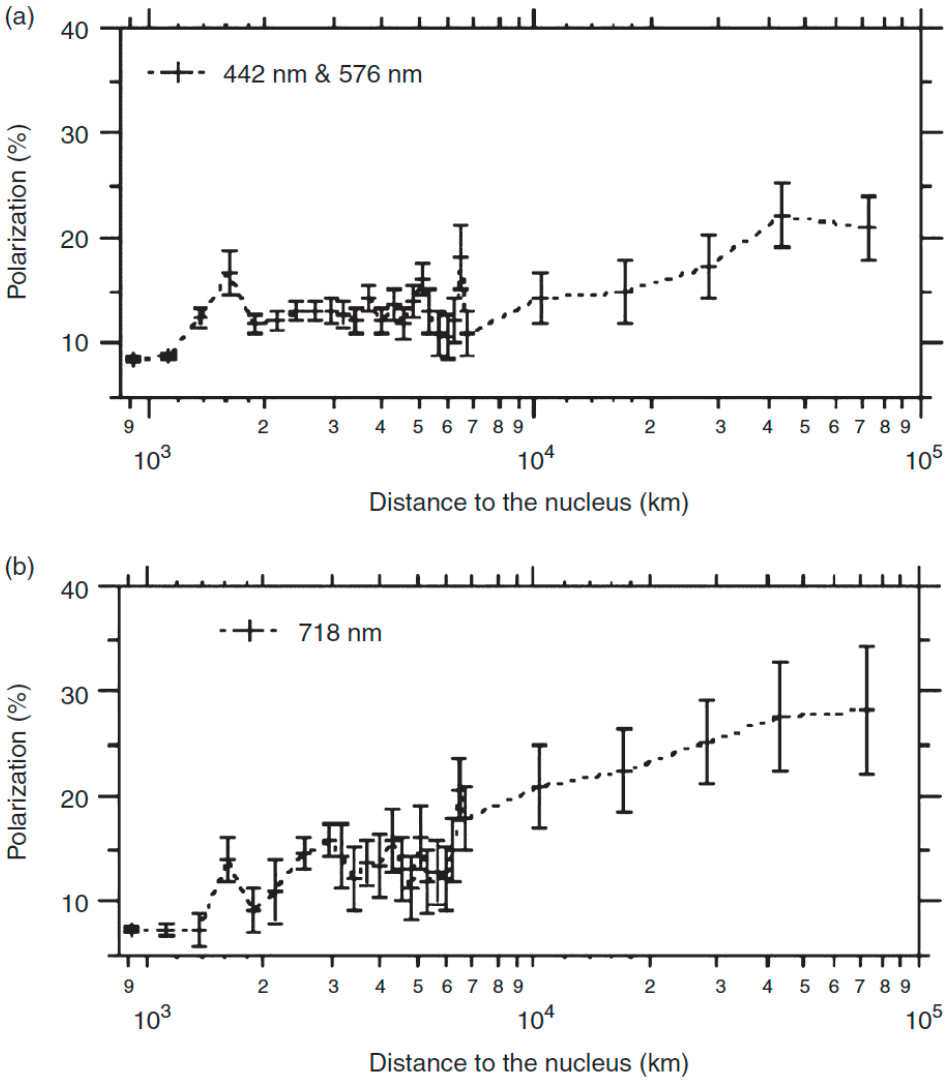

FIGURE 22.6 Changes in linear polarization with distance to the nucleus of 1P/Halley, along the Giotto spacecraft trajectory in the coma. Enhancements are seen at the crossing of jets; polarization is lower in the innermost coma.

From Levasseur-Regourd 2011; reproduced with kind permission from Springer Science and Business Media.

- 1P/Halley monitored with Halley Optical Probe Experiment (HOPE)
- sequential observations along the spacecraft track allow for localized polarization measurement

Distribution of polarization over the coma

- Three different regions were identified for Hale-Bopp
  - background coma
  - polarimetric halo near photocenter (lower positive polarization)
  - jet-like or arc-like features with higher polarization

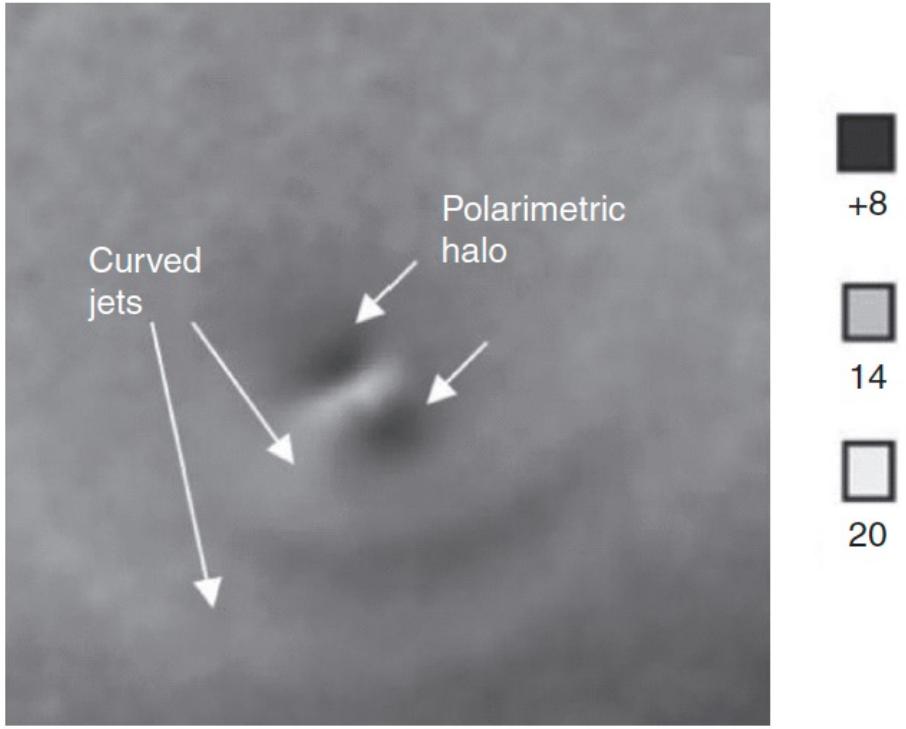

FIGURE 22.7 Polarimetric image of C/1995 O1 (Hale–Bopp) observed in 1997 (field of view 82 000 km^2; phase angle 43.6°; red continuum). Variations in dust properties result in a lower polarization halo in the innermost coma and in a higher polarization in the curved jets.

From Levasseur-Regourd (2014).

Specific phenomena in linear polarization

- Outburst and fragmentation events
  - fresh internal material coming to sight
  - variations in polarization observed and modeled
- Stellar occultations
  - nonzero linear polarization detected for zero-polarization stars when observed through comae
  - partially aligned nonspherical dust particles

Interpretation of linear polarization data

- Phase-angle dependence
  - compact regular particles
    - some early success with Mie spheres
  - agglomerates of small grains
    - substantial recent success with DDA and STMM
    - cosmogonic controversies: what can be assumed for the constituents?
  - mixture of compact and aggregated particles
- Spectral dependence
  - Rayleigh scattering, efficiency changes with x^4
  - spectral dependences otherwise hard to conceptualize
- Requirements
  - acceptable photometric and polarimetric fits
  - realistic geometric albedo, color, polarimetric color, and cosmogonic organics/silicates ratio, monomer sizes in aggregates
  - agreement with space mission data for aggregated vs. compact particles

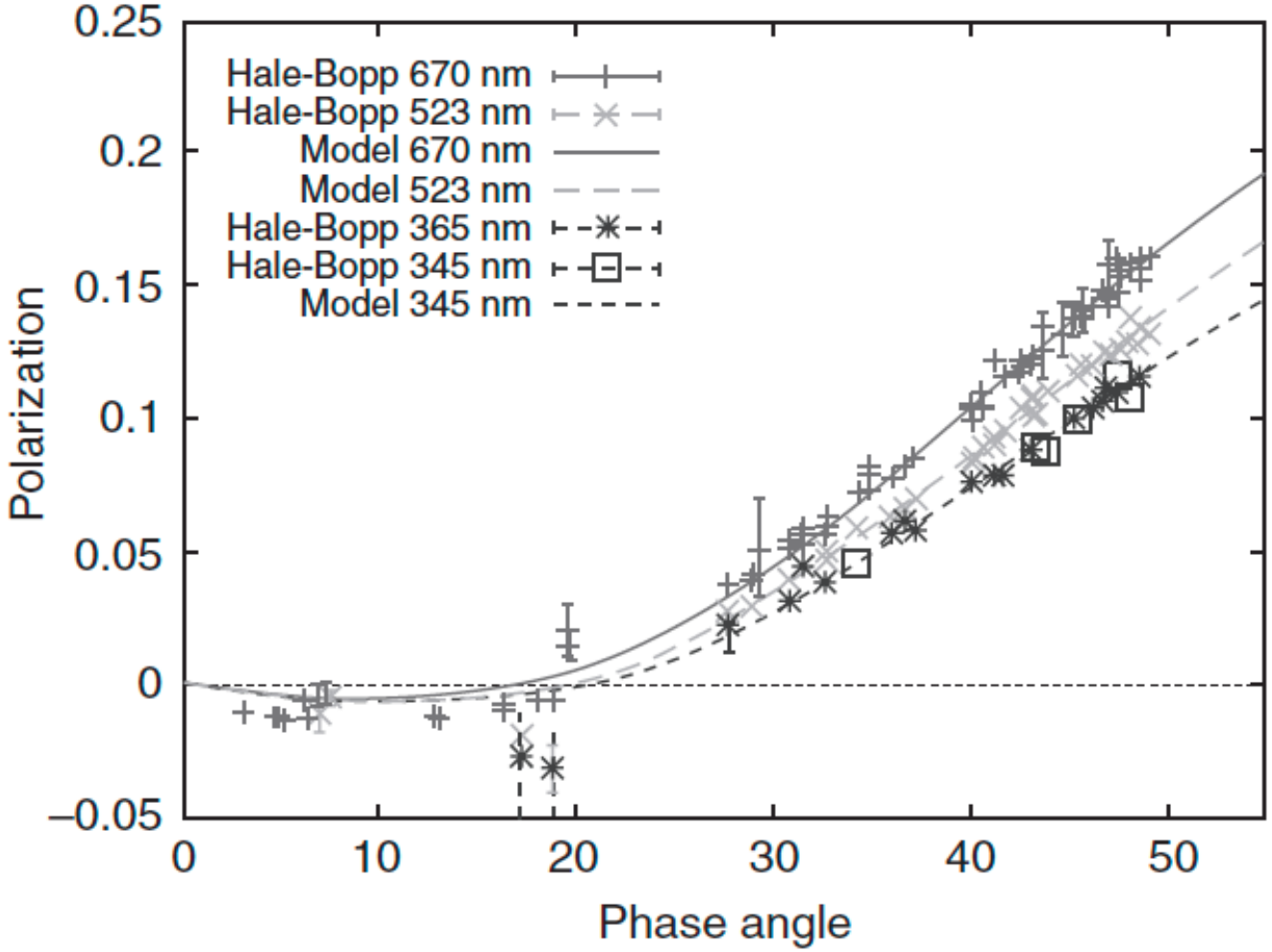

FIGURE 22.8 Observed (symbols) and modeled (lines) dependence of polarization for comet Hale–Bopp for several wavelengths.

From Levasseur-Regourd *et al.* (2008).

Comet nuclei

- Extremely important to study polarimetrically
- 2P/Encke
  - inversion angle agrees with that of F-type asteroids
  - slope at inversion angle substantially higher for F-types
  - red nucleus vs. bluish F-type asteroids
  - nucleus different from any other Solar System object
- 133P/Elst-Pizarro
  - phase-angle dependence similar to F-types

Circular polarization

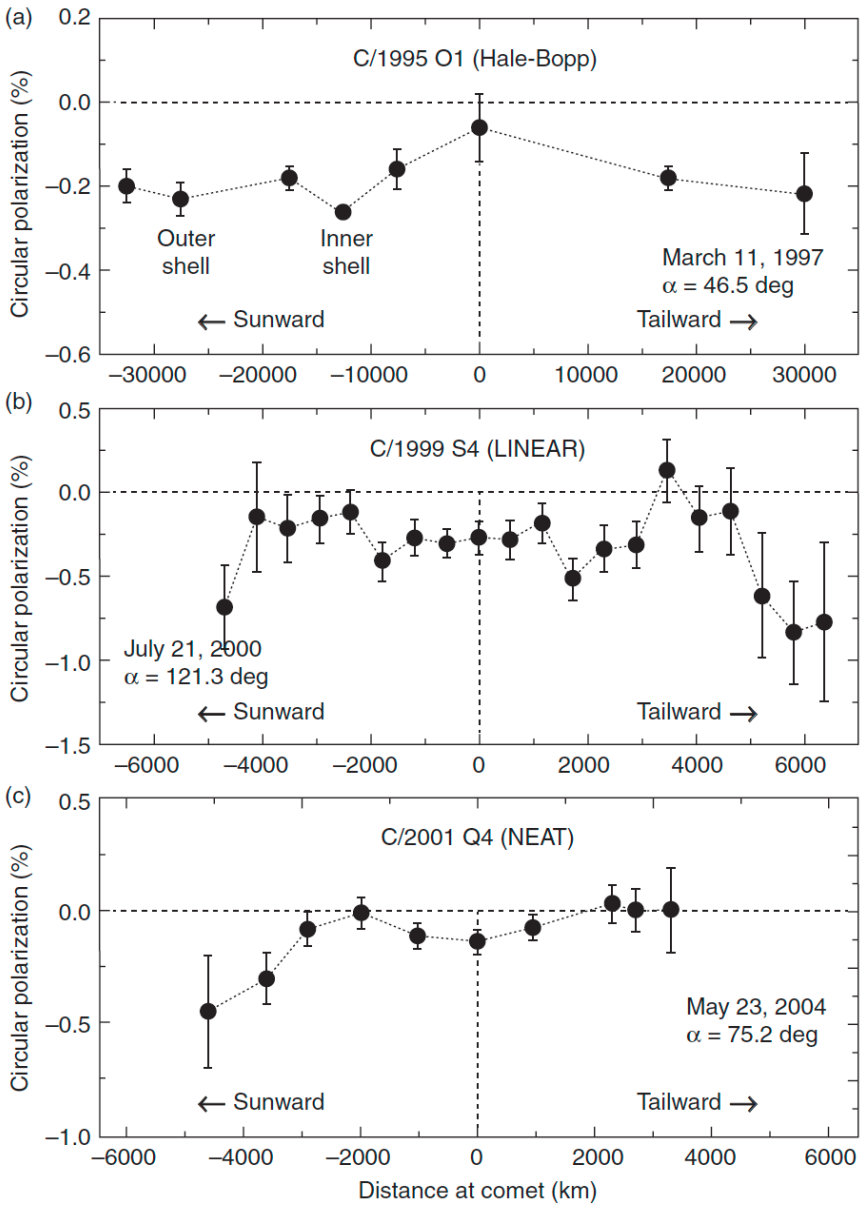

FIGURE 22.9 Variations of the degree of CP along a cut through the coma and nucleus of comets (a) C/1995 O1 (Hale–Bopp); (b) C/1999 S4 (LINEAR); and (c) C/2001 Q4 (NEAT). Error bars indicate the standard deviation of the mean value of polarization.

Reproduced from Mishchenko *et al.* (2010) with kind permission of *Akademperiodyka* of the NAS of Ukraine.

- Confirmed for comets with high confidence
- Difficult to interpret
  - violation of mirror symmetry in the medium or in the scatterers
  - optical activity, presence of chiral molecules
  - no mechanism identified in protoplanetary disks to favor certain handedness

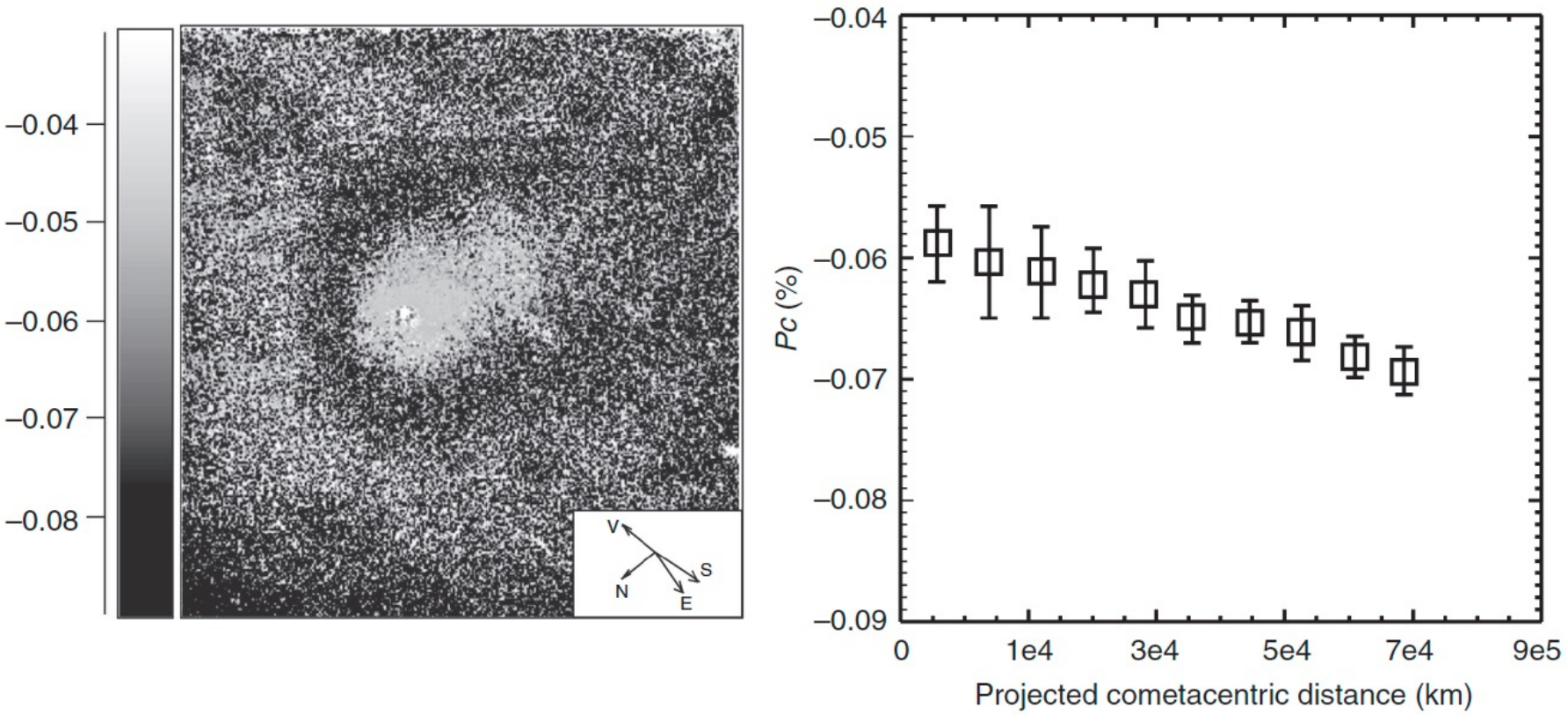

FIGURE 22.10 Circular polarization of comet C/2011 R1 (McNaught). Polarization map (left) and an average CP in 20-px-wide (~7″ at the comet) circular apertures (right) are shown vs. the distance from the comet nucleus.

TABLE 22.2 Mean values of CP in comets

Comet	Year	$P_c \pm \sigma P_c$, %	Phase angle, degrees
Halley[6]	1986	(+0.3 ÷ –0.5) ± 0.15	22–41
Hale–Bopp[6]	1997	(+0.2 ÷ –0.26) ± 0.02	40–47
S4 LINEAR[6]	2000	(+0.7 ÷ –0.8) ± 0.07	61–122
Q4 NEAT	2005	–0.1 ± 0.05	75–77
73P/S–W 3 (B)	2006	–0.2 ± 0.2	92
8P/Tuttle	2008	–0.60 ± 0.07	67.6
9P/Tempel 1	2005	–0.05 ± 0.02	41.2
Garradd	2012	(–0.07 ÷ –0.25) ± 0.02	35
29P/S–W 1	2012	–0.04 ± 0.01	6.2
PANSTARRS	2013	–0.08 ± 0.01	36
McNaught	2013	–0.07 ± 0.03	12.4

Note: The symbol ÷ signifies the range between two numbers.

Similarity and diversity of comets: classification issues

- High-polarization vs. low-polarization comets
  - warning: not agreed upon by all researchers
  - dust-to-gas ratio
  - evolution of dust and gas

Conclusions

- Dust aggregate model capable of describing photopolarimetric properties in the bulk comae
- Based on Stardust mission and numerical and experimental simulations, comet dust is likely to consist of dark aggregates and silicate solid particles
- Difference in polarization maxima attributed to the domination of smaller or more porous particles for high-polarization comets and the domination of large compact particles in low-polarization comets
- Nonzero circular polarization discovered in a number of comets but the physical mechanism is under discussion

Perspectives

- Observations
  - high-resolution spectropolarimetric observations over large phase-angle ranges
  - high-resolution polarization and color maps
  - time-dependent observations to study evolution
- Instrumentation
  - polarimeters designed for comets
  - polarimeters for space missions (Comet Interceptor has a polarimeter)
- Interpretation
  - interpretation based on spectral dependences
  - consistency with photometric, thermal infrared, dynamic, cosmogonic, in situ data