POLARIMETRY OF COMETS: OBSERVATIONAL RESULTS AND PROBLEMS

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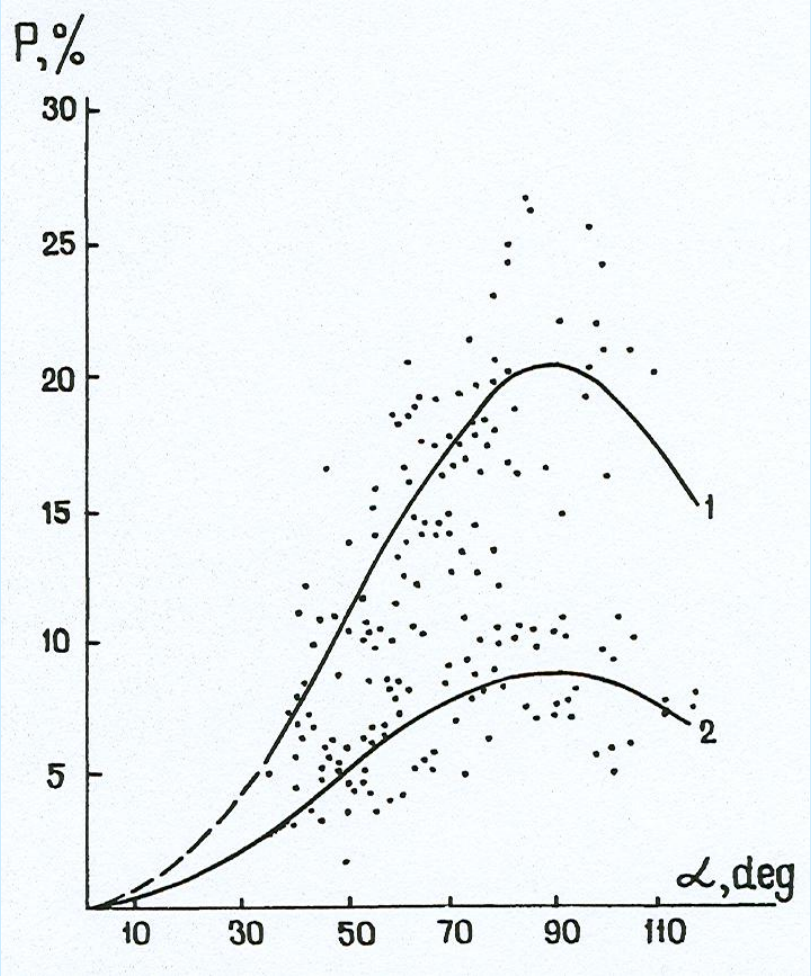
1st WG meeting in Warsaw, Poland, 7-9 May 2012

Outline of presentation

- ✓ Linear polarization of comets.
- ✓ Problems with the interpretation of diversity in the maximum polarization of comets.
- ✓ Circular polarization of comets.
- ✓ Next task

Polarimetric data for comets up to the mid 1970s (Kiselev, 1981; Dobrovolsky et al.,1986)



The polarization of molecular emissions was explained as being due to resonance fluorescence (Öhman, 1941; Le Borgne et al., 1986)

$$P(\alpha) = \frac{P_{90}\sin^2\alpha}{1+P_{90}\cos^2\alpha}\ , \text{where}\ \ P_{90} = 0.077$$

Curve (2) is polarization phase dependence for the resonance fluorescence according to Öhman's formula.

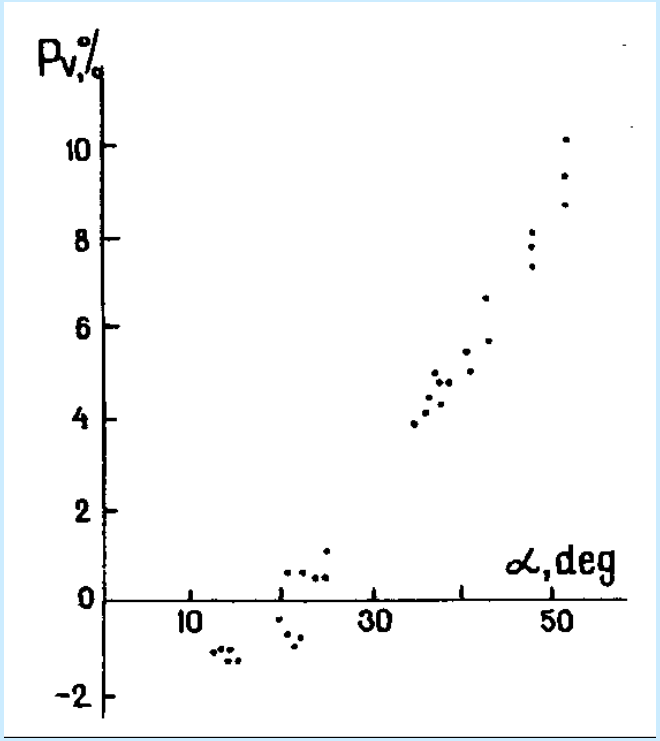
Curve (1) is a fit of polarization data in continuum according to Öhman's formula.

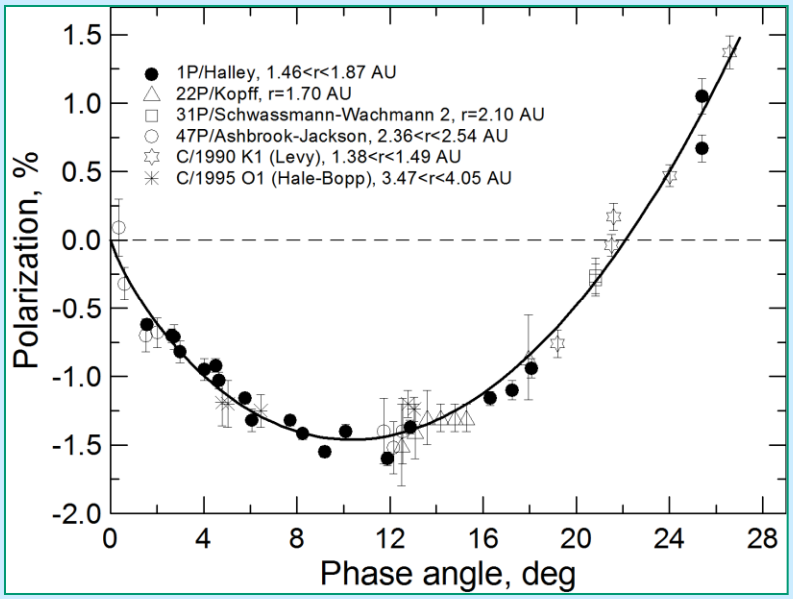
There are no observations of comets at phase angles smaller than 40° until 1975.

Open questions:

- **What is polarization phase curve for dust near opposition ?**
- **What is the maximum of polarization?**
- **Is there a diversity in comet polarization?**

Comets: negative polarization branch

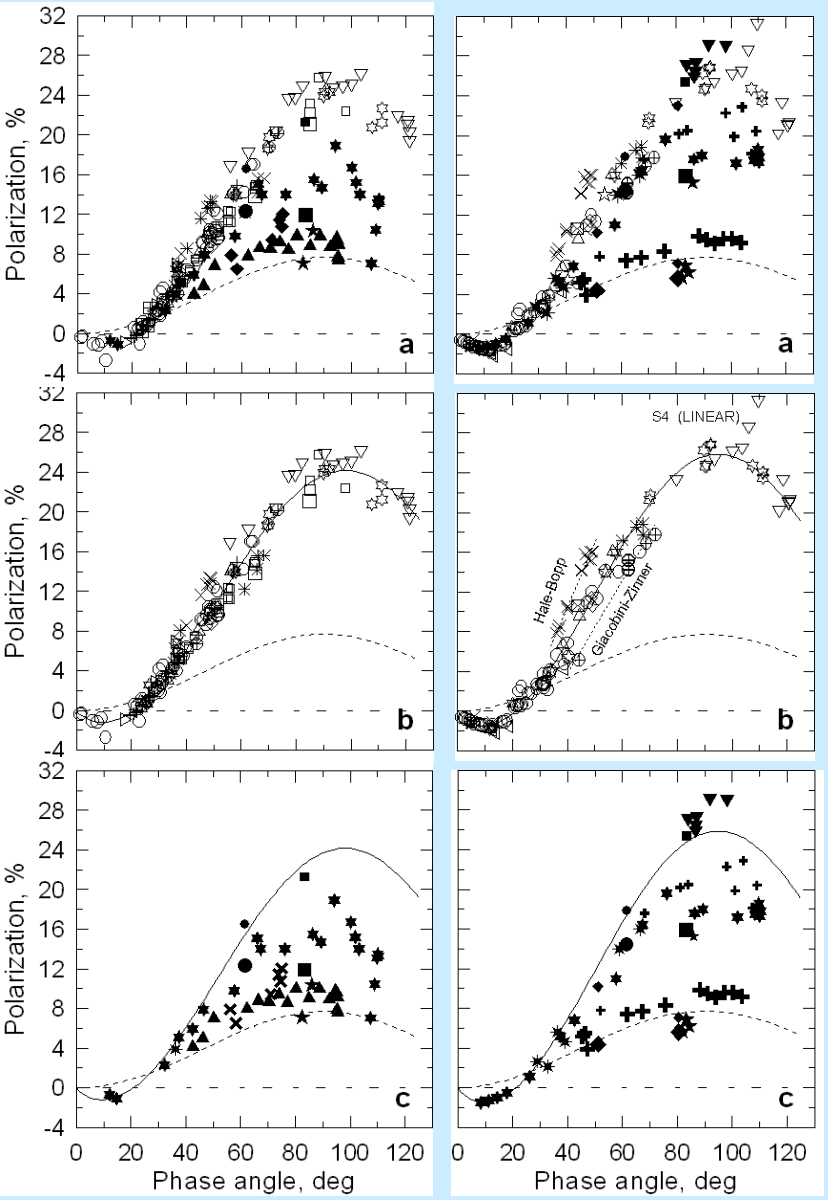




Observations of comet West revealed a negative branch of linear polarization at phase angles $\alpha \leq 22°$.
(Kiselev&Chernova, 1976)

Discovery of the NPB gave impetus to development of new optical mechanisms to explain its origin. Among them, the scattering of light by particles with aggregate structure.

Phase angle dependence of polarization for comets in the blue and red continuum (Kiselev, 2003)



blue red

All comets

Dust-rich comets (high dust/gas ratio)

Gas-rich comets (low dust/gas ratio)

The observed difference in the polarization of the two groups of comets is apparent. Why is this? There are three points of view:

- The polarization of each comet is an individual (Perrin&Lamy, 1986).
- The existence two (or even three) polarimetric classes of comets (according to the value of maximal polarization) with significant differences in the bulk properties (albedo, size distribution, porosity) of dust (Levasseur-Regourd&Hadamcik, 2003).
- Division of comet into two polarimetric classes with one class having a maximum polarization less 20 % is caused by ignoring the contribution of molecular emission and therefore is an artifact. (Kiselev, 2003; Jockers et al., 2006).

Pro et contra for two polarimetric classes of comets derived directly from observations

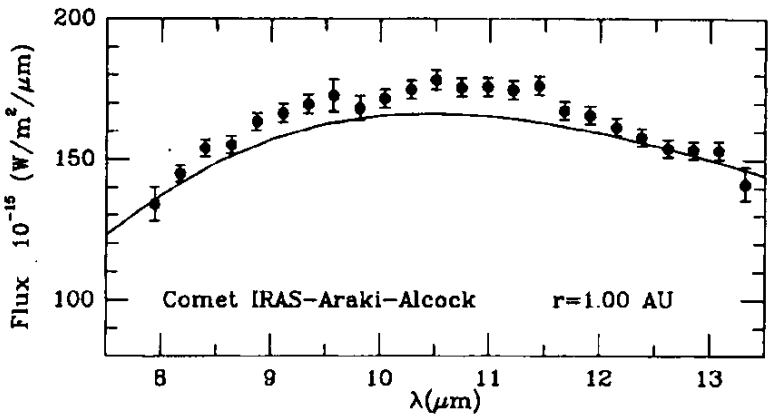


FIG. 1*b*

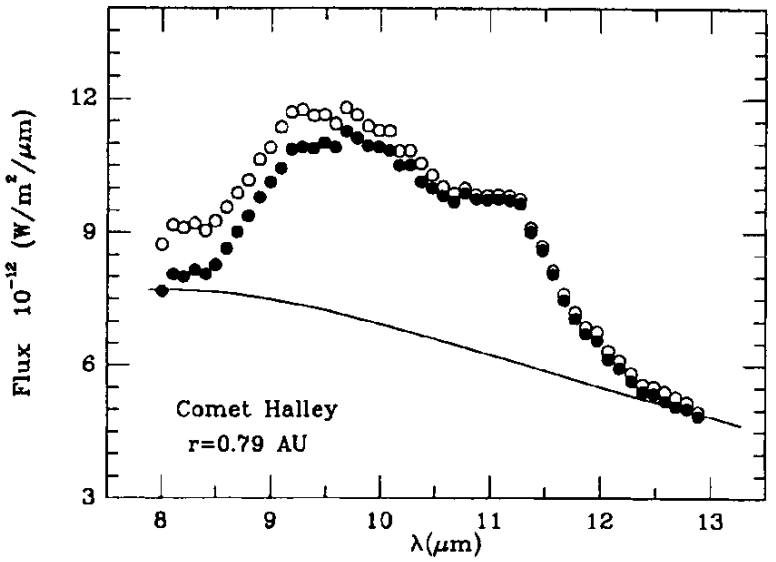
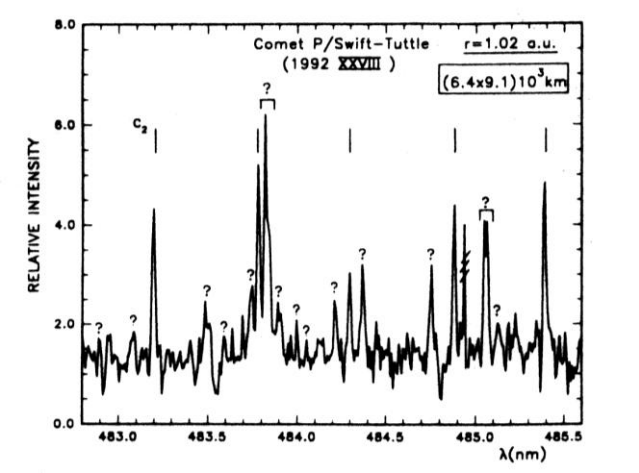


FIG. 1*d*

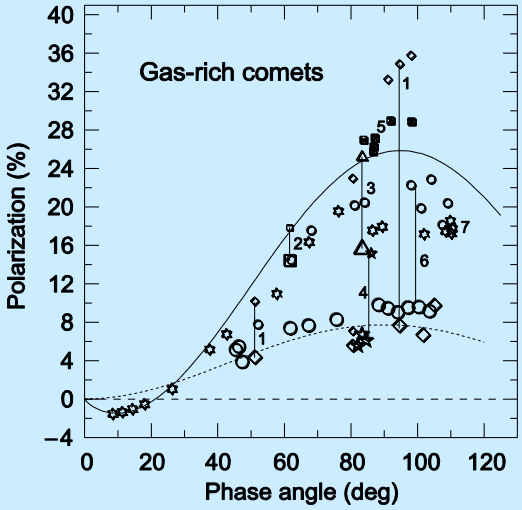
- **Correlation between a high degree of polarization and infrared color temperature for dusty comets (small particles).**
- **The low degree of polarization and the absence of an excess of color temperature for the gas comets (large particles).**

Observed fluxes near 10 mμ (symbols) and spectra for blackbody (solid lines) for gas-rich comet IRAS-Araki-Alcock and dust-rich comet Halley (Hanner et al., 1994).

Pro et contra for two polarimetric classes of comets derived directly from observations

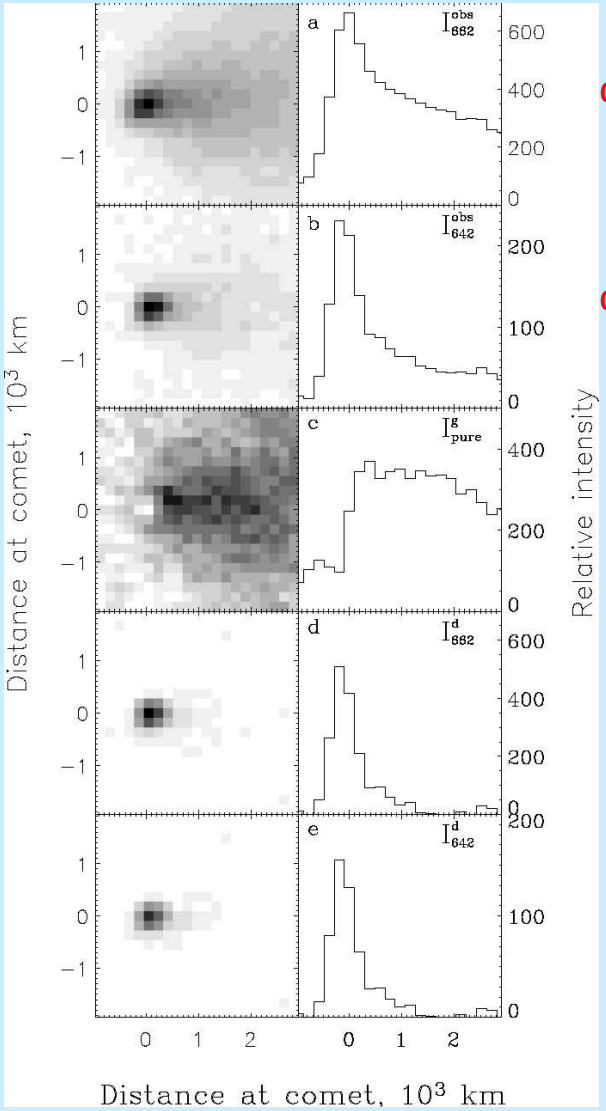


The unidentified lines was detected on high resolution CCD spectra (Arpigny, 1995).



- **The question arises - is there a continuum in gas-rich comets? There is a real depolarization of scattered light by the cometary grains due to contamination by gas. (Kiselev et al., 2001).**
- **Distribution of dust and gas in coma are very different. In the circumnuclear (<600 km) area of gas-rich comets is dominated by dust, whereas at nucleocentric distances >1000 km the dust-to-gas ratio is small, and the resulting polarization is dominated by the weakly polarized molecular emissions.**
- **Not all comets show a correlation between a high degree of polarization and infrared color temperature.**

Images and profiles of intensity and polarization along coma of gas-rich comet 2P/Encke (Jockers et al., 2006)



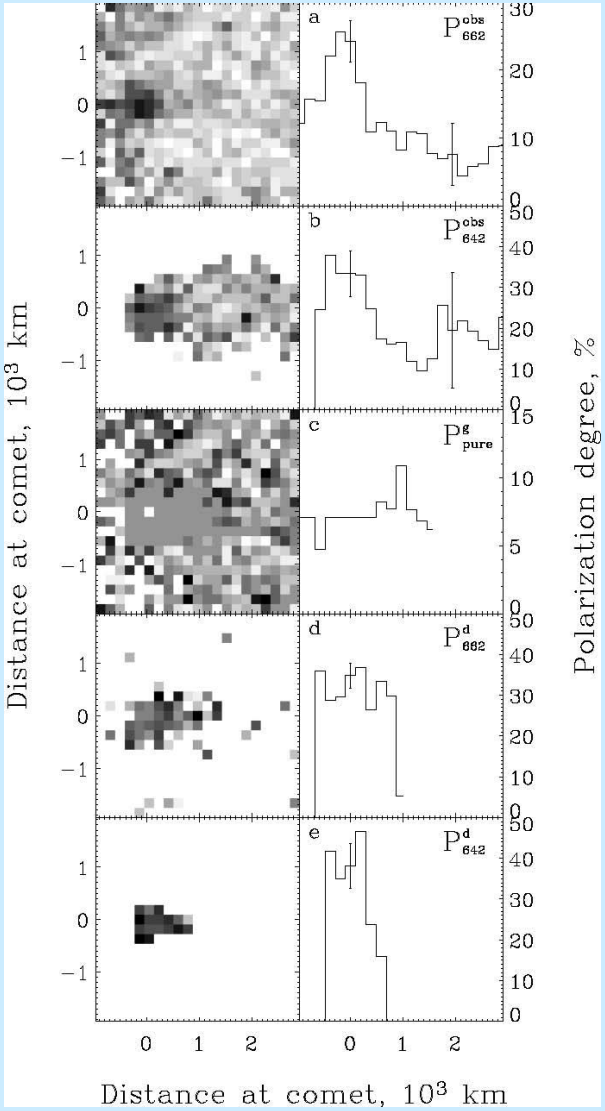
dust+emission

dust+emission

emission

dust

dust



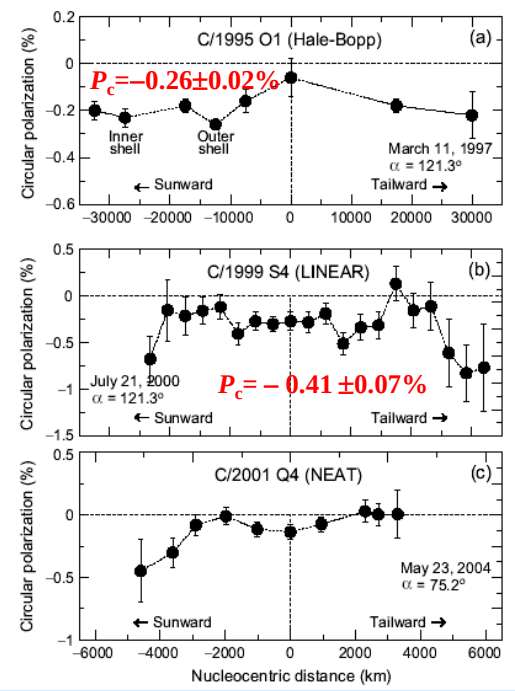
Polarization of the gas-rich comets averaged over large aperture is low.

Polarization of the gas-rich comets in the circumnuclear area is as high as that for the dusty comets.

Conclision

The *apparent* separation of comets into groups based on polarimetric data at large phase angles is an artifact caused by the low spatial and spectral resolution of the instrumentation traditionally used in cometary observations.

Circular polarization for comets

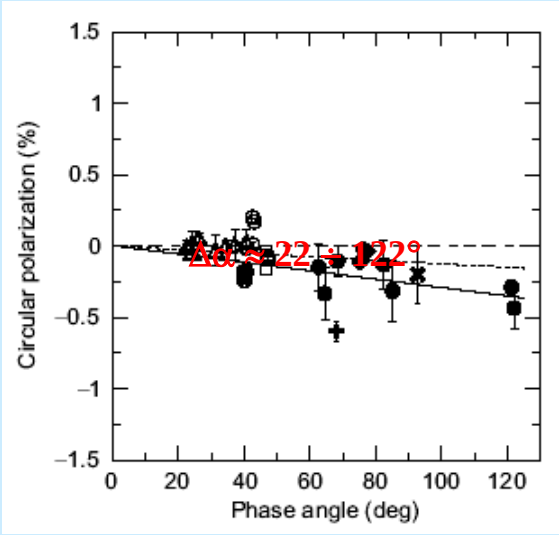


Variations of circular polarization along the line through the coma and nucleus of comets Hale–Bopp (a), S4 (LINEAR) (b), and Q4 (NEAT) (c).

So far circular polarization has been detected reliably only for 7 comets: 1P/Halley, C/1995 O1 (Hale–Bopp), C/1999 S4 (LINEAR), C/2001 Q4 (NEAT), 73P/Schwassmann–Wachmann 3, 8P/Tuttle, and 9P/Tempel 1.

The first five of them have been observed by us with the 2.6-m CrAO telescope.

These observations stimulated relevant theoretical research (Rosenbush et al. 2007a).



Composite phase-angle dependence of circular polarization for comets Halley, S4 (LINEAR), Q4 (NEAT), Schwassmann–Wachmann 3, and Tuttle (Rosenbush et al. 2008).

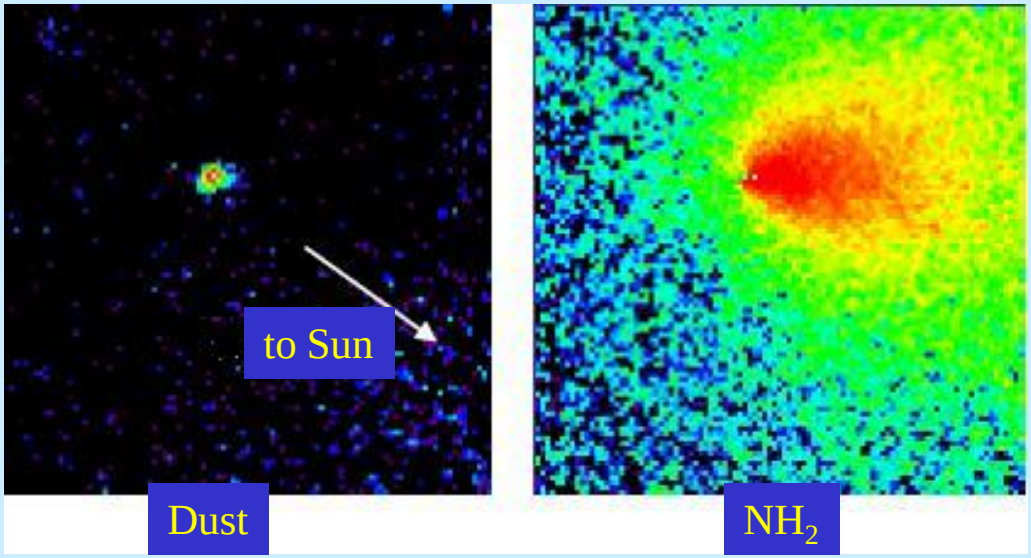
The solid line is a linear fit to the observed data, while the short-dashed line depicts the results of calculations for optically active (chiral) spherical particles (Rosenbush et al. 2007).

Summary of detections of circular polarization

Tentative conclusions:

- ✓Detection of mainly left-handed circular polarization in comets may be signature of organic grains and testifies in favor of L-enantiomeric excess (**homochirality)** in cometary organics.
- ✓Found one more confirmation (except for meteorites and dust in star-forming regions) that homochirality is not a property only of terrestrial origin.
- ✓The observed circular polarization in comets indirectly suggests that comets may have been sources of prebiotic organics on the Earth.

Future work



Comet 2P/Encke - the only gas rich comet, which can be observed at large phase angles. A favorable observation period once in ten years. The near future - October 2013.

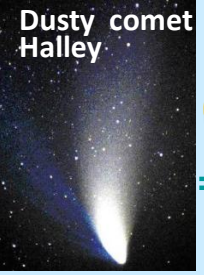
Date	RA	DEC	mag	phase (deg)
Oct 1	7 01	+43 30	9.3	62
8	8 15	+42 30	8.6	71
15	9 50	+36 40	7.9	84

We plan to carry out spectropolarimetry of the comet. Join us!!!

Thanks

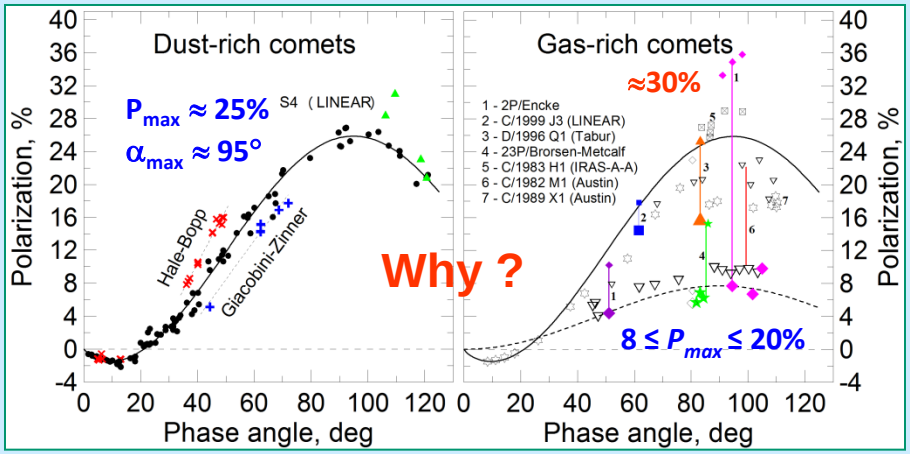
Acknowledgments

We thank Dr. Hervé Lamy, Chairman of the COST Action MP1104 and Prof. Hanna Rothkaehl (LOC) for support to participate in the first WG meeting of the COST.



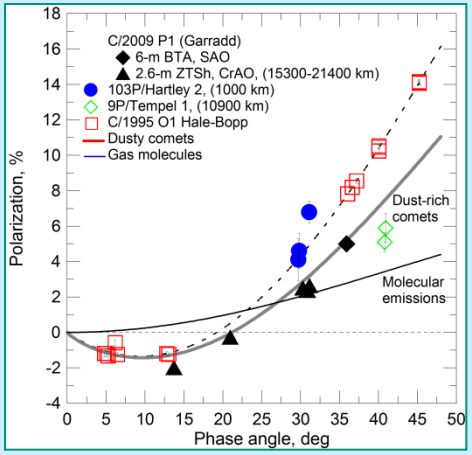
Comets: positive polarization branch

Polarimetric classes of comets ?



Phase-angle dependence of polarization for dust-rich and gas-rich comets in the red continuum.

Vertical lines show the range of polarization change as the distance from the nucleus is changing (Kiselev et al., 2005)



Observations of recent comets C/2009 P1 (Garradd), 103P/Hartley 2, 9P/Tempel 1.

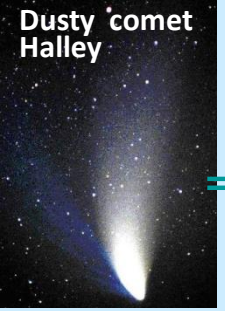
Comets Hale-Bopp, Giacobini-Zinner, S4 (Linear), and Hartley 2 are an exception.

The low polarization of gas-rich comets significantly depends on :

- -- contribution of gas emission in the narrow-band continuum filters that causes depolarization of the continuum. In comet Encke, *P* changed from ~8% to ~30% after correction for molecular emissions;
- -- measured area of the coma: *P* significantly decreases with an increase of aperture;

Division of comets into two polarimetric classes is caused by ignoring the contribution of molecular emissions in the continuum filters and aperture effect and therefore is an artifact.

Kiselev, Rosenbush et al., Solar System Research, 2001; Jockers, Kiselev, Rosenbush et al., A&A., 2005; Kolokolova, Kiselev, Rosenbush, A&A, 2007



Classification of comets

How and why polarimetric and infrared properties of cometary dust can be used for classification of comets.

-- high production rate of dust $Q_D \approx 15\,000$ kg/s;
-- low gas/dust ratio;
-- high polarization;
-- strong 10 μm silicate feature

↓

submicron particles

Gas/dust characteristics, polarization, and thermal properties of dust in dust-rich and gas-rich comets

-- low production rate of dust $Q_D \approx 120$ кг/s;
-- dust is concentrated near nucleus;
-- predominance of gas over dust in the outer coma;
-- low average polarization;
-- weak or absent silicate features;

↓

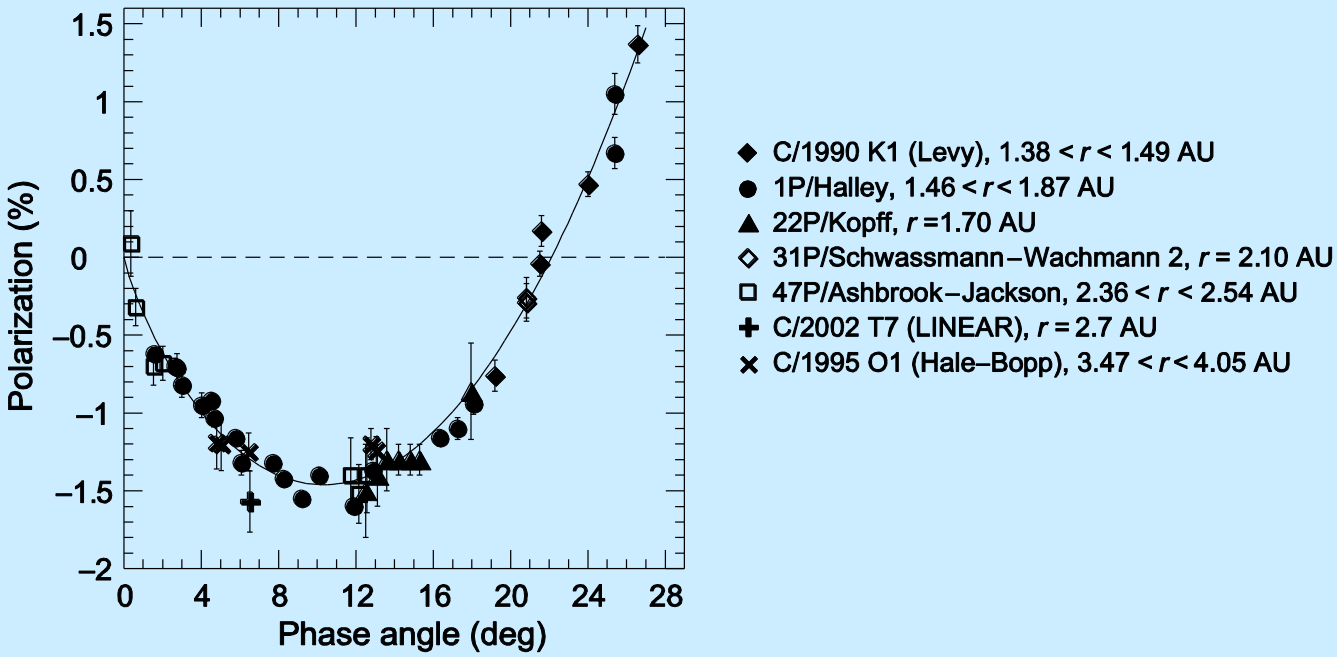
predominance of large particles, >5 μm

Classification of comets based on their polarimetric, infrared, and orbital characteristics:

Characteristic	Type I – gas-rich	Type II – dust-rich
Gas/dust ratio	high	low
Polarization		
-- averaged over large aperture	low	high
-- circumnuclear region	high	high
Silicate feature strength	low/absent	high
Average distance from the Sun	small	large
Specifics of dust particles	compact aggregates	high-porosity aggregates
Comets	“old” – short-period	“new” – long-period

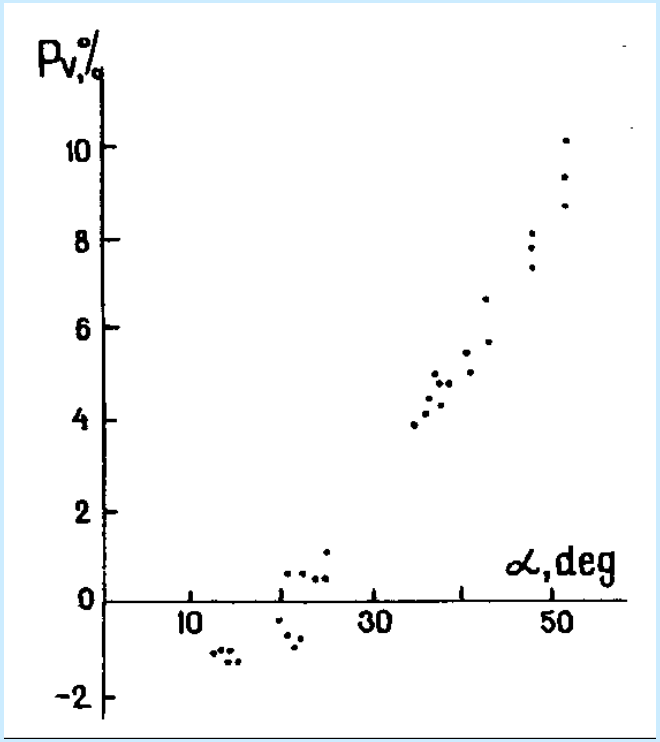
Kolokolova, Kiselev, Rosenbush, A&A, V. 463, 2007

“Asteroids-like” phase dependence of polarization for comets

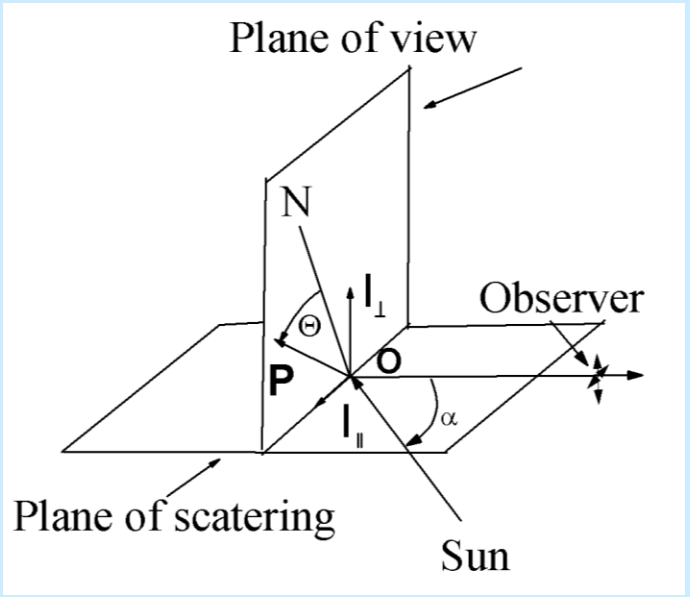


The phase-angle dependence of cometary polarization is similar to that for asteroids and interplanetary dust. The similarity of the polarization phase curves observed for different objects likely testifies to the similarity of the dust particle morphologies.

Phase angle dependence of polarization for comet C/1975 V1 (West)



Observations of comet West revealed a negative branch of linear polarization at phase angles $\alpha \leq 22°$.
(Kiselev&Chernova, 1976)



$$P = \frac{I_{\perp} - I_{II}}{I_{\perp} + I_{II}}$$

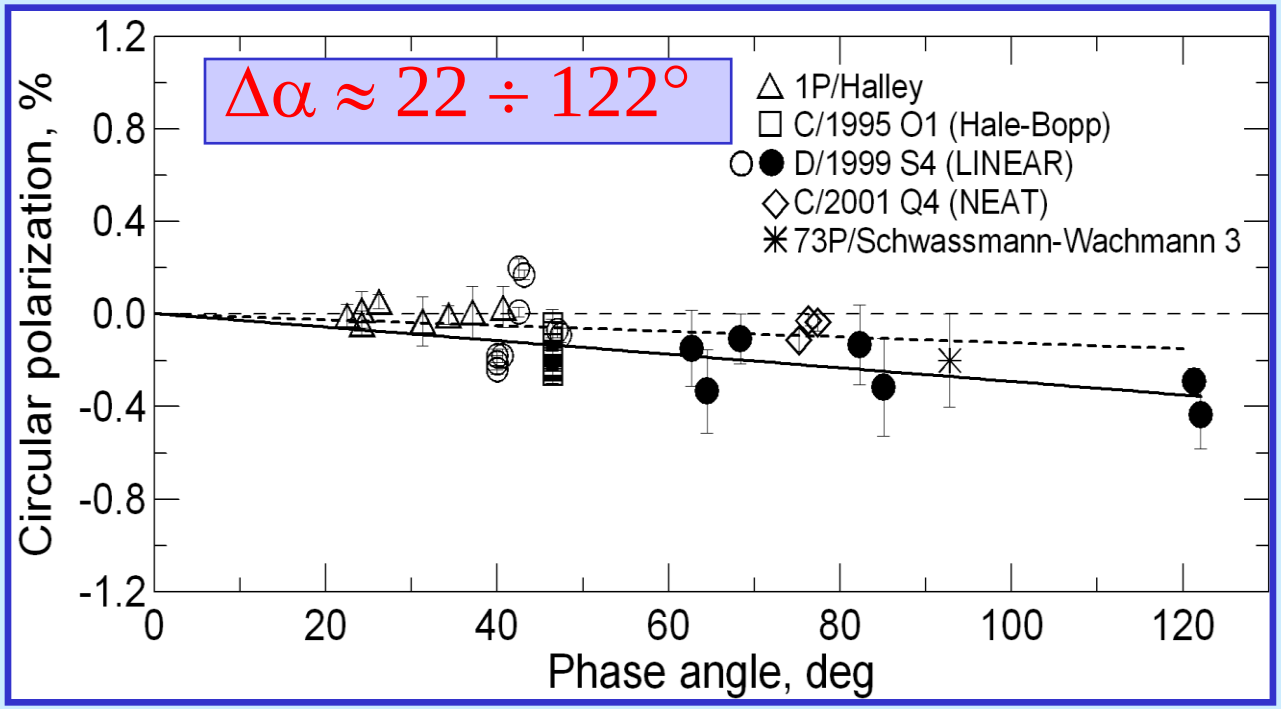
"Negative" branch of polarization

$$I_{II} > I_{\perp} \qquad P < 0; \qquad \theta \parallel \theta_{sca}$$

Positive branch of polarization

$$I_{II} < I_{\perp} \qquad P > 0; \qquad \theta \perp \theta_{sca}$$

Composite phase-angle dependence of circular polarization



The solid line is the linear fit to the observed data, dashed line is computer simulation of light scattering by optically active (chiral) particles (Rosenbush et al. 2007).

Observations

Comet Halley:
Dollfus & Suchail, 1987

Comet Hale-Bopp:
Rosenbush et al., 1997
Manset & Bastien, 2000

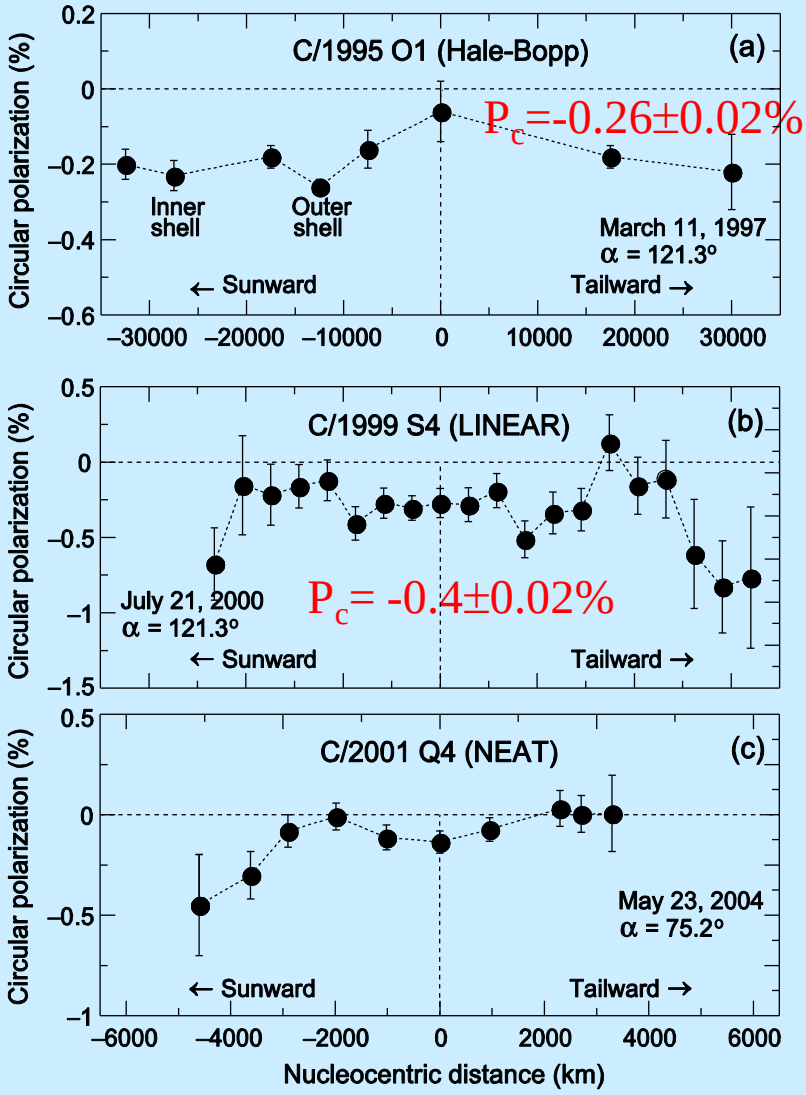
Comet S4 (LINEAR):
Rosenbush et al., 2007

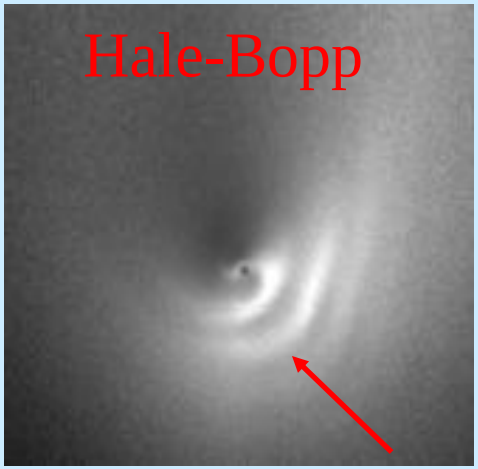
Comet Q4 (NEAT)
Rosenbush et al., 2007

Comet SW 3
Tozzi et al. 2006

Common feature: left-handed circular polarization

Circular polarization in comets





Circular polarization has been detected reliably only for seven comets: Halley, Hale–Bopp, S4 (LINEAR), Q4 (NEAT), 8P/Tuttle, 73P/SW 3, and 9P/Tempel 1.

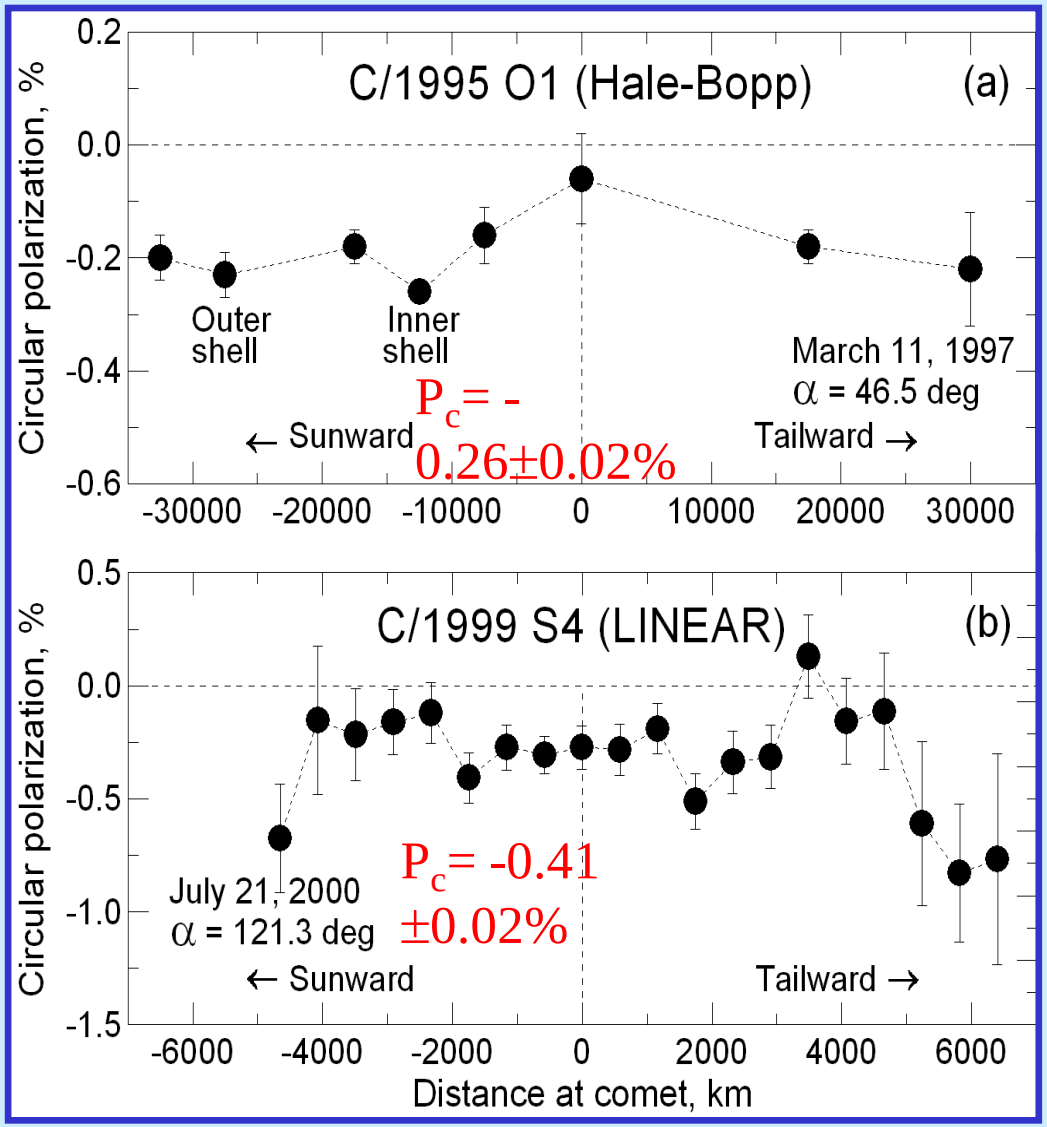
Variations of the degree of circular polarization with the cometocentric distance for comets Hale-Bopp (a), S4 (LINEAR) (b) and Q4 (NEAT) (c).

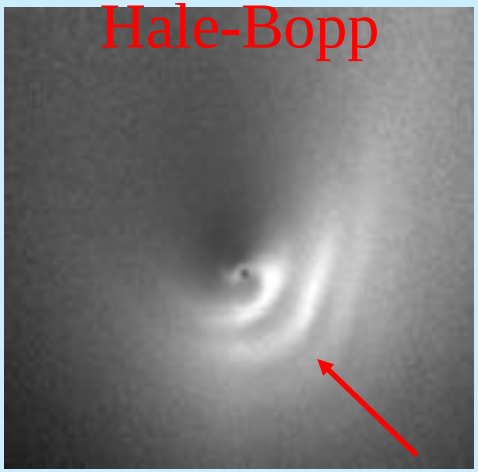
Polarization in gas-rich comets is influenced by the fact that dust in these comets is located in the near-nucleus area that is caused by the low dust production of these nuclei.

Gas-rich comets have low polarization at large phase angles and blue color mainly due to low spectral and spatial resolution.

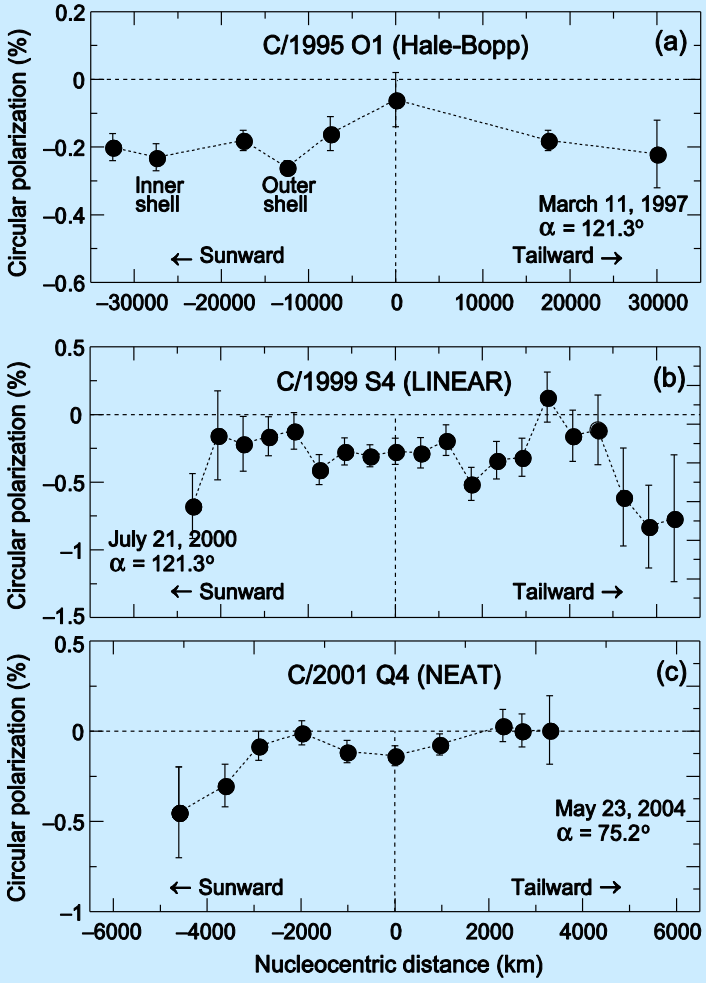
Thus, the division of comets into two classes with different polarization maximum is an artifact.

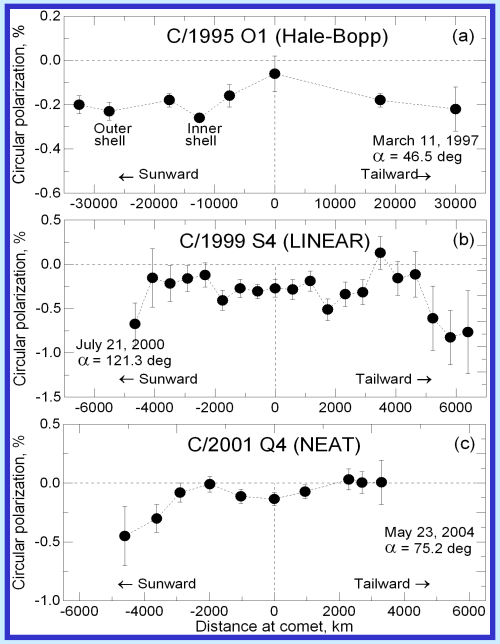
Circular polarization in comets Hale-Bopp and S4 (LINEAR)



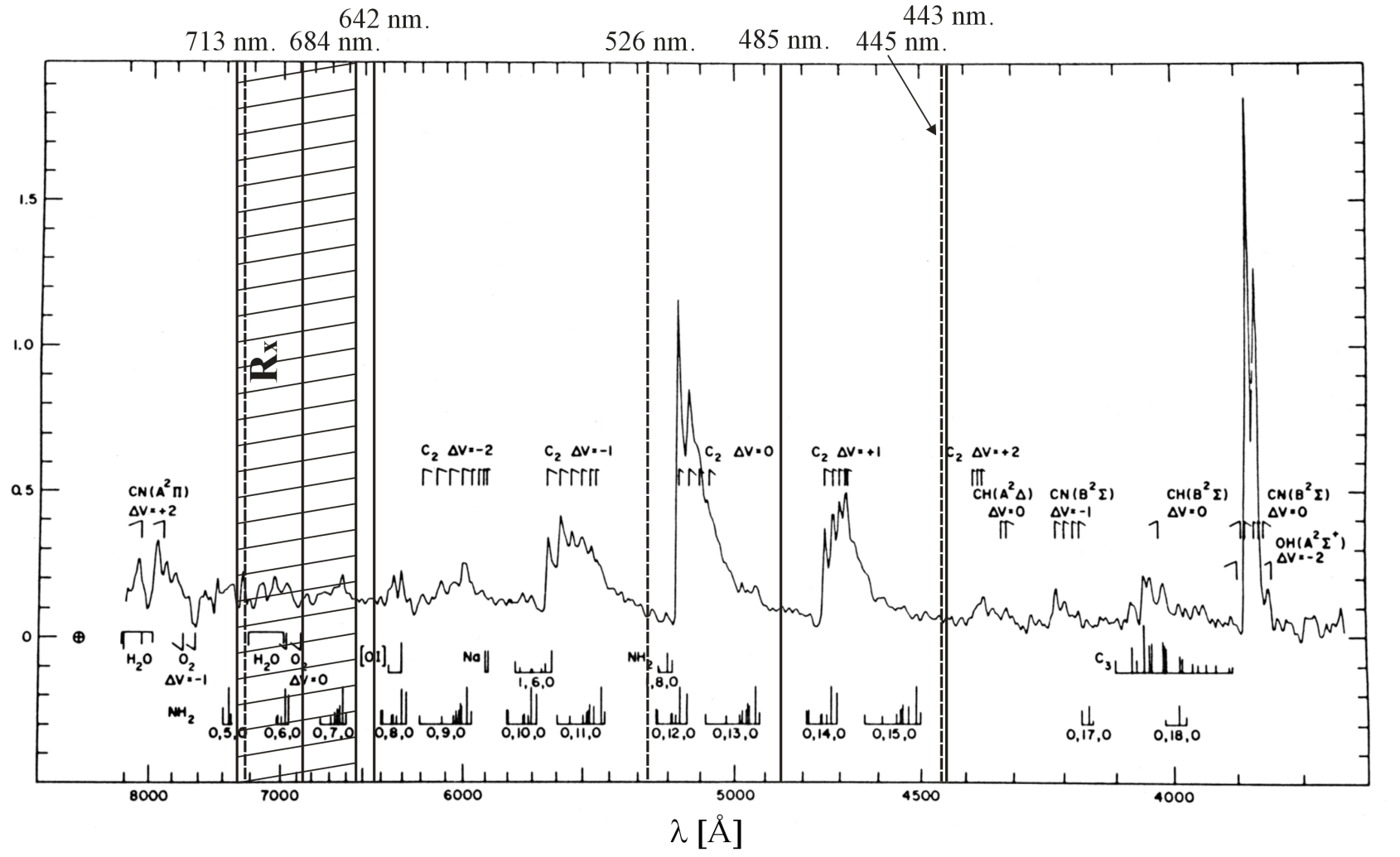


Variations of the degree of circular polarization with the cometocentric distance for comets Hale-Bopp (a) and S4 (LINEAR) (b).


C/1995 O1 (Hale-Bopp)
(a)
Inner shell
Outer shell
March 11, 1997
α = 121.3°
← Sunward
Tailward →
C/1999 S4 (LINEAR)
(b)
July 21, 2000
α = 121.3°
← Sunward
Tailward →
C/2001 Q4 (NEAT)
(c)
May 23, 2004
α = 75.2°
← Sunward
Tailward →
Circular polarization (%)
Nucleocentric distance (km)


C/1995 O1 (Hale-Bopp)
(a)
Outer shell
Inner shell
March 11, 1997
α = 46.5 deg
← Sunward
Tailward→
C/1999 S4 (LINEAR)
(b)
July 21, 2000
α = 121.3 deg
← Sunward
Tailward →
C/2001 Q4 (NEAT)
(c)
May 23, 2004
α = 75.2 deg
← Sunward
Tailward →
Circular polarization, %
Distance at comet, km

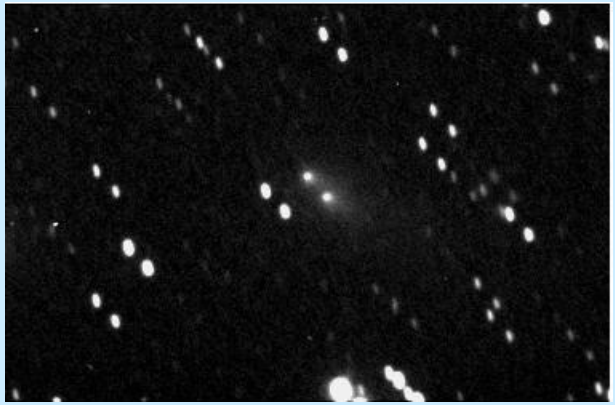
Average spectrum of comet C/1973 E1 (Kohoutek) at heliocentric distance ~1 AU (A'Hearn, 1975)

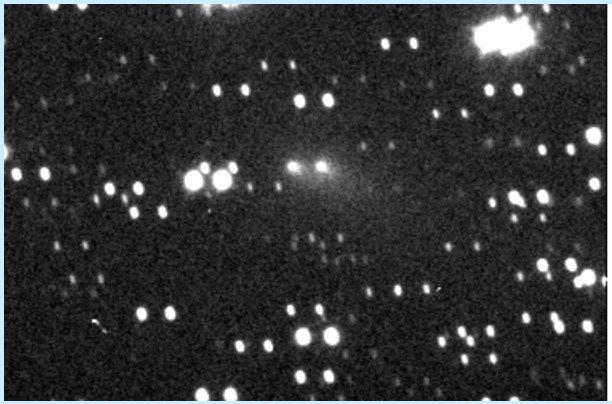


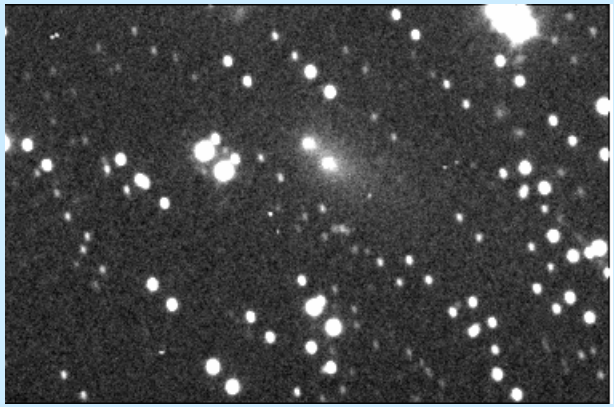
Properties of polarization in dust-rich comets (Kiselev, 2003)

- **A negative polarization branch with minimum polarization Pmin ≈ -1.5% at phase angle αmin ≈ 10°;**
- **A positive polarization branch with a maximum of Pmax ≈ 25-30% at αmax ≈ 95° ;**
- **The inversion phase angle at which polarization changes sign is close to 21°;**
- **The slope of the linear part of the positive branch is ΔP/Δα ≈ 0.3%/degree.**
- **The wavelength effect at small phase angles (≤30°) is weak.**
- **| Pmin |, αmin and αinv only slightly decrease with increasing the wavelength.**
- **Positive polarization of comets usually increases with increasing the wavelength in the visible spectral range.**

Objectives of polarimetric narrow-band observations of comets







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1st WG meeting in Warsaw, Poland, 7-9 May 2012