# Circular polarization in comets: calibration of measurements

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# Outline of presentation

- **Polarimetry of comets: linear and circular polarization**
- **Summary of circular polarization measured in comets**
- **Phase-angle dependence of circular polarization**
- **Mechanisms responsible for circular polarization in comets**
- **Reduction of polarimetric observations of comets**
  - instrumental polarization
  - instrumental efficiency
  - conversion of linear polarization into circular one
  - determination of sign of circular polarization in comets

***circular polarization* ≡ CP**

# Mechanisms of the origin of CP in comets

**Unpolarized solar radiation, being scattered by dust particles in the cometary coma, as a rule, becomes linearly polarized.**

**CP can appear only under special conditions. A completely isotropic medium, illuminated by unpolarized light, does not produce CP.**

Linear polarization is sensitive to the particle structure – sizes and shape.

*CP* can provide information on the nature of the particles – their composition.

## Sources of circular polarization in comets can be:

1. **multiple scattering in an asymmetric medium**
2. **scattering by non-spherical aligned particles**
3. **scattering on particles containing optically active molecules**

Each of these sources have their unique signatures that allow us to distinguish their contribution.

**CP can provide important information about properties of a scattering medium that is not available by other means:**

# Observational tasks

**Measurements of circular polarization in comets are still rare and conditions for its formation are poorly understood.**

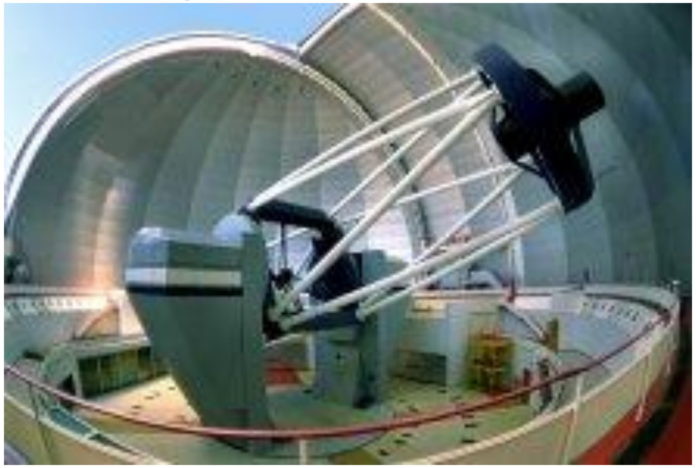
**The main purposes of polarimetric observations are:**

- **detection of CP of the scattered radiation in comets with high accuracy**
- **determination of the sign of circular polarization**
- **variability of polarization over the cometary coma**
- **dependence of the degree of circular polarization on the phase angle**
- **dependence of the degree of circular polarization in the continuum on the wavelength**
- **testing models of circular polarization in comets**

# Telescopes and polarimeters

## Our observations: circular polarimetry of 5 comets

2.6-m telescope and aperture polarimeter of the Crimean Astrophysical Observatory (Ukraine)



6-m telescope with the focal reducer SCORPIO in the polarimetric mode at the SAO (Russia)

Manset and Bastien observed comet S4 (LINEAR) with 1.6-m telescope at the Observatory du Mont Megantic with two-channel photoelectric polarimeter.

Boehnhardt et al. and Tozzi et al. obtained the CCD maps for two comets (Tempel 1 and Schwassmann–Wachmann 3) with instrument FORS at 8.2-m VLT of the European Southern Observatory.

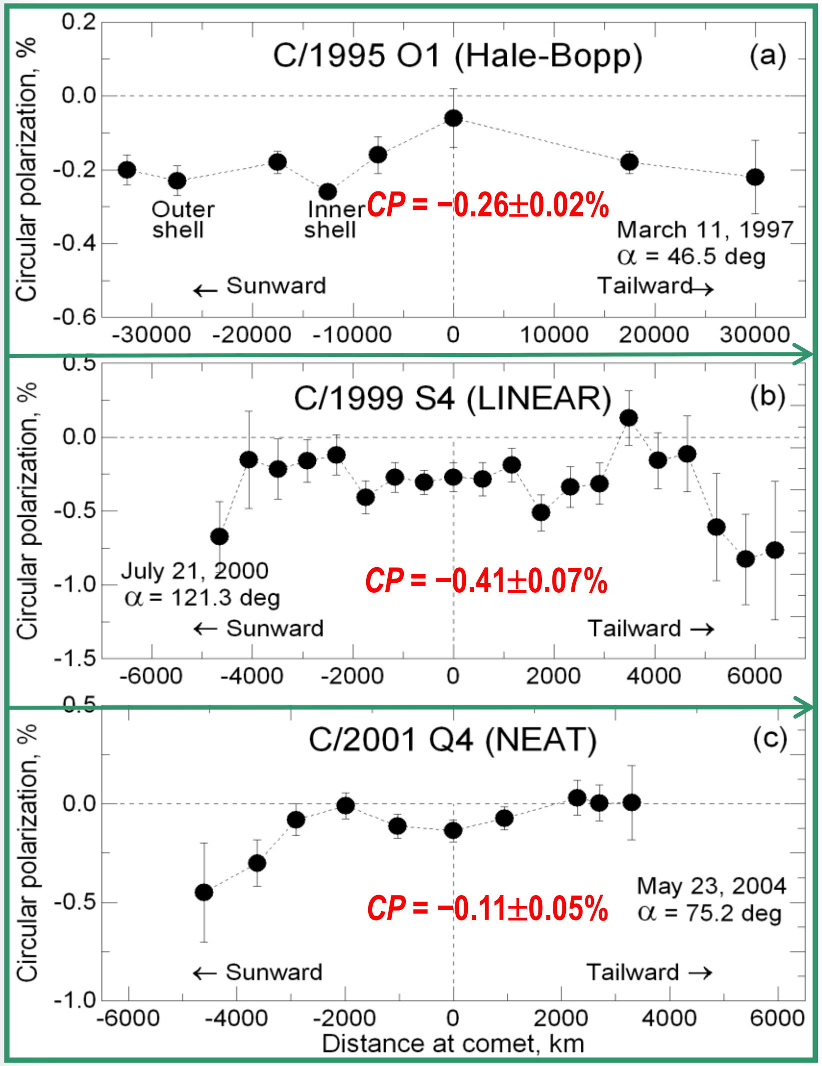
SCORPIO – Spectral Camera with Optical Reducer for Photometric and Interferometric Observations

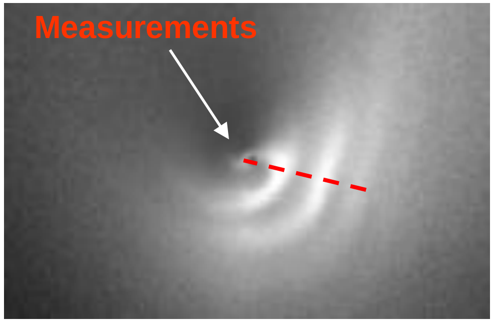
# Comets in which CP was measured

| Year | Comet | Phase angle, deg | Degree of CP, % | Telescope | Reference |
|---|---|---|---|---|---|
| 1986 | 1P/Halley | 22–41 | ±(0.04 – 0.54) ± 0.15 | 1.0m, Meudon Obs, France | Dollfus & Suchail 1987 |
| 1997 | C/1995 O1 (Hale−Bopp) | 46 | −(0.08 – 0.26) ± 0.02 | 2.6m, CrAO, Ukraine | Rosenbush et al. 1997 |
| 1997 | C/1995 O1 (Hale−Bopp) | 40–47 | −(0.07 – 0.24) ± 0.02 | 1.6m, OMM | Manset & Bastien 2000 |
| 2000 | C/1999 S4 (LINEAR) | 61–122 | −0.41 ± 0.07 | 2.6m, CrAO Ukraine | Rosenbush et al. 2007 |
| 2004 | C/2001 Q4 (NEAT) | 75-77 | −0.11 ± 0.05 | 2.6m, CrAO Ukraine | Rosenbush et al. 2007 |
| 2005 | 9P/Tempel 1 | | ~ −0.05 ± 0.02 | VLT, ESO | Boehnhardt et al.2005 |
| 2006 | 73P/Schwassmann-Wachmann 3 | | −0.2 ± 0.2 | VLT, ESO | Tozzi et al. 2006 |
| 2008 | 8P/Tuttle | 68 | −0.60 ± 0.07 | 2.6m, CrAO Ukraine | Kiselev & Rosenbush 2008 |
| 2012 | C/2009 P1 (Garradd) | 14–35 | –(0.04 – 0.40) ± 0.06 | 6m, SAO, Russia | Rosenbush, Kiselev, Afanasiev |

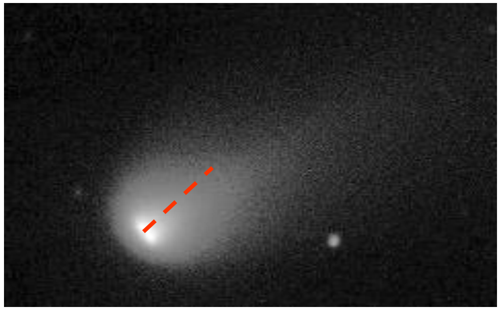
**All these comets showed a low degree of circular polarization, up to 0.2 – 0.8% with the best accuracy about 0.02%.**

# Spatial distribution of CP




**Hale-Bopp**



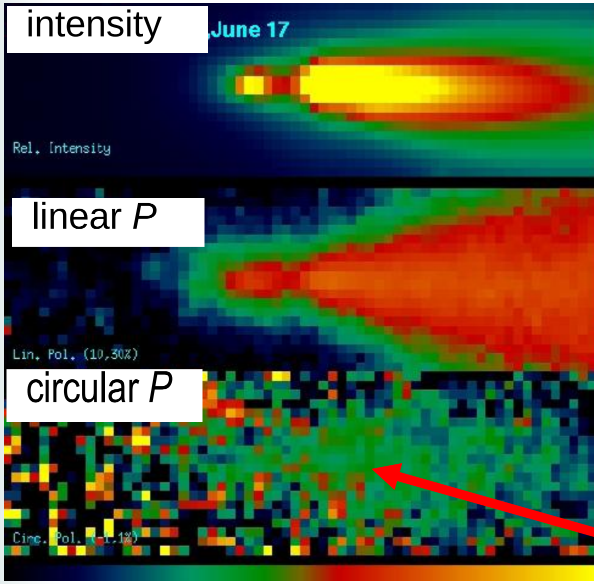
**S4 (LINEAR)**


**Q4 (NEAT)**

**Variations of *CP* with the distance from the cometary nucleus.**

It can be clearly seen that CP shows systematic, not chaotic, variations over the coma.

# Spatial distribution of CP

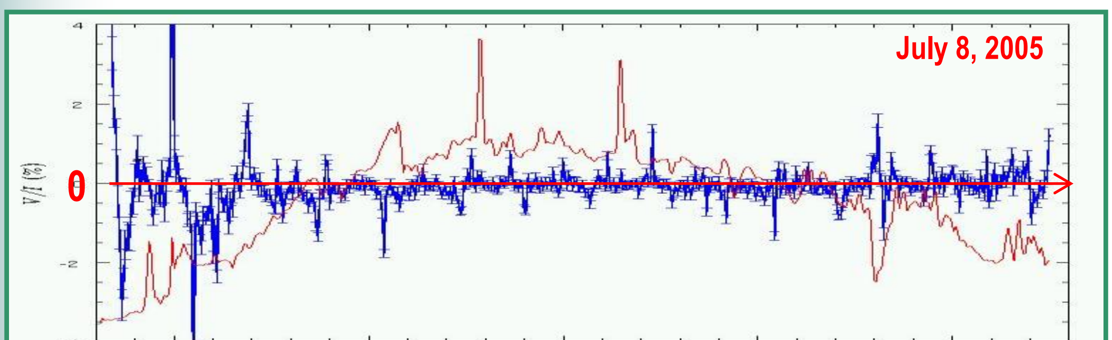




**73P/Schwassmann–Wachmann 3**

**CP = −0.2% ± 0.2%**

**The images of brightness (top), linear polarization, and circular polarization (bottom) for comet Schwassmann-Wachmann 3 obtained with FORS at ESO (Tozzi et al. 2006).**



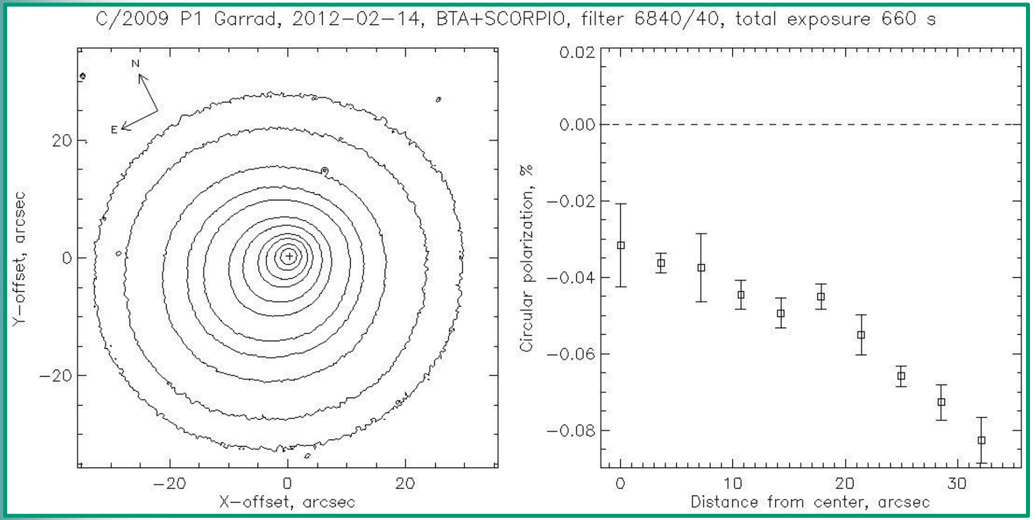


**9P/Tempel 1**

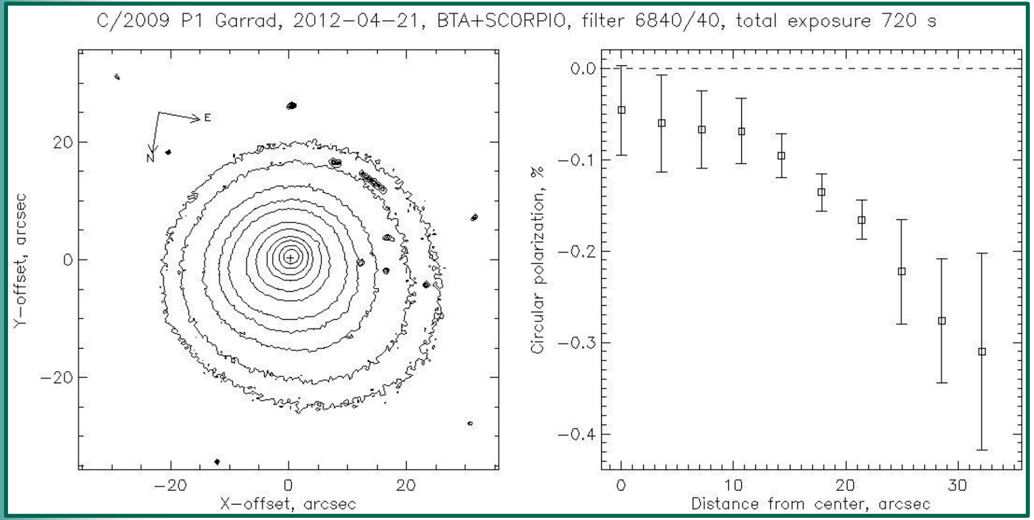
**Circular polarization for comet Tempel 1 measured with polarimeter FORS at VLT ESO (Boehnhardt et al. 2005).**

# Comet C/2009 P1 (Garradd)

**2012 Feb 14: r= 1.71 AU, Δ=1.39 AU, α = 35.2°**




**2012 Apr 21: r= 2.49 AU, Δ=1.92 AU, α = 26.8°**




## Imaging circular polarimetry

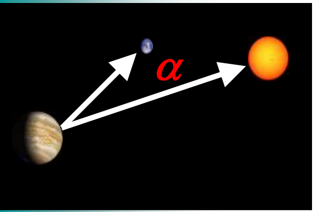
**Focal reducer SCORPIO at the 6-m telescope BTA (SAO RAS, Russia)**

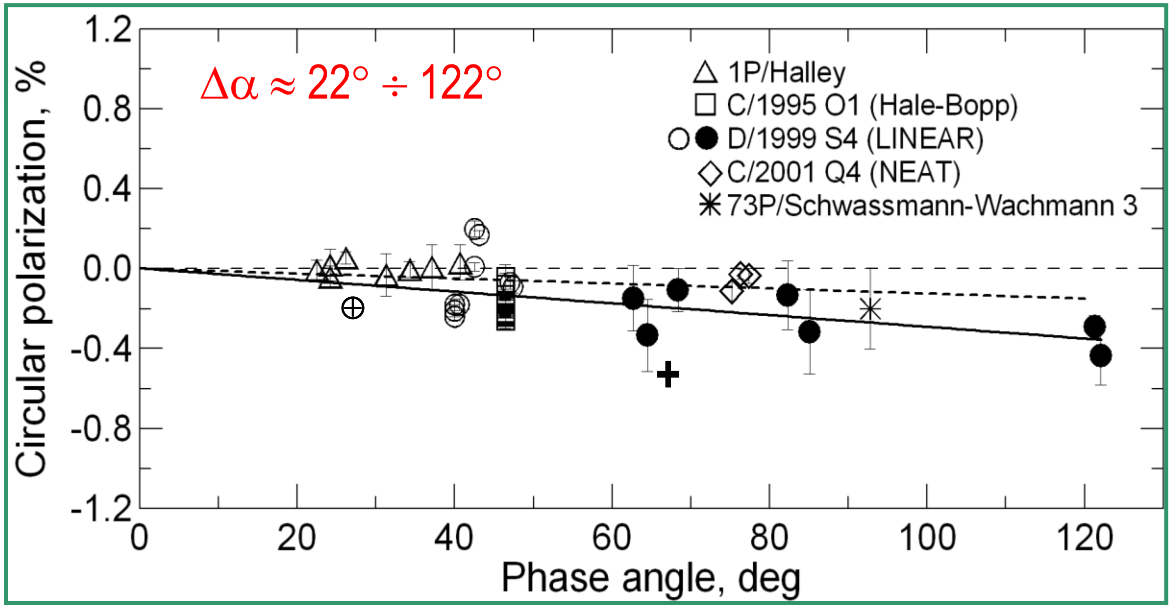
***CP*** **is –0.02% (near nucleus) up to –0.3% at the distance from the nucleus about 50000 km.**

**An accuracy of measurements varies depending on the distance from the comet nucleus: from 0.01% to 0.08%.**

**Variations of the averaged *CP* within the circular aperture with *D*=20 px (~7") in the red continuum filter 6840/40 Å with the distance from the cometary nucleus.**

# Phase-angle dependence of CP




**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 Sch-Wach 3
(Tozzi et al. 2006)

Comet Tuttle
(Kiselev et al., 2008)

Comet Garrad
(Rosenbush et al., 2007)

**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).**

Circular polarization in eight comets clearly show the phase-angle dependence: its absolute value is increased with phase angle and reaches ~ 0.4% at the phase angle 120°.

# Summary

**Summarizing our findings, we revealed a very important result.**

**Circular polarization detected in all observed comets is at a significant level and is predominantly negative, that is left-handed.**

**What is the reason of this?**

# Data reduction

When trying to detect a small polarization is always a danger that the observed effect may be due to unaccounted instrumental errors. However, the measurements are performed for different comets and at different telescopes.

## Initial data included reduction for:

- **sky background radiation** (was approximated by a polynomial and adequately subtracted during data reduction);
- **instrumental efficiency** using circular polarizers;
- **instrumental polarization** using nonpolarized standard stars;
- **conversion of linear polarization into circular polarization** using laboratory testing;
- **sign of CP** using observations of circularly polarized stars (polars)

# Determination of CP and its sign

**The degree of circular polarization can be found from the following expression:**

$$CP = P_1 \cos 2\psi_0 + P_2 \sin 2\psi_0$$

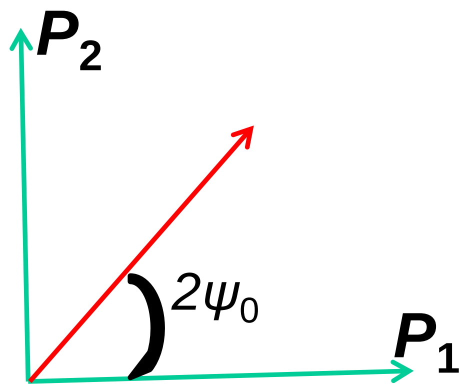
**where**

$$r_1 = \frac{N_1 - N_2}{N_1 + N_2} = \frac{2V \cos 2\psi_0}{\pi(1+Q/2)},$$

$$r_2 = \frac{N_3 - N_4}{N_3 + N_4} = \frac{2V \sin 2\psi_0}{\pi(1+Q/2)},$$

$$P_1 = \frac{\pi}{2} r_1 (1+Q/2) = V \cos 2\psi_0,$$

$$P_2 = \frac{\pi}{2} r_2 (1+Q/2) = V \sin 2\psi_0,$$




**The angle $\psi_0$ is determined for every observation set from $P_1$ and $P_2$ by the orthogonal regression procedure and is equal to about 80°.**

**The sign of *CP* is determined by observing circularly polarized stars (AM Her*)*.**

# Instrumental efficiency

**According to the laboratory tests:**

**for the light with a 100% circular polarization,**

**the efficiency of the instrument was close to 100%.**

# Instrumental circular polarization

The mean parameters of instrumental parameters of CP were measured for every observation set using the standard stars with zero CP taken from the lists of Serkowski.

The actual polarization which is measured for standards is believed to originate in the telescope optics and in the polarimeter itself. The observed degree of polarization is usually agreed well with the published values.

| Year | Comet | α, deg | Max CP, % | LP, % | Instr. CP, % | Standard stars | Telescope |
|---|---|---|---|---|---|---|---|
| 1986 | Halley | 22–41 | –0.54 ± 0.15 | 1–6 | <0.01 | | 1m, Meudon |
| 1997 | Hale-Bopp | 46 | –0.26 ± 0.02 | 8–12 | 0.006 ± 0.016 | AM Her | 2.6m, CrAO, |
| 1997 | Hale-Bopp | 40–47 | –0.25 ± 0.02 | 10–12 | < 0.02 ± 0.02 | RX11712.6-2414 | 1.6m, OMM |
| 2000 | S4 (LINEAR) | 61–122 | –0.80 ± 0.07 | 17–24 | 0.066 ± 0.008 | AM Her | 2.6m, CrAO |
| 2004 | Q4 (NEAT) | 75–77 | –0.11 ± 0.05 | 16–19 | | AM Her | 2.6m, CrAO |
| 2008 | Tuttle | 68 | –0.60 ± 0.07 | 9 | 0.026 ± 0.032 | AM Her | 2.6m, CrAO |
| 2012 | P1 (Garradd) | 14–35 | –0.40 ± 0.06 | | <0.01 | | 6m, SAO |

A similar result, not exceeding 0.1%, was obtained from the measurements of CP for the unpolarized light in laboratory tests by Shakhovskoy et al.

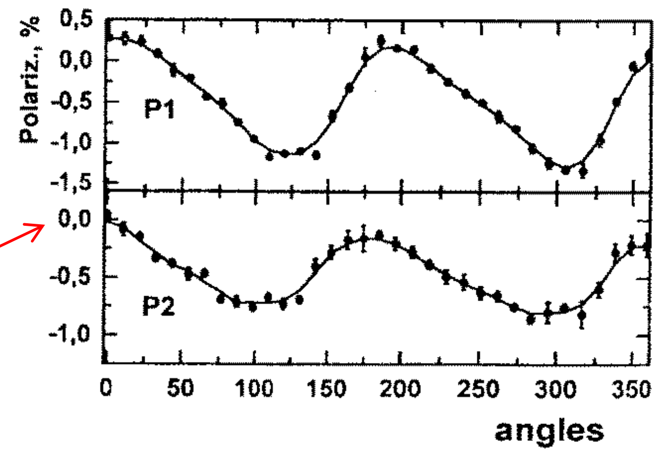
The systematic error introduced by instrumental polarization was significantly less than the random errors of the degree of CP in each measured area of the coma.

# Conversion of linear polarization into CP

The degree of linear polarization of comets can be quite high, up to 25–30% at phase angle about 90°. Therefore, there is a danger that a significant fraction of the linear polarization might be transformed to circular one. The result is the addition of a spurious signal in the V Stokes parameter.

**To estimate the systematic errors of measurements caused by the conversion of LP into CP, the results of laboratory tests were used (Shakhovskoy et al. 2001).**

**For the light with a 100% linear polarization, the spurious CP never exceeded the limits –0.5 ÷ +0.5%, depending on the position angle of the linear polarization.**

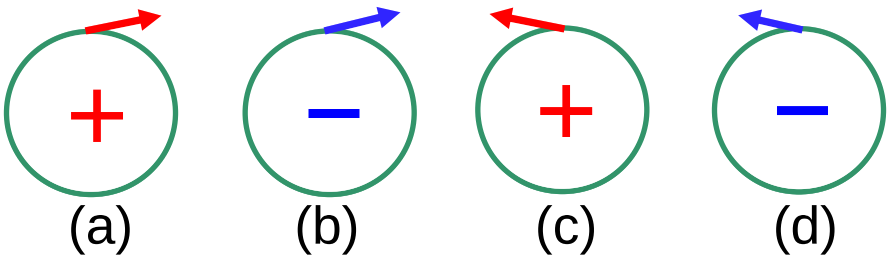


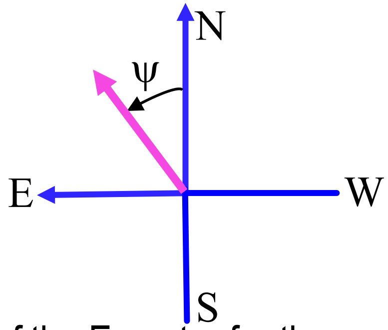

For example, the linear polarization of comet S4 (LINEAR), which was within the range from 17% to 24% during our observations, could produce the maximal spurious CP of several hundredths of a percent, which is within the limits of the observational errors.

# Some problems: handedness

## 1. Definition of handedness is a complex problem

**There are four cases that can be considered to describe the "sense" of CP (Clarke 2010).**




**(a) – Gehrels (1972):** right-handed polarization corresponds to a clockwise rotation of the E-vector for the radiation approaching the observer;

**(b) – Serkowski (1973):** right-handed polarization corresponds to rotate clockwise as seen by an observer looking against the direction of propagation;

**(c) – Martin (1972):** right-handed polarization corresponds to counterclockwise rotation of the E-vector for as see by the observer.

**The IAU adopted (c): CP is positive and right-handed when the E-vector rotates counterclockwise, as viewed by an observer looking in the direction of the light propagation.**
**or**
**CP is positive and right-handed when the E-vector rotates with increasing an angle ψ.**

**Biology: left-handed when the E-vector rotates clockwise, as viewed by an observer looking in the direction of the light propagation.**

Definition of the sense of CP for comets should correspond a definition of the sense of rotation of polarization plane for optically active molecules.

# Some problems: standard stars

## 2. Standard stars

**Most of the standard stars have a weak brightness, 12–15 mag, and variable circular polarization along the spectrum and in time.**

**Therefore it is difficult to verify the transmission efficiency of circular polarization in the instrument and it is needed to use laboratory tests that can not correspond to the data of astronomical observations.**

# Conclusion

**We did not offer a comprehensive interpretation of the data, but instead tried to show that the scattered radiation of comets really circularly polarized and there are real mechanisms that can operate in comets and generate the results consistent with our data.**

**Most likely, circular polarization in comets is a result of a complex of phenomena which take place in the cometary atmosphere.**

# Thank you for your attention

# Acknowledgments

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Hervé Lamy and Hans Martin Schmid
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