POLARIZATION IN MINOR BODIES OF THE SOLAR SYSTEM

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COST polarization school 5/6/2013

MINOR BODIES OF THE SS

According to IAU:

“All bodies in the SS except for the Sun, planets, dwarf planets and satellites”.

These are included:

- Comets.
- Asteroids.
- Trojans.
- Centaurs.
- Transneptunian objects others than dwarf planets.

We will focus on COMETS and ASTEROIDS.

Why?

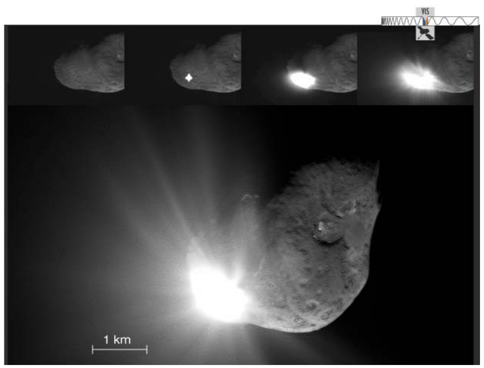
COMETS → Pristine material

ASTEROIDS → Lots of them closeby

RETRIEVING INFORMATION WITH POLARIZATION

WHAT ARE THE DUST GRAINS INSIDE THE COMET NUCLEUS LIKE?
(size, shape, composition, fluffy or not, aggregates or not ...)

· We can launch spatial missions to accelerate its production, analyze it, or even bring a sample back to Earth:



Deep Impact

Rosetta

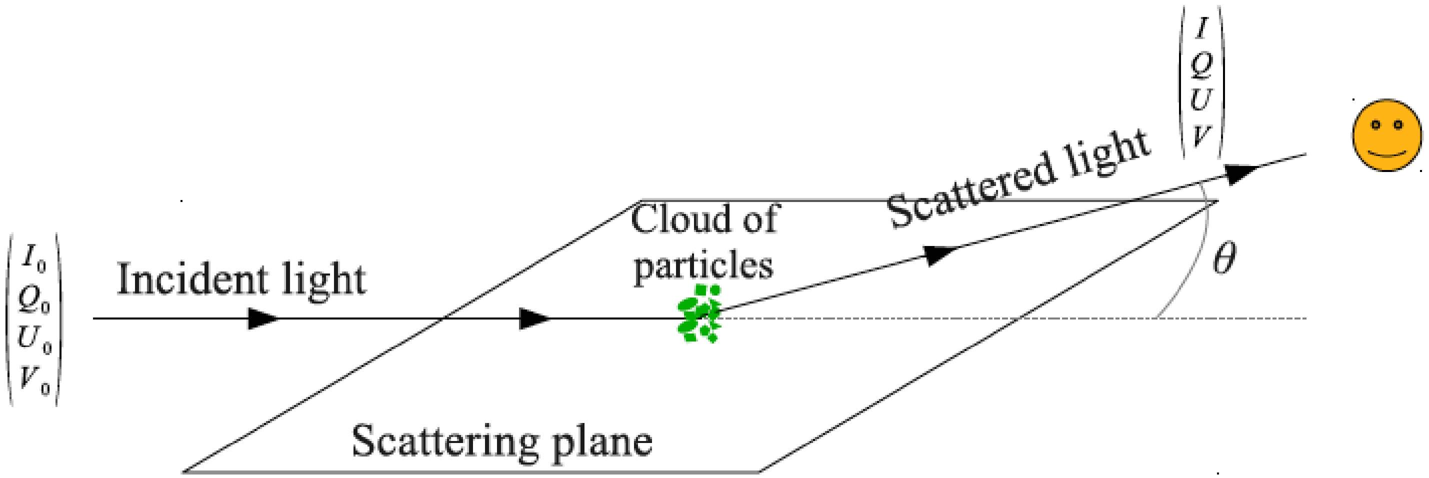
Stardust

· We also can analyze light scattered in comets:

Observed polarization + Correlation: scatterers features – polarization → Properties of the scatteres (dust particles or surfaces)

The Stokes parameters and the scattering matrix

Scattering event:



Light characterized by the Stokes parameters:

$$\begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix} = \frac{\lambda^2}{4\pi^2 R^2} \begin{pmatrix} F_{11} & F_{12} & F_{13} & F_{14} \\ F_{21} & F_{22} & F_{23} & F_{24} \\ F_{31} & F_{32} & F_{33} & F_{34} \\ F_{41} & F_{42} & F_{43} & F_{44} \end{pmatrix} \begin{pmatrix} I_0 \\ Q_0 \\ U_0 \\ V_0 \end{pmatrix}$$

Some special cases of scattering matrices

Reciprocity:

$$\begin{pmatrix} F_{11} & F_{12} & F_{13} & F_{14} \\ F_{12} & F_{22} & F_{23} & F_{24} \\ -F_{13} & -F_{23} & F_{33} & F_{34} \\ F_{14} & F_{24} & -F_{34} & F_{44} \end{pmatrix}$$

Mirror symmetry:

$$\begin{pmatrix} F_{11} & F_{12} & 0 & 0 \\ F_{21} & F_{22} & 0 & 0 \\ 0 & 0 & F_{33} & F_{34} \\ 0 & 0 & F_{43} & F_{44} \end{pmatrix}$$

Reciprocity & mirror symmetry:

$$\begin{pmatrix} F_{11} & F_{12} & 0 & 0 \\ F_{12} & F_{22} & 0 & 0 \\ 0 & 0 & F_{33} & F_{34} \\ 0 & 0 & -F_{34} & F_{44} \end{pmatrix}$$

Spheres:

$$\begin{pmatrix} F_{11} & F_{12} & 0 & 0 \\ F_{12} & F_{11} & 0 & 0 \\ 0 & 0 & F_{33} & F_{34} \\ 0 & 0 & -F_{34} & F_{33} \end{pmatrix}$$

Rayleigh domain=very small particles compared to λ ($F_{41} = 0$).

Degrees of polarization

Degree of linear polarization

$$DLP = \frac{\sqrt{Q^2 + U^2}}{I}$$

Extended degree of linear polarization

$$EDLP = \frac{-Q}{I}$$

$U = 0 \Rightarrow |EDLP| = DLP$
$EDLP > 0 \Rightarrow$ vibration $\perp$scattering plane.

Degree of circular polarization

$$DCP = \frac{V}{I}$$

In case of single scattering of natural incident light, i.e., $(I_0, Q_0, U_0, V_0) \propto (1, 0, 0, 0)$:

EDLP for natural incident light

$$EDLP\,(\theta) = -\frac{F_{21}\,(\theta)}{F_{11}\,(\theta)}$$

DCP for natural incident light

$$DCP\,(\theta) = \frac{F_{41}\,(\theta)}{F_{11}\,(\theta)}$$

COMETS

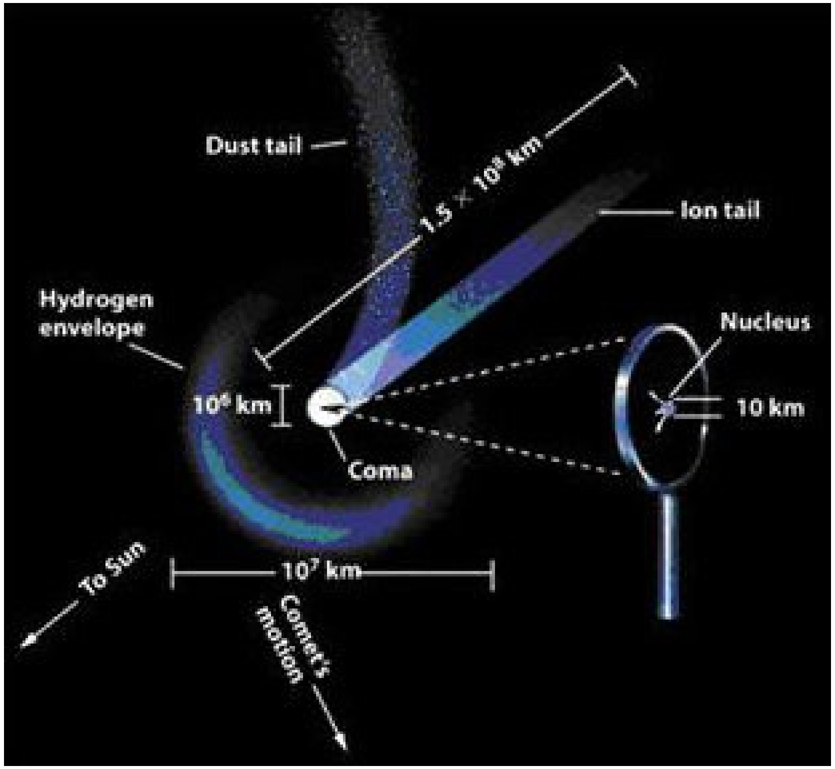
What is a comet?

Small icy body in highly elliptical orbit around the Sun.

Composition

water and dust grains
(silicates + carbon).

Comet structure (near the Sun)



* Nucleus:

* Coma: evaporated gas and dust forms halo around nucleus as comet approaches the Sun.

* Tail:
  - o grows as comet approaches Sun
  - o two types of tails
    - + ion tail (blown by solar wind)
    - + dust tail (less deflected by solar wind)

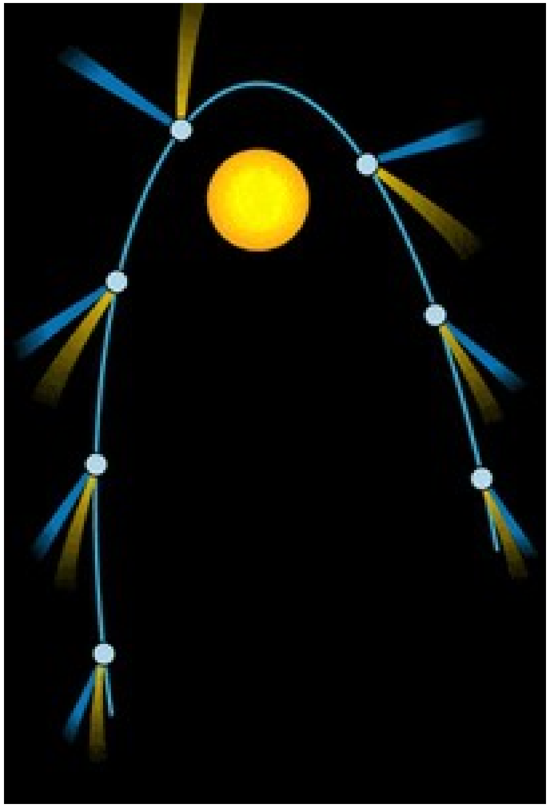
Comets contain the least processed material of the Solar System

TAILS OF COMETS

Two tails

* Gas tail (water vapor):
    - Ionized by ultraviolet radiation.
    - Strongly affected by solar wind.
    - Exact outwards direction.

* Dust tail (silicate and carbon dust grains):
    - Weakly affected by radiative pressure.
    - Slightly inclined to the outward direction.



TWO TYPES OF COMETS (I)

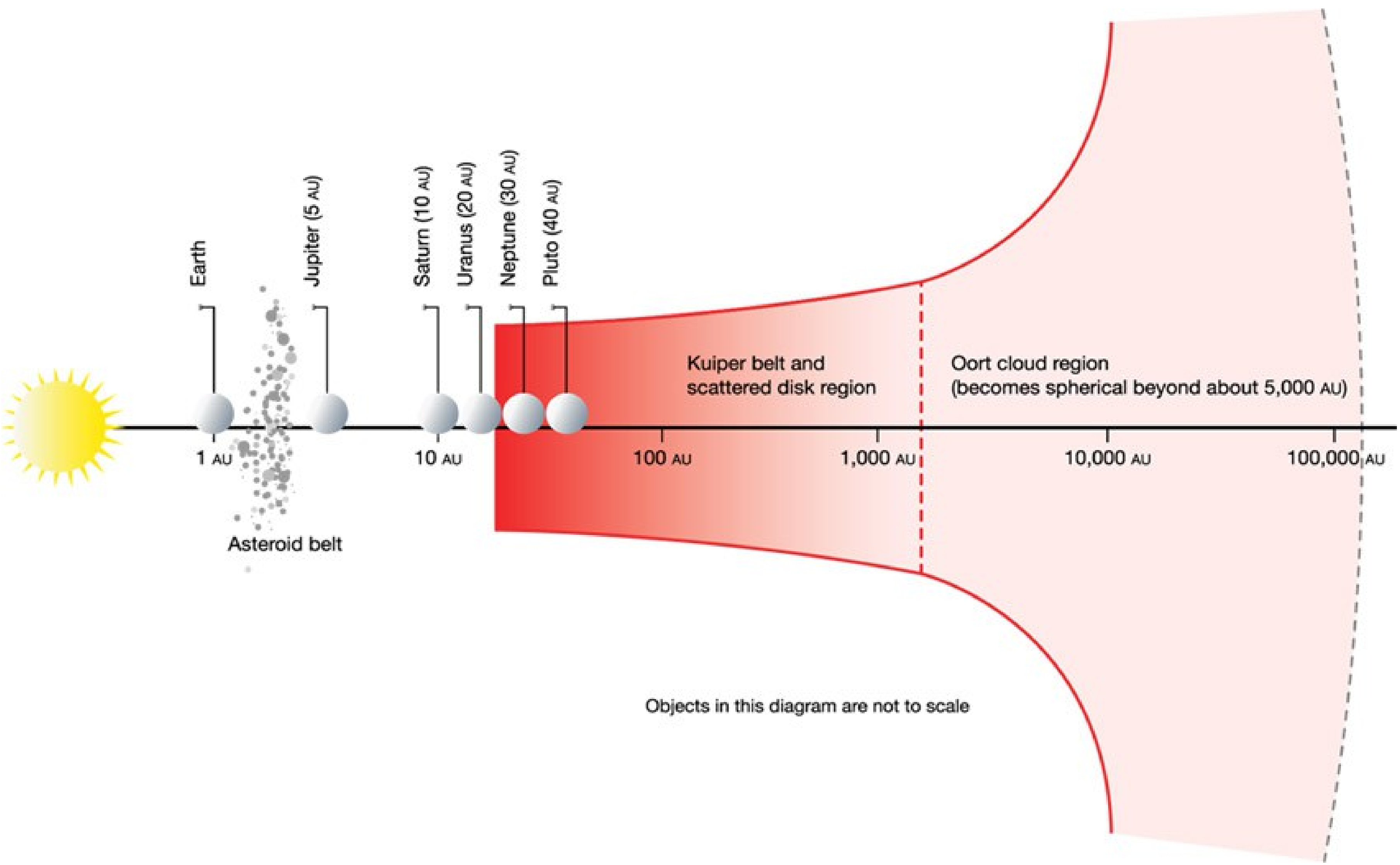
Two sets of orbits

* short-period comets (less than 200 years period):
    - o from Kuiper Belt (KBOs - Kuiper Belt Objects)
        - + orbits of 30 - 100 AU in diameter
        - + orbits with low inclination to ecliptic plane

* long-period comets (more than 200 years period):
    - o from Oort Cloud
        - + orbits of 100,000 AU in diameter
        - + Oort cloud has a spherical shape.

TWO TYPES OF COMETS (II)

Explanation to the two sets of orbits



ORIGIN OF COMETS

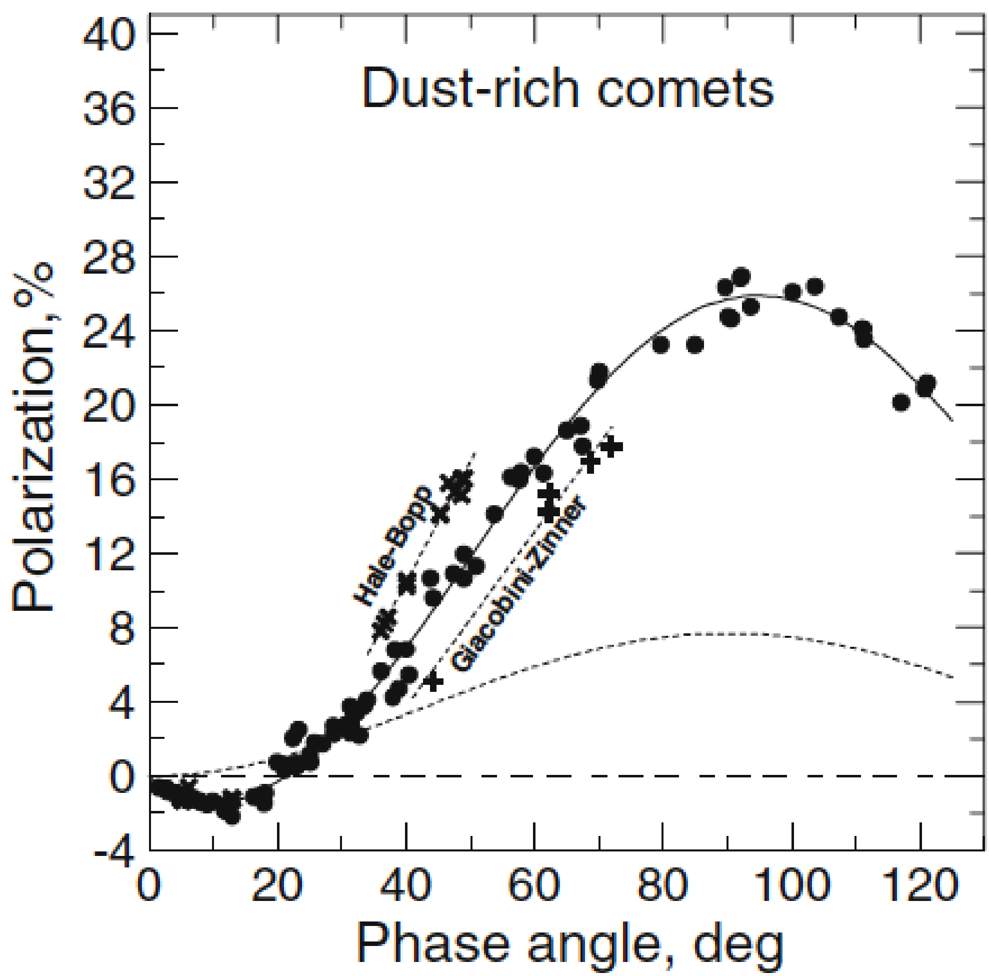
Kuiper Belt:

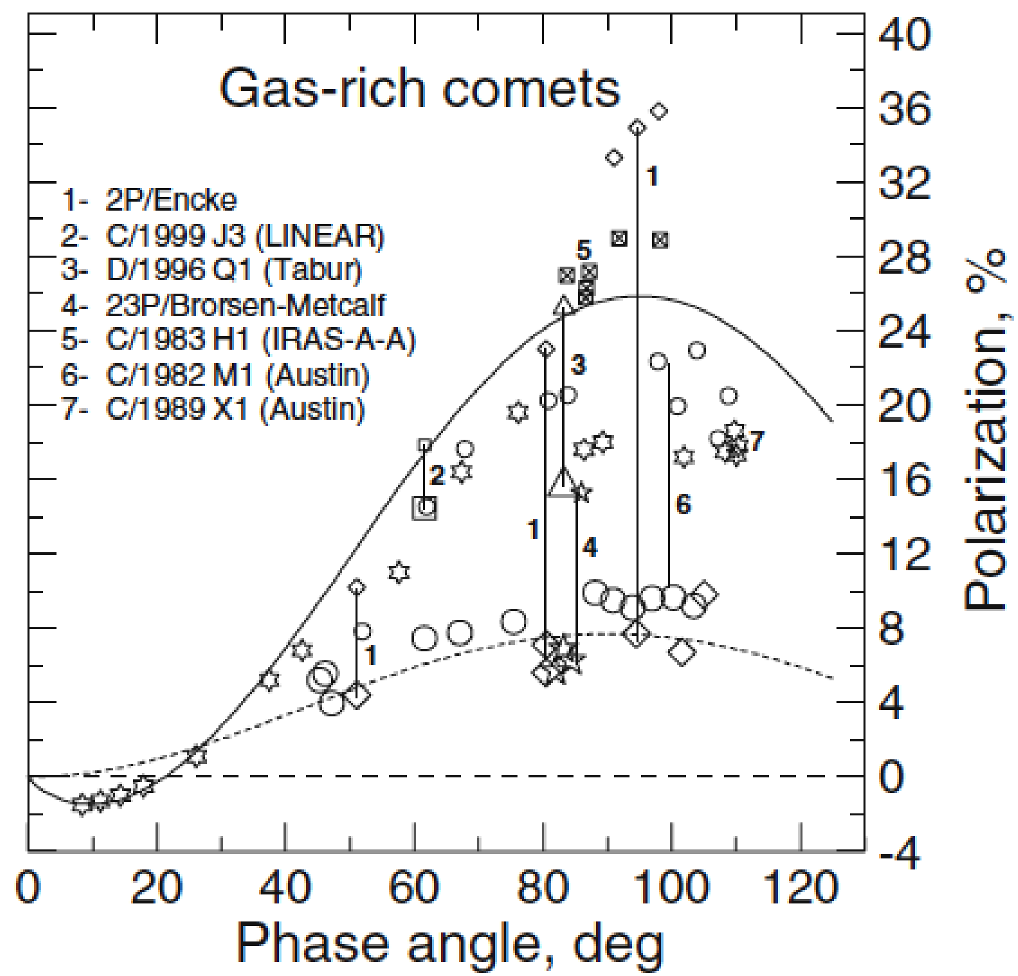
- Planetesimals form further than Neptune.
- Made of ice because they are further than the frost line.
- Not forming large planets because of low density and resonances with jovian planets.
- Planetesimals remain in the ecliptic plane.

Oort cloud:

- Planetesimals escaped from the region between Jupiter and Neptune.
- Made of ice because they are further than the frost line.
- They escaped in any direction because the interaction with jovian planets bended their trajectories..

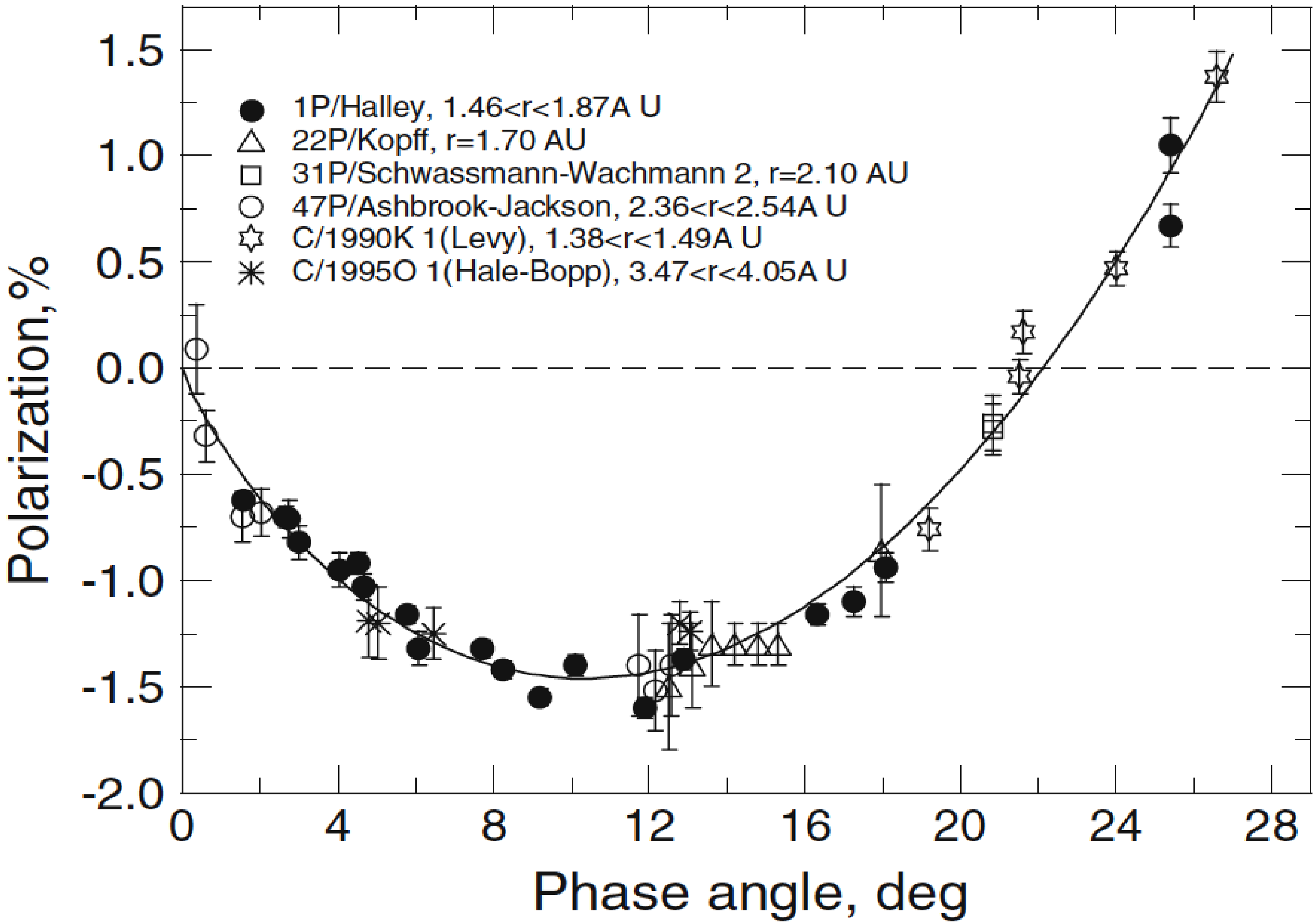
LINEAR POLARIZATION IN COMETS: WHAT DO WE OBSERVE?





(Kiselev et al. 2005)

LINEAR POLARIZATION IN COMETS: WHAT DO WE OBSERVE?



(Kiselev et al. 2005)

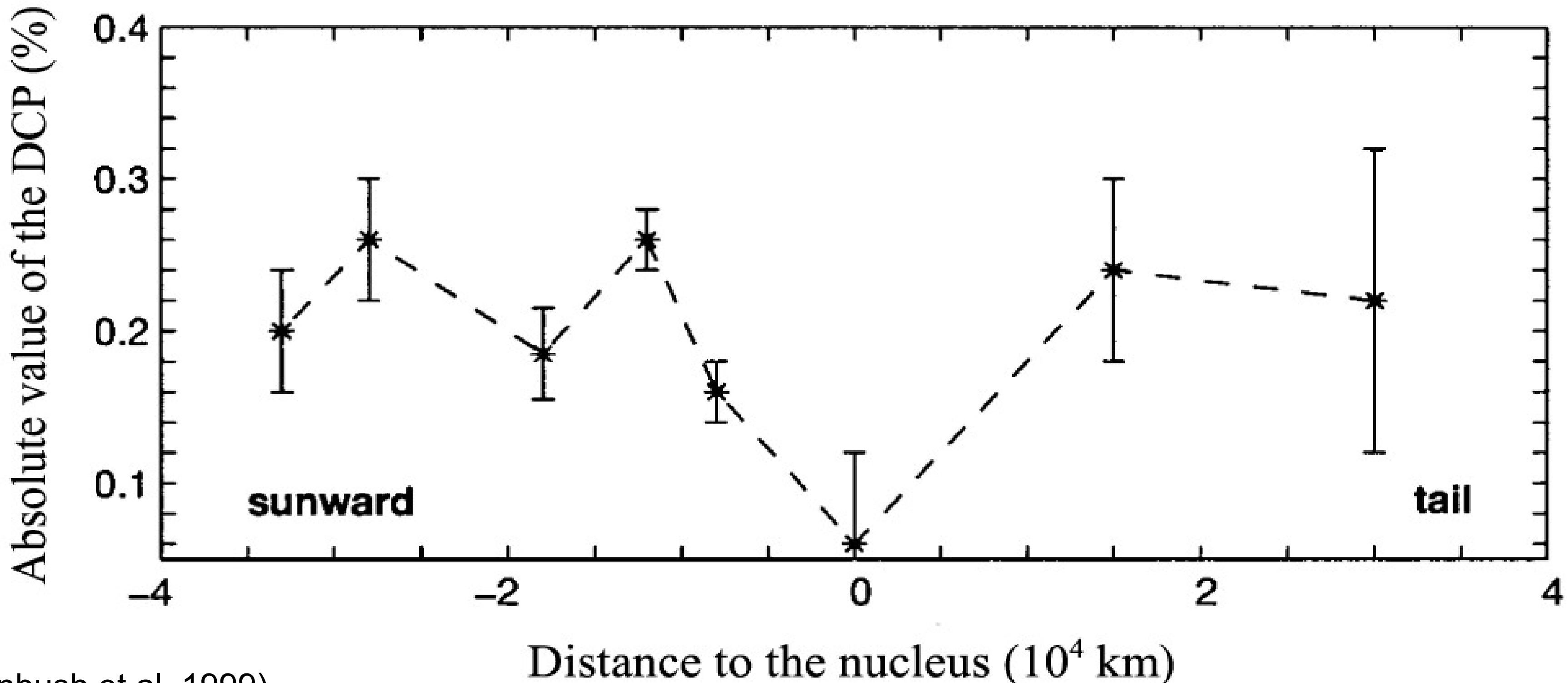
CIRCULAR POLARIZATION: OBSERVATIONS OF HALLEY (1986)

DATE 1986 March	Time (UT)	Direction *)	Distance from core (′)	Diaphragm **) (″)	Number of measure-ments	Start and end of ob-servation (UT)	P (%)	s.d.
16	$8^h\ 57^m$	N	0.5	10	2		−2.2	0.1
	9 01	S	0.5	10	2		−0.9	0.4
	9 05	W	0.5	10	2	$8^h\ 36^m$	−1.5	1.2
	9 10	N	1.0	10	2	-	−1.8	1.1
	9 14	W	1.0	10	2	$9^h\ 29^m$	−1.4	0.3
	9 17	W	3.0	10	1		−1.2	-
	9 21	E	0.5	10	1		−1.5	-
	9 24	CC	0	15	1		−0.9	-

(Metz & Haefner 1987)

- Width of the error bars comparable to the mean values.
- Values of the order of 1%.
- The DCP tends to zero when increasing the diaphragm.

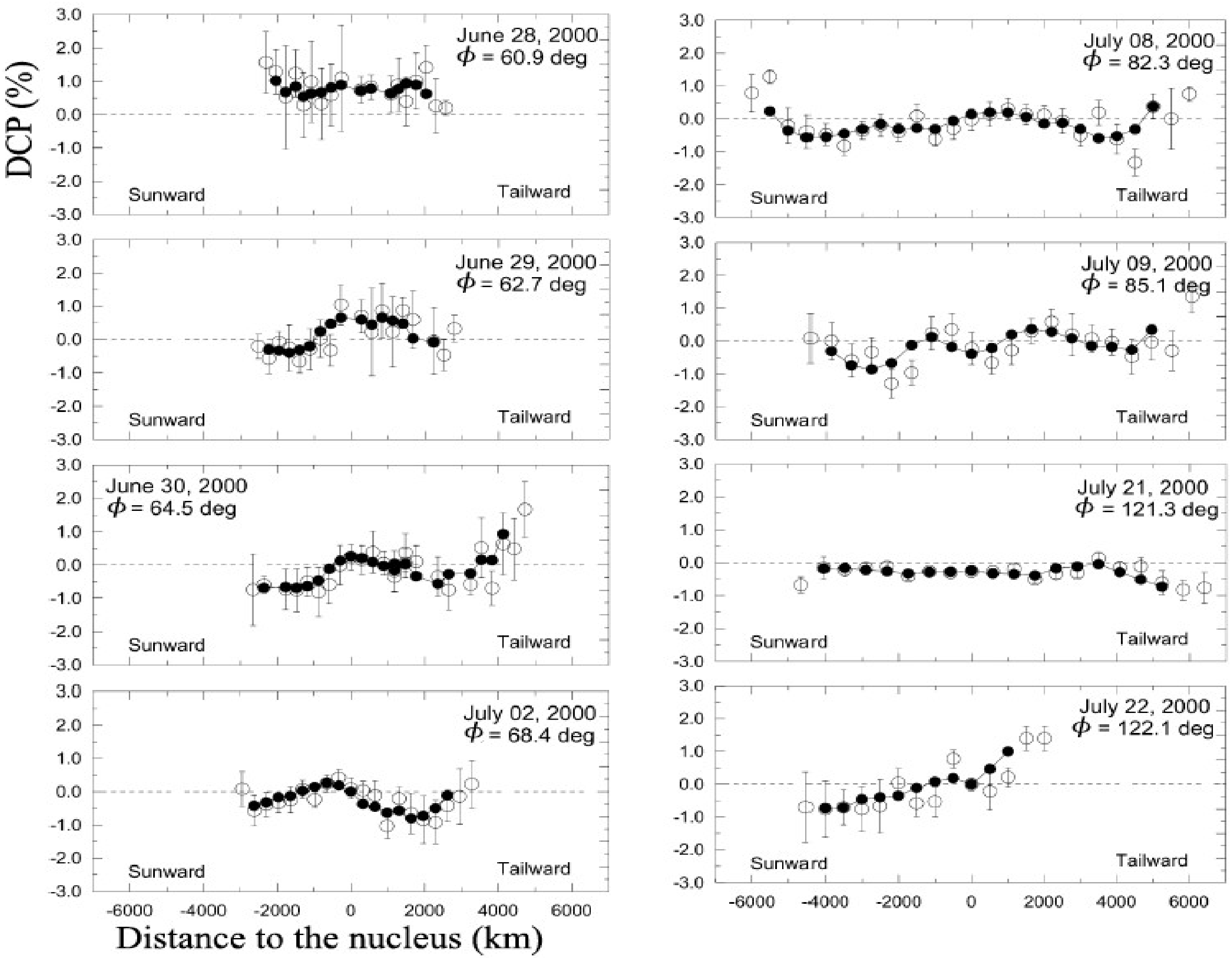
CIRCULAR POLARIZATION: OBSERVATIONS OF HALE-BOPP (1997)



(Rosenbush et al. 1999)

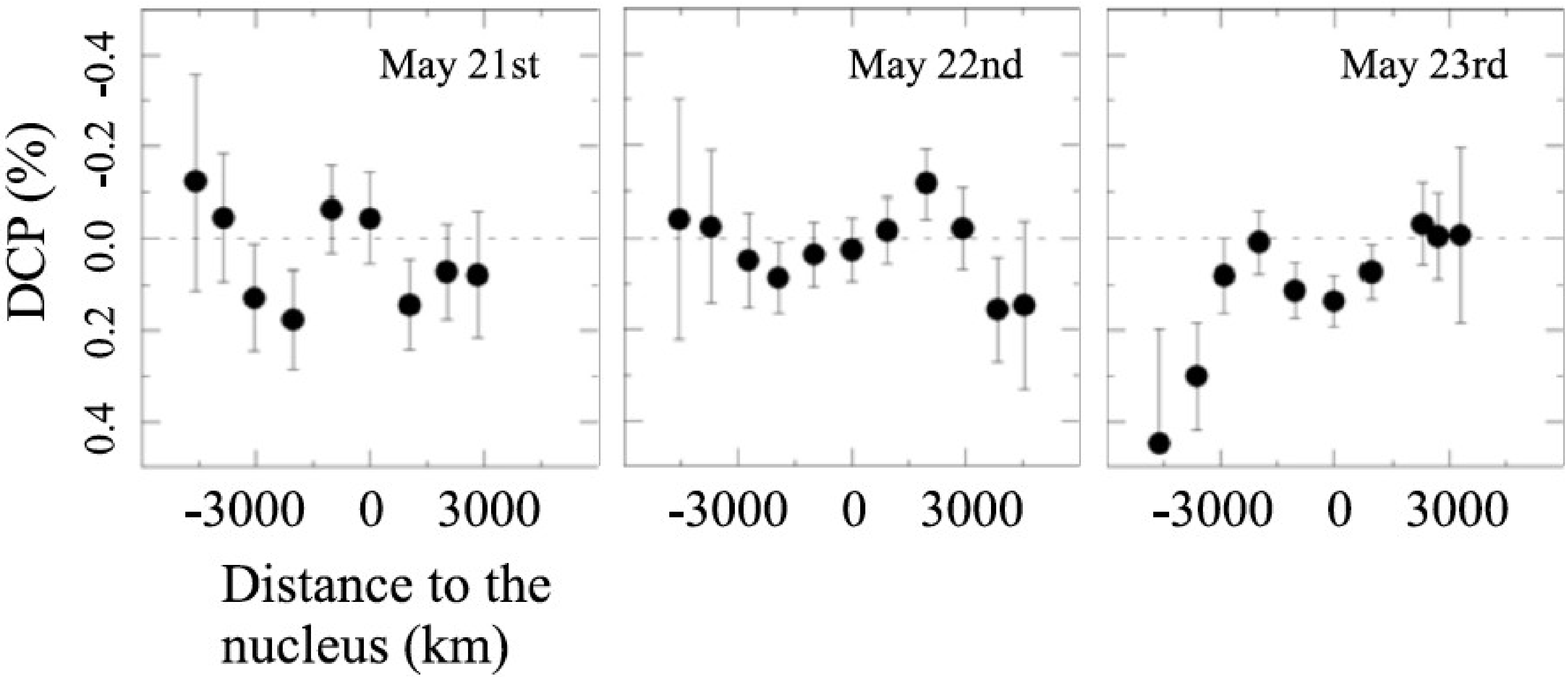
- Mean values significant compared to the error bars.
- Values of the order of 0.1%.
- The DCP vanishes when observing the optocenter.

CIRCULAR POLARIZATION: OBSERVATIONS OF C/1999 S4 (LINEAR)



(Rosenbush et al. 2007)

CIRCULAR POLARIZATION: OBSERVATIONS OF C/2001 Q4 (NEAT)



(Rosenbush et al. 2007b)

CIRCULAR POLARIZATION IN COMETS: SUMMARY OF OBSERVATIONS

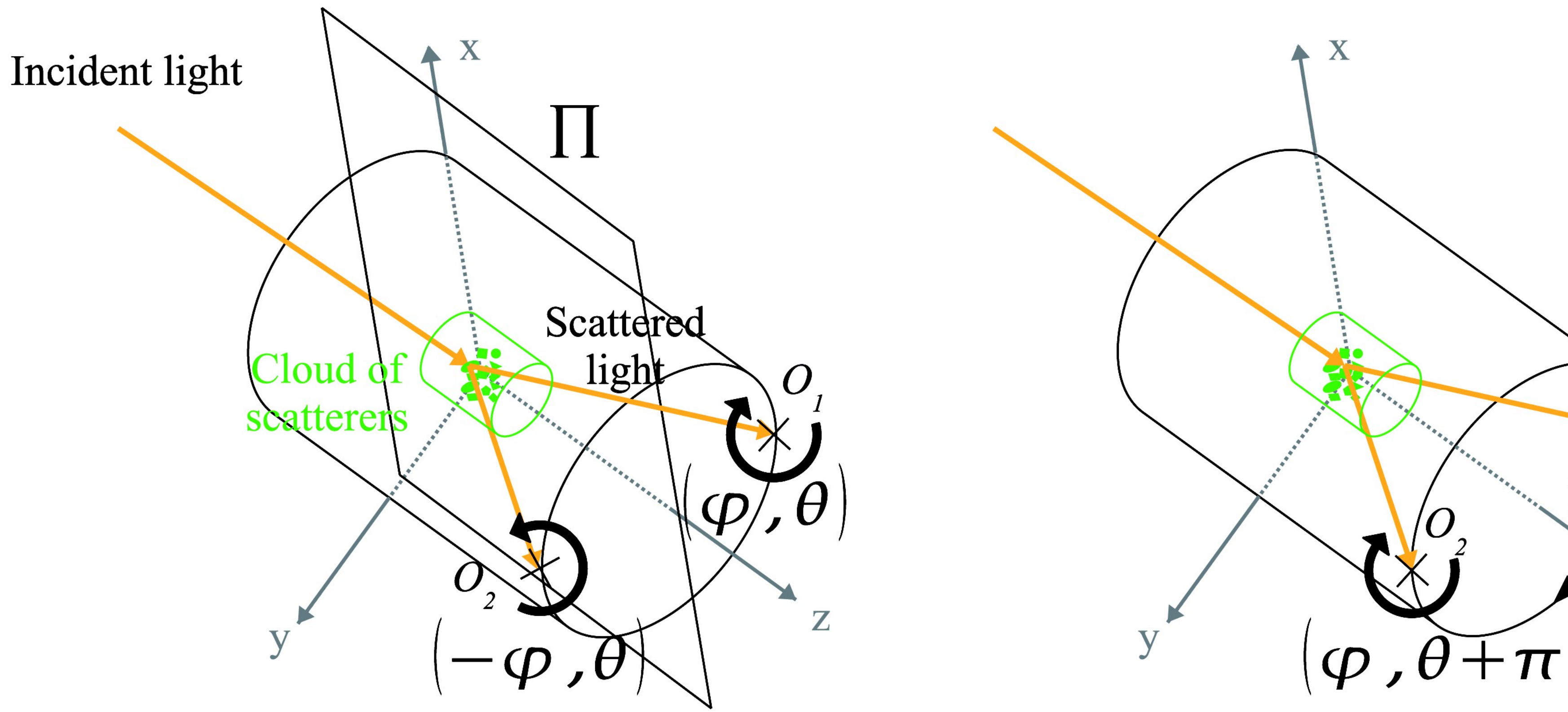
(1) Halley: DCP ~ 1 %, DCP ~ ΔDCP
Hale-Bopp and others: DCP ~ 0.1 %, DCP > ΔDCP

(2) Diaphragm aperture → ∞ ⇨ DCP → 0.

(3) Observation → center ⇨ DCP → 0.

(4) DCP predominantly <0 (?).

CIRCULAR POLARIZATION: NECESSARY CONDITION



The symmetry around the direction of the incident light must be broken.

CIRCULAR POLARIZATION IN COMETS: POSSIBLE MECHANISMS

A complete list of candidates to produce CP of light scattered in comets:

1. Alignment of non-spherical grains.

2. Breaking of the mirror symmetry.

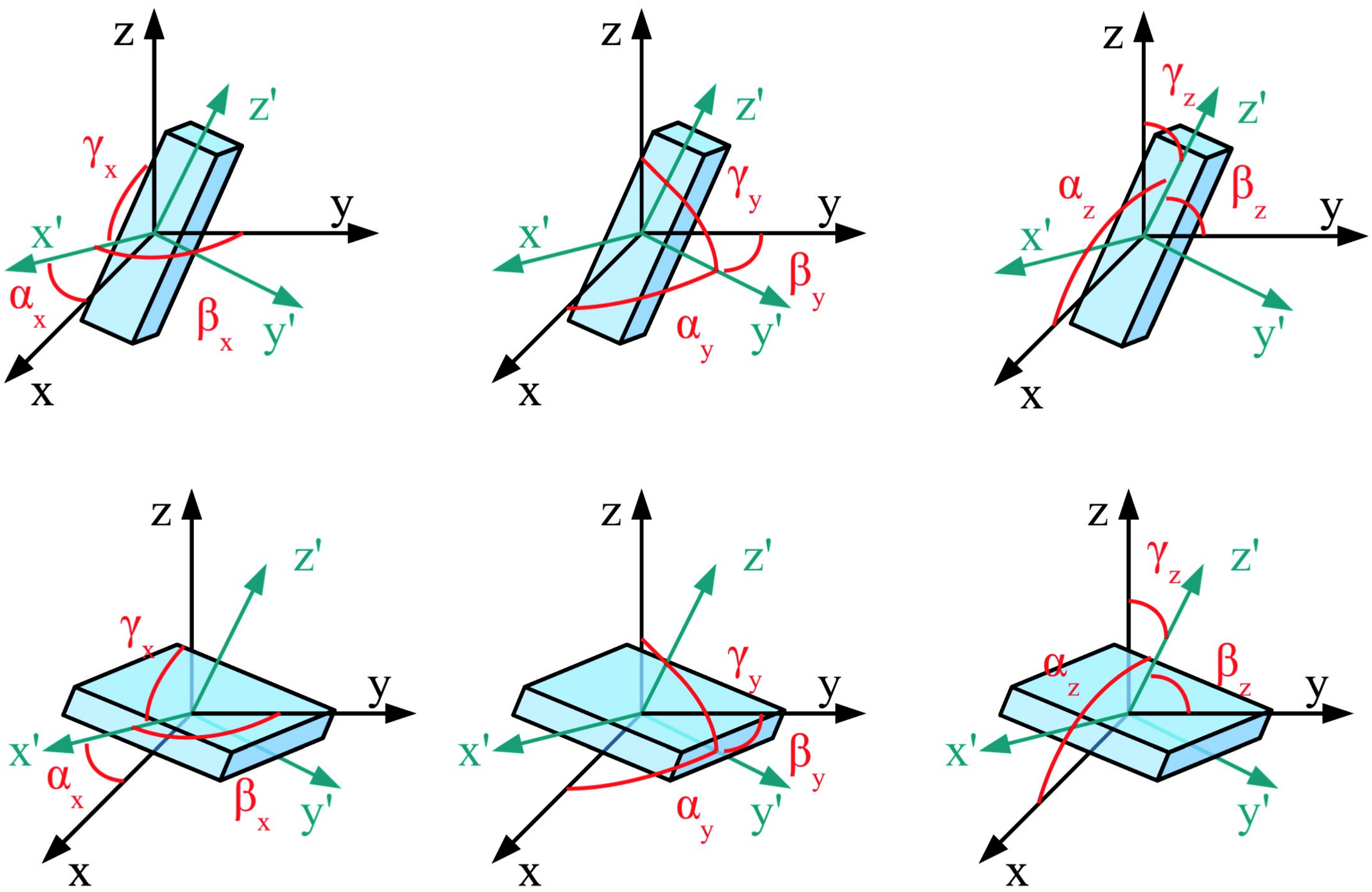
3. Optical activity of the material composing the particles.

4. Inhomogeneous distribution of particles in the coma.

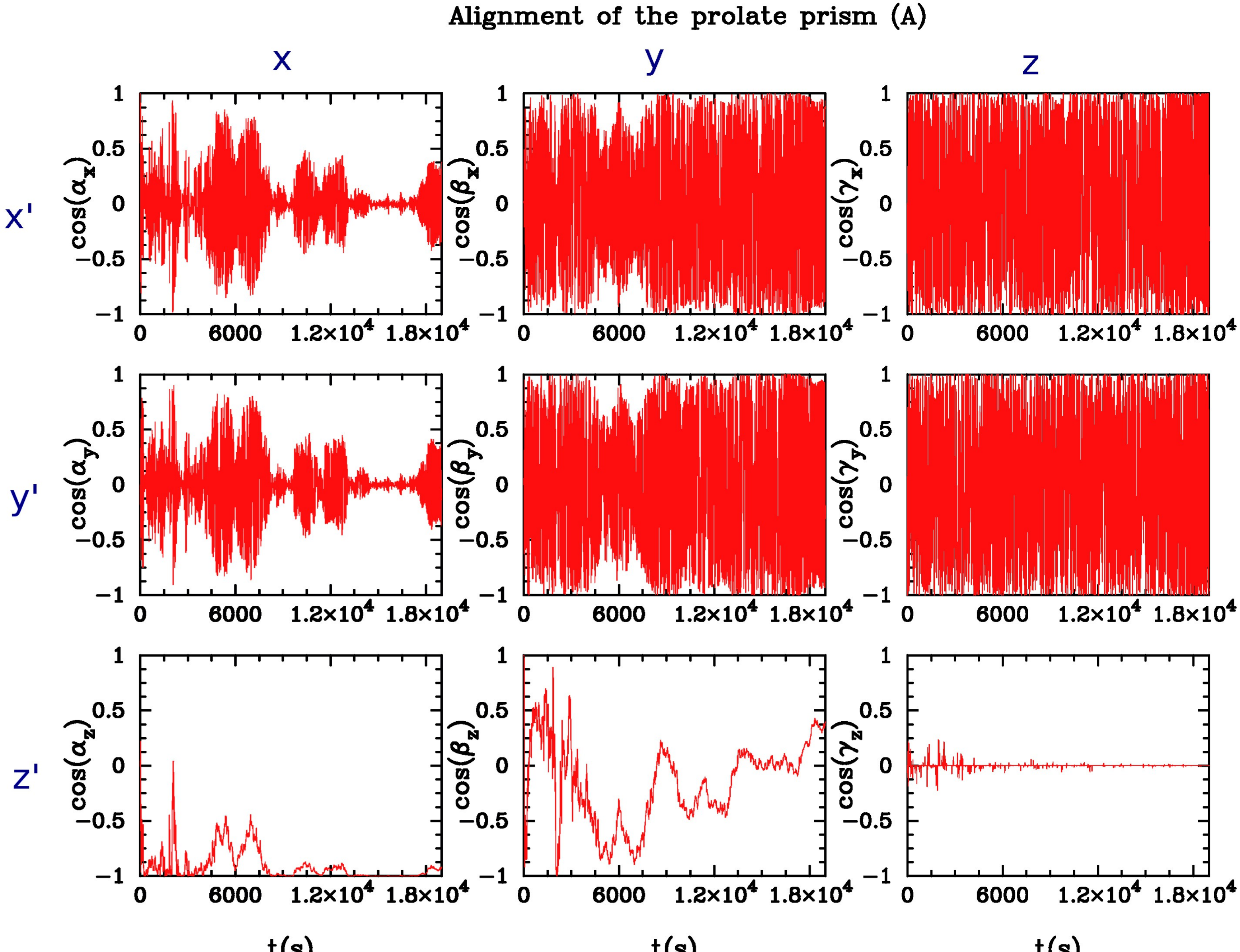
5. Asymmetrical nucleus of the comet.

6. Local observation of a non-central region.

CIRCULAR POLARIZATION IN COMETS: DUE TO GRAIN ALIGNMENT?

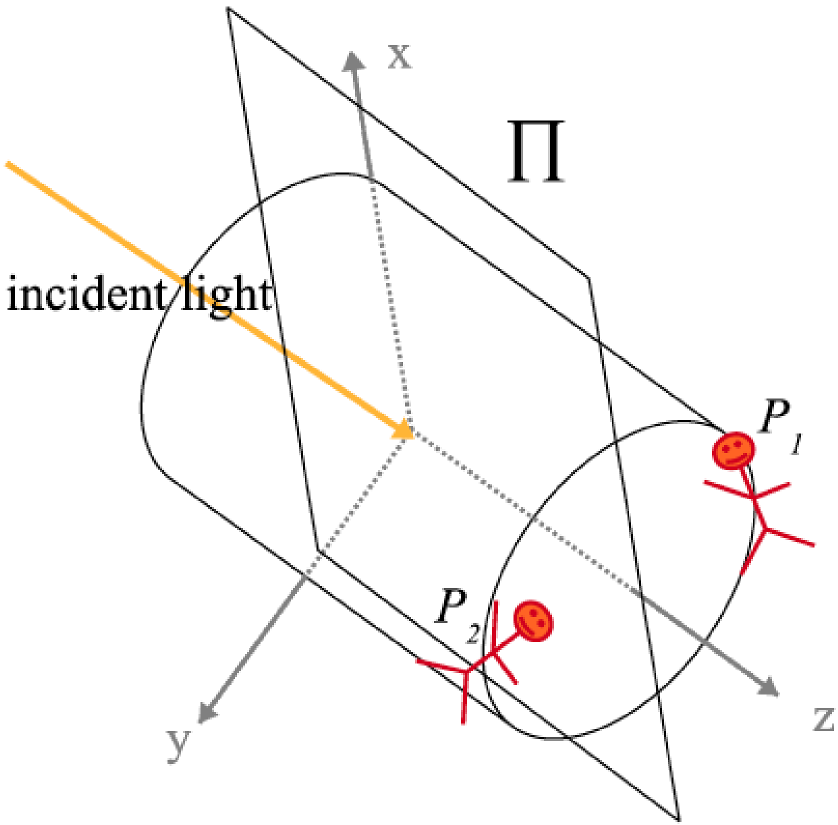


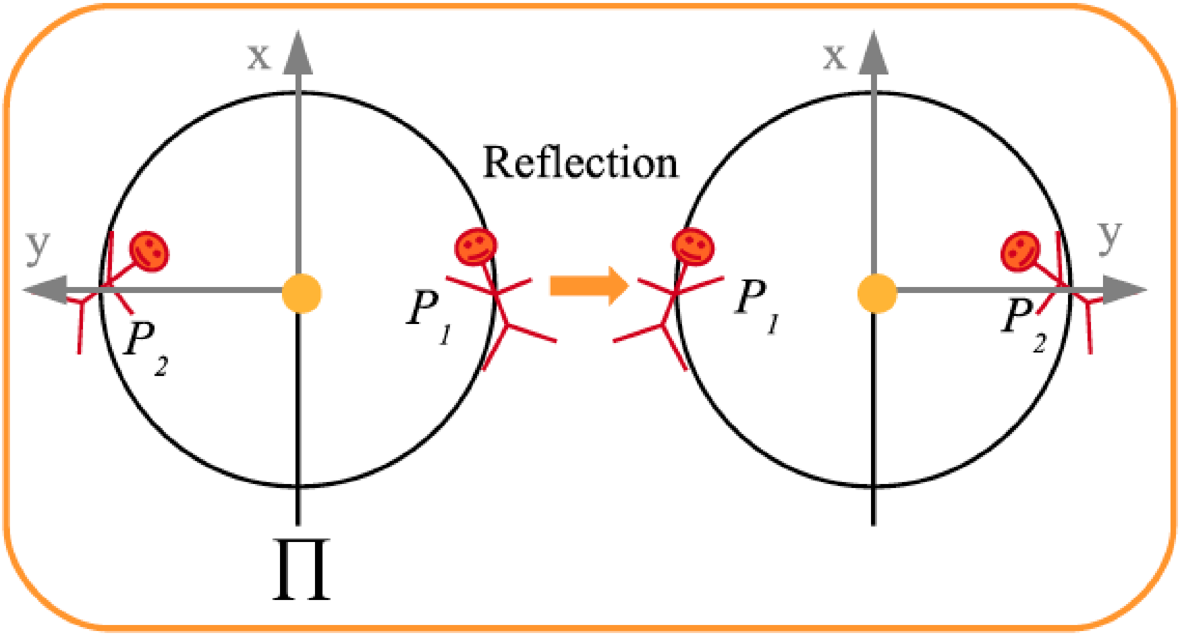
CIRCULAR POLARIZATION IN COMETS: DUE TO GRAIN ALIGNMENT?



NO!

CIRCULAR POLARIZATION IN COMETS: DUE TO BREAK OF THE MIRROR SYMMETRY?





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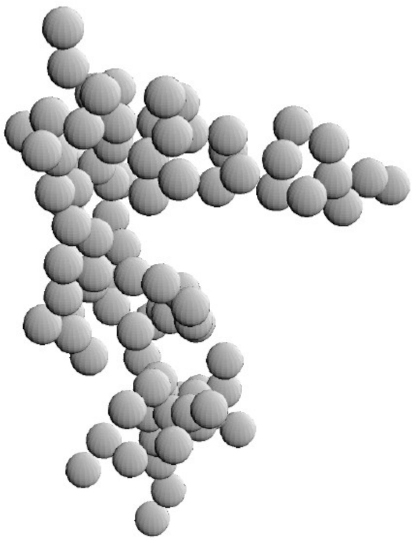
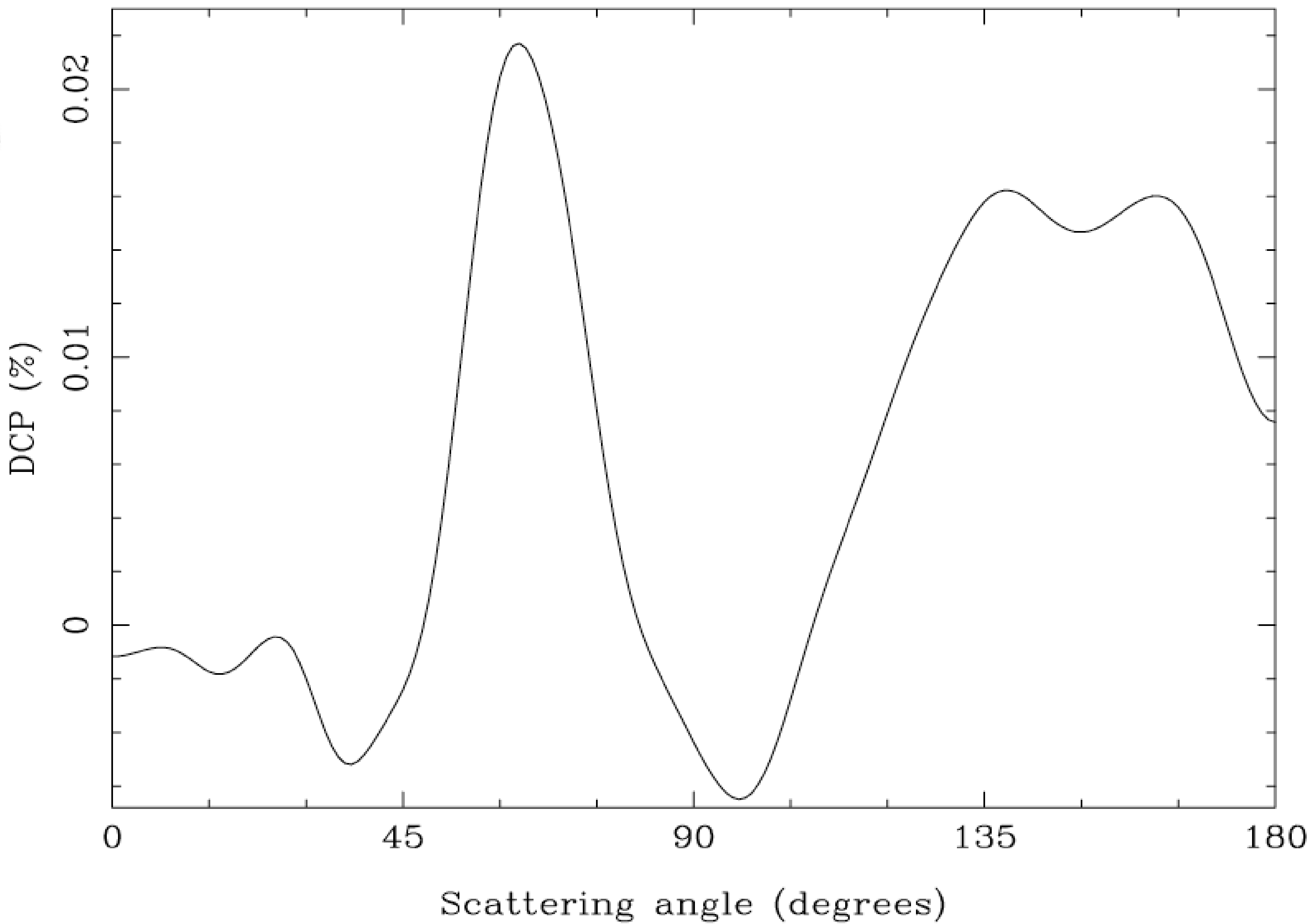
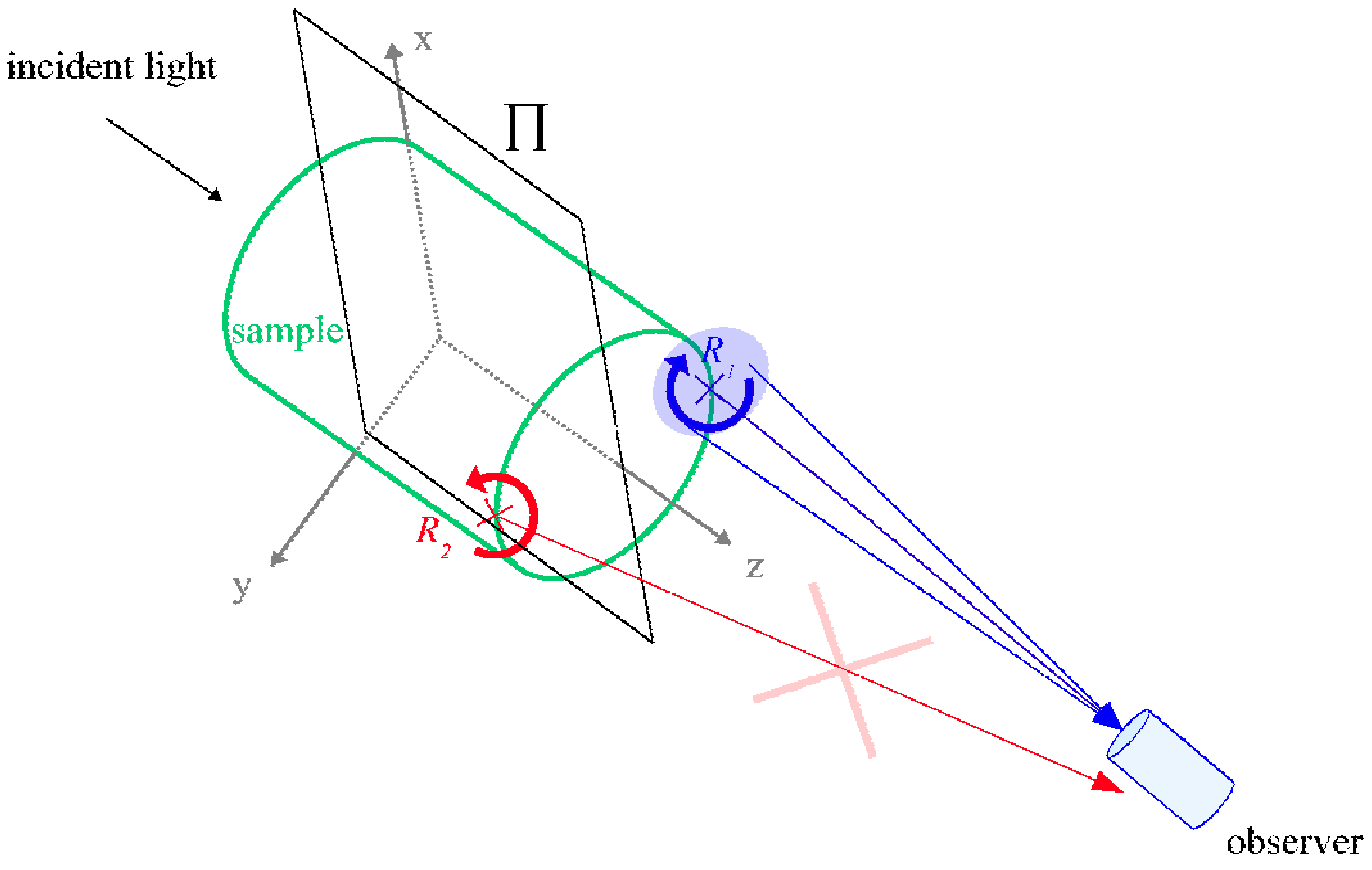


12 shapes
13 sizes

NO!



CIRCULAR POLARIZATION IN COMETS: DUE TO OBSERVATION OF A NON-CENTRAL REGION?



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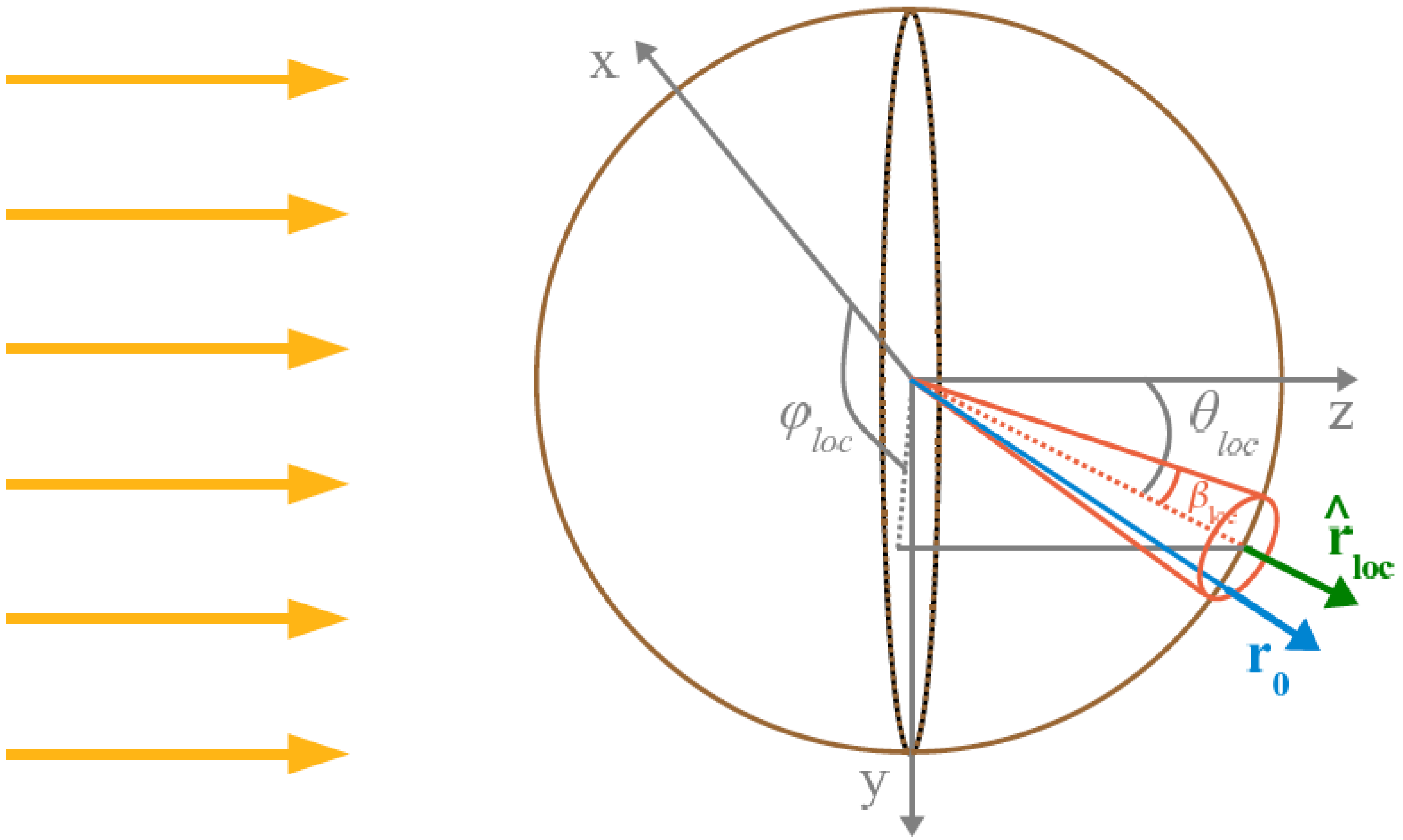
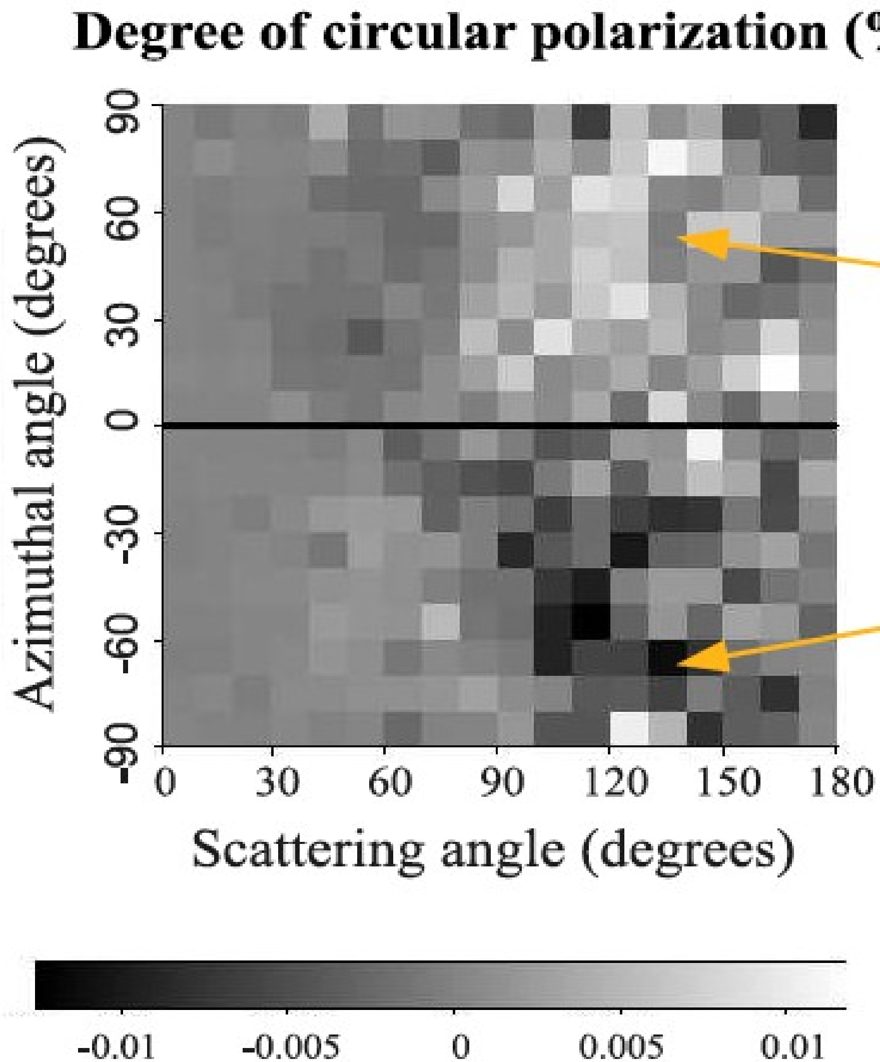
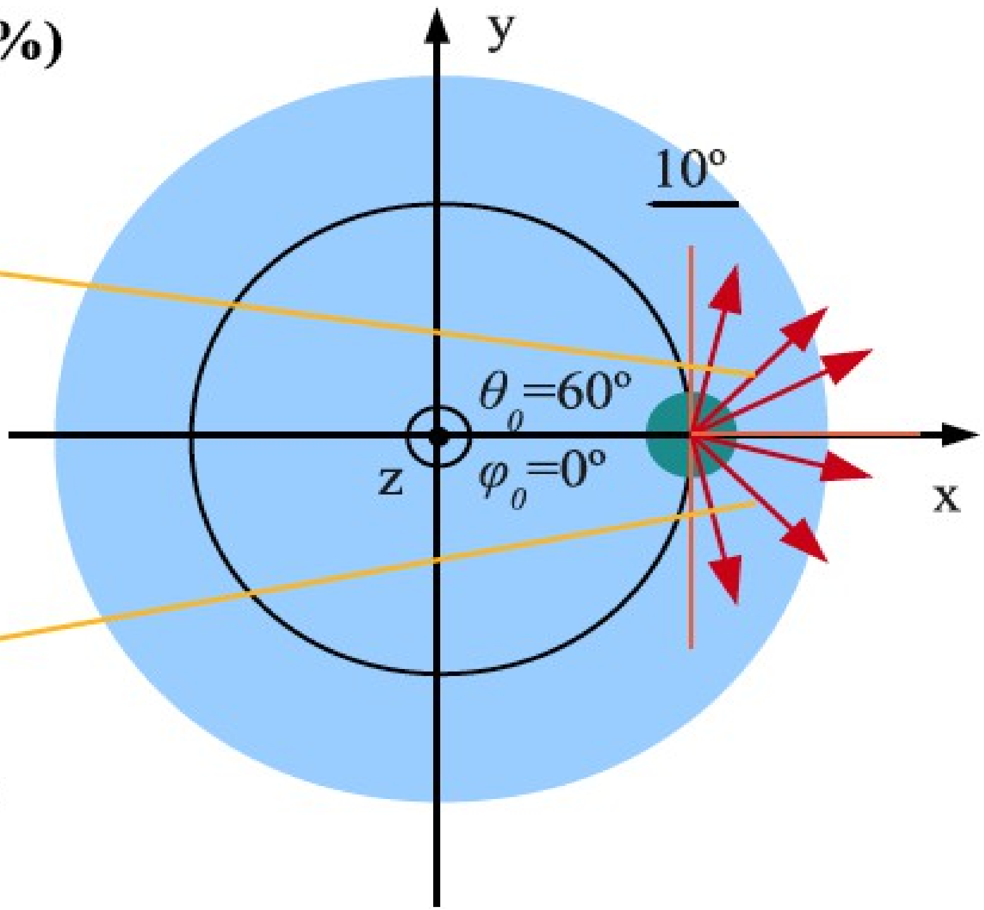


Power-law $\delta = 3.5$
$r_{min} = 0.05\ \mu m$
10^8 packets of photons
$m = 1.6 + i0.001$
$\tau_N = 2.5$
$\theta_{loc} = 60°$
$\varphi_{loc} = 0°$
$\beta_{loc} = 10°$

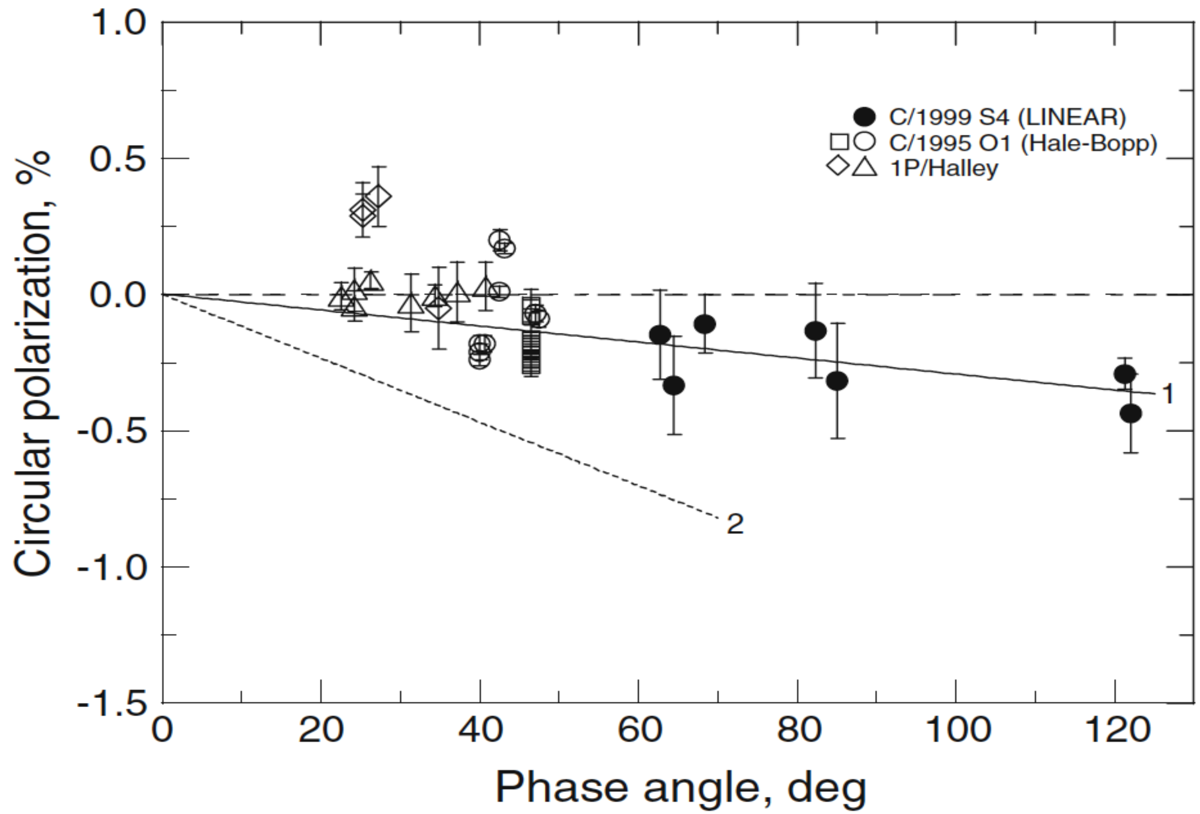
CIRCULAR POLARIZATION IN COMETS: DUE TO OBSERVATION OF A NON-CENTRAL REGION?





Maybe

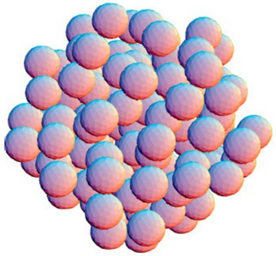
CIRCULAR POLARIZATION IN COMETS: DUE TO OPTICAL ACTIVITY?

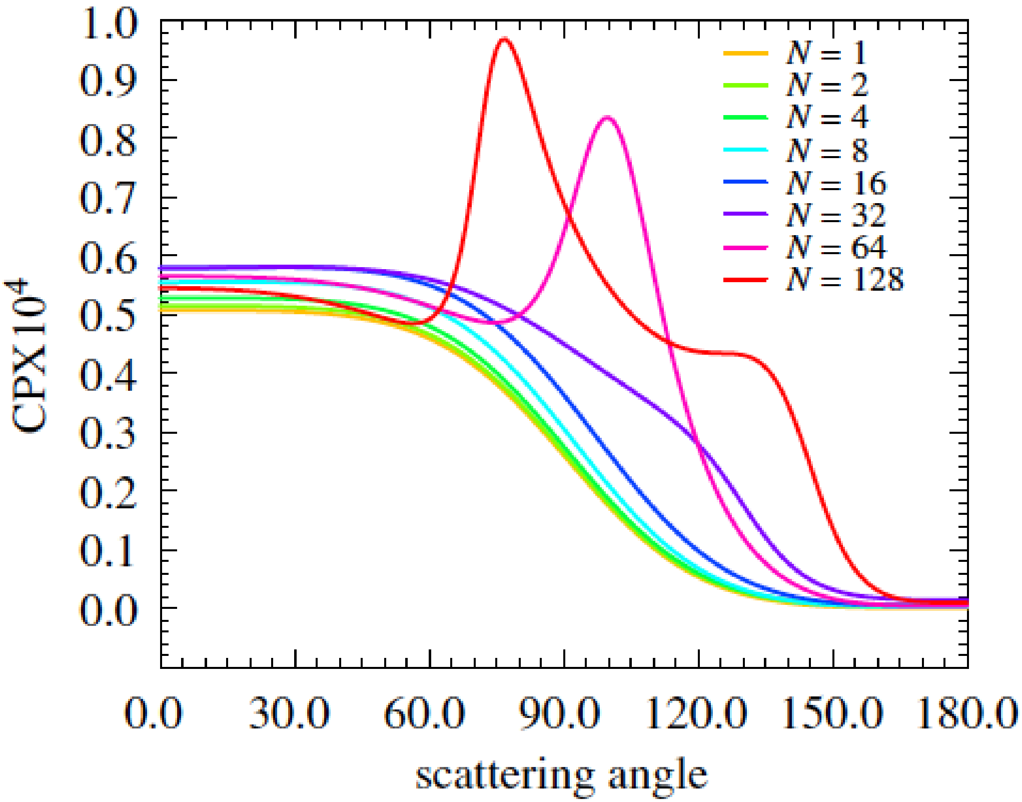


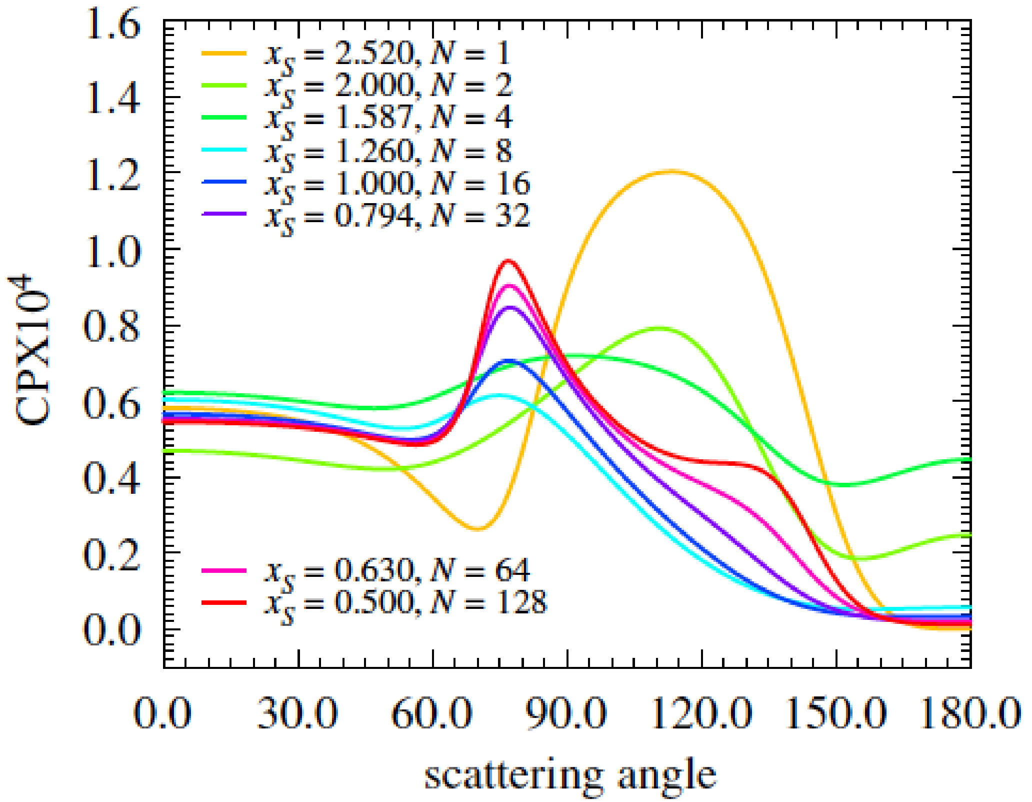
(Kiselev et al. 2005)

Some amines were found at very low abundances in the collected particles of Comet Wild 2 by Stardust mission. Some of these amines are optically active.

CIRCULAR POLARIZATION IN COMETS: DUE TO OPTICAL ACTIVITY?

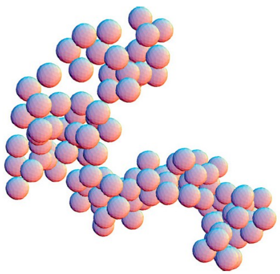


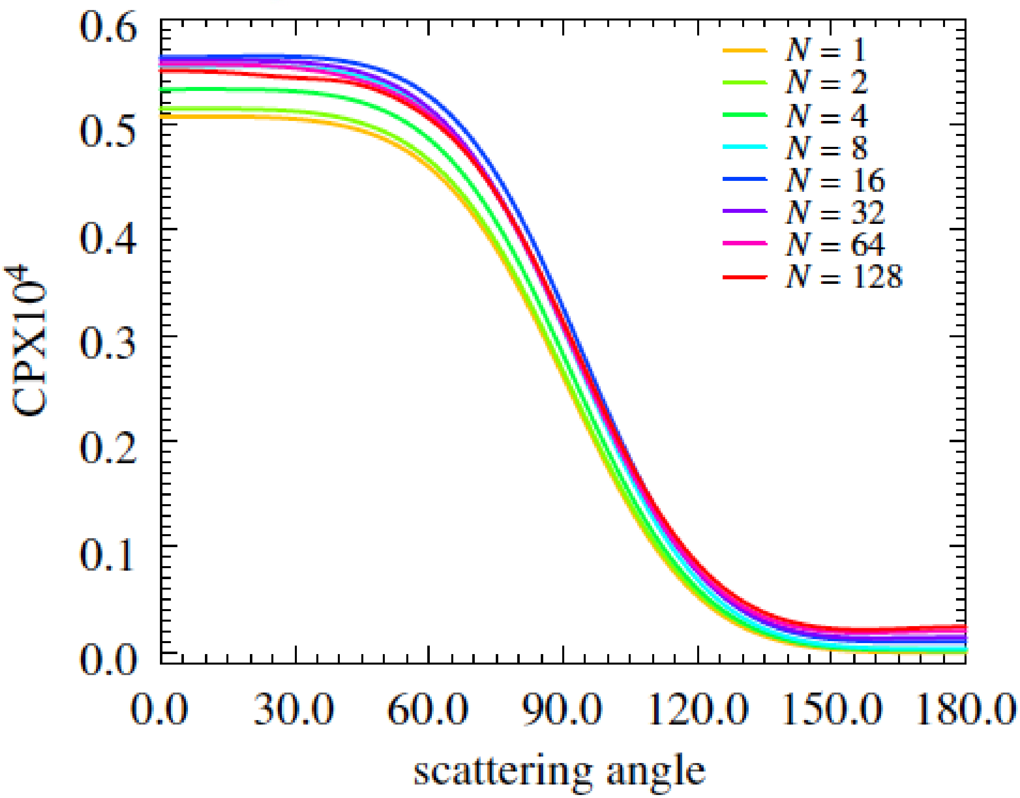


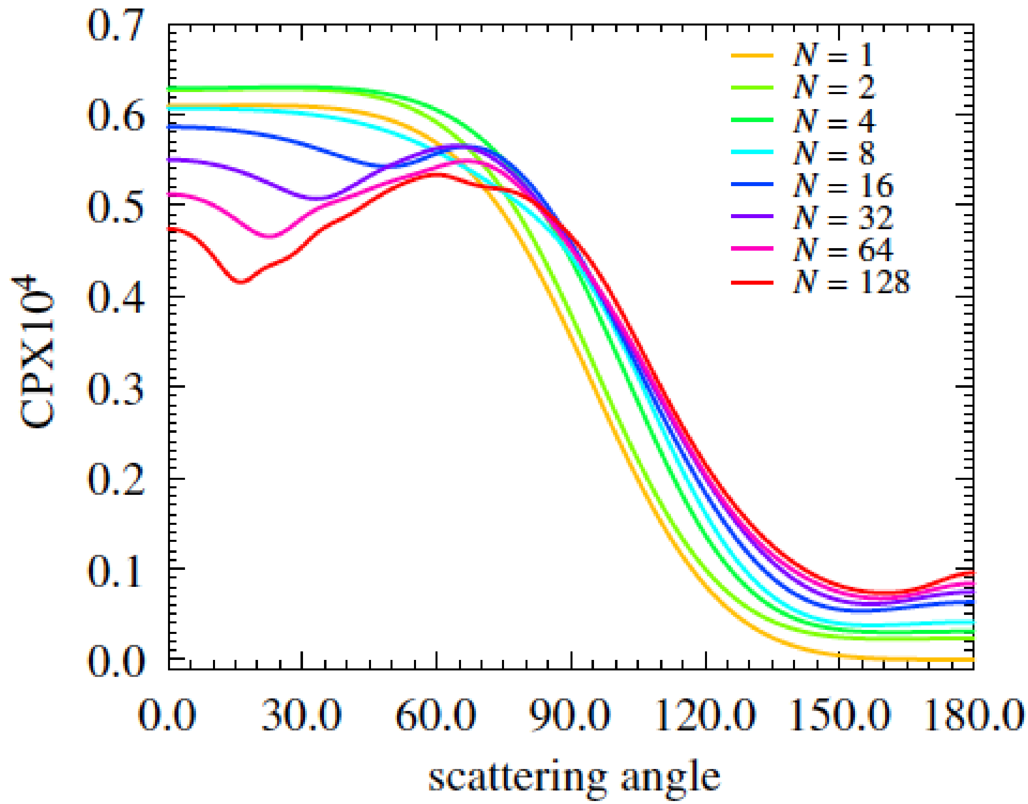


(Mackowski et al. 2001)

CIRCULAR POLARIZATION IN COMETS: DUE TO OPTICAL ACTIVITY?







(Mackowski et al. 2001)

Maybe

ASTEROIDS: DEFINITION & COMPOSITION

What are asteroids?

Rocky bodies in a wide range of sizes orbiting the Sun, excluding planets.

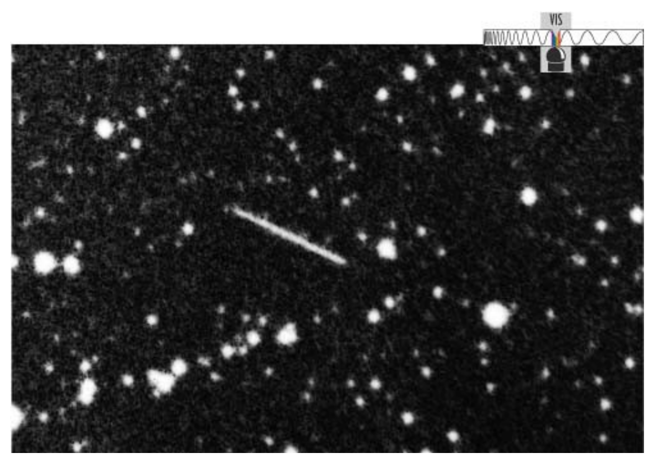
Composition (from spectroscopy)

C-type asteroids - carbons, 75% of known asteroids
S-type asteroids - silicates, 17% of known asteroids
M-type asteroids - metals, 8% of known asteroids

Observing asteroids

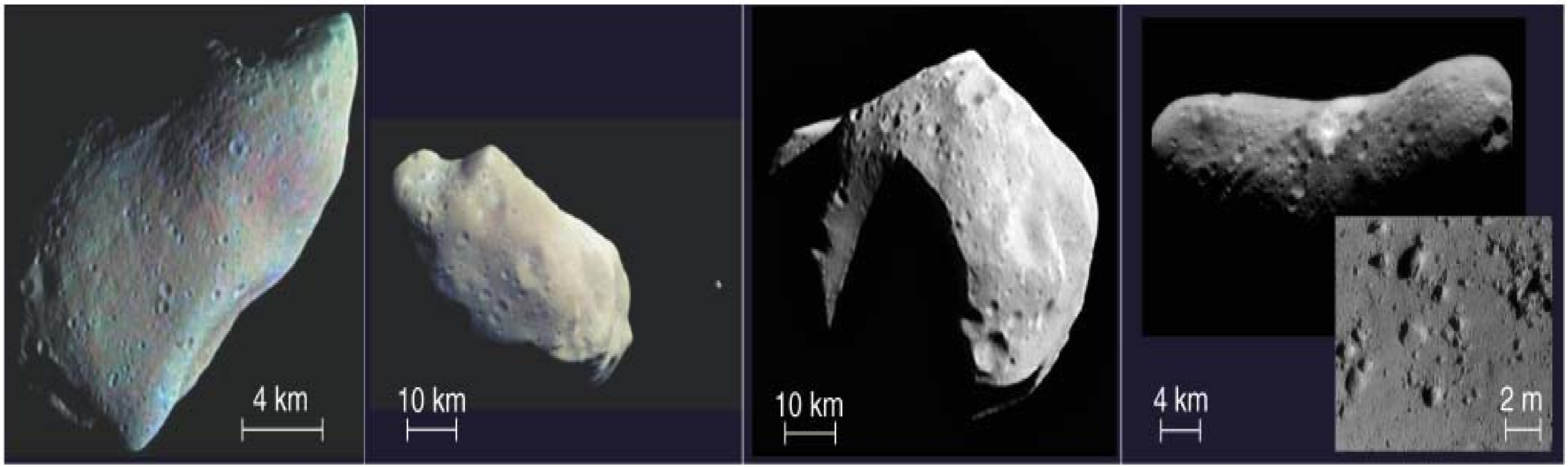
They draw a trace on images for long expositions

Observed
- From Earth (Spacewatch, SDSS, Subaru).
- Space missions.



ASTEROIDS SHAPE

Non large enough for self gravity to produce spherical shape



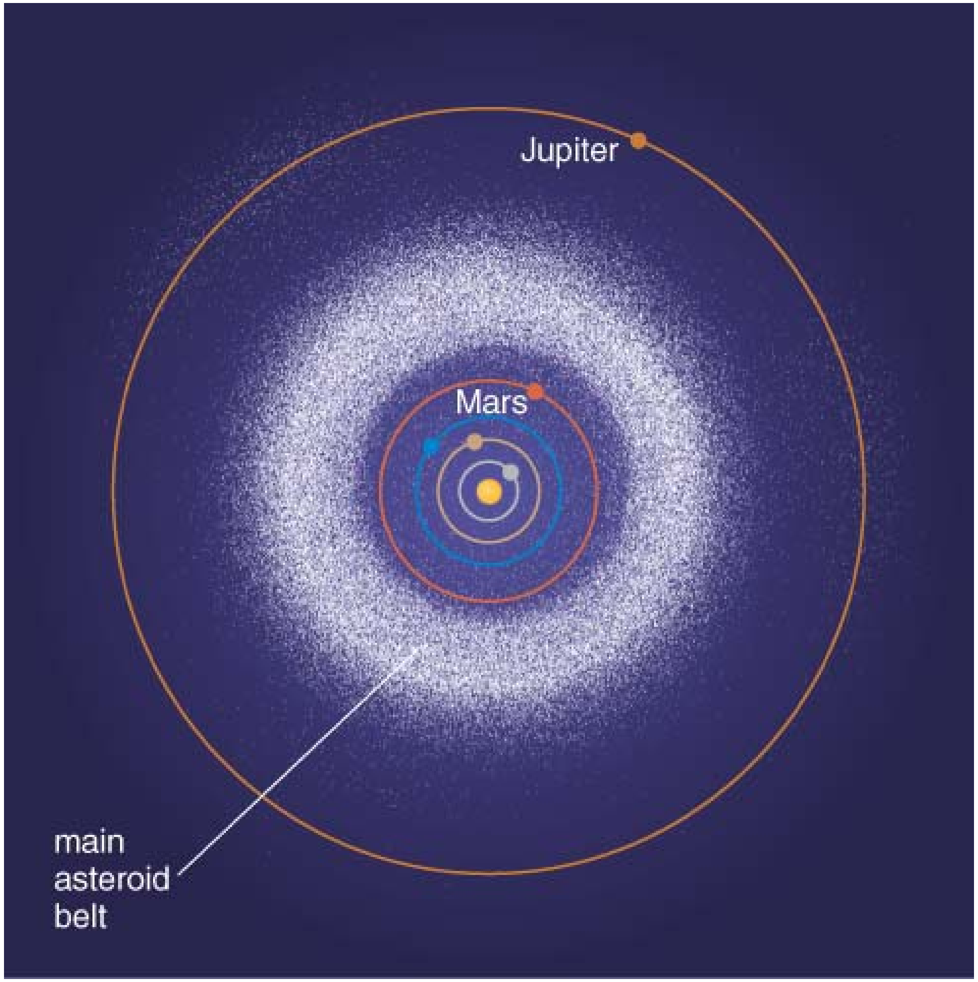
a Gaspra, photographed by the *Galileo* spacecraft.

b Ida, photographed by the *Galileo* spacecraft. The small dot to the right is Dactyl, a tiny moon orbiting Ida.

c Mathilde, photographed by the Near-Earth Asteroid Rendezvous (NEAR) spacecraft on its way to Eros.

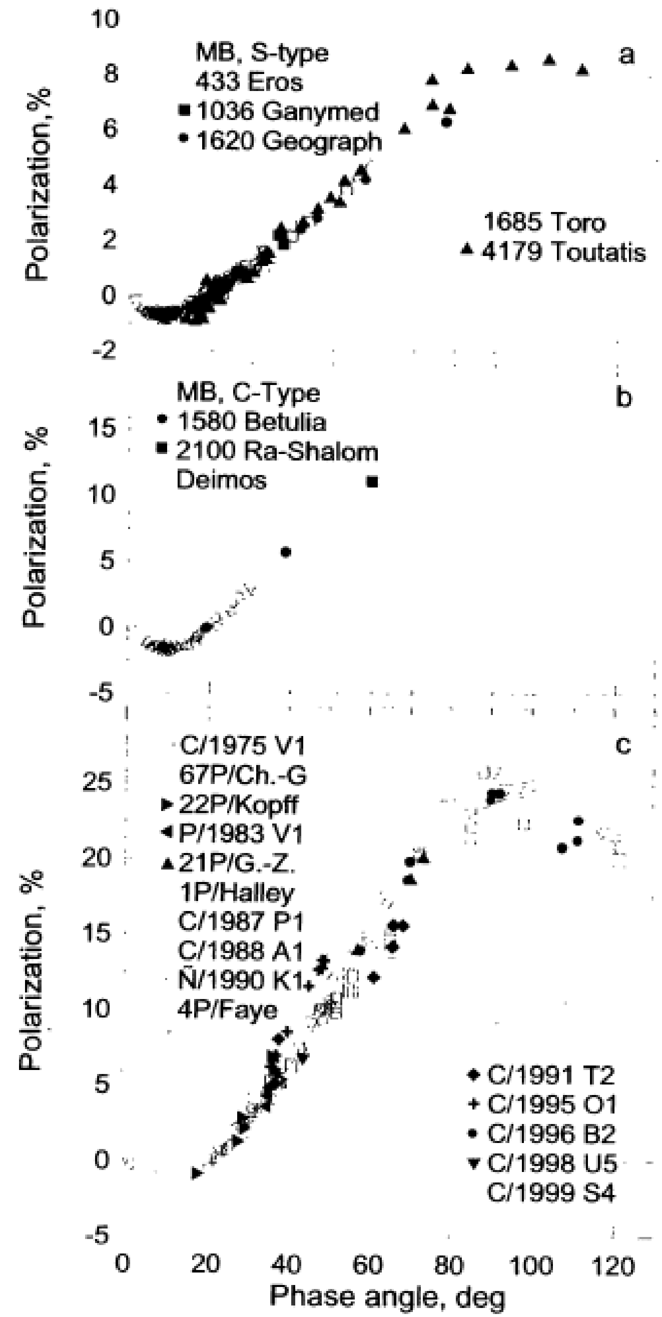
d Eros, photographed by the NEAR spacecraft, which orbited Eros for a year before ending its mission with a soft landing on the asteroid's surface. The inset photo was taken by NEAR just before it landed.

THE ASTEROIDS BELT (I)



ASTEROIDS ORBITS CONTAINED BETWEEN MARS' AND JUPITER'S ORBITS.

ASTEROIDS: WHAT DO WE OBSERVE?



(Kiselev et al. 2002)

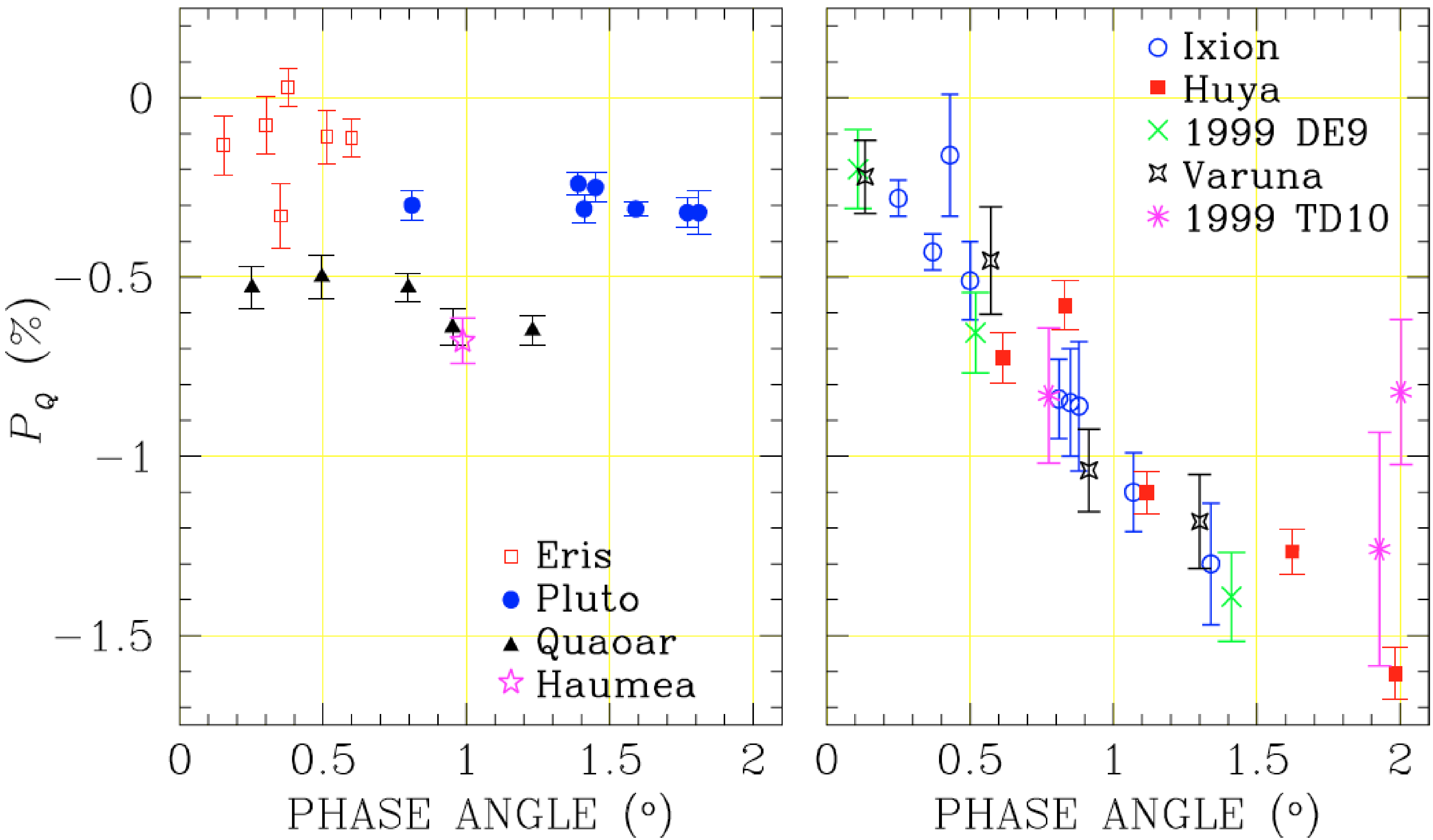
ASTEROIDS: INTERPRETATION

- The maximum of the degree of linear polarization is higher for comets than for C-type and S-type asteroids.

- Asymmetry of the negative branch of polarization increases as the albedo grows.

- The inversion phase angle decreases as the albedo increases.

TRANS-NEPTUNIAN OBJECTS



(Bagnulo et al. 2008)

Open problem

CONCLUSIONS

- The observation of linear and circular polarization of light scattered by minor bodies of the Solar System informs us about intrinsic properties of this objects and processes happening in there.

- The positive branch of the degree of linear polarization as a function of the phase angle is higher for dust-rich than gas-rich comets. The negative branch is the same.

- A small but significant degree of circular polarization is observed in comets. It's not due to alignment of the grains, as they align symmetrically regarding the direction of the incident light. The observation of local non-centered region plus the presence of organics contribute.

- The positive branch of linear polarization is lower for asteroids than comets. A correlation exists of the albedo with the asymmetry of the negative branch and with the inversion angle.

- Two polarimetric behaviors have been recognized in trans-neptunian objects depending on the size of the body.