Aperture-averaged photo-polarimetry of comets in visible

In visible band, photometry of comets measures the intensity (magnitude/flux density) of sunlight scattered by dust and gas in coma.

Intensity of scattered light depends on properties of dust particles and gas molecules.

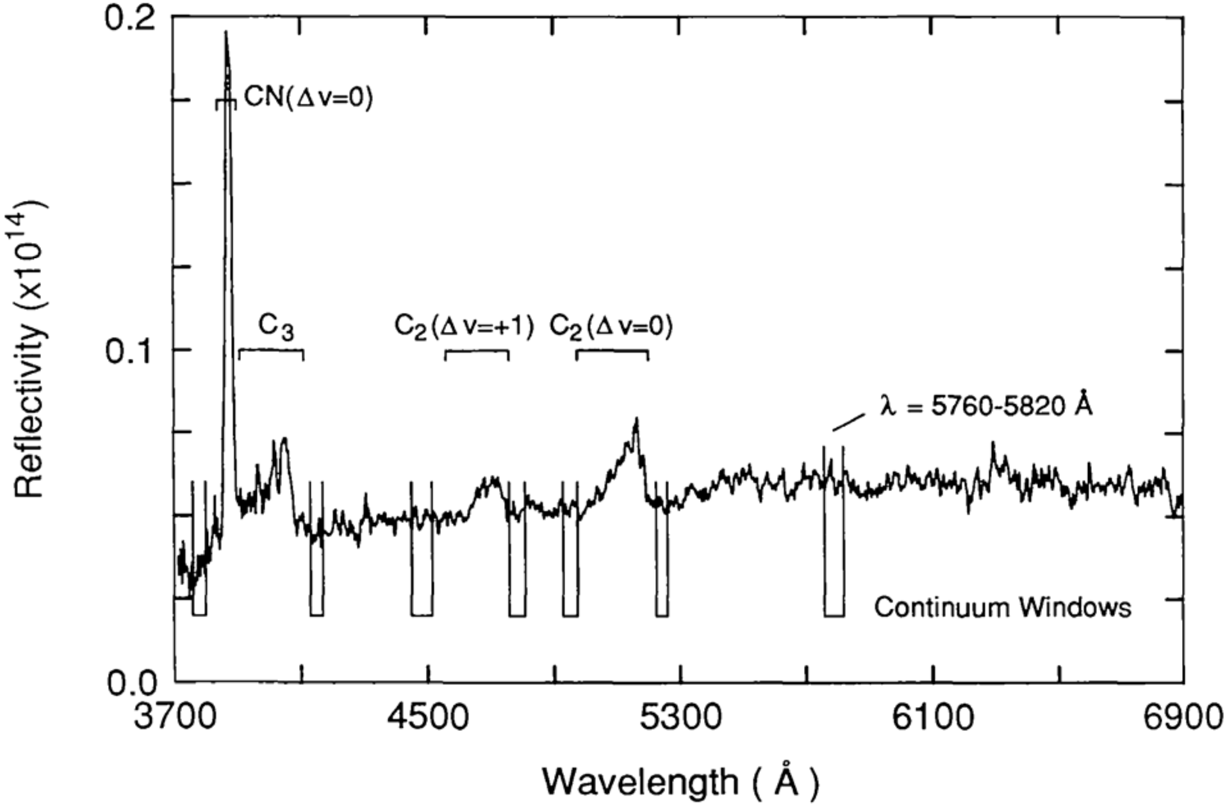
However, intensity also varies with wavelength λ, heliocentric R and geocentric Δ distances, production rates for dust and gases.

Gases contribute mostly at certain wavelengths (resonant scattering). However, there is also a non-resonant scattering by gases (but it is much weaker than the scattering by dust).

Resonant scattering is accompanied with absorption and secondary emission of photons. Therefore, resonant scattering by gas appears in spectrum as narrow emission lines.

The parts of spectrum which are not contaminated by resonant scattering by gas, is called *continuum*.

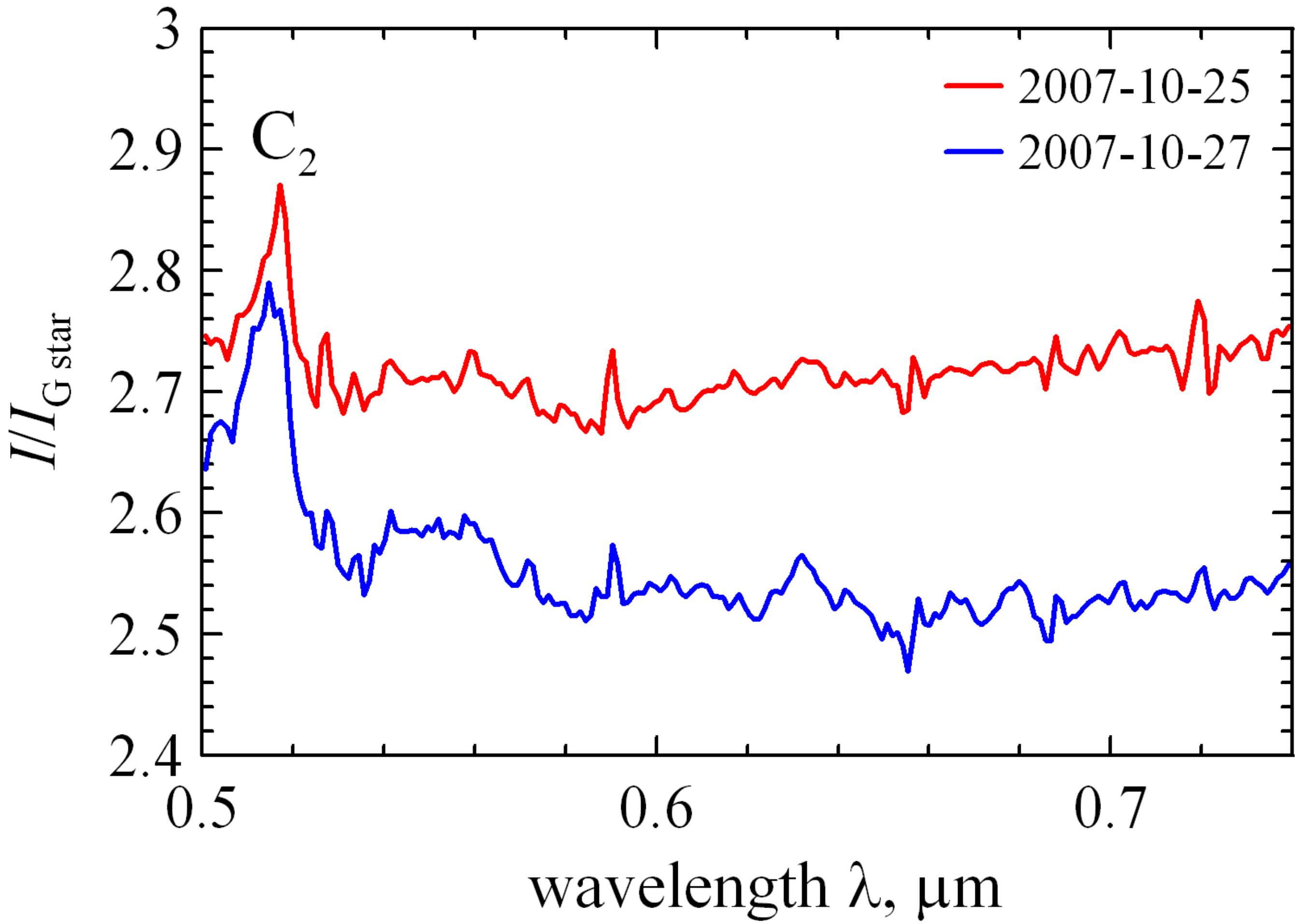
Average of nine spectra of comet 1P/Halley



Measurements were made with 8″ circular diaphragm centered at point 40″ west of the nucleus; R=1.72 AU; November 22, 1985.

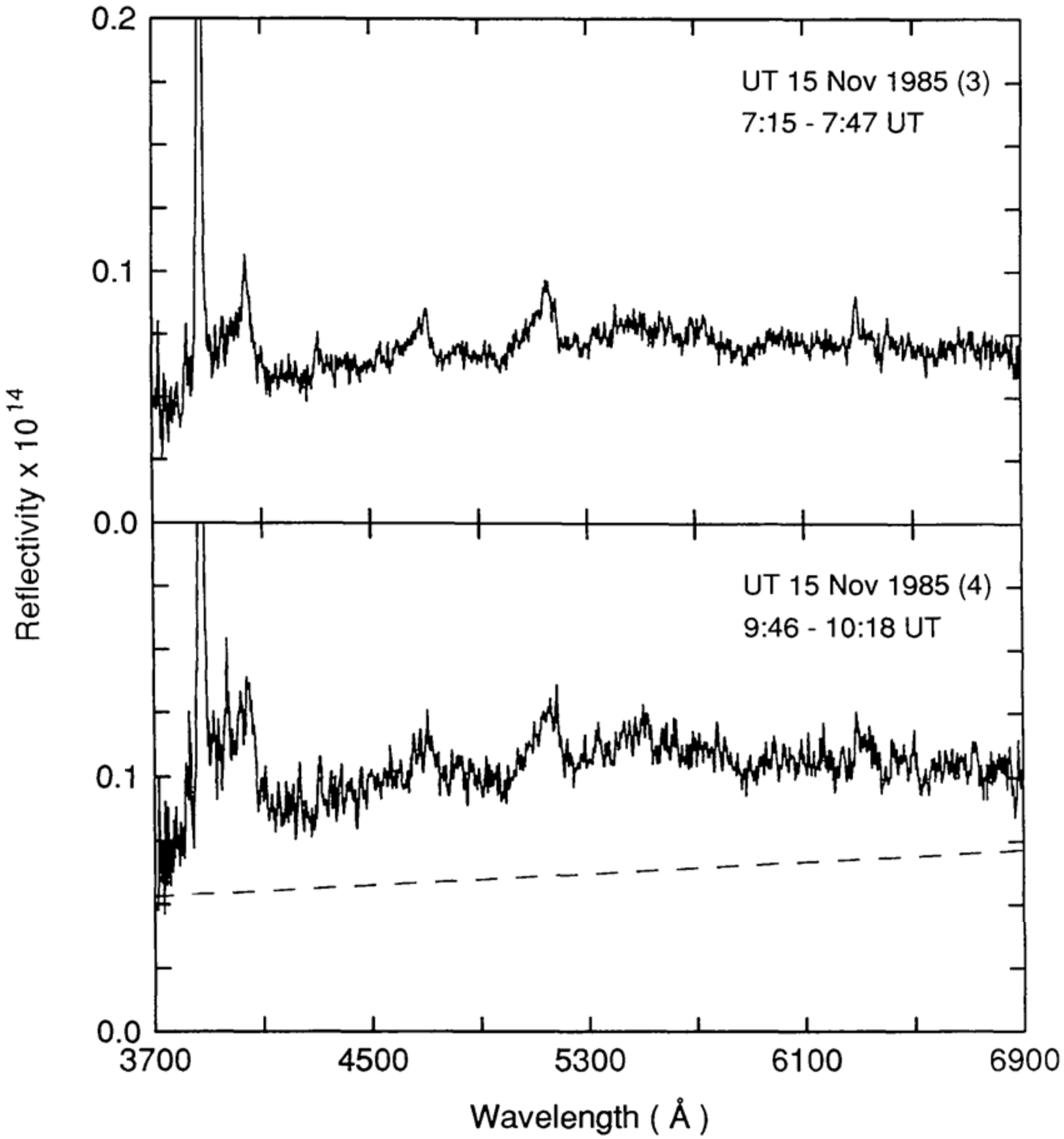
Species	Emission Å	Continuum Å
CN ($\Delta v = 0$)	3840–3900	3760–3800, 4130–4170
C_3	3910–4110	3760–3800, 4130–4170
C_2 ($\Delta v = +1$)	4560–4760	4450–4515, 4760–4810
C_2 ($\Delta v = 0$)	4975–5200	4930–4975, 5225–5260

Spectra of comet 17P/Holmes



The spectra were obtained shortly after mega-outburst on October 24, 2007. Measurements correspond to area 17000 × 4400 km centered at nucleus.

Changes in spectrum of comet 1P/Halley caused by outburst

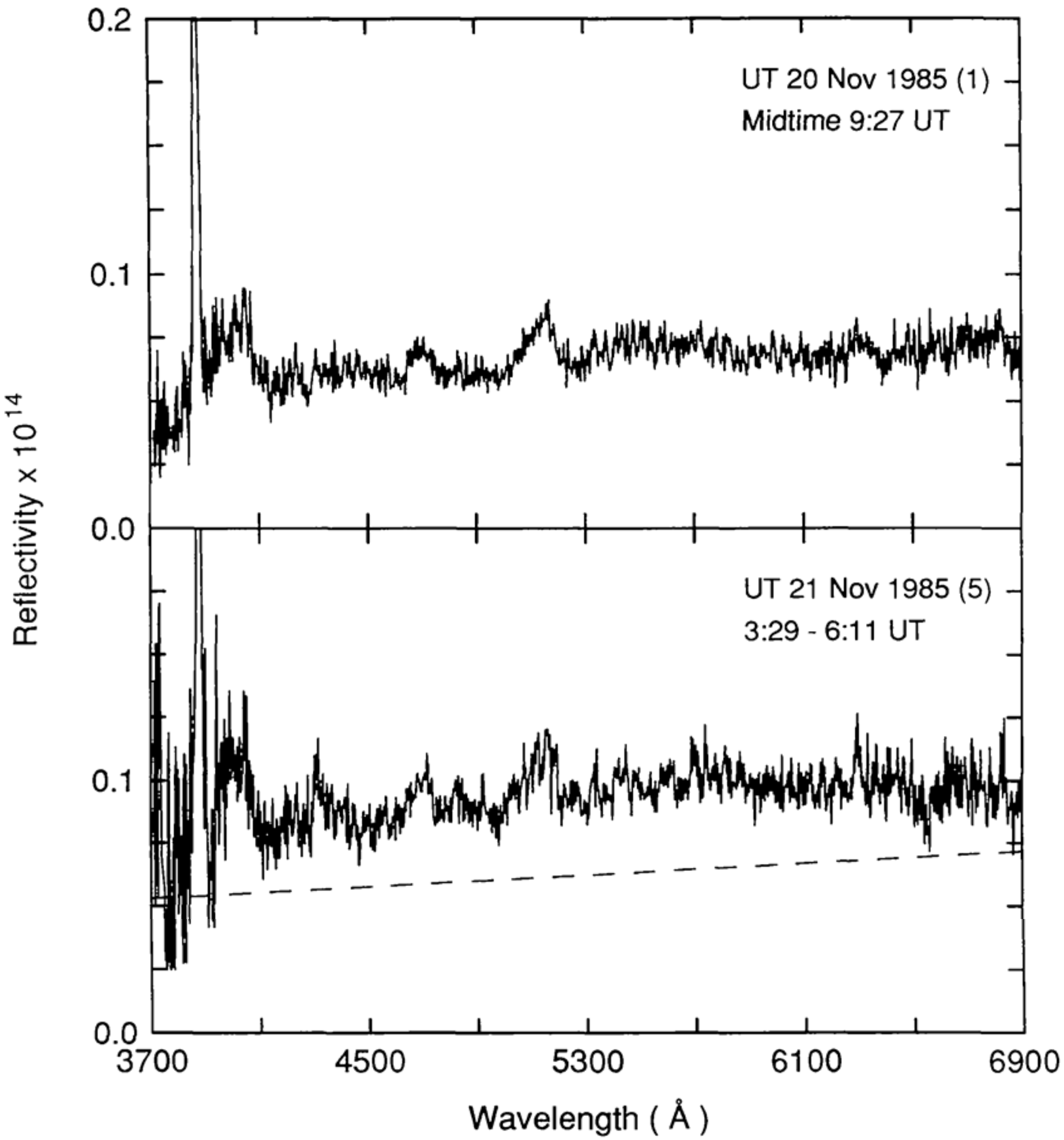


In general, outburst activity may suddenly increase and change continuum and emission lines.

Impact on continuum is caused by fresh dust particles; whereas, on emission lines by gases.

In this figure, impact on continuum is more pronounced than that on emission lines.

Changes in spectrum of comet 1P/Halley caused by outburst



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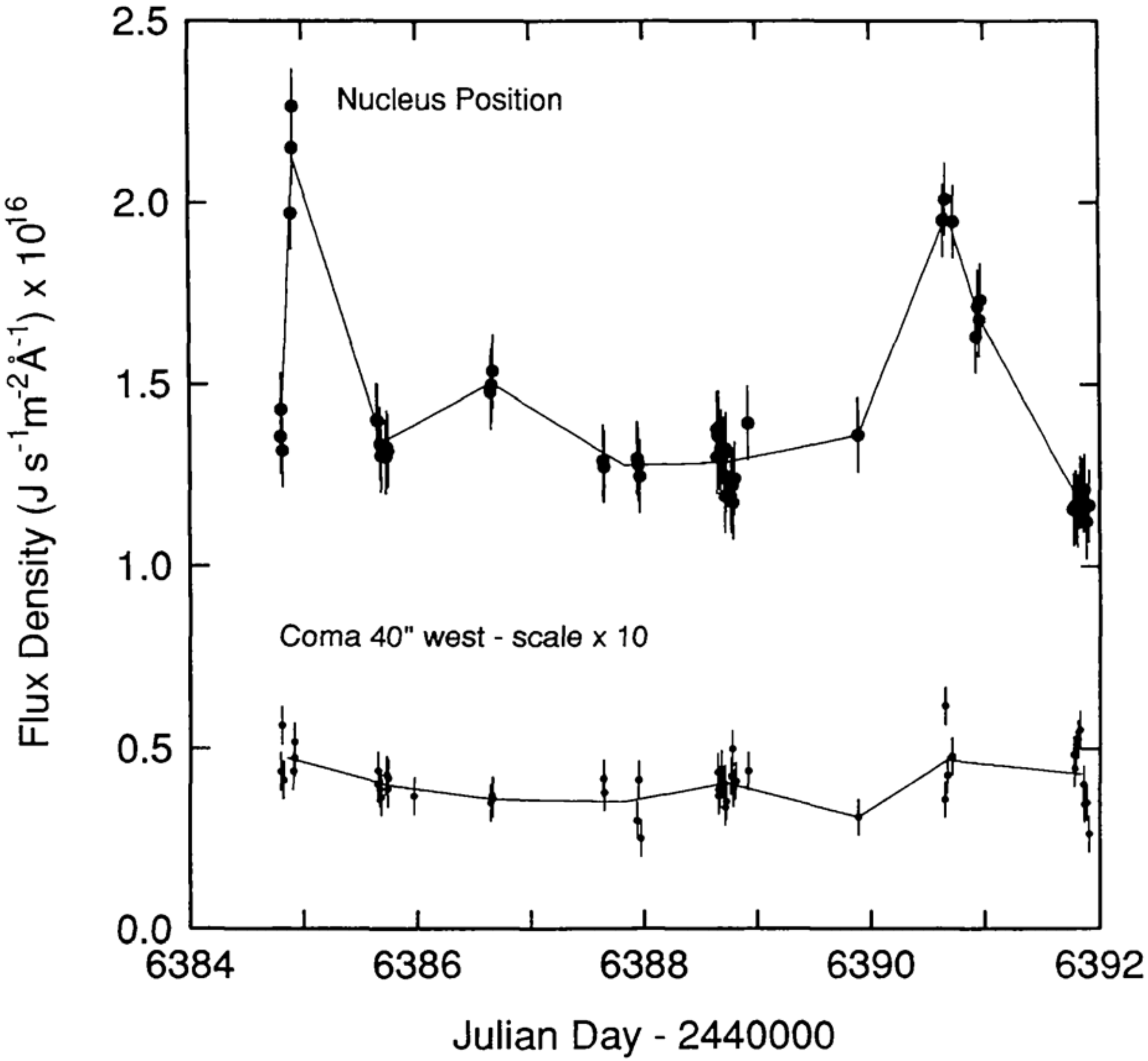
Time variations in intensity of the scattered sunlight



Variations in the flux density of comet 1P/Halley from 15 till 22 November, 1985; R=1.72–1.62 AU.

Upper curve presents area around the nucleus and bottom one ($\times$10 times) – the region of outer coma.

On November 15 and 21, for area around the nucleus, one can see two spikes caused by outburst activity.

The most challenging task for photometry of comets is to derive the phase dependence of intensity of the scattered light of cometary dust particles (i.e., *phase function*).

The problem is that the intensity varies not only with physical properties of dust particles but also with their number.

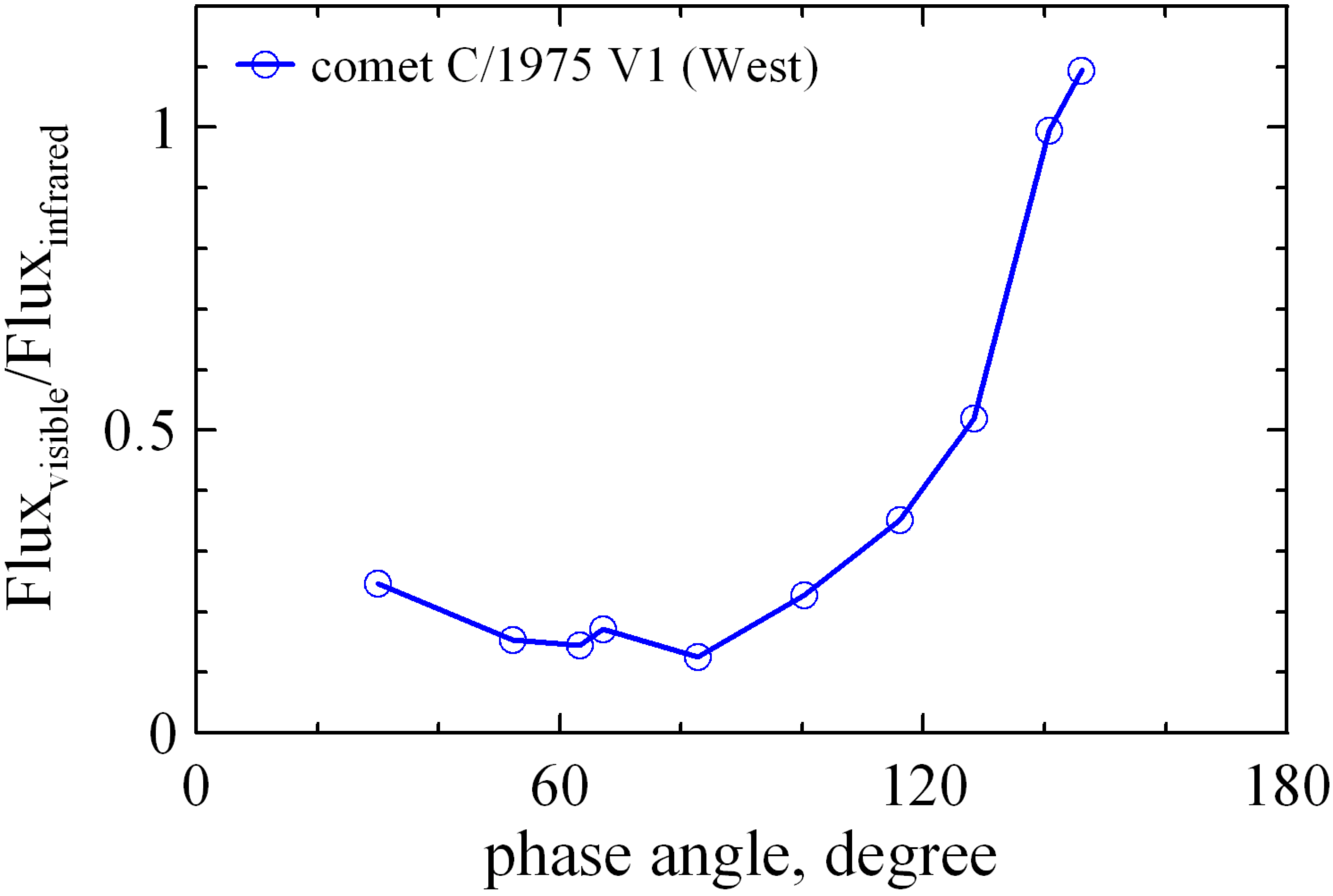
At present, there are three approaches solving this problem:

(1) doing nothing, i.e., it is assumed that the number of dust particles remains nearly the same within the coma. This assumption may have sense if heliocentric distance does not vary significantly during the observation period and there is no significant outburst activity;

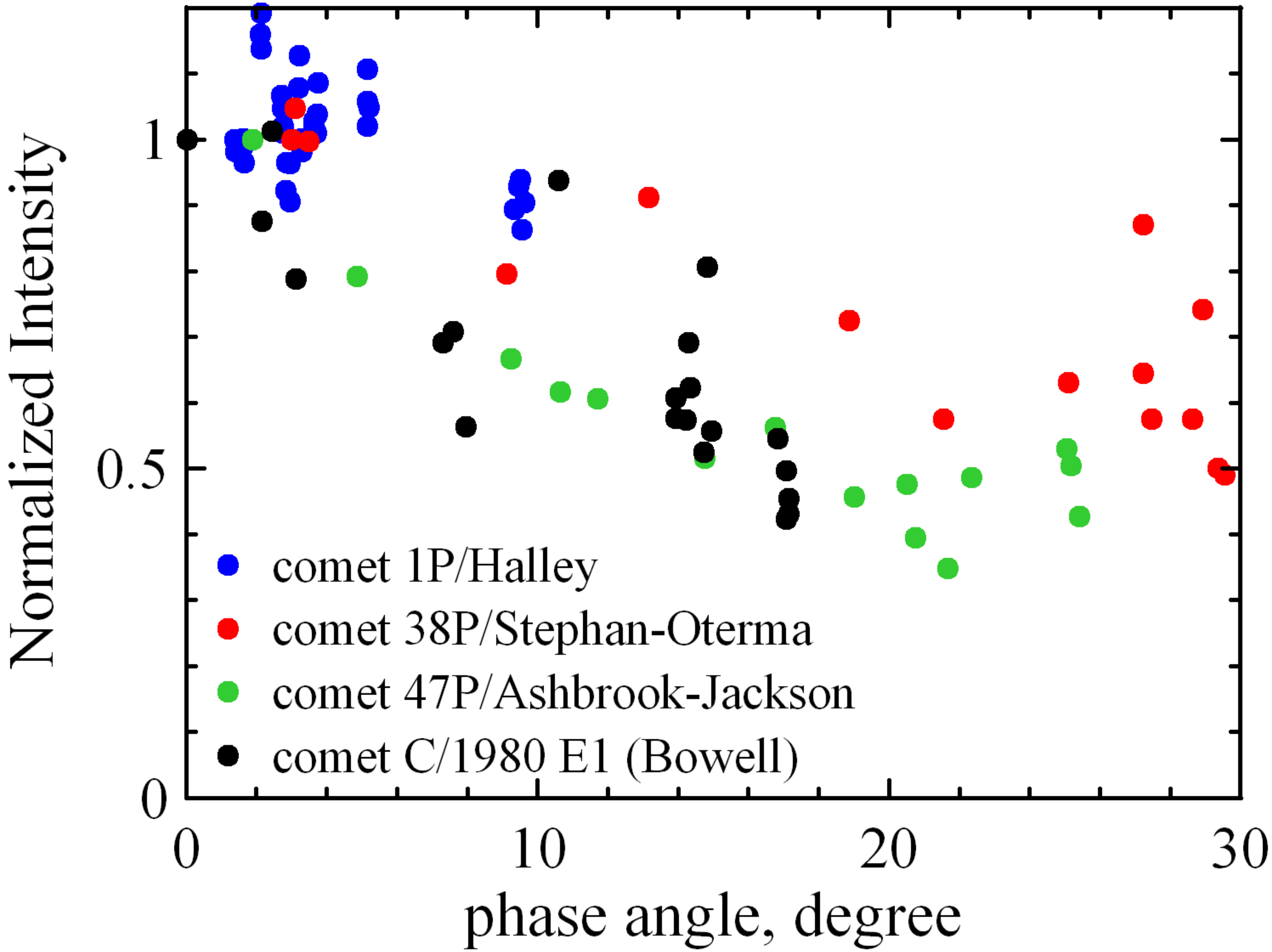
(2) the measured intensity of radiation is normalized to the mid-infrared emission (~ 10–20 μm) of coma;

(3) the measured intensity of radiation is normalized to strength of emission for some gas (i.e., invariable dust-to-gas ratio).

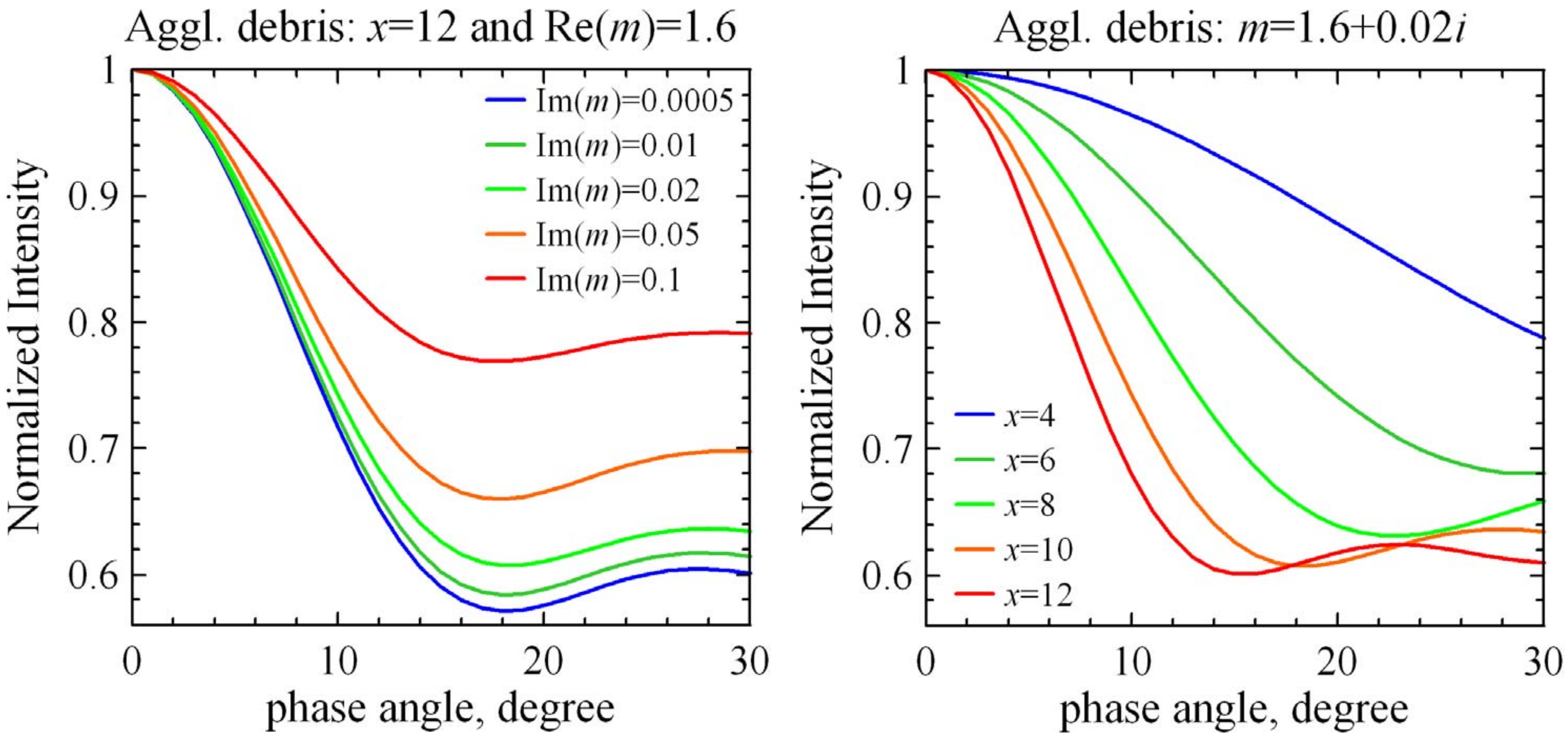
Angular profile of intensity of light scattering by comet C/1975 V1



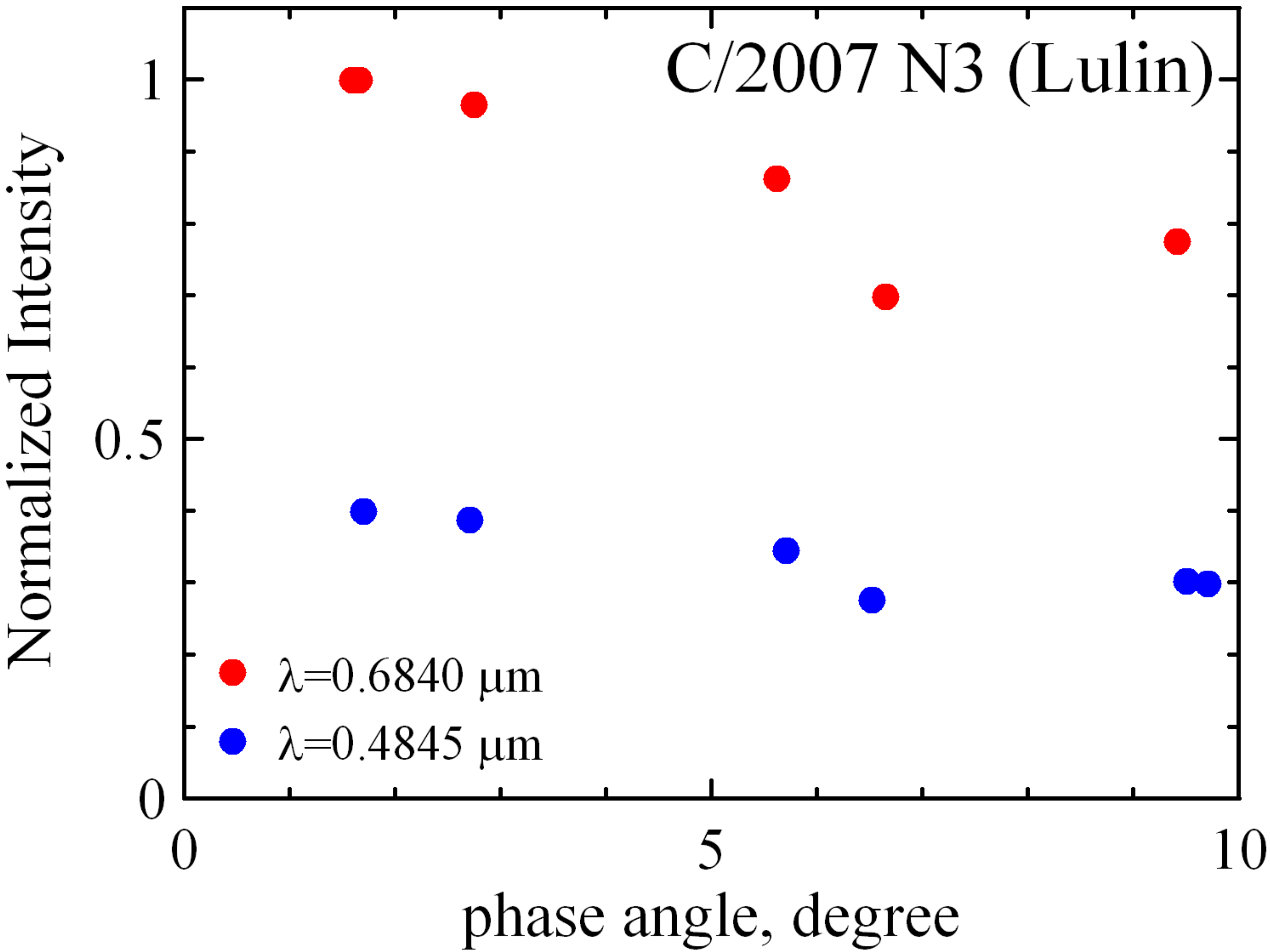
Intensity of light scattering at small phase angles



Intensity of light scattering by agglomerated debris particles



Phase dependences of intensity at different wavelengths



In visible band, polarimetry of comets measures the degree of linear polarization of sunlight scattered by dust and gas in coma.

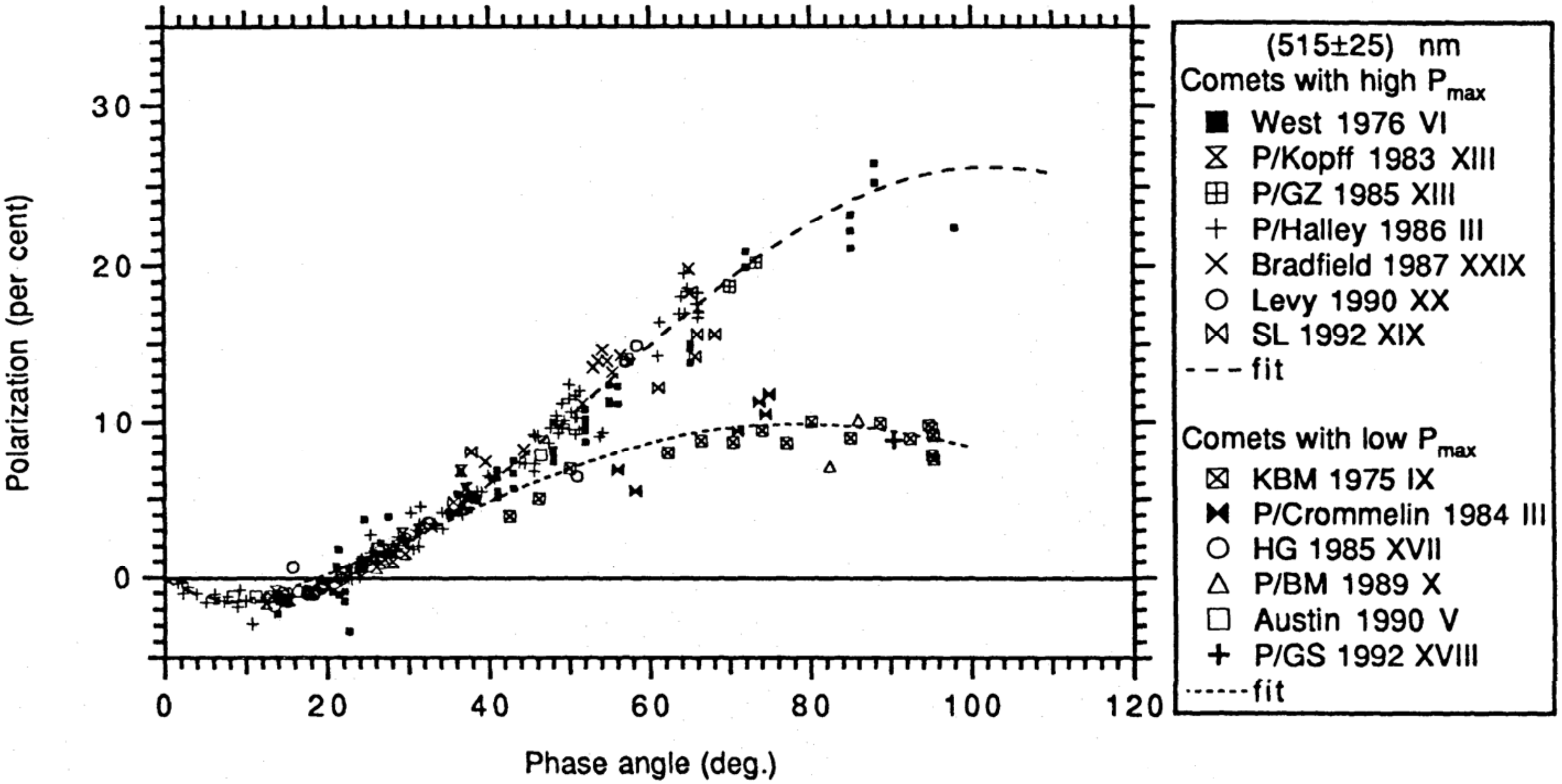
Degree of linear polarization of scattered light depends on properties of dust particles and gas molecules.

However, unlike intensity, degree of linear polarization is a relative parameter. So, it does not depend on number of dust particles. It increases role of the linear polarization in studies of comets at small heliocentric distances, which are typically accompanied with intense activity.

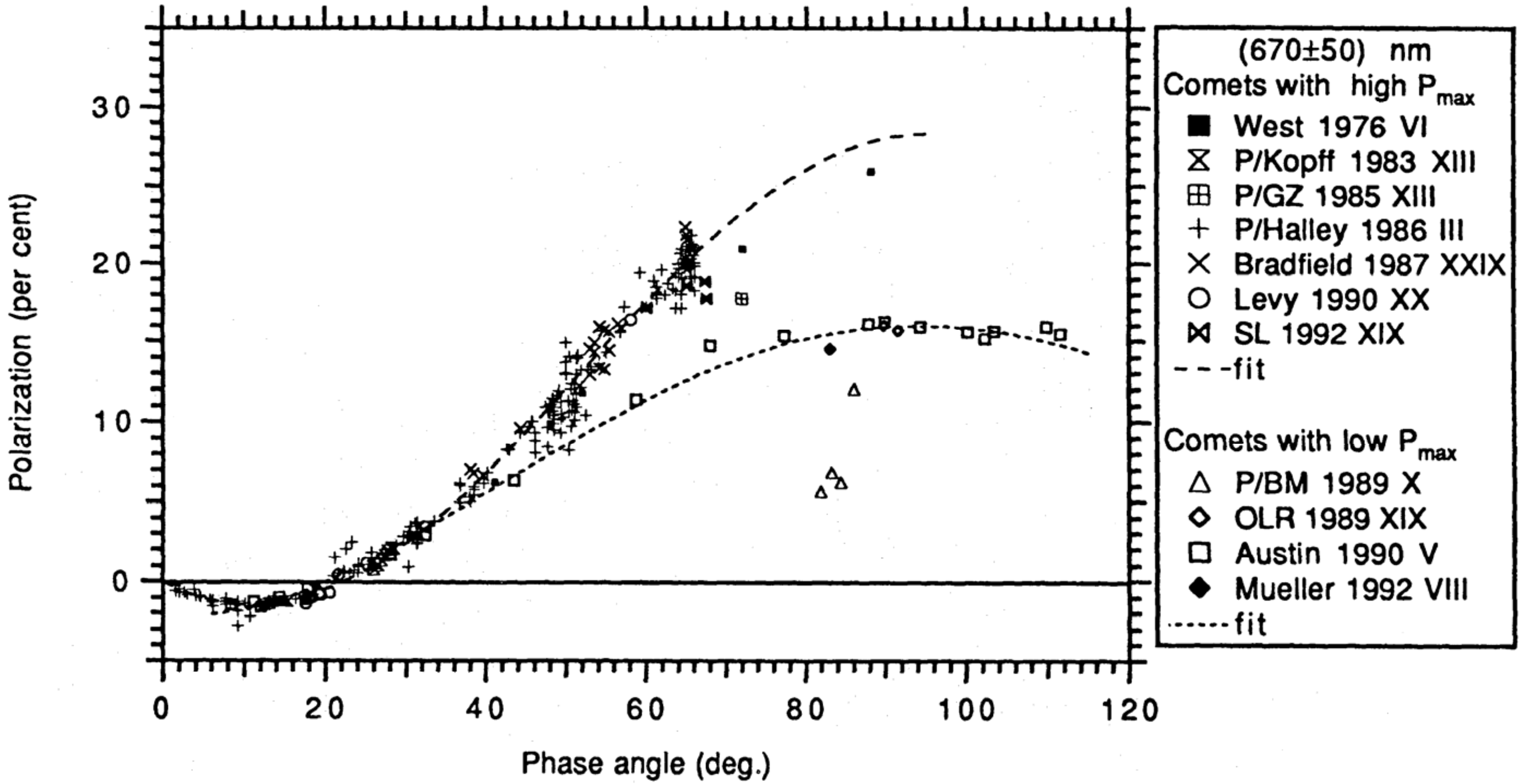
Degree of linear polarization is also important because its dependence on properties of scatterers is more regular and, as consequence, more predictable than that of intensity.

Linear polarization of comets is being studied since forties of last century. However, systematic research have been started only in late seventies (study of comet C/1975 V1 (West) reported by Kiselev and Chernova, 1978)

Phase dependence of the degree of linear polarization of some comets at λ=0.515 μm



Phase dependence of the degree of linear polarization of some comets at λ=0.670 μm



While various comets show nearly the same negative polarization at small phase angles. However, at large phase angles, all the comets can be split into two groups.

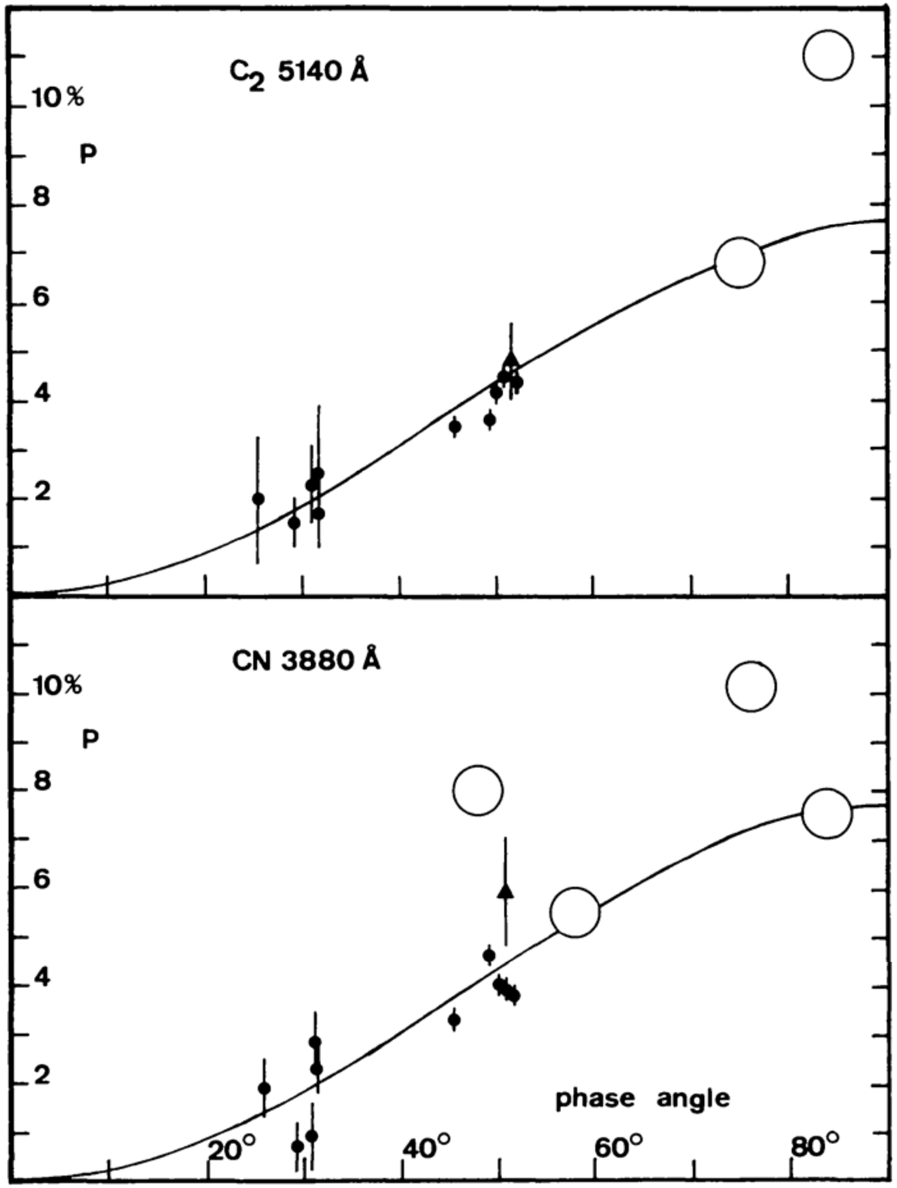
The peculiarity has been noticed first by Chernova, Kiselev, and Jockers (1993, Icarus, **103**, 144–158). These authors found that the amplitude of positive polarization branch correlates inversely with abundance of gas in coma: more gas, less amplitude of positive polarization. Therefore, they concluded that the decrease positive polarization is caused by depolarization effect of complex gas molecules.

Öhman (1941) was studying the fluorescence polarization of molecular bands of CN and C_2 and found the following dependence on phase angle α:

$$P = P_{max} \sin^2\alpha \,/\, (1 + P_{max} \cos^2\alpha), \quad \text{where } P_{max} = 7.7\%$$

This finding is confirmed by polarimetry of comets 1P/Halley and C/1985 R1 (Hartley-Good) in emission bands of CN and C_2.

Phase dependence of the degree of linear polarization of comets measured in emission lines of CN and C_2 gases



Filled triangles correspond to comet C/1985 R1 (Hartley-Good) and filled circles to comet 1P/Halley.

Le Borgne, Leroy, and Arnaud (1987, Astron. Astrophys., **173**, 180–182)

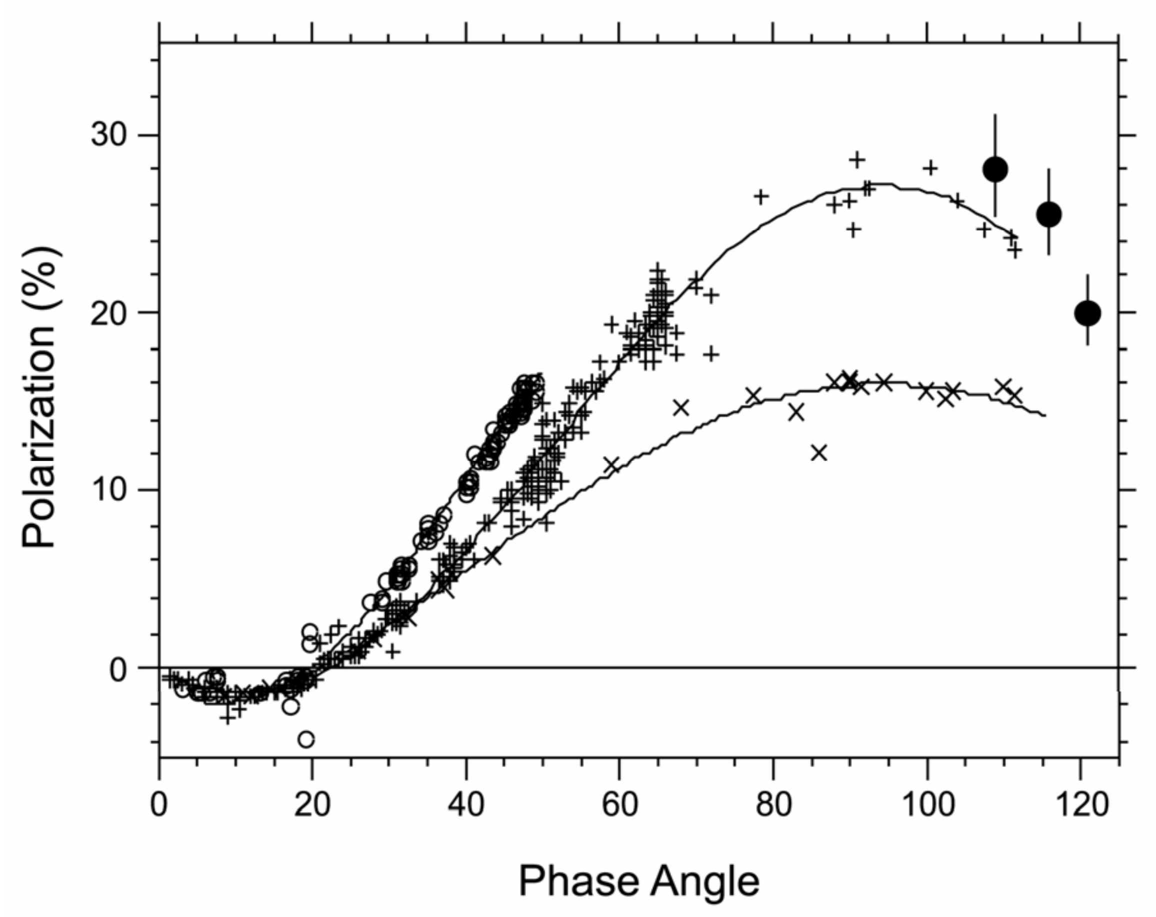
However, Levasseur-Regourd, Hadamcik, and Renard (1996, Astron. Astrophys., **313**, 327–333) used narrow band filters (0.515±0.025 μm and 0.67±0.05 μm) and confirmed presence of two types of comets. They called them as high P_{max} and low P_{max} comets.

The difference in positive polarization is attributed to difference in physical properties of cometary dust particles.

Note that within this classification there is no difference between long period and short period comets.

Nevertheless, Kiselev and colleagues continue to attribute the difference in maxima of positive polarization branches to gas-to-dust ratio rather than physical properties of dust (Kolokolova, Kimura, Kiselev, and Rosenbush, 2007, Astron. Astrophys., **463**, 1189–1196)

Possible extension of the classification of comets



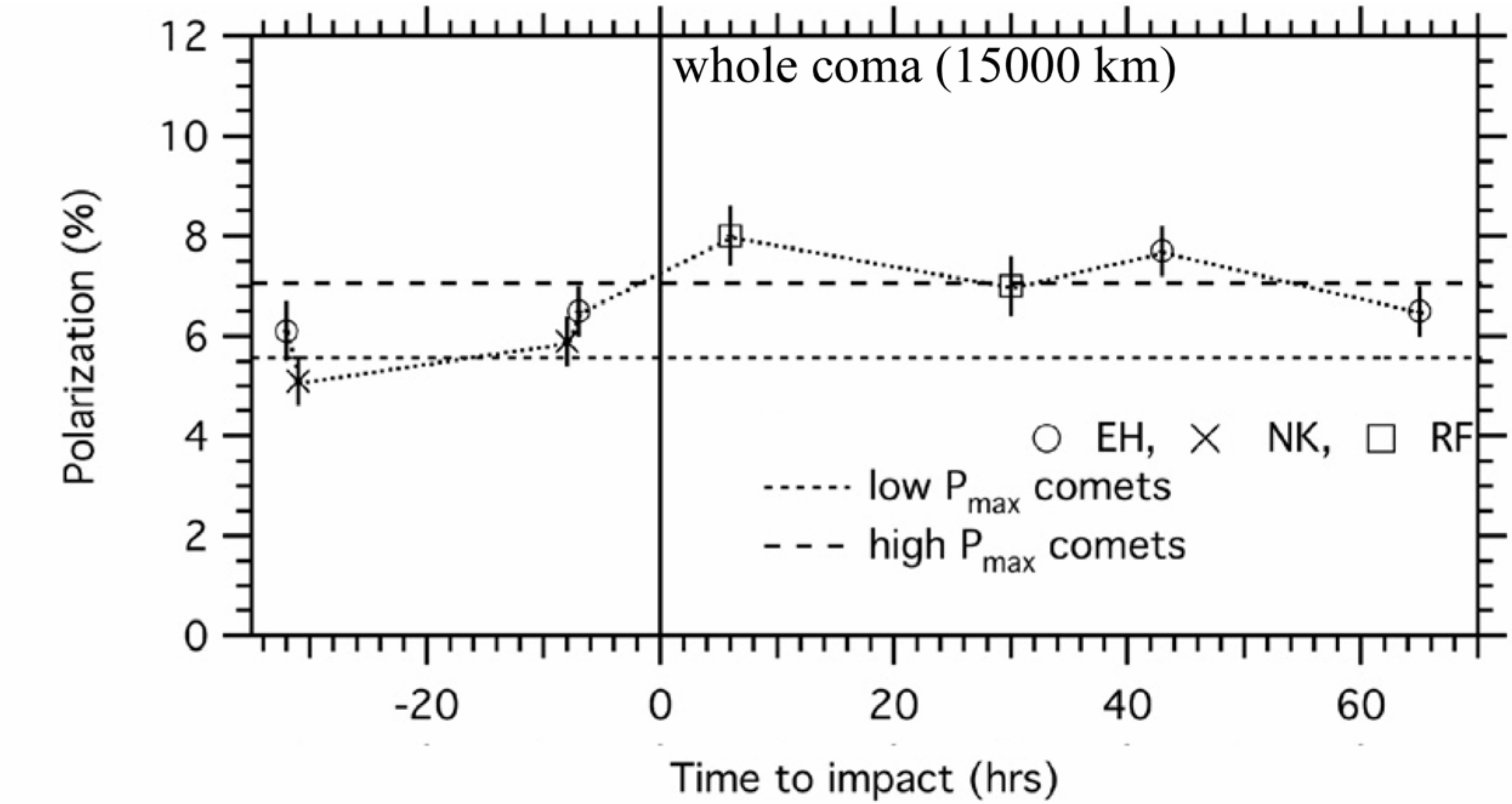
Bright comet C/1995 O1 (Hale-Bopp) does not follow neither high P_{max} nor low P_{max} comets. Thus, it forms a new class of comets. The data points corresponding to this comet are shown by open circles in Figure on the left.

Difficulties of the classification of comets are as follows:

(1) variations with time are not taken into account;

(2) the size of aperture is not specified.

An example of these difficulties can be found in polarimetry of comet 9P/Tempel during *Deep Impact* event.



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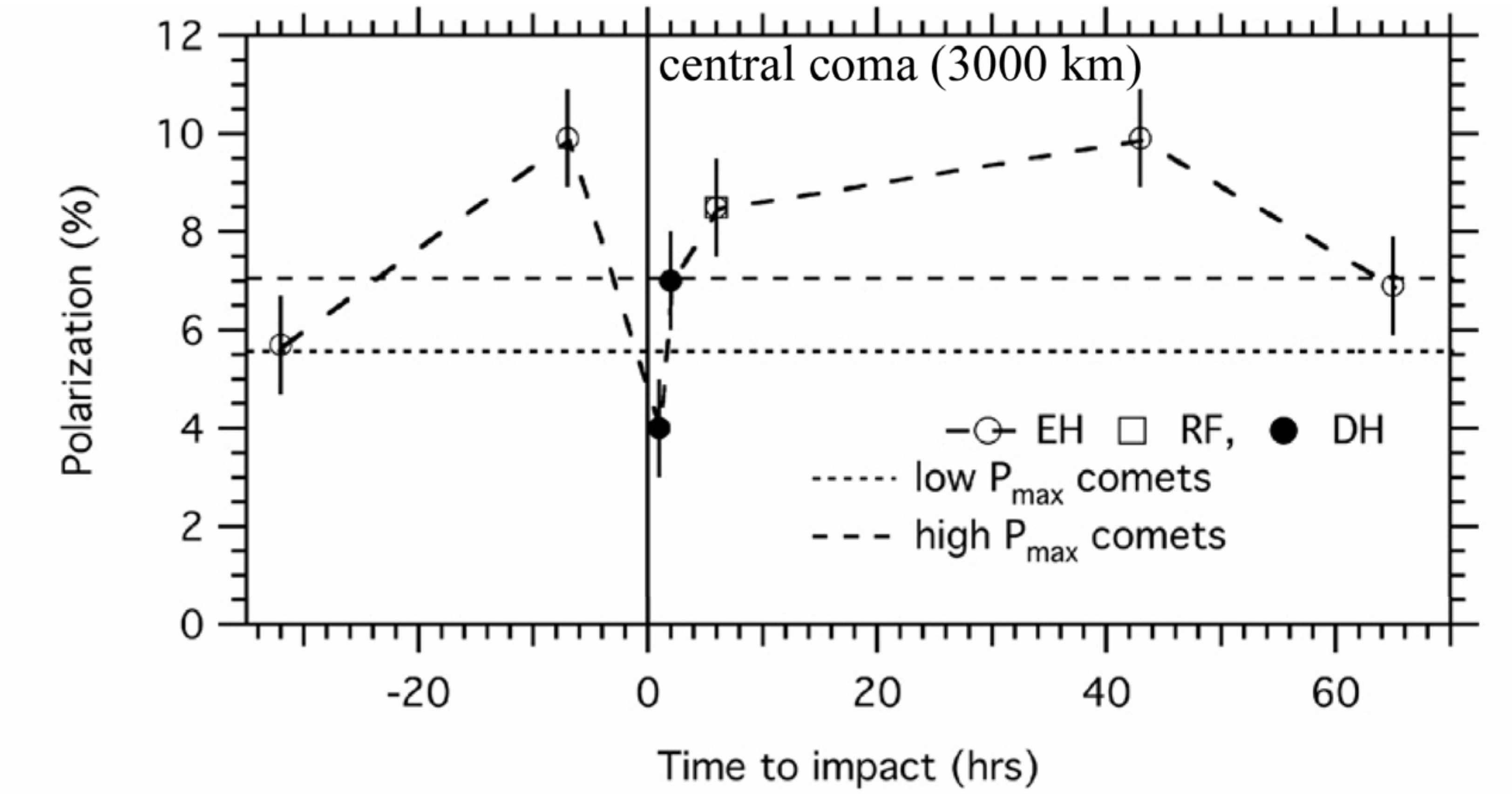
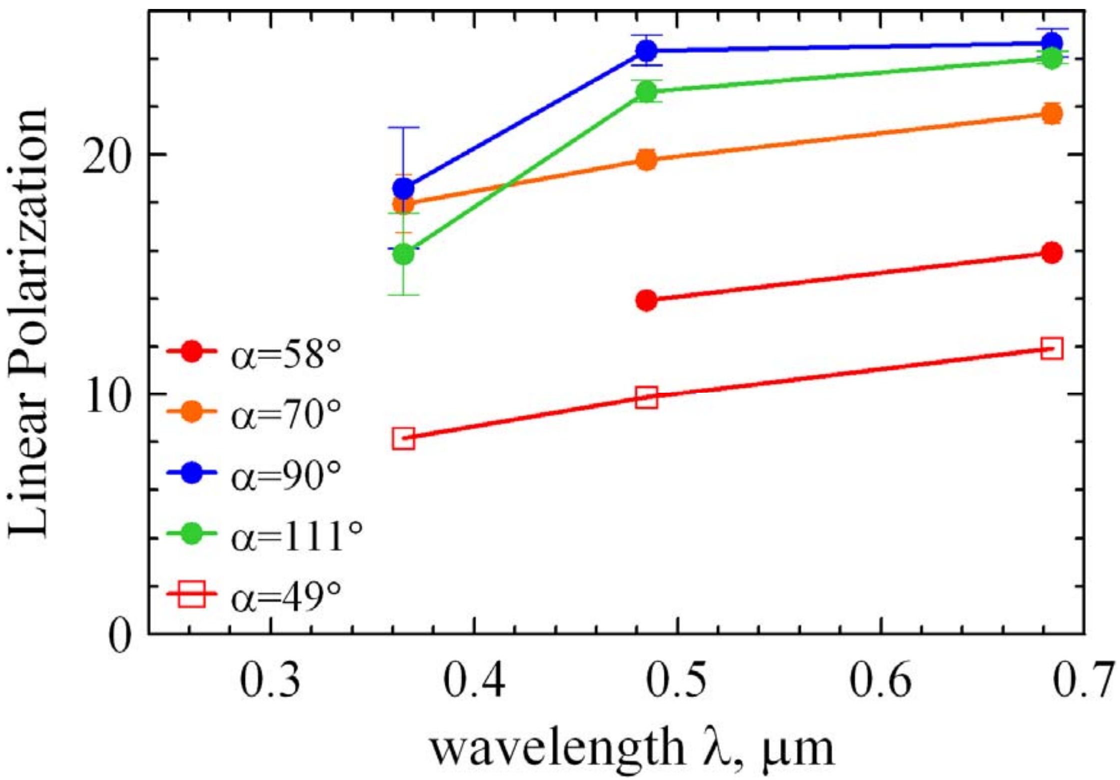


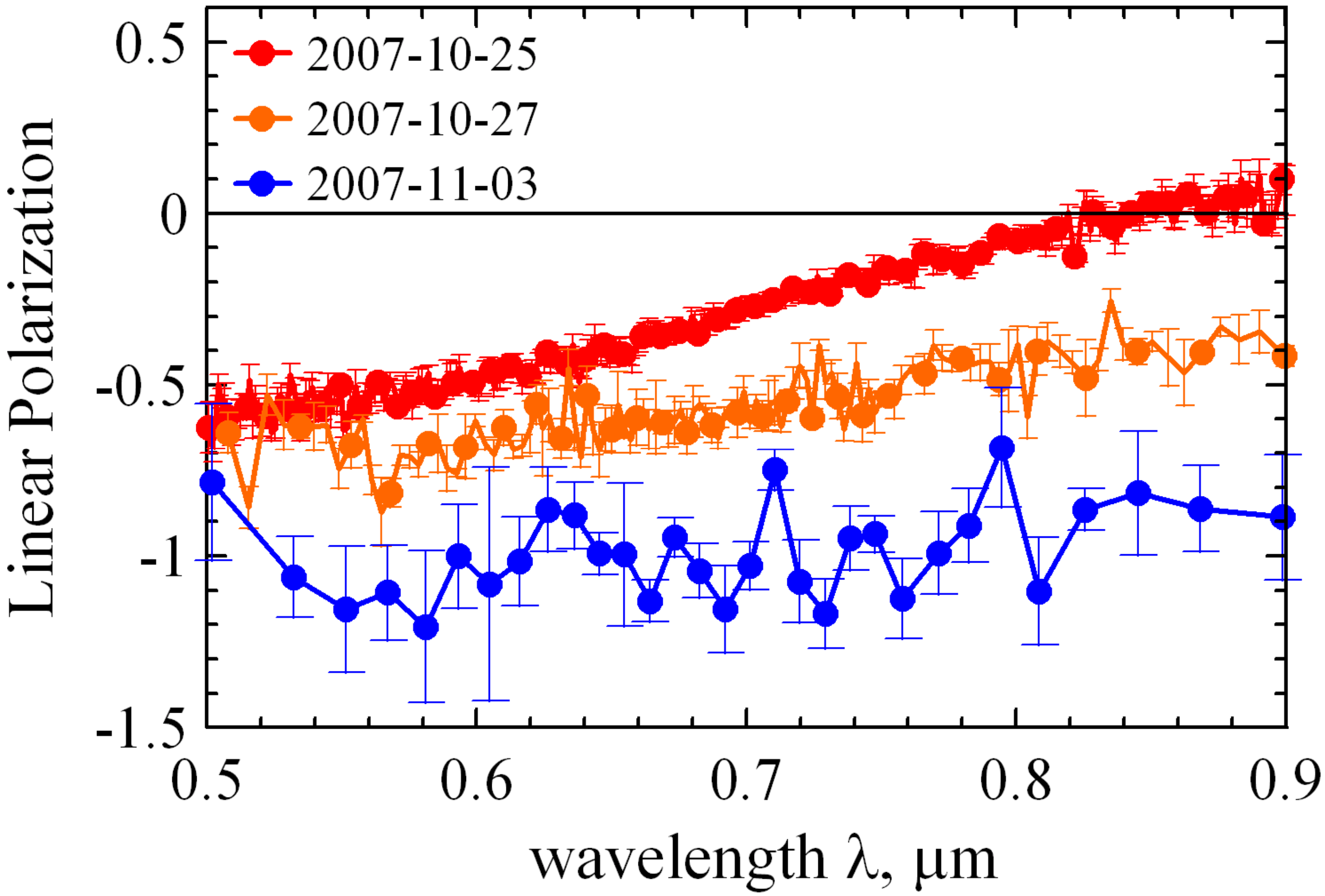
Dependence of aperture-averaged linear polarization on wavelength.

Note that, due to the obvious depolarization effect of complex gas molecules, the difference of linear polarization measured in emission lines and continuum is not considered but, only polarization measured in continuum.



Open symbols present the data for comet 1P/Halley; whereas, closed ones – comet C/1996 B2 (Hyakutake).

An example time-evolution of wavelength dependence of the negative polarization for very inner part of coma in comet 17P/Holmes shortly after its explosion on October 24, 2007.

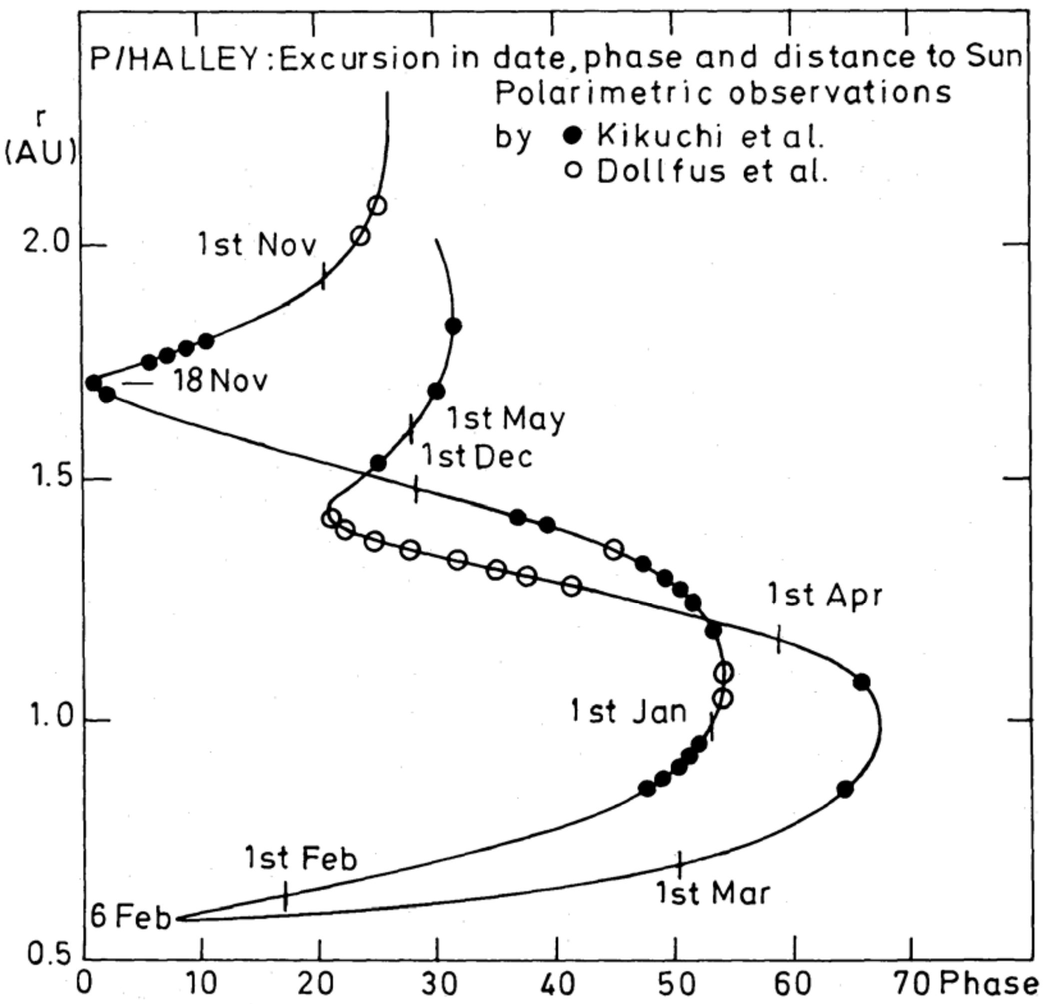


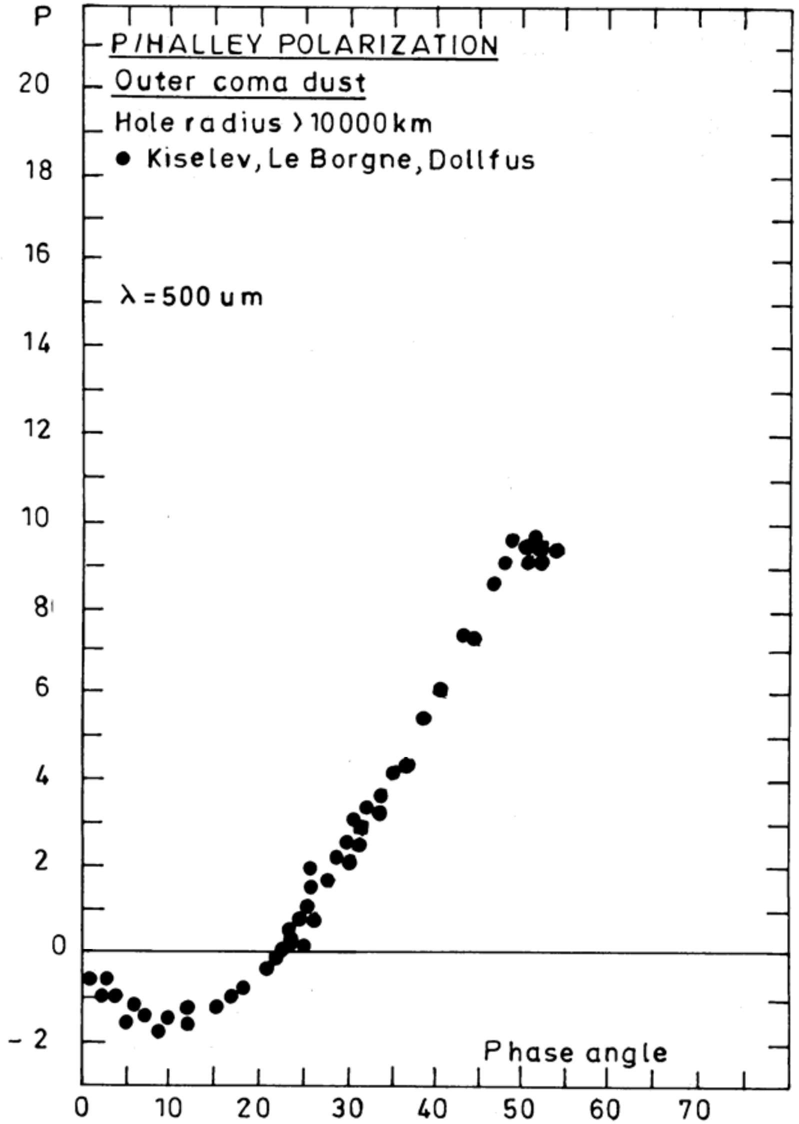
At present, it is widely accepted that the phase dependence of the degree of linear polarization does not depend on heliocentric distance R. When tracing the origin of this conclusion in literature, one can find that the most of the papers cite the paper by Dollfus et al. (1988, Astron. Astrophys., **206**, 348–356) devoted to comet 1P/Halley.

However, this conclusion seems to be quite strange. Indeed, it is well-known that the dust and gas production rates substantially depend on distance to the Sun. Lifting ability if the subliming gas also obviously has to depend on temperature (i.e., distance to the Sun). Moreover, it was found that the mid-infrared spectra often depend on heliocentric distance.

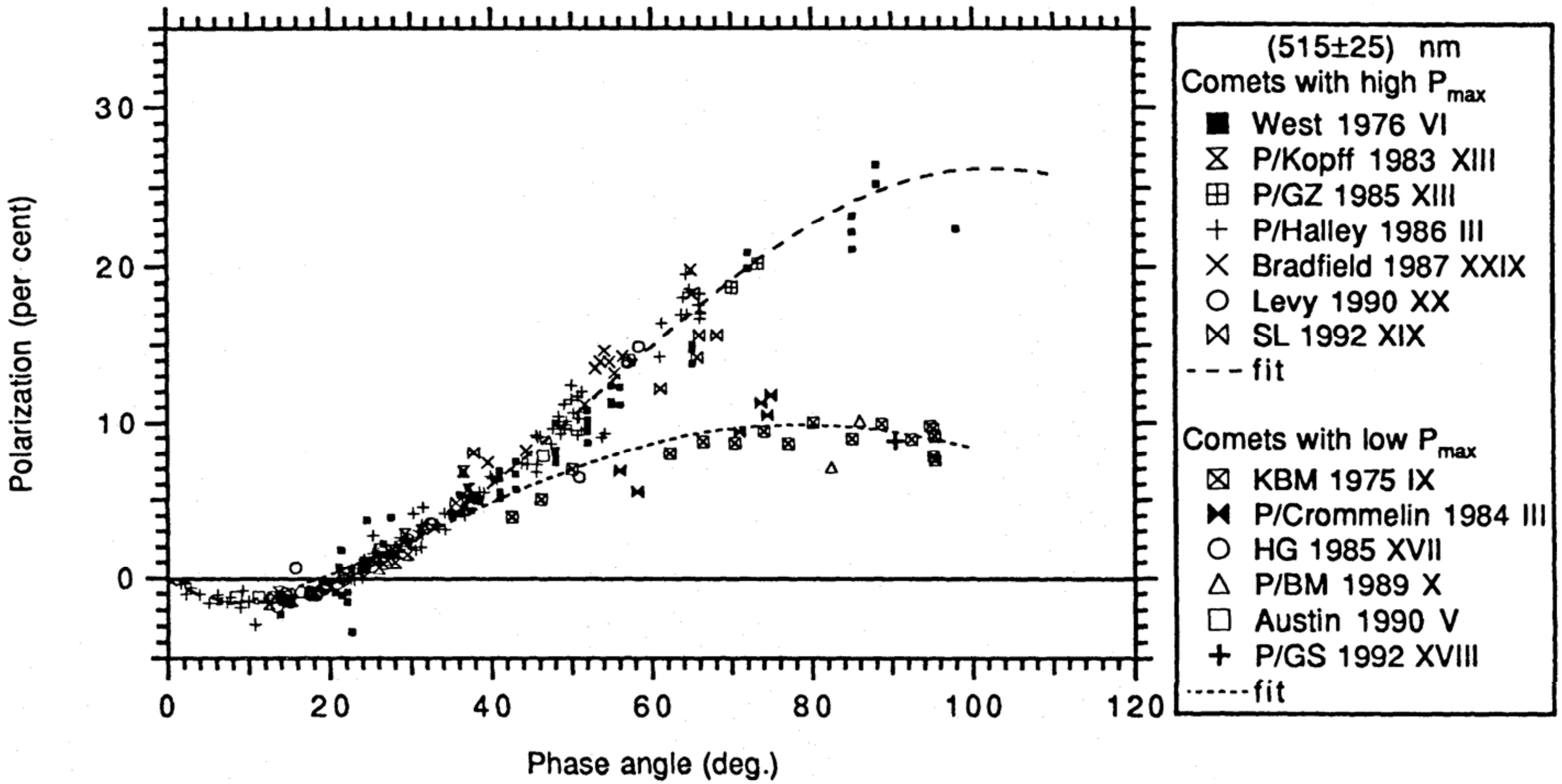
Finally, numerical simulation of light scattering by irregularly shaped particles shows that, the degree of linear polarization is quite sensitive parameter to properties of model particles.

Phase dependence of the linear polarization of comet 1P/Halley

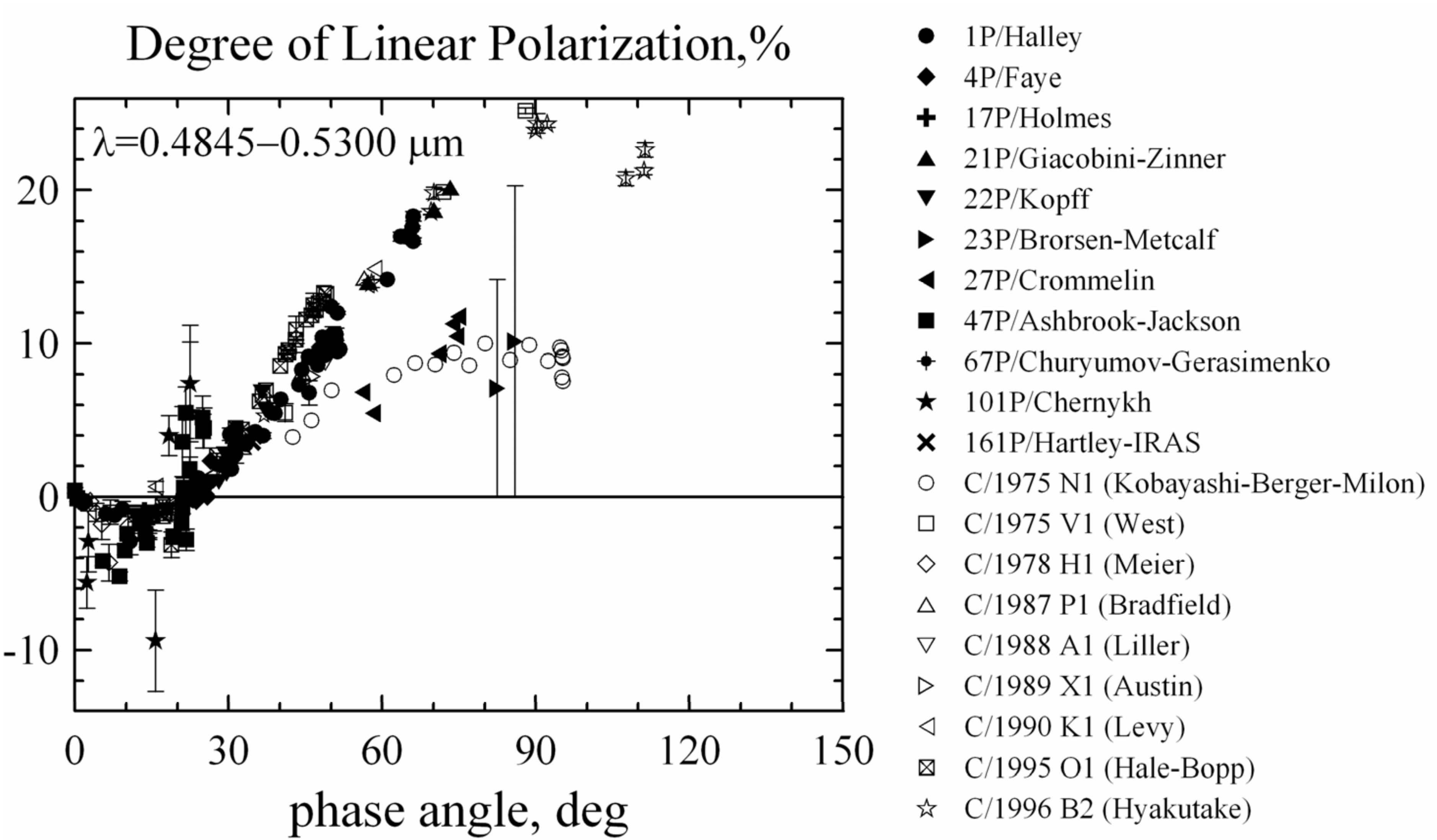




Another suspicious thing is a quite narrow profile of the negative polarization branch at small phase angles. Indeed, as one can see in Figure below, all the comets produce nearly the same branch of negative polarization; whereas, there is noticeable difference in positive polarization branches.



However, involving more comets may break this regularity.



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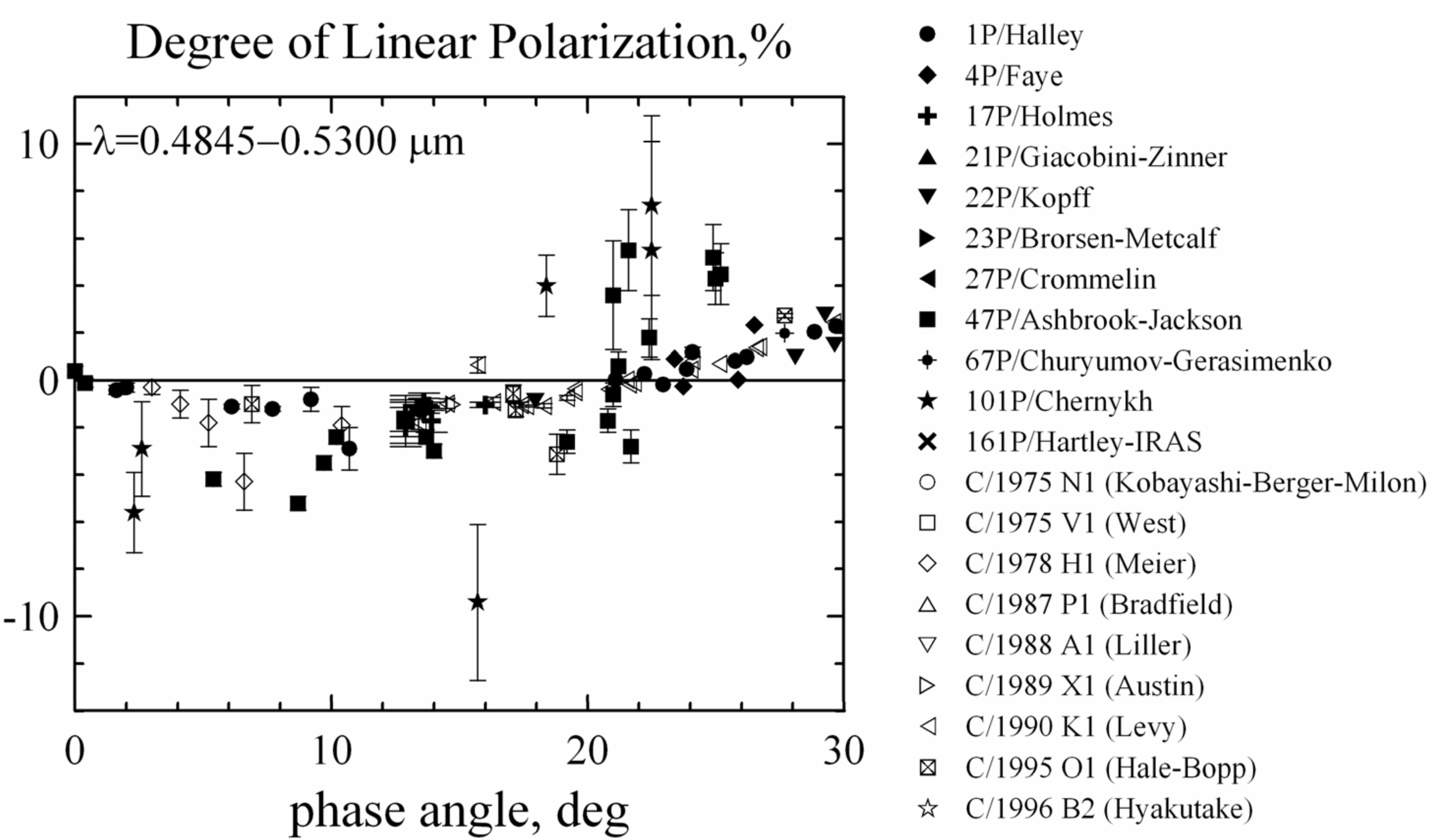
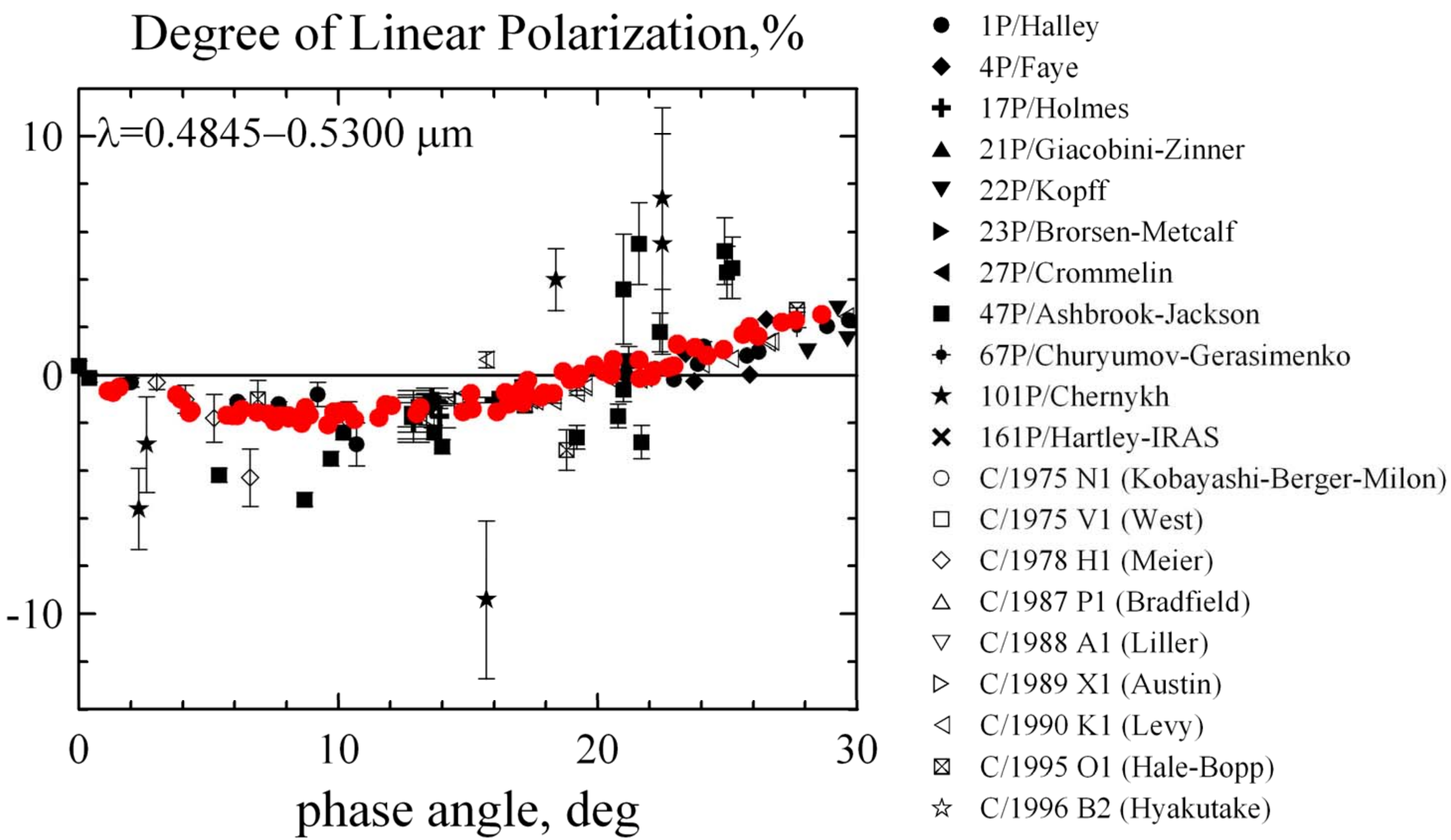


There are significant deviations from “typical” behavior.



Thus, one could formulate two tasks for project of the course:

1. Investigation of variations of aperture-averaged linear polarization with heliocentric distance (entire range of phase angles α)
2. Investigation of deviations of aperture-averaged negative polarization from the "typical" behavior (only small phase angles $\alpha < 30^\circ$).

Both projects suppose work only with literature. In order to find papers on comets, use web-service http://adsabs.harvard.edu

Look for the bright comets. These comets attracted attention of many observers, so, you may find more paper.

Amplify efforts: make two groups. Duration of the work 2 weeks.

Lecture on November 17, 2010 is assigned for your reports. Up to half of hour per team. Divide the report into a few parts, so, every member of the group will be speaking.

References:

(1) Ney, E. P., Merrill, K. M., (1976): Science, **194**, 1051–1053.

(2) Kiselev, N. N., Chernova, G. P., (1981): Icarus, **48**, 473–481.

(3) Millis, R. L., Ahearn, M. F., Thompson, D. T., (1982): Astron. J., **87**, 1310–1317.

(4) Meech, K. J., Jewitt, D. C., (1987): Astron. Astrophys., **187**, 585–593.

(5) Le Borgne, J. F., Leroy, J. L., Arnaud, J., (1987): Astron. Astrophys., **173**, 180–182.

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(9) Kolokolova, L., Kimura, H., Kiselev, N., Rosenbush, V., (2007): Astron. Astrophys., **463**, 1189–1196.

(10) Kolokolova, L., Hanner, M. S., Levasseur-Regourd, A. C., Gustafson, B. A. S., (2004): Chapter in *Comets II*, 577–604.