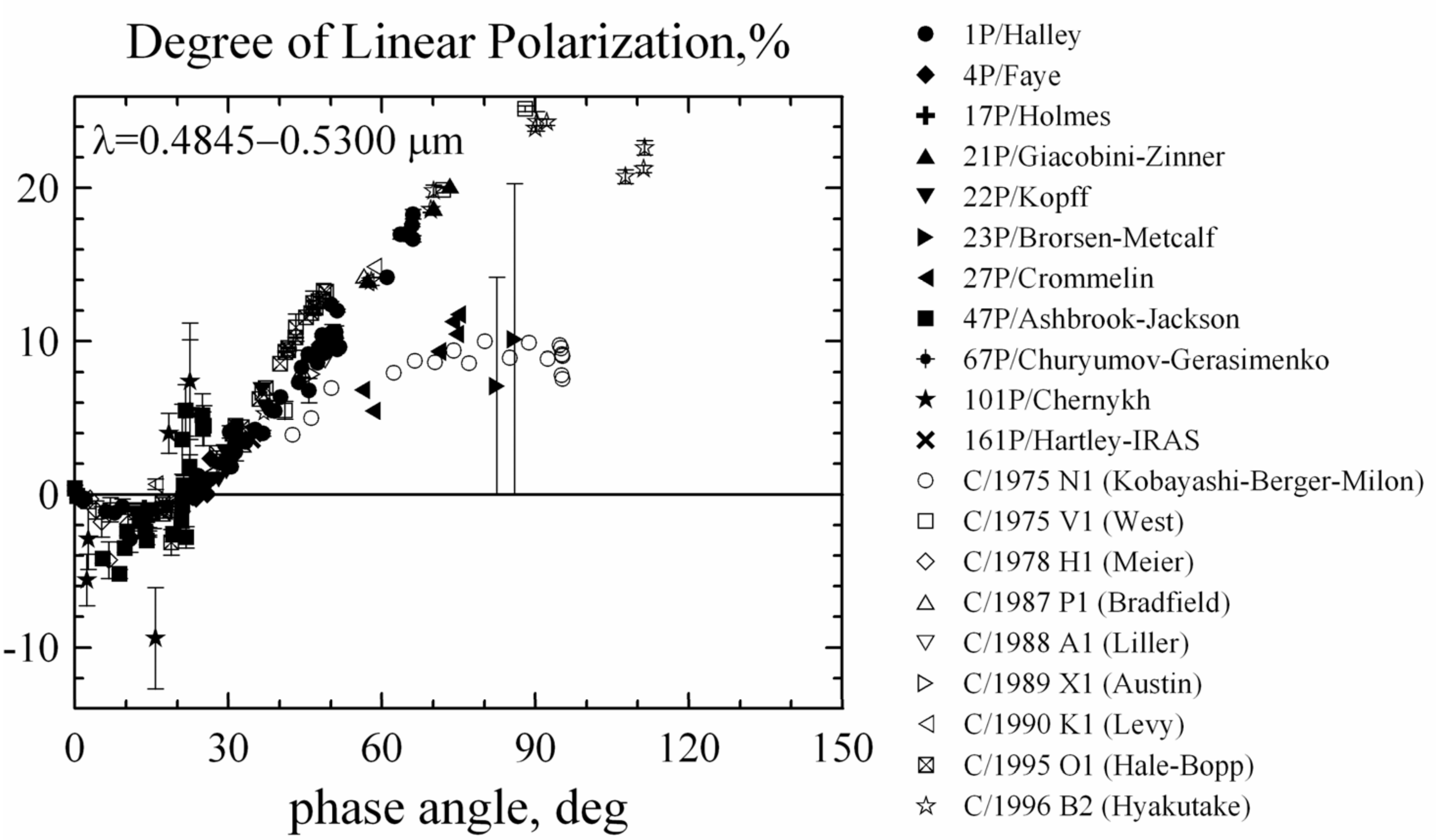
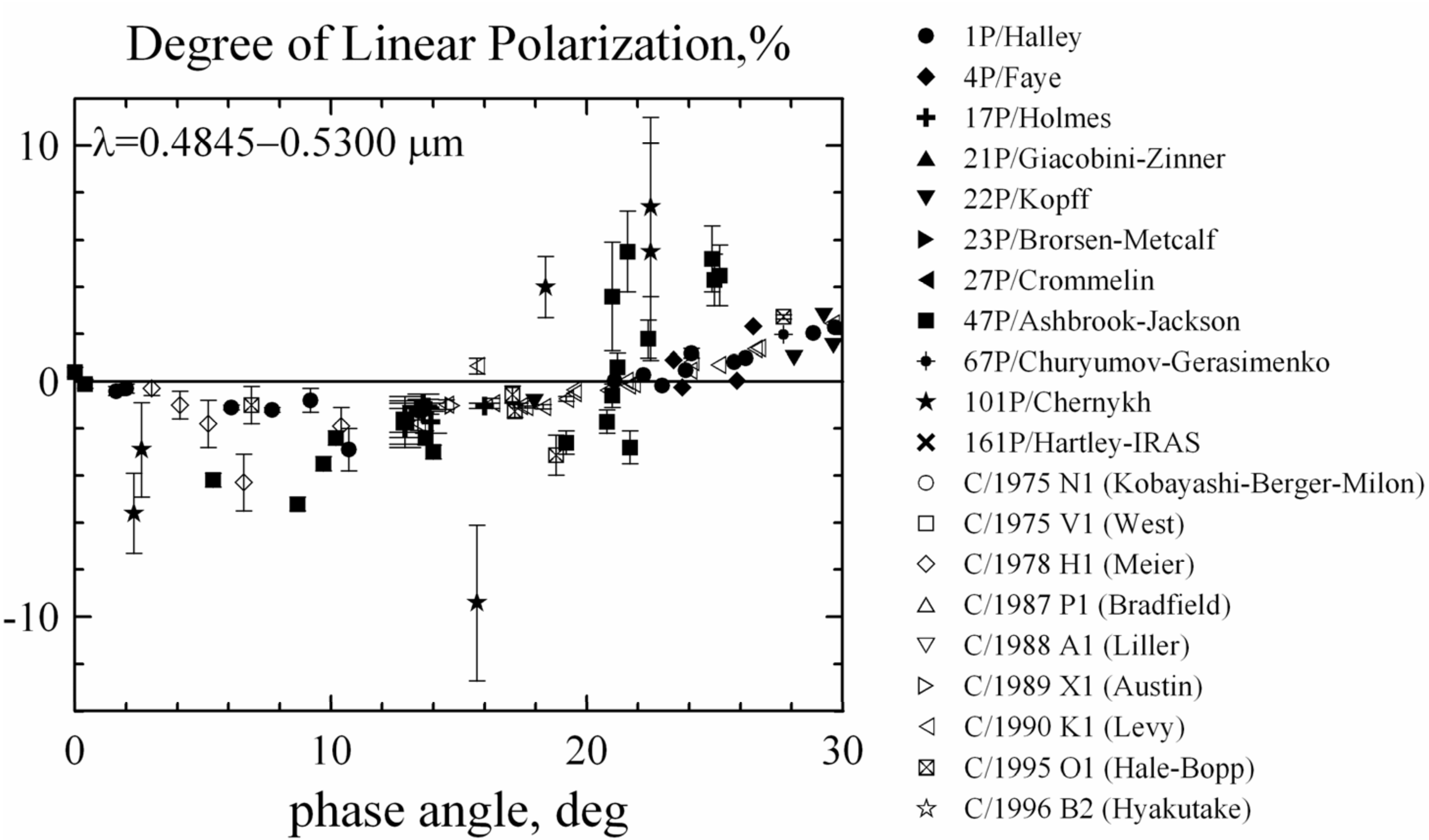
Imaging photo-polarimetry of comets in visible

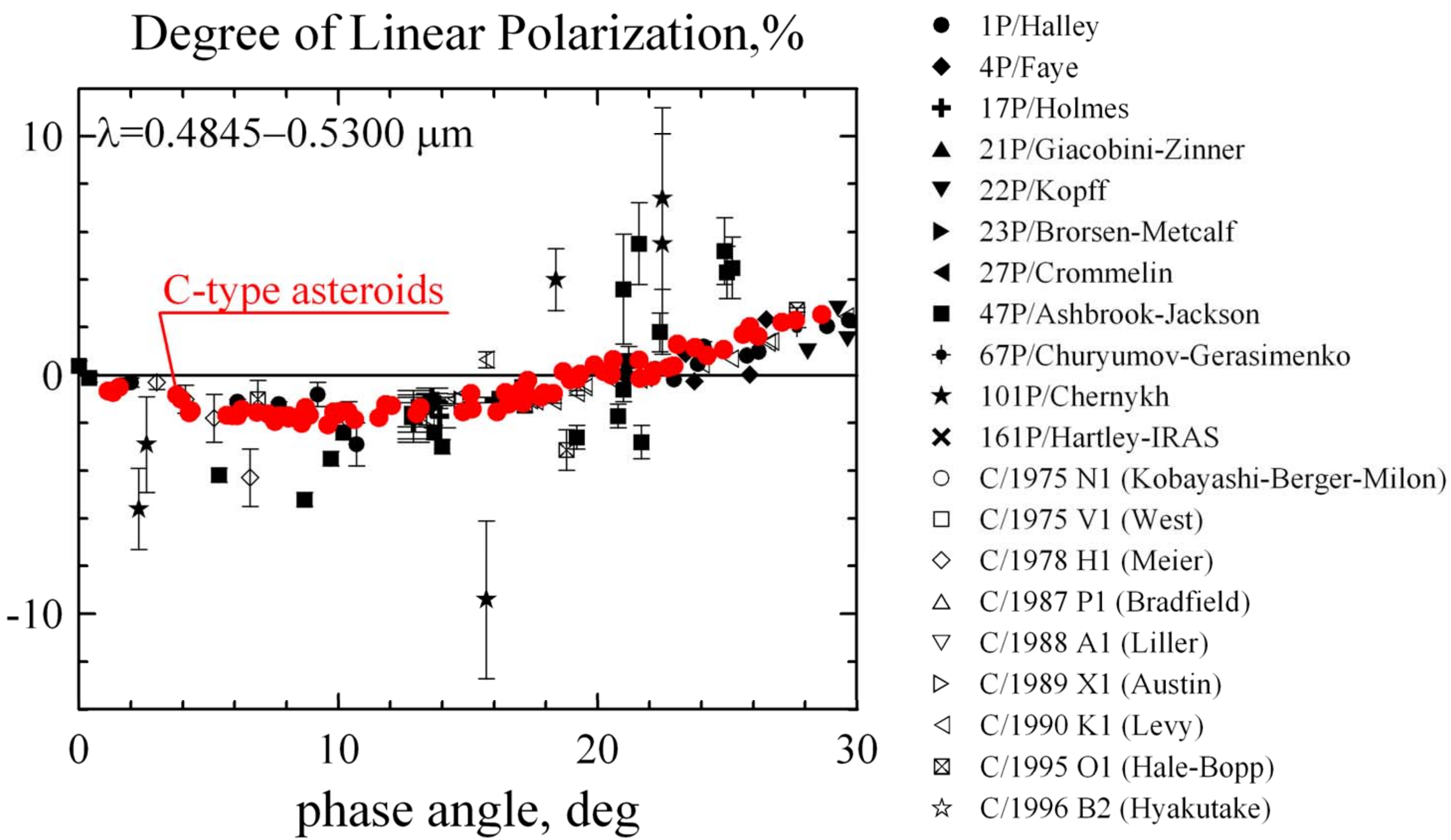
Synthetic curve of aperture-averaged linear polarization of comets



Synthetic curve of aperture-averaged linear polarization of comets



Coincidence between comets and asteroids is absolutely strange.



Does the coincidence in polarization profiles of comets and C-type asteroids mean that cometary dust particles are similar to regolith particles?

Obvious distinction between coma and regolith is the number density of particles. The fluffiest regolith remains substantially more compact medium than the densest cometary coma. In terms of light scattering, it implies difference in contribution of multiple scattering.

Rigorous computation of multiple scattering in dense medium of the micron-sized particles is a difficult problem.

However, the contribution of multiple scattering could be derived from comparative experimental study of light scattering by independent dust particles and regoliths made of those particles.

Such an investigation of multiple scattering in regolith was done in Shkuratov et al., 2004; 2006. Brief description of those works is as follows.

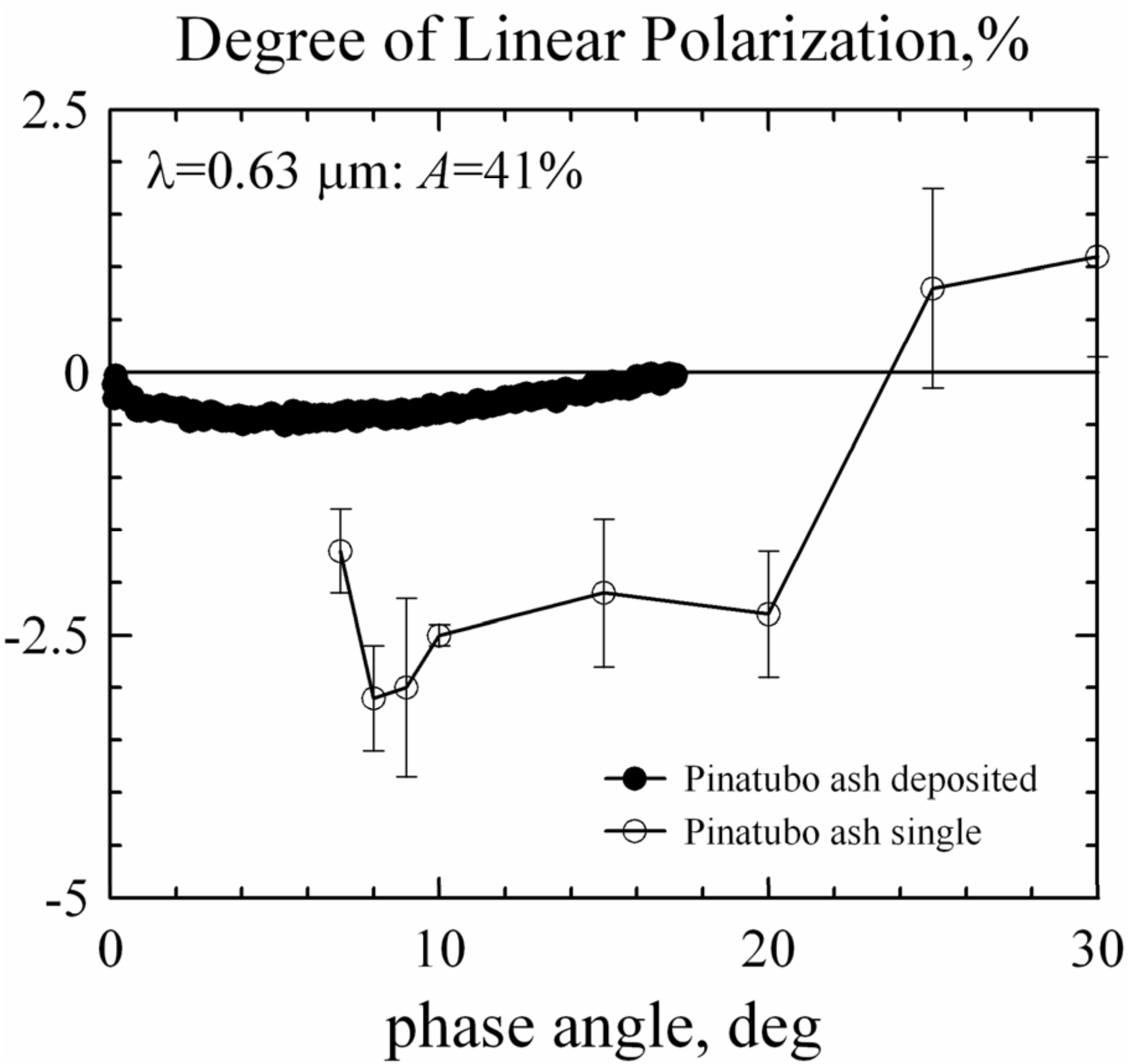
Set of 10 various samples was measured using the nephelometer of University of Amsterdam (The Netherlands) and photometer/polarimeter of Kharkov National University (Ukraine).

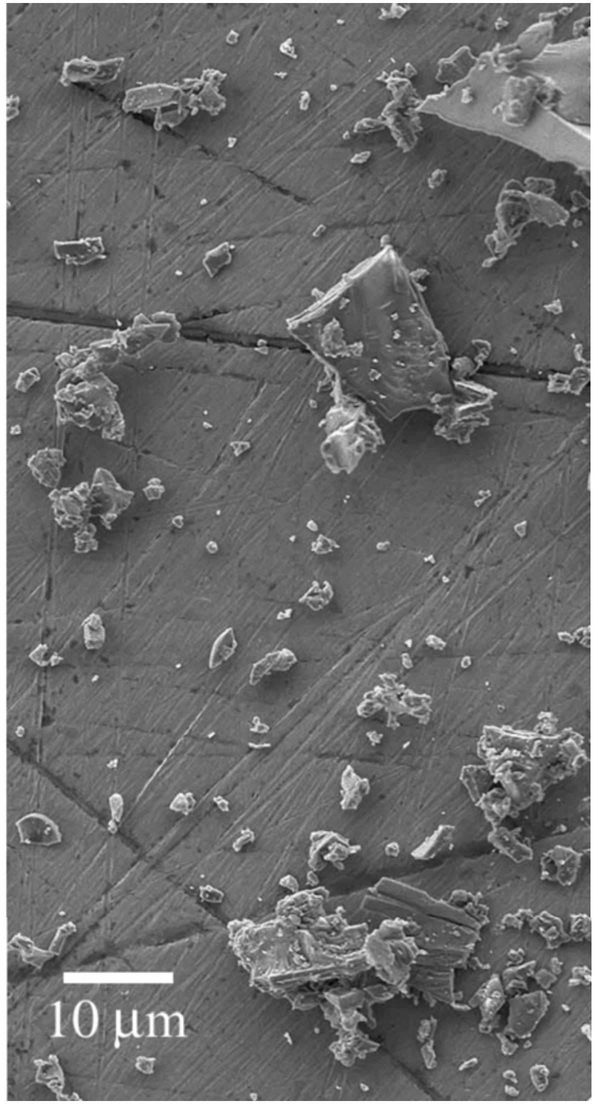
In the former case, independently scattering sample particles have been investigated; whereas, in the later case, the same particles but deposited on a surface were studied.

In Shkuratov et al. (2004), the regolith-like surfaces have been studied in the range of phase angles from 0 to 17 degrees; whereas, in Shkuratov et al. (2006), the range of phase angles was extended up to 60 degrees.

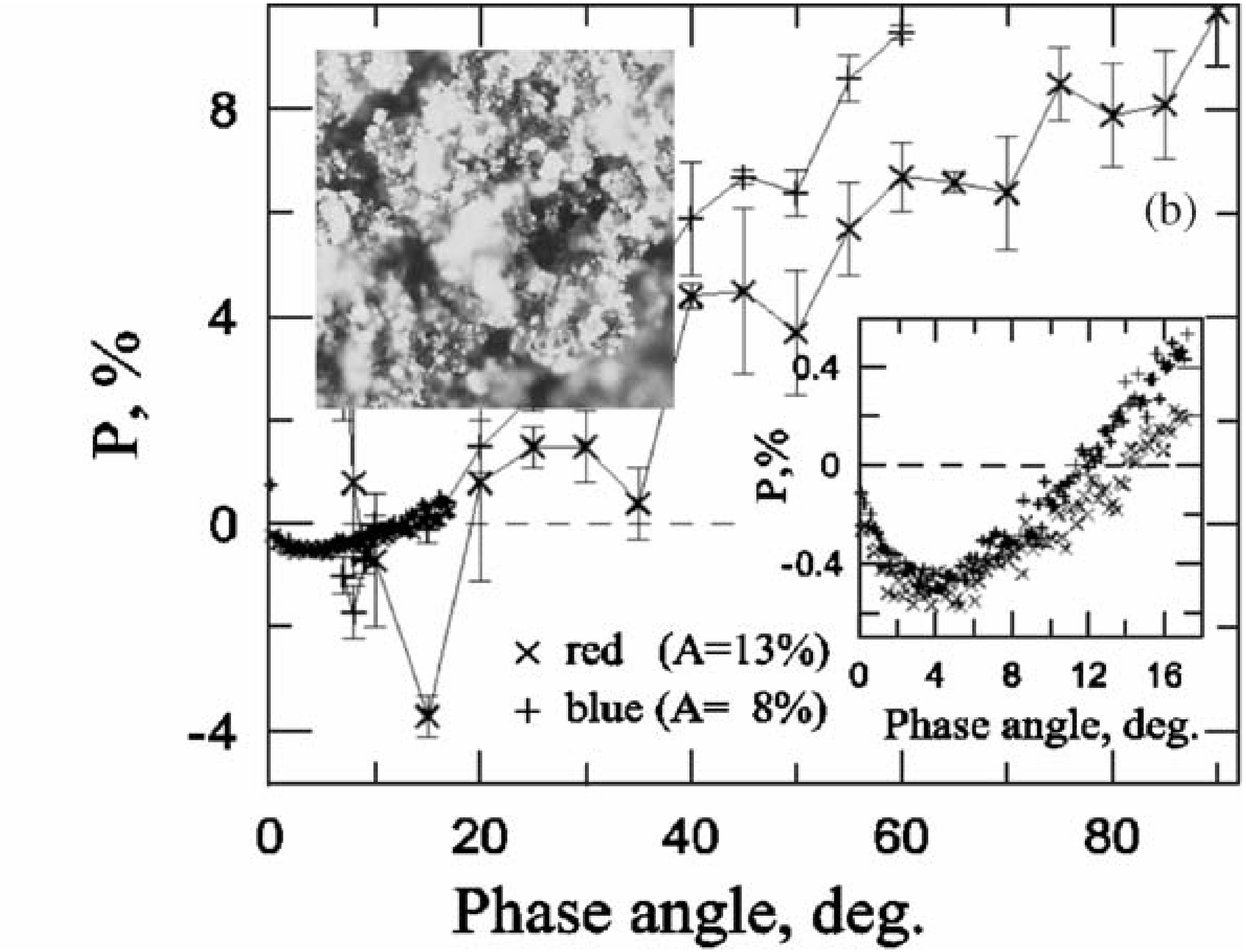
By comparison of those two results, one can study the contribution multiple scattering into light scattering by regolith. as was found, multiple scattering substantially depolarizes the radiation.

Scattering by single particles and regolith made of those particles.





Scattering by single particles and regolith made of those particles.



Does the coincidence in polarization profiles of comets and C-type asteroids mean that cometary dust particles are similar to regolith particles?

No. Instead, it must indicate a dramatic difference in the physical properties of particles.

However, it is very hard to believe this conclusion... Indeed:

1. interplanetary dust particles (IDPs) originated from comets are quite similar to those originated from asteroids (e.g., Brownlee et al., 1993; Brownlee and Joswiak, 1995);

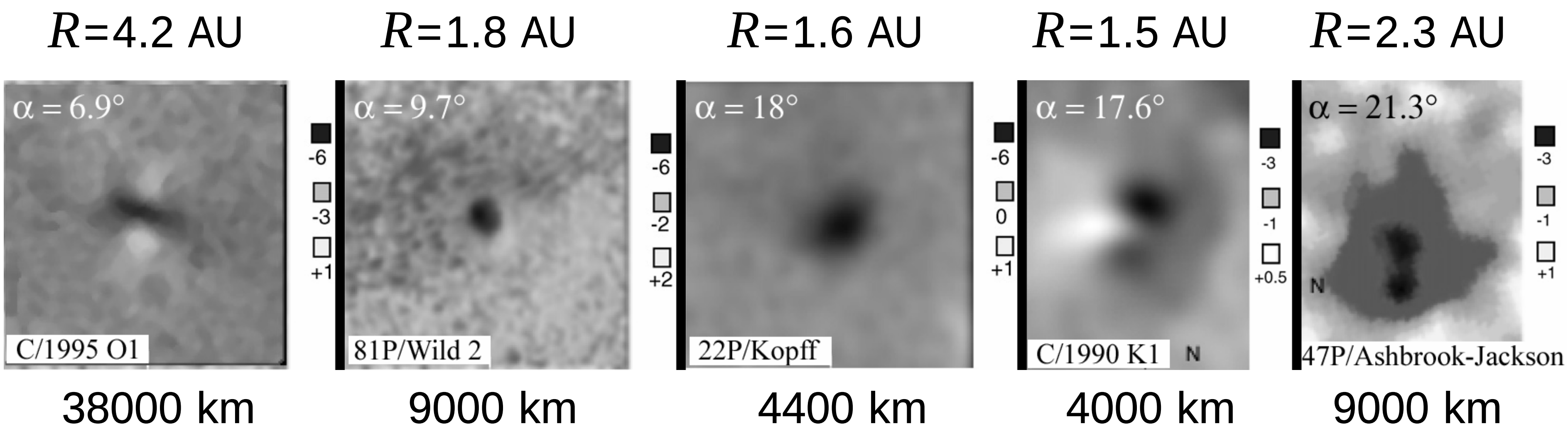
2. featureless visible spectra, color, low albedo, and surface morphology of cometary nuclei are typically similar to C-type and D-type asteroids (Weissman et al., 2001; also, compare images in Veverka et al., 1997 and A'Hearn, 2006).

Therefore, it has to be another explanation for the coincidence between negative polarization branches of comets and asteroids.

In order to understand, what is the reason for coincidence of NPB by comets and C-type asteroids, it is necessary to see the variations of the negative polarization through coma.

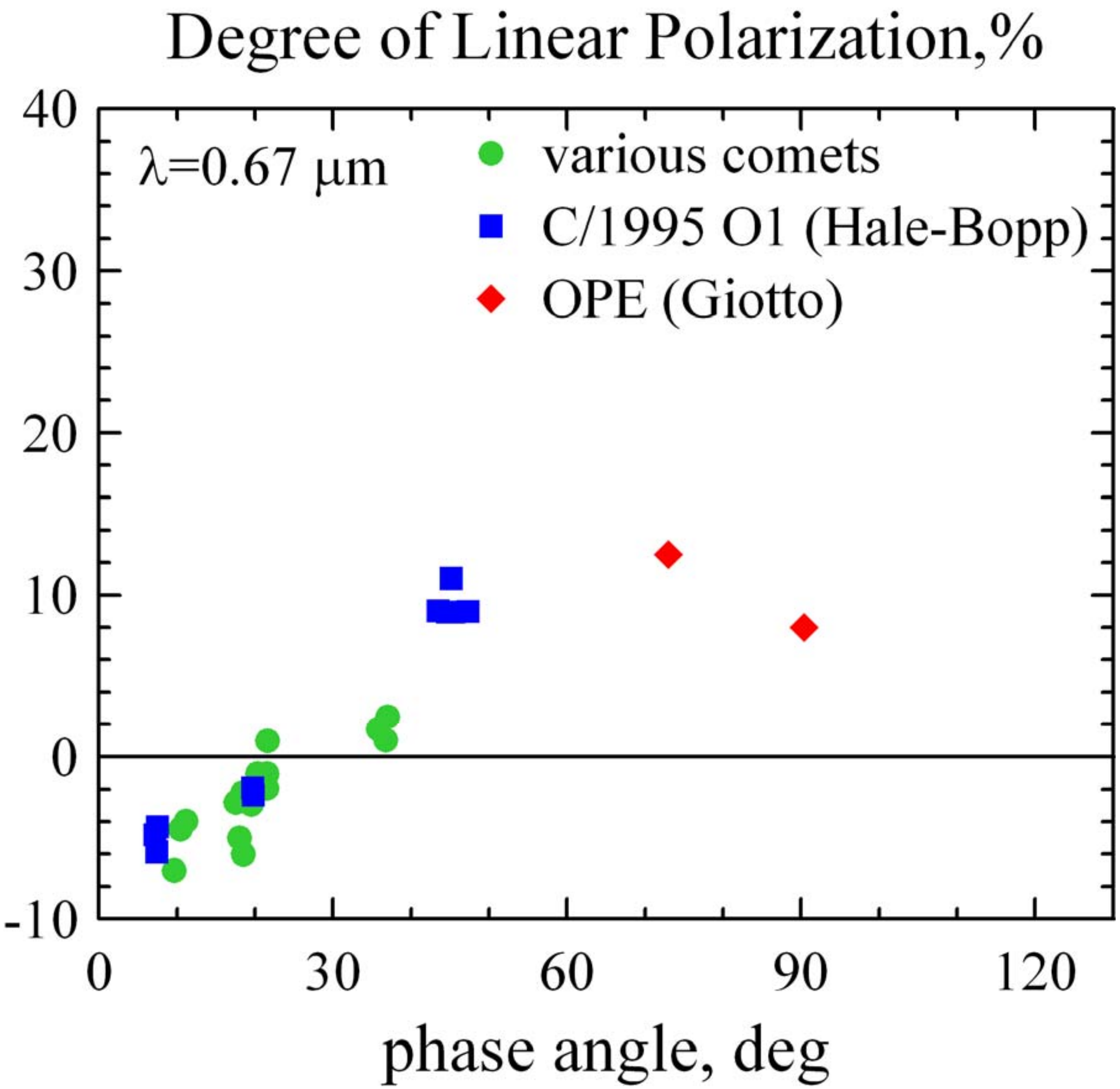
Imaging polarimetry reveals two noticeable features in coma:

- Jets (only positive polarization through all the phase angles)
- Circumnuclear Halo (high negative and low positive polarization; a few thousands km)



data adopted from Hadamcik and Levasseur-Regourd, 2003

Synthetic phase dependence of the degree of linear polarization of cometary circumnuclear haloes.

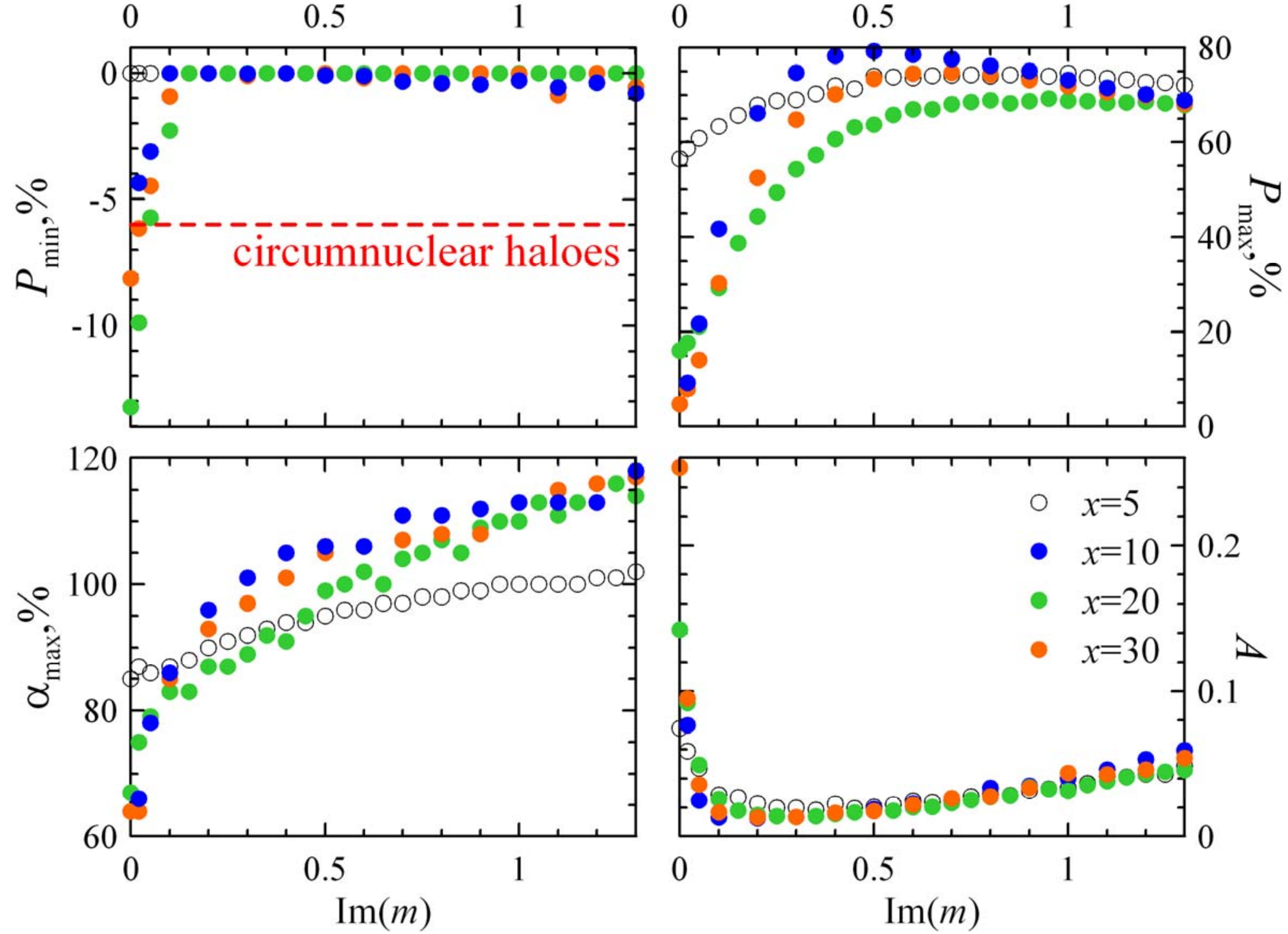


High jet-activity hides circumnuclear haloes.

It causes a difficulty in ground-based observations of halo at large phase angles. However, polarimetric data obtained from space mission Giotto could be used.

One can estimate the maximum of positive polarization about 12% located at 60°.

Interpretation of angular profiles of the degree of linear polarization of circumnuclear haloes.



data adopted from Zubko et al., 2009

Interpretation of angular profiles of the degree of linear polarization of circumnuclear haloes.

(1) Deep branch of the negative polarization (-6%) in cometary circumnuclear haloes implies low absorption in dust particles. Imaginary part of refractive index could be estimated Im(m) $\leq$ 0.02.
In practice it means an absence of highly absorbing CHON particles in the haloes.

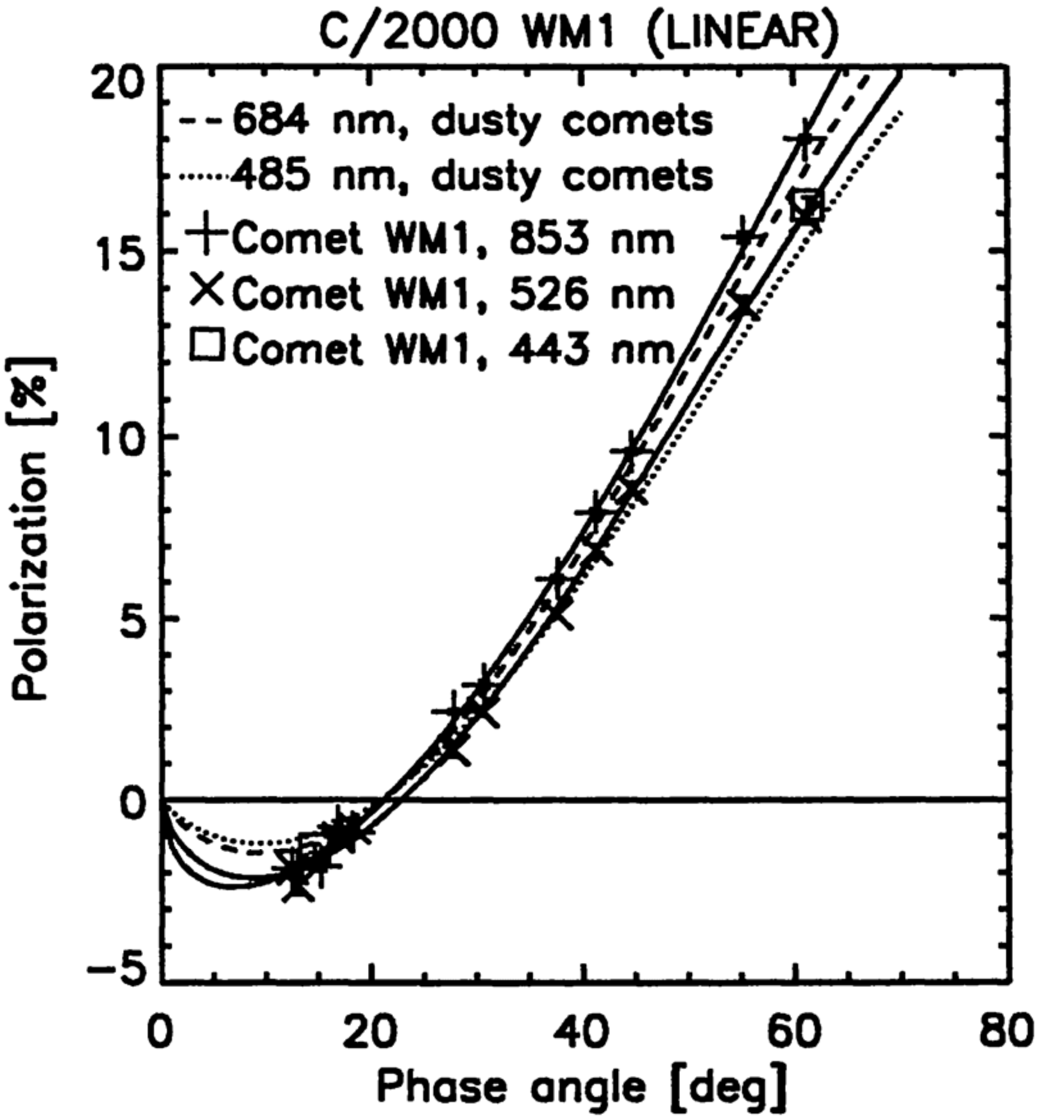
(2) High negative polarization strongly correlates with low positive polarization and a shift of maximum of positive polarization toward zero phase angle.
In practice, it means that the polarimetric measurements in vicinity of nuclei 1P/Halley and 26P/Grigg-Skjellerup carried out by Giotto space probe are indeed related to the haloes.

(3) Geometric albedo of dust particles forming the haloes could a few times higher than the average value through coma.

(4) In Hadamcik and Levasseur-Regourd (2003), basing on high negative polarization in haloes , the compact structure of dust particles was suggested. However, the meaning of term “compact” was not quantitatively specified.

In Zubko et al. (2008), the impact of packing density on light scattering by irregularly shaped particles has been studied. As was found, in the case of aggregate particles with constituent grains at x = 3–4, a decrease of the packing density from 1 to 0.2 does not change dramatically the amplitude of the negative polarization. However, it does change amplitude of positive polarization. Therefore, in order to derive packing density, one can study ratio of P_{max} to $|P_{min}|$. Since agglomerated debris particles may fit simultaneously both P_{max} and $|P_{min}|$ in haloes (Zubko et al., 2009), one can estimate the material density of particles in cometary circumnuclear haloes about 0.7 g/cm^3.

Traces of high negative polarization produced by circumnuclear haloes in aperture-averaged polarimetric observations of comets.



When geocentric distance Δ is rather small, one can measure inner part of coma.

An example is comet C/2000 WM1 (LINEAR) studied by K. Jockers and N. Kiselev in December, 2001.

At α=13.7° and Δ=0.387 AU, size of the aperture was 3100 × 3100 km.

However, an unexpected and unusual negative polarization may scare the observers.

WAVELENGTH DEPENDENCE OF POLARIZATION OF COMET C/2000 WM1 (LINEAR) IN THE NEGATIVE AND POSITIVE POLARIZATION BRANCHES.

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ABSTRACT

Cometary dust particles are likely to be aggregates. Models of aggregate particles predict that, if the aggregates consist of monomers of a single size, the negative branch of polarization critically depends on the size parameter of the monomers. For a given aggregate, if the wavelength increases (i. e. the size parameter decreases) the negative branch of polarization will gradually vanish. Similarly, if the imaginary part of the refractive index increases but all other quantities remain unchanged the phase curve of polarization becomes more positive. Again the negative branch of p[...] phase angle[...] cometary d[...] few comets[...] branch of p[...] negative br[...] affected. P[...] C/2000 W[...] 10 to Dec. [...] of Pik Ters[...] the comet [...] liocentric d[...] servations [...] dependence[...] the theory [...] length (as [...] the two effects, [...] will partly compensate each other and therefore provide some stability for the inversion angle and, consequently, reduced dependence of the negative branch of polarization on wavelength.

Key words: Comet C/2000 WM1 (LINEAR); polarimetry; light scattering; dust.

1. THE WAVELENGTH DEPENDENCE OF THE NEGATIVE BRANCH OF POLARIZATION OF COMETARY DUST

Like asteroid regolith, also cometary dust is negatively polarized at small phase angles (Kiselev & Chernova (1981)). The polarization minimum occurs at a phase angle of about 10°. In the visual wavelength range the polarization values in this so-called negative branch of polarization very little depend on wavelength (Chernova et al. (1993)). According to Kiselev et al. (1999), in Kiselev's data base the average minimum of the negative polarization is $-1.55 \pm 0.08\%$ for the blue continuum window and $-1.49 \pm 0.05\%$ for the red continuum window, i. e. within error limits there is no significant dependence on wavelength. From the comparison with asteroid regolith it is clear that the negative branch of polarization of cometary dust must be [...]

branch of polarization should disappear.

The effect is [...] Fig. 1. In this figure polarization phase curves of aggregates are shown which consist of 12 spherical monomers having the same size. The different curves belong to different size parameters X_i of the constituting monomers of the aggregate. In the upper panel the imaginary part of the refractive index (absorption index) equals 0.01 and in the lower panel 0.1. In both panels, in the positive branch of polarization the degree of polarization decrases with increasing size parameter of the

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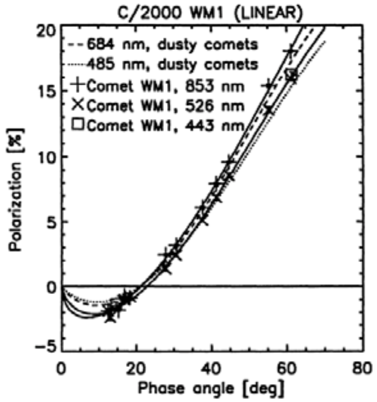
3. COMET C/2000 WM1 (LINEAR)

Table 1. Overview on the observations of comet C/2000 WM1 (LINEAR)

Date	Time [UT]	r [AU]	Δ [AU]	Phase °	Filters CW [nm]
November 2001					
Day					
10	20:50 – 26:07	1.565	0.631	19.0	526 – 853
12	22:35 – 23:54	1.534	0.588	17.6	526 – 713
17	20:31 – 21:38	1.455	0.487	13.7	526 – 853
18	20:08 – 21.42	1.439	0.468	13.0	526 – 713
23	15:09 – 25:08	1.359	0.387	13.7	443, 853
28	21:13 – 22.17	1.279	0.333	24.9	526 – 853
29	15:46 – 20:52	1.262	0.326	28.1	526 – 853
December 2001					
Day					
01	14:59 – 20:24	1.230	0.318	34.9	526 – 853
02	17:01 – 19:36	1.214	0.316	38.5	526 – 853
03	15:20 – 19:54	1.197	0.316	42.1	526 – 853
06	22:11 – 22:53	1.149	0.326	52.6	526 – 853
09	19:39 – 22:08	1.100	0.349	62.0	443 – 853

Comet C/2000 WM1 (LINEAR) (in the following WM1) provided another opportunity to study the phase curve of polarization of cometary dust in an extended range of phase angles. This comet was observed with the Two-Channel Focal Reducer of the Max-Planck-Institute of Aeronomy at the 2m RCC Zeiss-Telescope of Pik Terskol Observatory (Northern Caucasus) from Nov. 10 to Dec. 9, 2001 (Jockers et al. (2000)). The instrument was used in its imaging polarimetry mode. [...] blue continuum filter at 443 nm could only be used twice, once close to minimum polarization and once close to maximum polarization. In November, when the comet was expected to display negative polarization, the observing conditions, in particular the atmospheric seeing, were rather poor. Polarized and unpolarized standard stars were observed with all filters in all clear nights. The deviations in degree of polarization between measured and catalogue value of the polarized stars are of the order of a few tenths of percent At the time of this writing all polarization data except of the 713 nm filter are reduced. We do not discuss the polarization values derived from the 694 nm wide band filter, as with decreasing heliocentic distance the data of this filter are increasingly smaller as compared to the other measurements. This is caused by the emissions of NH2 transmitted by this filter. In December 2001 Comet WM1 displayed a plasma tail in wide angle images. Even though important H_2O^+ emissions fall in the passband of the wide-band filter, we do not see evidence for this in our images. The polarization images are featureless.



[...]*s observed* [...] *size of the* [...] *the comet* [...] 851 × 4851 [...] *he comet.*

[...]alues integ[...]sec, i. e. [...]h 2500 to [...]entric dis[...]an curves [...]iously ob[...]here is no [...]gative polarization branch. In the positive branch we see the usual positive wavelength gradient if we compare the green (526 nm) and infrared (853 nm) filters. The two observations in the blue (443 nm) filter, however, almost coincide with the ones of the green filter. The measurements of comet WM1 compare well with the average curves in the positive branch. In the negative branch they are significantly less (more negative) than the average curve. It is not clear if this deviation is real. At low phase angles comets usually have large heliocentric distances and often are observed with wide-band filters. But on the other hand gas emissions are weak at large heliocentric distances and therefore should not influence the measurements significantly.

average curves in the positive branch. In the negative branch they are significantly less (more negative) than the average curve. It is not clear if this deviation is real. At low phase angles comets usually

Despite the doubt in data for comet C/2000 WM1 (LINEAR), it is used if necessary.

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Polarization properties of odd comet 17P/Holmes

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ABSTRACT

We present results of polarimetric observations of comet 17P/Holmes that in 2007 surprised the observers by its outburst that resulted in dramatically increased brightness and unusual shape of the coma. Polarimetric properties of the comet also appeared to be very peculiar. Even though the comet showed negative polarization typical for the small phase angles, its absolute values were much lower than usually observed at these phase angles and the spectral gradient of the polarization was much more pronounced than usually observed for comets (although negative that is typical for other comets too). Both these results are different from the regular trends and indicate some specifics of the comet Holmes dust during the outburst. We discuss how such unusual polarimetric properties of the comet can be explained and show how a peculiar combination of aggregated and compact particles or a composition with a unique ratio of silicates to organics can explain the observational results.

1. Introduction

Comet 17P/Holmes belongs to the Jupiter-family comets with aphelion at the orbit of Jupiter and perihelion at 2.2 AU. After the discovery by Edwin Holmes in 1892, comet Holmes was observed in 1899 and 1906, then disappeared until 1964, when astronomers rediscovered it based on the predicted ephemeris. After its closest approach to the Sun in May 2007, comet Holmes went from magnitude 17 to magnitude 2.8 in just a few hours on October 24, 2007, doubling the brightness every half an hour. This was an unprecedented outburst especially as it is rather unusual for comets to get brighter as they move away from the Sun.

Extreme outburst of comet Holmes stimulated numerous photometric and spectral observations from optical to millimeter range. According to Kossacki and Szutowicz [1], observed increase of the comet magnitude correlated with a large ejection of dust. Schleicher and Bair [2] found a significant dust production $Af\rho \approx 5 \times 10^5$; this allowed us to treat the comet below as a dusty one. Mid-infrared (5.5–38 μm) spectra [3] taken soon after the explosion revealed a broad emission by fine-grained crystalline olivine. The region near the nucleus had less-structured spectrum indicating larger particles or particles dominated by carbonaceous or other featureless material. Two broad absorption bands were found in the reflectance spectra centered at 2 and 3 μm, respectively [4]. The centers and overall shapes of these two absorptions were

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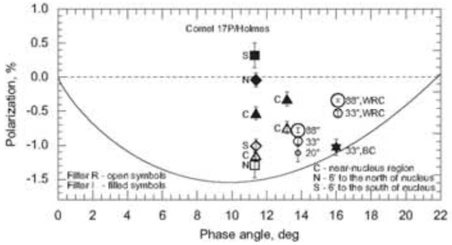


Fig. 4. The measured polarization of comet Holmes in different filters and diaphragms. The typical curve of negative polarization for comets is the same as in Fig. 2.

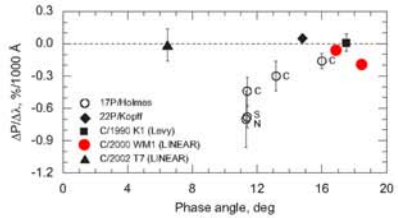


Fig. 5. The spectral gradient of polarization for comets 17P/Holmes, 22P/Kopff, C/1980 K1 (Levy), and C/2002 T7 (LINEAR).

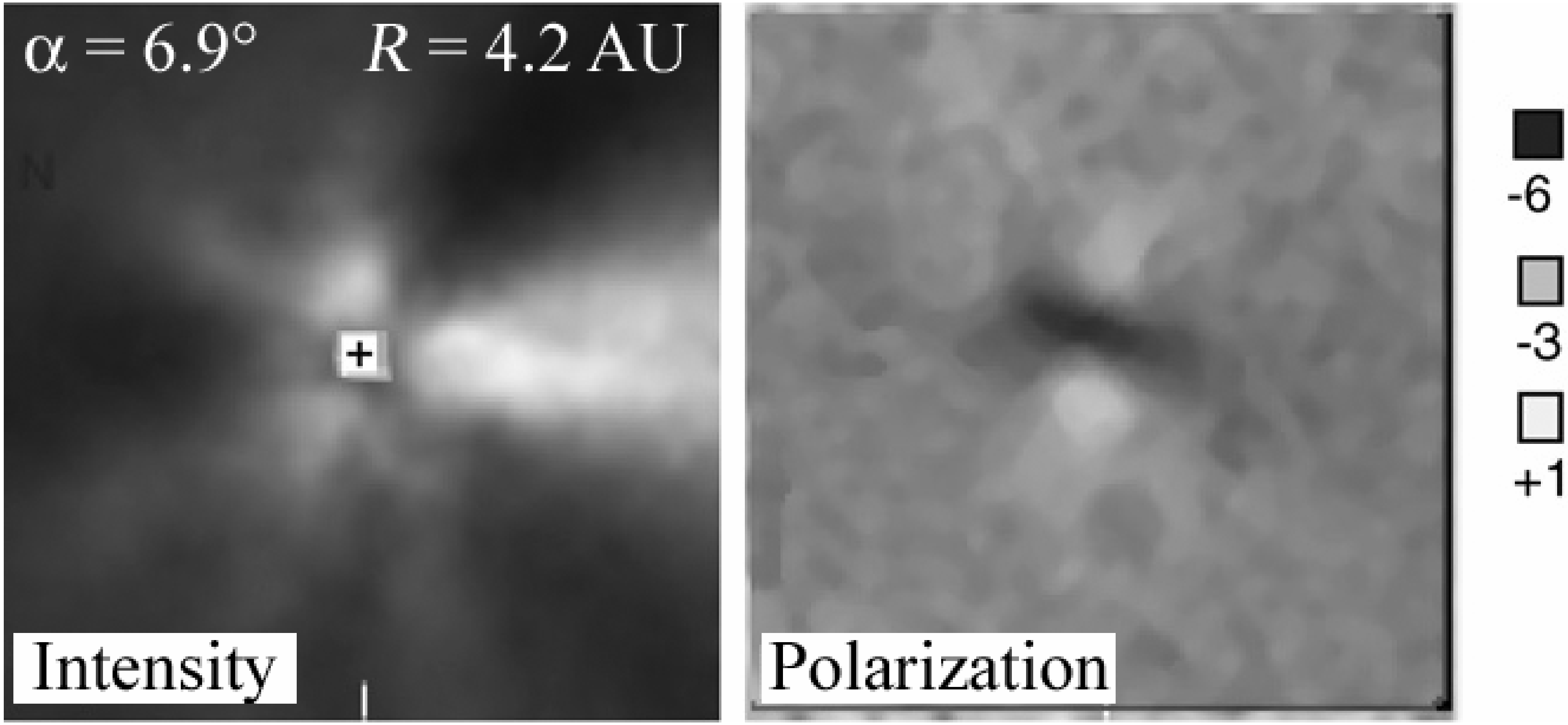
4. Discussion

As it was shown in Section 2, the results of aperture polarimetry for most comets show amazingly similar characteristics of negative polarization, namely they have almost identical position and value of the minimum and the inversion angle (Fig. 2). However, it is evident from Fig. 4 that the polarimetric properties of comet Holmes differ considerably from those for other comets. The comet showed typical for this range of phase angles negative polarization but its absolute values are the smallest among all previously observed in comets at corresponding phase angles, regardless of the position of the measured area in the coma. The degree of polarization near the minimum is approximately −1.1% in the R filter and about −0.5% in the I filter. According to the data in the red band (Fig. 4, open symbols), the expected inversion angle should be about 18° that is also the value unusually low for comets.

The other peculiarity of Holmes' polarization is its atypical spectral trend. Even though there is not enough data to draw a firm conclusion about the typical spectral behavior of comet polarization at small phase angles, none of the previously observed comets showed such a pronounced negative spectral gradient (Fig. 5). Comet Holmes is the first comet for which atypical spectral dependence of polarization with the large negative gradient, about −0.77%/1000 Å near the polarization minimum, has been found. Below we will try to find the reasons of such a peculiar behavior of the polarization of comet Holmes.

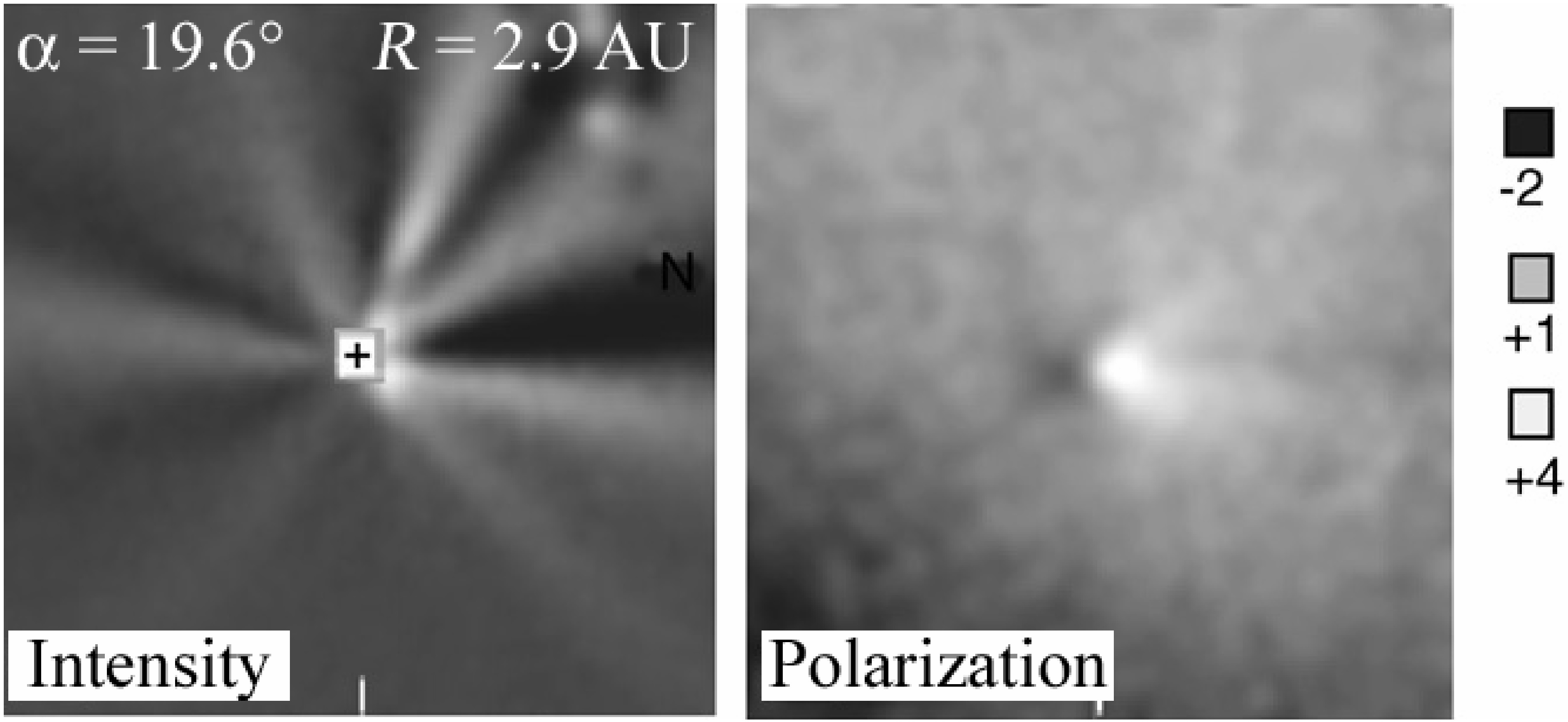
The observations were done at small phase angles, which means that the tail could be partially projected on the coma. Can the contribution of the tail dust be the reason of the peculiar polarization of comet Holmes, specifically its negative spectral gradient? We doubt this. First, the surface brightness of a comet tail is usually much smaller than that for a coma. The contribution of the tail for comet Holmes can be roughly estimated using the distribution of the surface brightness in the images obtained with the 8.2 m Subaru telescope on October 25–26, 2007 [5]. According to the data [5], the ratio of the flux of the coma to the flux of the tail was more than 3. Second, we detected the atypical polarimetric properties of comet Holmes for all three diaphragms 88, 33, and 20 arcsec in spite of the fact that the tail contribution in the flux should be different for different diaphragms. Finally, we also performed the observations for two regions of the coma at the distance of 6 arcmin to the North and the South of photometric center that is far from the tail and got the same atypical behavior of the polarization. All of these evidences that the projection of the tail on the coma cannot be a reason of the atypical polarization of comet Holmes.

Imaging photo-polarimetry of comet C/1995 O1 (Hale-Bopp).



Size of image side is 38000 km

Imaging photo-polarimetry of comet C/1995 O1 (Hale-Bopp).



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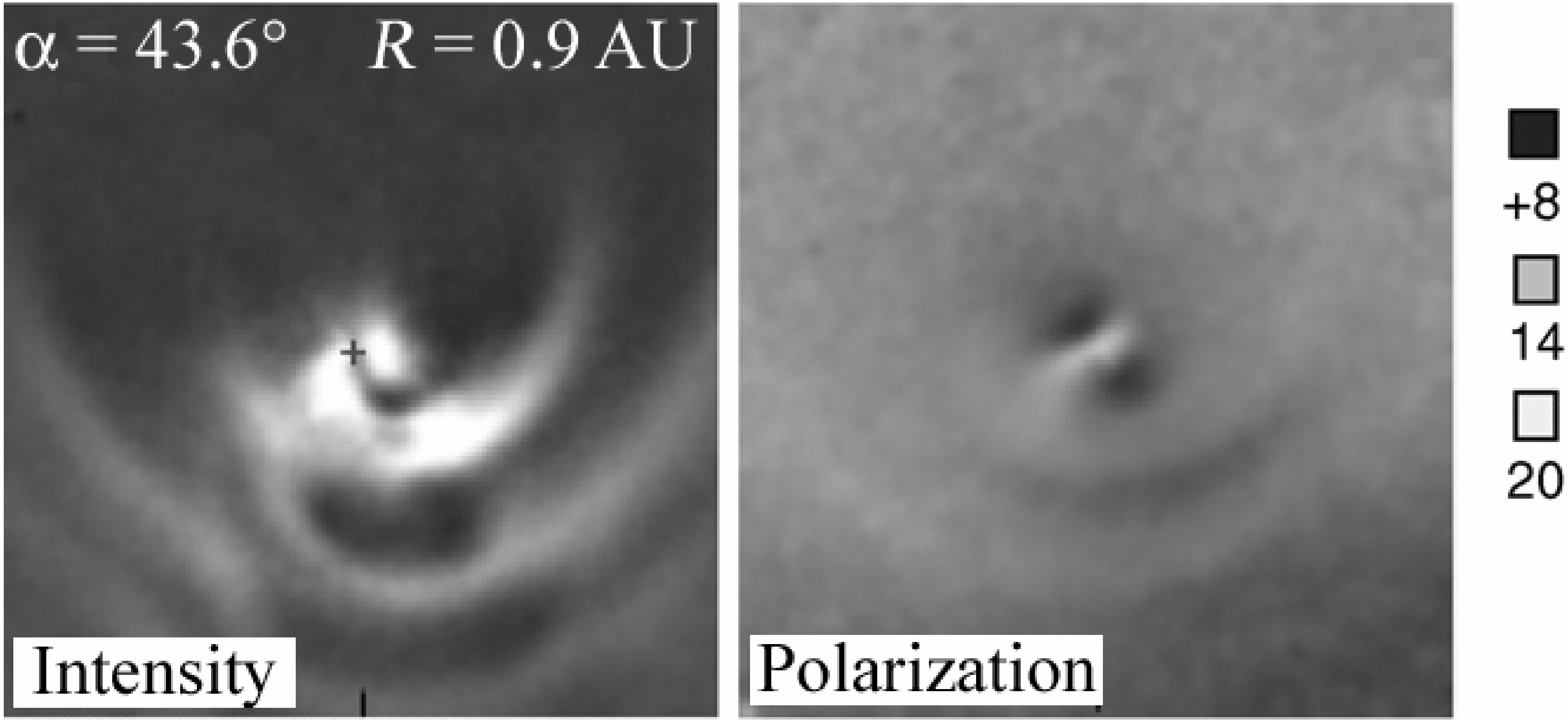
Imaging photo-polarimetry of comet C/1995 O1 (Hale-Bopp).



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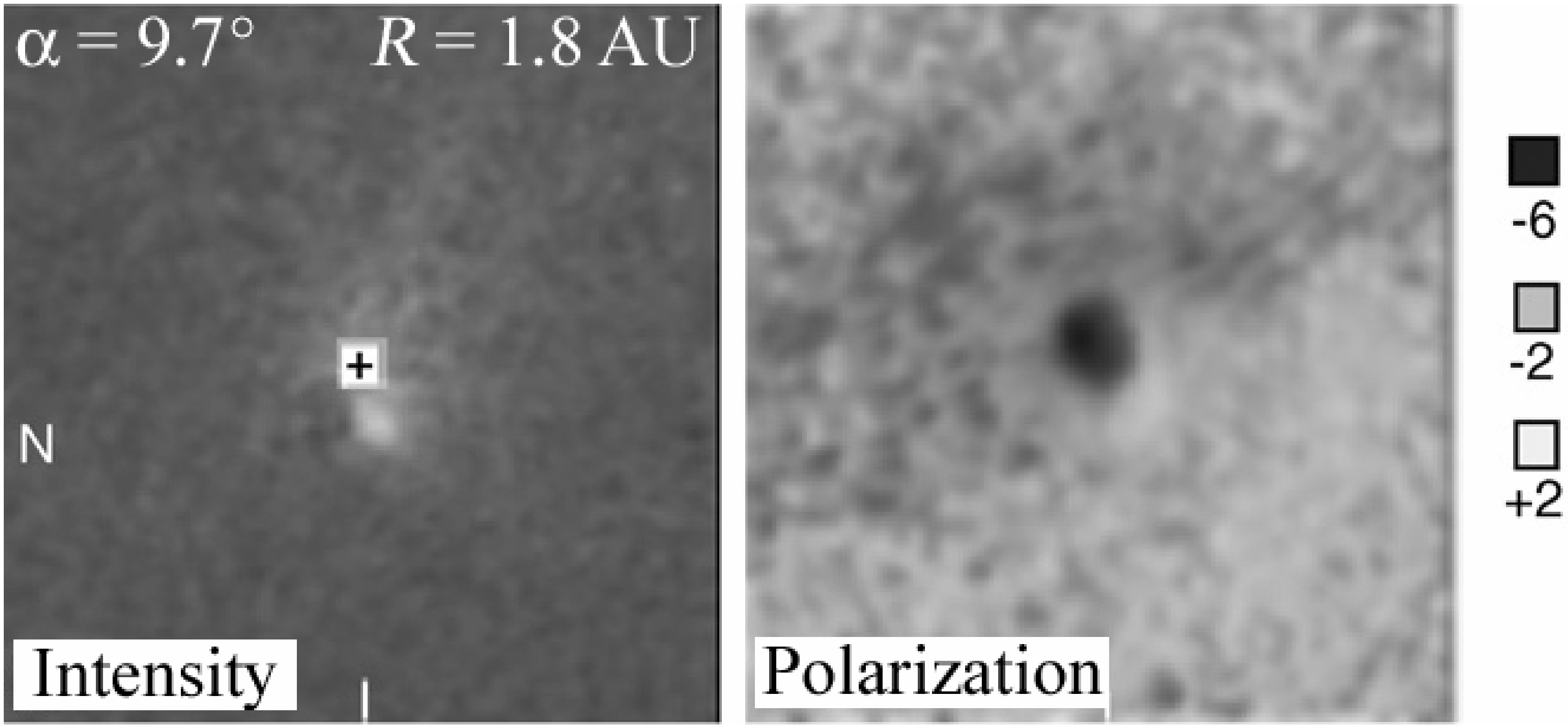
Imaging photo-polarimetry of comet 81P/Wild.



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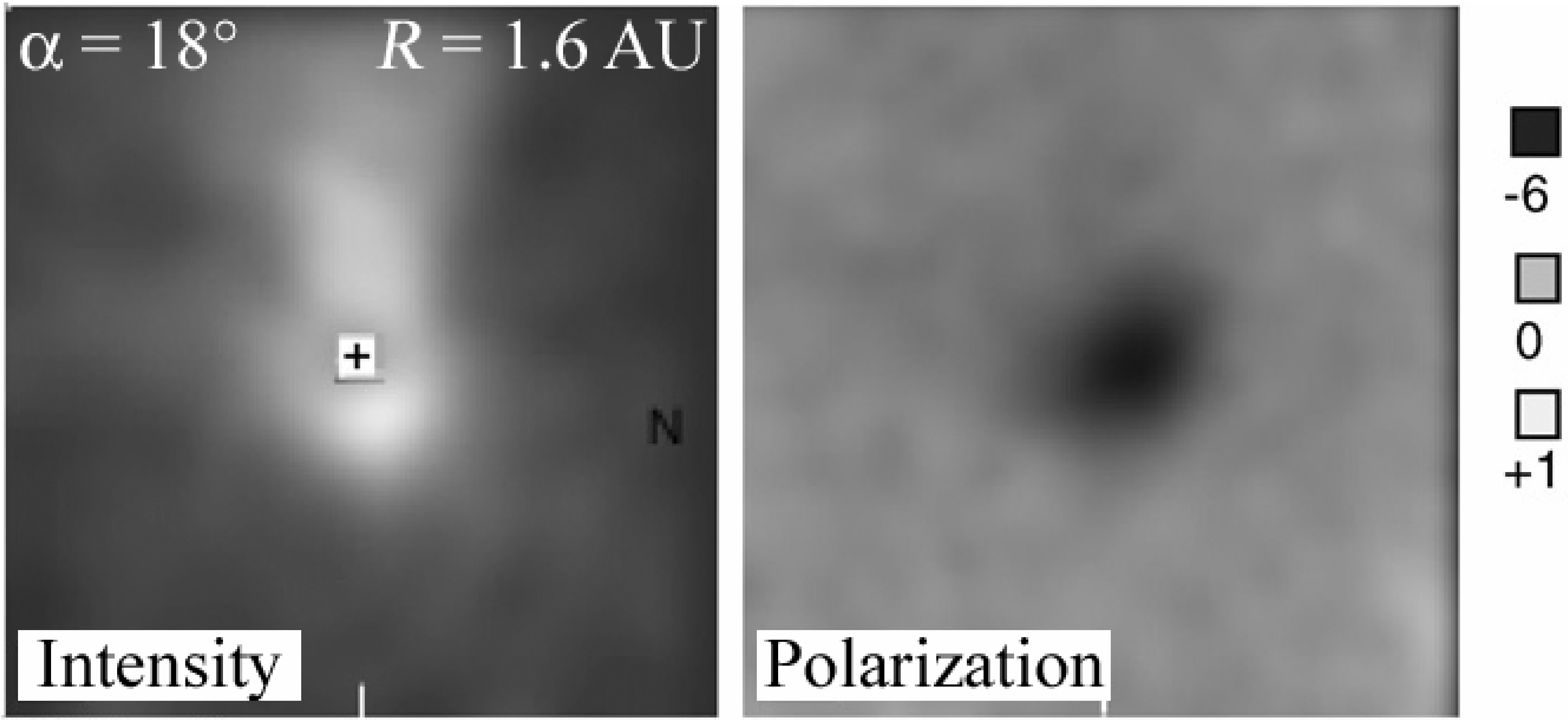
Imaging photo-polarimetry of comet 22P/Kopff.



Size of image side is 4400 km

Summary on cometary jets.

(1) Jets are highly collimated fluxes of dust particles. The outflow velocity of dust particles in jets could be as high as a few hundreds of meters per second.

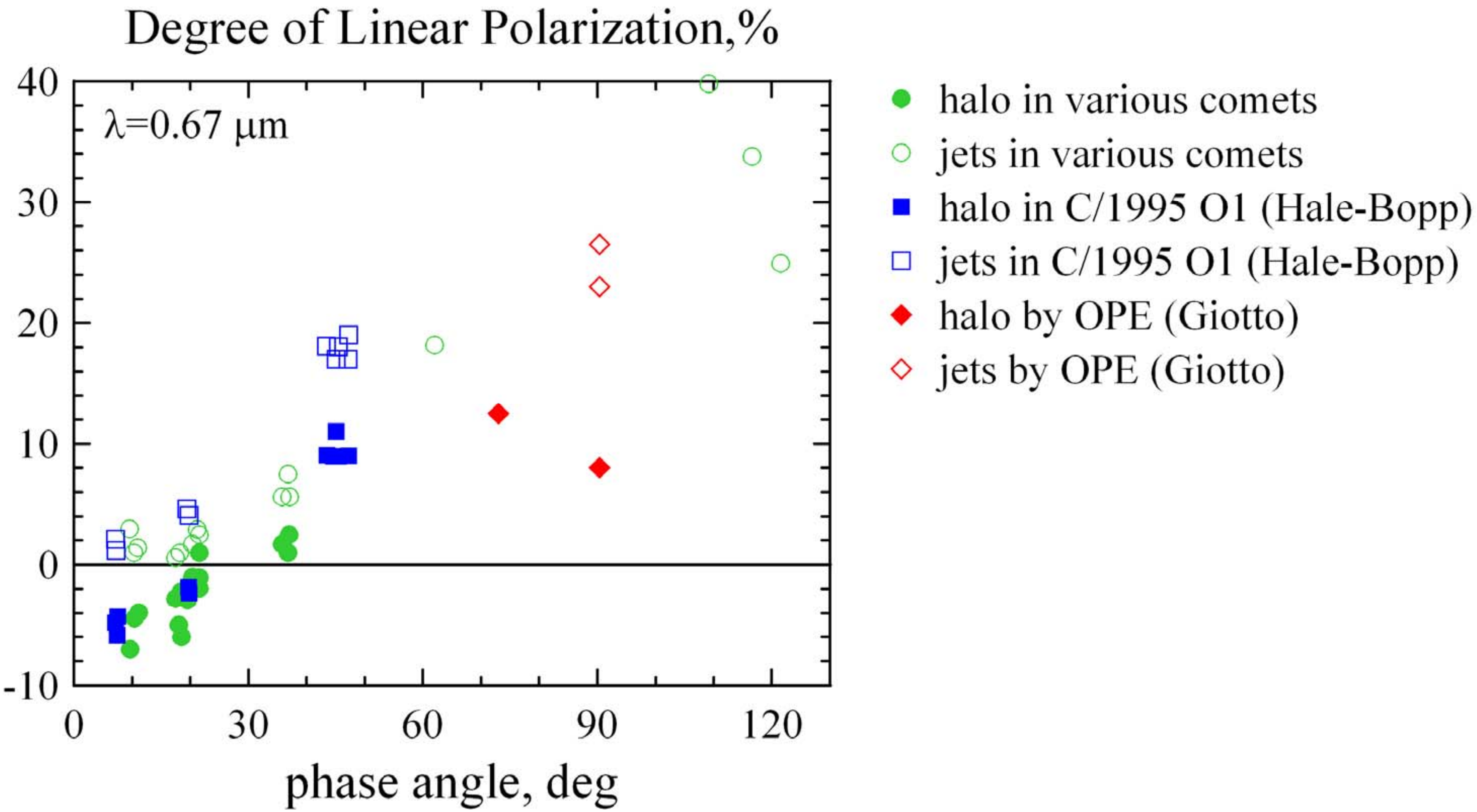
(2) In the case of comets studied by spacecraft, one can connect the jets observed in vicinity of nuclei and some jets seen in ground-based observations.

(3) In situ measurements show presence in jets super-volatiles CO and CO_2 gases. These gases sublime at quite low temperatures < 20 K and < 50 K, correspondingly. Therefore, presence of super-volatiles could indicate that jets are originated from deep undersurface layer.

(4) High jet-activity hides a circumnuclear halo. It implies that number of particles in halo is substantially less than in jets.

(5) Degree of linear polarization in jets is positive through all the phase angles.

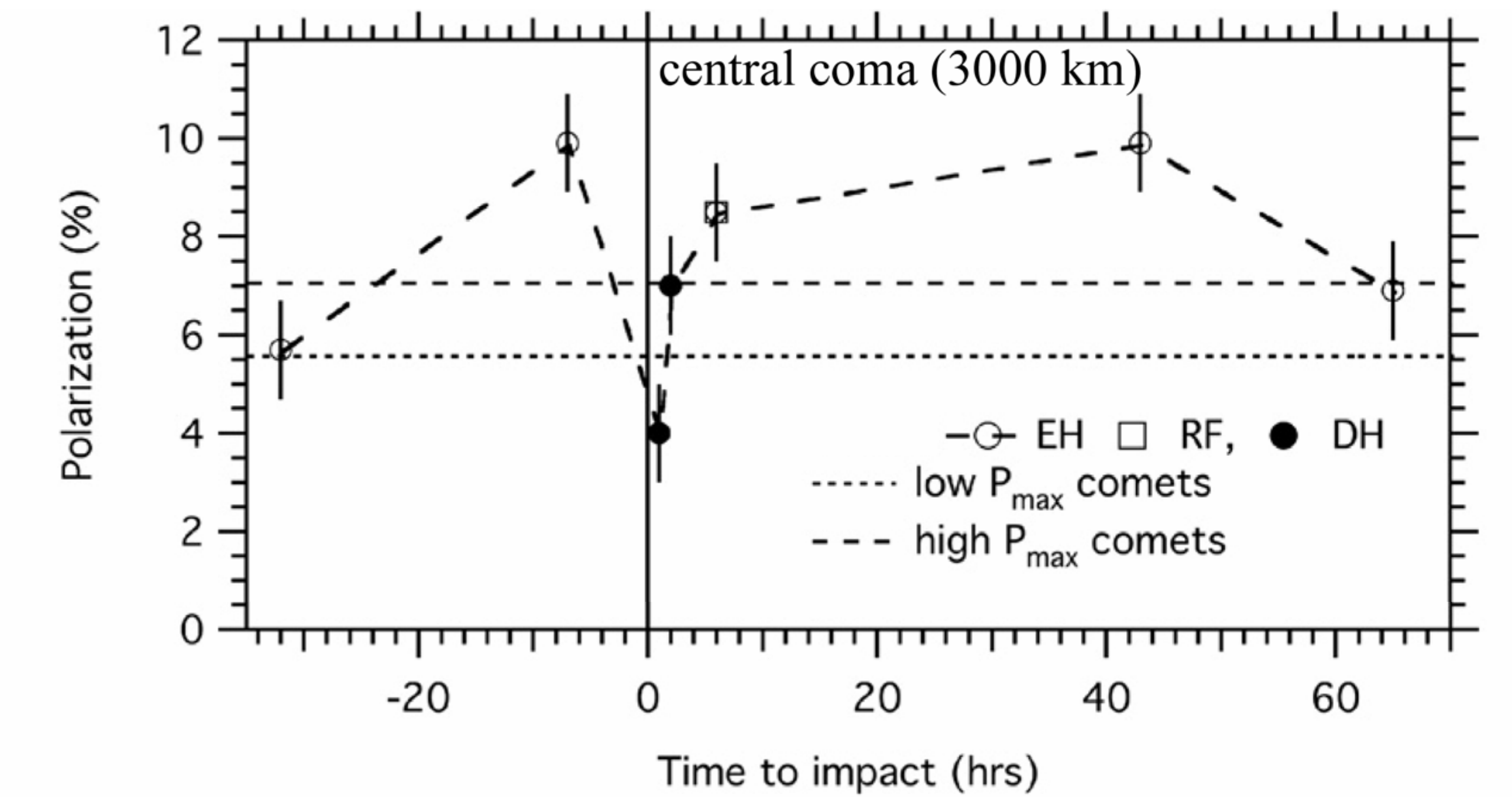
Phase dependences of the degree of linear polarization in cometary circumnuclear haloes and jets.



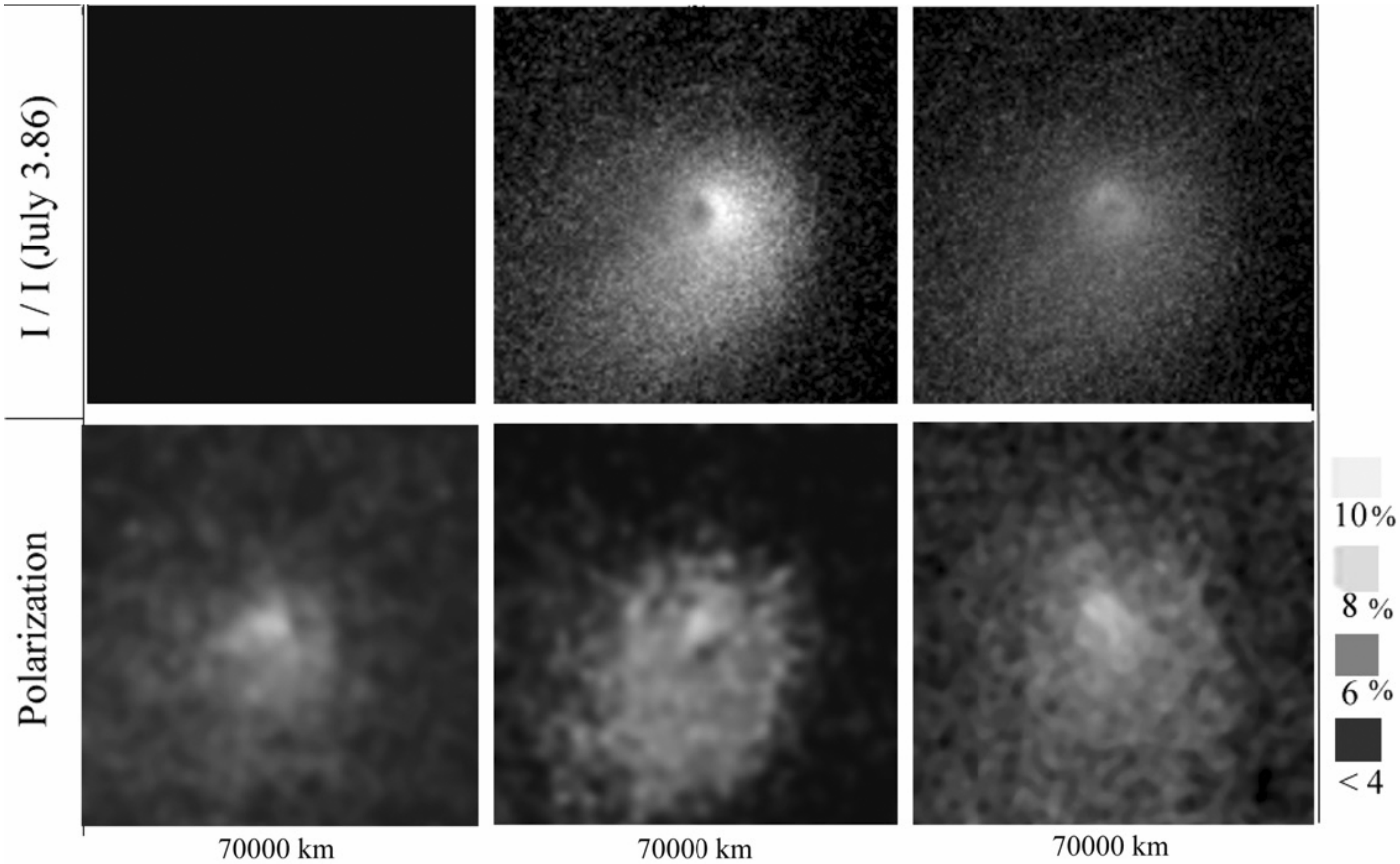
Interpretation of positive polarization in jets is a difficult task.

Like in the case of haloes, traces of high positive polarization produced by jets can be also found in aperture-averaged polarimetry of comets.

The effect produced by jets is more pronounced when area of signal integration is small. Below is the time-dependence of polarization in inner coma of comet 9P/Tempel before DI event.

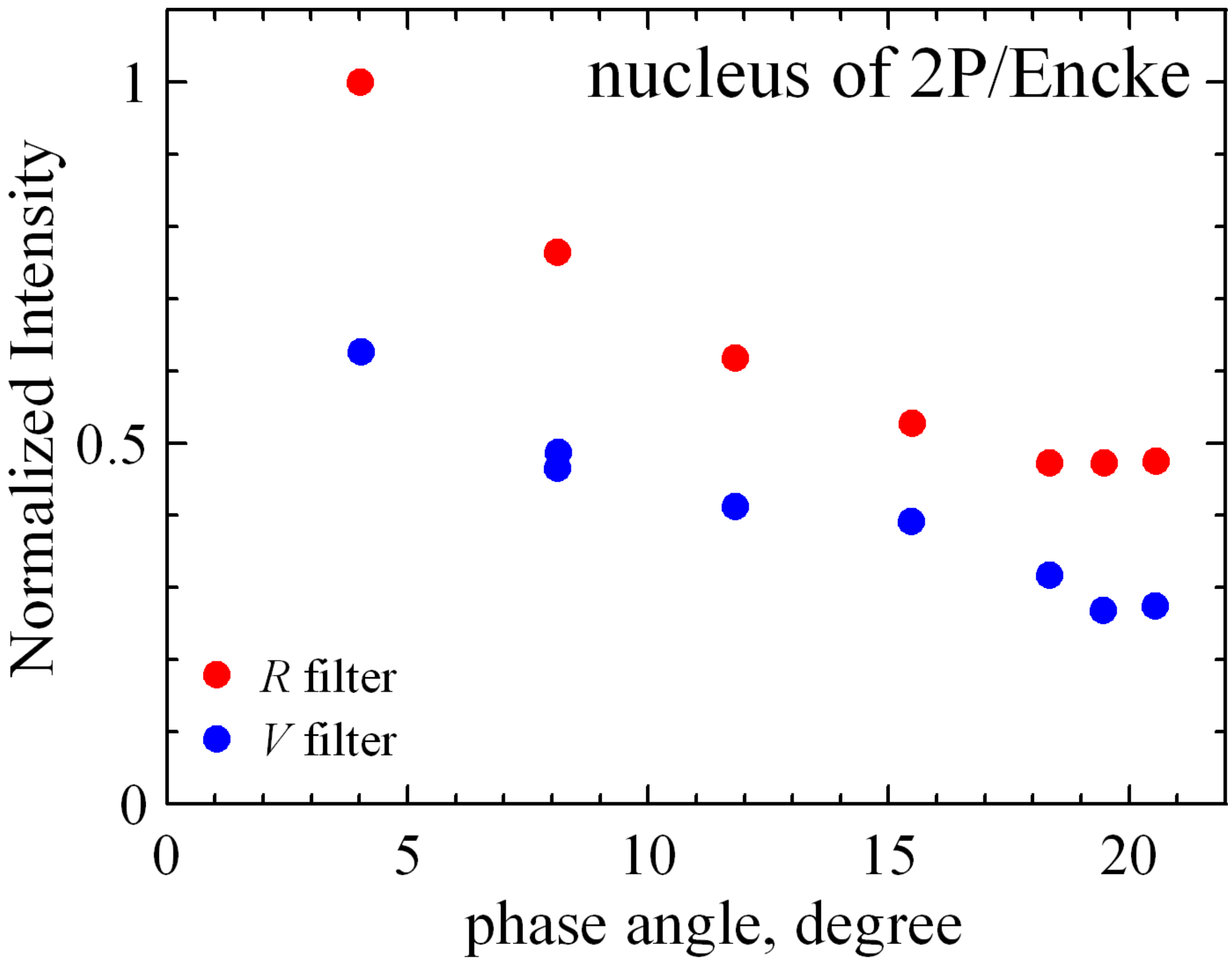


Imaging photo-polarimetry of comet 9P/Tempel during the *Deep Impact* event.



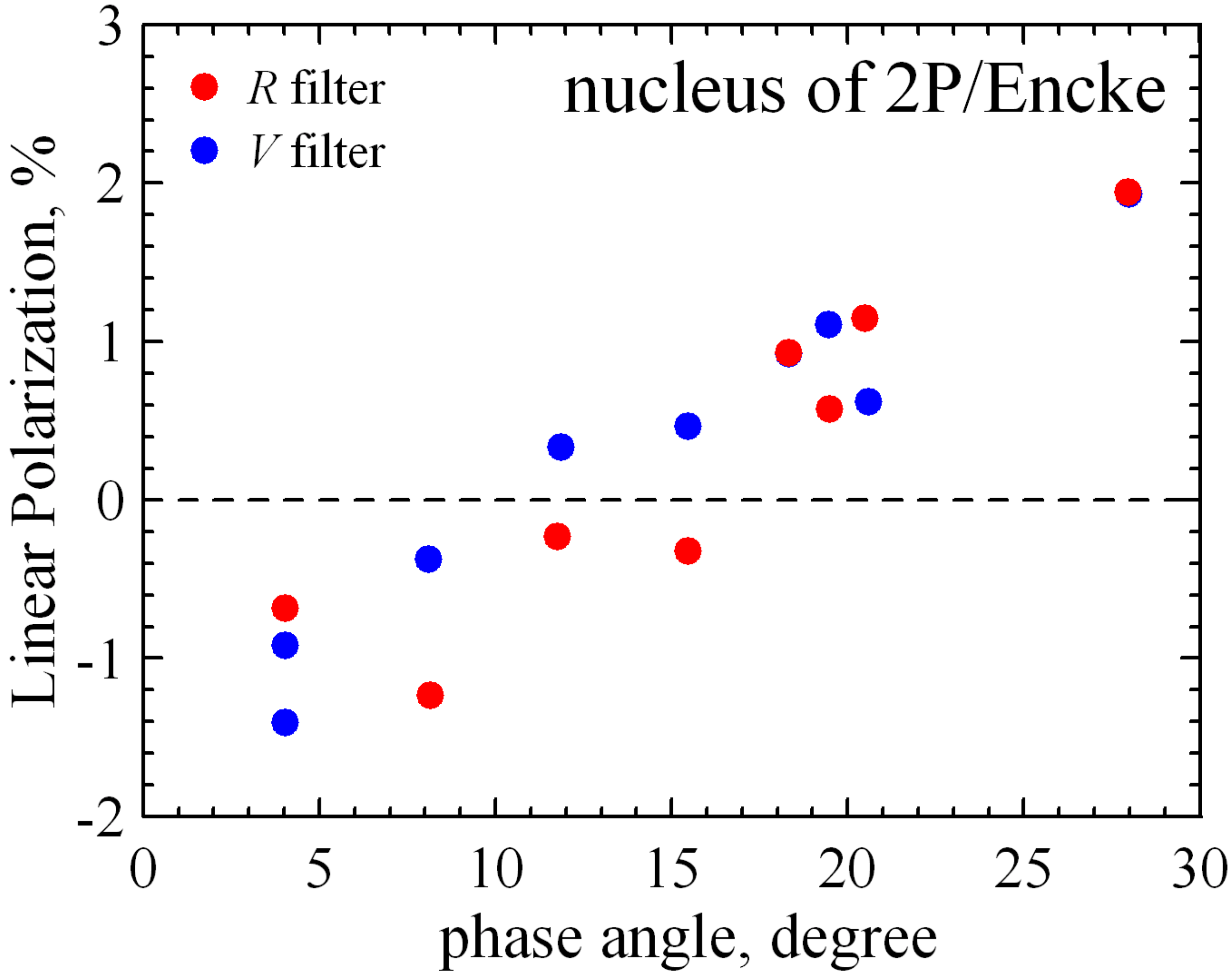
Outburst caused by the impact have increased the positive polarization in coma, which is qualitatively consistent with jets.

Photo-polarimetry of nucleus of comet 2P/Encke.



The cometary nucleus is essentially red in appearance.

Photo-polarimetry of nucleus of comet 2P/Encke.



The negative polarization of the nucleus 2P/Encke visibly differs from that of C-type asteroids.

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