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Polarimetry of comet P/Halley: properties of dust

A.K. Sen[1], M.R. Deshpande[1], U.C. Joshi[1], N.K. Rao[2], and A.V. Raveendran[2]

[1] Physical Research Laboratory, Navrangpura, Ahmedabad 380 009, India
[2] Indian Institute of Astrophysics, Bangalore 560 034, India

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Abstract. Comet P/Halley was observed polarimetrically for seven nights in IHW and other continuum filters, during its pre- and post-perihelion passages. These polarimetric observations have been combined with the observations taken by other investigators, to get a complete picture of phase angle and wavelength dependence of polarization of comet P/Halley. Assuming Mie type scattering by cometary grains, we have fitted the observed polarization data for different complex values of refractive indices of cometary grains. It has been found that a power law grain size distribution, suggested by Mazets et al. (1987), with grain size spectrum from 0.001 μm to 20 μm, fits into the observed data and the refractive indices of the grains are different at different values of the incident wavelength. The complex values of refractive indices are found to be (1.387 − i0.032) at 0.365 μm, (1.375 − i0.040) at 0.484 μm and (1.374 − i0.052) at 0.684 μm.

The polarization values obtained at other non-IHW filters have been discussed in light of this set of complex values of refractive indices.

Key words: comet – polarization – cometary dust – optical properties of dust

1. Introduction

Cometary polarizations are generally caused by two mechanisms: (1) scattering of sunlight by the cometary particles and (2) fluorescence emission by the cometary molecules. Linear and circular polarization measurements have been made by several investigators during the recent apparition of comet P/Halley (1982i) (Bastien et al. 1986; Brooke et al. 1987; Dollfus & Suchail 1987; Kikuchi et al. 1987; Lamy et al 1987; Le Borgne et al. 1987b; Metz & Haefner 1987; Sen et al. 1988 etc.). Most of these studies are aimed at understanding the nature of the polarization which occurs due to the scattering of the sunlight by cometary dust particles. These studies help us in understanding characteristics of cometary grains. Polarization occurring due to the resonance fluorescence mechanism in the molecular emission bands of comet P/Halley has also been studied by some investigators (Le Borgne et al. 1987a; Sen et al. 1989). The observed value of cometary linear polarization, which is caused by single dust scattering is generally a function of (1) incident wavelength (2) cometary phase angle (= 180° − scattering angle) (3) the geometrical shape and size of the dust particles and (4) the composition of dust particles in terms of complex values of its refractive index ($n - ik$); where the real part represents the actual refractive index and the imaginary part represents the absorption coefficient of the dust particle. Since cometary particles are irregularly shaped and at present there is no scattering theory available for irregularly shaped particles, we can reasonably make the assumption that cometary particles are spherical in shape and use Mie scattering formulation to explain the observed polarization values for a comet.

In the present paper we have attempted to study the characteristics of cometary grains based on polarimetric observations through IHW (International Halley Watch) and other continuum filters.

Send offprint requests to: M.R. Deshpande

2. Observations

Observations were made with the 1 m telescope of the Vainu Bappu Observatory, Indian Institute of Astrophysics, Kavalur, India on 9, 10 December 1985 and 14, 15, 17, 18 and 19 March 1986, covering both the pre- and post-perihelion passages of comet P/Halley. A photopolarimeter, described elsewhere (Deshpande et al. 1985), was used at the Cassegrain focus of the telescope. This instrument works on a rapid modulation principle, the sampling rate being 2 ms and the data are processed on line with a microprocessor. The error in polarization is estimated from the photon count statistics using a least square method. The error in position angle is estimated by the relation (Serkowski 1962)

$$E_\theta = 28.^\circ 65\, E_P/P; \quad (for\ E_P \ll P)$$

where E_θ is the error in position angle θ and E_P is the error in polarization P.

On the nights of 9, 10 December 1985 and 17, 18 and 19 March 1986, the observations were taken through the IHW (International Halley Watch) filter system which contains three continuum bands centered at 0.365, 0.484 and 0.684 μm, with FWHM 0.008, 0.006 and 0.009 μm, respectively. An entrance aperture of 60″ diameter was used on 9 and 10 December 1985 and 24″ diameter was used on 17, 18 and 19 March 1986. On 9 and 10 December the observations were taken at around UT 15-00 h. But the observations on 17, 18 and 19 March were taken after UT 23-30 h and since the observations were continued for an hour these observing dates are actually overlap between two nights such as 17–18, 18–19 and 19–20 March respectively.

However in the subsequent discussions (except in the Tables 1, 2, 3) we will refer these three nights as 17, 18 and 19 March for convenience. On the nights of 14 and 15 March 1986, the comet was observed through several other narrow band interference filters centered at 0.342, 0.442, 0.526, 0.575 and 0.641 μm, all the filters have FWHM $\sim$0.005 μm. These filters except 0.575 μm (which is slightly contaminated by NH_2 emission) are free from any cometary molecular emission. All the observations were centered around the nucleus and the diameter of the aperture was 15″ and 24″. As discussed above these two nights are also actually overlap between the two nights 14–15 and 15–16 March respectively. But in the subsequent discussion, except in Table 1, we will refer them as 14 and 15 March respectively. For these five overlapping nights we tabulate the phase angle values (in Tables 1 and 2) which correspond to the phase angle at the UT 00.00 h of the second night. Also we shall use these values for the Mie scattering calculations to be discussed later.

3. Results and discussion

In Table 1 we have listed all the polarization observations taken through non-IHW continuum filters, which are plotted in Fig. 1. From Fig. 1 we can clearly see that the polarization increases with wavelength on 14 and 15 March. The observations on 14 March were made also with the filter 0.575 μm which is slightly contaminated by NH_2 emission. On 14 March all the observations were taken through the 15″ aperture and we have joined these data points in Fig. 1 by straight lines except the point corresponding to 0.575 μm. Figure 1 shows that the polarization decreases across the band 0.575 μm. This is quite expected, since the molecular emission is generally polarized to a lesser extent as compared to the continuum polarization caused by dust (Le Borgne et al. 1987a; Sen et al. 1989). On 15 March we have observed the comet only through two continuum filters 0.526 and 0.641 μm, with 15″ aperture. Here also we see an increase in polarization with wavelength. In order to see whether the polarization changes with the size of the entrance aperture, we have repeated the observation at 0.526 μm with 24″ aperture on the

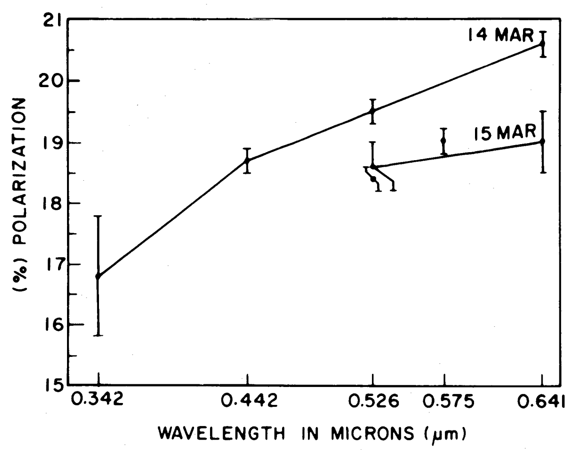

Fig. 1. Wavelength dependence of polarization observed through several non-IHW continuum filters on 14 and 15 March 1986

Table 1. Percent polarizations as observed during March 1986, through different narrow band non-IHW continuum filters

Date	Aperture (″)	Phase angle (°)	Wavelength (μm)	Polarization (%)
14–15 Mar.	15	64.3	0.342	16.8±1.0
			0.442	18.7±0.2
			0.526	19.5±0.2
			0.575	19.0±0.2
			0.641	20.6±0.2
15–16 Mar.	15	64.8	0.526	18.6±0.4
	24		0.526	18.4±0.2
	15		0.641	19.0±0.5

Table 2. Percent polarizations as observed during December 1985 and March 1986 through the three IHW continuum filters

Date	Aperture (″)	Phase angle (°)	*U* 0.365 μm	*B* 0.484 μm	*R* 0.684 μm
9 Dec.	60	44.3	9.3±4.5	8.3±1.1	9.3±1.1
10 Dec.	60	45.7	10.0±3.0	6.8±0.8	10.0±1.3
17–18 Mar.	24	65.9	15.9±0.6	17.6±0.1	20.0±0.3
18–19 Mar.	24	66.1	14.5±0.9	18.3±0.3	19.1±0.3
19–20 Mar.	24	66.1	13.9±1.3	16.7±0.2	18.2±0.4

same night. However as seen from Fig. 1 and Table 1. The polarization does not seem to change, within the errors, when we change the aperture size from 15″ to 24″. Bastien et al. (1986) have done similar studies and by changing the aperture from 3″.9 to 17″.7, they have found that barring some exceptions, there is a general trend for the polarization to decrease as the aperture size increases. Their experiments were conducted at wavelengths 0.764 and 0.684 μm, over a range of phase angle from 20° to 52°. Bastien et al. (1986) have also discussed the cases of other comets where sometimes the opposite trend has been noticed. Kikuchi et al. (1987) have changed the aperture from 13″ to 32″.6, for comet P/Halley and found no systematic dependence of polarization on the aperture size.

In Table 2 we have listed all the observations taken through the IHW continuum filters and in Fig. 2 we have plotted them. The observations taken on 18 and 19 March correspond to the largest phase angle for which ground based observations were possible on comet P/Halley. As seen from Fig. 2, the post perihelion polarization values increase with the wavelength, whereas for the pre perihelion observations no such trend is seen within the errors. In our case the post perihelion observations correspond to a phase angle ~66°, whereas pre perihelion observations were made at a phase angle of ~45°. As has been reported by other authors (Kikuchi et al. 1987; for a more general review see Dollfus et al. 1988) comet P/Halley's polarization showed a clear increase with the wavelength for higher phase angle values, but no such dependence was seen for smaller phase angles. Brooke et al. (1987) confirmed this trend from their IR polarimetric observations also.

The polarization observed in our case is always positive. In other words the direction of electric vector was always perpendicular to the scattering plane. Bastien et al. (1986) have found that the polarization becomes negative (electric vector becomes parallel to the scattering plane) when the phase-angle is ≤22°. As can be seen from Table 2 our IHW post perihelion observations correspond to a phase when the sun-comet-earth angle increased to a maximum of 66°.1 and remained there for next few days. In fact the phase angle on 17 March was 65°.9 which is also very close to the maximum phase angle value.

The linear polarization measurements of this comet have been made by several other authors during the recent apparition (Bastien et al. 1986; Kikuchi et al. 1987; Le Borgne et al. 1987b; Dollfus et al. 1987 etc.). We have plotted the linear polarization values as observed by them along with our observed polarization values at the three continuum filters centered at 0.365, 0.484 and 0.684 μm, in Figs. 3, 4 and 5 respectively. As a result we have

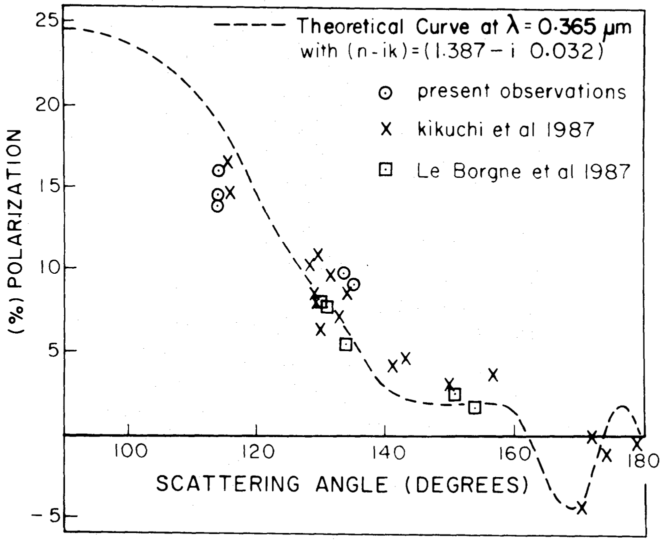

Fig. 3. Polarization values as observed at wavelength $\lambda = 0.365$ μm by different investigators are plotted along with the different scattering angles (= 180° − phase angle). The dashed curve has been fitted by the method of least square to the observed polarization data for complex value of refractive index (1.387 − i0.032)

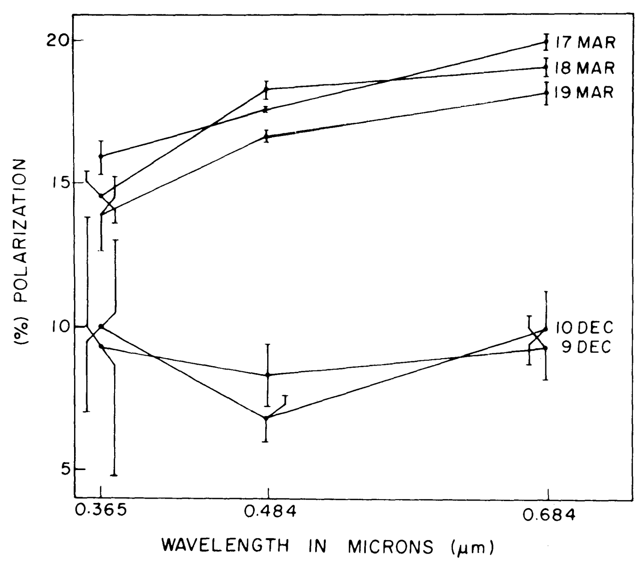

Fig. 2. Wavelength dependence of polarization observed through three different IHW continuum filters during December 1985 and March 1986

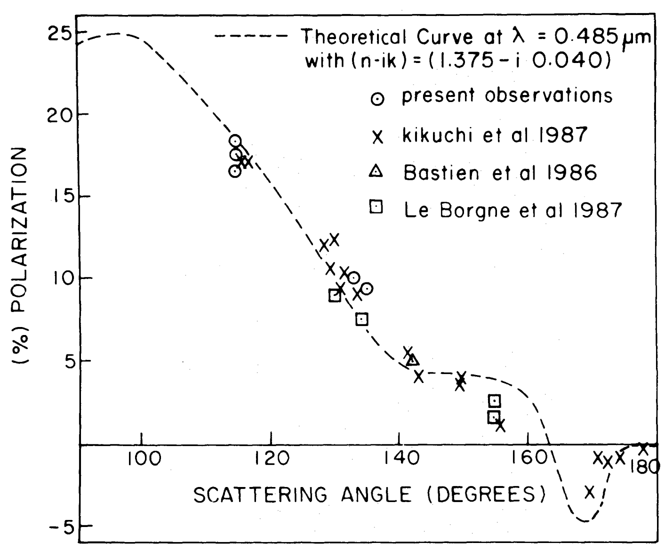

Fig. 4. Polarization values as observed at wavelength $\lambda = 0.484$ μm by different investigators are plotted along with the different scattering angles (= 180° − phase angle). The dashed curve has been fitted by the method of least square to the observed polarization data for complex value of refractive index (1.375 − i0.040)

observations from various sources covering a wide range of scattering angle almost from 110° to 180°. The features observed from Figs. 3, 4 and 5 are: (1) except at low phase angle (180° − scattering angle) the polarization is always positive. The cross over from positive to negative polarization occurs at the scattering angle of 160° ± 10°. (2) the polarization seems to increase with wavelength when the phase angle is high.

4. Cometary grain properties

In the following we make an attempt to find the size distribution and complex values of refractive indices of the grains, which will fit to these observed values of polarization at different wavelengths. The dust mass detectors on board Vega and Giotto spacecrafts, have already found out the dust mass distribution functions (Mazets et al. 1987; McDonnel et al. 1986) of comet P/Halley. Assuming that the grains are spherical in size and the density of the grain particle $\sim 1\ \mathrm{g\,cm^{-3}}$, the following dust size distribution functions are those obtained by Mukai et al. (1987) from the in situ measurements (Mazets et al. 1987)

$n(s) \sim \bar{s}^{2}$ where $s < 0.62\ \mu$m

$n(s) \sim \bar{s}^{2.75}$ where $0.62 < s < 6.2\ \mu$m

$n(s) \sim \bar{s}^{3.4}$ where $6.2 < s\ \mu$m

where s is the radius of the grain in micron and $n(s)$ is the number of grains having radius s. Krishna Swamy & Shah (1988) have discussed about the particle size limit for the reddening and polarization calculations. From Krishna Swamy & Shah (1988) we have adopted the lower limit of particle size to be 0.001 μm, for carrying out the Mie scattering calculations. Also from the same work, we have chosen the upper limit in the grain size to be 20.0 μm, as grains bigger than this do not contribute effectively to the observed polarization. Having the grain size distribution fixed, we explored a wide range of $(n - ik)$ values to calculate the expected values of polarization using Mie scattering formulations. For the phase angle values at which polarizations have been already observed, we have calculated the expected values of polarization and then calculated the sum of square of the difference between the observed and expected polarization values. Now by varying the values of $(n - ik)$, we found out the best fit value of $(n - ik)$ for which the above sum becomes minimum. We introduce a quantity σ^2 which is equal to the above sum divided by the number of data points. Thus at $\sigma_{\min}$ we get the best fit value of (n, k). The value of σ (which is in unit of percent polarization) gives the confidence level on our best fit value of (n, k). While doing these calculations we included the observed polarization values reported by several authors (Bastien et al. 1986; Dollfus et al. 1987; Kikuchi et al. 1987; Le Borgne et al. 1987b) as can be seen from Figs. 3, 4 and 5. These polarization values have been observed through different apertures and therefore a normalization of these values may be necessary. But as discussed earlier, since no definite trend of the aperture dependence of polarization has been established, we have not made any attempt to normalize these values. Another point to be noted here is that for $\lambda = 0.684\ \mu$m there are no polarization values available in the literature for this comet at a scattering angle > 160°. However, Kikuchi et al. (1987) have reported negative polarization measurements of this comet at $\lambda = 0.67\ \mu$m at phase angles > 160°. Therefore while making the least square fit we have made use of the negative polarization values of the comet observed at $\lambda = 0.67\ \mu$m reported by Kikuchi et al. (1987). The positive polarization values observed by Kikuchi et al. (1987) at $\lambda = 0.67\ \mu$m are also plotted in Fig. 5 along with all the other polarization values observed at 0.684 μm, but have not been included in the calculation for $(n - ik)$ at 0.684 μm.

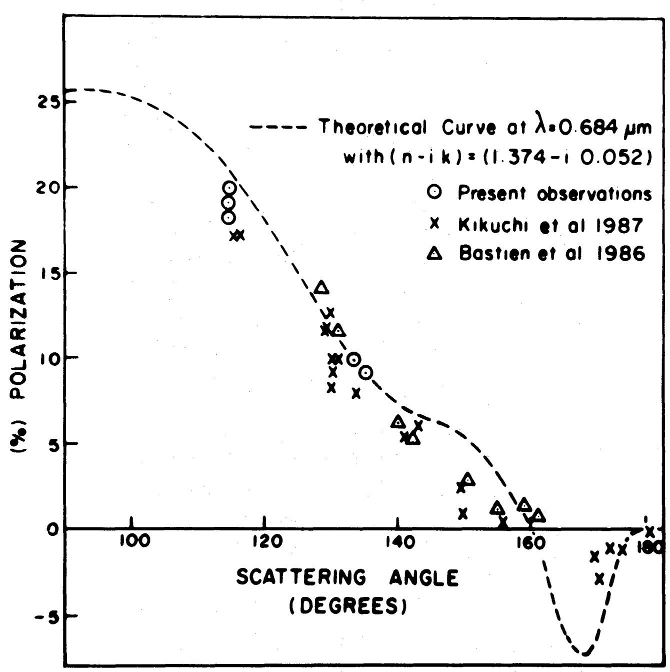

Fig. 5. Polarization values as observed at wavelength $\lambda = 0.684\ \mu$m by different investigators are plotted along with the different scattering angles (= 180° − phase angle). The dashed curve has been fitted by the method of least square to the observed polarization data for complex value of refractive index (1.374 − i0.052). The observations taken by Kikuchi et al. (1987) actually correspond to the wavelength value $\lambda = 0.67\ \mu$m (please see text)

The important findings are the following set of complex values of refractive indices $(n - ik)$ at the three discrete wavelengths which fit to the observed polarization data.

$(n - ik)$ is (1.387 − i0.032) at 0.365 μm with $\sigma = 2.9$

(1.375 − i0.040) at 0.484 μm with $\sigma = 1.6$

(1.374 − i0.052) at 0.684 μm with $\sigma = 2.4$.

In Fig. 6, we have plotted the above n and k values with the wavelength. All the k values can be fitted into a straight line '$k = 0.062\ \lambda + 0.009$' by the method of least square (vide Fig. 6). The dependence of n on the wavelength seems to be nonlinear. Apart from the IHW filter polarimetry, we also have the polarimetric information on this comet at the continuum wavelength 0.342, 0.442, 0.526 and 0.641 μm as listed in Table 1. Since these observations do not have good phase angle coverage, we do the following exercise to look into the nature of $n - \lambda$ dependence more closely, which is otherwise not possible only from the three data points, defined by the IHW filters.

From the $k - \lambda$ straight line, we interpolate the k values at the wavelengths 0.342, 0.442, 0.526 and 0.641 μm and list them in Table 3. Keeping these k values fixed, we try to find out the n values which can generate the polarization values as close as possible to the observed polarization values. These n values are

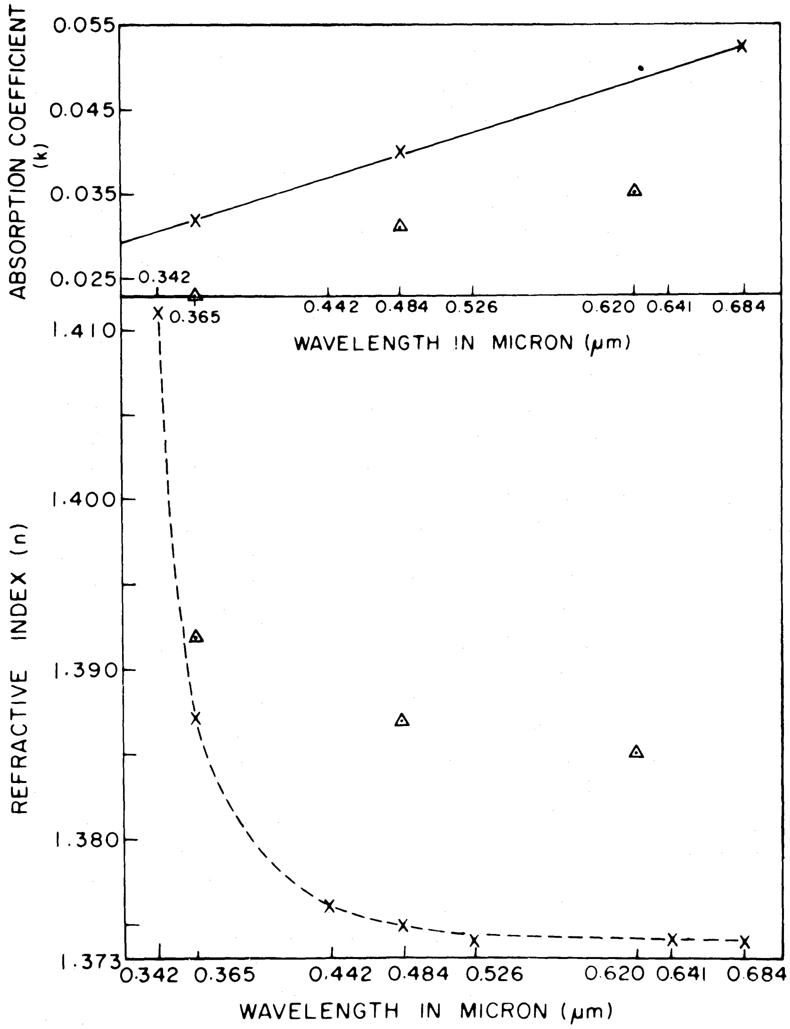

Fig. 6. Different n and k values (marked by X) as obtained from the least square fit are plotted across different wavelengths. The k values have been joined by a solid line of best fit, where the n values have been joined by a dashed curve by free hand. The similar values obtained by Mukai et al. (1987) are shown along with (marked by Δ)

also tabulated in Table 3. As a result we get more data points along the $n-\lambda$ curve, which now help us to see the $n-\lambda$ dependence in more detail. We have plotted the new set of n values in Fig. 6 and the different points are joined by a dashed curve. Finally in Table 3 we put the actual observed polarization values, along with the polarization values calculated by using these set of $(n-ik)$ values. The observed values of polarization seem to match very well with the theoretically calculated values for most of the cases as is clear from Table 3.

Mukai et al. (1987) have also found out the λ-dependence of the two parameters n and k. For a comparison we have also plotted their n and k values (marked by Δ) in Fig. 6. At a particular wavelength their n value seems to be higher than our n value and k value seems to be lower than our k value. Apparently there seem to be no reasons for the difference between our set and their set of $(n-ik)$ values. However, from the work by Mukai et al. (1987) it was not clear what were the upper and lower size limit of grain distributions they have used for the calculation of $(n-ik)$. If the size limits are different it may give rise to different $(n-ik)$ values for the two cases. As an example in Table 4, we have compared the polarization values at different scattering angles, with two different particle size ranges 0.001–20.0 and 0.01–20.0 μm. Moreover in order to fit the observed polarization data to the theoretical profile, we have used the method of least square. The influence of this method would be a finer selection of the best fit values of (n, k) for the observed polarization data. It is not clear from Mukai et al. (1987), whether they have also followed a similar approach to the problem, otherwise the discrepancy between the two sets of (n, k) values as discussed above may be resulted. It should be also noted that Mukai et al. (1987) have fitted the theoretical polarization curve on the polarization values which they have observed. But in the present case we have tried to include all the polarization values available in the literature till now, in order to find the best fit values of (n, k). As a result with more number of data points, we expect to get more accurate values of (n, k) which can fit to the observed data.

Already several attempts have been made by different authors to explain the polarization behaviors of comet P/Halley with the help of Mie scattering formulations (Kikuchi et al. 1987; Brooke et al. 1987). Brooke et al. (1987) have found that a two-component grain model explains better the IR polarization data. We have tried to extrapolate the (n, k) values towards the IR wavelength side (using Fig. 6 of the present work) and found that, in a single component grain model, the extrapolated (n, k) values fail to explain the IR polarization data reported by Brooke et al. (1987). (For the polarization calculations in the near-IR region, we have

Table 3. Percent polarizations observed through the non-IHW filters are compared here with the expected polarization values calculated, using n and k values estimated as discussed in the text

Phase Angle (°)	Wavelength (μm)	Observed Polarization (%)	Estimated values of (see text)		Expected polarization (%)
			n	k	
64.3	0.342	16.8±1.0	1.311	0.031	16.8
	0.442	18.7±0.2	1.376	0.037	18.2
	0.526	19.5±0.2	1.374	0.042	18.8
	0.641	20.6±0.2	1.374	0.049	19.1
64.8	0.526	18.6±0.4	1.374	0.042	19.0
		18.4±0.4			19.0
	0.641	19.0±0.5	1.374	0.049	19.3

Table 4. Percent polarization as expected at different scattering angles (in degrees) with particle size range 0.001–20.0 and 0.01–20.0 μm respectively ((n, k)=(1.397, 0.032), λ=0.365 μm)

	Particle size range 0.001–20.0 μm								
Scattering angle	100	110	120	130	140	150	160	170	180
Polarization	23.7	21.0	14.7	8.4	2.8	1.8	1.5	−4.4	0.0
	Particle size range 0.01–20.0 μm								
Scattering angle	100	110	120	130	140	150	160	170	180
Polarization	15.3	10.1	6.4	4.0	2.4	1.4	0.8	0.5	0.4

taken the upper limit in grain size spectrum as 140.0 μm, as has been used by Brooke et al. 1987.) While doing these calculations one should also keep in mind that the dust properties of comet may change with heliocentric distance and also they may be different for different parts of the comet, as can be seen from the works of Eaton et al. (1988) and Sen et al. (1990).

The present work demonstrated that the dust distribution obtained by Mazets et al. (1987) explains the observed degree of polarization of comet P/Halley at different phase angles for particular kind of grains whose properties have been discussed above.

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