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A polarization study of comet Hyakutake (C/1996 B2)

U.C. Joshi, K.S. Baliyan, S. Ganesh, A. Chitre, H.O. Vats, and M.R. Deshpande

Physical Research Laboratory, Ahmedabad 380 009, India

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Abstract. Observations for the linear polarization of comet Hyakutake (C/1996 B2) are carried out at three continuum wavebands: 3650Å, 4845Å and 6840Å. These observations were taken on March 13 and March 18, 1996 when the phase angles were 38.1 and 36.9^o, respectively. These results indicate an increase in the degree of polarization with phase angle and wavelength, in general. Present results show that comet Hyakutake (C/1996 B2) exhibits similar behaviour as comet P/Halley so far as the polarization property is concerned, indicating thereby that the grain size distribution may not be very much different from that of the comet Halley. We also produce theoretical curve for the polarization percentage as a function of phase angle and compare with the observed data. The polarization at various wavebands shows a sensitive behaviour in the phase angle range $20 \leq \alpha \geq 40\ ^o$.

Key words: polarization – comets: P/Halley; Hyakutake 1996 B2

1. Introduction

Comets are generally known to have high degree of polarization caused by the scattering of sunlight by cometary dust particles and fluorescence emission by cometary molecules. Comet polarimetry in the continuum is a sensible technique to investigate the properties of cometary dust (Ohman 1941; Blackwell & Willstrop 1957; Bappu et al. 1987; Sen et al. 1991a,b). The observed polarization in general is a function of (i) cometary phase angle (ii) shape and size of cometary particles (iii) refractive indices of the particles and (iv) the incident wavelength. High precision photopolarimetric observations in continuum wavebands and molecular bands are required to compare with the critically predicted values. Polarization observations on comet P/Halley, covering a large range of phase angle, were taken at different wave bands by various groups (Bastien et al. 1986; Dollfus & Suchail 1987; Kikuchi et al. 1987; Le Borgne et al. 1987; Sen et al. 1988, 1989). This database proved very useful to understand the characteristics of the dust grains in the comet Halley (Sen et al. 1991b; Mukai et al. 1987; Dollfus et al. 1988). Comet Austin provided another opportunity to study the polarization behaviour of continuum and molecular bands (Joshi et al. 1992; Sen et al. 1991a). From dynamical viewpoint, comet Austin was a new comet (Sekanina 1990) whereas comet P/Halley was an old one. A Comparison of polarimetric data on comet P/Halley and comet Austin with the help of Mie theory indicated that the polarization in the two comets was caused by scattering due to different type of grains: comet Austin was found to contain relatively finer grains compared to comet P/Halley (Sen et al. 1991a).

Recently a spectacular comet Hyakutake (C/1996 B2) appeared in the sky (Nakamura et al. 1996) which was bright enough to make high precision polarimetric observations during pre-perihelion phase. This comet is a new comet in the dynamical sense and gives us an opportunity to investigate the properties of its grains and to compare them with earlier results on comet P/Halley and comet Austin. Here we report the results on comet Hyakutake (C/1996 B2) based on the polarization observations obtained through continuum bands at 0.365 μm, 0.485 μm and 0.684 μm wavelengths.

2. Observations and analysis

The observations were made on March 13 and 18, 1996 with the PRL photopolarimeter attached at the Cassegrain plane of the 1.2 meter telescope at Gurushikhar (longitude $72^o46'47.5''E$; latitude $24^o39'8.84''N$; and altitude 1680 meters) near Mount Abu and operated by Physical Research Laboratory, Ahmedabad. The photopolarimeter is discussed elsewhere in detail (Deshpande et al. 1985). The polarimeter works on a rapid modulation principle- rapidly rotating superachromatic Pancharatnam half wave plate followed by a Wollaston prism acts as modulator. The data are processed on-line on a personal computer which also controls the polarimeter. The polarimeter was fitted with the IHW (International Halley Watch) filter system containing three continuum bands at 3650/80, 4845/65, 6840/90 and five emission bands at CN(38711/50), C_3 (4060/70); CO^+ (4260/65), C_2(5140/90) and H_2O^+(7000/175), all figures given in angstrom, Central wavelength/ band pass. An entrance aperture of $26.5''$ diameter was employed for observing the nuclear region of the comet.

On both nights, polarization standard stars of known polarization and zero polarization stars were observed to calibrate the

Table 1. Percentage polarization (%P), error in polarization (E_p), position angle and error in position angle (E_θ) as observed on two different dates in March 1996.

UT decimal date		Δ (AU)	r(AU)	phase	wavelength	%P	E_p	θ (deg)	E_θ
March	13.97	0.39	1.27	38.1	0.3650	6.38	0.50	16	2
					0.4845	5.77	0.26	11	1
					0.6840	6.32	0.29	14	1
March	18.88	0.23	1.17	36.9	0.3650	4.98	0.31	4	1
					0.4845	5.30	0.17	8	1
					0.6840	6.00	0.24	7	1

polarization angle and to estimate the instrumental polarization. For this purpose, we observed 9 Gem and O Sco as polarization standards and a couple of zero polarization stars from the list given by Serkowski (1962) to estimate the instrumental polarization. In all the filters instrumental polarization was found to be negligible (less than 0.03 %) compared to the error estimate in %P which essentially is due to photon noise. Therefore no attempt was made to correct it. The observed errors are listed in Table 1 along with the other data. In addition to the observations of standard stars and zero polarization stars, the overall performance of the polarimeter was regularly checked by measuring 100% polarized light, produced by inserting a Glan prism in the of light beam from a zero polarization star. The efficiency of the polarimeter was estimated to be $\approx$ 97% and the observed data is corrected to this efficiency.

The detailed procedure of the analysis is discussed elsewhere (Deshpande et al., 1985; Joshi et al. 1987). The error (in terms of standard deviation) in polarization is estimated using a least squares fit of theoretical modulation curve to the observed data. The error in position angle is estimated by the relation (Serkowski, 1962)

$$E_\theta = 28.65 E_p/P; \qquad (for \;\; E_p << P). \tag{1}$$

The observed degree of polarization (P), error in polarization (E_p), position angle (θ) and error in the position angle (E_θ) in the continuum filters on two different dates are listed in Table 1.

3. Results and discussions

The observed values of the percent polarization (%P) and position angle (θ) alongwith the errors are listed in Table 1 and are also plotted in Fig. 1. The polarimetric data in continuum bands are already published in IAU Circular 6371 (Ganesh et al. 1996). Table 1 also lists the Geocentric distance (Δ), heliocentric distance (r), and the phase angle (α) at the time of observations. These values are taken from comet Ephemeris based on orbital element given in IAU Circular 6329. As stated earlier, the observations have been made using an aperture of diameter of 26.5 $arcsec$, which corresponds to a linear scale of $\approx$ 7330 km and $\approx$ 4330 km respectively on March 13.97 and March 18.88.

Within the error of observations, the angle of polarization is found independent of wavelength and also perpendicular to the scattering plane. In other words, it is positive. The position angle in U-band (0.365μm) shows some deviation which, within the error of observations, appears to be insignificant. However, the possibility of small deviation of the position angle from the normal to scattering plane cannot be ruled out, especially for short wavelengths, since for certain particles the polarization may be negative (i.e. parallel to the scattering plane) for the small phase angles (Krishnaswamy 1978; Weinberg & Beeson 1976). In such situation the polarization vector may not be exactly perpendicular to the scattering plane. For the present purpose we consider the position angle, for all the three bands, to be normal to the scattering plane.

On March 13.97 (phase angle 38.1 degrees) the degree of polarization showed marginal decrease at wavelength 0.4845 μm compared to the value at 0.3650 μm and 0.6840μm. On the other hand, on March 18.88 (phase angle 36.9) there is a marginal increase in wavelength dependence of polarization from 0.3650μm to 0.6840μm.

Though the Sun-Comet-Earth phase angle has changed only by -1.2^o from March 13.97 to March 18.88 there is a noticeable change in the wave length dependence of polarization on these dates as is clear from Fig. 1. It appears that the wavelength dependence of polarization is very sensitive to change in the phase near 38^o. This point is further discussed in Sect. 4. Kikuchi et al.(1987) have made polarization observations on comet P/Halley using the similar IHW continuum filters covering a wide phase angle range. It is just a coincidence that two sets of observations from Kikuchi et al. (1987) on comet P/Halley are phase wise very close to the present observations on comet Hyakutake. Their polarimetric data at wavelengths 0.365 and 0.485 μm are available at phase angles 36.7 and 38.5 degrees which are very close to our observations on comet Hyakutake at the phase angles of 36.9 and 38.1 degrees. They also report observations at 0.670μm which is slightly different than the waveband used by us i.e. 0.684 μm. As the change in the degree of polarization with wavelength in this phase angle region is not much, the two data sets can be used for comparison. Comet P/Halley data (Kikuchi et al. 1987) is also plotted in Fig. 1 for comparison.

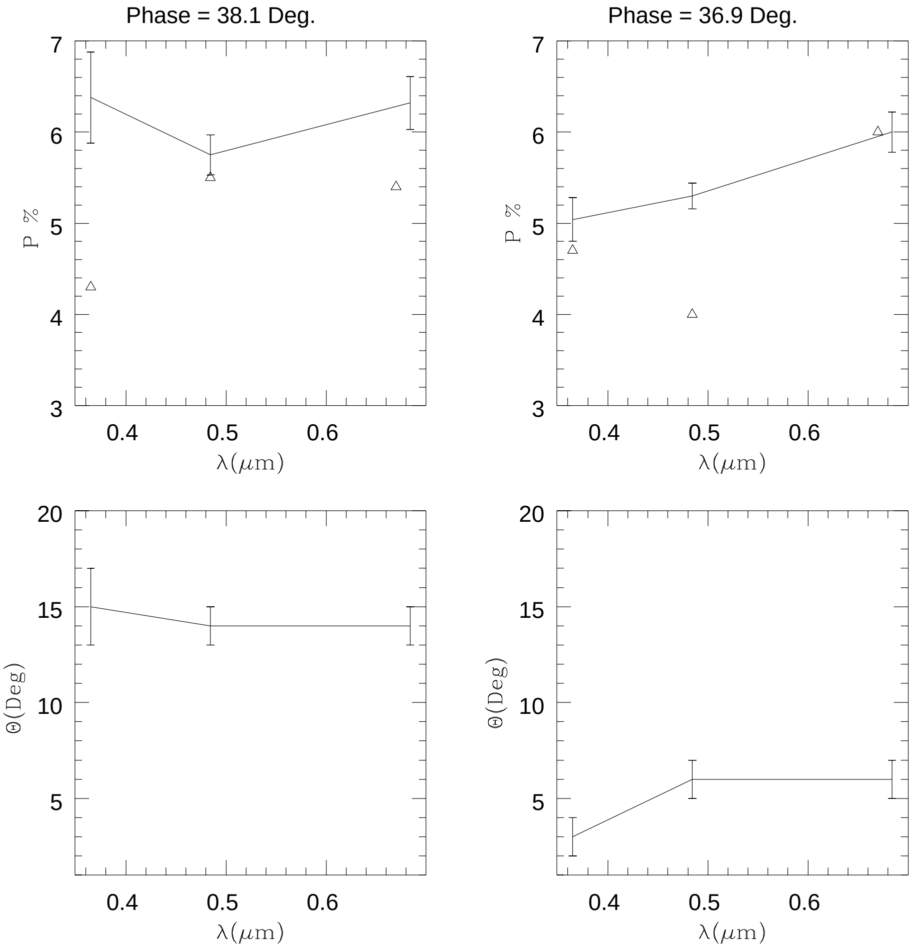

Fig. 1. Wavelength dependence of observed degree of percent polarization (% P) and position angle (θ) for comet Hyakutake. Present observations are connected with solid line. The symbols Δ represent Kikuchi et al. (1987) data for comet P/Halley.

The wavelength dependence of polarization for the two comets appears quite similar for the above phase angles. In principle this is expected if the comets have the same origin and the dust particles responsible for producing polarized light are similar in nature. In fact the polarization data at phase angle 36.7 and 38.5 for comet P/Halley compare better with the data at phase angle at 38.1 and 36.9 degrees respectively for comet Hyakutake. The small difference in the wavelength dependence of % P in case of the two comets at nearly the same phase angle may be due to various reasons. Firstly, the aperture sizes used in the observations, which correspond to the different linear scales on the comets, are different in the present observations from those used by Kikuchi et al. (1987) for comet P/Halley. Small but systematic differences are noticed in the polarization values for the same phase angle when observed through different aperture sizes which map different linear scales at the comet location (Bastein et al. 1986). Secondly, comets are active objects in the sense that ejection of dust and gas is a continuous process and some strong ejection episodes may change the environment considerably but temporarily. Strong ejections, not uncommon in comets, may change the dust size distribution which in turn changes the polarization behaviour. Also, the possibility of radial dependence of the dust size distribution can not be ruled out.

Within these limitations, the observed wavelength dependence of polarization for comets P/Halley and Hyakutake appears similar which can be taken to be indicative of the similar nature of the grains in the two comets. In the following section we have attempted to compare the observed polarization behaviour with the theoretically calculated ones as well as with the data on other comets, especially the comet P/Halley.

4. Model calculations

As discussed in Sect. 3, the wavelength dependence of polarization for comets P/Halley and Hyakutake (C/1996 B2) is almost same which indicates that the dust grains responsible for producing polarized light in Hyakutake are quite similar in size distribution and composition refractive indices to comet P/Halley.

It is well known that the Sun light gets scattered by cometary dust and this process is responsible for producing polarized continuum spectrum in comets. In principle, it is possible to calculate the continuum spectrum and degree of polarization in the scattered light. However, there is no viable theory which takes into account the actual nature of dust grains. We have attempted to theoretically calculate the polarization values at different continuum wavelengths using the simple Mie scattering theory.

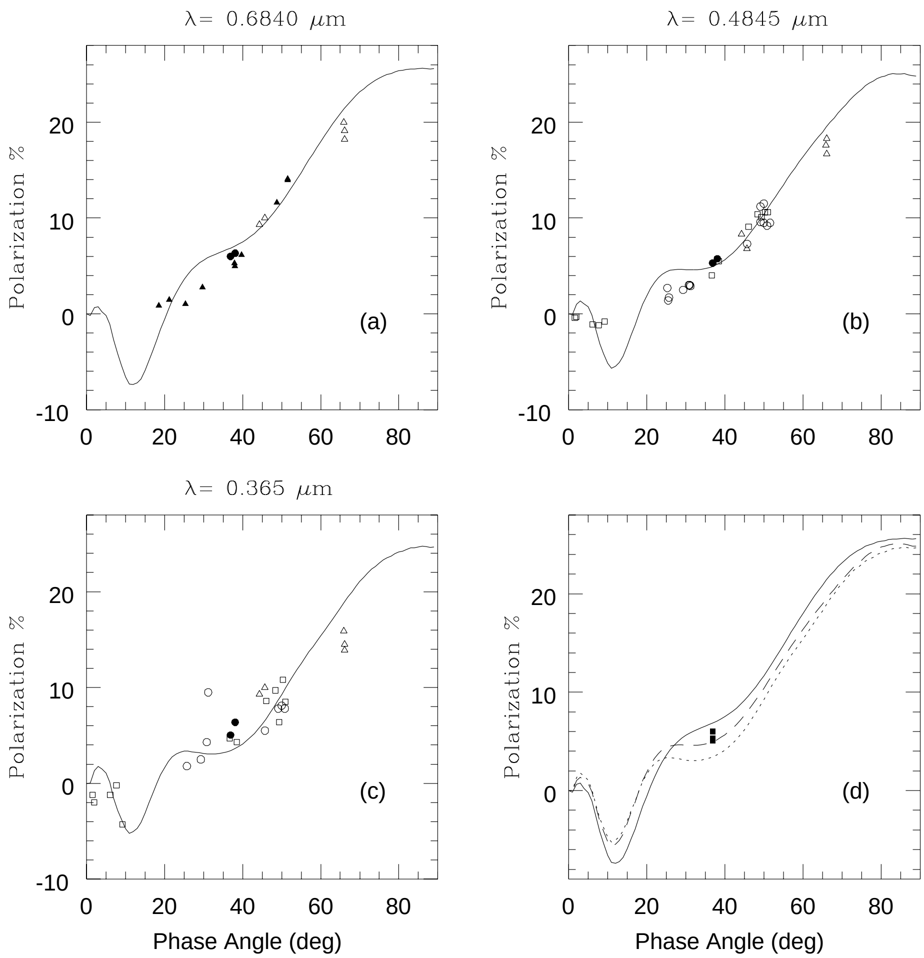

Fig. 2. Polarization percentage of comet Hyakutake plotted as a function of phase angle. Filled circles represent observations on comet Hyakutake. The comet P/Halley data are: Δ - Sen et al. (1991b) ; □ - Kikuchi et al. (1987) ; Filled triangles - Bastien et al. (1986) ; $\odot$ - Le Borgne et al. (1987). For **a–c**, the solid line represents theoretical results for respective wavelengths and for **d** the theoretical curves at wavelengths 0.6840μm, 0.4845μm, and 0.3650μm are shown by solid line, dotted line and dashed line, respectively. Also plotted in **d** are Hyakutake observations at phase angle 38.1^o(filled squares).

The validity of the Mie theory to explain the polarimetric behaviour has been questioned by some workers (Dollfus & Shuchail 1987) in recent years. Cometary grains are likely to be porous and irregularly shaped, therefore the Mie theory is not very suitable for them. However, Hage & Greenberg(1990) have suggested that the scattering properties (viz. Qext) of irregularly porous grains with refractive index m are very close to those of Mie particles if the refractive index in the latter case is replaced by an effective refractive index m', a function of m and porosity. Assuming the same thing to be true for polarization, the application of Mie theory to theoretically calculate the polarization values appears to be quite reasonable, if one remembers that the refractive indices which we are dealing with are effective refractive indices and not the actual ones. Also, in the absence of any other viable theory, use of simple Mie theory can be justified.

As Comet Hyakutake appears similar to Comet P/Halley, we adopt the same size distribution of grains as obtained by Mukai et al. (1987) from in-situ measurements (Mazets et al. 1987) for Comet P/Halley. The size distribution is given as,

$n(a) \ \approx a^{-2} \ \ for \ \ \ a < 0.62\mu$m
$n(a) \ \approx a^{-11/4} \ \ for \ \ \ 0.62 < a < 6.2\mu m$
$n(a) \ \approx a^{-19/5} \ \ for \ \ \ a > 6.2\mu m.$

where a is the size of the grain in micron and $n(a)$ is the number of grains having radius a. Sen et al. (1991b) have determined the values of refractive indices for comet P/Halley which is based on the polarimetric observations covering a wide phase angle range. The observed polarization values were fitted to the calculated values by using least square method. The final $(n, \ \ k)$ values were taken from the best fit situation. Since a large phase angle coverage was taken into consideration for the fitting process, the refractive index values $(n, \ \ k)$ determined by Sen et al. (1991b) for comet P/Halley are expected to be very close to the realistic ones. The composition of the grains in terms of complex refractive index $(n - ik)$ in the present case is assumed to be the same as estimated for comet P/Halley by Sen et al. (1991b).

The polarization values based on the Mie theory are plotted in Fig. 2a-c for the three continuum bands as a function of phase angle. For comparison, the present observations on comet Hyakutake are also shown along with the observed polarization values for comet P/Halley obtained by various workers (cf. caption of Fig. 2).

Let us now discuss Fig. 2 in some detail. The calculated polarization percentage is plotted as a function of phase angle (α) at three continuum wavebands; (a) 6840 Å, (b) 4845 Å and (c) 3650 Å. The present polarization observations for comet

Table 2. Polarization values (in percent) for different wavelengths based on model calculation. The grain sizes vary from 0.005 to 10 μm.

Phase angle	Wavelength(μm)		
	0.3650	0.4845	0.6840
38.1	7.05	5.16	3.64
36.9	6.87	4.96	3.42

Hyakutake are plotted at respective wavebands. To facilitate a comparison, comet P/Halley observations of Kikuchi et al. (1987), Bastien et al. (1986), Le Borgne et al. (1987) and Sen et al. (1991) are also shown, wherever available. As is evident from the figure, behaviour of the Mie scattering based theoretical curve matches quite satisfactorily with the comet observations at all the three wavebands considered here. It also makes it clear that comet Halley and comet Hyakutake are of same type as discussed above.

In Fig. 2d we have plotted theoretical curve for all three wavebands to compare the phase variation of percent polarization at different wavelengths. From the Fig. 2d, we see that there is some discrepancy between the wavelength dependences of the observed polarization values and the theoretically calculated ones. Our calculation shows that the wavelength dependence at the phase angle near 40^o is very sensitive to the parameters input to the model. The small change in the $(n, \ k)$ values or the particle size distribution makes significant changes in the wavelength dependence. The polarization values on the two phase angles calculated using Mie theory are given in Table 2. The various reasons which affect the degree of polarization at different wavelengths have already been discussed earlier in Sect. 3.

As the grains in the two comets are found to be similar in nature, it is quite likely that there origin is also same. Earlier studies indicate that the new comets may be different in grain characteristics than a dynamically older comet. Comet Austin, a dynamically new comet, was found to be richer in fine grains compared to comet P/Halley, which is an older comet (Sen et al. 1991a). This does not appear to be the case from the present study since comet Hyakutake is a new comet but possesses grain characteristics similar to comet P/Halley. This means that comet Austin is different, as far as grain characteristics are concerned, from comet P/Halley and comet Hyakutake. Some earlier studies have suggested interstellar origin for at least a small number of comets. The different origin of comet Austin than that of comet P/Halley and comet Hyakutake (C/1996 B2) can not be ruled out.

5. Conclusions

We have reported new photopolarimetric observations on comet Hyakutake taken in three continuum wavebands. These are compared with the polarization data from various groups on comet P/Halley to find any resemblance between comet Halley and comet Hyakutake. It is noticed that both the comets show almost similar wavelength and phase dependence of polarization percentage. However, to make any definitive statement, more data on comet Hyakutake covering large phase angle range are required. The present observations for the polarization at three continuum wavebands and two phase angles are also compared with a theoretical model calculation which is based on the Mie scattering. Different grain size distributions and refractive indices are used at different wavebands. The observations exhibit reasonable agreement with the theoretical results. The same is true with the data on comet Halley. From the present study we would like to infer that comet Hyakutake is of similar type as comet Halley and must have dust grain size distribution and refractive indices as those for comet P/Halley.

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