Optical polarimetry of
Comet NEAT C/2001 Q4

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Abstract

Comet NEAT C/2001 Q4 was observed for linear polarization using the optical polarimeter mounted at the 1.2m telescope at Mt. Abu Observatory, during the months of May and June 2004. Observations were conducted through the International Halley Watch narrow band (continuum) and B, V, R broad band filters. During the observing run the phase angle ranged from 85.6° in May to 55° in June. As expected, polarization increases with wavelength in this phase angle range. Polarization colour in the narrow bands changes at different epochs, perhaps related to cometary activity or molecular emission contamination. The polarization was also measured in the cometary coma at different locations along a line, in the direction of the tail. As expected, we notice minor decrease in the polarization as photocenter (nucleus) is traversed while brightness decreases sharply away from it. Based on these polarization observations we infer that the comet NEAT C/2001 Q4 has high polarization and a typical grain composition- mixture of silicates and organics.

Key words: Comets, polarimetry, dust scattering, comets - individual, Comet NEAT C/2001 Q4

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1 Introduction

Comets are considered to be primordial, icy bodies which are expected to retain imprints of physical conditions prevailing in the proto-solar system. Therefore, study of comets has proved very useful in our understanding of the origin of the solar system. Sun light is scattered by the cometary grains and in this process it gets polarized. The degree of polarization (P %) mainly depends on: the size distribution of the grains and their refractive index \((n - ik)\); wavelength of the light and the phase angle (sun-comet-earth angle, \(\alpha\)). Linear polarization measurements have been made on many comets to help understand their grain properties. The first major efforts for detailed polarization observations were made for Comet P/Halley by many groups (Bastien et al., 1986; Brooke et al., 1987; Dollfus and Suchail, 1987; Kikuchi et al., 1987; Lamv et al., 1987; Le Borgne et al., 1987; Metz and Haefner, 1987; Sen et al., 1988). There were other bright comets after P/Halley such as Comet C/1989 X1 (Austin), C/1996 B2 (Hyakutake), and C/1995 O1 (Hale-Bopp) for which polarization observations were reported (e.g., Sen et al. (1991); Joshi et al. (1997); Ganesh et al. (1998); Manset and Bastien (2000); Hadamcik and Levasseur-Regourd (2003)). A database of comet polarimetry has been created by Kiselev et al. (2005) which also includes some unpublished data.

The study of the dust grains in comets has been an active area of investigation for quite some time but the nature and composition of the cometary grains are still not well understood. A study of the variation of polarization with phase angle (\(\alpha\)) and the wavelength dependence of polarization helps to characterize the dust grains. Based on the data obtained by various researchers, Dollfus et al. (1988) established a typical polarization-phase curve describing the variation of the degree of linear polarization with the phase angle : small negative values of polarization for phase angle \(\alpha < 22^\circ\), increasing nearly linearly in the range \(30 < \alpha < 70^\circ\) and reaching a maximum value of 15-35 % in the phase angle range 90-110\(^\circ\). Dollfus (1989) pointed out the possibility of the grains giving rise to the polarization being large, rough and dark, resembling fluffy aggregates such as IDPs. In-situ measurements (Kissel et al., 1986; Mazets et al., 1986; Levasseur-Regourd et al., 1986, 1999) by space missions to Comet Halley and corresponding numerical simulations by Fulle et al. (2000) contributed important information on the nature of grains in that comet. Return of the dust particles by the Stardust Space Mission (Brownlee et al., 2006), has been a wonderful achievement in the study of cometary material. The preliminary studies suggest that most of the particles larger than a micron are anhydrous (dry) silicates or sulfides. They include forsterite \((\text{Mg}_2\text{SiO}_4)\), an olivine end-member that is one of the first condensates from the solar nebula. Apart from their amorphous nature, some such silicate minerals are crystalline solids as also inferred from IR studies in comet
Hale-Bopp ([Wooden et al., 1999] and Deep Impact mission comet 9P/Tempel 1 ([Lisse et al., 2006]). The range of iron/magnesium ratios exhibited by the particles indicates that comet Wild 2 is unequilibrated. The comet contains an abundance of silicate grains that are much larger than the predictions of interstellar grain models, and many of these are high-temperature minerals that appear to have formed in the inner regions of the solar nebula. Their presence in a comet proves that the formation of the solar system included mixing on the grandest scales ([Brownlee et al., 2006]). It is remarkable that so many of the impacting comet particles contained at least a few relatively large solid grains, an order of magnitude larger than the size of typical interstellar grains ([Mathis et al., 1977]). In addition to silicates and abundant sulfides, the collected comet samples contain organic materials ([Sandford et al., 2006]). The mixing of material from inner and outer solar nebula as indicated by the Wild 2 coma samples returned by Stardust and the great heterogeneity in comet nucleus make up shown by the gas and dust coming out of the Deep Impact comet 9P/Tempel 1 ([Schmitz and Brenker, 2008; A’Hearn, 2006; Harker et al., 2005]), make it more challenging to pin down the region of the formation of comets. It also underlines the need for more studies in this direction.

Space experiments are very expensive and demand long lead time. Therefore, data collected using ground based facilities play a significant role in this study. Ground based observations have indicated the detailed behavior of grains to change from one comet to another. This fact is corroborated by the Deep Impact, Stardust and comet Halley space missions also. At a basic level, the size distribution of impacted Wild 2 grains is different from the ejecta of the Tempel 1 ([Lisse et al., 2006]) and even that seen in the comet Halley. For example, as per Deep Impact results, Comet 9P/Tempel contains MgFe sulfides and carbonates, at odds with Stardust samples. These sulfides are also absent in IDPs. So, either the comet compositions are different or sampling regions are different. Another possibility could be improper laboratory constituents used to model Deep Impact spectra ([Brownlee et al., 2006]). Until more in situ measurements are carried out on many other comets, the information about dust grains in the comets has to come largely from ground based observations in conjunction with theoretical models/simulations ([Swamy, 1986; Xing and Hanner, 1997; Jockers et al., 1997; Petrova et al., 2001a,b]).

On the basis of the polarization behavior of 13 comets, [Chernova et al., 1993] pointed out the existence of two types of comets: gassy and dusty. Subsequently [Levasseur-Regourd et al., 1996] and [Hadamcik et al., 1997] expanded this work by studying the polarization phase curve for a large number of comets. Quantitatively, for $\alpha > 30^\circ$ it was thought that comets follow two distinct distributions in the polarization-phase angle diagram leading to two classes of comets: low polarization and high polarization comets ([Levasseur-Regourd et al., 1996]).
with high polarization comets being dusty and low polarization comets gassy. Kolokolova et al. (2007) present a strong argument in favour of the two classes of comets. They claim a strong correlation of the polarization behaviour with the strength of the 10\(\mu\text{m}\) silicate feature which is a direct signature of the dust grains. However, it is to be noted that cometary classification by IR spectra and by polarization values is highly correlated (Kolokolova et al., 2004). Any comet may belong to either class depending upon the dust activity. Also, the differences in the extent of polarization in the two classes could be due to molecular emission contamination (Jockers et al., 2005). In case of the gassy comets, the emission from molecules covers large fraction of the spectrum and contaminates the continuum, thus lowering the degree of polarization.

The apparition of comet NEAT C/2001 Q4 provided a good opportunity to make polarimetric observations at large phase angles which are useful to study cometary composition. During the observing run in May-June 2004, the comet was conveniently located in the sky and was bright enough to achieve good S/N ratio. In this communication we report the polarization observations made in May 2004 with the phase angle range 86 – 79°, and later in June with phase angle range 55 – 56° and discuss the results obtained.

### 2 Observations and analysis

Photopolarimetric observations of comet NEAT C/2001 Q4 were made during the period May-June 2004 with a two channel photopolarimeter (Deshpande et al., 1985; Joshi et al., 1987) mounted on the 1.2m telescope of Mt. Abu Observatory operated by Physical Research Laboratory (PRL), Ahmedabad. PRL photopolarimeter modulates the polarized component of the incident light at 20Hz with a rotating super-achromatic half-wave plate in front of a Wollaston prism. The instrument is equipped with IAU’s International Halley Watch (IHW) continuum filters (3650/80Å, 4845/65Å, 6840/90Å) (Osborn et al., 1990) and Johnson-Cousins’ BVR broad band filters. The IHW filters acquired for Comet Halley have been in regular use for observations of several other comets (Joshi et al., 1987; Sen et al., 1991; Ganesh et al., 1998; Joshi et al., 2003). The filters have been carefully stored in dry atmospheric conditions to preserve their transmission characteristics. The observations made with the same set of filters facilitate better comparison with other comets observed earlier, hence their continued use.

Table I shows the journal of the observations along with other information like phase angle of comet, UT, moon rise/set time at Mt. Abu etc. Heliocentric
distance and the aperture projected on the comet at the time of observations are plotted in Fig. 1. There are eight nights of observations in May and two in June 2004. During May 13-16, the dark period of the sky being short, making polarimetric observations on the comet in all the narrow band $IHW$ filters with good S/N was not possible. Therefore, observations were made with broad band $BVR$ filters. Later on, when the comet was available for longer dark-sky duration, the observations were made with $IHW$ filters. To facilitate a comparison of the data taken with two sets of filters, observations on some nights were made with both the sets of filters. After May 16, observations were made through two different apertures (cf Table 2) in each filter. During the course of our observations, phase angle ranged between 55-86° ($85.6-78.7°$ and $56.1-55.1°$ to be exact during May and June respectively). In Table 2 mean values of the observed parameters are listed. Compared to the background
stars, comet was moving relatively fast (during the observing run in May the estimated drift was $\sim 1''$ per 10 seconds) which demanded frequent re-centering of the comet in the aperture. To avoid significant drift of the comet within the aperture we kept integration time short (typically 40sec) and also guided visually through a finder telescope. Several such short exposures were taken in each filter keeping the comet centered in the aperture and the results were later averaged. In Table 2 mean values of polarization ($P\%$), position angle($\theta$) and error ($\epsilon_P\%$) are listed along with the integration time. A least-squares fit to the data gives $P\%$ and $\theta$ while the error in the fit gives the error in $P\%$ (Joshi et al., 1987). The errors in the position angle are obtained using the equation 8.5.4 given by Serkowski (1974).

The observations were taken with apertures (non-metallic diaphragms centered on the photocentre of the comet) of different sizes- 54" (a), 26" (b), 20" (c) and 10" (d). All the comet observations were made during dark sky conditions, and the comet being much brighter than the sky, sky polarization is negligible as compared to the comet degree of polarization. Nonetheless, to take care of the sky polarization, observations were made alternately centered on the photocentre of the comet and towards a region of the sky more than 30 arcmin away from the comet (along the anti-tail direction). It was noted visually that on nights subsequent to May 17, the comet became more and more diffused (the contrast between the nucleus, i.e. the photometric-center, and the coma reduced with time). Sky conditions were photometric throughout the observations in May.

In comets, it is likely that the nature of dust (size and composition) changes as one moves away from the nucleus. To study this behaviour, observations were made through different sized apertures. In order to explore this further, on May 20 comet was allowed to drift (starting from anti-tail side through nucleus to the tail side) across an aperture of 10" diameter and data were sampled every 10sec. These observations were made using R-band filter.

Polarization standards 9 Gem, HR6353, HD183143, HD204827 were observed to calibrate the observed position angle. Instrumental polarization ($\sim 0.03\%$) is much less compared to the photon noise in the observations and hence is neglected.
Table 2: Polarization data for comet NEAT C/2001 Q4. Listed entries are, date, time (UT), aperture (arcsec), Heliocentric (r) and Geocentric (∆) distance (AU), projected diameter (kms), phase angle (α), filter (F), total integration time (IT=integration time × number of integrations), degree of polarization (P%), error in polarization (εP%), position angle (θ in degrees) in equatorial plane, brightness magnitude.

| Date | UT | Ap | r  | ∆   | Dia | α | F    | IT | P% | εP% | θ | mag |
|------|----|----|----|-----|-----|---|------|----|----|-----|---|-----|
| 13:5:04 | 15:08:20 | 26” | 0.962833 | 0.389995 | 7337 | 85.6 | B   | 40*3 | 19.78 | 0.14 | 18.5 | 6.40 |
| 13:5:04 | 15:16:00 | 26” | 0.962829 | 0.389191 | 7338 | 85.6 | V   | 20*3 | 21.39 | 0.46 | 18.6 | 7.46 |
| 13:5:04 | 15:21:10 | 26” | 0.962826 | 0.389257 | 7339 | 85.6 | B   | 30*2 | 19.68 | 0.18 | 7.4  | 9.16 |
| 14:5:04 | 14:43:40 | 26” | 0.962253 | 0.407536 | 7684 | 84.8 | B   | 30*2 | 21.34 | 0.78 | 7.4  | 9.16 |
| 14:5:04 | 14:48:10 | 26” | 0.962252 | 0.407907 | 7685 | 84.8 | V   | 30*2 | 20.06 | 0.11 | 7.4  | 9.16 |
| 14:5:04 | 14:52:20 | 26” | 0.962250 | 0.407654 | 7686 | 84.8 | R   | 30*2 | 19.43 | 0.07 | 7.4  | 9.16 |
| 14:5:04 | 15:00:30 | 20” | 0.962248 | 0.407766 | 15972 | 84.8 | B   | 20*3 | 17.93 | 0.10 | 7.4  | 9.16 |
| 14:5:04 | 15:05:00 | 20” | 0.962247 | 0.407828 | 15974 | 84.8 | V   | 20*2 | 18.34 | 0.05 | 7.4  | 9.16 |
| 15:5:04 | 14:51:10 | 26” | 0.961979 | 0.427880 | 8070 | 84.0 | B   | 20*2 | 18.5  | 0.11 | 7.4  | 9.16 |
| 15:5:04 | 14:54:55 | 26” | 0.961979 | 0.427934 | 8072 | 84.0 | V   | 20*2 | 19.4  | 0.07 | 7.4  | 9.16 |
| 15:5:04 | 14:58:15 | 26” | 0.961979 | 0.427983 | 8074 | 84.0 | R   | 20*2 | 19.4  | 0.07 | 7.4  | 9.16 |
| 15:5:04 | 15:02:35 | 20” | 0.961978 | 0.428047 | 8076 | 84.0 | B   | 20*2 | 19.3  | 0.15 | 7.4  | 9.16 |
| 15:5:04 | 15:05:50 | 20” | 0.961978 | 0.428090 | 8078 | 84.0 | V   | 20*2 | 20.0  | 0.05 | 7.4  | 9.16 |
| 15:5:04 | 15:09:10 | 20” | 0.961978 | 0.428150 | 8080 | 84.0 | R   | 20*2 | 23.0  | 0.07 | 7.4  | 9.16 |
| 15:5:04 | 15:13:40 | 20” | 0.961978 | 0.428209 | 8082 | 84.0 | B   | 20*2 | 23.9  | 0.13 | 7.4  | 9.16 |
| 15:5:04 | 15:17:15 | 20” | 0.961978 | 0.428261 | 8084 | 84.0 | V   | 20*2 | 24.2  | 0.13 | 7.4  | 9.16 |
| 15:5:04 | 15:20:50 | 54” | 0.961978 | 0.428314 | 16772 | 84.0 | V   | 20*2 | 24.2  | 0.13 | 7.4  | 9.16 |
| 16:5:04 | 16:18:30 | 26” | 0.962041 | 0.450729 | 8498 | 83.0 | B   | 40*6 | 1 7.76 | 2.08 | 4.8  | 9.38 |
| 17:5:04 | 15:30:44 | 26” | 0.962411 | 0.472575 | 8911 | 84.0 | B   | 40*5 | 1 4.76 | 0.47 | 6.2  | 7.85 |
| 17:5:04 | 15:37:25 | 26” | 0.962413 | 0.472683 | 8913 | 84.0 | B   | 40*5 | 1 4.76 | 0.47 | 6.2  | 7.85 |
| 17:5:04 | 15:43:40 | 26” | 0.962415 | 0.472784 | 8915 | 84.0 | B   | 40*5 | 1 4.76 | 0.47 | 6.2  | 7.85 |
| 17:5:04 | 16:14:30 | 20” | 0.962427 | 0.473282 | 6864 | 82.0 | B   | 40*5 | 1 4.76 | 0.47 | 6.2  | 7.85 |
| 17:5:04 | 16:14:50 | 20” | 0.962427 | 0.473287 | 6866 | 82.0 | B   | 40*5 | 1 4.76 | 0.47 | 6.2  | 7.85 |
| 17:5:04 | 16:15:24 | 20” | 0.962427 | 0.473295 | 6868 | 82.0 | B   | 40*5 | 1 4.76 | 0.47 | 6.2  | 7.85 |
| 18:5:04 | 15:10:20 | 20” | 0.963095 | 0.495099 | 9350 | 81.0 | B   | 40*7 | 1 5.36 | 0.33 | 7.8  | 7.95 |
| 18:5:04 | 15:57:15 | 20” | 0.963123 | 0.495099 | 9350 | 81.0 | B   | 40*7 | 1 5.36 | 0.33 | 7.8  | 7.95 |
| 18:5:04 | 16:02:45 | 20” | 0.964148 | 0.520804 | 7554 | 79.9 | B   | 40*4 | 24.06 | 0.85 | 7.7  | 8.62 |
| Date    | UT   | Ap | r   | Δ   | Dia | α | F   | IT  | P% | ϵp% | θ | mag |
|---------|------|----|-----|-----|-----|---|-----|-----|-----|-----|---|-----|
| 20:5:04 | 15:52:10 | 20 | 0.965475 | 0.545449 | 7911 | 78.8 | 3650 | 40*5 | 20.22 | 3.05 | 9.3 | 10.34 |
| 20:5:04 | 16:00:20 | 20 | 0.965484 | 0.545592 | 7913 | 78.8 | 4845 | 40*5 | 19.38 | 0.51 | 7.9 | 9.22 |
| 20:5:04 | 16:08:35 | 20 | 0.965492 | 0.545737 | 7915 | 78.8 | 6840 | 40*5 | 23.27 | 0.64 | 7.5 | 8.17 |
| 20:5:04 | 16:14:50 | 20 | 0.965499 | 0.545847 | 7917 | 78.8 | B   | 10*5 | 16.70 | 0.25 | 7.7 | 9.76 |
| 20:5:04 | 16:20:45 | 20 | 0.965505 | 0.545951 | 7919 | 78.7 | V   | 10*5 | 16.59 | 0.09 | 6.8 | 8.79 |
| 20:5:04 | 16:24:50 | 20 | 0.965509 | 0.546022 | 7920 | 78.7 | R   | 10*5 | 20.50 | 0.17 | 7.8 | 8.39 |
| 10:6:04 | 16:54:40 | 26 | 1.061004 | 1.098940 | 20722 | 56.0 | V   | 60*4 | 9.92 | 0.13 | 9.5 | 9.78 |
| 10:6:04 | 16:43:15 | 26 | 1.060944 | 1.098735 | 20718 | 56.1 | R   | 60*3 | 12.50 | 0.25 | 8.8 | 9.38 |
| 10:6:04 | 17:05:30 | 26 | 1.061057 | 1.099129 | 20726 | 56.0 | 4845 | 60*7 | 14.29 | 1.08 | 5.8 | 10.65 |
| 10:6:04 | 17:20:50 | 26 | 1.061134 | 1.099400 | 20731 | 56.0 | 6840 | 60*10 | 16.04 | 1.71 | 9.4 | 9.48 |
| 11:6:04 | 16:56:10 | 26 | 1.068334 | 1.124172 | 21198 | 55.1 | B   | 20*3 | 7.64 | 0.53 | 26 | 11.94 |
| 11:6:04  | 17:01:40 | 26 | 1.068363 | 1.124268 | 21200 | 55.1 | V   | 20*2 | 14.50 | 0.99 | 43 | 11.37 |

2 sky condition: scattered cloud patches
Results from continuous photopolarimetric observations during May 13-20, and June 10-11, 2004, covering the comet in pre and post perihelion passages, are presented in Table 2 in the form of polarization percentage ($P\%$), error in $P$ ($\epsilon_p\%$), position angle ($\theta$) and magnitude at different phase angles, filters and aperture sizes.

In order to study the radial distribution of polarization, and hence the dust particles, we made observations through different sized apertures. In the case of Comet Halley, a fair degree of agreement is seen among the observations made by different groups with different size apertures as long as the polarization is estimated with apertures large enough to cover good part of the coma, centered on the nucleus, which averages out the effect of heterogeneity. In the case of comet Hale-Bopp also no significant difference was found in the polarization observed through two different apertures corresponding to linear scales of 14318km and 28313km respectively (Ganesh et al., 1998) and similar results were reported by Manset and Bastien (2000).

Figure 1 shows variation of the Heliocentric range and linear size sampled at the geocentric distance of the comet (corresponding to 26” aperture) during the observing run in May and June. The Heliocentric range ($r$) of the comet has not changed much during the observing run in May while it changes slightly in Jun 10-11, 2004. The total change in $r$ during the observing run (May-June) is less than 10 %. However, most of the observations are made in May and the change in $r$ during this period is less than 0.4%, thus resulting in a very small change in solar flux as seen by the comet. On the other hand the Geocentric distance ($\Delta$) has changed rapidly during the observing run, resulting in large change in the sampled area projected on the comet surface. Our aperture of 26” corresponds to a projected diameter ranging from $\sim$ 7350 to $\sim$ 21800kms over the course of the observations in May and June. Therefore the effects of inhomogeneities in the coma are expected to be averaged out. The observed data in Table 2 support this view. We also note that the overall polarization characteristics of NEAT C/2001 Q4 are similar to comet Halley and C/2000 WM1 (LINEAR) as is discussed later. Therefore, the comparison of the polarimetric observations on different dates for NEAT C/2001 Q4 is meaningful.

3.1 Wavelength dependence of polarization

Wavelength dependence of polarization as observed in $IHW$ filters on various dates in May and June is plotted in Fig. 2. Observation date, phase angle and
the apertures used are marked in the figure. As mentioned in earlier section, apertures a, b, c stand for 54", 26", 20", respectively. The figure shows that the degree of polarization increases with the wavelength. The errors are relatively large for 3650Å IHW filter, but the trend of increase in polarization with wavelength is clear. Similar behaviour is noted by Kiselev and Velichko (1998) for comet Hyakutake and by Manset and Bastien (2000) for comets Hale-Bopp and Hyakutake who also report polarization observations at large phase angles.

On May 20, observations have been made through both the sets of filters ie IHW and BVR and plotted in the panel labeled 20/5/04 of Fig.2 The values of polarization for broad band filters are lower compared to the IHW filters. This is expected as the broad bands usually encompass several emission lines. The R-band is least contaminated by molecular lines while V-band contains the C2 emission band and the B-band is contaminated by CN-band emission. Polarimetric observations on May 13-16, 20 and June 10-11 are made through BVR filters. It is clear from the Fig. 3 that there is a noticeable change in the polarization in V-band at different dates while the other two bands (BR) do not show such pattern. This indicates significant variation in the molecular emission (eg C2 band emission) in V band.

Considering the behaviour of polarization in apertures of different sizes, in general, the degree of polarization and its wavelength dependence do not depend significantly on the sampled size of the comet unless size difference is really large. For example, Manset and Bastien (2000) report a decrease of 2% in polarization in the coma of comet Hale-Bopp in going from 8” to 80” aperture size. At the same time, they do not find any change in the polarization values obtained through 8.2” and 10.6” apertures. As explained in the earlier section, we also do not expect any appreciable change in the polarization behaviour in the apertures used. On May 17 polarization is marginally lower at shorter wavelengths in larger aperture while on May 18, there is a relative increase in the polarization in 4845Å band and a decrease in 3650Å band in smaller aperture. However, the errors in polarization are large in the later case (cf Figure 2) and therefore any definite conclusion might be misleading here. Nonetheless, if the change in polarization behaviour in two apertures is genuine, it could be due to cometary activity, perhaps before May 17 resulting in temporary non uniform distribution of dust. Subsequently, the grain distribution gets homogenized after the activity has subsided, leading to similar wavelength dependence of polarization seen through different apertures on May 19. This also corroborates well with our visual observations of slightly diffused appearance of the comet on May 19 and 20 leading to slightly lesser contrast between the photocentre and background coma. However, it is worthwhile to note that non-variation of polarization with aperture does not rule out presence of any other activity in comet.

Now let us discuss how the polarization colour (spectral gradient of polariza-
Fig. 2. Wavelength (IHW narrow band) dependence of the degree of polarization for the comet NEAT. Polarization observed through different apertures is marked with letters ‘b’, ‘c’ representing the apertures 26” and 20” respectively. At phases $\alpha = 56$ and $\alpha = 79$ (panels in right column) observations are plotted in both broad and narrow bands (see text).

Polarization changes with time. We computed polarization color in IHW continuum bands using the expression:

$$PC = \frac{(P_r - P_b)}{(\lambda_r - \lambda_b)}$$

Where $P_r$ and $P_b$ are polarization values at 0.6840$\mu$m and 0.4845$\mu$m, respectively. The polarization colour (PC) and photometric colours $\delta_{Mag}(b-r)$ in two apertures are listed in Table 3 on different dates. We note that PC decreases during May 17 to May 19 in 26” aperture while in smaller (20”) aperture, it decreases on 18th May but increases during 19 to 20th May 2004. The phy-
Fig. 3. Wavelength dependence of the degree of polarization for the comet NEAT in the BVR broad bands. The aperture 'a' is of size 54" and the apertures 'b', 'c' are the same as in Fig. 2.

tometric colour also decreases on 18th May and then shows an increase in both the apertures. That means that coma of comet NEAT Q4 gets bluer in polarization as well as in photometric colour during 17-18 May 2004. An increase in blue colour in intensity together with increase in linear polarization is generally interpreted as decrease in the average grain size distribution. It could mean an increase in the number of fluffy (porous) aggregate particles and/or finer grains due to sublimation of organics or some other activity as referred to earlier also. It could also indicate a change in composition due to decomposition of organics since at about 1 AU heliocentric distance, it is the dominant process in near-nuclear region [Kolokolova et al. 2001]. On May 19, polarization and photometric colors have increased again in small aperture, indicating, probably, a fresh activity on the comet. Such correlation can be explained by sublimation of some absorbing material- such as dark organics.
Fig. 4. Variation of polarization and instrumental magnitude with location in a 10” aperture. See text for details.

However, present observations do not allow us to make any definitive statement about the type of activity.

Considering the polarization values in $IHW$, we also note that the wavelength dependence of polarization is steeper at larger phase angle ($82^\circ$) compared to what it is at lower phase angle ($55^\circ$) i.e., polarization colour is redder at higher phase angle.

3.2 Spatial variation of polarization

On 20th May 2004, we made polarimetric observations on the comet at various points tail-ward. This was done by pointing the telescope ahead of the path of the comet while tracking at the sidereal rate. Over a period of 360 seconds...
the comet was allowed to drift across the 10” aperture with sampling time of 10 sec. During this period, the movement of the comet was in a direction parallel to the direction pointed by the tail. The observations were made using the R-band filter and a running average of 5 measurements of polarization and intensity are plotted in Fig. 4. An aperture of 10” corresponds to a linear scale of ∼ 4000 km at the distance of the comet at that time. Any heterogeneity at scales larger than this should show up in the observed polarization. We notice a decrease in polarization as the nucleus is approaching, becoming near minimum at the photocenter while showing a systematic, albeit small, increase tail-ward. Similar behaviour was noticed by [Jewitt (2004)] for comet 2P/Encke, suggesting a change in the mean scattering properties of dust particles on time of flight timescale of one hour- the likely cause of fragmentation being disaggregation of the composite, porous dust particles. [Manset and Bastien (2000)] measured polarization in the coma and tail of comet Hale-Bopp up to a distance of about 200” and found the polarization to increase and then decrease when going away from the nuclear region. In our case, perhaps the duration of observation and linear distance covered were not sufficient enough to notice such variation. The brightness reaches maximum, as expected, at the photocenter (nucleus) and then decreases sharply. One can infer, broadly, the presence of large compact particles (aggregates) near the photocenter while more finer grains and fluffy aggregates tail-ward. However, too much should not be read in this behaviour as the sampled region (4000 km) is larger than the typical size of the Comet nucleus and we might not have sampled the circumnuclear region of lower polarization. The position angle does not show any appreciable change during the observation.

3.3 Polarization phase curve

The variation of polarization as a function of phase angle throws light on various properties of comet such as composition, albedo, size distribution of grains etc. Though there exists large amount of observational data related to polarization at many phase angles, polarization values at lower phases (negative polarization branch region) and larger phase angles, including the region where it peaks (90 - 105°) are very scanty. Such scarcity of data causes problems for the proper modeling/fitting of the polarization phase curve for the comets.

As mentioned earlier, apparition of Comet NEAT Q4, provided us the opportunity to measure linear polarization covering a good part of the higher phase angle branch of the curve. These measured values are plotted in the polarization phase curves for the continuum bands 4845 Å and 6840 Å in Figs. 5 and 6 respectively along with observed values for other comets taken from the catalog compiled by [Kiselev et al. (2005)]. Our observed values are in fairly good
agreement with the polarization values obtained for various comets. A large scatter is evident from the figures, more so in blue continuum towards the larger phase angles. On some nights observations were made through broad band $BVR$ filters (mostly with $R$-band) to get better S/N as explained in Section 2. On May 20 and June 10, 2004, observations have been made with both broad and narrow band filters to look for any systematic difference in the polarization behaviour. We note such a difference in the degree of polarization obtained in two sets of filters which has been applied to the broad band data ($V$ and $R$) as correction before plotting in Fig. 5 and Fig. 6, respectively. With this correction, the observations through $R$-band and the $IHW$ 6840Å band compare well on different nights. Same is true for the $V$ and $IHW$ 4845Å band apart from a slightly larger scatter which may be attributed to the effect of variable molecular emission observed by Singh et al. (2006) almost simultaneously.

The present observations indicate expected behaviour of polarization as a function of phase angle, polarization increasing with phase in the larger phase angle regime. However, phase angles reported here fall short of the phase values for maximal polarization. For comet C/1996 B2 Hyakutake, Kiselev and Velichko (1998) report 24% (blue continuum) and 26% (red continuum) as maximum polarization at $\alpha \sim 94$ deg, while Manset and Bastien (2000) mention a value of 28.6% as maximum polarization in red at $\alpha \sim 91$ deg for the same comet. Though our observations do not cover the phase angles of maximal polarization, our projected values ($P \sim 27\%$ in the range $\alpha \sim 90-95^\circ$) for maximum P are almost similar.

3.4 On the nature of the grains

We see that the polarization behaviour of comet NEAT C/2001 Q4 (Figs. 5 and 6) is very similar to other high polarization comets, such as comet Hyakutake(C/1996 B2), at similar phase angles indicating that their dust grains have similar characteristics.

The grains in comets are identified to be mainly amorphous and crystalline silicates (Brownlee et al., 2006; Harker et al., 2005; Wooden et al., 2004) and CHON (Kissel et al., 1986) particles. In comet NEAT C/2001 Q4, Mg-rich olivine crystals and Mg-rich crystalline pyroxene were detected in IR spectra (Wooden et al., 2004). The mid-IR spectra of comet C/2001 Q4 (NEAT) and Hale-Bopp (Harker et al., 2002; Wooden et al., 2000, 1999) show remarkable similarity suggesting the presence of similar silicate minerals in approximately equal relative abundance of sub-micron grains (Wooden et al., 2004). Thermal emission models for the 7.7 - 13.1 $\mu$m SED of comet C/2001 Q4 on two epochs May 11.25 UT and May 11.30 UT, 2004 (just two days prior to our polari-
Fig. 5. The phase dependence of polarization of Comet NEAT C/2001 Q4 for blue wave bands centered at 4845 Å are shown as black solid dots with error bars. Observations in V broad band are shown as open squares (with an additional offset of 2.6% - see text). Open circles represent observations with the 4845 Å IHW filter extracted from the Kiselev et al. (2005) database with errors less than 1% for various comets.

metric observing run) indicate the dust grains to be highly porous with size distribution peaking at the grain radius of $a_p = 0.3$ μm (Wooden et al., 2004). Wooden et al. (2004) have also reported a drop in silicate-to-amorphous carbon by a factor of $\sim 2$ in 2 hours. As far as the dust grain characteristics are concerned, polarization observations corroborate with the finding made with the study of thermal emission spectra. Based on the polarization behaviour, the mean grain size of monomer is expected to be in the range 0.2 - 0.3 μm.

As discussed in section 3.1, the polarization color shows significant change during the observing run indicating change in the average grain and aggregate characteristics. Kolokolova et al. (2001) mention three possibilities for
Fig. 6. The phase dependence of polarization of Comet NEAT C/2001 Q4 for red wave bands centered at 6840 Å are shown as black solid dots with error bars. Observations in $R$ broad band are shown as open squares (with an additional offset of 2.6% - see text). Open circles represent observations with the 6840 Å $IHW$ filter extracted from the [Kiselev et al. (2005)] database with errors less than 1% for various comets.

The change in the dust characteristics: i) grain size decreases due to grain fragmentation leading to higher abundance of smaller grains; ii) change in chemical compositions as volatile materials evaporate or are destroyed; iii) porosity increases as embedded volatile evaporate.

In the present study, polarization color is always red, though it shows significant variation. One interesting finding is that the change in polarization color is larger in smaller aperture. In fact the polarization color observed in the two apertures compare well on May 17 and May 19, but on May 18 it shows significantly lower polarization color and photometric color in the smaller aperture. This indicates that the comet has been active during this period.
The detection of the change in polarization color may be attributed to the change in the composition of the dust grains rather than the change in particle size.

4 Conclusions

This work reported optical linear polarization observations on comet NEAT C/2001 Q4 in the phase angle range 86 - 55° where there are very few observations. In general, polarization and brightness of the coma increase with wavelength, phase angle and size of the apertures used. Comet NEAT C/2001 Q4, at these large phase angles, shows similar degree of polarizations as comet Hyakutake, indicating similar grain characteristics in two comets. Observations reveal that Comet NEAT Q4 exhibits polarimetric behaviour typical to high polarization comets and therefore, should contain substantial number of small dust particles and fluffy aggregates with submicron sized monomers. As expected, polarimetric colour increases with wavelength and phase angle range of present observations. The polarization and photometric colours on May 18 indicate some cometary activity, leading to either change in composition due to decomposition of organics or change in grain size.

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Table 1. Observation log and comet parameters; 4th column represent the observation time: beginning and end are given in first and second row along with corresponding RA, DEC, Heliocentric and Geocentric distances in subsequent columns.

| Date       | Moon-rise | Sun-set | UT   | RA(2000) | Dec(2000) | r     | ∆    | φ(SCE) |
|------------|-----------|---------|------|----------|-----------|-------|------|--------|
| 2004:05:13 | 21:02     | 13:47   | 15:08| 8:23:16.17 | 13:43:25 | 0.96283301| 0.38909076| 85.639  |
|            |           |         | 15:22| 8:23:20.00 | 13:45:31 | 0.96282576| 0.38926712| 85.632  |
| 2004:05:14 | 14:43     | 8:29:38.26 | 17:05:21 | 0.96225326 | 0.40752694| 84.872 |
|            |           |         | 15:10| 8:29:45.21 | 17:09:00 | 0.96224519| 0.40789635| 84.857  |
| 2004:05:15 | 14:50     | 8:35:44.56 | 20:12:30 | 0.96197946 | 0.42786269| 83.996 |
|            |           |         | 15:21| 8:35:52.02 | 20:16:18 | 0.96197713| 0.42831640| 83.977  |
| 2004:05:16 | 22:36     | 13:47   | 16:17| 8:41:46.18 | 23:10:22 | 0.96204080| 0.45070562| 82.993  |
|            |           |         | 16:19| 8:41:46.63 | 23:10:35 | 0.96204111| 0.45073662| 82.991  |
| 2004:05:17 | 23:08     | 13:47   | 15:30| 8:46:56.12 | 25:36:42 | 0.96241040| 0.47256353| 82.020  |
|            |           |         | 16:14| 8:47:05.47 | 25:41:05 | 0.96242694| 0.47327385| 81.989  |
| 2004:05:18 | new moon  | 13:47   | 15:10| 8:51:53.52 | 27:51:45 | 0.96309469| 0.49570033| 80.987  |
|            |           |         | 15:48| 8:52:01.10 | 27:55:10 | 0.96311726| 0.49633426| 80.959  |
| 2004:05:19 | new moon  | 13:48   | 15:12| 8:56:37.81 | 29:55:49 | 0.96410640| 0.51993316| 79.905  |
|            |           |         | 16:04| 8:56:47.58 | 30:00:03 | 0.96414883| 0.52082508| 79.866  |
| 2004:05:20 | 15:00(set) | 13:48  | 15:50| 9:01:12.08 | 31:50:51 | 0.96547329| 0.54541115| 78.771  |
|            |           |         | 16:25| 9:01:18.29 | 31:53:25 | 0.96550969| 0.54602547| 78.744  |
| 2004:06:10 | 20:09     | 13:58   | 16:52| 9:58:17.23 | 49:43:48 | 1.06098967| 1.09889026| 56.057  |
|            |           |         | 17:22| 9:58:19.45 | 49:44:17 | 1.06114008| 1.09942081| 56.037  |
| 2004:06:11 | 20:40     | 13:58   | 16:55| 10:00:39.92| 50:07:05 | 1.06832835| 1.12415131| 55.120  |
|            |           |         | 17:02| 10:04:43  | 50:07:11 | 1.06836446| 1.12427407| 55.116  |

* observations were made until the moon was up
Table 3
Polarization colour (PC) and photometric colour 
([4845]-[6840]) in 26 & 20 ” apertures

| Date   | PC     | Phot. colour |
|--------|--------|--------------|
|        | 26”    | 20”          | 26”  | 20”  |
| 17:5:04| 22.86(± 0.47) | 20.40(± 0.67) | 1.09 | 1.06 |
| 18:5:04| 18.80(± 0.50) | 14.10(± 1.32) | 0.94 | 0.81 |
| 19:5:04| 15.54(± 0.69) | 16.10(± 1.11) | 0.97 | 1.11 |
| 20:5:04| —      | 19.50(± 0.82) | —    | 1.05 |
| 10:6:04| 8.80(± 2.02) | —             | 1.17 | —    |