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Study of grain alignment efficiency and a distance estimate for small globule CB4

Ajoy Barman and Himadri Sekhar Das

Department of Physics, Assam University, Silchar 788011, India; *hsdas@iucaa.ernet.in*

Abstract We study the polarization efficiency (defined as the ratio of polarization to extinction) of stars in the background of the small, nearly spherical and isolated Bok globule CB4 to understand the grain alignment process. A decrease in polarization efficiency with an increase in visual extinction is noticed. This suggests that the observed polarization in lines of sight which intercept a Bok globule tends to show dominance of dust grains in the outer layers of the globule. This finding is consistent with the results obtained for other clouds in the past. We determined the distance to the cloud CB4 using near-infrared photometry (2MASS JHK_S colors) of moderately obscured stars located at the periphery of the cloud. From the extinction-distance plot, the distance to this cloud is estimated to be (459 ± 85) pc.

Key words: polarization — ISM: clouds — dust, extinction — ISM: individual objects: CB4

1 INTRODUCTION

Linear polarization measurement of background field stars in a star forming cloud has been used to study the large scale structure of the interstellar magnetic field (Heiles 2000; Fosalba et al. 2002; Bertrang et al. 2014). The efficiency with which polarization is produced by dust grains is sensitive to the physical conditions of the cloud, with a tendency to drop systematically with increasing extinction or optical depth inside interstellar clouds (Goodman et al. 1995; Gerakines et al. 1995; Whittet et al. 2008; Chakraborty et al. 2014). This observation suggests that the observed polarization in a particular direction or line of sight which intercepts a dark cloud shows dominance by dust grains in the outer layers of the cloud. However, background stars observed through a dense region of the cloud show a smaller degree of polarization which suggests much lower dust columns in the observed lines of sight. This also suggests that the polarization studies of background stars in a cloud can explain the external magnetic field well, but it cannot provide information on the magnetic field structure within the cloud (Whittet 2005).

To model the observed variation in polarization with extinction along different lines of sight, Jones (1989) and Jones et al. (1992) studied this in terms of a magnetic field with distinct random and uniform components. It has been observed by different investigators that the polarization efficiency decreases with an increase in extinction (Tamura et al. 1987; Goodman et al. 1992; Gerakines et al. 1995; Whittet et al. 2008; Chakraborty et al. 2014). This can be represented by a power law $p/A_V \propto A_V^{-\alpha}$ for some power law index α. From the study of dust grain alignment in the Taurus Dark Cloud

Complex, Gerakines et al. (1995) found a strong correlation between polarization efficiency and extinction, which was fitted by power law $p/A_V \propto A_V^{-0.56}$ in the magnitude region ($0 \leq A_V \leq 25$). Whittet et al. (2008) also studied the polarization efficiency toward molecular clouds with an aim of understanding grain alignment mechanisms in dense regions of the interstellar medium and found an empirical relation $p_\lambda/\tau_\lambda \propto [A_V]^{-0.52}$ (where τ_λ is the optical depth). They did not find any significant change in the behavior in the transition region between the diffuse outer layers and dense inner regions of clouds. Recently, Chakraborty et al. (2014) studied the polarization efficiencies in three selected Bok globules: CB56, CB60 and CB69. They found a trend of decreasing polarization efficiency with increasing extinction which can be well represented by a power law, $p_V/A_V \propto A_V^{-\alpha}$, where $\alpha = -0.56\pm0.36$, -0.59 ± 0.51 and -0.52 ± 0.49 for CB56, CB60 and CB69, respectively. To study the alignment of grains, a radiative torque mechanism has been used by researchers to calculate the expected relationship between polarization efficiency and extinction through a homogeneous cloud (Dolginov & Mitrofanov 1976; Draine & Weingartner 1996, 1997; Lazarian & Hoang 2007; Whittet et al. 2008; Hoang & Lazarian 2014). Hoang & Lazarian (2014) studied grain alignment by radiative torques for various environmental conditions, including the interstellar medium, dense molecular clouds and accretion disks.

The determination of the distance to interstellar clouds helps researchers to obtain luminosities of the protostars embedded in the clouds (Yun & Clemens 1990) and to estimate the sizes, masses and densities of the clouds (Clemens et al. 1991). Several methods have been adopted to estimate the distance to a cloud. These are the Wolf diagram method (Wolf 1923), star count method (Bok & Bok 1941), spectroscopic method (Hobbs et al. 1986; Hearty et al. 2000), photometric method (Snell 1981; Peterson & Clemens 1998; Maheswar & Bhatt 2006; Maheswar et al. 2004, 2010), etc. Maheswar & Bhatt (2006) determined the distances to nine dark globules by a method which uses optical and near-infrared (NIR) photometry of stars projected towards the field containing the globules. Recently, Eswaraiah et al. (2013) determined the distance to the starless dark cloud LDN 1570 using NIR photometry from 2MASS.

In this work, we plan to study the polarization efficiency of background field stars of the isolated Bok globule CB4. We also determine the distance to the cloud CB4 using a technique developed by Maheswar et al. (2010) which uses JHK NIR photometry.

The paper is organized as follows. In Section 2, a brief discussion on cloud CB4 is presented. The polarimetric and photometric data collected from literature survey are presented in Section 3. Our results are discussed in Section 4. Finally, we conclude with a summary in Section 5.

2 OBJECT

2.1 CB4

CB4 is a small, nearly spherical and isolated Bok globule situated at a distance of 600 pc (Dickman & Clemens 1983). CB4 is situated far away from the Galactic plane ($b \approx -10°$). The angular size of this cloud on the Palomar Observatory Sky Survey (POSS) maps is $2' \times 1'$ and the position angle (PA) of the major axis (measured east from north) is $45°$. An IRAS point source is located at the southern edge of the cloud which is detected only at $100\,\mu m$ (Clemens & Barvainis 1988). No further evidence of an embedded source has been observed up to $160\,\mu m$. CB4 has been spectroscopically studied in CO and its isotopes (Dickman & Clemens 1983; Clemens et al. 1991). The observations have shown that the velocity of the globule is about -11.3 km s^{-1} with a velocity dispersion of 0.57 km s^{-1}. Furthermore, the study of deep IRAS aperture photometry and molecular line observations showed that CB4 is cold (≈ 7K) and does not contain a dense core ($n > 10^4$ cm^{-3}) (Clemens et al. 1991; Kane et al. 1994; Turner et al. 1997).

3 DATA

3.1 Polarimetric Data

The polarimetric data of 80 field stars in CB4 at the V-band have been taken from Kane et al. (1995). Four fields were initially observed by them to cover a region of $\sim 8' \times 8'$ surrounding the cloud CB4. Two other fields were also observed again with a slightly larger pixel size and using longer integrations. The histogram of polarization PAs of 80 field stars displayed a strong peak around the mean PA of $65°$ with a dispersion of $13°$. This PA represents the preferred magnetic field direction and the narrow width of the peak indicates a largely uniform field. The unweighted mean polarization and weighted mean polarization were calculated by Kane et al. to be $(2.84\pm0.25)\%$ and $(0.96\pm0.07)\%$ which indicate a largely uniform magnetic field.

3.2 Photometric Data

The NIR photometric data (J, H and K_S) of the field stars of CB4 have been taken from the 2MASS All-Sky Catalog of Point Sources (Cutri et al. 2003) which satisfies the following criteria:

(1) photometric uncertainty σ_J, σ_H, $\sigma_{K_S} \leq 0.035$ in all three filters,
(2) signal-to-noise ratio (SNR) >10 which is shown by the photometric quality flag of "AAA" in all three filters.

The positions of 80 stars are shown by RA(2000) and Dec(2000) in table 2 of Kane et al. (1995). It can be noted that we will designate all field stars by their serial number used in Kane et al. (1995)'s paper and this numbering has been shown in column number two of Table 1.

Table 1 The J, H and K_S magnitudes of 20 stars along with spectral type, absolute magnitude (M_{K_S}) and extinction (A_V). The second column refers to the star number which corresponds to the serial number in table 2 of Kane et al. (1995).

S/N	Star	J (mag)	H (mag)	K_S (mag)	Sp Type	M_{K_S}	A_V
1	1	10.942±0.021	10.604±0.018	10.533±0.018	G4V	3.45	0
2	9	11.026±0.021	10.461±0.019	10.305±0.018	K4V	4.22	0.40
3	11	11.888±0.021	11.412±0.019	11.282±0.018	K2V	4.15	0.23
4	14	11.555±0.021	11.185±0.018	11.099±0.018	G9V	4.03	0
5	17	11.653±0.021	11.186±0.019	11.1±0.018	K1V	4.13	0
6	18	12.715±0.022	12.515±0.023	12.396±0.023	A8V	1.64	1.05
7	23	13.083±0.021	12.702±0.023	12.607±0.025	K0V	4.15	1.34
8	26	11.52±0.021	11.206±0.019	11.108±0.018	G3V	3.34	0.24
9	32	12.978±0.022	12.552±0.023	12.382±0.023	G2V	3.29	1.44
10	35	10.335±0.021	10.199±0.021	10.127±0.018	F0V	1.86	0.16
11	36	13.332±0.022	13.036±0.029	12.98±0.031	G2V	3.29	0
12	41	12.897±0.026	12.354±0.029	12.268±0.029	K3V	4.15	0
13	52	11.055±0.021	10.863±0.019	10.773±0.02	F1V	2.00	0.45
14	61	12.691±0.021	12.418±0.021	12.321±0.025	F7V	2.75	0.44
15	62	13.038±0.025	12.693±0.027	12.566±0.029	G0V	3.19	0.81
16	66	13.19±0.025	12.865±0.031	12.789±0.034	G4V	3.45	0
17	71	12.091±0.021	11.881±0.021	11.783±0.023	F1V	2.00	0.59
18	76	12.551±0.022	12.238±0.023	12.104±0.024	F6V	2.62	0.98
19	77	13.3±0.024	12.9±0.027	12.784±0.03	G9V	4.03	0.35
20	79	13.483±0.026	13.103±0.026	13.037±0.032	G9V	4.03	0

The photometric magnitude of each field star has been searched via CDS's VizieR service, using $2'$ search radii as a query. The J, H and K_S magnitudes of 80 stars are available in the catalogue. We also checked the SIMBAD astronomical database to search for any variable star out of 80 field stars, but we could not find any variable star. We found that only 60 stars satisfy the above criteria and our analysis is restricted to only these stars. Furthermore we could not find the uncertainties in magnitudes of six stars in the 2MASS catalog which are star numbers 4, 20, 27, 50, 51 and 74. So, we discarded them from our analysis. Thus the total number of stars considered in our analysis is 54.

4 RESULTS

4.1 Spectral Types and A_V

We used the technique developed by Maheswar et al. (2010) to infer spectral type, and hence absolute magnitude and intrinsic colors of normal main sequence stars and giants from NIR photometry. This method gives distances to globules that are relatively close ($\lesssim 500$ pc) with a precision of $\sim 20\%$. In this technique, the fields containing the cores are divided into small sub-fields to avoid complications created by the wrong classifications of giants into dwarfs. Actually, the increase in extinction caused by a cloud should occur at almost the same distance in all the fields; if the whole cloud were located at the same distance, the wrongly classified stars in the sub-fields would show high extinction not at the same but at random distances (Maheswar et al. 2010). But for small and isolated clouds, it would be difficult to divide the field containing the cloud into sub-fields with a sufficient number of stars projected on to them. Therefore, the distance measurement is rather hard for cloud CB4 as it is a small, nearly spherical and isolated Bok globule. It would be difficult to subdivide the field with only a limited number of stars. So, we consider a single field surrounding the core of the cloud CB4.

In this technique, stars with $(J - K_S) \leq 0.75$ were selected from the fields containing the cloud to eliminate M-type stars from the analysis. Then a set of dereddened colors $(J - H)_\mathrm{o}$ and $(H - K_S)_\mathrm{o}$ was produced for each star from their observed colors $(J - H)$ and $(H - K_S)$ using trial values of A_V and a normal interstellar extinction law (i.e., total-to-selective extinction value, $R_V = 3.1$) in the equations (Rieke & Lebofsky 1985):

$$(J - H)_\mathrm{o} = (J - H) - 0.107 \times A_V, \qquad (1)$$
$$(H - K_S)_\mathrm{o} = (H - K_S) - 0.063 \times A_V. \qquad (2)$$

The maximum extinction that could be computed using this method is limited to $A_V \approx 4$ mag. The trial values of A_V are chosen in the range $0 - 10$ mag with a step size of 0.01 mag. The calculated set of dereddened color indices is then compared with the intrinsic color indices $(J - H)_\mathrm{in}$ and $(H - K_S)_\mathrm{in}$ of normal main sequence stars and giants, produced using the procedures discussed in Maheswar et al. (2010). The best fit of the dereddened colors to the intrinsic colors that yield a minimum value of χ^2 then give the corresponding spectral type and A_V for the star. The solutions which give $\chi^2_\mathrm{min} \leq 0.1$ are considered for this analysis.

The uncertainty in A_V is given by

$$\sigma(A_V) = \sqrt{4.7^2 \cdot \sigma^2_{JH} + 7.9^2 \cdot \sigma^2_{HK_S} + 2 \times 37 \times \mathrm{cov}(JH, HK_S)}, \qquad (3)$$

where $\sigma^2_{JH} = \sigma^2_J + \sigma^2_H$, $\sigma^2_{HK_S} = \sigma^2_H + \sigma^2_{K_S}$ and $\mathrm{cov}(JH, HK_S) = r_\mathrm{s} \times \sigma_{JH}\sigma_{HK_S}$. The Spearman rank-order correlation coefficient (r_s) is calculated from uncertainties in $(J - H)$ and $(H - K_S)$ colors and shows a strong correlation between them. The maximum uncertainty in A_V in our case is estimated to be 0.5 mag.

We found that 14 stars have $(J - K_S) > 0.75$, so we also discarded them from our analysis. We used this technique to estimate the A_V and absolute magnitudes for 40 stars. It has been found
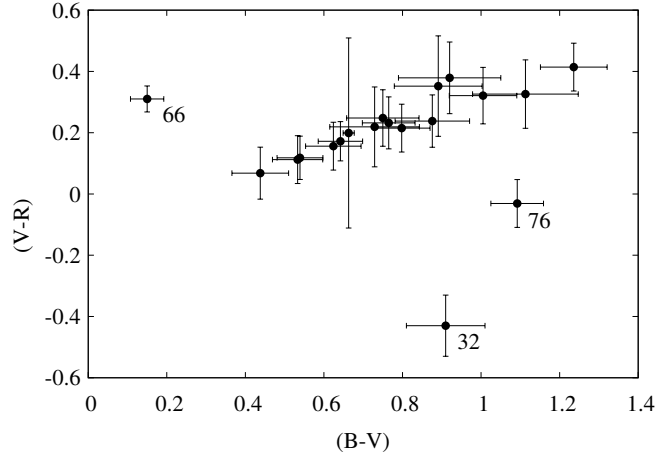
Fig. 1 Plot of the $B - V$ versus $V - R$ color – color diagram of 19 field stars in CB4. Diagonally clustered points represent stars that are in the main sequence. The stars that do not belong to the main sequence are represented by their serial numbers as mentioned in Table 1.

that only 20 stars have $\chi^2_{\min} \leq 0.1$ for which it is possible to infer the spectral type and the A_V. The results are shown in Table 1.

In Maheswar et al. (2010)'s technique, the field stars in the globule are assumed to be normal main sequence stars and therefore the luminosity class V has been assigned to all stars. However, the presence of non main sequence stars may result in the wrong distance to these stars. The intrinsic color and luminosity may be reliable if the spectral type is correctly determined and happens to be a main sequence star. For this we need to plot the $(B - V)$ vs. $(V - R)$ color – color diagram. The photometric data (BVR) of the field stars of CB4 have been taken from the VizieR database of astronomical catalogues, namely, UCAC4 (Zacharias et al. 2013) and NOMAD (Zacharias et al. 2005). The B, V and R data of the star with serial number 79 are not available in these catalogues.

In Figure 1, the color – color diagram along with error bars for 19 field stars of CB4 has been plotted. It can be seen from the graph that most of the field stars are clustered together along a diagonal locus. These diagonally clustered stars in the color – color diagram represent the main-sequence stars, while the scattered ones (Stars 32, 66 and 76) represent non-main-sequence stars. So, we discarded these three stars from our analysis. To calculate r_s, we plotted uncertainties in $(J - H)$ and $(H - K_S)$ colors for 16 stars which are shown in Figure 2. The value is found to be 0.95. The results obtained from this technique are shown in Table 2.

4.2 Polarization Efficiency

The study of the variation of background star polarization with extinction (A_V) and polarization efficiency (defined as the ratio of p to A_V) can provide useful information regarding the nature of dust and the magnetic field associated with the cloud (Gerakines et al. 1995; Arce et al. 1998). The polarization efficiency depends on both the properties of the dust grains and the degree of alignment of the grains. Whittet (2003) calculated the theoretical upper limit which is given by $p/A_V \leq 14\%$ mag^{-1}. However, the observational upper limit of p/A_V is found to be $\sim 3\%$ mag^{-1}, a factor of four less than the predicted value for the ideal scenario.
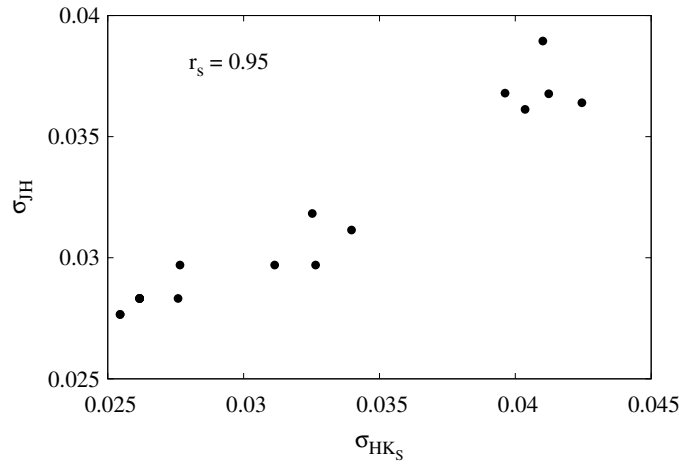
Fig. 2 The relation between σ_{HK_S} and σ_{JH} of the 16 stars. The r_s value indicates a strong correlation between the uncertainties of the two colors.

Table 2 Polarization (p), extinction (A_V), polarization efficiency (p/A_V) and distance (in pc) of 16 background stars in CB4. The second column refers to the star number which corresponds to the serial number in table 2 of Kane et al. (1995).

S/N	Star	p	A_V	p/A_V	d
		(%)		(% mag^{-1})	(pc)
1	1	0.30±0.05	0	–	261±48
2	9	1.66±0.41	0.40	4.15±0.53	161±30
3	11	1.26±0.38	0.23	5.48±0.51	264±49
4	14	0.49±0.08	0	–	259±48
5	17	2.85±0.38	0	–	248±46
6	18	1.52±0.06	1.05	1.45±0.41	1342±249
7	23	1.37±0.12	1.34	1.02±0.43	459±85
8	26	1.07±0.04	0.24	4.46±0.34	353±65
9	35	0.27±0.07	0.16	1.69±0.36	446±83
10	36	1.16±0.15	0	–	867±162
11	41	1.94±0.23	0	–	420±78
12	52	0.97±0.12	0.45	2.16±0.37	555±103
13	61	0.47±0.08	0.44	1.07±0.40	802±149
14	62	1.14±0.27	0.81	1.41±0.55	720±134
15	71	0.55±0.12	0.59	0.93±0.40	878±163
16	77	1.51±0.25	0.35	4.31±0.54	553±103

In this work, we will study the polarization efficiency of background field stars of CB4 to investigate the alignment of non spherical dust grains. It can be noted that we designated all field stars by their serial number used in Kane et al. (1995)'s paper and this numbering is shown in column number two of Table 1. The extinction value and polarization efficiency of background stars are shown in Table 2. In Figure 3(a), we plot A_V versus p for all the field stars in cloud CB4. The solid line in the figure represents the optimum alignment in the general interstellar medium according to Serkowski et al. (1975): $p_{max}/A_V = 3\%$ mag^{-1}, where $R_V = 3.1$. It can be seen that only four stars

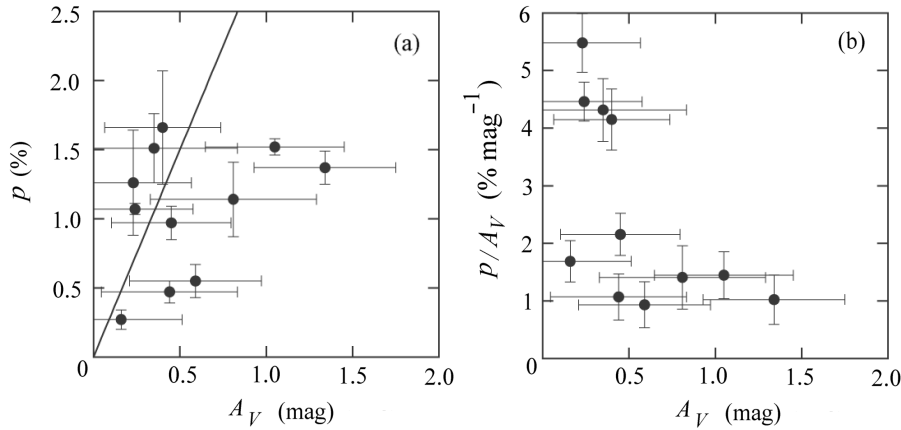**Fig. 3** (a) Plot of A_V versus p for 11 field stars. The solid line in the figure represents the optimum alignment in the general ISM according to Serkowski et al. (1975): $p_{\mathrm{max}}/A_V = 3\%$ mag^{-1}, where $R_V = 3.1$. It can be seen that four stars are located outside the limit. (b) plot of A_V versus p/A_V (where $R_V = 3.1$) for 11 background stars (see Table 2).

are located outside the limit and the majority of stars lie below the solid line which suggests that the characteristics of material composing CB4 are consistent with those of the material found in the diffuse interstellar medium (ISM).

In Figure 3(b), we plot A_V vs. p/A_V for CB4. The plot shows that the polarization drops with increasing extinction. Thus background stars observed through the dense region of the cloud show a smaller degree of polarization, suggesting much lower dust columns in the observed lines of sight. This suggests that the observed polarization at the optical region in a particular line of sight which intercepts a dark cloud shows a dominance by dust grains in the outer layers of the cloud. Recently, Chakraborty et al. (2014) found a trend of decreasing polarization efficiency with increasing extinction which can be well represented by a power law, $p_V/A_V \propto A_V^{-\alpha}$, where $\alpha = -0.56 \pm 0.36, -0.59 \pm 0.51$ and -0.52 ± 0.49 for Bok globules CB56, CB60 and CB69, respectively. It can be noted that the study of polarization efficiency at the optical region can give us information about the grain alignment in outer layers of the cloud. The alignment of grains by radiative torque has been used by researchers to calculate the expected relationship between polarization efficiency and extinction through a homogeneous cloud (Dolginov & Mitrofanov 1976; Draine & Weingartner 1996, 1997; Lazarian & Hoang 2007; Hoang & Lazarian 2014).

4.3 Estimation of Distance

The photometric distance d to a star is estimated using equation

$$d \text{ (in pc)} = 10^{(K_S - M_{K_S} + 5 - A_{K_S})/5}, \tag{4}$$

where K_S, M_{K_S} and A_{K_S} are the apparent magnitude, absolute magnitude and extinction, respectively. The distance to the cloud is typically estimated from the first star that shows a sharp peak in extinction in an A_V vs. d plot. It can be noted that $A_{K_S} = 0.112 \times A_V$.

The uncertainty in distance is estimated using the expression (Maheswar et al. 2010),

$$\sigma_d = \sqrt{(\sigma_{K_S}^2 + \sigma_{M_{K_S}}^2 + \sigma_{A_{K_S}}^2) \times (d/2.17)^2}, \tag{5}$$
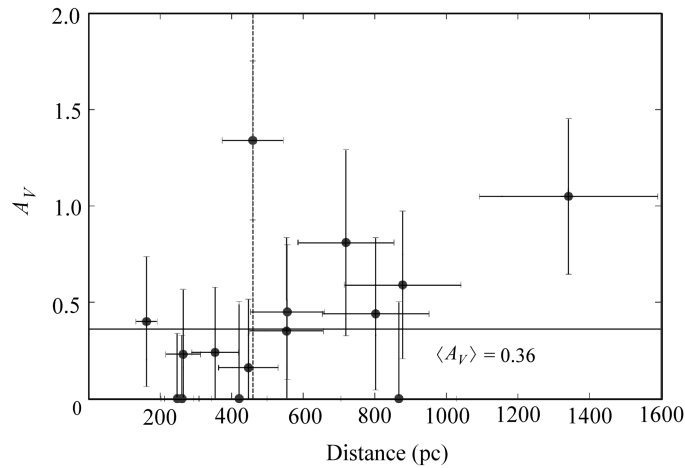
Fig. 4 Extinction (A_V) versus distance to stars in the vicinity of CB4. The average extinction ($\langle A_V \rangle$) of all the field stars is 0.36 and is shown by the solid line. The vertical dashed line is drawn at a distance of 459 pc where a sudden rise in the A_V occurs.

where σ_{K_S} is the uncertainty in the K_S band, $\sigma_{M_{K_S}}$ is the uncertainty in the estimation of the absolute magnitude and $\sigma_{A_{K_S}}$ is the uncertainty in the A_{K_S} estimated by the method. The uncertainty in the $\sigma_{M_{K_S}}$ is assumed to be 0.4 while calculating σ_d in the distances to all the stars. The typical errors in our distance estimates for the field stars in CB4 are $\sim 19\%$.

The extinction (A_V) versus distance (d) plot has been extensively used by several investigators (Dickman & Clemens 1983; Kenyon et al. 1994; Peterson & Clemens 1998; Maheswar et al. 2004, 2010 etc.) to determine the distance to globules. It can be noticed that the extinction of stars located in front of the dark globule shows a reddening value of almost zero. The presence of the cloud causes a sudden rise in extinction at a certain distance. The distance to the cloud is typically estimated from the first star that shows a sharp peak in A_V. We notice from Figure 4 that star number 23 shows a sudden rise in extinction and then a fall in extinction is observed. Thus the distance to the cloud is (459 ± 85) pc. Using the foreground star method and color excess approaches, Dickman & Clemens (1983) estimated the distance to CB4 to be $\sim 500 - 700$ pc. They therefore adopted 600 pc as the distance to this globule. The distance determination using JHK NIR photometry is slightly smaller than the distance derived by Dickman & Clemens (1983). However, the present analysis is restricted to a limited number of data points.

5 SUMMARY

(1) The polarization efficiency of CB4 is studied and shows a decrease in polarization efficiency with an increase in extinction along the observed line of sight. This finding is consistent with the results obtained for other clouds in the past.
(2) The method for determining distances to Bok globules using the NIR photometric technique has been described. The plot of A_V versus d has been made and the distance at which A_V shows a sudden rise of extinction is taken as the distance to the cloud. From the study of the distribution of reddening, we estimate a value of (459 ± 85) pc for the distance to CB4.

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