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Distance Estimation of Bok globule CB69

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Abstract— Determining the distance of small, opaque dark clouds is particularly challenging due to their compact size. In this research, we have employed the near-infrared (NIR) photometric technique to compute the distance of Bok globule CB69. This method involves estimating the extinction (Av) of field stars using NIR data taken from the 2MASS catalogue, in conjunction with distance data obtained from Gaia. From the extinction (Av) versus distance (d) plot, the stars that exhibit an unexpected rise in extinction are considered the distance of the cloud. Consequently, we have estimated the distance to this CB69 cloud, as approximately 461±4 parsecs, respectively. This value aligns with previously published literature.

Keywords: dark clouds, extinction-ISM, distance-stars, formation-stars.

INTRODUCTION

For understanding the process of star formation, knowledge of the structure and physical conditions in molecular clouds is of great importance. The basic property of a molecular cloud is distance and is commonly a crucial part of molecular cloud catalogues (Miville-Deschênes *et al*. 2017; Colombo *et al*. 2019) The most simple and reliable way to estimate molecular cloud structure is to evaluate the dust extinction of background starlight. We have designed a new powerful approach for estimating and mapping the distribution of dust through a molecular cloud utilising data acquired in a near-infrared imaging survey. The estimation of the distance to an interstellar cloud is crucial for any celestial object. To calculate numerous significant physical properties, including masses, and densities (Clemens *et al*. 1991), distances to interstellar clouds are essential. The significant properties, like the luminosity of the star-forming cloud, cannot be determined without knowing the distance.

The accurate measurement of the distance of the molecular cloud is very tough, though it is not impossible. As an illustration, star counting is a technique of low accuracy (Wolf 1923) that experiences large systematic errors established by the assumed distribution of stars. Regardless of the difficulties, presently the NIR photometric technique appears to be of the utmost trustworthy for estimation of the distance. Previous research by Choudhury *et al.* (2019) utilised Gaia DR3 to estimate distances to faint stars near molecular clouds, a method useful for determining stellar extinction and absolute magnitudes—key parameters for near-infrared photometry. In this investigation, we refine this approach by the introduction of a near-infrared photometric technique and employing the Gaia database to evaluate the distance to Bok globule CB69 as 461±4 pc.

DETAILS OF THE GLOBULE CB69

It is an A-type cloud and is designated by another name, B49. In this cloud CB69, while the polarisation vectors exhibit good alignment, their collective orientation does not conform to the expected Galactic Plane alignment (120^0). Six *IRAS* sources are available in the CB69 cloud (16594 - 3315, 16595 - 3311, 16586 - 3304, 16589 - 3315, 16590 – 3313, and 16590 - 3305: Clemens and Barvainis 1988). The average location angle and polarisation values for CB69 field stars are θ_{av} = 155.8^0 and p_{av} = 2%, having standard deviations σ_θ = 13.06^0 and σ_p = 1.12%, respectively.

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DISTANCE TO DARK MOLECULAR CLOUD

Bok globules or dark clouds are small, compact, and isolated neighbouring molecular clouds. Bok (Bok and Reilly 1947) was the first to recognise the significance of this globule in the star formation process. In general, the distance measurement of bok globules is very difficult due to their small size and opaqueness, which limits the application of star counts or photometric techniques as distance indicators. Addressing the challenge of determining distances to small Bok globules, (Das *et al.* 2015) applied the near-infrared photometric technique developed by (Maheswar *et al.* 2010) using extensive JHKs photometric data from the 2MASS catalog. Building upon this method, (Barman and Das 2015) estimated the distance to CB4 as 459±85 pc. More recently, Zuicker *et al.* (2019) utilised Gaia DR2 to create a catalogue of precise distances to molecular clouds according to extinction breakpoint. (Yan *et al.* 2019) determined distances to molecular clouds at high galactic latitudes using parallax (Lindegren *et al.* 2018) and G-band extinction estimates of stars along the clouds' sight lines from Gaia/DR2. Interstellar extinction gives a further approach to infer molecular cloud distances. Generally, the method of extinction was classified as a member of low accuracy, but because of the release of the Gaia DR3 catalogue (Gaia collaboration 2022), its precision has grown remarkably. The distance and visual extinction of molecular clouds is investigated (Sun *et al.* 2021) in the Milky Way (MBM) catalogue at |b| > 20°, combining accurate colour excess measurements with distance metrics from the third release of Gaia Early Data (Gaia/EDR3). A previous study employing a near-infrared photometric method and Gaia data (Choudhury *et al.* 2019) determined the distance to Bok globule CB17 as 253±43 pc. Launhardt and Henning (1997) estimated the distance to the CB69 cloud using the kinematic distance method, which was the best available technique at the time, as Gaia data was not yet available. Their estimate, approximately 500 pc, was based on the motion of the cloud relative to the local standard of rest. With the release of the Gaia data by the (Gaia collaboration 2022), more accurate and precise stellar distances became accessible. To determine the distance of Bok globule CB69, we employed a near-infrared (NIR) photometric technique. This method involves estimating the extinction (Av) of field stars using NIR data taken from the Two Micron All-Sky Survey (2MASS) catalogue, combined with the precise distance data from Gaia. In this research, we build upon this approach by utilising the near-infrared photometric technique and Gaia DR3 to estimate the distance to the dark cloud CB69. The key selection criteria for the sources analysed in this research are outlined in Table 1.

Table 1: Observational Log of Dark Cloud CB69 within 25×25 arcmin^2 Star Field Area.

Sl No.	ID(25′×25′)	RA(2000) (hms)	DEC(2000) (° ′ ″)	l(⁰)	b(⁰)	Distance, d (ref.) (pc)
1.	CB69	17:02:42	-33:17:00	351.23	5.14	500(1)

Distance References: (1) Launhardt & Henning (1997)

ESTIMATION OF EXTINCTION (AV)

Near-Infrared Photometric Study

The near-infrared photometric approach relies on determining absolute magnitude (M_{K_s}), distance (d), and extinction (Av) using information from the Two Micron All-Sky Survey (2MASS) catalogue, intrinsic colours of main-sequence stars, and the reddening law of (Rieke and Lebofsky 1985). This method validated by (Maheswar *et al.* 2010), has been extensively embraced for estimating stellar distances. While it's been successfully applied to evaluate the distances of some small Bok globules by (Das *et al.* 2015), its accuracy is limited by the existence of three unknown variables within the model.

By combining Gaia DR3 parallax measurements with stellar photometry, we can infer the distances to faint stars in the vicinity of a molecular cloud, which enables us to approximate the extinction in the region and absolute magnitudes of stars (for three filters, J, H, and K_s) precisely by applying the NIR approach. The technttique evolved in this instance by (Choudhury *et al.* 2019) is explained below.

The photometric distance of a star can be evaluated utilising the subsequent equation

$$X - M_X = 5(\log d - 1) + A_X \quad (1)$$

where X, A_X, and M_X are the apparent magnitudes, extinctions, and absolute magnitudes of stars in the three filters J, H, and Ks, respectively.

Simplifying equation (1), we get

$$A_V = \frac{1}{\left(^{A_X}/_{A_V}\right)}[(X - M_X) + 5(1 - \log d)] \quad (2)$$

Observationally, visual extinction (Av) is associated with A_J, A_H, and A_{Ks}. As stated by the law of extinction (Rieke and Lebofsky 1985), $A_J/A_V = 0.282$, $A_H/A_V = 0.175$, $A_{Ks}/A_V = 0.112$. Instead of 2MASS, the Galactic Centre in the Arizona-Johnson photometric system provided this extinction law. Since the values of MJ, MH, and MKs are unknown, the visual extinction (Av) is estimated using the iteration technique, which finds the collection of values for MJ, MH, and MKs that best fits the equations obtained for three filters using equation (2). Specifically, we have integrated the Gaia database into our method to estimate the parallax of stars within the dark cloud. With the use of parallax and parallax uncertainties, the individual star distances connected to the dark cloud are quantified in addition to their uncertainty.

Determination of Av

Near-infrared photometric data for field stars within 30′ × 30′ field of view centred on CB69 were extracted from 2MASS All-Sky Catalogue (Cutri *et al.* 2003). Data selection criteria included:

(i) The photometric uncertainty ≤ 0.045 magnitudes in all J, H & K_S bands.

(ii) High quality photometric flag 'AAA' in all three bands that exhibits a SNR > 10.

(iii) The difference in magnitudes ($J-K_s$) ≤ 0.75 to exclude M-type stars from the study.

We have assessed the parallax of stars whose J, H, and Ks magnitudes are first acquired from the two MASS catalogues using the Gaia DR3 database (Gaia collaboration 2016, 2022). Table 2's second column displays data for 62 CB69 field stars in addition to their 2MASS identification numbers. In the same way, we have categorised all the parallax information that would have been used to estimate the uncertainty in the distance and the distance of individual stars, provided that the uncertainty in the distance is less than 2500 pc and the parallax of a single star is greater than zero.

Table 2: Identified Stars of Field in CB69. Columns 1, 2, 3, and 4 Represent the Star Serial Number, 2MASS Identification Number, Distance (in pc), and Visual Extinction (in mag).

Star	2MASS	d(pc)	Av(mag)	Star	2MASS	d(pc)	Av(mag)
1	17014317-3309016	1901.502	0	32	17023251-3322039	462.3209	1.02937
2	17014342-3314353	586.3727	0.84089	33	17023308-3305259	1002.506	0.95235
3	17014346-3321593	490.148	0	34	17023765-3313184	193.6333	0.00035
4	17014412-3317253	802.1176	0.17663	35	17024339-3318002	461.2121	0.68261
5	17014784-3308558	423.4776	0.60585	36	17024501-3324185	1835.199	0.8886
6	17014846-3312338	565.6109	1.31706	37	17024569-3326096	415.0928	0.02934
7	17014858-3323172	1557.39	0.77664	38	17024661-3307354	1152.472	1.60584
8	17014877-3316280	1418.239	0.28813	39	17024868-3321172	1635.858	1.06479
9	17014975-3322592	1015.125	0	40	17025090-3325049	868.7343	0.8708
10	17015174-3311414	1827.485	0	41	17025100-3308426	1245.795	0.14101
11	17015232-3328588	1155.001	0	42	17025518-3322361	1141.683	0.63572
12	17015385-3315034	1186.662	0.04739	43	17025838-3325516	890.8686	0.77636
13	17020259-3315269	283.1337	0.00015	44	17025930-3304563	1258.495	0.14093
14	17020408-3309232	1010.816	0.31787	45	17030252-3324122	1508.751	0
15	17020519-3323350	1373.815	0.02964	46	17030664-3311351	850.1955	0.04753
16	17020779-3311355	309.8757	1.61724	47	17031058-3310232	1995.211	0
17	17021052-3328473	1841.621	0	48	17031348-3328133	1635.59	0
18	17021120-3305314	553.5872	0.00025	49	17031456-3308454	377.3727	0.00052

(Table 2 Contd....)

(...Contd. Table 2)

19	17021145-3321030	554.0166	0.04747	50	17031677-3307210	1211.681	1.41156
20	17021353-3319306	1507.386	0.57049	51	17031828-3321263	1763.047	0
21	17021475-3318182	876.0403	1.11127	52	17031895-3310435	682.2213	0.88785
22	17021846-3318154	1037.129	0.01715	53	17031901-3305435	1362.398	0.0939
23	17021894-3310219	169.0674	0.09468	54	17031958-3327413	398.8354	0.00011
24	17021908-3318380	757.6332	0.74718	55	17032325-3315357	1805.38	0
25	17022078-3329073	945.1796	0	56	17032335-3307260	720.0461	1.0468
26	17022124-3327059	1617.338	0.57091	57	17032379-3324455	1007.151	0.47705
27	17022423-3309219	348.5171	0.15915	58	17032546-3307211	1301.236	0.04688
28	17022455-3323578	843.4548	0	59	17032688-3311385	738.607	0.98203
29	17022676-3316383	1323.627	0.00061	60	17032833-3305173	1452.855	0
30	17023048-3315108	239.3432	0.3826	61	17033111-3319297	570.4181	0.77685
31	17023196-3324140	1951.22	0.09386	62	17033308-3321107	966.4637	0.77685

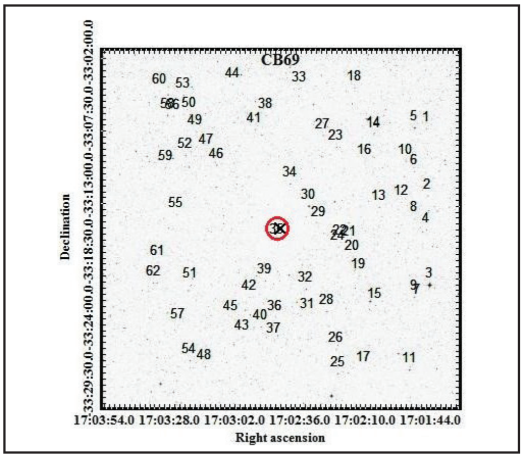

Fig 1: Designated Field Stars in the Neighbourhood of the CB69 Cloud with 30×30 Arcmin^2. The × Mark Indicates the Centre of the Cloud. A Circle Around Star Number 35 Denotes the Cloud's Distance from us and Shows an Abrupt Increase in Visual Extinction.

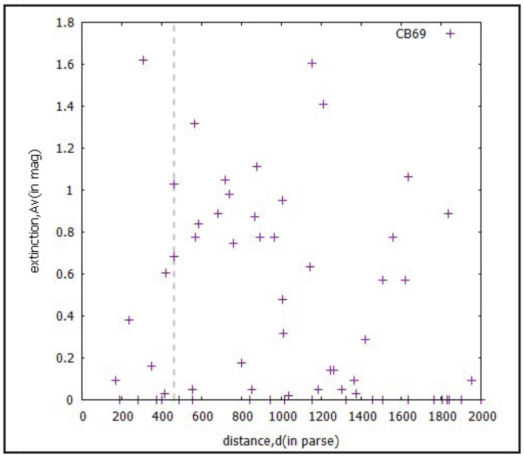

Fig 2: Distance, d Versus Visual Extinction, Av be Designed for Stars Projected Towards the CB69 Cloud. The Upright Dotted Dash is Represented at a Distance of 461±4 pc (Star 35; Table 2), where an Abrupt Rise in Av Occurs.

Thus, the values of visual extinction (Av) of individual stars are obtained by utilising the Gaia data and the near-infrared photometric technique. Plotting each star's distance (d) against visual extinction (Av) yields the distance indicator for that specific dark cloud. The vertically dotted line denotes an unexpected increase in extinction. As illustrated in Fig. 1, 62 field stars of the dark cloud CB69 are estimated in the current study. Furthermore, based on the results of this work shown in Table 2, we have created a distance versus extinction plot for each and every field star in this dark cloud, which is displayed in Fig 2. For the CB69, this plot shows a rapid surge in the value of extinction at a distance of 461±4 pc. As a result, we estimated the CB69 cloud's distance to be 461±4 pc, which is in good accord with (Launhardt and Henning 1997). In that investigation, Gaia DR3 is presented to determine the first accurate distance to the cloud CB69 for the first time. Table 3 highlights the literature distance together with the distance acquired from our present study.

Table 3: Details of Distance of the CB69 Dark Cloud.

S. No.	Cloud	d (Literature) (pc)	d (Our Study) (pc)
1	CB69	500	461±4

CONCLUSIONS

We have evaluated the distance to dark cloud CB69 utilising the technique of near-infrared photometry and Gaia data. Our new estimate for the distance to CB69 is 461±4 pc which is almost comparable with previously published work suggested by (Launhardt and Henning 1997). The difference between our distance estimate of 461±4 pc and the previously reported 500 pc can be attributed to the superior precision of Gaia data, which offers direct measurements of stellar distances. Furthermore, the variation of distance and visual extinction for 62 field stars of the CB69 cloud is designed, where a sharp rise in the extinction value represents the first real distance indicator for this dark cloud.

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