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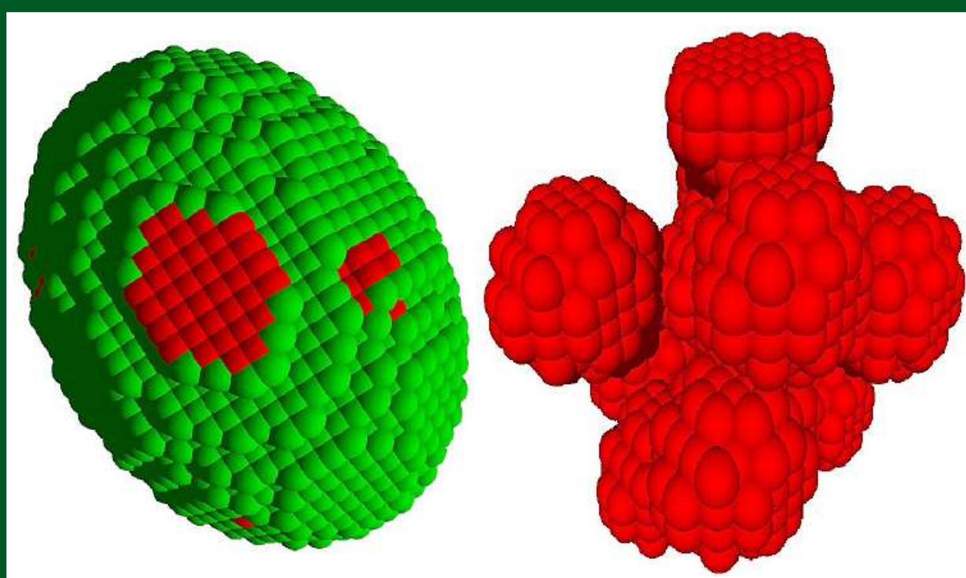

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Extinction map of a small globule CB 224

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The column density distribution of molecular cloud can be studied through thermal continuum imaging of the cold dust, CO mapping or extinction maps. The Near Infrared Color Excess (NICE) method is an excellent tool to determine the visual extiction from measurement of NIR color excess and also to map the dust column density through star forming clouds. In the present work, the visual extinction map of a small and roundish globule CB 224 has been constructed using the NICE method. The map shows one core near to the center of the globule which is highly extincted and shows the maximum optical extinction of 17.2 magnitude. The central column density is estimated to be $N_H = 3.4 \times 10^{22}$ cm^{-2} mag^{-1}. The visual extinction map is also compared with the SCUBA 850 μm continuum map which also shows one prominent core close to the center of the globule. This study shows that the visual extinction map matches well with 850μm continuum map which is quite expected as the region of higher visual extinction corresponds to higher densities of dust.

Keywords: Molecular cloud, Near Infrared Color Excess (NICE) technique, Visual extinction map, Cygnus region.

1 Introduction

The study of molecular clouds at eary stages of star evolution is important to understand the star formation process. To determine the projected structure of a molecular cloud, the variation of an observeable column density across the cloud need to be estimated. Measurement of dust extinction using near- infrared color excess technique is an excellent tool to determine the column density distribution of molecular cloud. The mapping of extinction at optical and NIR wavelengths can be done using star counting [1,2], color excess techniques (e.g. NICE, NICER & NICEST) [3-7] and combination of both [8].

Kandori *et al* [9] constructed the visual extinction maps of some globules using both star count and NICE method which were used to study the distribution of visual extinction. They also studied the stability of the equillibrium state of these globules against gravitational collapse using Bonnor-Ebert sphere model. Racca *et al* [10] used the NICE method to construct visual extinction map of a sample of 21 southern Bok globules (11 are starless and 10 have associated IRAS point sources). Lombardi [7] applied NICEST to 2MASS data of Pipe molecular complex and showed a few preliminary properties of the resulting extinction map.

2 The globule CB 224

CB 224 is a small and roundish globule located in the northern Cygnus region at a distance of about (378 ± 70) parsec [11]. The core of this cloud has two millimeter (mm) sources which are detected at all three (sub) mm bands. One of the sources located in northeastern position is associated with the cold IRAS source and with a red star which can be observed at optical domain. The other source (located at southwest position) which is brighter than the first source is associated with a very faint and diffuse NIR nebula [12].

3 NICE method

The Near-Infrared Color Excess (NICE) method was originally developed by Lada *et al* [3] which combines measurement of NIR color excess to directly determine the extinction and also to map the dust column density through a molecular cloud. In this work we adopted the NICE method developed by Rowles and Froebrich [6] to construct the visual extinction map. In this method, the median color of all stars at the position of each pixel has to be determined. Then, each of median color maps has to be converted into the

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respective color excess map so that one can determine the extinction/column density of material. Since the median color of the stars without Bok globules varies with position in the Galaxy due to different stellar populations, it is necessray to fit spline function describing the median color of stars in extinction-free regions in the maps.

The main advantage to use the median color instead of the mean color is that it eliminates instrinsically red, young stars, which may influence the mean. Further, the median ensures that one either determines the correct color excess/extinction of a cloud or measures no extinction. This ensures that if there are more background stars located in the cloud, one can determine the median color of background stars which can result a correct color excess. If more number of foreground stars are located in the given lines of sight of the cloud, the median corresponds to the color of the foreground stars and we could not estimate the extinction.

To construct the extinction map, we collected the J, H and K_s magnitudes of stars from the 2MASS all Sky Catalog of Point Sources [13] which show photometric quality flag of "AAA" in all three filters which actually corresponds to signal-to-noise ratio (SNR) > 10.

The color excess is determined using the following relation [6]

$$< J - H >_{(l,\,b)} = [J - H]_{(l,\,b)} - \text{fit}[J - H]_{(l,\,b)} \tag{1}$$

where (l,b) denotes the position of the map. The extinction in the H-band can be determined as

$$\mathrm{A}_{H,<J-H>} = \frac{<J - H>}{\left(\frac{\lambda_H}{\lambda_J}\right)^{\beta} - 1} \tag{2}$$

$$\mathrm{A}_{H,<H-K>} = \frac{<H - K>}{1 - \left(\frac{\lambda_K}{\lambda_H}\right)^{-\beta}} \tag{3}$$

Rowles and Froebrich [6] used the value of β to be 1.7 since the previous studies show that it lies between 1.6 and 2.0 [14,15]. The Optical extinction is thus given by [6]

$$A_V = \frac{5.689}{2}.(A_{H,<J-H>} + A_{H,<H-K>}) \tag{4}$$

where, the factor 5.689 is the conversion of H- band into optical extinction taken from Mathis [16].

3.1 Statistical uncertainties

The uncertainties of the median colors of stars in each pixel are given by Rowles & Froebrich [6],

$$\sigma_{J-H} = \frac{1.253}{\mathrm{N}}.\sqrt{\sum_{i=1}^{N}(\sigma_J^i)^2 + \sum_{i=1}^{N}(\sigma_H^i)^2}, \tag{5}$$

where N denotes the total number of stars used for this pixel and are the individual J-band and H-band uncertainties in the photometry of the star i.

The corresponding errors in the H-band extinction determined from the color excess are given by

$$\sigma_{\mathrm{A}_{H,<J-H>}} = \frac{\sigma_{<J-H>}}{\left(\frac{\lambda_H}{\lambda_J}\right)^{\beta} - 1} \tag{6}$$

and

$$\sigma_{\mathrm{A}_{H,<H-K>}} = \frac{\sigma_{<H-K>}}{1 - \left(\frac{\lambda_K}{\lambda_H}\right)^{-\beta}}, \tag{7}$$

Thus the uncertainty in the A_v is given by

$$\sigma^2_{A_v} = \left(\frac{5.689}{2}\right)^2 \cdot (\sigma^2_{A_{H,<J-H>}} + \sigma^2_{A_{H,<H-K>}} + 2.\sigma_{cov}) \tag{8}$$

where σ_{cov} is the covariance of the two extinction maps.

4 Extinction map

In Fig 1(a), the visual extinction map of CB 224 has been constructed using NICE method which has a dimension of ~ 25′ × 25′, and a spatial resolution of 34". The map shows a prominent core near the center of the globule which is highly extincted and shows the maximum optical extinction of 17.2 magnitude. The hydrogen column density in terms of visual extinction is given by Bohlin *et al* [17]

$$N_H = 2 \times 10^{21}\ A_v\ cm^{-2}\ mag^{-1}, \tag{9}$$

In the above equation NH is the total column density of hydrogen atoms (= $N_{H\,I} + 2\ N_{H2}$), and A_V is the extinction in the V-band. The central density of CB224 is estimated to be $N_H = 3.4 \times 10^{22}$ cm^{-2} mag^{-1}. Knowing total column density and distance to the cloud, it is possible to determine the total mass of the embedded dense core, but this is beyond the scope of the present work.

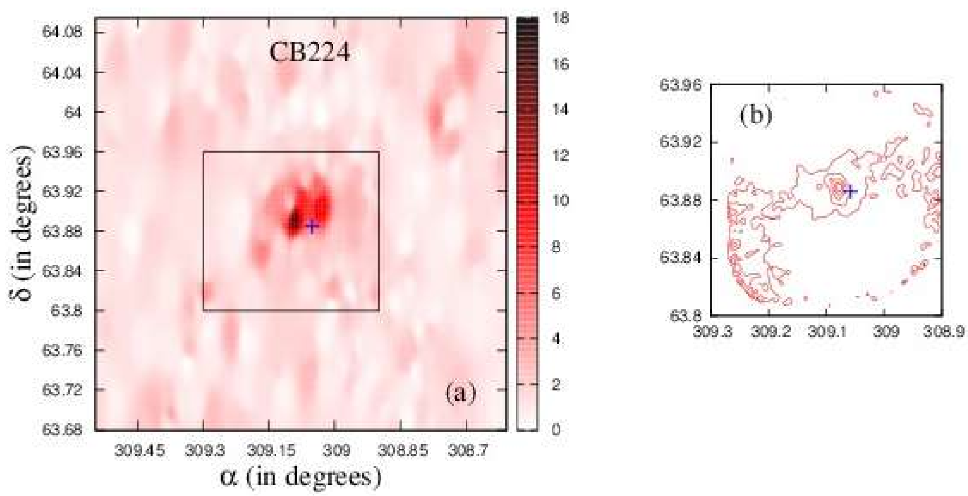

Fig 1. (a) Visual extinctio map (A_V) of CB 224 has been contructed using NICE method having dimension of ~ 25□ × 25□, and a spatial resolution of 34□□ and (b) the SCUBA 850 µm contour map constructed from the Extended Dataset. The contours are drawn at 0.04 to 0.44 J_y beam^{-1} in steps of 0.08 Jy beam^{-1}. In both figures, the '+' symbol represents the center of the globule having RA (2000) = $20^h\ 36^m 17.2^s$, DEC (2000) = 63° 53' 15". The box in Fig 1(a) denotes the dimension of 850 µm contour map.

In Fig 1(b), the Submillimetre Common User Bolometer Array (SCUBA) 850 µm contour map of CB 224 has been constructed. The SCUBA 850 µm continuum map of this cloud has been downloaded from CADC repository of the SCUBA Legacy Catalogues [18]. The contours are drawn at 0.04 to 0.44 Jy beam^{-1} in steps of 0.08 Jy beam^{-1}. One prominent core is observed close to the center of the globule whereas the second fainter core is not visible in this map. It is noticed from Fig 1(a,b) that the visual extinction map matches well with continuum map which is quite expected as the regions of higher visual extinction correspond to higher densities of dust.

5 Summary

- The visual extinction map of CB 224 has been constructed using the NICE method. One prominent core with maximum optical extinction of 17.2 magntude is observed close to the center of the globule.
- The central colun density is estimated to be $N_H = 3.4 \times 10^{22}$ cm^{-2} mag^{-1}. The total gas mass of a molecular cloud can be estimated from the knowledge of total column density of the cloud if the distance to the cloud is known.
- It is observed that both visual extinction map and SCUBA 850 µm contour map of CB 224 show one prominent core close to the center of the globule. It is further noticed that the visual extinction map matches well with 850 µm continuum map.

Acknowledgements

The SCUBA 850 µm continuum map of CB 224 cloud has been downloaded from CADC repository of the SCUBA Legacy Catalogues which is highly acknowledged. We also acknowledge the use of the VizieR database of astronomical catalogues namely Two Micron All Sky Survey (2MASS), which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the Natioonal Science Foundation. This work is supported by the Science and Engineering Research Board (SERB), a statutory body under Department of Science and Technology (DST), Government of India, under Fast Track scheme for Young Scientist (SR/FTP/PS-092/2011).

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Dr Das was honored by Hon'ble President of India **Shri Pranab Mukherjee** in the Inspired Teachers' In-Residence Programme at Rashtrapati Bhavan held during **6th June to 12th June, 2015**. Inspired Teacher (alternatively termed President's Inspired Teacher) is the highest civilian recognition for University-level teachers in the Republic of India in the form of an In-Residence Programme with the President of India at Rashtrapati Bhavan, New Delhi. He was also honored by Paragon, an NGO in Badarpur (Assam), with **Paragon Excellence Award-2015** on **January 30, 2016** for the service rendered in the field of Education and Nation building.

Dr Das is also President of Barak Astronomy Club, Silchar (Assam). He conducted many sky watching programme at different regions of North East India to popularize Astronomy.

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