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Mapping dust column density in dark clouds using NIR scattered light

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Abstract. A method of mapping dust column density in dark clouds using near-infrared scattered light is presented. Deep NIR observations have revealed that the Lupus 3 dark cloud appears as a NIR reflection nebula. The observations indicate that there is a well-defined relationship between (1) the $H - K_s$ color of individual stars behind the cloud, i.e., the dust column density, and (2) the surface brightness of scattered light towards the stars in each of the J, H, and K_s bands. Using a simple one-dimensional radiation transfer model, we derived the empirical equations that plausibly represent the observed relationship between the surface brightness and the dust column density. Using the empirical equations, we estimated the dust column density of the cloud for any direction towards which even no background stars are seen. We obtained a dust column density map with a pixel scale of $2.3'' \times 2.3''$ and a large dynamic range of up to Av = 50 mag.

Keywords : ISM: clouds — dust, extinction — infrared: ISM

1. Introduction

Dark clouds are seen as dark patches against bright star fields, while they are observed as reflection nebulae at near-infrared (NIR) wavelengths. The Lupus 3 dark cloud is one of the nearest dark clouds at a distance of 150 pc. Nakajima et al. (2003) showed that the Lupus 3 dark cloud appears as a NIR reflection nebula. The surface brightness of the nebula can be explained by scattering of light from the background stars by dust inside the dark cloud (Nakajima et al.

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2003). This is not just the case for the Lupus dark cloud. NIR scattered light from a dark cloud called the Thumbprint Nebula was first reported by Lehtinen and Mattila (1996). Recently, Foster and Goodman (2006) also reported one from dark clouds in Perseus. The images of NIR reflection nebulae give us an insight that darker areas with fewer background stars have larger column densities. The purpose of this study is to quantify the relationship between the surface brightness and the column density.

Star counting, colour excess of background stars, molecular gas and thermal dust emissions have been used for column density mapping of dark clouds. Juvela et al. (2006) and Froebrich & Rowles (2010) (in this issue) reviewed these methods intensively. Each of these methods has limitations. A common limitation to all these methods is that it is hard to obtain a high spatial resolution. Padoan et al. (2006) and Juvela et al. (2006) examined the use of scattered NIR surface brightness as a new high resolution tracer of the interstellar clouds. They derived an analytical formula to convert NIR surface brightness to visual extinction. The formula is linear at low visual extinctions and starts to saturate when visual extinction reaches ~ 10 mag. Juvela et al. (2006) used numerical simulations and radiative transfer calculations to show that the NIR surface brightness can be converted to column density in the range of $A_V < 15$ mag with an accuracy of better than 20%. Juvela et al. (2008) applied the method to a filamentary cloud in Corona Australis. The method using surface brightness and one using colour excess of background star agrees below $A_V \sim 15$ mag.

We proposed an empirical method of estimating column density of dark clouds up to $A_V \sim 50$ mag using NIR surface brightness. We re-examined the NIR data of the Lupus 3 dark cloud in Nakajima et al. (2003) and obtained plausible empirical equations which fit the observed relationship between the surface brightness and column density. Using this relationship, we obtained the dust column density map from the surface brightness with a spatial resolution as high as a few arcsec.

2. Data and analysis

We obtained the J, H, and K_s band data of the Lupus 3 dark cloud on 2001 June 4 and 7 with the IRSF 1.4 m telescope and the NIR camera SIRIUS. The total integration time was 135 minutes for each band. The details of procedures of observations and data reduction are described in Nakajima et al. (2008).

Firstly, we carried out photometry of the background stars to measure the $H - K_s$ colours of the background stars. The values of A_V towards the background stars are shown in Fig. 1(a). The A_V is estimated from the observed $H - K_s$ colour of each background star by $A_V = 18.0 \times [(H - K_s) -$

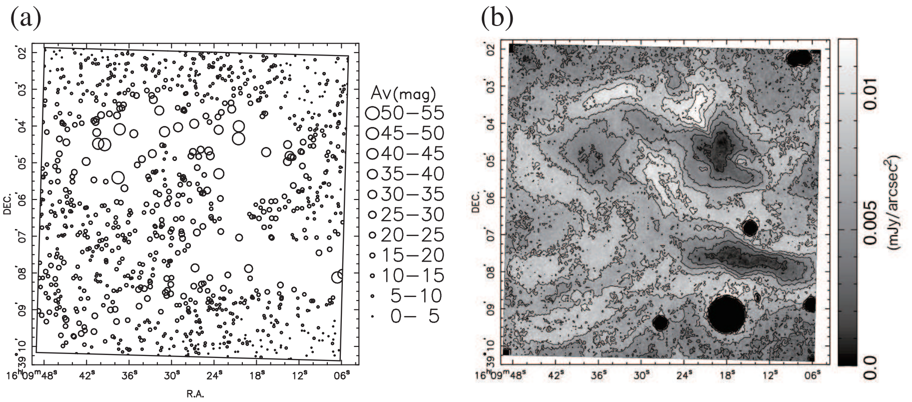

Figure 1. (a) : The A_V towards the background stars. The radius of circles represents the A_V. (b) : Surface brightness of the Lupus 3 dark cloud in the H band. Saturated stars are masked with circles in black. The lowest contour level denotes the 3-sigma limiting flux and the interval of contours is set to the 3-sigma limiting flux value at each band.

$(H - K_s)_{\rm intrinsic}]$. The conversion factor between A_V and the colour excess is calculated from the theoretical curve No. 15 of van de Hulst (1946).

Secondly, we calculated the surface brightness towards each pixel by taking the median value of $5 \times 5 = 25$ pixels centered at the pixel after subtraction of stars by using SUBSTAR routine in IRAF. This area corresponds to 2.3×2.3 arcsec^2, and the error was estimated from the standard deviation of the 25 pixels. The surface brightness in the H band is shown in Fig. 1(b).

Then, we compared the observed $H - K_s$ colour and the surface brightness in each band towards each background star. For this comparison we used $H - K_s$ instead of A_V, because $H - K_s$ is an observed quantity and A_V can have some uncertainty due to the conversion factor. We have shown the results in Fig. 2. We used only stars with a colour error of $\sigma_{H-K_s} < 0.14$ mag and a surface brightness (i) with a flux error less than 0.002 mJy arcsec^{-2} and (ii) with a flux larger than the 3-sigma limiting flux at each band. There is a well defined relationship between the observed $H - K_s$ colour and the surface brightness for each band.

3. Empirical formula

The surface brightness is, technically, a result of complex processes among dust grains and incident starlight, which depends on optical characteristics of dust and cloud geometry. However, we did not take such complex physical processes

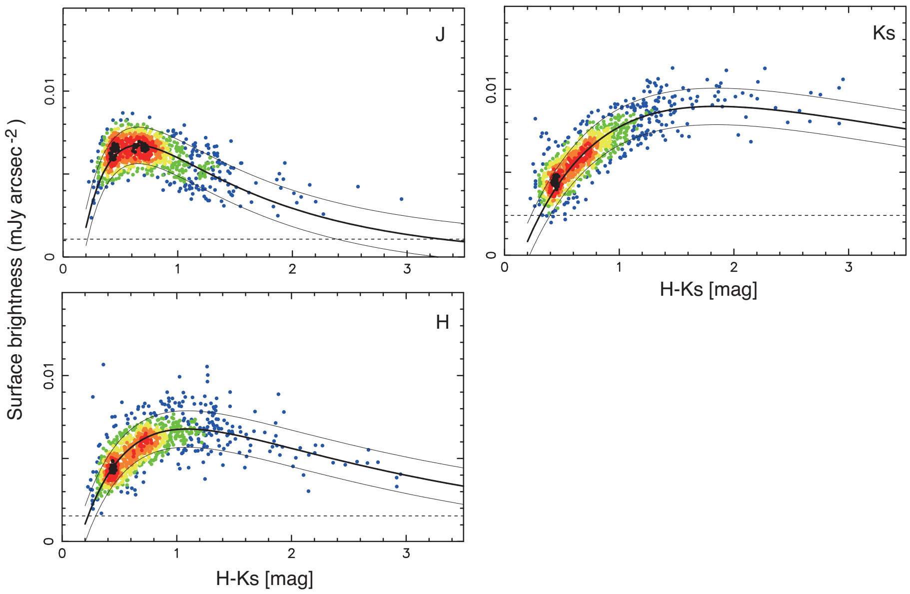

Figure 2. Relationship between $H - K_s$ and surface brightness towards background stars at J, H, and K_s. Colors of the points denote number density of the plot in the diagram; blue, green, yellow, orange, red, and black from low to high. The 3-sigma limiting fluxes are indicated by dashed lines.

into account; we considered the dark cloud as a black box and we tried to obtain an empirical relationship between the observed $H - K_s$ colour and the surface brightness. Then, using the empirical relationship, we tried to estimate the column density based on the surface brightness towards any direction even without background stars. We considered a simple scattering model to make an adequate fitting function to obtain an empirical relationship.

When dark clouds are illuminated uniformly by background radiation field and forward scattering by dust is dominant at the wavelengths, then, general one-dimensional radiation transfer equation is applicable; $dI_\lambda/ds = -(\alpha_\lambda + \sigma_\lambda)I_\lambda + \sigma_\lambda J_\lambda$. Here, α_λ, σ_λ and J_λ are the absorption coefficient, the scattering coefficient, and the mean intensity of the scattering material, respectively. If we define the parameter g'_λ as the probability of radiation being scattered in the forward direction, then J is replaced by $g'_\lambda I_\lambda$. Then we obtain $dI_\lambda/ds = -\kappa_\lambda I_\lambda + g'_\lambda \gamma_\lambda \kappa_\lambda I_\lambda$. Here, $\kappa_\lambda = \alpha_\lambda + \sigma_\lambda$ is the total opacity and $\gamma = \sigma_\lambda/(\alpha_\lambda + \sigma_\lambda)$ is the albedo. The observed intensity of scattered radiation is then $I_\lambda = I_{\lambda 0}[exp(g'_\lambda \gamma_\lambda \tau_\lambda) - 1]exp(-\tau_\lambda)$. Here, $I_{\lambda 0}$ is the average surface brightness of the initial intensity of radiation of background stars and $\tau_\lambda = \int \kappa_\lambda ds$ is the optical depth along the line of sight. Using the relationships $A_J = 4.39\ E(H - K_s)$, $A_H = 2.55\ E(H - K_s)$, and $A_{K_s} = 1.58\ E(H - K_s)$, we write $\tau_\lambda = 0.921 A_\lambda$ using $H - K_s$.

Consequently, we get the following equation with two free parameters, $I_{\lambda 0}$ and f_d.

$$I_\lambda = I_{\lambda 0}\ \{exp[f_d \times \alpha_\lambda(H - K_s - 0.15)] - 1\}\ exp[-1 \times \alpha_\lambda(H - K_s - 0.15)] \quad (1)$$

Here, α_λ is $\tau_\lambda/(H - K_s - 0.15)$ and equals to 4.04, 2.35 and 1.46 for J, H, and K_s, respectively. We set $(H - K_s)_{\rm intrinsic} = 0.15$ for this equation. The parameter f_d represents the product of g'_λ and γ_λ.

We fitted the relationship between the extinction and surface brightness by this equation and determined the two parameters. The results are indicated by the curves in Fig. 2. The central thick curve is the best fit and the thin curves above and below are best fit$\pm\chi_\nu$. Here, χ_ν denotes the reduced chi-square or dispersion around the best fit: 0.001. We considered that the area between the two thin curves defines the empirical relationship between the surface brightness and $H - K_s$, i.e., dust column density, in the diagram for each band.

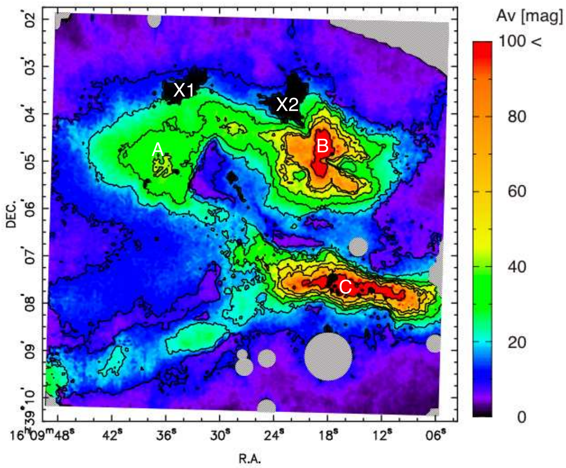

Figure 3. A_V map estimated from the surface brightnesses. Color scale indicates A_V in magnitude. The contour levels are 10, 20, 30, 40, 50, 60 and 100 mag. The pixels suffering from bad pixel clusters and saturated stars are hatched. Pixels with no solution are expressed in black.

4. Extinction map

We estimated a column density for each pixel from the surface brightnesses using the equation (1) and the best fit parameters. The resultant A_V map is shown in Fig. 3. The typical error is 30%. The procedure is as follows. Suppose that a pixel has surface brightnesses of $F_J \pm \sigma_{F_J}$, $F_H \pm \sigma_{F_H}$, and $F_{K_s} \pm \sigma_{F_{K_s}}$ at

J, H, and K_s, respectively. For example, in the J band graph of Fig. 2, intersections of $y = F_J$ and the empirical relationship give solutions of $x = H - K_s$ for the J band. Their errors are given by intersections of $y = F_J \pm \sigma_{F_J}$ and *the curved empirical relationship band*. When $y = F_J$ and the empirical relationship do not intersect but $y = F_J \pm \sigma_{F_J}$ and *the curved empirical relationship band* do intersect, a solution is given as the most likely point defined by the two areas; we assumed that each function has a gaussian probability distribution along the y-direction with σ=σ_{F_J} or the standard deviation of 0.001 mJy arcsec^{-2}, and calculated the product of the two gaussians to find the point with the maximum probability in the x-y plane. See Nakajima et al. (2008) for details. There are three dense cores; A, B and C. The maximum extinction is more than $A_V = 100$ mag. Since the fitting of the relationship was done in the range A_V less than 55 mag, the estimated extinction of $A_V > 60$ may be unreliable.

There are two outstanding black areas X1 and X2. There is a YSO with jet and cavity in the core B (Tachihara et al. 2007). The area X2 may be illuminated by the YSO through the cavity. Thus, the assumption of being illuminated by uniform background radiation field may be corrupted. Similarly, the area X1 may be illuminated by another unidentified source.

5. Comparison with previous studies

Padoan et al. (2006) and Juvela et al. (2006, 2008) developed a new method of mapping column density of dark cloud using NIR scattered light. Our method is based on similar considerations; however, our method has some new aspects. Our method uses an empirical formula whose parameters are directly calibrated by the colour excess of the background stars, while the previous studies used an analytic formula and used an extinction map derived from the colour excess just for comparison as an independent tracer. We do not use a smoothed extinction map but the colour excess of individual stars for comparison with the surface brightness towards each star. The use of individual background stars avoids the problems with the bias when there are few background stars (Juvela et al. 2008). By adopting a different formula, our method covers a part beyond the point where surface brightness starts to decrease with increasing column density, while the previous studies were done for only the non-saturated part of the relation.

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References

Foster J.B., & Goodman A.A., 2006, ApJ, 636, L105
Froebrich D., & Rowles J., 2010, in Proc. "Interstellar matter and star formation: A multi-wavelength perspective," ed. D.K. Ojha, 1
Juvela M., Pelkonen V.-M., Padoan P., et al., 2006, A&A, 457, 877
Juvela M., Pelkonen V.-M., Padoan P., et al., 2008, A&A, 480, 445
Lehtinen K., & Mattila K., 1996, A&A, 309, 570
Nakajima Y., Nagata T., Sato S., et al., 2003, AJ, 125, 1407
Nakajima Y., Kandori R., Tamura M., et al., 2008, PASJ, 60, 731
Padoan P., Juvela M., & Pelkonen V.-M., 2006, ApJ, 636, L101
Tachihara K., Rengel M., Nakajima Y., et al., 2007, ApJ, 659, 138
van de Hulst H.C., 1946, Rech. Astron. Obs. Utrecht, 11, 1