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DUST DISTRIBUTION IN L1217/L1219: NICE vs. NICER

S. Nikolić[1,2] and M. Kun[3]

[1] *Departamento de Astrononomía, Universidad de Chile*
Casilla 36-D Santiago, Chile

[2] *Astronomical Observatory*
Volgina 7, 11160 Belgrade 74, Serbia and Montenegro

[3] *Konkoly Observatory of the Hungarian Academy of Sciences*
H-1525 Budapest P.O.Box 67, Hungary

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SUMMARY: The dust in molecular clouds reliably traces the molecular gas within. We used this assumption to get an estimate of the dense cores size and mass in L1217/L1219 by deriving the total optical extinction, and therefore, the total column density. In this, two methods were used, the "standard" Near–Infrared Color Excess (NICE) and the Near–Infrared Color Excess Revisited (NICER). Results confirm that NICER is better in tracing the low level extinction areas, consequently making the total cloud's mass significantly larger, as compared to the NICE derived value.

Key words. ISM: clouds – dust, extinction

1. INTRODUCTION

Molecular clouds consist mostly of H_2. By mass, hydrogen makes up to 63%, helium amounts to 36%, while about 1% of the mass consists of dust, trace molecules and atoms. Obviously, to study molecular clouds the most appropriate would be if the most abundant molecule was observed. Unfortunately, direct emission from hydrogen in molecular form is rare: being a molecule without a permanent dipole moment it has very weak rotational transitions with the rotation levels energies much larger than the average kinetic temperature of, generally cold, molecular clouds. The lowest vibrational transitions occur in the near-infrared, difficult to observe from the Earth surface. Since the discovery of CO in the '70s molecular spectroscopy has become a powerful tool for these studies. The huge body of the trace molecules data in molecular clouds is often difficult to interpret e.g., the LTE approximation usually does not hold, opacity differs, chemical composition varies, clouds possess a small-scale structure, some molecules are depleted, interaction of the gas and the dust sometimes is not easy to understand... All this leaves the dust in the clouds as the most reliable tracer of H_2. Measurements of dust extinction of background starlight in the near infrared (NIR) wavelengths, where dust opacity is low, directly give a measure of the dust content of a molecular cloud. Only two assumptions are needed: that the interstellar extinction law is universal and that the gas–to–dust ratio in the clouds is constant. The accuracy of these assumptions may be assessed. Some studies suggest that the gas–to–dust ratio in a galaxy is inversely proportional to metalicity, $\sim 1/Z$ (Franco and Cox 1986), or even to $\sim 1/Z^2$ (Lisenfield and Ferrara 1998). Both Large and Small Magellanic Clouds have metalicities significantly smaller compared to Milky Way, $Z_{\rm LMC} \sim Z_{\rm Orion}/2$ and $Z_{\rm SMC} \sim Z_{\rm Orion}/5$, respectively. Yet, comparison of the UV to NIR extinction curves has shown that there is no difference between the galaxies for wavelengths longer than $0.3\,\mu$m (Gordon et al. 2003). In the visual to UV parts the extinction curves differ only for the lines of sight towards regions with an extensive star formation activity. In the Galaxy, the existence of metalicity gradient of about -0.09 dex/kpc is well known (e.g. Carraro et al. 1998). On length–scales we deal with when studying dark clouds, the metalicity gradient appears to be insignificant. The "standard" interstellar extinction law, an average of interstellar extinction curves for a sample of stars in the Solar neighbourhood has ben recently tested and proved to be valid up to 5.2 kpc from the Sun (Clayton et al. 2000). We, therefore, accept that in quiescent region of the Solar neighborhood both assumptions hold to a reasonable level.

1.1. The L1217/L1219 dark cloud

L1217/L1219 lies at the southernmost edge of the Cepheus flare cloud complex. Kun et al. (2000b) studied stars having far-infrared excess (a signature of youth) in the vicinity of the cloud. There are indications that star formation is still going on in the cloud. We conducted extensive molecular line observations and gathered available IR data in order to study YSOs, dust and molecular gas distribution (Nikolić and Kun 2004). Some results are reported in Kun et al. (2000a). In this paper we present further results.

The paper is organized as follows: in Section 2 we describe the input data, Section 3 reviews the two techniques used to derive total optical extinction in the direction of the cloud, in Section 4 we present our results of the application of both techniques on L1217 followed by a short discussion about significance of the differences in the derived physical properties of the dark cloud (size and mass of the cores).

2. INPUT DATA

The Two Micron All Sky Survey (2MASS, Kleinmann et al. 1994) is an all–sky–survey in the J, H and K_s band ($1.25\,\mu$m, $1.65\,\mu$m and $2.17\,\mu$m, respectively). The catalog is publicly available both as a DVD box–set and on–line at `http:// www.ipac.caltech.edu/2mass/`.

For our study of dust distribution in L1217/L1219 i.e., derivation of the total optical extinction, we have selected an area of $40' \times 40'$ centered on $\alpha = 22^{\rm h}12^{\rm m}45.2^{\rm s}$, $\delta = 70°14'30''$ (1950). The area contained altogether 4786 stars. However, only a subset of the data was used i.e., only stars with good quality measurements in *all* bands were considered for the NIR color excess calculations.

3. METHODS

In the V broad band, the extinction (absorption and scattering by interstellar dust) in magnitudes is denoted by A_V. The $B-V$ color of a star is altered by an amount E_{B-V}, i.e., the color excess or selective extinction. The quantity R_V, the ratio of total to selective extinction, is thus:

$$R_V = \frac{A_V}{E_{B-V}}. \qquad (1)$$

Extinction is generally determined by the color-difference method: the intrinsic colors of unreddened stars are assumed known, and photometric or spectroscopic observations are made of stars of similar type which suffer extinction. From the differences, the wavelength dependence of the extinction can be derived. In the wavelength range from 1 to 13μm Rieke and Lebofsky (1985) reported R_V value for the diffuse interstellar medium of 3.09 ± 0.03, and this became known as the (normal) interstellar extinction law. Along some lines of sight, those passing through dense molecular clouds, this ratio can be as high as 5 (e.g. Whittet et al. 2001, Kandori et al. 2003). However, for wavelengths longer than 0.7μm the shape of the extinction law is independent of R_V (Cardelli et al. 1989).

3.1. NICE

The Near-Infrared Color Excess (NICE) technique was developed by Lada et al. (1994). This method combines measurements of near-infrared color excess to directly measure extinction and map the dust column density through a molecular cloud.

The color excess, $E(H-K)$, can be directly derived from observations, provided the intrinsic color of the star is known. Assuming a normal reddening law (Rieke and Lebofsky 1985) we have:

$$\begin{aligned} E(H-K) &= (H-K)_{\rm obs} - (H-K)_{\rm int} \\ &\equiv 0.063 A_V, \end{aligned} \qquad (2)$$

where H and K represent the near-infrared H and K-band (centered at 1.65μm and 2.2μm, respectively), subscripts "obs" and "int" denote observed and intrinsic quantities, respectively. The intrinsic $(H-K)$ colors of normal main sequence and giant stars have a relatively small range: for stars with spectral types between A0 and late M, $0.0^{\rm magnitude} < H-K < 0.3^{\rm magnitude}$ (e.g., Koornneef 1983). From here we may either assume that the average $(H-K)$ color of a typical star is $0.15^{\rm magnitude}$, or aim for more accurate color excess determination. Provided that the stars in a nearby control field are extinction-free, their colors are equal to intrinsic colors of the cloud's background stars.

The efficiency of NICE has been demonstrated with the studies of several dark clouds (Alves et al. 1998, Lada et al. 1999, Alves et al. 2001). However, as pointed out by Lada et al. (1994) this method has several limitations and uncertainties. First, there are uncertainties associated with the determination of color excess, largely statistical in nature. Second, in the derivation of physical quantities we may be ultimately interested in, such as extinction, gas column density and cloud mass, uncertainties are systematic.

Statistical errors encompass photometrical errors which effectively set the lower limit to the reliably measured extinction; variable reddening to the background stars produced by random, unrelated background and/or foreground dust clouds significantly contributes to the methods' uncertainty for low extinction regions; foreground stars contamination likely has a larger effect in regions of highest extinction, while the method will not work at all for regions of molecular clouds containing embedded clusters where the surface density of the embedded stars exceeds that of backgrounds stars. In principle, the effect of the embedded stars can be minimized by elimination of all stars with infrared excess. Finally, the major source of statistical uncertainty is probably the cloud structure, if the cloud is significantly structured or clumpy on scales smaller than the achieved resolution. There are of course, at least partial remedies for each problem. Photometric errors caused by the intrinsic scatter of the colors of stars are reduced by averaging over angularly close objects, assuming they are subject to the same amount of extinction. Thus, in practice the extinction is estimated as

$$\hat{A}_V = 15.87 \left[\frac{1}{N} \sum_{1}^{N} (H-K)_i^{\text{obs}} - \widehat{(H-K)}^{\text{int}} \right] \quad (3)$$

where the sum is over a set of N angularly close stars. Foreground stars should have colors indicative of zero extinction i.e. should be significantly bluer than nearby stars.

The major sources of systematic uncertainties are the interstellar extinction law for A_V, the actual gas–to–dust ratio for gas column density derivation and the distance to the cloud for mass determination. Obviously, the mass is the most uncertain quantity we derive, since it scales with the gas column density, which in turn scales with the optical extinction, which itself scales with the measured color excess.

3.2. NICER

The Near-Infrared Color Excess Revisited method (Lombardi and Alves 2001) is an optimized, multi–band method. It is designed to address two of the sources of the statistical errors that the NICE method recognizes in a uniform way. Firstly, a local extinction estimate for each star uses a multi–band approach; secondly, spatial smoothing of individual estimates introduces three techniques, each specificly aimed to target one of the sources of errors in the derived total optical extinction.

As we have shown, in the NICE method the total optical extinction, A_V, is measured by comparing the $H-K$ colors of reddened and unreddened stars. However, other combination of colors could be used, e.g. $J-H$. From the normal reddening low of Rieke and Lebofsky (1985) the color excess $E(J-H)$ scales with the total optical extinctions as:

$$\begin{aligned} E(J-H) &= (J-H)_{\text{obs}} - (J-H)_{\text{int}} \\ &\equiv 0.106 A_V, \end{aligned} \quad (4)$$

and the extinction is estimated as

$$\hat{A}_V = 9.35 \left[\frac{1}{N} \sum_{1}^{N} (J-H)_i^{\text{obs}} - \widehat{(J-H)}^{\text{int}} \right] \quad (5)$$

Which NIR colors combination should be used is not easy to decide, since both have *pros* and *cons*: stars have a larger scatter in $J-H$ than in $K-H$, but the photometric errors on J are smaller than errors on K. NICER shows that the best choice one can make is to use *all available bands*. For each color the following is valid:

$$(J-H)^{\text{obs}} = (J-H)^{\text{int}} + k_1 * A_V + \varepsilon_1$$

$$(H-K)^{\text{obs}} = (H-K)^{\text{int}} + k_2 * A_V + \varepsilon_2, \quad (6)$$

where the extra terms $\varepsilon_{1,2}$ represent the resulting photometric error of the estimates of color excess. If A_V is linear function of the both color excesses,

$$\hat{A}_V = a + b_1 * (J-H)^{\text{obs}} + b_2 * (H-K)^{\text{obs}}, \quad (7)$$

then the coefficients a, b_1 and b_2 have such values that two conditions are satisfied: 1) an expected value of A_V is the true extinction and 2) $\hat{A}_V$ has minimum variance. For technical details of the method see the source paper reference. Although here is given only a combination of two particular colors, any other available bands can be used.

Spatial smoothing is used in order to obtain a smooth extinction map with high signal-to-noise ratio. Usually we use a weighted mean where the A_V values for stars close to a specific direction on the sky are used to estimate the extinction in that direction. The weight is combination of a spatial term, usually a Gaussian with the appropriate width and an error weight which is inversely proportional to the variance of $\hat{A}_V$. Suspected foreground stars are excluded from the sample by using a sigma–clipping criteria or a median estimator. The sigma–clipping technique is an iterative process: first, $\hat{A}_V$ is estimated, then all stars that have $\hat{A}_V$ different by more than a factor of e.g. $3\sigma_{\hat{A_V}}$ from the first estimate are dropped out. The process is repeated until convergence. An alternative for discriminating foreground stars is to use a weighted median, a robust estimator having (unfortunately) noise properties that are difficult to study.

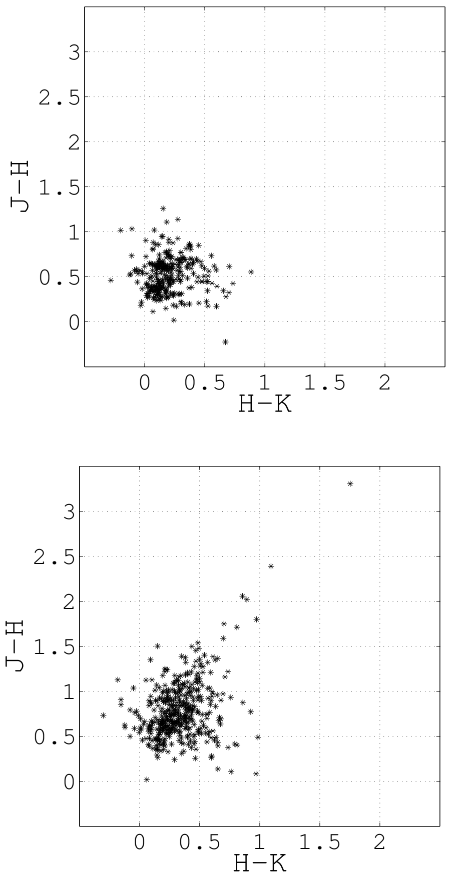

Fig. 1. *The color-color diagram for stars in the control/reference field (top) and for stars in the L1217/1219 cloud region (bottom). The reddening due to the dust in the cloud stretches the locus of stars in the plot.*

4. RESULTS AND DISCUSSION

Fig. 1. shows the color dispersion of stars in the control field and the cloud area. Stars in the control field are used to set the intrinsic colors and color dispersions.

The preliminary total extinction maps, A_V, of the L1217/L1219 area are shown in Fig. 2. For the NICER map all three bands, J, K, H, are used; the NICE map is constructed from only $H - K$ colors. Both maps were spatially smoothed using a weighted mean Gaussian. With condition of a minimum two stars in a beam satisfied we achieved spatial resolution of $3'$. At this stage, we assumed that the fair closeness of the cloud (400 ± 50 pc, Kun 1998) means that there is no foreground stars contamination. Table 1. lists the areas with the optical extinction greater than the values specified in the first column. The assumed distance to the cloud is 400 pc.

Table 1.

A_V	L1217	[deg^2]	L1219	[deg^2]
[mag]	NICER	NICE	NICER	NICE
0.5	0.0332	0.0315	0.0193	0.0169
1.0	0.0283	0.0276	0.0168	0.0135
2.0	0.0221	0.0159	0.0112	0.0088
3.0	0.0112	0.0088	0.0074	0.0062
4.0	0.0065	0.0055	0.0051	0.0047
5.0	0.0036	0.0030	0.0037	0.0032

Both maps basically give the same values for the peak column densities: NICER has the maximum optical extinction of 16.68 (± 0.07) magnitudes, while NICE peaks at 17.4 (± 0.1) magnitudes. The main difference between these two methods, pointed in Lombardi and Alves (2001) and also visible in Fig. 2 is the significantly reduced noise level in the NICER map. This enables us to distinguish regions with extremely low extinction levels of $A_V \approx 0.5$ magnitudes. This low gas column density would otherwise be undetectable. Our CO maps (Nikolić and Kun 2004) of the cloud further confirm this conclusion - namely, the CO molecular cloud is spread over much smaller area. This, of course, is based on the observed CO spectra that have $\sigma = 0.1$ K where we required a significant emission to be above the 3σ level.

Assuming that the absorption caused by dust in the Galaxy is linearly related to the hydrogen column density, as obtained from Lyα and H_2 absorption line, spectroscopy of stars withing ~ 1 kpc of the Sun (Bohlin et al. 1978):

$$\frac{N_{\rm H}}{A_V} = 1.9 \times 10^{21} {\rm cm}^{-2} {\rm mag}^{-1}, \qquad (8)$$

provides us with a tool to calculate the total gas mass of a molecular cloud. In the equation $N_{\rm H}$ is the total column density of hydrogen atoms, $N_{\rm H} + 2N_{\rm H_2}$, and A_V is the extinction in the V-band (Spitzer 1978). The area which is considered turns out to be critical for the comparison of masses obtained from the two methods. L1219, with just a small low extinction "halo" around the dense core has the total gas mass of 37 and 31 $M_\odot$ derived from NICER and NICE, respectively. With an error estimate of a few Solar masses, this is an excellent agreement. The discrepancy between the estimated masses in the case of L1217 is significant, 62 vs. 50 $M_\odot$ for, again, NICER and NICE, respectively. If molecular cloud's mass were to be calculated as a the total gas mass over an area with significant extinction, NICER would be the best method to derive the total spread of the gas. However, a definition of a molecular cloud/core requires that the optical extinction in the area is above some threshold level, usually $A_V \geq 4^{\rm magnitude}$, equivivalent of the hydrogen number densities that are $> 10^3\,{\rm cm}^{-3}$. At this level, the areas defined by the different methods agree within the errors (see Table 1.), thus canceling advantage of NICER.

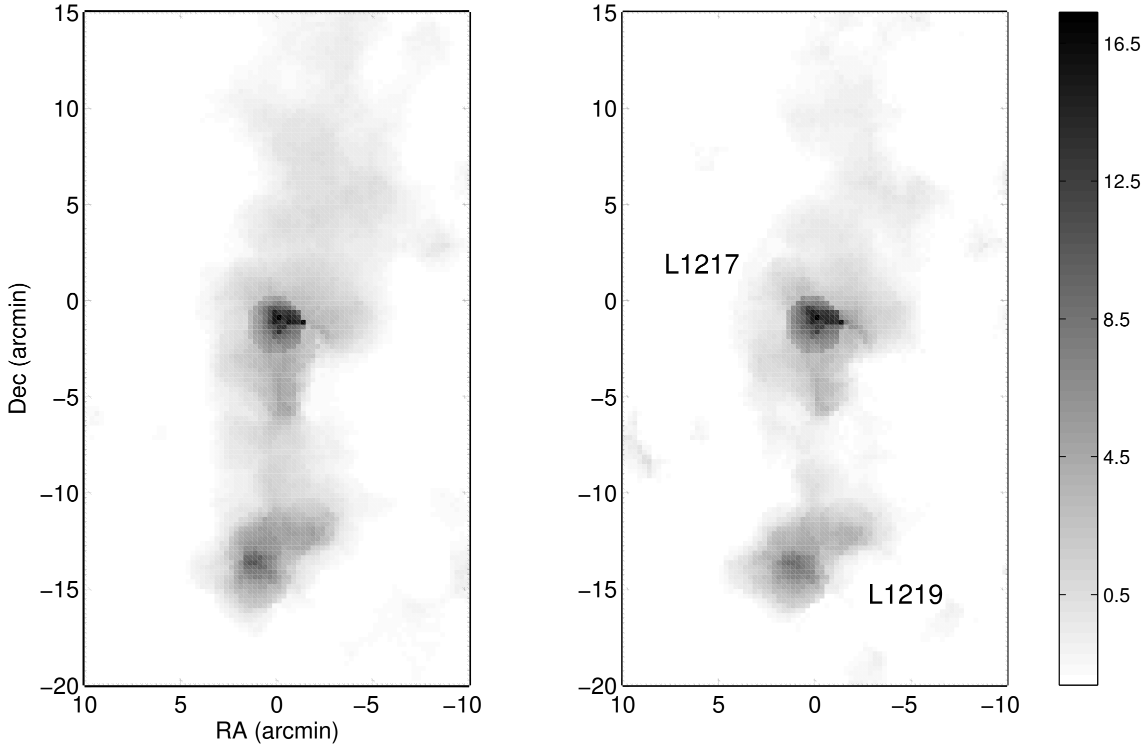

Fig. 2. *Total optical extinction of L1217 derived according to NICER (left) and NICE (right panel). Grayscale is representative of both panels.*

The true value of this method may be in the "generalization" i.e., simultaneously treated multi–wavelength data. We plan to apply this method on the combined 2MASS and MSX (REF) data on some other cloud (covered by the MSX survey; MSX is the Midcourse Space eXperiment, a satellite astronomy experiment which has mapped the entire Galactic Plane in the 4.2–26 μm wavelength range (Price et al. 2001).

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УКУПНА ОПТИЧКА ЕКСТИНКЦИЈА У ПРАВЦУ МОЛЕКУЛСКОГ ОБЛАКА L 1217/L 1219 ИЗВЕДЕНА ИЗ ДВЕ РАЗЛИЧИТЕ МЕТОДЕ ОДРЕЂИВАЊА ЕКСЦЕСА БОЈА У БЛИСКОМ ИНФРАЦРВЕНОМ ДЕЛУ СПЕКТРА

С. Николић[1,2] и М. Кун[3]

[1]*Departamento de Astrononomía, Universidad de Chile*
Casilla 36-D Santiago, Chile

[2]*Астрономска опсерваторија*
Волгина 7, 11160 Београд 74, Србија и Црна Гора

[3]*Konkoly Observatory of the Hungarian Academy of Sciences*
H-1525 Budapest P.O.Box 67, Hungary

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Оригинални научни рад

На основу изведене вредности укупне оптичке екстинкције, а полазећи од претпоставке да расподела прашине у молекулском облаку верно одсликава расподелу гаса, у овом раду смо проценили величину и масу густих молекулских језгара у комплексу L1217/L1219. Прорачун укупне оптичке екстинкције заснива се на две методе одређивања ексцеса боја у блиском инфрацрвеном подручју спектра, тзв. "стандардна" (енглески: NICE) и "проширена" (енглески: NICER) метода. Резултати потврђују да је сврсисходније користити проширену методу уколико желимо да уочимо и области молекулског облака којима је својствена веома мала вредност оптичке екстинкције, одн. крајњег спољњег гасног омотача облака. Повећањем укупне површине распростртости молекулског облака повећава се и прорачуната укупна маса облака.